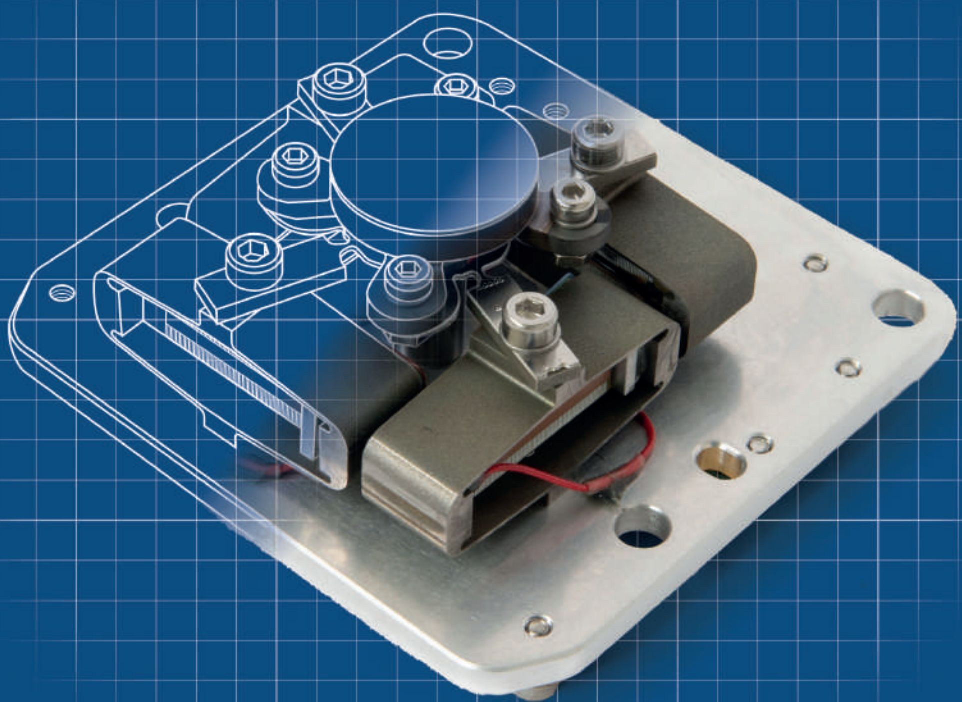
MECHATRONIC SOLUTIONS

COMPACT - DYNAMIC - PRECISE



CEDRAT TECHNOLOGIES
Innovation in Mechatronics

ACTUATORS - MOTORS - MECHANISMS - CONTROLLERS

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1. CEDRAT TECHNOLOGIES PRODUCTS, SERVICES & FACILITIES

1.1. INTRODUCTION TO PIEZO & MAGNETIC ACTUATORS FROM CEDRAT TECHNOLOGIES

Since the middle of the 90s, CEDRAT TECHNOLOGIES (CTEC) has been constantly upgrading and enlarging its range of actuators and related electronic solutions available commercially of the shelves (COTS). In order to keep pace with its customers' needs and demands for efficient and robust mechatronic systems, CTEC has been developing **Compact, Dynamic and Precise** components. "Compact" means low mass, low volume and low power consumption, "Dynamic" means both the ability to provide fast motion as well as the capability to withstand and to survive vibrations and shocks and "Precise" means an outstanding position resolution, accuracy and stability.

These components are presented through several families of "Actuator" product:

- Piezo actuators (APA® & PPA™),
- Piezo mechanisms (XY stage, Tip Tilt platform, Shutter) with several degrees of freedom (dof),
- Piezo motors (MSPA series),
- Magnetic actuators (MICA™, BLMM),
- Fast Steering Mirrors (M-FSM & P-FSM).

These actuators as well as the dedicated drivers, sensors and controllers are presented all along the sections of this catalogue. These actuators coupled with the relevant drive, sensor and controller offer a wide range of standard components and functions to build your own mechatronic systems and applications. In order to satisfy specific requests and demanding environments, CTEC can develop both customized components and mechatronic systems under your technical specifications, from building blocks briefly described here below.

To offer its customers the "state of the art" of products, some new products are given with "preliminary data", which means that the product has been designed but has not been tested as much as requested by CTEC quality standards at the time of printing.

1.2. SYNTHESIS OF CEDRAT TECHNOLOGIES OFFER

All products from CEDRAT TECHNOLOGIES (CTEC) can be assembled to build a complete mechatronic system *(Table 1.a)*. CTEC offers a complete range of products, either standalone or OEM.

Note that mechanisms can produce larger stroke than the elementary actuators. All these electromechanical devices can be driven and controlled with the appropriate electronics.

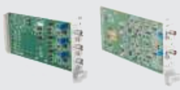
Technology	**PIEZO**					**MAGNETIC**		
Actuator / mechanism	 Amplified Piezo Actuators	 Parallel Pre-stressed Actuators	 Fast Piezo Shutters	 Piezo Stages	 Piezo FSM	 Magnetic FSM		 Magnetic Actuators
Power supply	 RK series powered racks	 PLa series	Not included	Optional	Optional	Not included	Not included	Not included
Amplifier	 LA75 SP75 SA75		 CAu10	 CCBu20	 CCBu40	 MCLA18	 MCSA480	 CMAu10
Controller	 UC55	Optional	Not included					Not included
Sensor conditioner	 SG75 ECS75	Optional	Not included			 ECS45 ECSF		Not included

Table 1.a: Summary of possible configurations using CTEC products

1.3. OVERVIEW OF CEDRAT TECHNOLOGIES PRODUCTS & TECHNOLOGIES

CTEC COTS linear (piezo & magnetic) actuators cover a range of max free displacements from 10 µm to 10 mm and more, see Fig. 1.b.1. They have been designed in order to offer the largest possible stroke while keeping a compact size. The selection of a linear actuator solution is made regarding the need in force, displacement and working frequency (Fig. 1.b.1).

Regarding CTEC mechanisms like XY stages and Fast Steering Mirrors (FSM), the stroke vs bandwidth performance are summarized respectively in the plots (Fig.1.b.2) & (Fig.1.b.3).

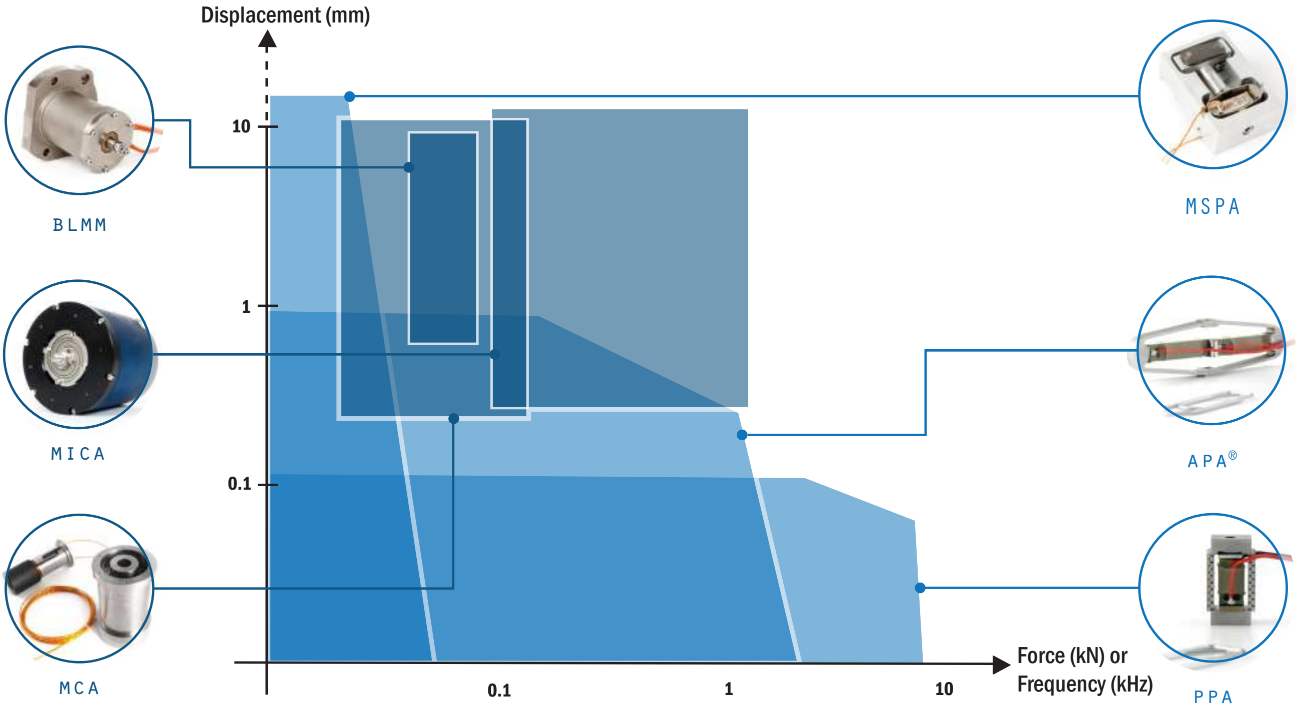


Fig. 1.a: CEDRAT TECHNOLOGIES range of products

XY PIEZO STAGES

Displacement up to 300 µm

Resonance frequency from 200 to 3000 Hz

TIP-TILT STAGES & FSM

Angular stroke up to 150 mrad

Resonance frequency from 100 to 3000 Hz

1.3.1. PARALLEL PRE-STRESSED ACTUATORS PPA

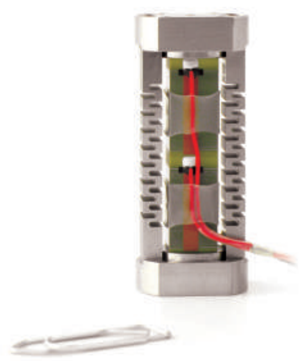


Fig. 1.b: PPA40L

PPA are solid-state linear actuators. They only use the expansion of the active material, in 33-mode, to produce a useful displacement. This displacement is proportional to the voltage within a 170 V range.

Typically, the actuator's deformation is about 0.1% of its length (1 µm/ mm), so their displacements are limited to about 100 µm. However, the forces are naturally high, easily higher than 1 kN.

PPA use an external deformable frame to pre-stress the ceramics. PPA are cheaper, more compact, and display a much better dynamic behaviour than conventional direct piezo actuators.

More info on chapter 4.4, page 71.

1.3.2. AMPLIFIED PIEZOELECTRIC ACTUATORS APA®


Fig. 1.c: APA120ML

APA® are solid-state long-stroke linear actuators (Fig. 1.d). They are based on the expansion of the active material and on a mechanism to amplify the displacement. This amplified displacement is proportional to the

voltage within a 170 V range. The advantages of APA® are their relatively large displacements combined with their high forces and compact size along the active axis. It leads to a deformation of 1% (10 µm/mm) or more. Therefore, their stroke may achieve up to 2 mm.

Thanks to their compactness, APA® can be stacked in series to reach longer strokes. Since APA® are robust, they can also be used in dynamic applications, including in resonant devices.

More info on chapter 4.2, page 60.

1.3.3. PIEZOELECTRIC MOTORS


Fig. 1.d: MSPA integration within a mechanism

CTEC has over 20 years of expertise in piezoelectric motor technology, encompassing ultrasonic, stick-slip, and inch worm technologies. Each type of motorization has its own advantages:

- Ultrasonic motors excel in speed.
- Stick-slip motors are known for their reliability and robustness in demanding environments.
- Inch worm motors offer high power and minimal vibration rejection.

CTEC recently achieved the world record for power density in an inch worm piezoelectric motor (for more information, click here).

Our MSPA technology, based on the stick-slip principle, is available in standard configuration and customizable for seamless integration into our customers' environments.

1.3.4. MOVING IRON CONTROLLABLE ACTUATOR MICA™

For applications where long strokes and highly dynamic actuators are required, CEDRAT TECHNOLOGIES (CTEC) develops magnetic actuators, the MICA™. With strokes up to 10 mm, forces up to 500 N, MICA™ are perfectly complementary products to our well-known piezoelectric offer.

MICA™ are robust, long lasting and powerful controllable actuators, with a force proportional to the current and can be used either for high frequencies or static applications. They come with an embedded position sensor and convenient mechanical interface for an easy integration.

They are the preferred option for high force continuous nonstop operations that require efficient heat sinking, and long lifetime fatigue requirements.

More info on chapter 7.1, page 92.

Fig. 1.e: MICA300CM

1.3.5. BISTABLE LINEAR MOVING MAGNET BLMM

BLMM actuators, are bi-stable actuators providing two locked positions at rest, without electrical power. Electrical power is required only to switch from one position to the other one, which is achieved with a very fast switching time, as per required in latching operations. Such actuators present high miniaturisation capabilities, as well as a high degree of response time performance tuning.

More info on chapter 7.2, page 95.

1.3.6. MOVING COIL ACTUATORS MCA

MCCA are the actuators having the best linearity performance achievable for very long stroke requirements beyond 10 mm. MCCA are the best controllable actuator reference for fine precision control and linearity, and are the preferred option for large motions in translation or rotation.

Compared to other technologies such as moving magnets and moving iron, moving coil actuators present some limitations with regard to heat dissipation, coil temperature, and flying electrical connection reliability.

1.3.7. SENSORS SOLUTIONS

CTEC has developed a deep know-how in strain gauge integration to control the displacement of piezo actuators. Demanding requirements, such as long term stability or vacuum environment compatibility can be achieved by this technology.

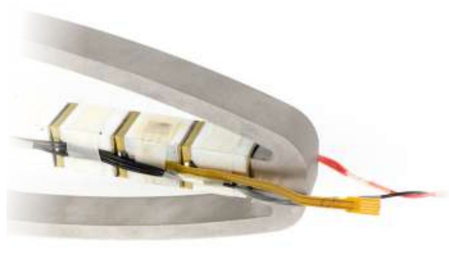


Fig. 1.f: Strain gauge sensor on an APA500L actuator

Also CTEC offers magnetic position sensors which provide a contactless distance measurement. Different technologies and topologies are proposed, to cover a wide range of applications, from nanometric to metric range. Some of these sensors are exclusively integrated as standard to CTEC actuators and mechanisms in order to provide a position or state (open/close) information. For instance, strain gauge sensors are proposed as an option for most PPA and APA® piezo actuators. Eddy Current Probes are integrated in mechanisms like M-FSM45 or M-FSM62. Other sensors are delivered in the frame of custom development projects, either as a spares or integrated into custom mechanisms.

More info on chapter 9, page 119.

1.4. CEDRAT TECHNOLOGIES SERVICES & FACILITIES

CEDRAT TECHNOLOGIES (CTEC) heritage in space industry makes us used to work on complex problems in deep interaction with our customers.

From specific interface to dedicated design, through testing, system integration and assistance, our sales engineers help you all along your project.

1.4.1. ENGINEERING SERVICES

CTEC develops custom mechanisms for your actuating or sensing function. We can assist you with:

- Consulting and feasibility studies
- Modelling (FEA), design work,
- Control law simulation, control SW development
- Prototyping and testing
- Industrial projects leading to a turn-key solution
- R&D collaborative projects funded by the European Commission (Horizon Europe projects) or other frameworks (Eureka, national, regional projects)
- Manufacturing for the account of customers under QA
- Technology transfers (Licensing)
- IP management and patent support

CTEC's know-how, facilities and experience allow its team to efficiently develop new actuators, sensors, mechanisms, electronics, control laws or high level mechatronic systems, with its optics or its load, accounting for its environment.

CTEC performs step-by-step developments in partnership with its customers. Expertise, optimization, design, prototyping, testing, manufacturing, any of these phases can be addressed to help our customers reaching their demanding application targets.

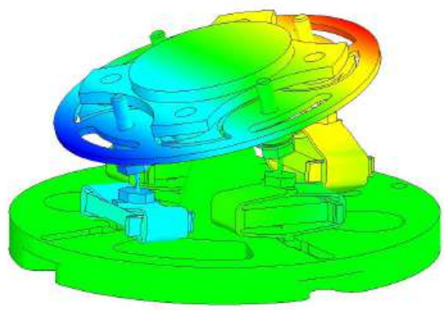


Fig. 1.g: CAD view of a CTEC mechansism

Fig. 1.h: Measurement of the flatness of a FSM mirror using Zygo interferometer

CTEC is permanently developing its mechatronics technologies: please do not hesitate to take a look at our website for any updated information or ask for questions.

In terms of service through a project, CTEC can also customize an existing product or technology to new environmental conditions: thermal range, resistance to particular vibration spectrum, lifetime... as found in aerospace, medical, oil industries... Some examples of customization for particular applications are given at the end of each chapter.

1.4.2. PRODUCTION & LAB' CAPABILITY

CTEC produces thousands mechatronic products a year for its customers in its facilities in France (Meylan).

Our production and labs teams exploit a surface of 1000 m² and about 100 workbenches equipped for soldering, high-precision assembly, testing...

New ISO7 and ISO5 clean rooms allow to comply with demanding applications for space, optronics, ultra-high vacuum (UHV) instrumentations.

We can apply several quality standards (ECSS, MIL-STD, ANSI/IPC3) above our ISO9001 certification.

CTEC makes use of specialized test equipment for functional characterization and environment testing of mechatronic devices, which include:

- Dimensional metrology and Zygo interferometer allow for measuring dimensions and mirror flatness (WFE).
- Several interferometres, vibrometres and autocollimators are used to measure the actuator's main linear or angular displacement & speed as well as parasitic displacements with high precision.
- Climatic and Thermal Vacuum chambers allow the analysis of thermal behaviour and/or of the effects of primary or ultra vacuum (such as Paschen effect).
- Electrodynamic shaker is used for testing resistance and/or performances of products under shocks and vibrations.

Additionally, we use to work in collaboration with specialized laboratories and industries to answer to more specific needs, such as Destructive Part Analysis, Radiation tests, EMC measurement and CE marking.

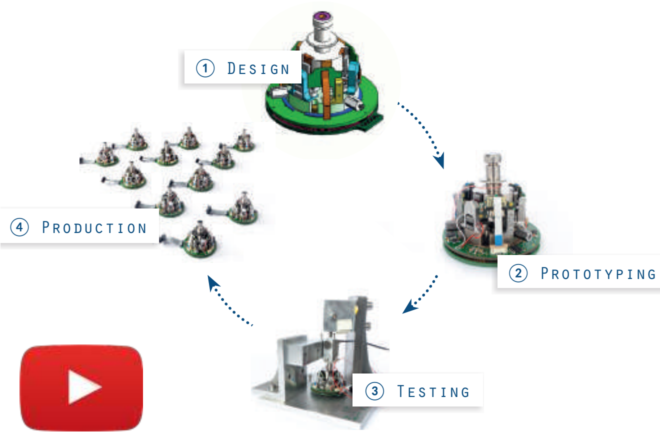


Fig. 1.i: Click to watch our video "From design to batches"

1.4.3. TECHNICAL ASSISTANCE & TRAINING

Fig. 1.k: Training at CTEC

CTEC can help you to turn your ideas into innovative projects! From training to dedicated assistance, we respond precisely to the way you wish.

CTEC provides comprehensive training courses dedicated to engineers and technicians who wish to discover, improve, or recover their knowledge in various fields of electrical engineering and mechatronics. Training sessions are performed by CTEC's experts, using their experience in mechatronics or detection components and systems. Our training offer covers the fields of actuators, motors, transducers, sensors based on electric, magnetic, piezoelectric, ultrasonic effects or materials, electronics driving and control as well as their applications.

Beyond the topics approached in our catalogue, we can also provide customized training courses to meet the customer's specific needs.

We can offer you two kinds of training courses:

- Intercompany training courses organized in our premises,
- Customized sessions : In this case, we define a program together. These courses can be held either in your premises or ours in Meylan (France) .

Last but not least, CTEC has a partnership with the CETIM to promote mechatronics training courses. As a cross-over point between skills, knowledge, and organizations, CETIM is a key player in mechanical innovation used to increase companies' competitiveness . This partnership provides you with state-of-the-art infrastructures and services.

For more information about our training offer visit our dedicated webpages and/or feel free to contact our training department by phone **+33 (0)4 56 58 04 00**.

Fig. 1.j: CETIM technical training center

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Actuator & Sensor

2. TUTORIAL

2.1. TUTORIAL ON PIEZOELECTRIC ACTUATORS

2.1.1. INTRODUCTION TO PIEZOELECTRIC MATERIALS

In 1880 the Curie brothers first examined the piezoelectric effect on crystal materials, which has the ability to produce electrical charges in response to externally applied forces. This is called the direct effect. This effect is reciprocal; meaning that the piezoelectric material changes its dimensions under applied electrical charges.

In 1922 Langevin proposed the first actuator based on crystal materials. To enhance its efficiency, this actuator was driven at resonance. The discovery of piezoelectricity in PZT (lead zirconate titanate) in the late 1960's increased the number of applications for industrial use. Piezoelectric transducers based on bulk PZT rings have been developed for sonar, ultrasonic welding, ultrasonic cleaning applications, etc. Sensor technology using piezoelectric ceramics (pressure or force sensors, hydrophones, accelerometers...) has matured since then. Based on piezoelectric bulk PZT rings, actuators for positioning purposes have also been studied. However, to obtain the deformation level required for this type of applications, it is necessary to use high input voltages. For instance, 0.5 mm thick PZT rings require an excitation voltage of approximately one thousand volts, which is clearly too high for several practical purposes. Multilayer Actuators (MLA), derived from the high capacitor technology, were introduced on the market in 1988 to circumvent the previous limitations. Because MLA are easy to operate, they have been increasingly used in various applications. The required excitation voltage of 150 Volts or less is well adapted to modern electronics.

These new materials are used by CEDRAT TECHNOLOGIES (CTEC) to build high energy density actuators and other devices, which are available either as standard or customised products, and which can be supplied with the dedicated electronics.

2.1.2. CHARACTERISTICS OF PIEZOELECTRIC MATERIALS

Piezoelectric materials are crystalline solids whose asymmetric structures create an electric dipole moment in the crystal lattice, which is sensitive to both the elastic strain and applied electrical field.

PZT materials are ferroelectric materials under the Curie temperature: the poling process gives the material its remanent polarization. During the poling operation, the material is subjected to a high electric field at the Curie temperature. If the material is subjected to a greater temperature than its Curie temperature, it is no longer piezoelectric. It can be repolarised to be piezoelectric again under certain conditions.

Stresses and strains are related to each other by the Young's modulus of the ceramic. In addition, a stress generates an electric field through the inverse piezoelectric effect. Since the ceramic is a dielectric medium, the electrical displacement is related to the electric field. These relationships can be combined in several sets of equations.

For example:

$$S_\alpha = s^E_{\alpha\beta} T_\beta + d_{n\alpha} E_n$$

$$D_m = d_{m\beta} T_\beta + \varepsilon^T_{mn} E_n$$

α, β = 1, ..., 6
m, n = 1, 2, 3
S: Strain
T: Stress
D: Induction
E: Field
sE: Compliances at constant field
d: Piezoelectric strains per unit of field
εT: Permittivity at constant stress

The previous equations can be combined to define the electro-mechanical coupling coefficient, which can be seen as the ratio of the convertible energy to the total energy supplied to the piezoelectric actuator. Practical values of the material's coupling coefficient can be higher than 50 %, but in actuators, or in resonant transducers, the effective coupling factors k_{eff} are usually lower. The electromechanical coupling coefficient should not be regarded as the actuator's efficiency. The set of equations shown above does not take any loss into account. Commercial piezoelectric ceramics can be classified as soft-type or hard-type materials based on the ease or the difficulty of depolarising them. Table 2.a lists some typical properties of active materials.

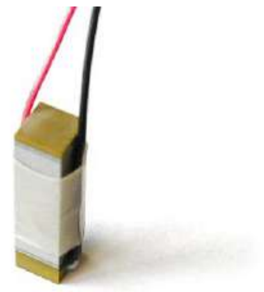


Fig. 2.a: View of a piezo ceramic stack (MLA)

Actuators made from single crystals or Electro-Active Polymer's (EAP) are still in their infancy, but may lead to new actuators in the future: their strain capabilities up to respectively 3 % and 300 % are outstanding.

Magnetostrictive materials like Terfenol-D are also studied at CEDRAT TECHNOLOGIES (CTEC). They expand when subjected to a magnetic field. Despite the losses occurring in the excitation coil, actuators based on this material may be well suited for very low-voltage or power applications. Customised actuators and transducers based on this material can be built by CTEC upon request.

Electrostrictive materials, such as PMN-PT also exist in multilayer. This material displays a low hysteresis (<2 %), but is much more temperature-dependent than PZT material.

2.1.3. ADVANTAGES & LIMITATIONS OF PIEZO ACTUATORS

- Their solid-state design with no rolling parts, so that they are not subjected to wear
- Unlimited resolution, making them ideal for nanopositioning
- Low power consumption
- Low heat dissipation
- High force / mass ratio, allowing their fast response time
- Possible non-magnetic option
- Possible operation in ultra high vacuum
- Possible operation in cryogenic temperatures
- Limited displacements range (below 2 mm)
- Limited to temperatures below 100 °C (or 150 °C in H.T. option), although some progress is being made for automotive applications

2.1.4. PARALLEL PRESTRESSED ACTUATORS PPA

Direct piezo actuators are the most simple type of actuators: they consist of a stack of pre-stressed piezo ceramic. CTEC configuration consists in pre-stressing the MLA stack through an external elastic frame, leading to a Parallel Pre-stressed Actuator PPA.

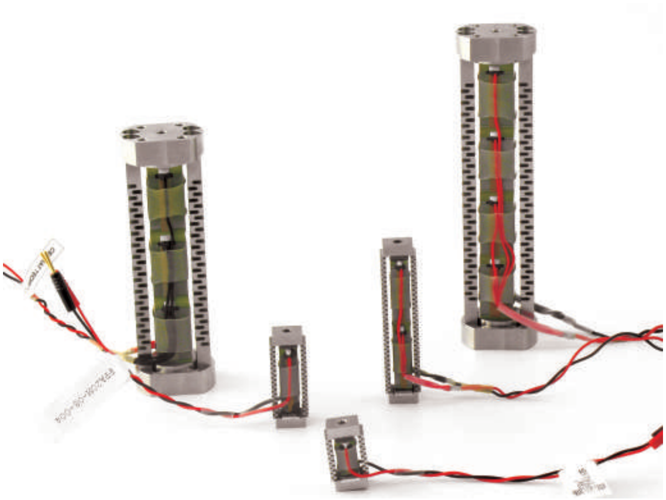


Fig. 2.b: View of PPA

PPA use the expansion of the active material, to produce a useful pushing displacement. As most of the energy strain is stored into the active material, the effective coupling factor of this structure is high, generally higher than 50 %, as well as the elastic energy per unit of mass.

MATERIALS	CONTROL FIELD	YOUNG'S MODULUS AT CONSTANT FIELD (GPA)	MECHANICAL QUALITY FACTOR (QM)	ELECTRO-MECHANICAL COUPLING COEFFICIENT K33 (%)	QUASISTATIC MAXIMUM STRAIN (PPM)
> Bulk piezoelectric					
PZT-8	Electric	74	1 000	64	+/- 110
PZT-7	Electric	72	600	67	-
PZT-4	Electric	66	500	70	+/- 150
PZT-5	Electric	48	75	75	+/- 300
Single-crystals (PZN-PT)	Electric	10	-	90	3 000
> Multilayered piezoelectrics (MLA)					
Soft-type	Electric	45	25 - 50	70	1 250
Hard-type	Electric	62	200 - 500	60	800
> Electroactive polymers (EAP)					
PVDF	Electric	1	20	30	1 000
Dielectric elastomers	Electric	1	-	-	3 000 000
> Magnetostricives					
Terfenol-D	Magnetic	25	10 - 20	70	1 600

Table 2.a: Properties of piezoactive materials

Because the pre-stress level of PPA is well controlled, they display a good dynamic behaviour and can be operated at resonance.

The displacement is roughly proportional to the voltage, from -20 to 150 V, which can be produced with special power electronics. The relation between the displacement and the voltage is not exactly linear because of the hysteresis of the active material. This effect can be well controlled with the appropriate feedback electronics, which linearise the system's behaviour.

As the strain of present piezo materials is limited to 0.12 %, the induced displacement is necessarily small, even with very long actuators. That is the reason why there is no direct piezo actuator offering 200 µm of stroke available on the market.

Due to non active pieces (end parts, prestress mechanism), the deformation of the actuator is smaller than that of the material itself, leading to values from 0.08 % to 0.10 % (0.8 to 1 µm/mm) in the PPA80L. Thus, a 100 mm long PPA can reach about 80 to 100 µm. The longest PPA can hardly be longer than 200 mm because of the risks of breaking in buckling. That is the reason why there is no direct piezo actuator 200 µm of stroke available on the market (in this case Amplified Piezoelectric Actuator APA® offer an alternative solution).

2.1.5. AMPLIFIED PIEZOELECTRIC ACTUATORS APA®

The displacement limitation of Parallel Prestressed Actuators PPA can be overcome thanks to an elastic mechanical amplifier. Various designs, most of them using flexural hinge, have been proposed in the past. Stresses become very high in the hinges during actuation, resulting in fatigue effects.

Amplified Piezoelectric Actuators APA® are based on a shell without any hinges. High displacements of APA® combined with high forces show that these actuators achieve displacement amplifications of 2 to 20 and have a good mechanical efficiency. Thanks to this amplification and to their shape ratio, they can achieve deformations from 1 % to 10 %. Note that their deformation for a positive voltage is a contraction, meaning that APA® are pulling actuators.

Fig. 2.c: View of an APA120S

For example, at 150 V, the APA400M produces free displacements up to 400 µm and blocked forces up to 38 N along its 14.3 mm short axis. It corresponds to a deformation of 2.8 % along the short (active) axis. This large deformation can also be found on large APA®: the APA2000L produces free displacements up to 2000 µm and blocked forces up to 66 N, along its short axis, which is about 27 mm height, meaning 7.4 % deformation.

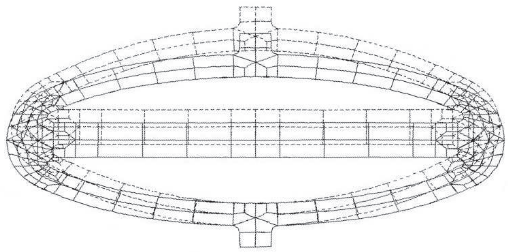


Fig. 2.d: Finite element computation of an APA®
Dotted lines: Structure at rest
Full lines: Structure deformed by the piezoelectric effect (Atila FEM result)

APA® present the following features:

- The actuators are small and compact relative to their strokes,
- The displacement magnification and the stiffness are functions of the eccentricity of the shell,
- It can be operated in a wide range of frequency including the resonance frequency,
- The bending behaviour of the shell under the piezoelectric actuation allows an acceptable distribution of stresses in the amplifier
- Bending and / or twisting moments can be exerted (to a certain extent) on the shell, which prevents the MLA from breaking. From this specific point of view, APA® are considered to be more robust than PPA.

2.1.6. STATIC BEHAVIOUR OF PIEZOACTIVE ACTUATORS

This section gives some guidelines to choose the best Parallel Prestressed Actuator PPA or Amplified Piezoelectric Actuator APA® for quasi-static applications.

Two parameters define the actuator: the stroke ΔU_0 (defined as maximum displacement) and the blocked force F_0 (max force at max voltage with no displacement).

With a stiffness:

$$K = \frac{F_0}{\Delta U_0}$$

and the force factor:

$$N = \frac{F_0}{V_{max}}$$

with V_{max}, the higher voltage value allowed for the actuator.

In most cases, the displacement ΔU is the first interest, it is controlled by a voltage input V as follows:

- **Simple case:** If there is no load and no external force on the actuator, we can talk of free displacement:

$$\Delta U(V) = \frac{NV}{K}$$

when $V=V_{max}$ by definition $\Delta U(V_{max})=\Delta U_0$:

$$\frac{NV_{max}}{K} = \frac{F_0}{K}$$

- **Extended case:** If there is a load on the actuator, when we apply a voltage, a force F is generated on the load. The resulting displacement will be:

$$\Delta U(V) = \frac{NV - F}{K}$$

when the generated force F reaches F_0, with $V=V_{max}$, it is clear that the maximum possible displacement $\Delta U(V_{max})$ becomes 0. (See *Fig. 2.e*)

It means that the actuator cannot provide both the maximum displacement and the maximum force, but a single working point along the characteristic curve is defined.

If a constant load F_{ext} (i.e. weight) is applied (smaller than the blocked force), it does not affect the stroke of the piezoelectric actuator, but only results in a shift of the maximum voltage position to a distance ΔL:

$$\Delta L = \frac{F_{ext}}{K}$$

And the maximum displacement in this situation becomes (see *Fig. 2.f*):

$$\Delta U_0 - \Delta L$$

A very different situation occurs when the piezoelectric actuator acts against a spring with a stiffness K_t (see *Fig. 2.g*).

The stroke becomes:

$$\Delta U = \frac{NV - K_t \Delta U}{K}$$

that gives:

$$\Delta U = V\frac{N}{K + K_t}$$

And with the maximum voltage $V=V_{max}$:

$$\Delta U = \Delta U_0 \frac{K}{K + K_t}$$

Piezoactive actuators can be mechanically arranged in series and/or in parallel. In the first case, displacements are added and the force stays constant, while in the latter, the forces are added and the displacement remains the same (see *Fig. 2.h* and *Fig. 2.i*).

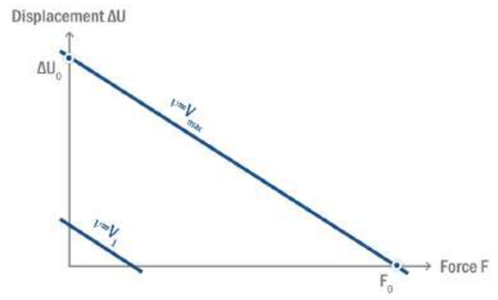


Fig. 2.e: Load characteristics of a piezoelectric actuator

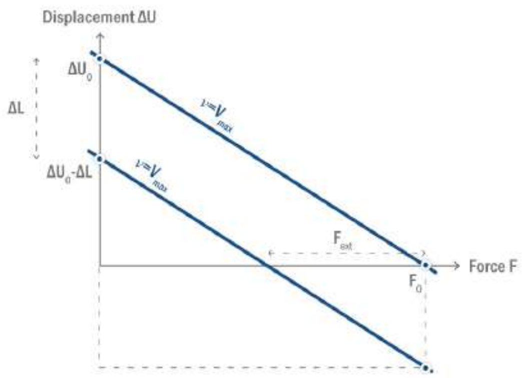


Fig. 2.f: Position shift and load characteristics of the actuator under a constant force

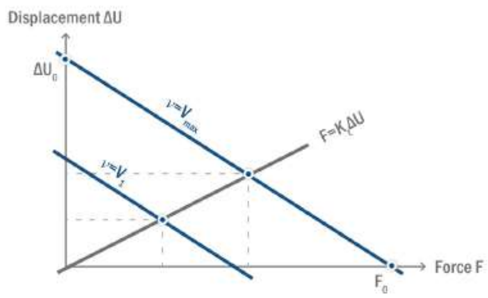


Fig. 2.g: Load characteristics under a spring with a stiffness k_t.

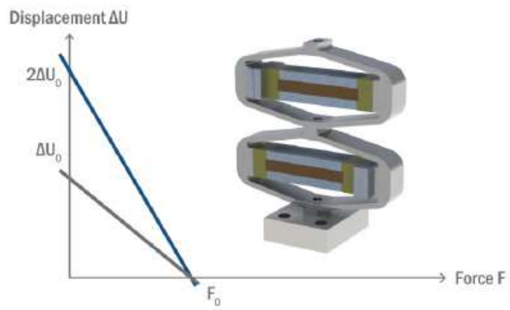


Fig. 2.h: Series arrangements of APA®

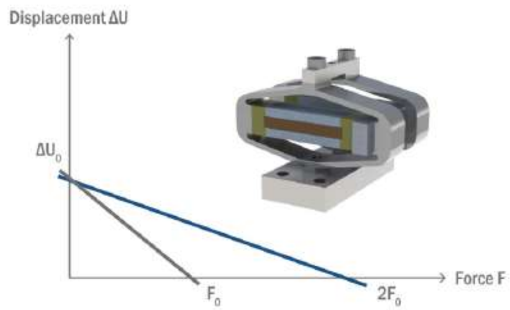


Fig. 2.i: Parallel arrangements of APA®

2.1.7. DYNAMIC BEHAVIOUR OF ACTUATORS (LOW LEVEL)

What is the effect of electromechanical resonance on actuators?

If either the applied voltage or the external force varies with the time, the displacement still follows the excitations until dynamic behaviours appear. The previous relationships remain valid in the quasi-static bandwidth, which is limited by about one third of the resonance frequency. If the actuator is unloaded, the resonant frequency is:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K}{m}}$$

where m is the effective mass of the piezoelectric actuator. If the actuator is loaded with an additional mass M, the resonance frequency f_r then becomes:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K}{M+m}}$$

The resonance frequency is also affected by external masses, spring constants or damping effects.

Dynamic operations are more complex because of the acceleration acting on the piezoelectric actuator. Displacements (and consequently stresses) can become very high.

At resonance, considering a constant voltage amplitude, they are magnified by the mechanical quality factor Q_m:

$$\Delta U_0 = Q_m \frac{NV}{K}$$

The values of the Q_m factor depend on many parameters coming both from the actuator and the load. Typical values are in the range of 20 (high level) to 200 (low level) under free condition. They decrease in case of resistive load (load exhibiting damping or energy radiation).

The settling time t_s of the actuator is limited by the resonance frequency f_r:

$$t_s \approx \frac{1}{f_r}$$

In practical situations, the settling time of the actuator can be limited by the charging time value of the electronics.

Note: The use of piezo actuators under dynamic conditions requires a careful design and a lot of experience, because of the mechanical breaking risks.

Please do not hesitate to contact CEDRAT TECHNOLOGIES (CTEC) for design and tests or to use CTEC CADs for preliminary analysis.

2.1.8. LIMITATIONS OF PIEZOELECTRIC ACTUATORS

Piezoelectric actuators have several limitations that must be taken into account in order to properly design the applications. These limits are electrical, mechanical and thermal. The impact of these limits depends a lot on the frequency region the actuators are used in (see *Table 2.b*). These frequency regions are governed by the requested function and applications.

ELECTRICAL LIMITS

The maximum voltage range is limited between -20 V +150 V. Out of this range, the piezo ceramic will be either reversed in polarisation or electrically breakdown.

In static operations (S region), their lifetime is mainly limited by the combination of DC voltage and humidity, which penetrates through the external insulation layer and leads to an increase in current leakage. A larger current leakage can lead to an electrical breakdown.

In dynamic strain non-resonant operation (DS region), electrical limits may be encountered. Because of the capacitive nature of piezo actuators, the higher the frequency is, the higher the current is (see chapter *2.1.9, page 26*). This current need may reach the power amplifier limits. To solve this problem CEDRAT TECHNOLOGIES (CTEC) develops high power linear and switching amplifiers.

MECHANICAL LIMITS

In dynamic operations, especially in resonance region (R), the piezo actuator mechanical stress limits may be encountered. To avoid tensile forces during dynamic operation a well defined mechanical pre-stress is applied on all the piezo actuators from CTEC.

The level of pre-stress is responsible of the force limit (0-peak), or max dynamic peak force for the limitation of the actuator's stroke (or its vibration amplitude).

Examples of impacts of electric or mechanical limits on an actuator's capabilities:

The advantage of a high pre-stress is shown with the APA120ML example under blocked-free conditions, loaded with a 180 gr mass.

Note: The blocked-free condition means that one interface is fixed to a rigid body and the other interface of the actuator is free to move the load. The free-free condition is where the two interfaces of the actuator are free to move.

This offers a static stroke of 130 µm @ 170 V, so 0.76 µm/V. Its blocked force is 1400N so 8.2 N/V. Its loaded resonance frequency is 1 kHz. The graphs of *Fig. 2.j* show the actuator response in harmonic analysis (sine excitation) and the 4 frequency regions. Thanks to the nominal high pre-stress of the APA120ML, the maximal dynamic peak force can reach 700 N (*Fig. 2.k*).

Thus the maximal dynamic stroke below resonance (DS region) is higher than its maximal static stroke, while the stroke at resonance (R region) is similar to the static stroke (*Fig. 2.l* and *Fig. 2.m*). It gives a very large bandwidth for displacement generation. Dynamic forces above resonance (DF region) can reach the blocked force. All these dynamic properties are important for non-resonant dynamic applications such as forced vibration generation or active damping, as well as for resonant applications such as vibration generation at resonance.

REF	FREQUENCY REGION	BANDWIDTH DEFINITION
S	Static & quasistatic	From 0 to Fr/3
DS	Dynamic Strain	Between Fr/3 and resonance region
R	Resonance	3 dB-bandwidth around mechanical resonance frequency Fr
DF	Dynamic Force	Frequency above resonance region
I	Impulse (S + DS + R + DF)	Whole frequency spectrum

Table 2.b: Different methods to use piezoelectric actuators

For the same reason, the APA120ML can survive large external vibrations and has successfully passed space qualifications. To improve even more the ability to generate or withstand dynamic movements in APA®, CTEC proposes solutions such as the Parallel Pre-stress Actuator PPA.

Note: below resonance, the displacement can be higher than at resonance, but the needed current is high, which may reach the power limit of the electric amplifier.

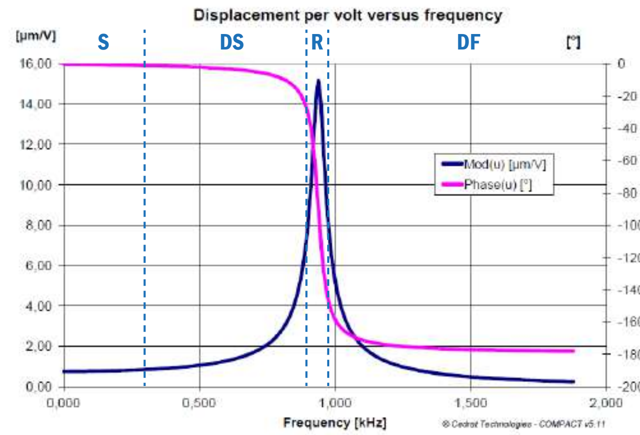


Fig. 2.j: APA120ML in blocked-free conditions, loaded with a mass of 180 gr: Displacement per volt versus frequency (See *Table 2.b*)

If a 10 times lower pre-stress were applied on the APA120ML, the maximal dynamic peak force (in DS region) could only reach 70N and so the maximal dynamic stroke at resonance (R) and below resonance would be much smaller than its maximal static stroke (*Fig. 2.n* and *Fig. 2.o*).

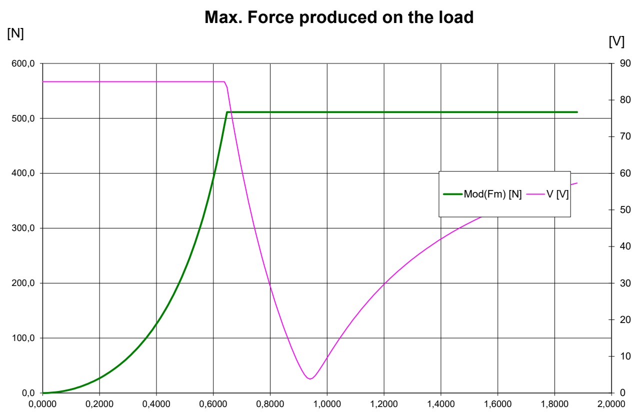


Fig. 2.k: APA120ML in blocked-free conditions, loaded with a mass of 180 gr : Maximal forces vs frequency

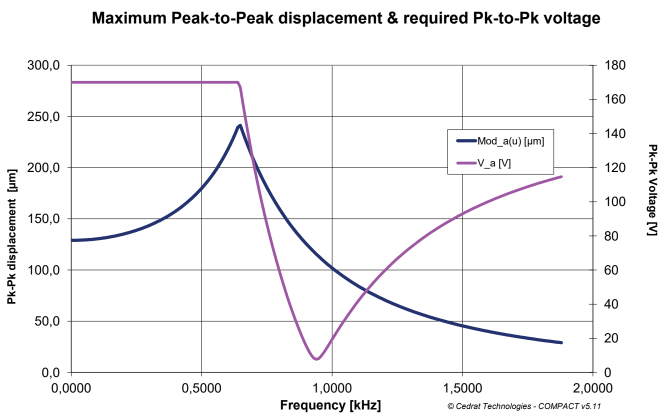


Fig. 2.l: APA120ML in blocked-free condition, loaded with a mass of 180 gr: Maximal displacement and maximal applicable voltage versus frequency.

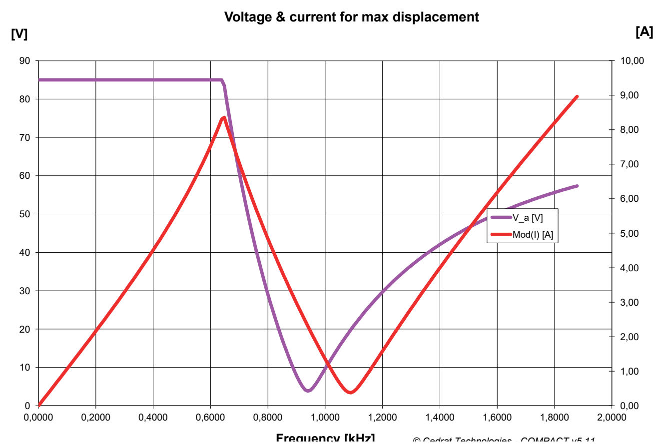


Fig. 2.m: Requested peak voltage and peak current to reach the displacement of *Fig. 2.l*

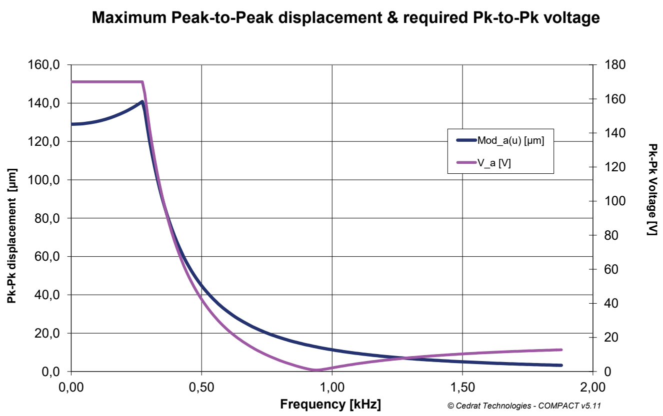


Fig. 2.n: Modified APA120ML with a low pre-stress (90 % less than nominal) under blocked-free conditions, loaded with a mass of 180 gr: Maximal displacement and maximal applicable voltage versus frequency.

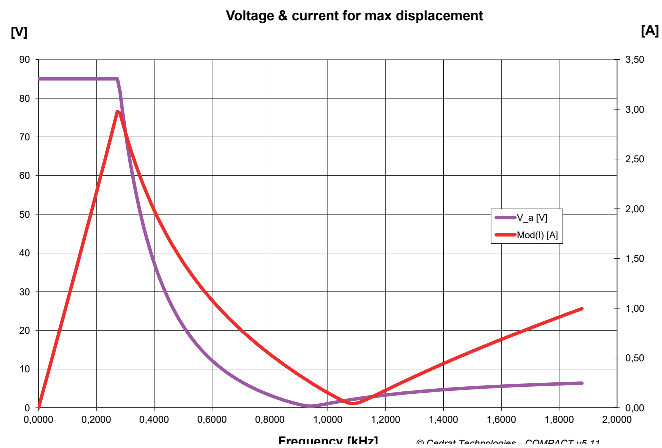


Fig. 2.o: Requested peak voltage and peak current to reach the displacement of *Fig. 2.n*

Note also that APA® with large amplification as the APA900M have reduced pre-stress. That is why their maximal dynamic stroke in DS an R region is lower than their static stroke in S region, even much below resonance. It limits their application to quasi-static conditions. Therefore an APA200M can produce more displacement at 100 Hz than an APA900M, although an APA200M static stroke is smaller (*Fig. 2.p* and *Fig. 2.q*).

Impulse applications found for example in injectors and shutters are the most complex cases regarding an actuator's limits. In these applications, a step excitation signal is typically used. This causes overshoots which clearly excite resonance and can break the actuator.

Impulse response is due to a transient excitation signal. It can be analysed as a spectrum of frequencies by Fourier Transform. This signal spectrum can be multiplied with the above transfer functions to get the actuator's response. Thus an impulse excitation uses the actuator under dynamic conditions combining resonance and non resonance frequency regions (DS, R, DF), which generates a lot of stresses in the actuator. For this reason, high-prestressed actuators are preferable to get a long life time under Impulse strain conditions. In safety preloading conditions the life time of CEDRAT TECHNOLOGIES (CTEC) piezo actuators is higher than 10 billion cycles.

THERMAL LIMITS

Due to the dielectric and mechanical losses, the piezoelectric actuator warms up under continuous excitation. Losses are mainly non-linear and depend on the excitation frequency, the voltage amplitude and the humidity level. To avoid a depoling effect of the ceramic, the temperature in the actuator should be monitored to ensure that it stays well below the ceramic's Curie temperature. So the typical temperatures range from -40°C to +80°C.

As a consequence, the duty cycle of a piezoelectric actuator in dynamic operation is limited by its thermal behaviour. For instance, to maintain a constant temperature on the APA60SM actuator, the duty cycle should be reduced or a forced convection should be applied as the driving frequency increases. There are currently a lot of researches on materials that aim at producing MLA displaying higher working temperatures (up to 200°C). Upon request, CTEC can produce actuators with these new components.

Similarly, the standard MLA work at low temperature and have already been tested in liquid nitrogen (77 K, -196°C): at this cryo-temperature, their strain is only one third of the one obtained at room temperature. As a consequence, PPA and APA® offer a reduced stroke; LSPA, LSPS present a reduced speed.

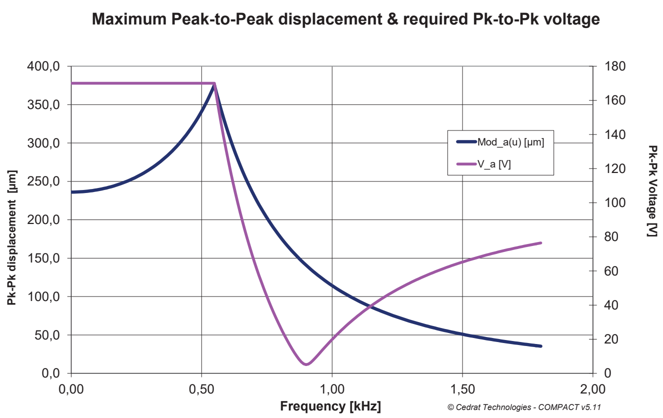


Fig. 2.p: APA200M in blocked-free condition, unloaded: Maximal displacement according to prestress and maximal applicable voltage versus frequency

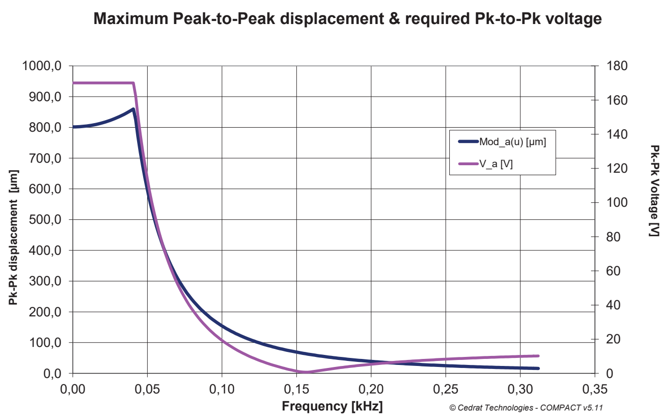


Fig. 2.q: APA900M in blocked-free condition, unloaded: Maximal displacement according to pr/stress and maximal applicable voltage versus frequency

2.1.9. DRIVING OF PIEZOELECTRIC ACTUATORS

A piezoelectric actuator is a capacitive device, which capacitance is often very large (as much as 110 µF) and varies according to voltage and frequency. Such a device is a difficult load for its driving electronics, since a significant charge transfer rate is necessary to achieve a fast response. In addition, the actuator will produce electrical energy when submitted to a mechanical load.

Linear amplifiers are the most common amplifiers and have high signal to noise ratio. Switched power amplifiers are more efficient under reactive loading in dynamic applications but have frequency limits due to switching. The general synoptic of the driving system for a piezoelectric system is given in *Fig. 2.r*.

With a linear amplifier the voltage applied to the actuator is directly proportional to the input signal. The gain of the power amplifier is set to 20.

- Input signal: –1 V to +7.5 V
- Output signal: -20 to 150 V

The current for a piezo capacitive load is given by the following expression:

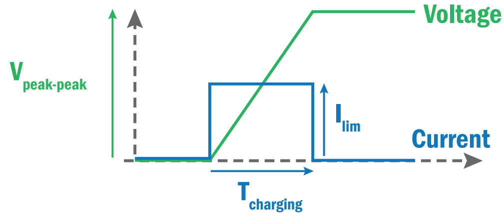
$$I_{piezo} \approx C_{piezo} \frac{dv}{dt}$$

where v is the output voltage and C_{piezo} is the capacitance value of the piezo actuator. This value may vary depending on the output voltage level.

When the variation speed of the input signal (order) increases, the current limitation I_{lim} of the amplifier limits the slew rate of the output voltage.

For a given current limitation I_{lim}, the shortest charging time is given by:

$$t_{charge} = \frac{V_{peak-peak} \cdot C_{piezo}}{I_{lim}}$$

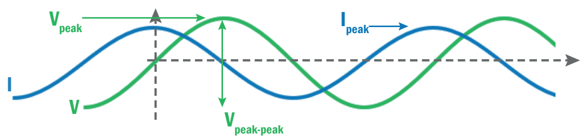


where $V_{peak-peak}$ is the voltage variation applied to the actuator.

$$V_{peak} = \frac{V_{peak-peak}}{2}$$

In case of a sine signal, the peak current I_{peak} flowing into the actuator linearly increases with the signal frequency.

$$I_{peak} = 2\pi f C_{piezo} V_{peak}$$



Where V_{peak} is the peak value of the sine voltage applied to the actuator.

Due to the electronics' current limitation, the maximal frequency for a sine signal is given by:

$$f_{\sin max} = \frac{I_{lim}}{V_{peak-peak} \cdot C_{piezo}\, \pi}$$

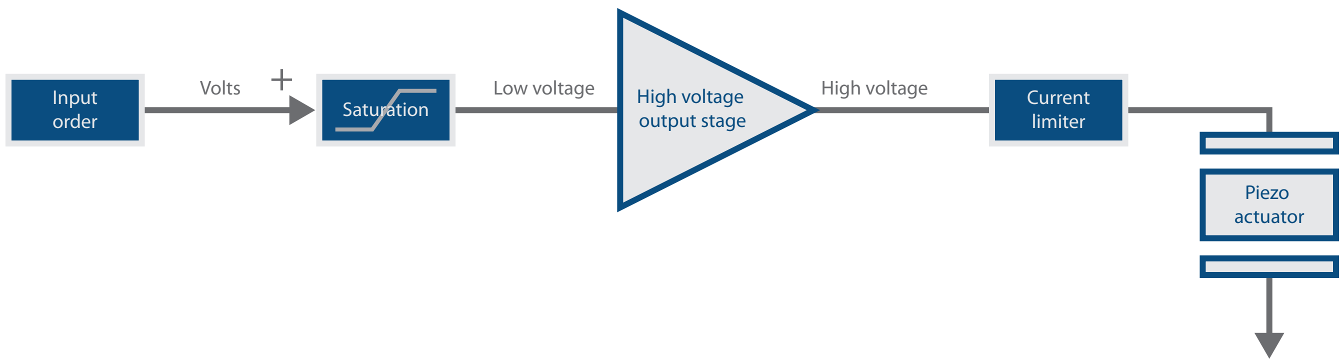


Fig. 2.r: Synoptic of driving system

PUSH-PULL MODE

In piezo mechanisms like stages, tip-tilt platforms or FSMs, each axis is moving with actuators working in push-pull mode. This brings several advantages, such as improved stiffness and thermal stability.

To drive 2 actuators in push-pull mode, complementary signals must be used, so that one actuator is pushing while the other one is pulling.

A single actuator is driven with a voltage between -20 V and +150 V. To drive 2 actuators in push-pull mode with the same voltage range, 3 connection points are used: 0V, 130V and a variable voltage between -20 V and + 150 V. (see *Fig. 2.s*)

Using 2 actuators in push-pull mode is equivalent to driving 2 actuators in parallel. Therefore, the total capacitance is doubled, and so is the required driving current.

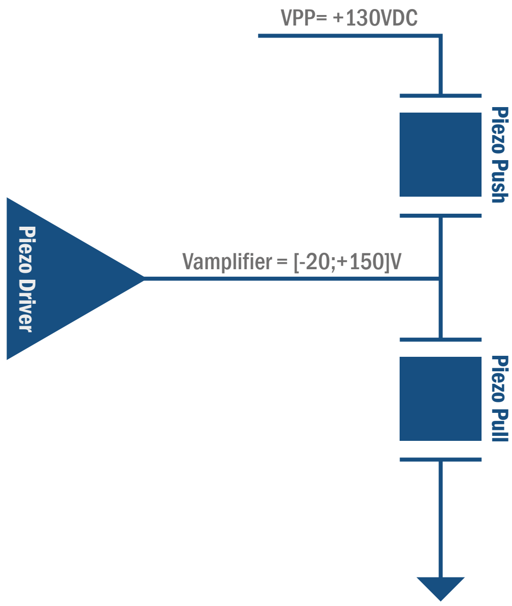


Fig. 2.s: Push-pull operation using one electric driver

PIEZO ACTUATOR'S CAPACITANCE VALUE

On an electrical point of view, a piezo actuator can be considered as a capacitance. Its value is an important parameter, as it will determine the current required to drive the actuator at a given frequency.

In CTEC actuators' datasheets, the capacitance is given at low voltage, low frequency, and no load. However, using the actuators at full voltage can increase the capacitance up to 2 times the low signal value. This should be considered while dimensioning the electronics.

In practice, the actuator is not a perfect capacitor, due to electric losses and mechanical losses. The resulting capacitance will vary according to the frequency.

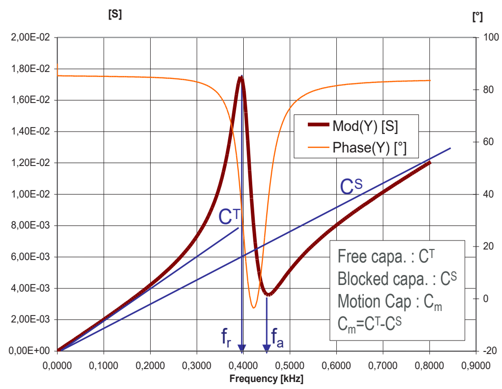


Fig. 2.t: Variation of the piezo capacitance with frequency

2.1.10. PIEZOELECTRIC AMPLIFIERS' LIMITS

The performances of CTEC's amplifiers are described in their brochures and user's manuals, with the following properties.

MAX OUTPUT CURRENT

Max output current is available for a limited time.

On LA75C amplifier, which includes an EPC (Enhanced Peak Current) feature, the amplifier can deliver a current that is higher than its permanent output current, during 600µs with a max repetition rate of 20ms (*Fig. 2.u*). This current is internally limited.

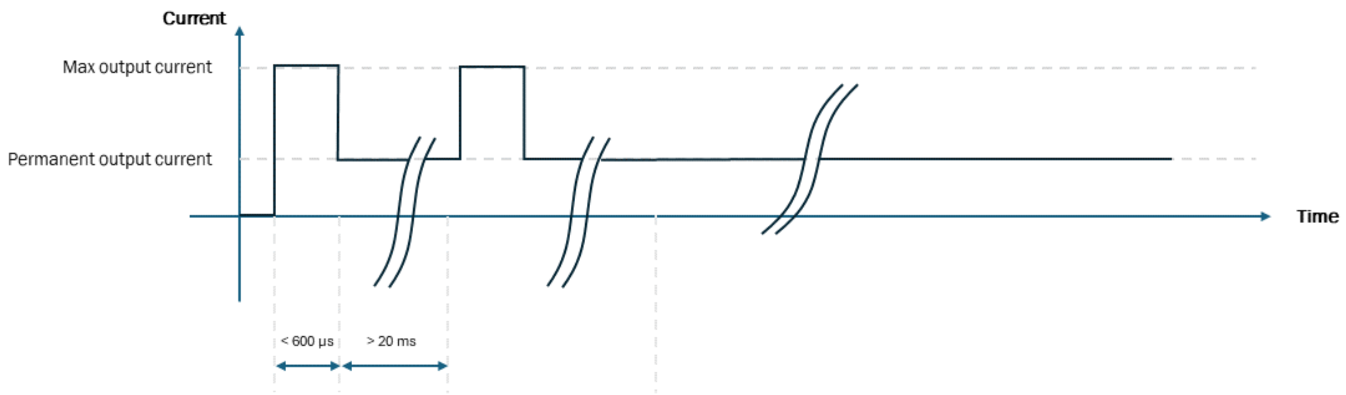


Fig. 2.u: Max output current on LA75C.

For compact embedded amplifiers like CCBu20 and CCBu40, this max output current is available for a limited time which depends on the heat dissipation performance of the integrated system (*Fig. 2.v* left).

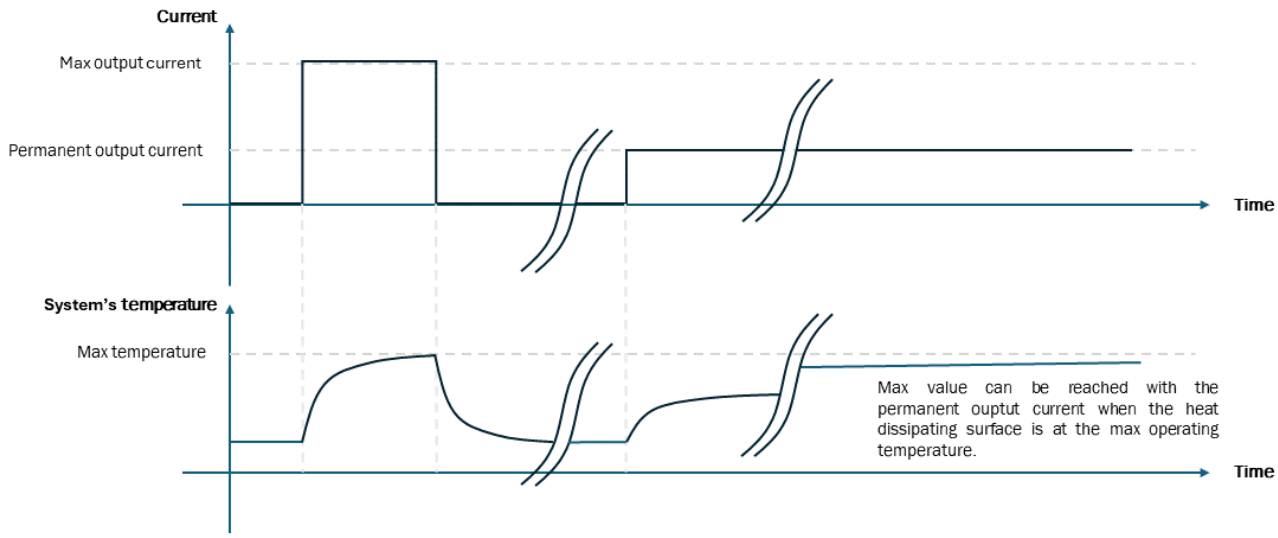


Fig. 2.v: Peak output current and max output current on CCBu20 and CCBu40 amplifiers.

PERMANENT OUTPUT CURRENT

This is the RMS current that can be delivered continuously by the amplifier. On compact embedded amplifiers like CCBu20 and CCBu40, this value is taken in the worst-case scenario: maximal environment temperature and lowest possible heat dissipation (*Fig. 2.v* right).

CONTROLLING PIEZO ACTUATORS

The resolution of a piezoelectric actuator is limited by the electrical noise of the driving system. Typical values of the signal to noise ratio of the driving electronic (below the resonance frequency of the actuator) range from 70 to 85 dB.

MLA always display a hysteresis (*Fig. 2.w*), which limits the positioning accuracy. Other effects, such as drift (*Fig. 2.x*), also limit the actuator's linearity. Therefore, displacement sensors are often used to ensure a linear response of the piezoelectric actuators through a closed-loop (*Fig. 2.z*).

When accuracy or speed is required, additional controllers are implemented in specific control loop to improve the performances of the piezoelectric mechanisms. Coupled with Strain Gauges sensors (SG75 conditioner option) or Eddy Current Sensor (ECS75 conditioner option), the servo controller (UC55) is ideally the best solution to control the displacement or to reduce the settling time of the actuators by regulating the applied order (see *Fig. 2.y*). For more information on control laws see §II.3.

For more information on advanced control laws see cedrat-technologies.com/wp-content/uploads/downloads/advanced-control-brochure.pdf

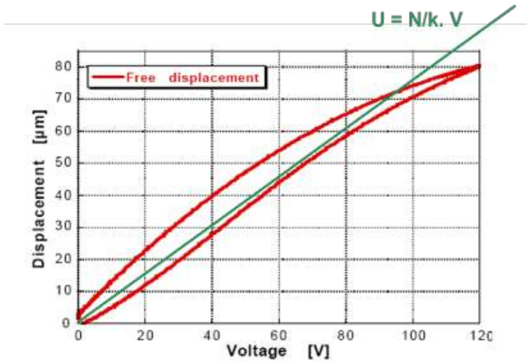


Fig. 2.w: Free displacement of a piezo ceramic under sine voltage

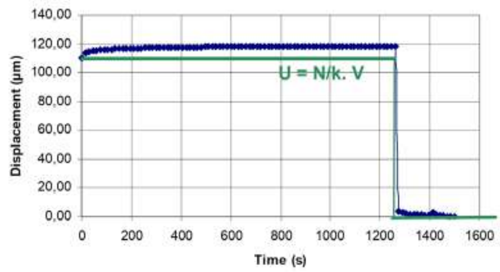


Fig. 2.x: Drift effect on a piezo actuator under constant voltage

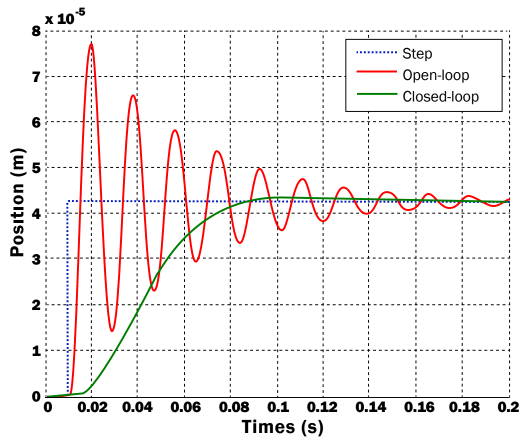


Fig. 2.y: Comparison between open loop and closed loop responses

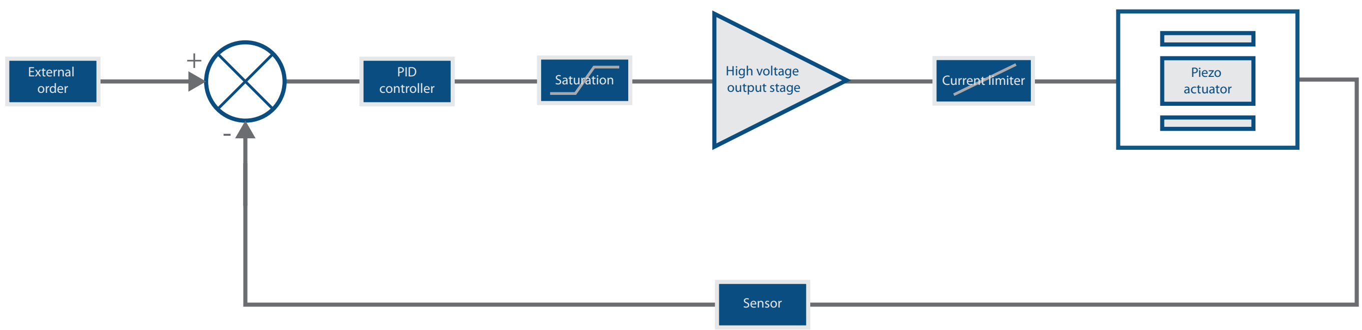


Fig. 2.z: Synoptic of a closed loop system

2.2. TUTORIAL ON PIEZOELECTRIC MOTORS

Piezoelectric actuators are widely used in high force and high dynamic applications. However, their limited strain (typically 0.1%) restrains applications to limited stroke. Even though our amplified actuators (APA®) with prestressed shell extend the initial strain of the ceramic, stroke is still limited to around 1 or 2mm.

To overcome this drawback, piezoelectric motors have been introduced. These devices can generate unlimited rotary or linear movements by accumulating small motion from the actuator. **Piezo motor technology becomes relevant when one of the following requirements emerges: Fine positioning with high holding force while unpowered vacuum operation, non-magnetic environment, cryogenic temperature**. These motors are classified into three main classes: inertial drives, inchworm and resonant drives.

2.2.1. PIEZO MOTORS CLASSES

INERTIAL DRIVE MOTORS

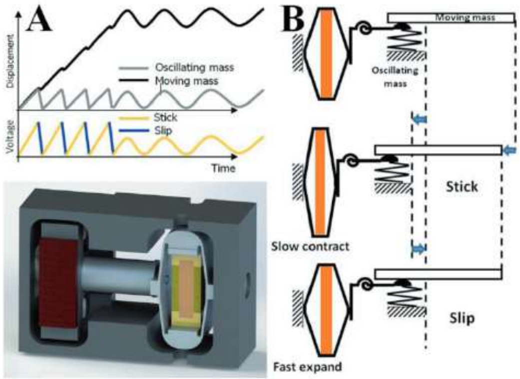


Fig. 2.aa: Working principle of inertial drive motor

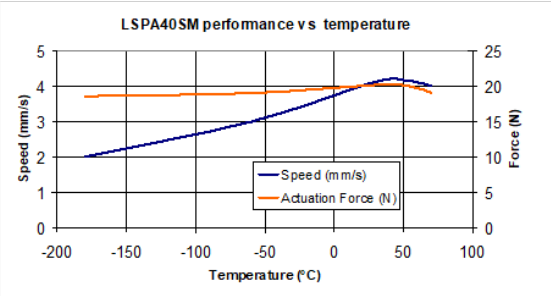


Fig. 2.ab: Performance stability over a large temperature range of stick slip motor


Fig. 2.ac: FSPA35XS

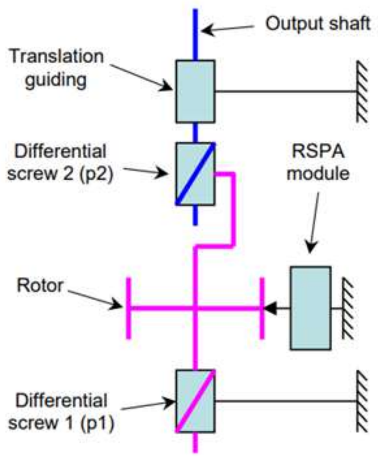


Fig. 2.ad: FSPA kinematic chain

The inertial motors are based on the «stick-slip» phenomenon (see *Fig. 2.aa*). Thanks to a sawtooth movement of the motor, the moving mass is slipping on the oscillating mass in one direction and gripping in the other direction. Long stroke can be achieved by accumulating small steps. Modular Stepping Piezoelectric Actuators (MSPA) from CTEC are long-stroke linear inertial-drive piezoelectric motors benefiting from the APA® heritage. Between each step the actuator is locked in position and a fine resolution mode can be achieved by using the actuator stroke only (powered only). Advantages are simplicity, miniaturization, single phase, not using resonance. Therefore, they operate in a wide temperature range, typically from -180°C to 70°C (see *Fig. 2.ab)*.

The main drawback of inertial drive motors is the produced force, generally limited to a fraction of the piezo available force.

$$Fam = \frac{Fba}{10}$$

$$Fbm = \frac{Fba}{3}$$

This type of motor uses friction to operate so the selection and the qualification of the friction pair of material is the key in the success of its design. Feasibility studies and developments have been conducted with partner laboratories to meet the requirements for demanding environments and longevity.

SCREW MOTORS

As an alternative, FSPA screw motors from CTEC combine the advantages of inertial stepping mode with an irreversible, reduction screw mechanism (see *Fig. 2.ac* and *Fig. 2.ad*). Its main advantage is no backlash and very high resolution which can be lower than 10nm. The internal structure allows decoupling high external forces from actuation mechanism.

Therefore, it makes the motor compatible with high loads and high levels of external vibration. The result is a motor that provides 100N of blocked force (200N at rest) with a total mass of 160grams. The prototype is based on small amplified piezo actuators, derived from standard APA35XS. The main drawback of this FSPA motor is the maximum speed achieved in standard configuration <0,5mm/s.

INCHWORM MOTORS

Another piezo motor typology, called inchworm, is based on several actuators. Some actuators are used as clamps, which allows to connect/disconnect the fixed and the moving part. Other actuators are used as extenders, providing displacement/ force to the moving part. Those motors are typically known to produce large force thanks to the active clamp. The main challenge of this motor is to compensate wear and thermal expansion effects on the clamp to operate on large temperature range. It has been realized in the frame of the Audacity project. More information on this project can be found here: cedrat-technologies.com/wp-content/uploads/technologies/collaborative_projects/AUDACITY.pdf

These motors are also very precise since they use the nanometric resolution of extenders. The primary limitation comes from the number of channels: since three or four piezo channels are required to display a walking step. In addition, the global cost depends on the number of channels.

In the framework of the ESA LISA space mission, CTEC developed a large inchworm motor composed of 4 modules of stepping piezo actuators (MSPA) with active preload (controlled with actuators). These modules are composed of clamp actuators (ensure the friction with the moving mass) and extender actuators (give the movement to the mass) as seen in *Fig. 2.ae*. These modules operate 2 by 2, one pair is clamped and extend while the other isn't clamped (see *Fig. 2.af*). With an optimization of the switch between these pairs the result is a smooth and continuous motion with limited backlash between each clamp.

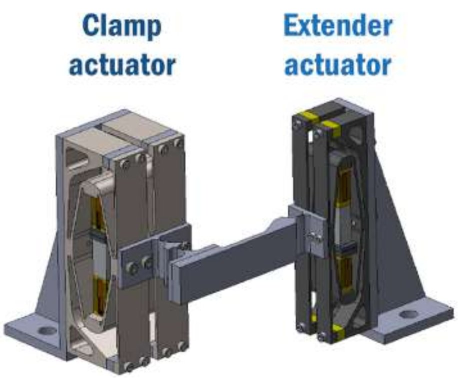


Fig. 2.ae: MSPA with active preload

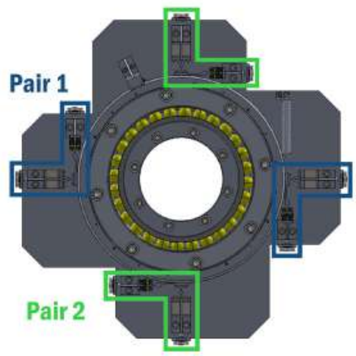


Fig. 2.af: Inchworm motor with 2 pairs of MSPA with active preload

Specific category based on the walking principle are using numerous driving channels to act like four legs: several piezo actuators perform a walking motion that leads to forward feed of a runner.

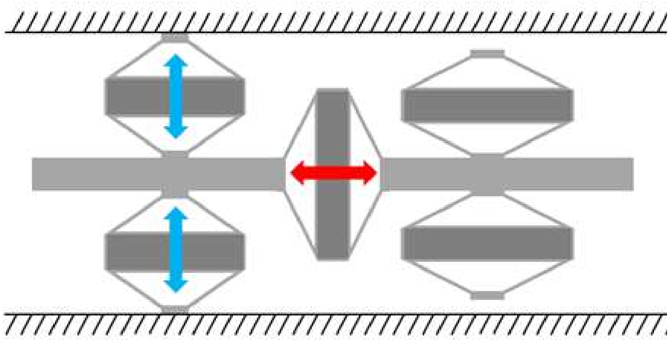


Fig. 2.ag: Inchworm motor principle

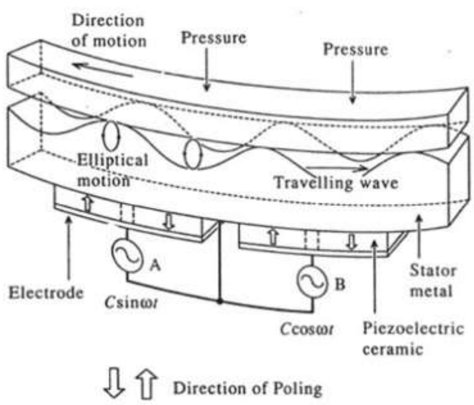


Fig. 2.ah: Principle of travelling wave piezo motor

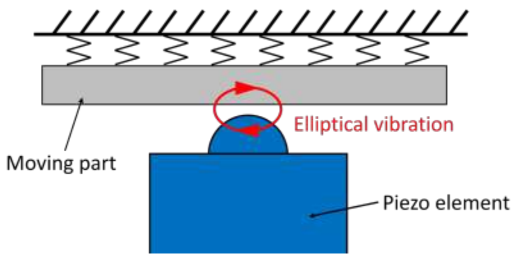


Fig. 2.ai: Principle of multimode ultrasonic piezo motor

Fig. 2.aj: Space qualified resonant piezo drive: rotary motor (left), linear motor (right)

RESONANT DRIVE MOTORS

Resonant drives motors use one or more piezo vibrating elements to generate either stationary or progressive waves. Motion is achieved by a coupling of the piezoelectric strain displacements in a stator with the rotor's motion via the friction force between stator and rotor. These motors can reach high speed and force as they accumulate kinetic energy at ultrasonic frequencies. The main drawback relies on their high sensitivity to thermal environment (and payload): their operating temperature range is limited to -10 to +55°C. Since they operate at resonant frequencies, effects such as material expansion due to temperature and wear of the friction pad can affect their performances.

Travelling wave ultrasonic motors are the most efficient piezo motors but they can only be rotative motors: if a linear motion is needed an additional mechanical system is required, leading to additional mass and efficiency loss. In the frame of a Technology Research Programme (TRP), CTEC successfully upgraded this motor to meet space standards for aerospace and defense customers including the motorization of SWARM space magnetometers. The goal of this project was to increase the reliability and lifetime of this motor for space applications in demanding environments. The tribological aspect is very important to guarantee reduced wear and a stable friction coefficient. A resonance frequency shift may lead to instability of the motion and low efficiency of coupling between the electrical energy input and kinetic output (coupling coefficient).

SYNTHESIS

The table below presents a trade-off matrix to justify the most suitable type of piezo motor according to your requirements.

The development and design of inertial and inchworm motors require transversal knowledge including:

- Tribology for better evaluation of the transmitted force.
- Signal processing for optimizing the driving signal.
- Mechanical design for thermal management.
- Mechanical design for dynamic behavior.

PROPERTIES	INERTIAL MOTORS	INCHWORM MOTORS	RESONANT MOTORS
High speed	++	+	+++
High force	+	+++	++
Temperature operating range	+++	++	+
Resistance to vibration & shocks	+++	+++	++
Low μvibrations generated	+	+++	+
Precision	++	+++	+
Force to volume ratio	++	++	+++
Miniaturization	+++	++	+

Table 2.c: Trade-off matrix of piezo motors by type

Motors are characterized by the following features:

Both inchworm and inertial motors offer blocking force at rest, options for compatibility with harsh environment, and resistance to external forces such as shocks and vibrations.

Inchworm motors provide better resolution and greater holding force/ torque, making them ideal for. pointing and position- holding applications. They also generate less micro-vibration and experience reduced wear.

Inertial motors allow for higher speeds and good resolution. In addition, they are compact and require only one channel input to be controlled. They are more suitable for scanning applications, miniaturization, wide temperature range and reduced series costs.

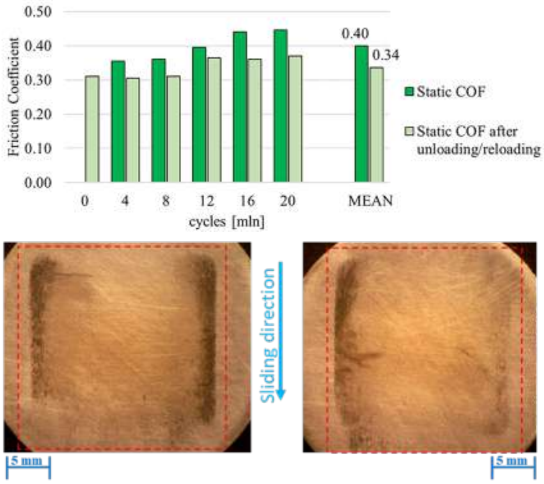


Fig. 2.ak: Friction coefficients and Microscope images after 20mln cycles.

2.2.2. TRIBOLOGICAL ASPECT

The tribological aspect of the friction surface is a critical factor in the performance of piezo motors. The choice of materials is based on a compromise between achieving a high coefficient of friction, which allows for the transmission of high forces, and minimizing wear.

CTEC has experience in the use of several pair of materials for both inertial and inchworm applications in several environments (ambient, vacuum) and across a wide temperature range (-180 to 70°C).

It is known that the tribological properties of material can change drastically depending on pressure (ambient/vacuum) and temperature. CTEC heritage in this domain is a key knowledge to develop piezo electric motors for harsh environments. The contact geometry is also designed to reduce wear and improve performance stability.

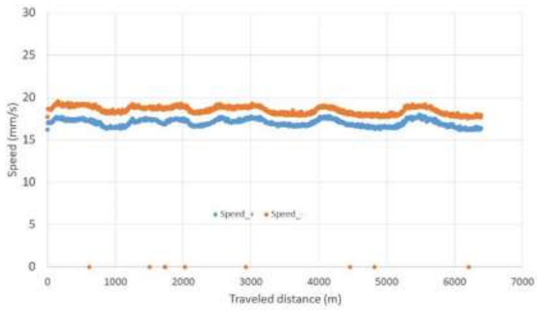


Fig. 2.al: MSPA35XS speed evolution during lifetime test

The following figure presents results of a study performed in a previous project on a test bench codesigned between UNIROMA and CTEC. Homogenous wear and stable friction coefficient were observed after 20 million cycles.

The MSPA35XS was subjected to a long-distance lifetime test, in ambient conditions, under nominal actuation signal. Working against two low stiffnesses springs, the MSPA is cycled from one side to the other until the maximum force is reached.

Fig. 2.am: View of MSPA

With the nominal settings, the MSPA travels 100mm per cycle. **A total of 28km was covered through the test,** corresponding to around 700.106 MSPA steps.

This dispersion of the speed value (due to environment conditions) could be easily compensated by a closed-loop control which was not used for this test, excitation signal remaining unchanged. During this test, 60µm of wear occurred within the friction materials. Assuming a linear wear, it’s expected to reach 1mm after 466km. The MSPA is designed to compensate for wear of up to 1 mm, after which the pad can be replaced.

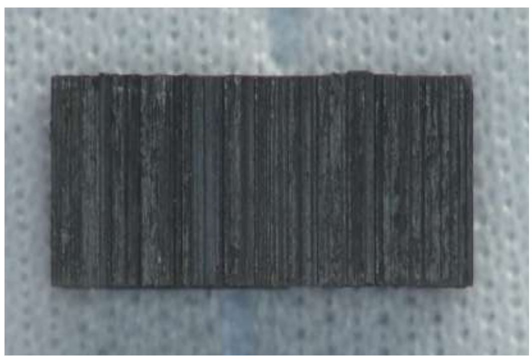


Fig. 2.an: Used friction pad

2.2.3. DRIVING SIGNALS

In the case of inertial motors, the command is based on sawtooth signal. The performance of the motor can be optimized by changing the rising, the falling time and the amplitude of the voltage. The rising time corresponds to the stick phase (the load is moving), the falling time corresponds to the slip phase (the load stays in place). The falling time must be short to generate slippage. Nevertheless, the falling time is constrained by the current limitation on the driver.

One possible architecture for inchworm motor is to use 2 pairs of actuators. For each pair, one actuator is the clamp, the other one is the extender (provides stroke to the payload).

The operating principle is the following (see *Fig. 2.ap*):

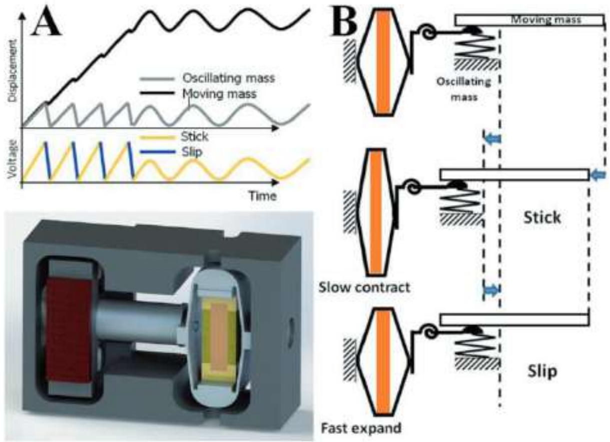


Fig. 2.ao: Working principle of inertial drive motor

1. 1st actuator pair clamping phase
2. 1st actuator pair stroke phase
3. 2nd actuator pair clamping phase, followed by the 1st pair unclamping phase
4. 2nd actuator pair stroke phase, with 1st pair retraction

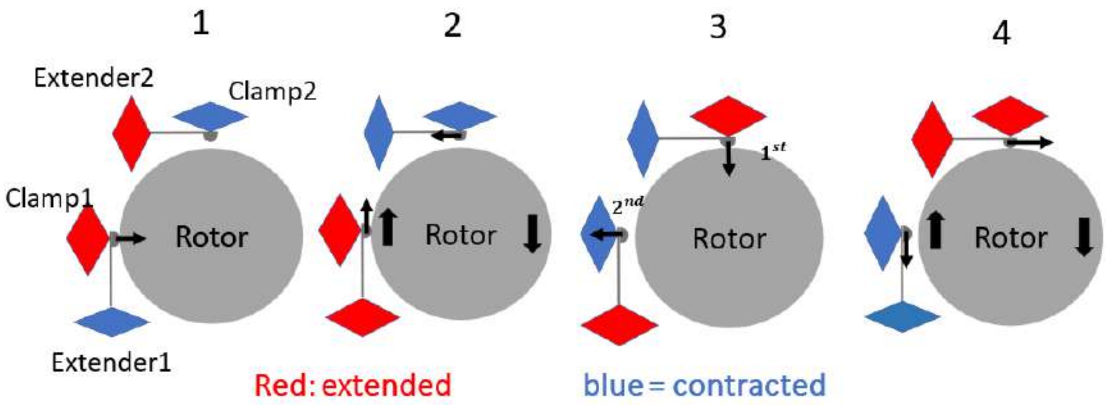


Fig. 2.ap: Inchworm motor operating principle.

Typical signals corresponding to this working principle is the following (see *Fig. 2.aq*).

In order to improve the speed performance of large piezoelectric motor we offer a large range of **embedded and laboratory electronics, with current ratings up to 20A** (see *chapter 8, page 125*). These electronics are designed to meet the specific current demands of such mechanisms.

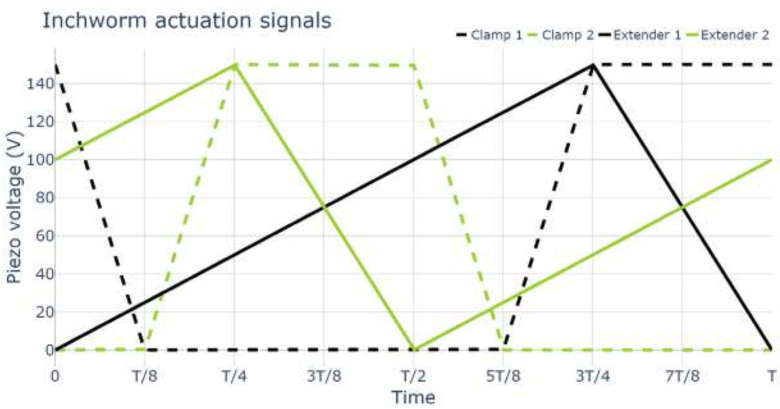


Fig. 2.aq: Typical signals used for inchworm motors.

2.2.4. BACKLASH BEHAVIOR & MICRO-VIBRATIONS

Inertial and inchworm motors are based on step accumulation. Irregularities of torque, displacement and speed are an intrinsic properties of stepping motors. The optimization of driving signals is key to enhance the performance of the motors. Specific driving signals are developed for both motorizations in order to reduce the **backlash**. This disturbance is due to the load transfer from a set of clamps to another. **Backlash also generate micro-vibration rejected in the motor environment**.

A “backlash compensation” method has been designed to remove the effect of the load directly from the driving signals (see *Fig. 2.as*). CTEC’s dedicated electronics can be used to optimize signals in order to improve the performance of piezo motors (see *chapter 8, page 125*). **This optimization is realized with feedforward profiles and pre-shaped signals**.

The *Fig. 2.at* presents the impact of signal optimization on the displacement of an inchworm motor. The orange curve presents the results obtained on the displacement after optimization. The discontinuity of the curve between the steps is reduced (spikes are related to backlash). By reducing this backlash effect the displacement is much more linear (here the remaining backlash is around 0.5% of the actuation step).

On *Fig. 2.au*, another example of backlash optimization on an inchworm motor. Only the parasitic displacement is plotted: the amplitude of the backlash is reduced by almost 70 % (red curve compared to blue curve).

Another solution to reduce micro-vibrations is to monitor internal forces and reduce them when needed. A force sensor is included in each module. It’s then used to modify the module tension in order to cancel the clamp friction force before releasing the clamp.

This solution offers the additional opportunity to also adjust the expander voltage to avoid the internal tensions that would otherwise result from the unpredictable creep (slow extension/retraction after excitation change).

Backlash can also be suppressed through the mechanical design of the motor. For instance, with motorized screw such as in the FSPA and BSMA (see *chapter 5, page 95*)

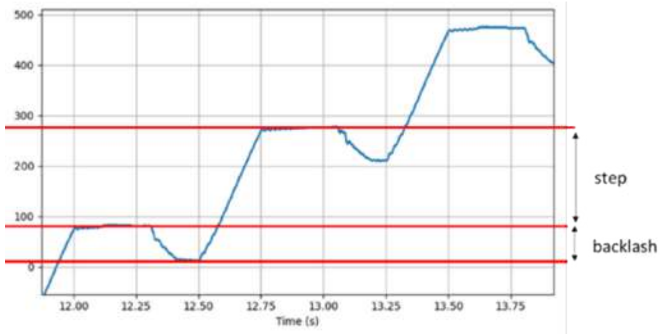


Fig. 2.ar: Step and backlash

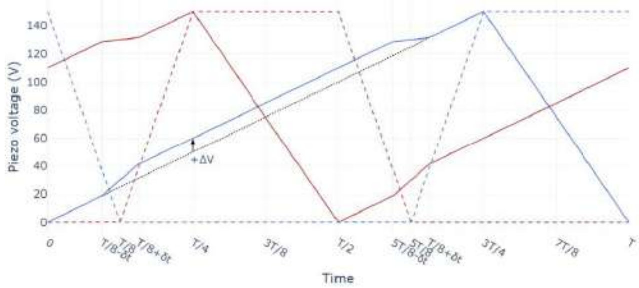


Fig. 2.as: Constant velocity mode with backlash compensation

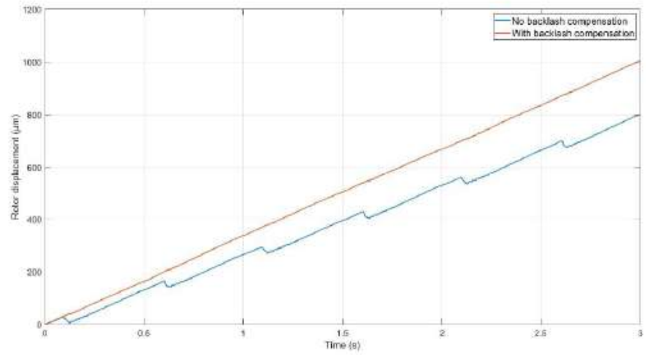


Fig. 2.at: Backlash compensation effect on displacement

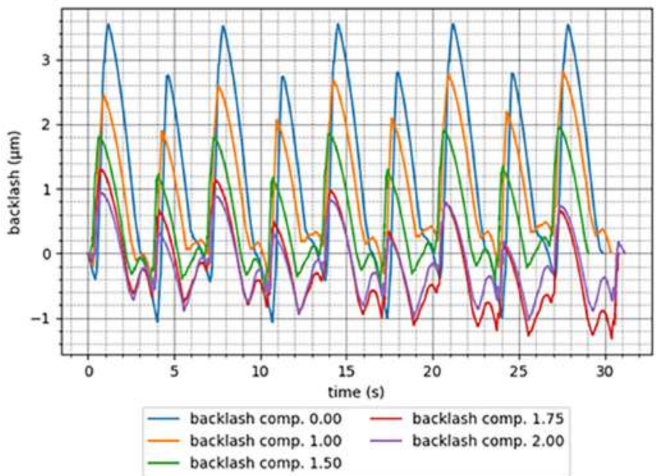


Fig. 2.au: Typical results obtained after backlash compensation

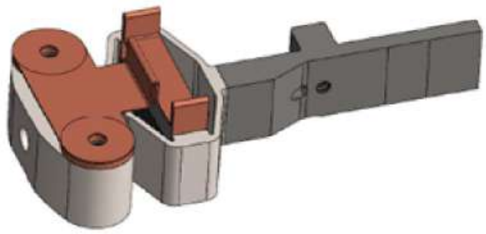


Fig. 2.av: Thermal draining solution design

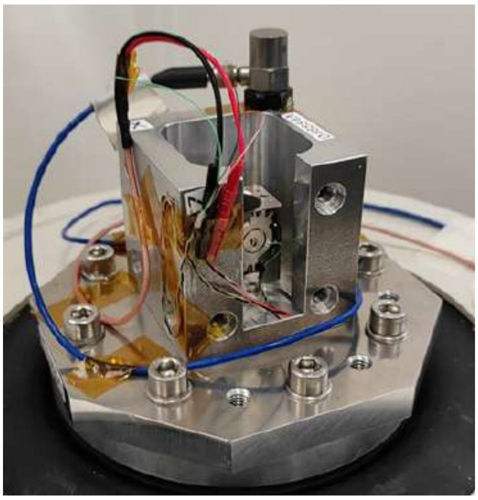


Fig. 2.aw: Random vibration operating test on piezo motor

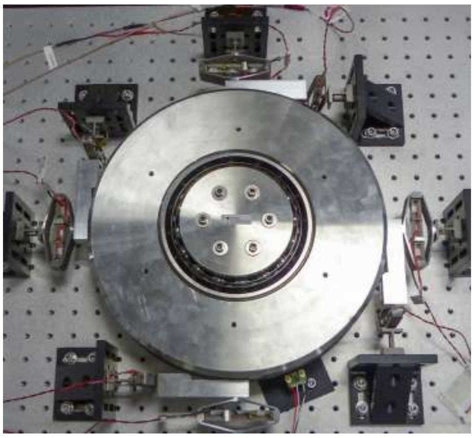


Fig. 2.ax: Inchworm motor prototype (300mm diameter)

2.2.5. SELF-HEATING

The environment temperature is an important constraint to withstand for some applications besides the motor's self-heating. For some environmental conditions (high temperature, vacuum...) and motor duty cycle, thermal draining is mandatory to ensure the motor performance and to not damage the motor and especially the piezoelectric material.

Thermal draining solutions are designed to dissipate the self-heating. These solutions are designed to respond to the thermal constraint with limited impact on mechanical performance (stroke, speed, lifetime, wear compensation ...).

A thermal drain designed for an inertial motor allowed to reduce the thermal resistance by half in vacuum configuration compared to a version without drain. The thermal drain carries heat away from the ceramic (see *Fig. 2.av*).

PARAMETER	UNIT	CASE 1	CASE 2
> Thermal draining		**No**	**Yes**
Dissipated power	W	0.47	0.72
Temperature rise	°C	52	39
Thermal resistance	°C/W	111	54

Table 2.d: The temperature on motor with and without drain

2.2.6. SEVERE ENVIRONMENT

CTEC piezo motors are well known for their capability to withstand severe environmental conditions such as high vibrations and chocs, high and low temperature, vacuum, non-magnetic, radiations, etc. These advantages are obtained thanks to dedicated design and qualification campaigns.

2.2.7. MOTOR PERFORMANCE

Several motors have been developed by CTEC based on both motorizations previously described on this chapter, such as the inchworm motor prototype presented here (*Fig. 2.ax*). For a better understanding of the advantages of each type of technology, the table below gives an order of magnitude of their main properties:

PARAMETER	UNIT	SCREW MOTORS	INERTIAL MOTORS	INCHWORM MOTORS	ULTRASONIC MOTORS
CTEC Example	-	FSPA	MSPA-based motor	APA®-based motor	LPM20
Min. step	µm	0.1 - 1	1 - 10	1 - 100	10 - 100
Speed	mm/s	0.001 – 1	1 - 100	0.01 - 100	10 - 200
Actuation force	N	1 - 50	0.1 - 10	10 - 500	1 - 20
Force at rest	N	100 - 1000	0.1 - 50	10 - 1000	10 - 100
Temperature range	°C	-200 ... +80	-200 ... +80	-20 ... +80	-10 ... +40
Volume	cm^3	10 - 100	1 - 10	10 - 1000	10 - 100

Table 2.e: Performances comparison of piezo motor technologies

2.2.8. MODULAR STEPPING PIEZO ACTUATORS (MSPA)

Modular Stepping Piezoelectric Actuators MSPA are new driving piezo stators for long-stroke piezoelectric motors for micro/nano positioning applications benefiting from the APA® heritage. The MSPA relies on a simple design: an APA®, a blocking back side, a clamp and a rod. They operate by accumulation of small steps by stick-slip (step mode). Between each step the actuator is locked in position. When the long stroke is performed, it can also be operated in a deformation mode for a fine adjustment in this case, the stroke is proportional to the applied voltage, which leads to a nanometer resolution and a high bandwidth.

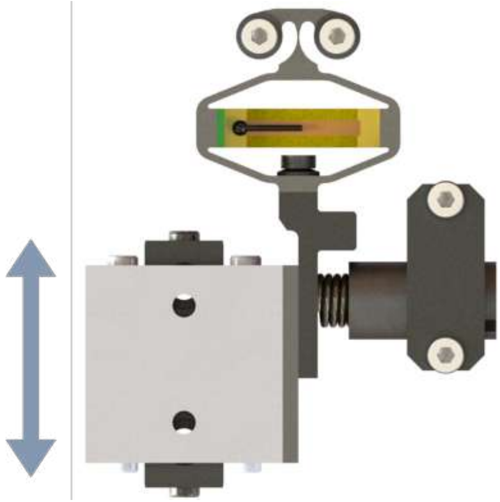


Fig. 2.ay: MSPA coupled with linear motion

To summarize, MSPA offers:

- A stepping mode producing strokes of several mm,
- A linear, curved or rotational motion,
- A blocking at rest in any position (locking without power supply), leading to a high stiffness,
- A nano positioning resolution all along the stroke,

The MSPA can be driven by a one-channel CEDRAT TECHNOLOGIES linear amplifier, LA75 , or by dedicated control box.

Many MSPA can be defined starting from the standard range of APA®. MSPA find applications as micro positioning, locking mechanisms. They can be non-magnetic and/or vacuum compatible. This concept leads to different product families:

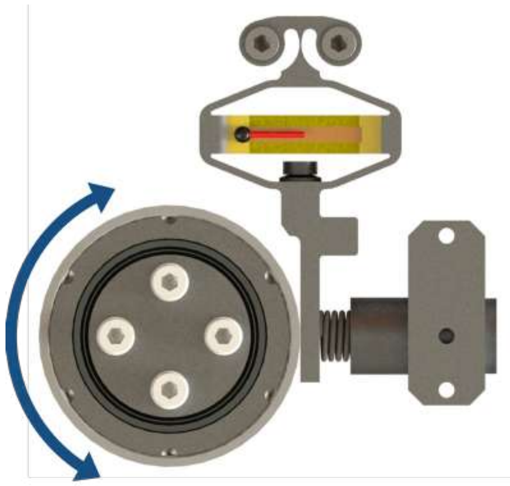


Fig. 2.az: MSPA coupled with rotary motion

- MSPA: Modular Stepping Piezo Actuators, which provide a linear, curved or rotational stepping motion,
- FSPA: Fine Stepping Piezo Actuators, which is an original variation of the MSPA that allows sub-micrometric stepping resolution combined with large forces in a linear motion.

All these products can perform in harsh environment:

- Wide temperature range (including cryogenic): - 200 °C to + 70 °C (70 K to 343 K)
- Vacuum
- External vibrations and shocks

2.3. TUTORIAL ON MAGNETIC ACTUATORS

2.3.1. MAGNETIC ACTUATORS TECHNOLOGIES

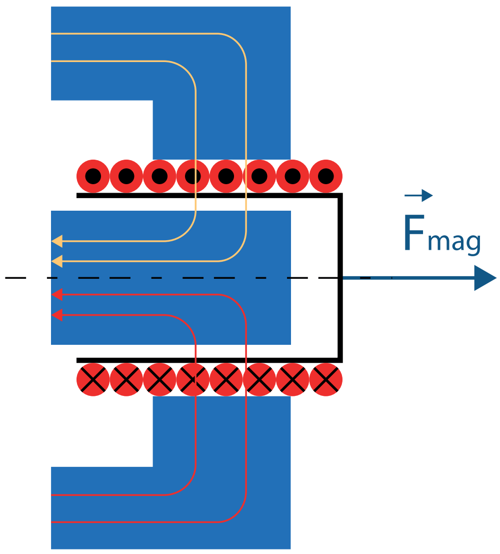


Fig. 2.ba: Voice coil actuator

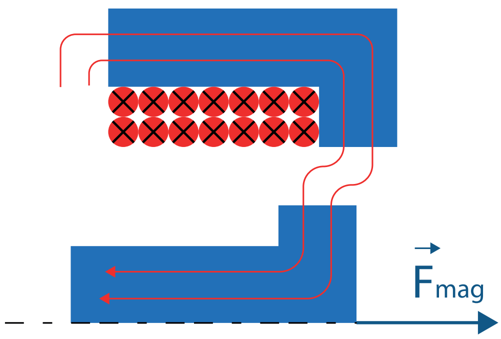


Fig. 2.bb: Electromagnet actuator

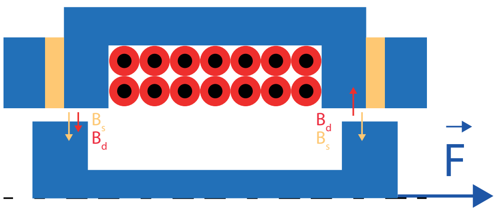


Fig. 2.bc: MICA™ actuator

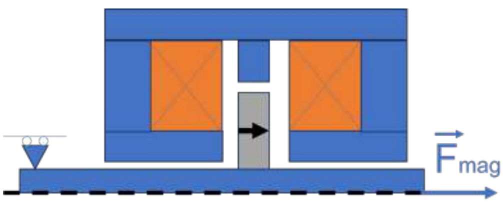


Fig. 2.bd: BLMM (Bistable Linear Moving Magnet) actuator

Electromagnetic actuators use electrical power to drive a moving part, using magnetic energies in the main air gap. This main air gap separates the fixed mechanical part attached to a support and a moving mechanical part attached to the load. They use the magnetic flux density to generate force (or torque) across the air gap. They show large variety of actuator technologies, which is the consequence of the three types of flux density sources (Coil current, magnets, soft magnetic parts) that can be distributed in the fixed or mobile parts. Theses interactions of magnetic sources generate forces and allow conversion between electrical power and mechanical power.

Magnetic actuators are based on different magnetic design principles, which produce magnetic forces, in order to generate motions, such as linear / angular displacement or acceleration, mechanical power, or static forces / torques. In particular cases, as M-FSM mechanisms, the generation of magnetic torques allows 2 degrees of freedom or more (see *Fig. 2.be*).

The magnetic principles allow to take advantage of both types of forces according to actuators topologies, which are the Laplace Forces, and Reluctant forces. Reluctant forces are linked to the minimization of energy, while the simplified Laplace force formula can be used when the supplied coil is inserted in a magnetized aera, which is the typical configuration of voice coil actuators.

Magnetic actuators properties are strongly influenced by the mechanical implementation of moving parts, and the type of motion guiding devices such as compression/traction springs, flexure bearings, sliding bearings, ball bearings, or gas bearing.

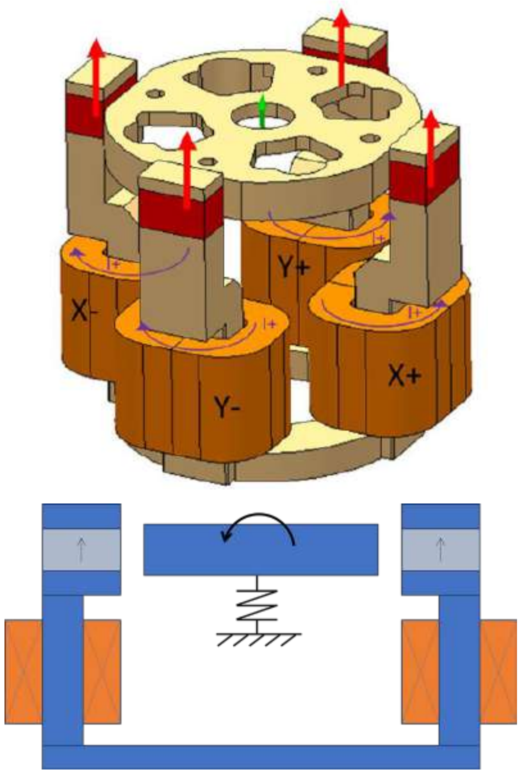


Fig. 2.be: M-FSM™ (Magnetic Fast Steering Mirror) mechanism (derived from MICA™ actuator)

MOVING IRON CONTROLLABLE ACTUATOR MICA™

Moving Iron Controllable Actuators MICA™ are based on reluctant forces, as per electromagnets, but with a magnetic topology polarised with permanent magnets, in order to achieve a variable reluctance force driven according to the current direction.

This topology (*Fig. 2.bf*) combines the force density of reluctant actuators and the linearity of the Lorentz force actuator, which makes it controllable. The permanent magnets ensure a bias of the air gap, which is the baseline of the produced linearization of the actuation force produced with applied current.

$$F_{mag} = k_A . B_M . Ni$$

Where B_M is the static magnetic field in the air gap due to the permanent magnet.

This formula established for the force when the moving part is in the central position and below saturation shows that the force is proportional to the coil current.

In general, a good proportionality can also be achieved in large ranges of positions and currents around the center and the zero current.

However, in general, the force is not constant for non-zero axial position. Similarly, the force/current gain may also vary when the mobile part is off-centered.

In that case, a force map is usually used to analyze the performance of the MICA actuator. This tool displays the force with respect to the current and the axial position of the mobile part (*Fig. 2.bg*).

Compared to the moving coil technology, the **MICA™** achieves a performance breakthrough in terms of efficiency, compactness, low heating and long life nonstop continuous operations over years without maintenance.

In particular, both coils and magnets are fixed and integrated in the stator. This allows an efficient heat dissipation by conduction. If not enough, it is easy to exploit convection with thermal drain and/or forced air cooling. Moreover, moving iron parts have compact dimensions and low mass compared to moving coils. Additionally, moving parts need no electrical connection nor heat dissipation.

And finally, **MICA™** topology makes possible to obtain mechanical designs that reduce eddy current losses in both fixed and moving Iron assemblies.

The MICA™ mechanical simplicity allows design configuration over wide range of possibilities, using **square** or **cylindrical** housing structures, as well as direct or reversed coaxial arrangements to fit custom solutions with either "**Moving Rod**" or "**Moving Cylinder**" application requirements.

Core improvement achieved by the MICA™ technology is the suppression of any limited life wire electrical flying connection, which helps achieving **infinite fatigue life**.

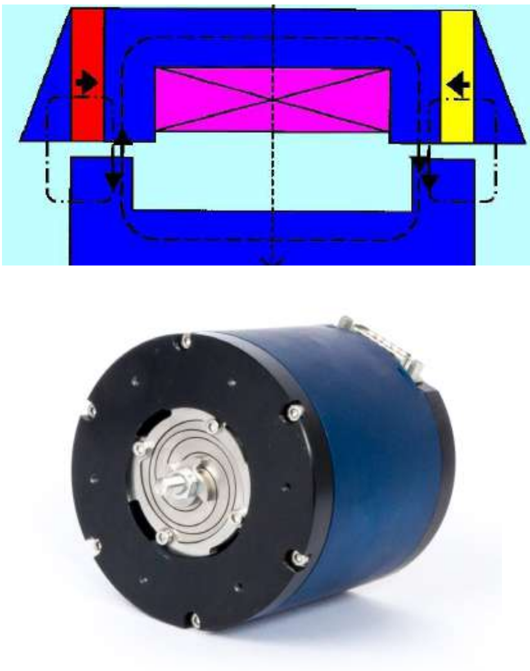


Fig. 2.bf: CTEC MICA™ Moving Iron Magnetic Principle

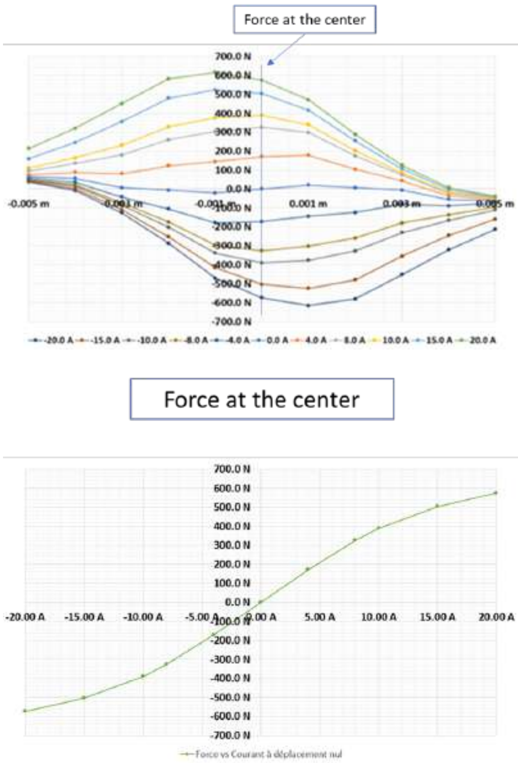


Fig. 2.bg: Example of force map of a MICA Actuator

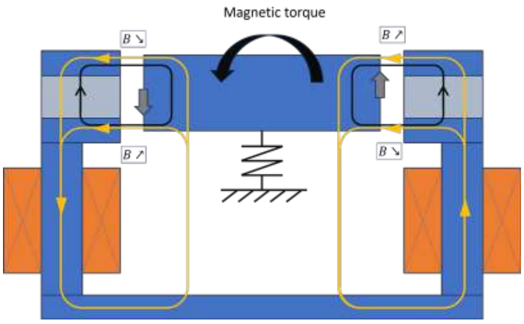


Fig. 2.bh: CTEC M-FSM Moving Iron Magnetic Principle

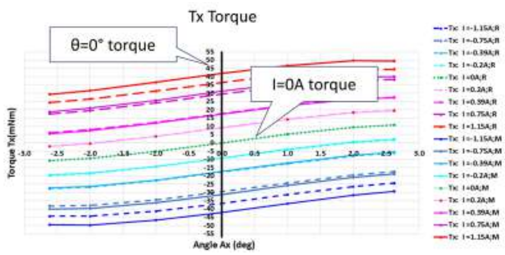


Fig. 2.bi: Magnetic force map of a M-FSM

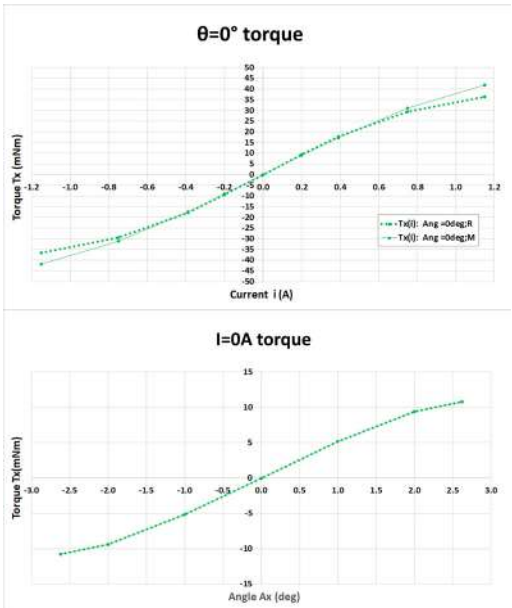


Fig. 2.bj: Key plots of the Magnetic Torque Map

This is especially the case when used in combination with **frictionless flexure bearings** (see "Flexure guiding blades", page 41) instead of classical sliding friction bearings, or ball bearings. This featuring allows achieving on going nonstop operation over years without maintenance.

In this case, the stiffness of the guiding kG should be considered in the actuation force F versus the position u to the center:

$$F = k_A . B_M . Ni - k_{axi} . u$$

Because of this dependency, the actuator presents a mechanical resonance linked to the moving mass (for example the moving part and its load). This effect resonance is exploited to improve efficiency in the proof mass MICA configuration (as MICA300CM-PM) for making active dampers. More detailed analysis about guiding, dynamic and proof-mass are detailed in further parts.

In short, **MICA™** technology offers higher force density, larger lifetime operation at stabilised low coil temperature, reduced coil Joule's effect, no electrical flying connection issues, and optimum electrical input power efficiency compared to Voice Coil technology.

MAGNETIC FAST-STEERING MIRROR M-FSM

Magnetic Fast-Steering Mirror M-FSM rely on MICA™ principle applied to rotational motions. The magnets and the coils are combined such that a magnetic torque is created.

Similarly to the **MICA™**, the magnetic circuit relies on permanent magnets that preload the circuit. As a result, the magnetic torque is proportional with respect with current, which makes the control efficient in a compact volume.

Additionally, the mobile part is connected to the stator with **guiding blades** that are designed to withstand an **infinite number of cycles**.

As for the MICA™, the torque is computed for different values of current and angular displacements to obtain a **Magnetic Torque Map**. This tool is used to study the mechanical behavior of the device (natural frequency, guiding blades design, etc.). In the example showed in *Fig. 2.bi*, a torque map is provided for a M-FSM that has 5° mechanical angle range (±2.5°) and approximately 1A excitation current.

Two particular plots are useful to understand how this map can be used for dynamic analyses (see *Fig. 2.bj*).

- **The torque at θ=0°**, with the current ranging from minimum to maximum values (say ±1A in this example). This torque is useful to know **the current to torque gain** (expressed in N.m/A), useful for control design, for example.
- **The torque at I=0A**, with the angular displacement ranging from minimum to maximum values (say ±2.5° in this example).

Fig. 2.bj gives the system stiffness (elastic guiding + magnetic stiffness), which is useful to estimate the **natural frequency** of the mechanism in open loop. This parameter is a key feature for the guiding blade design.

FLEXURE GUIDING BLADES

Resonant flexure bearing actuators are actuators having a specific mechanical design based on **frictionless bearing components** called "**Flexures**", which consist in **planar springs** of thin thickness having infinite fatigue lifetime capability. Flexure bearing actuators can be realized with any magnetic topology, such as **moving coil**, **moving magnets**, **moving iron**, and **MICA™**. The flexures are anchored in the stator mechanical parts and ensure the moving mass motion guiding in both axial and radial directions, with no sliding friction, no lubricant, and no material wearing.

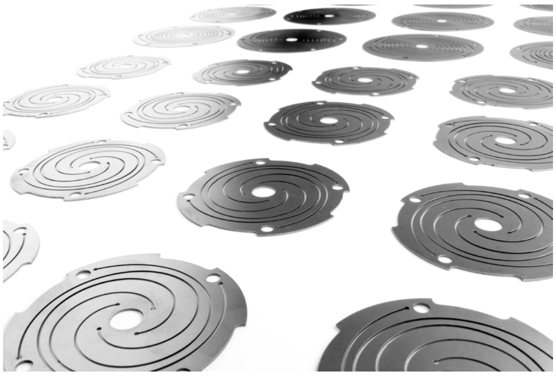


Fig. 2.bk: Examples of flexure bearings

When a "fixed coil" actuator magnetic topology is chosen, such as **moving magnet**, **moving iron**, no coil wire flying lead connection is submitted to cyclical fatigue. Therefore, when used in combination with flexure bearings, the complete actuator assembly achieves infinite fatigue lifetime capability. Flexure bearing actuators are therefore best candidates for applications requiring **long lifetime without maintenance**.

The flexure bearing actuators have enhanced position control performances and allow achieving ideal "**step and stay**" control precision and response time. This performance is reached because the moving mass motion is free of any stick slip parasitic effects, unlike friction bearings actuators.

Additionally, flexure bearing actuators can take advantage of the **mechanical resonance** given by the association of the moving assembly mass and the stiffness of the bearings.

This resonance can be used either to achieve inertial force higher than the magnetic force alone (for application such as vibration cancellation applications using proof mass actuators, for example), or to achieve high efficiency for power application such as pumps and compressors.

VOICE COIL ACTUATOR

Laplace force actuators, commonly named "**Voice Coil actuators**", are based on the force resulting from the interaction of current flow through a magnetic field. Such actuators can be realized either with moving coils or moving magnets topologies (i.e. fixed coils; see *Fig. 2.ba*). The Laplace force is proportional to the magnetic field B_0 in the air gap.

$$F_{mag} = B_0 L I$$

The force being proportional only to current and magnetic field, a good linearity of force versus position of the coil is achieved at small stroke and small force levels, leading to low distortions between force and displacement. Therefore Voice-Coil actuators have been widely used in loudspeakers, or in some precision instruments, where high linearity behavior in the high frequency domain is required. For example, CEDRAT TECHNOLOGIES has developed high performance voice-coil for several operational space equipment requiring high linearity.

At higher stroke and force level with low to medium frequencies, this linearity performance decreases due to side effects, imperfect winding patterns, non-homogenous magnets' assemblies, and non-parallel line of field in large air gaps due to the coil thickness. Voice-Coil Actuators are well suited for long stroke and high precision positioning requirements, when compactness, input electrical power, and long operation time, are not the main drivers for a given application.

A main disadvantage of the Voice-Coils is their fast heating and the difficulty to cool them.

As the moving coil is the source of heating and as it is the moving part, it is difficult to cool it by conduction. Air cooling remains the usual way. Forced cooling can be an option but it is not possible in confined environment. In vacuum conditions, cooling is quite difficult.

Because of heating issues, continuous operations may be not possible for large power applications, and operating duty cycle shall be fitted according to temperature limit.

Voice-Coil are known to have low power density, especially for long strokes. As a result, Voice-Coils have poor compactness, reduced efficiency and large heat dissipation due to Joule effect, compared to other magnetic actuators.

The main advantages of the Voice-Coil are the mechanical simplicity of its magnetic circuit, and the low parasitic radial forces generated on its moving part.

However, the moving coil requires special care on to the flying wire electrical lead connections, which are submitted to cyclical fatigue. As a result, such actuators are not recommended for applications where low maintenance and extra-long lifetime (several years in continuous operation) are needed.

Fig. 2.bl: Linear Voice-Coil VC15 (mobile part only) for Meteosat Third Generation (MTG) flying on EUMETSAT

Fig. 2.bm: Linear Voice-Coil VC60 (mobile part and stator) for VIGPRAN space experiment onboard the ISS

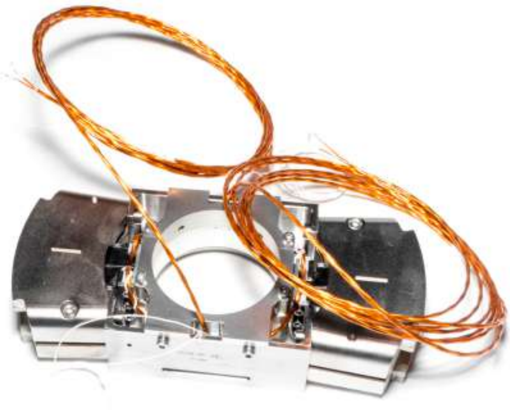


Fig. 2.bn: Rotating Voice Coil Motor for Meteosat Third Generation (MTG) flying on EUMETSAT

Fig. 2.bo: Rotating Voice Coil Motor, based on Limited Angle Torque (LAT) concept

ALTERNATIVES FOR VOICE COIL ACTUATORS

First alternative for Voice Coil Actuator is given by the RVCM (Rotatory Voice Coil Mechanisms). These are high resolution cog-free rotational actuators with a voice coil as rotatory moving part. Therefore, they are also called **LAT (Limited Angle Torque)** actuator. They are the counter part of controllable linear magnetic actuators, achieved with same magnetic principles but in rotational configuration instead.

LAT actuators are composed of fixed parts called “**Stators**”, and moving parts in rotation called “**Rotors**”. They can be realized using either **moving iron**, **moving magnet**, or **moving coil** actuator topologies. The previous table shows a moving magnet LAT.

LAT actuators are single phase actuators, which are an alternative solution, compared to multiphase electric motors. The LAT actuator technologies take advantage of dedicated limited angle actuator designs, which makes them more relevant for angular position control applications.

LAT technologies feature **high resolution angular motions**, without any magnetic incremental stepping, and so, with cogging and vibrations. LAT actuators’ topologies are achieved with single phase coil assemblies, allowing true DC control, without any electrical commutation electronic required, and with two ways motional directions according to current direction. This feature allows achieving both **closed loop feedback control**, as well as **open loop proportional control** using angular spring back flexural pivots.

ELECTROMAGNETS ACTUATORS

Reluctance force actuators principle relies on the force that tends to minimize the magnetic energy in the air gap between two parts within a magnetic circuit, which, in practice, always attracts the two parts. The magnitude of the force is proportional to the square of the magnetic field B^2 in the air gap. Such actuators can be realized either with moving permanent magnets or moving irons (i.e. fixed coils and permanent magnets such as "**MICA™**"), or even without magnets (i.e. "**Electro-Magnets**").

This type of actuator has a higher force capacity compared to Laplace actuators.

The **electromagnet actuators**, which include "**Solenoid**" actuators, are based on reluctant forces, with an actuator topology defined without magnets, i.e. only coils and soft materials, which require very simple mechanical designs.

The stator is built by assembly of coils and magnetic circuits, defining a one pole magnetic architecture resulting in a single force direction (attraction). The moving part, also called "**Plunger**", is a soft magnetic core, typically an Iron alloy, which allows classifying such actuators in the category of **Moving Iron Actuators**.

When the coil is supplied by a current I, an attractive magnetic force F_{mag} is developed in the air gap between the plunger and the electromagnets actuator poles. For actuators with stroke perpendicular to the air gap F_{mag} is given by:

$$F_{mag} = B^2 S / 2\mu_0$$

B is the magnetic field in the air gap and S is the pole surface. The force is only attractive, whatever the current direction. This force is highly nonlinear versus the plunger position, which cannot be controlled without implementing a spring back force, using a mechanical flexure bearing, or a compression spring, in order to generate an equilibrium position at a given current value. The force and stroke available from such actuators are very high compared to their size, which make it especially attractive for miniature and fast position switching and control applications, such as on/off and fast regulation valves in fluid applications.

In order to generate a position proportional to the current, at first the moving part is attached to a spring generating a back force. Secondly, the reluctant force non-linearity versus position can be partially suppressed in a given stroke range using FEM optimization of poles shape.

The main performance of such an actuator, compared to other magnetic ones, is the force response time performance achieved over very compact and light moving part, which makes it best applicable for demanding fast operational requirements.

Electronic control can also be used to improve the dynamic behavior of the system (reduce response time, reduce shock impacts, etc.).

The next figures shows variant of electromagnet actuators which are designed to fit special applications.

Fig. 2.bp: Bruce (Hold-Down and Release Mechanism) developed by CTEC with CNES (French Space agency)

Fig. 2.bq: Moving iron electromagnet 80N

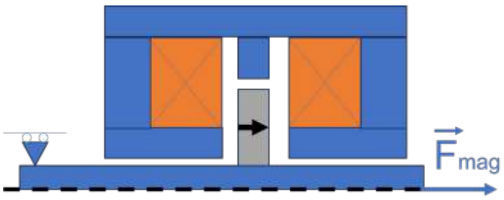


Fig. 2.br: BLMM magnetic principle

BISTABLE LINEAR MOVING MAGNET ACTUATOR

Bi-stable Linear Moving Magnets actuators BLMM are based upon the reluctant force principle, achieved with a combination of permanent magnets, and electromagnets. Such an actuator topology allows achieving two stable positions at rest, maintained by the magnetic holding force provided by magnets, and without requiring any electrical power nor dissipating any heat. Commutation between the two positions is achieved by applying short electrical impulses, at fast speed, and short response time.

The BLMM are composed of two fixed parts, realized with two back-to-back electro-magnets (see *Fig. 2.br*), each combining coils and soft materials, and a moving part composed of a magnet assembly and a shaft structure.

Bi-stable actuators are perfectly suited for commutation mechanism, such as contactors, locking devices, and latch mechanisms (*Fig. 2.bt*). Most common application of bi- stable actuators is for on/off latch electro-valves in fluid applications. The advantage of **bi-stable actuators**, realized with **BLMM** permanent magnets magnetic topology, is the high level of miniaturization achievable (see *Fig. 2.bs*), while keeping a fast commutation speed, and a high holding force at rest.

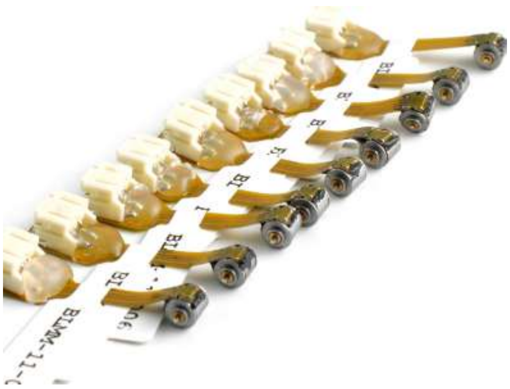


Fig. 2.bs: CTEC miniature BLMM1XS actuators

CUSTOMIZATION IS POSSIBLE

The possibilities of actuator design are not limited by the actuator technologies shown previously. Several customized configurations allow to adapt the actuator characteristic to industrial application. Move may be linear or rotative and the obtained direct force may be adapted by using amplifier like lever arm or multi symmetric actuation. Fixed part of mobile part may be inversed topologically like inside outside of functionally like light part and heavy part. The link between the two actuator parts may be completed with spring, which is generally the case for electromagnet to insure the return move.

Fig. 2.bt: Customized BLMM200M
offering 200 N locking force

SUMMARY & COMPARISON

PARAMETER	VOICE COIL ACTUATOR	MICA™ & M-FSM	ELECTRO-MAGNETS	BI-STABLE MOVING MAGNETS
Locking at rest	**No**	**No** in standard **Yes**, 1 or 2 positions with custom design	**No** **Yes**, with spring	**Yes**, 2 positions
Magnetic Force when supplied	**Almost constant** along the stroke	**Rather constant** along the stroke	**Varying a lot** along the stroke	**Varying a lot** along the stroke
Motion Controllability	**Good** Force can be reversed all along the stroke; Small Hysteresis	**Good** Force / Torque can be reversed all along the stroke Small Hysteresis	**Poor** Only attractive force available	**No** Intermediate position cannot be controlled
Heating	**Fast**	**Slow**	**Slow**	**Fast**
Force / power	**Fair**	**High**	**High**	**Very high**
Force characteristics & comments	*Fig. 2.bu*	*Fig. 2.bv*	*Fig. 2.bw*	*Fig. 2.bx*
Typical application	**Close loop positionning** **Force generation**	**Power application** **Close loop positionning** **Force generation**	**State positionning application** Positioning (if linearised)	**State positionning application** Positioning (if linearised)
Example	*Fig. 2.bl* *Fig. 2.bn*	*Fig. 2.bf* *Fig. 2.bh*	*Fig. 2.bp* *Fig. 2.bq*	*Fig. 2.bs* *Fig. 2.bt*
Factor Of Merit (actuator efficiency)	**5 N/√W** (typical value)	**25 N/√W** (typical value)	-	-
Factor Of Merit (actuator compactness)	**<10 N/√W/kg** (typical value)	**45 N/√W/kg** (typical value)	-	-

Table 2.f: Summary & comparison of CTEC magnetic actuators technologies (see *chapter 2.3.2, page 46* for FOM definitions)

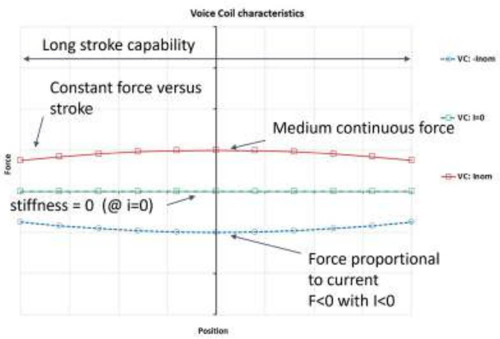


Fig. 2.bu: Typical force map for a Voice-Coil

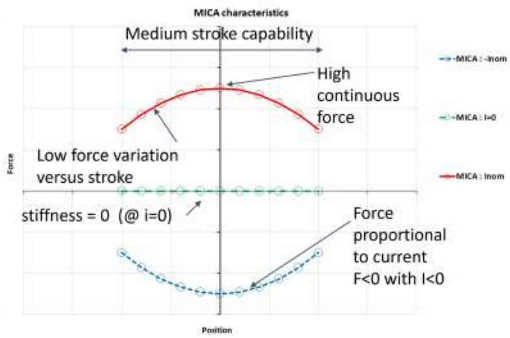


Fig. 2.bv: Typical force map for a MICA™

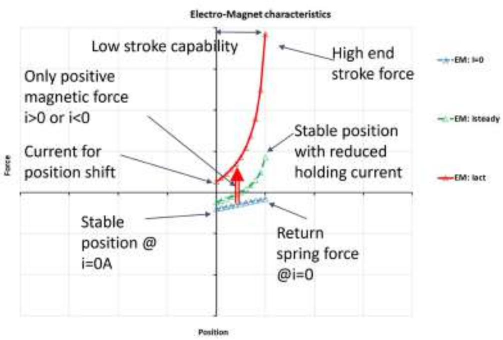


Fig. 2.bw: Typical force map for an electro-magnet

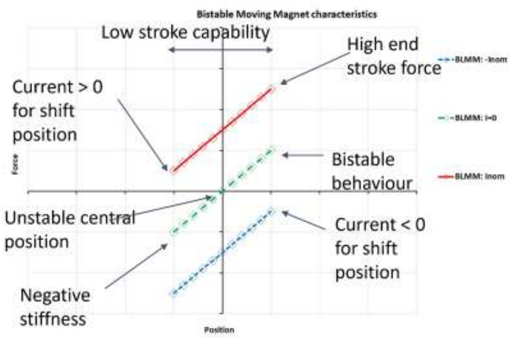


Fig. 2.bx: Typical force map for a BLMM

2.3.2. DESIGN KEY POINTS

QUASI-STATIC: JOULE LOSSES

In static conditions, losses of a magnetic actuator are mainly due to the joule losses P_J in the windings, which is generated when the required current i flows in the winding resistance R:

$$P_J = R \cdot i^2$$

THERMAL PARAMETERS

The current flowing through the coil induces Joule power that tends to increase temperature in the actuator. Failure can occur if the final temperature exceeds the limits of the wire insulation or the Curie temperature of the Magnets.

Therefore, the thermal characteristics are a key parameter for the performance of the actuator.

In the following, the main thermal parameters are exposed.

Thermal inertia

Time constant τ_{th} illustrates how quickly the temperature **increases** with a given input power.

This factor is defined as(f.1):

$$\tau_{th} = \frac{\rho c V}{h S}$$

Where ρ $[kg.m^{-3}]$: mass density, c $[J.kg^{-1}.K^{-1}]$: specific heat, V $[m^3]$: volume, h $[W.m^{-2}.°C^{-1}]$: convection heat flow factor, S $[m^2]$: contact area between cold and hot bodies.

This formula illustrates that the coils that are integrated to the stator (MICA™, Electromagnets) are more beneficial than flying coils (Voice-Coils) in terms of thermal performance, because of larger volume V and lower contact area S. In fact, in the former case, the user can maintain a given current intensity much longer than the latter before the temperature increases significantly.

Thermal resistance

The thermal resistance links the **final** temperature with the input electrical loss power (Joule).

Its relationship with the input power can be described as:

$$T_f = T_0 + R_{Th} \cdot P_J$$

Where T_f $[K]$: the **final** temperature of the coil, T_0 $[K]$: the initial temperature, R_{Th} $[K]$: the thermal resistance, P_J $[K]$: the input Joule power.

T_f must remain lower than a certain temperature T_{max}, generally linked to the wire insulation, the limitations in temperature of the internal components of the actuators (magnets, etc.).

$$T_f < T_{max}$$

T_0 is typically related to the temperature of the heat sink of the application, while R_{Th} illustrates how easily the heats flows through the actuator. For a given input power, the higher the thermal resistance, the higher will be the final temperature.

For a Voice-Coil, typically, the coil support is the only component through which the heat can flow, which is not optimal. On the other hand, the MICA™ coil is integrated to the stator, similarly as for usual electromagnets. In this case, it is much easier for the heat to flow out, thus the steady state temperature is reduced.

In addition, it is much easier to connect a heat sink to the stator efficiently (unlike for the Voice-Coil), which tends to reduce the initial temperature T_0. When combined, thermal inertia and thermal resistance show that MICA™ provides key advantages from thermal perspective. For the same input power P_f, the final temperature of the MICA™ is much smaller than for Voice-Coil, and it takes more time to reach it.

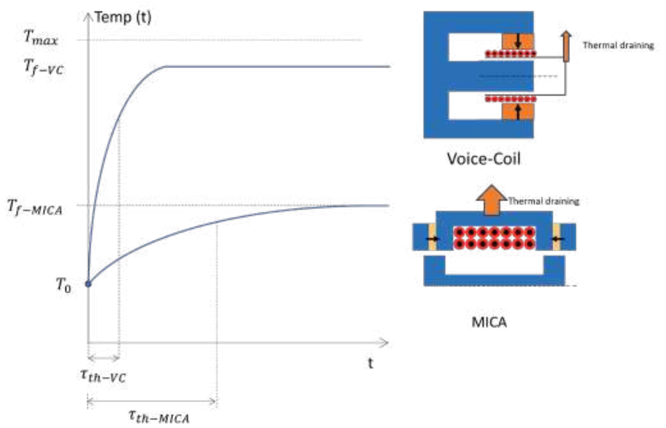


Fig. 2.by: Comparison of heating of Voice-coil versus MICA at constant actuation force

Consequently, the maximum current density of the MICA™ can be larger than for Voice-Coil, which allows to increase the force density significantly. Based on this analysis, the currents can be defined as:

Continuous current: the current for which the maximum temperature of the coil does not exceed the wire insulation limit (typically: 150°C).

Peak current: the current for which the temperature of the coil reaches the wire insulation limit in a short amount of time (typically: 10s.).

f.1 *Convection only (simplified approach)*

Continuous current/ Continuous Force

Continuous current *[A]*: the current for which the maximum temperature of the coil does not exceed the wire insulation limit (typically: 150°C) in typical laboratory conditions (in air at atmospheric pressure and 20°C).

Continuous force *[N]*: the force generated by the actuator with the moving part is located in **centered position** and the coil is energized with the **continuous current**.

Peak current/Force

Peak current *[A]*: the current for which the temperature of the coil reaches the wire insulation limit in a short amount of time (typically: 10s.) in typical laboratory conditions (in air at atmospheric pressure and 20°C).

Peak force *[N]*: the force generated by the actuator with the moving part is located in **centered position** and the coil is energized with the **continuous current**.

Force factor

The force factor is defined as the ratio between the **Continuous force** and the **Continuous current** in **centered position**.

$$K_m[N/A] = \frac{F_{cont}}{i_{cont}}$$

Back-electromotive force factor

The **Back-electromotive force factor** gives the voltage induced by the speed of the mobile part of the actuator.

$$e_{bemf} = K_v \frac{dx}{dt}$$

As for any electrical machine, the **Back-electromotive force factor** equals the **Force factor** defined previously, though units can be different.

$$K_v[Vs/m] = K_m[N/A]$$

Actuator Factor Of Merit (FOM)

In case of magnetic actuators, the **Factor Of Merit (FOM)** is the ratio between the actuator force and the square root of Joule power in **quasi-static conditions**.

This **FOM** is independent from the coil windings and provides a good image of the efficiency of the actuator. In this document, the **FOM** is computed with the **continuous current**.

$$FOM[N/\sqrt{W}] = \frac{F_{Cont}}{\sqrt{P_J}}$$

Compactness Factor Of Merit

The **FOM** can also by divided by the actuator mass to give an indicator of the **compactness** of the device, especially for applications where the best compromise between force and mass is needed (in spatial applications, for example):

$$FOM_m[N/\sqrt{W}/kg] = \frac{FOM}{M_{act}}$$

Magnetic saturation

The required actuator current can be easily evaluated from the application required force divided by the force factor (the force is linear with respect to current). However, this formula is valid only for a limited current, i.e. when the magnetic circuit is not saturated. Nevertheless, if the current is too high, the magnetic material starts to saturate, and so for the magnetic force.

An actuator is well designed if the continuous current induces magnetic field in material that reaches the typical working point (see *Fig. 2.bz*).

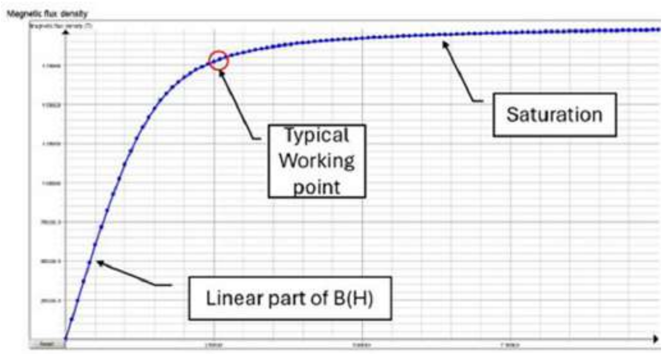


Fig. 2.bz: Example magnetic material B(H) saturation curve

DYNAMIC EQUATIONS OF ELECTROMAGNETIC ACTUATORS

The analysis of electromechanical actuators requires to deal with the flow of power between the electrical domain (useful to choose the electronic driver) and the mechanical domain (useful to meet the customer requirement).

Most MICA™ and Voice Coil systems can be described with a lumped model where the electrical side is a R/L system, and the mechanical side is a mass/spring system (*Fig. 2.ca*).

The electromechanical equations can then be written as:

$$\begin{cases} (-M_{mob}\omega^2 + jC_{act}\omega + K_{act})X = K_m I \\ (jL\omega + R)I + jK_m\omega X = V_{PS} \end{cases}$$

With V_{PS} the Power Supply voltage.

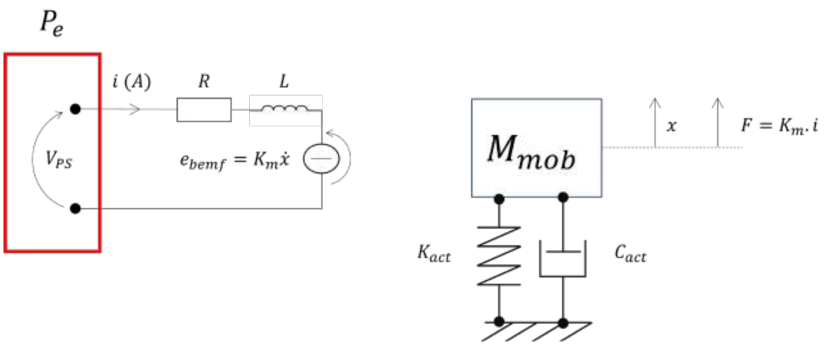


Fig. 2.ca: lumped_model_magnteic_actuator.png

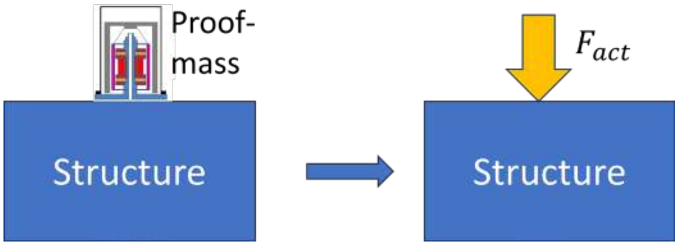


Fig. 2.cb: Flexure bearing actuator model

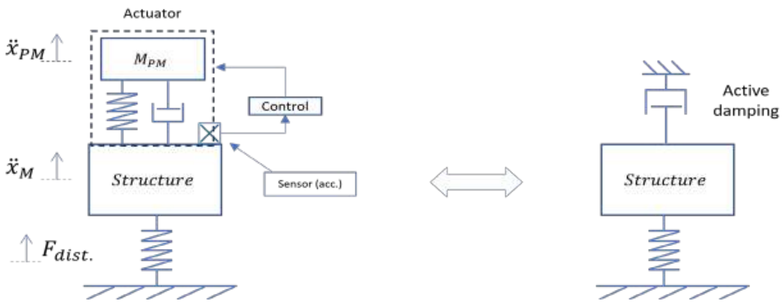


Fig. 2.cc: Example of skyhook strategy applied to active damping

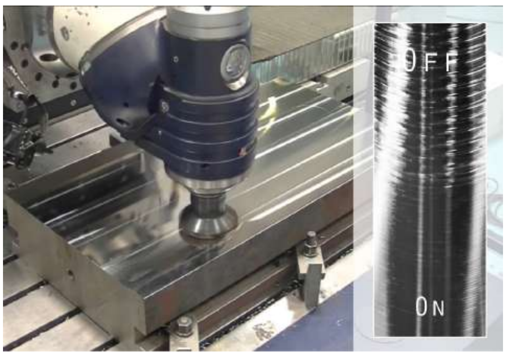


Fig. 2.cd: Example of machining with MICA-based anti-vibration actuation

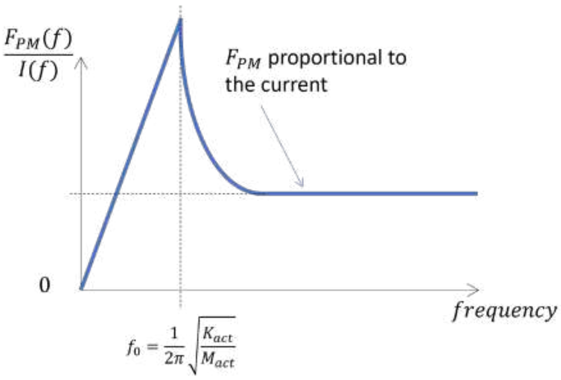


Fig. 2.ce: Actuator force vs frequency with constant current excitation

Active damping applications: Proof-Mass configuration

In active damping applications, the actuator may be used as a Proof-Mass actuator.

The force generated by the actuator corresponds to the inertial force, as :

$$F_{PM} = -\omega^2 M_{mob}.X$$

In this configuration, the actuator can be used as a pure force generator without the need to clamp it to an additional support.

It becomes then easier to drastically reduce the vibrations on the system with a proper active control strategy (ex: skyhook strategy).

Nevertheless, to be used properly, the frequency range of actuation must be above the first natural frequency of the actuator (see *Fig. 2.ce*).

The equation of the Proof-Mass actuator force can be written as :

$$\frac{F_{PM}(\omega)}{I(\omega)} = \frac{-M_{mob}.K_m.\omega^2}{(K - M_{mob}\omega^2) + j\omega C_{act}}$$

Note: this equation is valid as long as the stiffness and/ mass of the structure is large compared to the actuator. More analysis is needed if this hypothesis is not verified.

Additionally, as the first natural frequency is related to the moving mass and the flexible guiding, it can be **adjusted** to meet specific requirements.

Nevertheless, for extra-low frequency applications (below the first natural frequency of the actuator), specific control approach can be used that would involve sensors for the motion of the moving mass.

Typical domains of applications: active damping. The typical frequencies involved for ω_0 are >30-40Hz.

Active Power applications

In *Active Power Applications*, it can be important for the customer to reduce the consumption power as much as possible.

In that case, the designer can take advantage of the natural frequency of the actuator to reduce the current that is necessary to achieve the force needed.

An example of the force response versus frequency is given in *Fig. 2.cg*. In this example, the customer load includes a resistive component. It can be seen how the use of the actuator at the resonance frequency is an advantage thanks to the amplified force.

The actuator efficiency of the actuator is the ratio between the output power and the input power. The difference between these two powers input and output is due to the losses.

The efficiency is of interest for power applications. One typical application domain for power applications is the gas compression.

The instantaneous electrical power is the product of voltage and current.

The efficiency is the ratio between the output power (useful for the customer) and the input power (the cost). For magnetic actuator based on MICA™ technology, the efficiency is about 80% around the natural frequency of the system.

$$\eta_{\%} = \frac{P_{output}}{P_{input}} \times 100$$

Similarly, the power factor $cos(\phi)$ achievable by MICA™ technology-based actuators can be above 0.85-0.9, with ϕ [rad or degrees] defined as the phase shift between the current and the voltage.

Domains of applications: gas compression

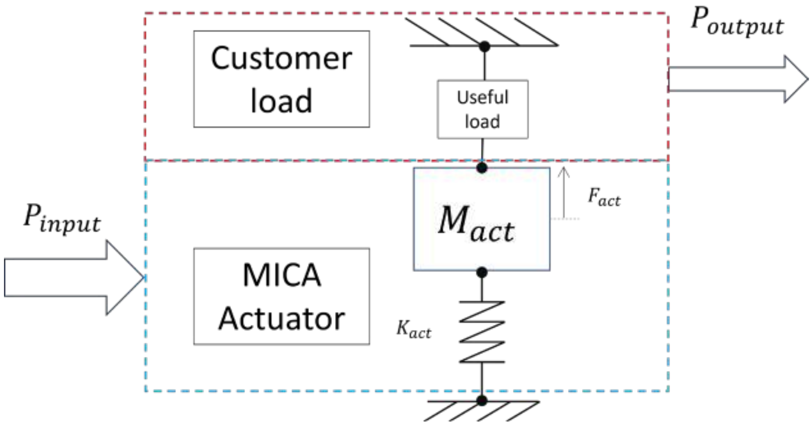


Fig. 2.cf: Flexure bearing actuator model

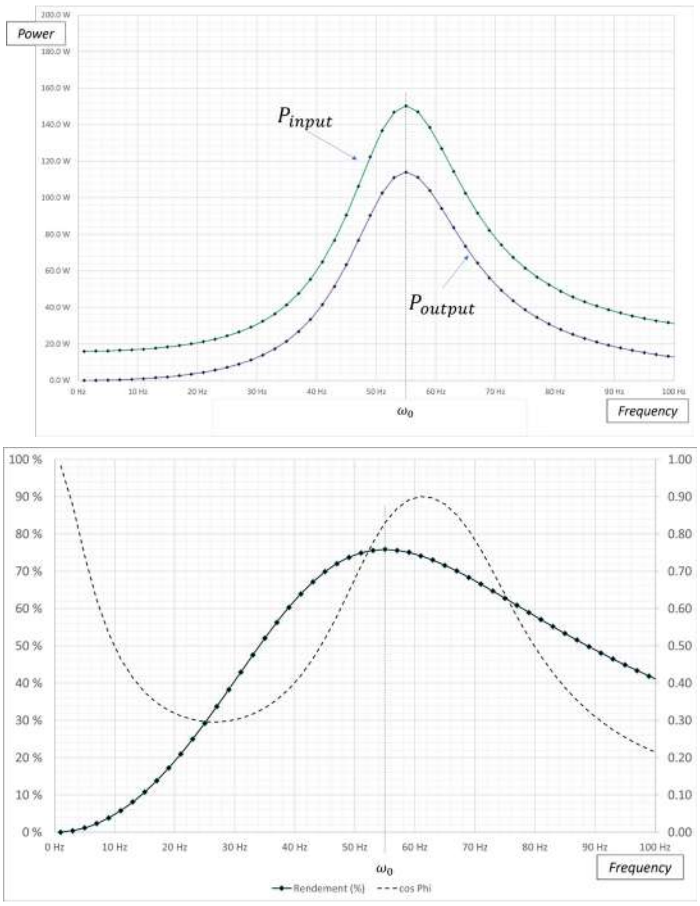


Fig. 2.cg: Flexure bearing actuator force response on a resistive load

MANAGEMENT OF LOSSES

Analysis of magnetic actuators with Losses is a key analysis which can be performed using the CTEC in house COMMACT™ software. This analysis allows estimating true actuator performances, taking in account the different sources of loss that will be converted into heat, and which will reduce the actuator targeted performances:

- Joules losses
- Mechanical viscous and solid frictions losses
- Actuator Iron losses
- Application nonlinear effects (like friction)

Mechanical losses reduce the magnification factor of a given actuators moving mass, which means that higher forces are required to achieve the targeted stroke and acceleration.

Iron losses are magnetic losses that include Eddy currents and Hysteresis losses, which reduce both the moving mass magnification factor, and the actuator frequency bandwidth.

Cumulating all losses can result in a significant decrease of performance compared to expected, if not taken in account. In custom designs for power efficiency application such as thermal machines, pumps, and compressors, all losses are to be reduced as much as possible by design, using frictionless flexure bearings, as well as soft material assemblies composed of optimized slotted, sintered, or laminated mechanical parts.

2.3.3. POWER SUPPLY

CTEC has a wide range of power supplies in order to comply with most applications.

Fig. 2.ch: CMAµ10 ±32V/0.5A driver

Fig. 2.ci: CSA96 ±96V/20A driver

Fig. 2.cj: MCLA18 ±32V/1A driver

Fig. 2.ck: MCSA480 ±48V/10A driver

CHOOSING THE RIGHT POWER SUPPLY

The electromechanical behavior of the magnetic actuator has an impact on the power supply to use.

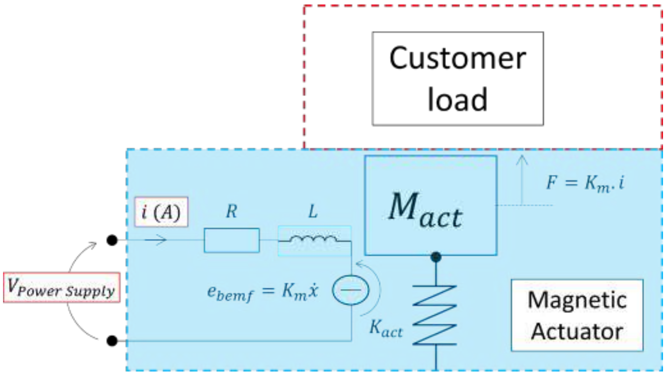


Fig. 2.cl: Simplified model of a compressor application

The **drive electronic principle** for a given actuator application must be chosen not only according to electrical requirements of the actuator itself, but also according to the control logic. The existing drive electronic options are divided in two categories, i.e. **voltage control** electronics, or **current control** electronics.

Voltage control electronics

If the actuator is **voltage driven**, the dynamics between the **input** voltage and the **output** displacement involved are (in Laplace variables) :

$$\left(-\frac{M\omega^2}{K_m}\underbrace{(jL\omega + R)}_{\substack{Electrical\\dynamics}} + jK_m\omega + K_{act}\right).\boldsymbol{X} = \boldsymbol{V_{PS}}$$

In practice, the actual magnetic force acting on the system is delayed due to:

- The electrical time constant:

$$\tau_{elec} = \frac{L}{R}$$

- The mechanical time constant, mainly because the electro-motive force acts as a viscous damper on the system (force proportional to speed):

$$\tau_{mech} = \frac{M}{K_m^2/R}$$

Voltage control electronics provide optimized control to apply a given voltage at the actuator wire lead connection. The current delivered to the actuator coil is then the result of the actuator electrical impedance.

Current control electronics

If the actuator is **current driven**, the dynamics between the **input** current and the **output** displacement involved are (in Laplace variables):

$$(-M_{act}\omega^2 + K_{act}).X = K_m I$$

In that case, an internal control loop is involved in the driver to provide in real-time the voltage that is required to impose the current in the system.

The max current generated by the driver is generally limited by its maximum voltage available. In harmonic conditions, the current (and magnetic force) available decreases for higher frequencies such as:

$$i_{max} < \frac{V_{max}}{L\omega}$$

As a consequence, the max displacement of the actuator can no longer be reached above a given frequency.

Current control electronics provide optimized control to apply a given current to the actuator wire lead connection. These are the most adapted drivers for magnetic controllable actuators as their force is proportional to the current. The voltage applied to the actuator coil is then the results of the actuator electrical impedance.

SUMMARY

When used with the objective of increasing transient performances, such as enhanced **moving mass acceleration**, and **reduced response time** in actuator position control, current based drive electronics have far better performances. Indeed, this second category has the so called "**Current Shaping**" capability, which differs from output current control achieved by a **PID** type controller (Proportional Integral Derivative) driving a voltage based electronic. Linearization of force versus current, as well as fast response time are achieved with far better performance with an electronic that control current, instead of voltage. Indeed, the current based drive electronics have the capability to withstand output peak voltage shapes not accessible by PID voltage control, which results in **enhanced actuator response time** in position control.

IMPEDANCE

The impedance integrates most constitutive parameters of the complete system, and therefore can be used to identify the right power supply for the application.

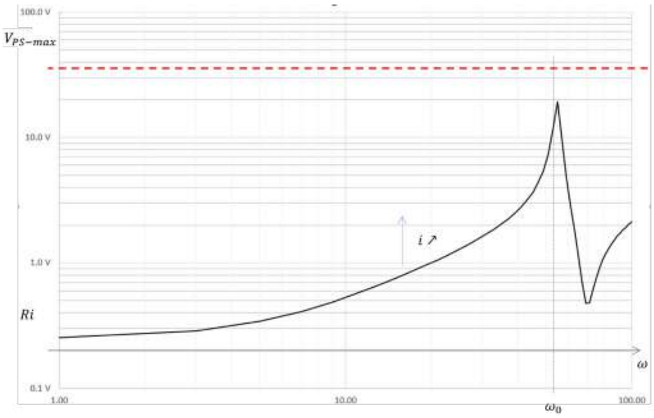


Fig. 2.cm: Voltage needed for a given constant current with respect to frequency

Sometimes, the impedance can be adapted to fit better with the application and to the characteristics of the driver (in case that the current is too high, for example). The adaptation of impedance consists in changing the winded wire diameter, the number of turns of the coils and keeping unchanged the rest of the actuator including the magnetic circuit.

In this case, the number of windings has an impact on the relevant parameters as follows (for a given frequency):

ADAPTATION OF IMPEDANCE	PARAMETER
$L_f = L_i\left(\frac{N_f}{N_i}\right)^2$	Inductance
$I_f = I_i\frac{N_i}{N_f}$	Current
$K_{m-f} = K_{m-i}\frac{N_f}{N_i}$	Force factor
$R_f = R_i\left(\frac{N_f}{N_i}\right)^2$	Resistance
$U_f = U_i\frac{N_f}{N_i}$	Voltage

2.3.4. EXAMPLES OF APPLICATIONS

COMPRESSOR APPLICATION

"As part of a cryogenic application, a customer needs to develop an useful power of 100W (P_u) in a gas at 50Hz, at 10mm peak-peak stroke. The efficiency needs to be as high as possible."

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K_{act}+K_{gas}}{M_{act}}} = 50Hz$$

In this type of application, it is more efficient to rely on the natural resonant frequency of the combined system "actuator + compressed gas" such that is corresponds to the target frequency (50Hz):

$$F_{act} = \frac{2.P_{gas}}{v} \approx 130N$$

Additionally, the force required to achieve the power is computed as:

With $v=2.\pi.f.x_0$, the speed is m/s, and x_0 the 0-peak amplitude of the displacement.

For the family of **MICA300CM**, $i \approx 6A$, with

$$i = \frac{F_{act}}{K_m}$$

The voltage needed is given by:

$$V_{max} = i\sqrt{(L\omega)^2 + R^2}$$

For the family of **MICA300CM**, $V_{max} \approx 20V$.

The efficiency achievable is around η_{act}>80%

In this example, the power supply **CSA96** should be more than sufficient (see *Fig. 2.ci*).

ACTIVE DAMPING

"For an optical application, a customer needs to reject micro-vibrations from his plant up to 150Hz. The expected force needed is below 5N".

For this type of application, a proof-mass solution is chosen quite often as it only requires the actuator to be fixed on the plant (embedded). For frequencies greater than the natural frequency of the actuator, the generated force is constant. For smaller frequencies, a control loop is needed to achieve a constant force.

For the family of **MICA20CS-PM**, the minimum frequency is 30Hz. The current is $i \approx 60mA$, with

$$i = \frac{F_{act}}{K_m}$$

The maximum voltage is achieved at the maximum frequency with $V_{max} \approx 30V$. In this example, a set **MICA20CS–PM/ CMAµ10** should be sufficient.

OPTICAL POINTING

"For an optical application, a customer needs to follow a signal on ±20mrad angle (θ_0) up to 50Hz with a clear aperture >15mm".

For this application, the inertia of the mirror is a key parameter for the analysis. The larger the mirror, the more power is required to drive the system.

For the family of **M-FSM45**, combined with a ~15mm clear aperture SiC mirror, the required torque to actuate at this frequency is about $T_{act} \approx 10mN.m$.

$$T_{act} = \theta_0 . |(K_\theta - J_t . \Omega^2)|$$

For this model, the electrical parameters are $i \approx 0.45A$ and $V_{max} \approx 25V$. In this example, a set **M-FSM45/MCLA18** should be sufficient.

FAST POSITIONING

"For a scientific experiment, a client needs to move a 1kg mass (M_{Load}) by 20mm (x_{final}) in less than 0.1s (Δt)."

This example is analyzed with a simplified approach (see *"Voice coil actuator", page 41*). The total mass of the moving part is estimated as:

$$M_T = M_{mob} + M_{Load}$$

From the second law of Newton:

$$F_{act} = M_T . \frac{d^2x}{dt^2}$$

Under the assumption of a constant force excitation, the displacement is given by (simplified approach):

$$x_{final} = \frac{1}{2} \frac{F_{act}}{M_T} \Delta t^2$$

The actuation force can then be estimated as:

$$F_{act} = 2 \frac{M_T . x_{final}}{\Delta t^2}$$

Which gives $F_{act} \approx 5N$.

The current needed depends on the force factor of the chosen actuator, as:

$$i_{act} = \frac{F_{act}}{K_m}$$

If a **VC60** actuator is chosen, the current achieved should be around 250mA. The minimum voltage required for the driver is defined such that the current is established much quicker than the time needed for the application (typically $\Delta t/10$):

$$V_{max} > L \frac{di}{dt} = L . i_{act} . / (\Delta t / 10)$$

If a **VC60** actuator is chosen, the maximum voltage achieved should be more than 3.5V.

For this application, a **CMAµ10** driver combined with a **VC60** actuator should be sufficient to meet the requirements.

Note on the results: this approach is simplified. It does not take into account the friction due to the motion of the mobile part, the iron losses, etc. If a more complex displacement profile is required, a control loop based on displacement sensors can be added.

2.3.5. LIST OF SYMBOLS

SYMBOL	NAME	UNIT
R	Resistance	Ω
L	Inductance	mH
I_p	Peak current	A
F_{mag}	Magnetic force	N
V_{PS}	Power supply voltage	V
F_p	Peak Force	N
I_{cont}	Continuous current	A
F_{cont}	Continuous Force	N
K_m	Force factor	N/A
K_v	Back-electromotive force factor	Vs/m
FOM	Actuator Factor Of Merit	$N/\sqrt{W}$
FOM_m	Actuator Factor Of Merit density (compactness)	$N/\sqrt{W}/kg$
τ_M	Mechanical time constant	ms
f_0	Resonant frequency	Hz
P_J	Joule losses	W
$\eta_{\%}$	Actuator efficiency	$\%$
R_{Th}	Thermal resistance	Ts/W
τ_{th}	Thermal inertial	s
M_{mob}	Mobile mass of the actuator	kg
M_{load}	Load mass (useful)	kg
$M_{act} = M_{mob} + M_{load}$	Total mobile mass	kg
M_{stat}	Stator mass of the actuator	kg
$M_{tot} = M_{mob} + M_{stat}$	Total mass of the actuator	kg
K_{act}	Axial stiffness	N/mm
D_e	Actuator diameter	mm
L_e	Actuator length	mm

Table 2.g: List of reference symbols

2.4. TUTORIAL ON CONTROL LAWS

2.4.1. INTRODUCTION ON CONTROL LAWS

The role of a control law is to reduce the error of an actuator response vs an input order for a given application, for example mitigating the effect of hysteresis or creep for piezoelectric actuators or controlling dynamic stroke above resonance frequency for magnetic actuators.

The development and implementation of a control law depends on the application / function like static or dynamic (fast positioning), microscanning, tracking, microvibrations' rejection or isolation....

The table below summarises the needs in term of error analyses for different applications.

	SLOW POSITIONING	FAST POSITIONING	TRACKING	REJECTION OF VIBRATION
> **Application**	Static	Dynamic	Dynamic	Dynamic
> **Analysed Performances**	Amplitude error	Combined error: amplitude and phase error, Jitter, Settling time	Combined error: amplitude and phase error, Jitter, Rising time	Jitter, rejection of disturbances
> **Examples**	Slow payload motion or pointing, Point Ahead Mechanism or Positioner	Fast steering mirror or XY stage for micro-scanning, Shutter	Fast steering mirror For Line of sight stabilisation or deblurring function	Fast steering mirror Proof mass damper

Table h : Analysed parameters in regards of the application

2.4.2. PERFORMANCE CRITERIA

The performance of a closed-loop controlled system is defined according to several indicators, which are taken into account or not depending on the application:

- Transient response: provides the rising time, settling time, etc.
- Frequency response: bandwidth, flatness, etc.

Those parameters are illustrated opposite.

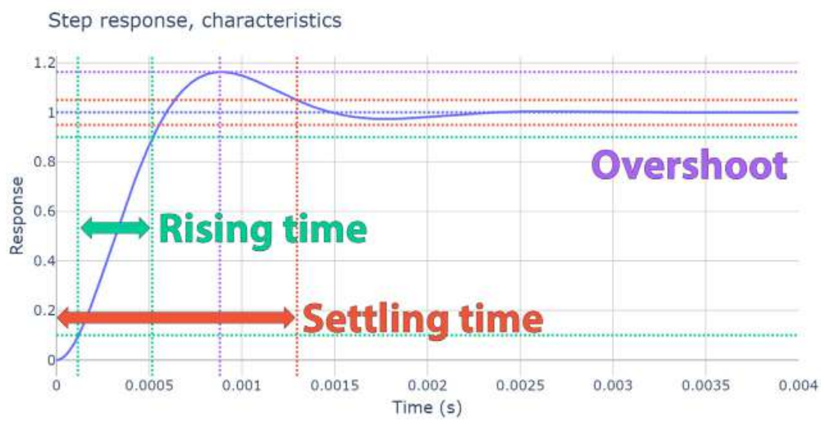


Fig. 2.cn: Step response and associated parameters

The settling time is the time needed for the system to stay in a +/- x% band around its final value. Here the settling time at 5% is given. The rising time is the time needed for the system to go from 10% to 90% of its final value.

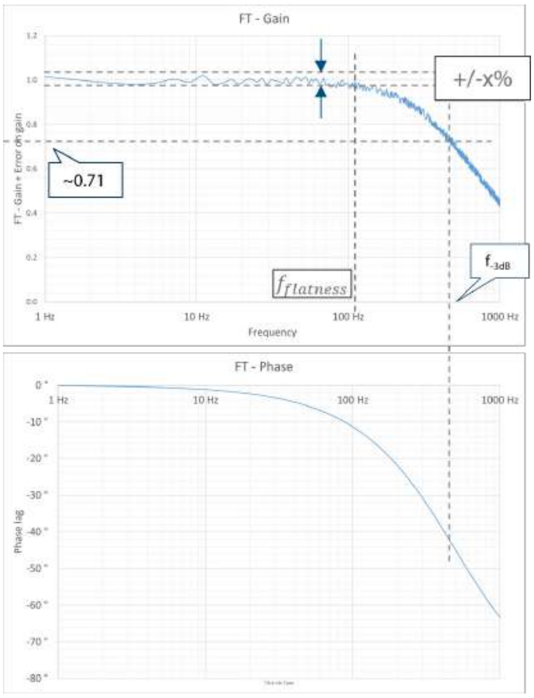


Fig. 2.co: Control loop flatness (top) and bandwidth (bottom)

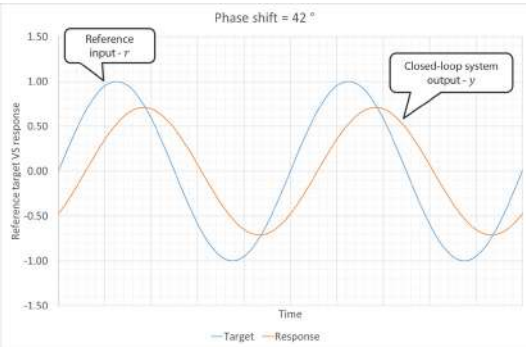


Fig. 2.cp: Control loop delay

From the control loop bandwidth Bode diagram, several parameters are extracted:

- The cut of frequency where the gain of the closed loop response goes below 0.707 (see *Fig. 2.co*).
- The flatness which is the relative gain error before the cut off frequency (see *Fig. 2.co*).
- The delay or phase which represents the delay between the command and the position (see *Fig. 2.cp*).

2.4.3. TYPE OF CONTROL LAWS AND IMPLEMENTATION

To reach the expected performances cited above, CTEC is able to design several types of control laws and to implement them inside its digital controllers.

The fast mechanical response of CTEC mechanisms (thank to their high mechanical resonant frequencies) requires very fast processing (few tens kHz) which is the main difference with standard control of motor (few kHz).

CTEC digital controllers are characterised with their capability to emulate in few microseconds the designed control law for several channels. Additionally, they are more versatile and can permit a calibration, look up table correction, an adaptation/optimisation of parameters to different loads and operating conditions, mechanisms / controller interchangeability. They can be implemented with advanced control laws with the same fast processing.

In complement, communication port with high-speed rate allows to work as deterministic time which is an important factor in control loop providing with a short and stable delay between each acquisition.

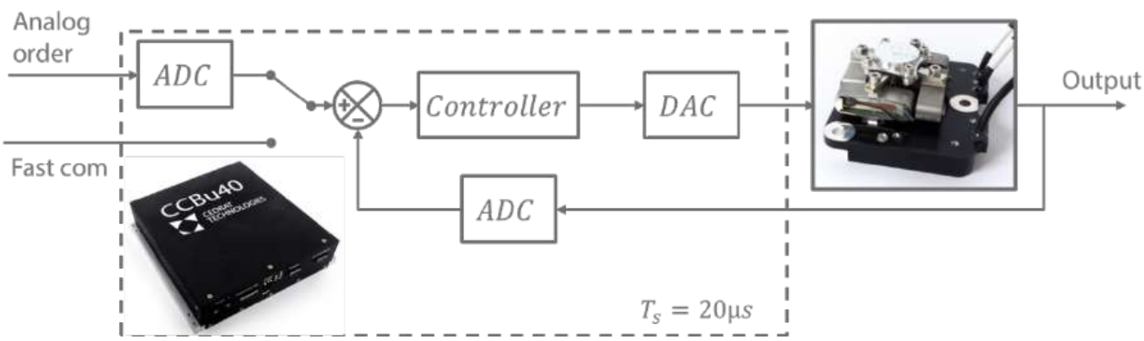


Fig. 2.cq: Synoptic of numeric control processing from CCBu40 for piezo mechanism P-FSM150S-SG

PID CONTROL

At first, CTEC provides control laws based on PID regulator& filters with the following advantages:

- A versality of the control law built around the standard industrial PID controller
- An easy adjustment by the customer of different parameters depending on its application

APPLICATION	STANDARD PID CONTROL FOR STATIC APPLICATION	TUNED PID FOR DYNAMIC APPLICATION	SPECIFIC TUNING AND ADVANCED CONTROL
System bandwidth compared to mechanism resonance frequency Fr	Fr/10	Fr/4 to Fr/3	Depending on customers' needs and CTEC state of the art

Table i : Typical bandwidth achievable depending on customer application

The main drawback comes from the inherent principle of these controllers to improve its stability: Such controller notches specific resonant frequencies to avoid instabilities due to peak gains over frequency. A result is they limit their bandwidths and the tracking error cannot be deleted (impact in dynamic error)

In the following plots, standard bandwidths are provided with impacts of programmed terms.

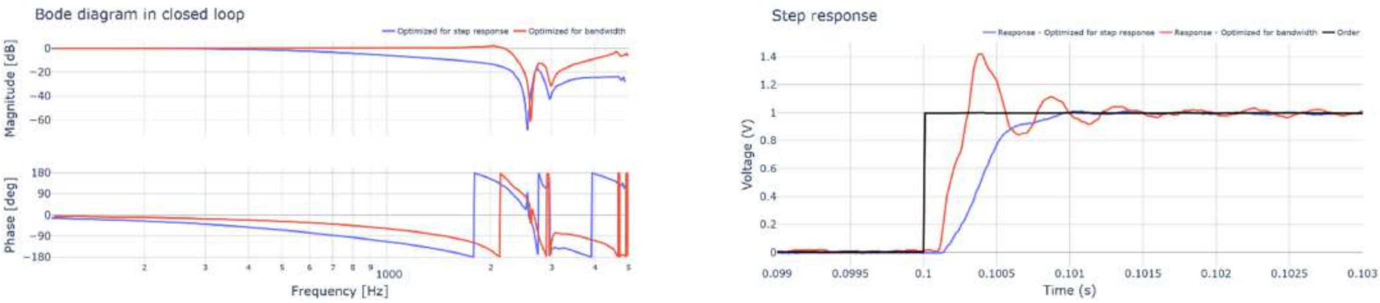


Fig. 2 : Bode and Step response for two controllers optimized for different targets, bandwidth or time response (Controller tuned on DTT15XS)

ADVANCED MODEL-BASED CONTROL

Standard Control law based on PID & Notch filters cannot provide controller with the capability to react to external perturbations at resonance frequencies.

An advanced control law based on full state feedback and model identification allows to damp these perturbation inputs at resonant frequencies of the system…

The dynamic of the system is directly improved: the cut off frequency is higher (depending on the sensor, it is possible to control over the resonance frequency of the mechanism) and the system response time shorter. A comparison between such advanced control and standard PID is given in *Fig. 2.cs*. The trajectory is improved because the delay (the phase plot on the figure) is reduced.

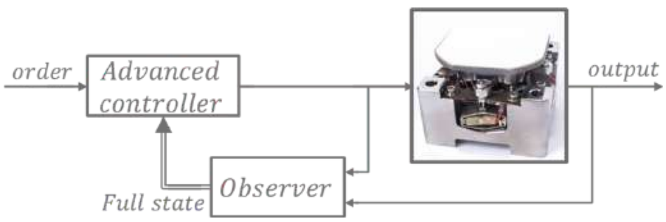


Fig. 2.cr: Synoptic of an advanced control system

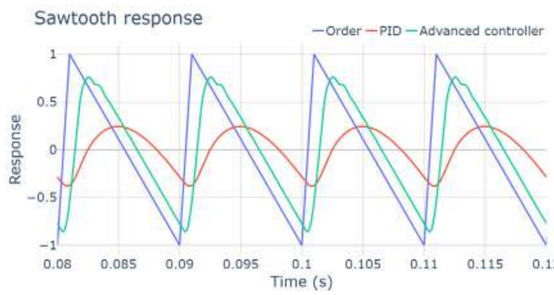


Fig. 2.ct: Temporal response to sawtooth input – comparison between PID and advanced control with full state feedback

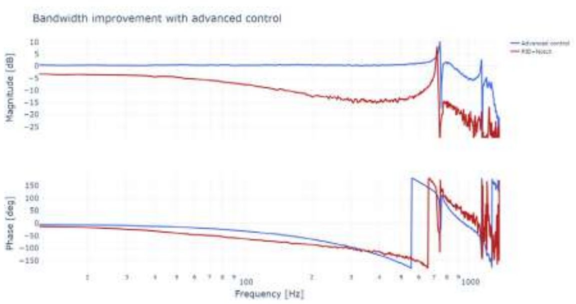


Fig. 2.cs: Comparison between standard PID + Notch and advanced full state feedback controls

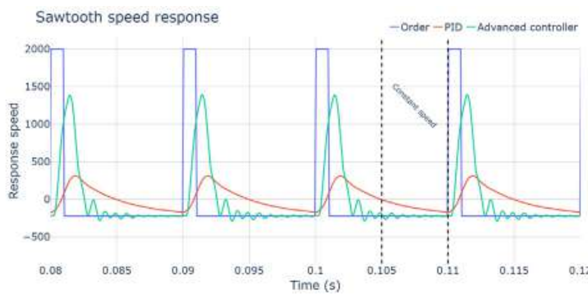


Fig. 2.cu: A définir

More information about sawtooth signal applications can be found in the advanced control for mechatronic application brochure.

Fig. 2.cv: Example of embedded ECS on mechanism: TT60SM-ECS custom

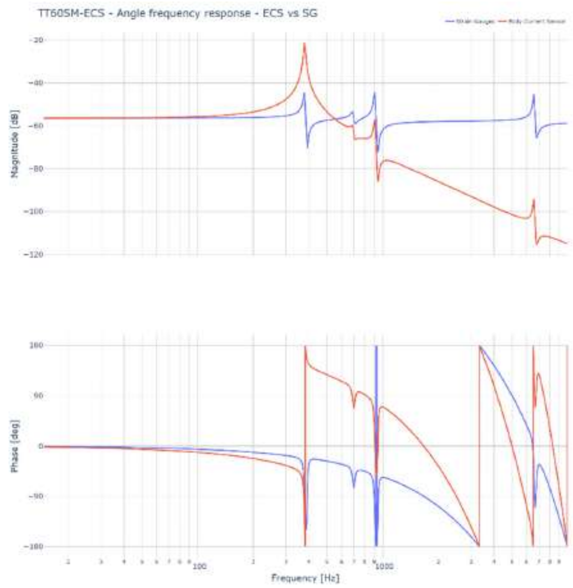


Fig. 2.cw: ECS allow a better accuracy of the measured data, especially after the resonance frequency of the mechanism

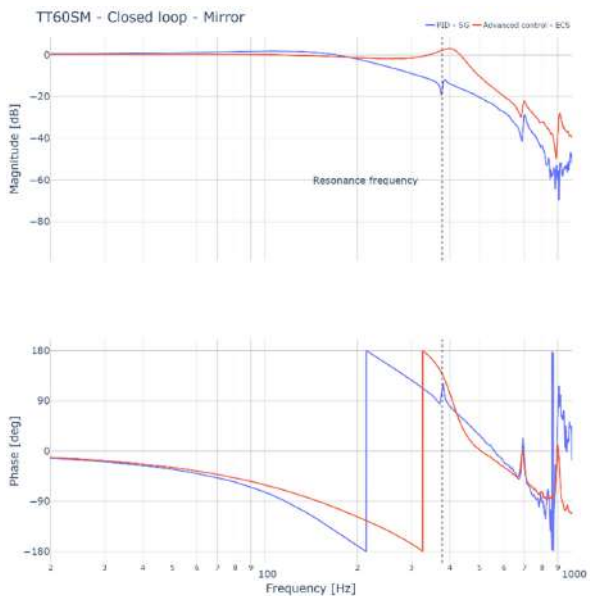


Fig. 2.cx: Comparison between PID control on SG sensor and advanced control on ECS

SENSOR OBSERVABILITY

To achieve high accuracy both statically and dynamically, fast, accurate and repeatable sensors are needed. CTEC usually embed Strain Gauges (SG) in its piezoelectric actuators and mechanism. Strain Gauges measure the strain of the actuating piezoelectric ceramics, which is an indirect estimation of the mechanism position.

SG sensors have the advantages of being compact, accurate and easily integrable. Nevertheless, as SG give an indirect measure, their dynamic response is somewhat different from the one of the mechanism positions, especially after the first resonance frequency of the mechanism. For high bandwidth applications, this lack of observability can be detrimental to the performance or the dynamic precision of the controlled mechanism.

To overcome these difficulties, CTEC is able to implement new sensors to have a more direct measure of the mechanism position. Such sensors can be embedded Eddy Current Sensors (ECS) to directly measure the position or the angle of the mechanism.

Specifically Magnetic Fast Steering Mirrors are factory equipped with Eddy Current Sensor to accurately measure the angle of their mirror and can be controlled over the resonance frequency.

These embedded sensors closer to the useful displacement of the mechanism allow better observability and thus faster and more accurate mechanism positioning.

FAST STEERING MIRRORS

CTEC as a line up of fast steering mirror for applications like optical pointing, perturbation rejection...

This line-up takes advantage of the high bandwidth and accurate control laws to perform in these applications.

2.4.4. CONCLUSION

CTEC offers a wide range of control law and associated sensors to accurately control its mechanisms, both statically and dynamically.

More information can be found in the CTEC control brochure.

3. APPLICATIONS & FUNCTIONS

3.1. FROM COTS PRODUCTS TO CUSTOMIZED SOLUTIONS

Products and developments provided by CEDRAT TECHNOLOGIES (CTEC) find applications in all the fields of mechatronics. The major ones are **air & space, optronics, scientific instrumentation, production and manufacturing** and **medical technology**.

All these application fields gather advanced functions requiring: precise positioning, fast actuation, fast displacement, vibration or force generation, vibration generation and damping. Some related applications and their working conditions are given in section 3.2, page 63.

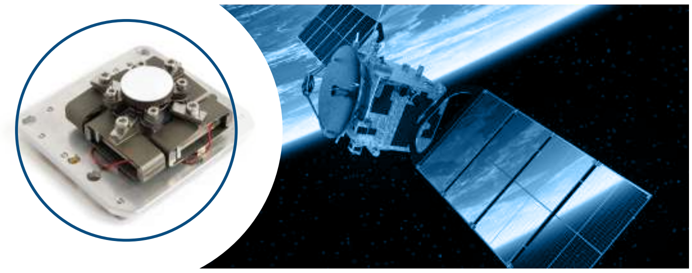
CTEC, as a customer-oriented company, manufactures and sells not only standard products, but also customised solutions, especially for OEM (Original Equipment Manufacturer) series.

The range of standard actuators from CTEC is a first commercialy off the shelves (COTS) solution for satisfying a wide spectrum of technical specifications & environmental conditions in short time delivery. Some of the products presented in this catalogue are in “preliminary data” as noted in their performance table. It means those products are not available off the shelves and may require some extra engineering work to be so. To satisfy some demanding customer requirements met in OEM business, CTEC can optimise, adjust and extend the performances of its actuator technologies. The aim is to be compliant with technical, environmental, economical or other specifications that are necessary to provide the customer with the best value added on its system integration. Several situations may arise:

- Some performances like stroke or force of standard actuators have to be increased,
- The mechanical interfaces have to be adjusted to make the final integration easier,
- The application requests a more complex mechanism than a single actuator,
- A special feature such as non-magnetism or harsh environment compatibility is required.

Solutions to remove these limitations are shown through applications in section 3.2, page 63 and are completed with additional technological solutions introduced in section 3.3, page 73.

In all these cases, CTEC can provide all the services presented in section 1.4, page 14 to help the customer with a fast solution combining its existing products, its building blocks, its experience and its development facilities.



> cedrat-technologies.com/applications/space-and-new-space

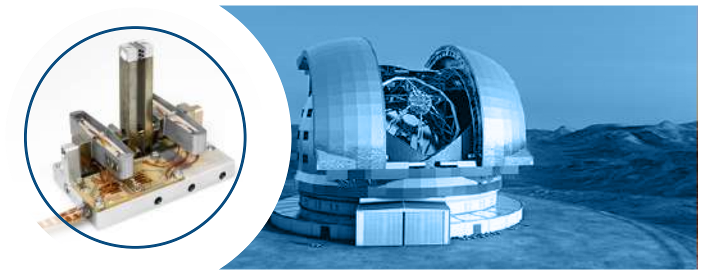
SPACE & NEWSPACE

- Optical mechanisms flight hardware
- Scan mechanisms for earth observation
- Hold-Down Release Mechanisms (HDRM)
- Fast Steering Mirrors for laser pointing

> cedrat-technologies.com/applications/optronics

OPTRONICS

- Micro-scanning & pixel shifting
- Optical image stabilisation
- Autofocus
- Embedded mechatronic functions



> cedrat-technologies.com/applications/scientific-instrumentation

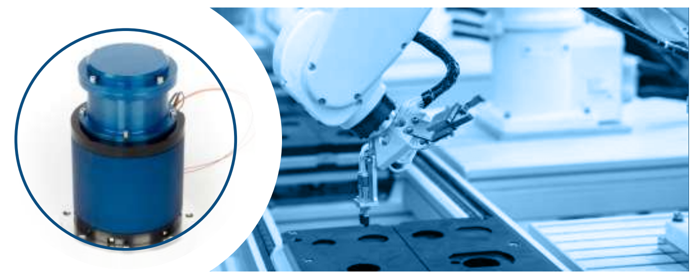
INSTRUMENTATION

- Telescope mirror motorisation
- Synchrotron Fasts Piezo Shutters (FPS)
- Environmental & material testing
- Beam shaping

> cedrat-technologies.com/applications/medtec

MEDTEC

- Micro actuation
- Miniaturised motorisation
- Microfluidic control device
- MRI-compliant actuation



> cedrat-technologies.com/applications/production-machine

MANUFACTURING

- Chatter cancellation
- Vibration assistance for machining
- Active clamping fixtures
- Laser processing

3.2. APPLICATIONS & FUNCTIONS CLASSIFIED BY WORKING CONDITIONS

The working conditions are the kinematic conditions so that the inertia and dynamic force impacts on the actuator are taken into account. The working conditions are split into several kinematic conditions: static, dynamic non resonant, resonant...

The function is the type of physical action or operation (force, motion, vibration,...) that the actuator generates on the user's system. The function is the answer to the following question: How is the actuator used inside the system?

The application is the result of the actuator's function inside the system. The application is the answer to the question: What is the actuator's operation/function used for?

The working conditions can be more or less demanding for the actuator and the electronics. They are associated to different frequency regions, introduced in previous section. Most of CEDRAT TECHNOLOGIES (CTEC) actuators can operate under dynamic conditions, which opens them to a wide range of applications and markets. To select an actuator for a given application, it is useful to know its function and working conditions (see table below).

WORKING CONDITIONS	INERTIAL FORCES	ELECTRIC POWER	FUNCTIONS/USED AS	APPLICATIONS/USED FOR
Static	Negligible	Negligible	• Micropositioner • Slow actuator • Force Generator • Slow Long-stroke actuation by steps accumulation (case of Quasi static piezo motor)	• Micro & Nano positioning • Flow control & valves • Material Stress testing
Dynamic Strain non resonant	Not negligible	Can be very high and may be the limiting factor	• Wide bandwidth • Vibration generator • Vibration damper • Fast actuator • Fast Long-stroke actuation by steps accumulation (case of fast inchworm piezo motor)	• High frequency Shaker • Forced Vibration Assistance • Active damping, Stabilization • Shutter, XY Scanning • Fast positioning • Material stress cycling
Dynamic Strain at resonance	High	Not negligible (Applied voltage should be monitored)	• High amplitude • Vibration generator • Sonic transducer • Ultrasonic transducers	• Resonance Vibration • Assistance to process • Ultrasonic cutting, welding, vibration assisted insertion... • Fluid degassing, cleaning
Dynamic force	High	High	• Proof-mass vibration / force generator • Proof-mass vibration damper	• SHM structure exciters • Hammer • Active damping of structures
Impulse Strain (Dynamic)	Can be high	Can be very high and may be the limiting factor	• On-off fast actuators • Impactors • Fast Long-stroke actuation by steps accumulation (case of SPA Inertial static piezo motor)	• Shutter • Fluid injection • Circuit breaker • Fast positioning • Long-stroke positioning
Dynamic Sensing	Can be high (Due to external vibrations)	Negligible (Generated voltage should be monitored)	• Electric generator • Force sensor	• Energy Harvesting • Force Sensing

Table 3.a: Applications, functions & working conditions

3.2.1. APPLICATIONS OPERATED UNDER STATIC CONDITIONS

Fig. 3.a: Point Ahead Mechanism PAM30

MIROR POINTING MECHANISMS

As Amplified Piezoelectric Actuators (APA®) are rather flat, they can be arranged in parallel. It is interesting either to increase the force or for tilting applications (*Fig. 3.a*). In this last case the flat structure of APA® allows to place their actuation axes close together to get a relatively large tilt angle. Using this possibility, standard tilt (TT) or double tilt (DTT) mechanisms or steering platforms have been designed for optical deflection or steering mirror: TT60SM-SG, DTT60SM-SG and DTT35XS (see chapter *7, page 117*), respectively based on respectively two & four APA60SM and four APA35XS mounted with flexural hinges. Customised tilt mechanisms can also be easily derived from other standard actuators.

Fig. 3.b: DTT60SM based on 4 APA60SMSG (courtesy of Airbus DS Sodern)

For instance, a space version of the DTT60SM-SG has been developped for Airbus DS within the ATLID project (see *Fig. 3.b*). This mechanism has to withstand external vibrations and benefits from the APA® properties.

Last but not least, CTEC designed and manufactured the Engineering, Qualified and flight models of the Point Ahead Mechanism PAM30 integrated in the Deep Space Optical Communication (DSOC) terminal on board of the NASA Psyche mission launched in October 13th 2023. PAM30 (*Fig. 3.a*) is a Silicon Carbide (SiC) mirror integrated on a 4 APA150S based piezo steering platform.

Fig. 3.c: P-FSM400MML Tip-Tilt Mechanism

XY & XYZ MICRO POSITIONING MECHANISMS

Several XY or XYZ stages have been designed at CEDRAT TECHNOLOGIES (CTEC) for various needs. The customised XYZ smart mechanism for the MIDAS instrument of ROSETTA space mission was developed under an ESA/ESTEC contract, starting from standard APA50S and PPA10M. The function of this mechanism is to ensure the nano-resolution scanning motion of an Atomic Force Microscope (AFM) under a severe environment (see *Fig. 3.e*). Although operated under static conditions, the ability of CTEC actuators to withstand large vibrations thanks to their pre-stress allowed the mechanism to pass vibration tests. It was launched in 2004 and run in 2014 when Rosetta reaches Churyumov-Gerasimenko comet.

Fig. 3.d: XYZ200M-SG stage for IR Spectroscopy (courtesy of GES Lab / Montpellier University)

Another example of XYZ mechanism developed for an optical application is given with *Fig. 3.d*. This mechanism is able to perform any stroke in the volume [-100,+100 µm]× [-100,+100 µm] × [0.200 µm]. It is entirely based on standard components. It combines a standard XY200M stage based on 4 APA200M for centred XY displacements (scanning function) with a set of 3 APA200M for Z displacements (focussing function).

Fig. 3.e: Midas Space Instrument (courtesy of ESA)

TRIPODS & HEXAPODS

CTEC's actuators have also been used to build complex nanopositioning mechanisms such as tripods, hexapods or 5 d-o-f mechanisms in the fields of astronomical & scientific instruments as well as space optics. For example, CSEM (Switzerland) and SENER (Spain) had to develop a tripod mechanism for nano-positioning and stabilisation of the M5 mirror in the Extremely Large Telescop (ELT) of ESO. The mirror mass is more than 600 kg. Therefore this induces a static load but also dynamic loads (due to possible earthquakes) have to be added to the functional dynamic load. After a trade-off analysis, CSEM and SENER have selected the APA® technology. CTEC has then developed 3 customised extremely-large actuators APA500XXL meeting these severe requirements (see *Fig. 3.f*).

Fig. 3.f: APA500XXL for ELT M5 mechanism (courtesy CSEM, NTE and ESO)

Piezo motor technology is well known for its ability to move and to position payload at rest in compact size. Several scientific instruments, used for sample analysis for instance, integrates compact piezo motorised tripods based on CTEC MSPA.

Other examples of piezo actuators applications in mechanisms are given in:

cedrat-technologies.com/technologies/actuators/piezo-mechanisms/

HIGH-PRECISION QUASISTATIC PIEZO MOTORS

Fig. 3.h: BSMA piezomotor for IASI-NG

High-precision instruments involving moving parts with blocking at rest require specific motors generating long stroke, no backlash, high stability, low exported vibrations, and/or non-magnetism. This is the case for example in space instruments such as IASI-NG or LISA. For these applications, CTEC develops custom piezoelectric stepping motors operating in static mode. They offer long linear or rotating stroke with blocking at rest, and meet specific requirements.

In the case of IASI-NG, CTEC has developed the BSMA (*Fig. 3.h*), a derivation of its standard FSPA piezo motor (see chapter 7). The FSPA is a very high resolution linear stepping piezo motor using a differential screw driven by inertial piezo effect. The BSMA for IASI-NG keeps the differential screw but this screw is driven by a clamp mechanism operated at very low frequency. The screw concept ensures zero backlash (<5 nm), meaning that when switching off the power supply, the motor position is stable.

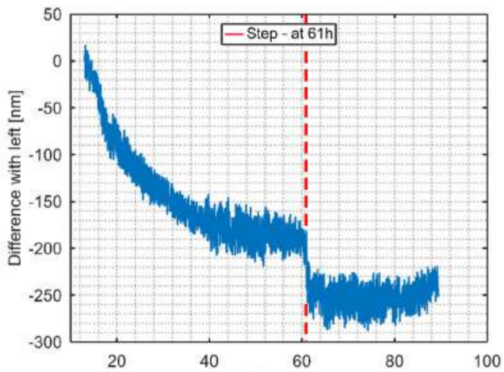


Fig. 3.g: BSMA 100h stability test

This BSMA motor can produce steps of 50nm, while offering a very high stability, with drift typically less than 50nm/week. This is demonstrated by tests on the next figure as well as the 0 backlash (see *Fig. 3.g*). In addition, this motor has passed launching vibration and shock tests. A series of Flight Models has been delivered in 2022.

ELECTROMAGNETS FOR FORCE GENERATION

Customised electromagnets are developed by CTEC to generate the maximum of force / torque in the minimum of volume / mass. Such a feature is deemed essential for aerospace applications and these solenoids remain usual for static operation.

Within a volume of 10 cm3 and less than 90 grams, rotary electromagnets are capable of providing up to 10 degrees angle with a torque higher than 160N.mm. Such a design complies with ECSS standard and this technology is delivered as flight models for Orion-ESM mission. More than a hundred electromagnets has been produced (see *Fig. 3.i*).

Fig. 3.i: Brake solenoid flight model

LONG STROKE VOICE COIL MOTORS

Rotary and linear voice coil motors are designed by CTEC for space and demanding environments using multi-physics simulations skills, high performances material knowledge and system integration and qualification know-how.

Both rotary (RVCM) and linear (VCM) have been developed to equip the SCan Assembly (SCA) of Meteosat Third Generation (MTG) satellites. 20 years of operational lifetime are required for this application. Typical stroke designed for MTG are +/-12 degrees angle / 0.4 N.m or +/- 15 mm stroke / 13 N.m. Beyond its ability to withstand environmental requirements (thermal, vacuum, vibration 30 Grms, shocks...), these motors demonstrate high stability of the force constant according to both position and current. Their unique balanced design allows to reduce parasitic forces and eases the integration of guiding system.

Fig. 3.j: RVCM flight model

Fig. 3.k: Linear Voice Coil Motor

3.2.2. APPLICATIONS OPERATED UNDER DYNAMIC NON-RESONANT CONDITIONS

FAST XY STAGES FOR SCANNING, STABILISATION...

Several OEM XY stages for fast micro-scanning and stabilisation are produced in series by CEDRAT TECHNOLOGIES (CTEC).

XY25XS stage (*Fig. 3.l*) uses parallel piezo actuation, which is also used in XY200M products. This configuration is optimal for fast motion and renders feasible new optical functions. For example fast micro-scanning is highly beneficial in defence infrared cameras to improve the camera resolution. In this application the short response time of the actuators is used to perform a complex pattern to allow image reconstruction from several pictures at a rate of 100 Hz. Therefore the actuators are used under almost impulse strain conditions. In addition, the XY stage should operate in spite of external vibrations, the camera being embedded in land, aerial and sea vehicles. Therefore CTEC actuators' performances in dynamics are suited to this class of application.

Parallel magnetic actuation is another option when even larger strokes are needed. Fig. 3.k is a XY stage based on small Moving Iron Controllable Actuators (MICA™) offering 2 mm × 2 mm stroke, designed for optical stabilisation.

Fig. 3.l: XY stage based on APA25XS used for micro-scanning

Fig. 3.m: XY stage based on MICA™ used for stabilisation

SERVO PIEZO TOOLS

The Servo Piezo Tools (SPT) developed by CTEC can realise both fast and precise machining: applications vary from oval piston machining to aspherical lens machining.

For example, the SPT400MML (*Fig. 3.n*) prototype uses the Amplified Piezoelectric Actuator (APA®) APA400MML to obtain a large and fast motion of the diamond tool (400µm at more than 100Hz). The SPT400MML is arranged in a casing and dry air is used to expel dust from the casing. It includes an Eddy Current proximity Sensor for position control.

Fig. 3.n: Servo Piezo Tool SPT400MML

ACTIVE VIBRATION DAMPERS

When coupled to well suited driving and control electronics, piezo actuators are excellent deemed candidates to actively damp the vibrations on a mechanical structure. CTEC has already developed and set up several OEM solutions based on APA® & Parallel Pre-stressed Actuators (PPA) for Active Control of Vibrations (ACV) on machine tools (see *Fig. 3.o*), ski and medical robot.

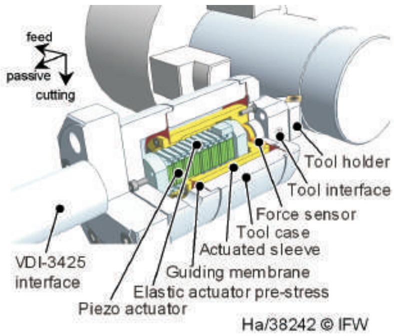


Fig. 3.o: Smart Tool based on PPA60L (courtesy of IFW)

ACTIVE FIXTURE USING MICA200M

A technological breakthrough has been achieved with a new version of the MICA™. The MICA200M actuator and its

dedicated compact power electronics has been developed in the frame of the INTEFIX FP7 project to address the field of active fixture (*Fig. 3.p*). That application is challenging since the MICA™ actuator's response is used for both vibration and deformation control during the machining of low rigidity parts. Therefore a better controllability of the actuator is needed in terms of force along the stroke, and on a wider range of frequency including static control.

Actuators or systems for vibrations damping are also available upon request. Other examples of applications of active damping are given in:

cedrat-technologies.com/technologies/mechatronic-systems/vibration-control

Fig. 3.p: Active fixture using MICA™

VIBRATION GENERATOR OPERATING IN FORCED VIBRATION MODE

Amplified Piezoelectric Actuators (APA®) and Parallel Prestress Actuators (PPA) find several applications for vibration generation in forced vibration mode (below resonance): APA® and PPA used in forced vibration mode are typically used in machines for material mechanical testing, such as the lifetime test of Semicon silicon parts or films by stress cycling, or machines for vibration testing such as piezoelectric shakers (see *Fig. 3.q*).

Moving Iron Controllable Actuators (MICA™) are a new alternative for vibration testing. It offers more stroke (up to 10mm) compared to electrodynamic shakers while being much more compact.

Another range of industrial applications of this mode is the vibration assistance to processes. Forced vibrations provide a useful assistance in many processes such as food cutting, glass cutting, engraving, machining (milling, drilling...), extruding etc... Typically vibration assistance improves

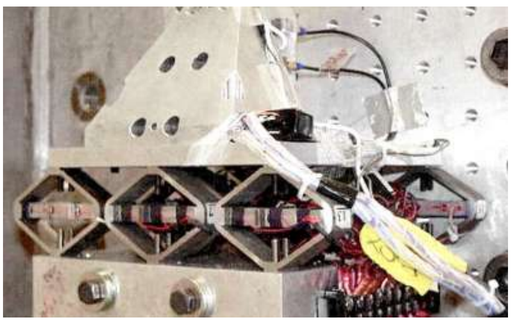


Fig. 3.q: Piezoelectric shaker (courtesy of Sandia Lab)

Fig. 3.r: AVIBUS VAD tool holder

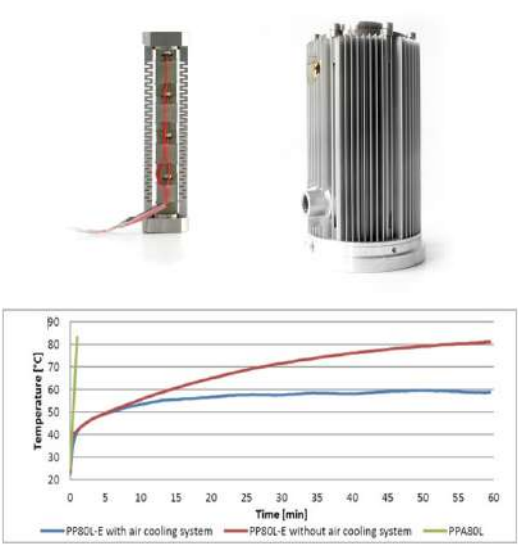


Fig. 3.s: From standard to encapsulated piezo actuators: PPA801L to PPA80L-E. The graph shows temperature rise at 235Hz, full stroke

Fig. 3.t: Audacity piezoelectric motor

the process speed and/or surface quality.

An example in the field of Vibration Assisted Machining (VAM) or Modulation Assisted Machining (MAM) results from the AVIBUS project coordinated by CTEC. From tests of Arts et Métiers ParisTech (ARTS) and CETIM, the Vibration Assisted Drilling (VAD) tool holder of *Fig. 3.r* allows to reduce the drilling time by a factor of 3.

POWERFUL VIBRATIONS GENERATION

CTEC has enhanced standard piezo actuators in order to address continuous high energy vibration generation. Firstly the preload of the active component has been doubled without any performance limitation. Secondly, a dedicated encapsulation technique combined with the use of high temperature material allow to dissipate and withstand heat generation. Thirdly, a new generation of Switching Amplifier, called SA, has been developed to drive these powerful actuators at their maximum possible energy (see section *8.1.5, page 131*).

Any APA® or PPA actuator can now be supplied with an encapsulation option and their preload can be improved if required. As an example, an encapsulated PPA80L (see *Fig. 3.s*) has been driven continuously at full stroke up to 1 000 Hz, whereas its standard version does not exceeds 50 Hz. These powerful piezo actuators are commonly used in manufacturing process for vibration assistance or acoustic generation and operate within harsh/humid environments.

Other examples of applications of forced vibrations using CTEC's products are given in:

[cedrat-technologies.com/technologies/actuators/sonic-ultrasonic-generators]

FAST INCHWORM PIEZO MOTORS

Within the frame of AUDACITY Cleansky 2 collaborative project, a piezo motor has been developed for compact and powerful locking applications. The topology proposed in this motor is based on a 100% piezoelectric actuator technology (PPA & APA). It is a non-resonant motor based on walking principle. The long stroke is achieved by an accumulation of steps at low frequency. In operation, this motor can lift 35kg (350N)at 11mm/s speed along a stroke of 15mm. This motor displays more than 500N of force at rest (stall force).

The demonstration of this motor has been successfully performed between -55°C up to +70°C, with no compromise on the force and speed.

Nowadays this motor is the **one of the most powerful piezo motors in the world**.

https://youtu.be/JvY9KM5u828

3.2.3. APPLICATIONS OPERATED UNDER DYNAMIC RESONANT CONDITIONS

PIEZO VIBRATORS OPERATING AT RESONANCE

CEDRAT TECHNOLOGIES (CTEC) Parallel Pre-stressed Actuators (PPA) and Amplified Piezoelectric Actuators (APA®) are also successfully used in resonant mode for vibration generation at a fixed frequency in that case full stroke is achieved with less than 10 V instead of 170 V in quasi static conditions.

In some cases, special interfaces are useful, for example the Ultrasonic Piezo Actuators (UPA) deriving from the APA® have been developed to offer a more compact solution than Langevin transducers for the generation of ultrasonic vibrations. UPA structures are the same as APA® structures, but they are maintained on the side of the long axis in order to decouple the support from the vibration generation (free-free mode).

UPA are customised products finding applications in machining (for example ultrasonic engraving) or in ultrasonic piezo motors.

Fig. 3.u: Moving cylinder MICA™20CS actuator for pump and compressor

Fig. 3.v: MICA300CM actuator for clean gaz compression

COMPRESSORS, EXPANDERS, PUMPS

Dynamic resonant conditions are used when the working frequency is well-defined and low electrical power is needed. These conditions perfectly fit with balanced compressor, and pump applications, using low vibration back to back linear reciprocators. Moving Iron Controllable Actuators (MICA™) are well-suited for resonant conditions since they feature high efficiency to provide high output force, with low electrical input power. They feature also ultra-long lifetime, using frictionless, and free of lubricant, flexure bearings. Custom output mechanical power can range from 3 W to higher than 1000 W on demand, with housing designs featuring fluid leak tightness, biocompatibility.

Resonant MICA™ flexure bearings actuators are especially relevant as pressure wave generators, or expanders inside high frequency Stirling machines, for wasted heat energy recovery, refrigerators, and cryogenic coolers, as well as positive displacement compressors, using read valves, inside Rankine and Joules Thomson machines.

In the frame of a TRP project with ESA, a double stage reed valve compressor has been developed. This mechanism is using Moving Iron Controllable Actuators concept (MICA). This actuator is based on magnetic technology. (see *Fig. 3.x*)

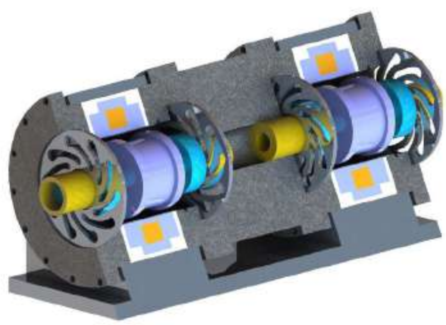


Fig. 3.w: CAD integration of MICATM inside back to back balanced compressors

3.2.4. APPLICATIONS OPERATED UNDER DYNAMIC FORCE CONDITIONS

Fig. 3.x: MICA20CS proof-mass

Fig. 3.y: MICA300CM proof-mass

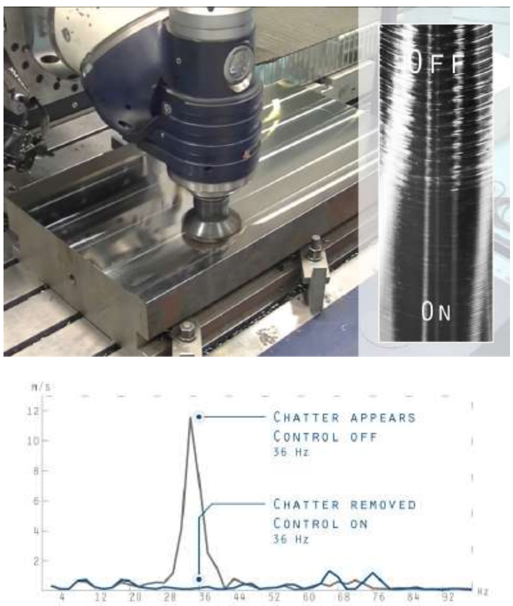


Fig. 3.z: Active vibration damping through MICA™

PROOF-MASS ACTUATOR

A Proof-Mass Actuator aims at generating dynamic forces into a structure to either excite vibrations in the structure (proof-mass shaker) or to damp vibrations of the structure (proof-mass dampers).

CTEC piezoelectric proof-mass dampers are made of an APA®, a back mass fixed on one side of the actuator, and optionally some guiding functions (Fig. 3.y). The second side of the actuator is fixed on the structure. By reaction, because of mass inertia, dynamic forces can be produced in the structure at the resonance frequency and above resonance. In this condition, the Proof Mass Actuator may provide dynamic forces up to the APA® blocked force.

Standard MICA™ actuators have been successfully integrated inside milling machine, to perform active vibration damping in a proof mass configuration. For such a configuration, MICA™ with flexural bearing (see §7.1. Moving Iron Controllable Actuator MICA™, page 92) is preferred. Then there are different possibilities for the reaction masses. The actuator can be fixed to the structure via its moving part, then the stator plays the role of the reaction mass. Alternately, the actuator can be fixed to the structure via its stator, then the moving part plays the role of the reaction mass. In that case, an additional mass is generally added to the moving part in order to tune the resonant frequency.

This work has been performed in the frame of the DynXpert FP7 project "Factories of the Future" (see Fig. 3.aa). The main purpose of the MICA™ integration was to suppress the chatter occurring at different ranges of frequency. Standard MICA™ actuators are capable of providing forces up to 1000 N, working at low to high frequency. The main advantages of MICA™ actuators are the capabilities to be integrated in relatively small allowed volumes for the requested force, and the capabilities to withstand harsh environment such as vibrations, shocks, and high ambient temperature that can be found in machining tools. Derived from this successful R&D activity, standard MICA-based Tunable Proof-Mass Actuators are commercialised (see §7.3. Tunable proof mass actuators, page 96).

3.2.5. APPLICATIONS OPERATED UNDER IMPULSE CONDITIONS

FAST & PRECISE VALVES

The well-known advantages (rapid response and precise positioning) of Amplified Piezoelectric Actuators (APA®) have been used in valve designs to obtain both rapid and precise-flow proportional valves.

CEDRAT TECHNOLOGIES (CTEC) has already designed and developed hydraulic piezo valves within the European project FP6 MESEMA. CTEC is also providing space piezo valves under ESA contracts for the propulsion of micro satellites or under CNES-ARIANE contracts. Using a dedicated test bench (*Fig. 3.aa*), APA-based piezo valves (*Fig. 3.ab*), are developed for fine pressure regulation for ARIANE 6 launcher. Such piezo valves offer advantages to solenoid valves for example to reduce power consumption. However solenoid valves are still developed by CTEC, especially based on MICA™ actuators for large fast & precise flow control...

CTEC has also experience in design of Synthetic Jet Actuators and Pulsed Jet Actuator mechanisms (see *Fig. 3.ac*).

For specific designs of piezo valves, please contact CTEC or visit:

cedrat-technologies.com/technologies/mechatronic-systems/electro-fluidic-devices/

Fig. 3.aa: Bench for testing pressure-regulation piezo valve for ARIANE 6 launcher

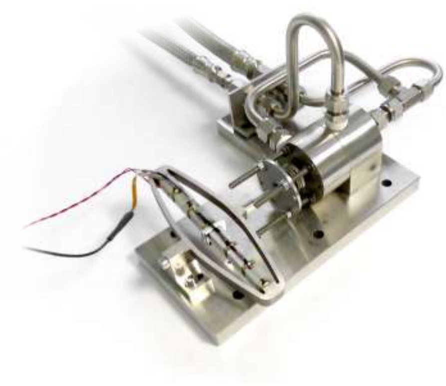


Fig. 3.ab: Pressure-regulation APA-based piezo valve for ARIANE 6 launcher

LONG-STROKE ACTUATION WITH STEPPING PIEZOELECTRIC ACTUATORS (SPA) PIEZO MOTOR

SPA are piezo motors for long stroke actuation whose principle and product characteristics are introduced in section §2.1.6. Stepping Piezo Actuators SPA, page 19. An SPA is basically an Amplified Piezoelectric Actuator (APA®) exploiting both slow and fast strains to get stick slip effects. Thus the SPA uses the APA® under Impulse strain conditions.

As a first consequence, the SPA takes advantage of the APA® pre-stress to demonstrate the following performances:

- fast response time,
- ability to withstand external vibrations,
- robust structure (no dismounting during operation),
- good resistance to transverse forces...

As a second consequence, all APA® offering good dynamic capabilities can be used to make new SPA. Therefore new customised SPA can easily be developed upon request from the large range of standard APA®.

The LSPA30uXS (*Fig. 3.ad*) is an example of customised miniature piezomotor developed for a MRI-compatible medical implant. It is based on the SPA motor concept and the APA30uXS micro actuator. This motor is fully-non magnetic, passing MRI tests. Its mass is less than 1 gr.

Fig. 3.ac: Pulsed Jet Actuator designed in the frame of the Cleansky VIPER project

Fig. 3.ad: SPA30uXS piezo motor

It performs stroke of 3 mm with a controllable speed from 0 to 70 mm/s. The blocking force at rest is higher than 0.5 N while the actuation force is higher than 0.2 N.

The SPA technology has received a Golden Micron award at MICRONORA 2008 micro technology fair because of its relevance for precision and miniaturisation positioning functions.

Examples of CTEC piezo motors and applications are given in:

cedrat-technologies.com/technologies/actuators/piezo-motors-and-electronics

MULTI-AXIS ACTUATION WITH SPA PIEZO MOTOR

Fig. 3.ae: Tripod mechanism based on 3 piezo motors

Multi degree of freedom (dof) mechanisms are widely required into micro or macro manipulation fields as well as in optronics functions. Thanks to their versatility and robustness, SPA motors can be combined to generate such multi-axis movement.

The SPA-FSM (*Fig. 3.ae*) is a 3 degrees of freedom mechanism offering +/- 3° rotation around X and Y axis and a 2.5 mm Z translation stroke into a low volume.

This large displacement capability is combined with a 0.5 µm resolution allowing to achieve micro-radian and nanometric pointing or positioning.

Watch our video: youtu.be/i7aSoCC3kq0

3.2.6. APPLICATIONS OPERATED UNDER DYNAMIC SENSING CONDITIONS

PIEZO GENERATORS & ENERGY HARVESTING

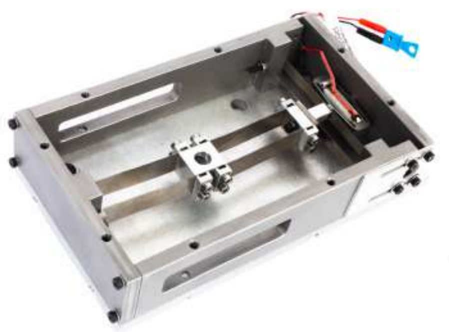


Fig. 3.af: Bistable energy harvester based on piezo actuator APA®

Piezo actuators can also be used as electric generators. When subjected to an external source of vibration or to a shock, a piezo actuator produces electrical energy.

Among different actuators, APA® are good candidates to perform such a function with reliability and efficiency because they are pre-stressed and because their shell contributes to a favourable dynamic stress distribution.

It has been demonstrated for example that a small APA® encapsulated within a frame box can produce 4mW power at 400 Hz (see Fig. 3.ah).

CTEC can develop customised piezo generators using its range of standard piezo actuators. Examples of other piezo harvesting applications are given in:

cedrat-technologies.com/technologies/mechatronic-systems/energy-harvesting

3.3. ADDITIONAL TECHNOLOGICAL SOLUTIONS

This section presents technological solutions that can be proposed in addition to technological solutions introduced in section §3.1. Market overview, page 43 or to standard products described in chapters 4, page 57 to 7, page 91.

3.3.1. HOLLOW PARALLEL PRESTRESSED ACTUATOR HPPA

CEDRAT TECHNOLOGIES (CTEC) has delivered some annular multilayers piezo ceramics pre-stressed (preloaded) by an external elastic frame. This structure called Hollow Parallel Prestressed Actuator (HPPA) allows to increase the life time and reliability of the piezo rings under severe environment (high level of vibrations) and in dynamic applications. It enables to reach very high frequencies, with a resonance over kHz. Several HPPA, including flight models, have been delivered for various space missions.

Fig. 3.ag: HPPA for the first European space Lidar, Aladin / Aeolus (courtesy of Galileo Avionica)

3.3.2. EXTREMELY AMPLIFIED ACTUATORS

The Amplified Piezoelectric Actuators (APA®) shape is a highly effective amplification mechanism offering a high efficiency. However, it is sometimes required to achieve even larger displacements.

A second stage amplification is then a good solution to build an extremely amplified actuator. Very compact actuators can provide high displacement, with amplification ratio up to 40 or more. Careful design is needed with these actuators to preserve acceptable stiffness and positioning stability. The Fig. 3.aj shows a two-stages amplified and monolithic actuator developed for a synchrotron beam shaping mechanism, with a stability under the micron, for a displacement of 400 µm.

Fig. 3.ah: Two-stages amplified and monolithic actuator designed with SOLEIL for the SixS beamline

3.3.3. APPLICATIONS REQUIRING A HIGH STATIC STABILITY IN CLOSED LOOP

Many applications require long-term position stability, which relates to the notion of absolute precision over time. CTEC has demonstrated nanometric position stability of a closed-loop piezo-mechanism with integrated strain gauges sensors. This technology opens a wide range of new possibilities for industrial, aeronautical, and space applications. In the nanometric range, contributions that are usually considered negligible become main contributors. Dedicated test equipment has been set-up in order to perform high precision instrumentation of systems, based on a high precision laser interferometer. Measurements are done in a primary vacuum chamber and with thermal control.

The resolution can reach the nanometric range, with a tested 500 hours stability of ±10 nm (see Fig. 3.ak).

For dynamic positioning in closed loop, see section 2.3.

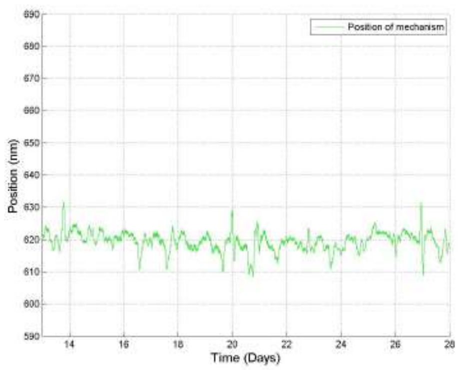


Fig. 3.ai: Stability test of two weeks long

4. PIEZO ACTUATORS

4.1. SELECTION GUIDE

4.1.1. INTRODUCTION

cEDRAT TECHNOLOGIES (CTEC) offers a wide range of commercially off-the-shelf piezo actuators: Amplified Piezoelectric Actuators (APA®) and Parallel Pre-Stressed Actuators (PPA) based on multilayer & low voltage piezo electric ceramics (MLA). These actuators benefit from 20 years of space heritage and industrialization efforts. A non-exhaustive list of options is presented in the § *4.1.2* / *4.1.3* / *4.1.4*. These options aim at meeting different requirements in terms of mechanical or electrical interfaces and environmental conditions. Thanks to the development of these dedicated options, some of these piezo actuators have been used successfully in the following environmental operating conditions:

- Vacuum and Ultra High Vacuum
- Extreme temperatures (< 4 K, > 200°C) & large thermal gradient (from -50°C to +80°C)
- Shock & vibrations
- High dynamics & self-heating
- High Magnetic field
- High radiation (> 100 kRAD)
- High energy laser (> 100 kW)
- High pressure fluid
- Corrosive fluid
- Clean room

Please do not hesitate to contact CTEC for more information about an actuator's additional features.

APA200M-SG-NM

Type of actuator | Stroke in µm | Serie | Option(s)

Fig. 4.a: Products designation

SPECIFIC PERFORMANCES

(1) Resolution : Resolutions of these actuator are obtained with an amplifier SNR of 85dB

(2) Force limit : External on-axis pulling or pushing. Inertial forces should be assimilated as external forces

4.1.2. MECHANICAL INTERFACE OPTIONS

TH - THREADED HOLE

The actuator has one or two identical mechanical interfaces: a flat interface with a centered threaded hole.

FI - FLAT INTERFACE

The actuator has one or two identical flat interfaces for pressing or bonding assembly process.

H - HOLE

The actuator has one or two identical mechanical interfaces: a flat interface with a non-threaded hole.

SI - SPECIFIC INTERFACE

To make the mechanical integration of its actuators easier as OEM products, Cedrat Technologies (CTEC) can design and machine a Specific Interface on top of its actuators to meet the customer's needs. For any question regarding mechanical integration, please contact CTEC.

4.1.3. STANDARD OPTIONS

To know the available options for a specific actuator, please consult the associated datasheet.

SG - STRAIN GAUGES

The SG option consists in gluing strain gauges to the piezo ceramic stacks. This allows monitoring the ceramic stack strain and thus the displacement of the piezo actuator (See *Fig. 4.b* and chapter *7.2, page 147*). Standard SG is connected via a flex cable; other plugs are available on request. The SG signal is conditioned by the SG75 electronic board integrated either in a rack amplifier or in a control box. Adding a digital controller board allows a closed loop position control.

NM - NON MAGNETIC

With this option the actuator is made of non-magnetic (NM) material: it does not disturb any external magnetic field and is also completely insensitive to an external applied magnetic field.

Some properties (e.g. thermo-mechanical behavior, mass, width, characteristics) may differ from the standard actuator's features.

VAC - VACUUM
UHV - ULTRA HIGH VACUUM

Our actuators can be compatible with vacuum environment, with one of these two options.

The VAC option consists in adapting the integration process to avoid the presence of any dust and make the actuator compatible with vacuum environment. The VAC option is generally used till down 10-6 mbar.

The UHV option goes further with a specific integration process and the adaptation of materials used. The UHV option is compatible with vacuum down to 10-9 mbar. It enables low outgassing and no pollution of optical components.

Would you have any specific constraints, as for space projects, please contact us with your requirements.

TS - THERMOCOUPLE SENSOR

For certain dynamic applications, it may be necessary to follow up the self-heating of the piezo ceramic to avoid overheating and damages.

For such application cases, we developed a dedicated option where we bond a thermocouple sensor on the piezo ceramic to monitor its inner temperature.

4.1.4. SPECIFIC VERSIONS

CFRP - CARBON FIBRE REINFORCED POLYMER

The CFRP option relates to the use of a CFRP composite instead of metal to make the APA® shell.

This change leads to several advantages: significant mass reduction, higher bandwidth, lower Q-factor, much lower thermal expansion.

This option results of a collaboration with ONERA considering helicopter flap applications (See *Fig. 4.c*).

HT - HIGH TEMPERATURE

The HT option refers to special piezo material and processes (bonding) that can be used to build High Temperature compliant piezoelectric actuators.

TC - THERMO-COMPENSING

The TC option is a special construction which allows the improvement of the behavior within a wide temperature range, especially at the liquid nitrogen temperature (77 °K); Its objective is to reduce the actuator coefficient of thermal expansion.

G - GUIDING

To obtain a better dynamic movement, it is possible to add a flexible guiding to the actuator's shell. This can be added at the application integration level or designed monolithically with the shell. Please contact CTEC to discuss your application.

E - ENCAPSULATION

Dedicated encapsulation design protects and enhance the performance of piezo ceramic against particles pollution and/or corrosion and/or overheating. For instance, encapsulation combined with an oil cooling system allowed to increase 20 times the driving frequency of an actuator compared to its regular performance with air cooling system. The encapsulation structure itself acts like a heat sinking structure (*Fig. 4.d*).

ECP - EDDY CURRENT PROBE

The ECP option refers to an APA® equipped with an ECP sensor. The ECP sensor providing a nanometric resolution and a direct measurement of the displacement of the head of the actuator. This option provides with the best observability & accuracy for motion control. The ECP sensor signal is monitored with the ECS75 conditioner board (See *Fig. 4.e* and chapter *7.3, page 148*).

MD - MECHANICAL DAMPING (PRELIMINARY)

The MD option consists in added elastomeric parts inside the APA®. This option provides damping and lowers the Q-factor at resonance (see chapter *3.2.3, page 69*). This also reduces overshoot in on-off applications and improves resistance to external vibration. This option results of R&T works for CNES.

SV - SPECIFIC VERSION

In some cases, the change of mechanical interfaces or the piezo components on the shell materials leads to a modification of the functional properties. In that case, the Specific Version of an existing standard actuator is called the SV option. For any question regarding mechanical integration, please contact CTEC (See *Fig. 4.f*).

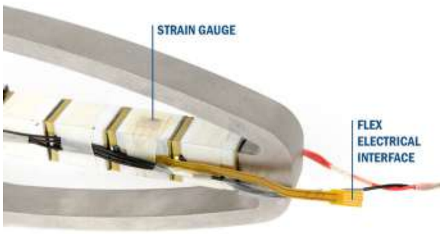


Fig. 4.b: APA500XL-SG

Fig. 4.c: ECP test bench for APA500L-CFRP-ECS

Fig. 4.d: High temperature encapsulation on PPA80L-E

Fig. 4.e: Test bench for APA2000L

Fig. 4.f: Specific Version Twin Amplified Piezoelectric Actuator APA®

4.2. AMPLIFIED PIEZOELECTRIC ACTUATORS APA®

4.2.1. APA® UXS & XXS SERIES

Some applications of APA® uXS and XXS are:

- Earing implants
- Actuation in Micro Aerial Vehicle
- Energy harvester for pacemaker
- Micro electro optical systems

Fig. 4.g: APA150XXS

PARAMETER	UNIT	APA30UXS	APA150XXS
Quasistatic performances			
Nominal stroke	µm	34	130
Min stroke	µm	31	120
Resolution (1)	nm	1,9	7,4
Blocked force	N	3,7	3,2
Stiffness	N/µm	0,11	0,024
Dynamic performances			
Resonance Frequency (free - free)	Hz	25000	3800
Resonance Frequency (blocked - free)	Hz	4800	1100
Force limit (2)	N	7,5	2,2
Control & driving			
Voltage Range	V	-20 ... 150	-20 ... 150
Capacitance	µF	0,043	0,18
Dimensions & interfaces			
Height	mm	4,0	4,5
Length	mm	8,6	14
Width incl wires	mm	6,4	9,0
Mass	g	0,15	1,3
		See datasheet	**See datasheet**

Table 4.a Characteristics of APA® uXS and XXS series

4.2.2. APA® XS SERIES

Some applications with APA® XS are:

- Micro optical mechanisms
- Micro controllable dynamic valves
- Space qualified micro tip tilts
- Miniature brakes

Fig. 4.h: APA35XS

PARAMETER	UNIT	APA35XS	APA50XS
Quasistatic performances			
Nominal stroke	µm	52	66
Min stroke	µm	47	59
Resolution (1)	nm	2,9	3,7
Blocked force	N	27	16
Stiffness	N/µm	0,52	0,24
Dynamic performances			
Resonance Frequency (free - free)	Hz	18000	12000
Resonance Frequency (blocked - free)	Hz	3900	2700
Force limit (2)	N	37	13
Control & driving			
Voltage Range	V	-20 ... 150	-20 ... 150
Capacitance	µF	0,30	0,30
Dimensions & interfaces			
Height	mm	5,5	4,7
Length	mm	13	13
Width incl wires	mm	10	10
Mass	g	2,0	2,0
		See datasheet	**See datasheet**

Table 4.b Characteristics of APA® XS series

4.2.3. APA® S SERIES

Some applications with APA® S are:

- Shaking powder for X-ray diffraction
- Optical stabilization for embedded cameras
- Space qualified optical stages
- Nano-indentation

Fig. 4.i: APA60S

PARAMETER	UNIT	APA60S	APA120S
Quasistatic performances			
Nominal stroke	µm	75	140
Min stroke	µm	68	130
Resolution (1)	nm	4,2	7,9
Blocked force	N	130	46
Stiffness	N/µm	1,7	0,33
Dynamic performances			
Resonance Frequency (free - free)	Hz	13000	7200
Resonance Frequency (blocked - free)	Hz	2900	1300
Force limit (2)	N	120	32
Control & driving			
Voltage Range	V	-20 ... 150	-20 ... 150
Capacitance	µF	1,1	1,1
Dimensions & interfaces			
Height	mm	15	13
Length	mm	29	29
Width incl wires	mm	10	10
Mass	g	8,5	7,2
		See datasheet	**See datasheet**

Table 4.c Characteristics of APA® S series

4.2.4. APA® SM SERIES

Some applications with APA® SM are:

- Shock energy harvester in wireless switches
- Material Stress cycling
- Injectors

Fig. 4.j: APA60SM

PARAMETER	UNIT	APA40SM	APA60SM
> Quasistatic performances			
Nominal stroke	µm	54	77
Min stroke	µm	49	69
Resolution (1)	nm	3,0	4,3
Blocked force	N	260	140
Stiffness	N/µm	4,9	1,8
> Dynamic performances			
Resonance Frequency (free - free)	Hz	15000	10000
Resonance Frequency (blocked - free)	Hz	4100	2800
Force limit (2)	N	170	110
> Control & driving			
Voltage Range	V	-20 ... 150	-20 ... 150
Capacitance	µF	1,1	1,1
> Dimensions & interfaces			
Height	mm	15	13
Length	mm	27	27
Width incl wires	mm	14	14
Mass	g	11	10
		> See datasheet	> See datasheet

Table 4.d Characteristics of APA® SM series

4.2.5. APA® M SERIES

Some applications with APA® M are:

- Fast X-Ray vacuum compatible shutters
- Dynamic valves
- Laser cavity tuning
- Miniature Active flaps for aero vehicles

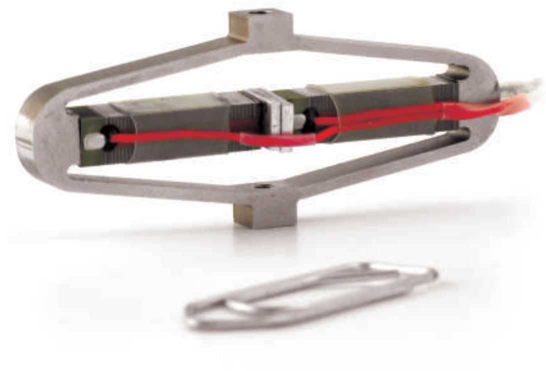


Fig. 4.k: APA150M

PARAMETER	UNIT	APA100M	APA150M	APA200M
Quasistatic performances				
Nominal stroke	µm	130	190	240
Min stroke	µm	110	170	210
Resolution (1)	nm	7,0	10	13
Blocked force	N	240	130	87
Stiffness	N/µm	1,9	0,68	0,37
Dynamic performances				
Resonance Frequency (free - free)	Hz	8000	5000	4600
Resonance Frequency (blocked - free)	Hz	1900	1300	910
Force limit (2)	N	150	98	56
Control & driving				
Voltage Range	V	-20 ... 150	-20 ... 150	-20 ... 150
Capacitance	µF	2,2	2,2	2,2
Dimensions & interfaces				
Height	mm	25	22	17
Length	mm	53	53	53
Width incl wires	mm	9,0	10	10
Mass	g	20	17	16
		See datasheet	**See datasheet**	**See datasheet**

Table 4.e Characteristics of APA® M series

4.2.6. SUPER APA® M SERIES

Some applications with super amplified APA® M are:

- Clamping in wire feeding system
- Inverted microscope positionner
- Haptic technology feedback for display panels
- Energy harvesters

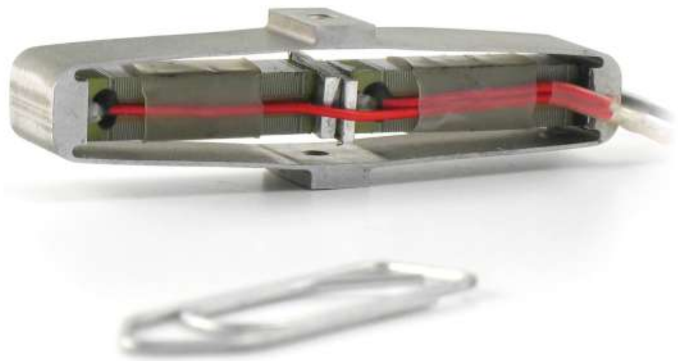


Fig. 4.l: APA400M

PARAMETER	UNIT	APA400M	APA600M	APA900M
> Quasistatic performances				
Nominal stroke	µm	460	550	790
Min stroke	µm	410	500	710
Resolution (1)	nm	26	31	44
Blocked force	N	34	24	18
Stiffness	N/µm	0,074	0,043	0,023
> Dynamic performances				
Resonance Frequency (free - free)	Hz	1800	1300	1100
Resonance Frequency (blocked - free)	Hz	420	320	260
Force limit (2)	N	21	16	1,7
> Control & driving				
Voltage Range	V	-20 ... 150	-20 ... 150	-20 ... 150
Capacitance	µF	2,2	2,2	2,2
> Dimensions & interfaces				
Height	mm	13	13	10
Length	mm	49	49	47
Width incl wires	mm	14	14	14
Mass	g	15	14	12
		> See datasheet	**> See datasheet**	**> See datasheet**

Table 4.f Characteristics of super APA® M series

4.2.7. APA® SL SERIES

Some applications with APA® SL are:

- Tool clamping

Fig. 4.m: APA60SL

PARAMETER	UNIT	APA60SL
Quasistatic performances		
Nominal stroke	µm	57
Min stroke	µm	51
Resolution (1)	nm	3,2
Blocked force	N	390
Stiffness	N/µm	6,8
Dynamic performances		
Resonance Frequency (free - free)	Hz	11000
Resonance Frequency (blocked - free)	Hz	3100
Force limit (2)	N	480
Control & driving		
Voltage Range	V	0 ... 150
Capacitance	µF	6,2
Dimensions & interfaces		
Height	mm	20
Length	mm	32
Width incl wires	mm	15
Mass	g	38

> **See datasheet**

Table 4.g Characteristics of APA® SL series

4.2.8. APA® MML SERIES

Some applications with APA® MML are:

- Active stabilisation of a watt balance
- High frequency shakers
- Elasto MRI
- Long range cavity modulation in interferometers

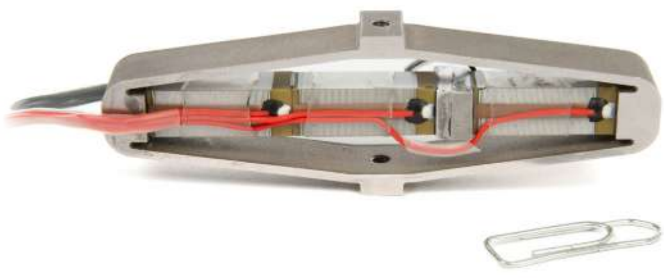


Fig. 4.n: APA400MML

PARAMETER	UNIT	APA100MML	APA400MML	APA600MML
Quasistatic performances				
Nominal stroke	µm	100	360	650
Min stroke	µm	90	320	590
Resolution (1)	nm	5,6	20	37
Blocked force	N	830	180	78
Stiffness	N/µm	8,3	0,52	0,12
Dynamic performances				
Resonance Frequency (free - free)	Hz	6500	2800	1500
Resonance Frequency (blocked - free)	Hz	1700	630	320
Force limit (2)	N	510	150	47
Control & driving				
Voltage Range	V	-20 ... 150	-20 ... 150	-20 ... 150
Capacitance	µF	6,3	6,3	6,3
Dimensions & interfaces				
Height	mm	58	24	17
Length	mm	81	77	76
Width incl wires	mm	15	15	15
Mass	g	76	48	41
		> See datasheet	> See datasheet	> See datasheet

Table 4.h Characteristics of APA® MML series

4.2.9. APA® ML SERIES

Some applications with APA® ML are:

- Active control of vibration on medical robots
- High frequency shakers
- Fretting fatigue testing
- Space qualified positionner

Fig. 4.o: APA120ML

PARAMETER	UNIT	APA95ML	APA120ML	APA200ML	APA300ML	APA60ML
Quasistatic performances						
Nominal stroke	µm	99	120	220	300	65
Min stroke	µm	89	110	200	270	59
Resolution (1)	nm	5,6	6,7	12	17	3,7
Blocked force	N	2100	1500	780	540	3300
Stiffness	N/µm	21	12	3,6	1,8	51
Dynamic performances						
Resonance Frequency (free - free)	Hz	6500	5800	4200	3100	7000
Resonance Frequency (blocked - free)	Hz	2100	1900	1000	760	2600
Force limit (2)	N	1100	910	470	340	1700
Control & driving						
Voltage Range	V	-20 ... 150	-20 ... 150	-20 ... 150	-20 ... 150	-20 ... 150
Capacitance	µF	13	13	13	13	13
Dimensions & interfaces						
Height	mm	60	45	34	30	85
Length	mm	80	79	79	79	83
Width incl wires	mm	25	25	25	25	25
Mass	g	160	160	120	110	230
		> See datasheet	> See datasheet	> See datasheet	> See datasheet	> See datasheet

Table 4.i Characteristics of APA® ML series

4.2.10. APA® L SERIES

Some applications with APA® L are:

- Helicopter flaps
- High frequency shakers
- Material stress cycling
- Mirror positioning in telescopes & instruments

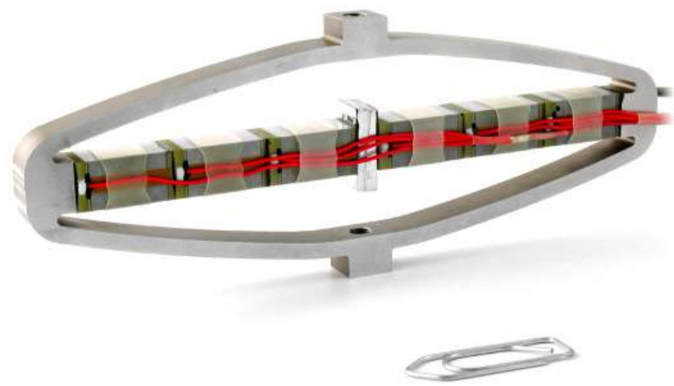


Fig. 4.p: APA500L

PARAMETER	UNIT	APA230L	APA500L	APA1000L	APA1500L	APA2000L
> Quasistatic performances						
Nominal stroke	µm	230	510	870	1500	2000
Min stroke	µm	210	460	780	1300	1800
Resolution (1)	nm	13	29	49	83	110
Blocked force	N	1300	580	350	99	62
Stiffness	N/µm	5,8	1,1	0,40	0,067	0,031
> Dynamic performances						
Resonance Frequency (free - free)	Hz	3100	2000	1300	720	520
Resonance Frequency (blocked - free)	Hz	860	460	290	140	87
Force limit (2)	N	910	430	110	72	21
> Control & driving						
Voltage Range	V	-20 ... 150	-20 ... 150	-20 ... 150	-20 ... 150	-20 ... 150
Capacitance	µF	26	26	26	26	26
> Dimensions & interfaces						
Height	mm	85	55	35	30	27
Length	mm	150	150	140	140	140
Width incl wires	mm	19	19	19	25	25
Mass	g	280	200	190	140	130
		> See datasheet	> See datasheet	> See datasheet	> See datasheet	> See datasheet

Table 4.j Characteristics of APA® ML series

4.2.11. APA® XL SERIES

Some applications with APA® XL are:

- High frequency shakers
- Fretting Fatigue testing
- Positioning of heavy loads
- Force Testing

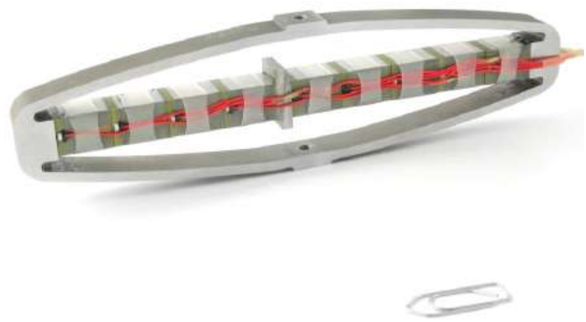


Fig. 4.q: APA1000XL

PARAMETER	UNIT	APA500XL	APA1000XL
> Quasistatic performances			
Nominal stroke	µm	590	1100
Min stroke	µm	530	990
Resolution (1)	nm	33	62
Blocked force	N	1400	770
Stiffness	N/µm	2,4	0,70
> Dynamic performances			
Resonance Frequency (free - free)	Hz	1500	1000
Resonance Frequency (blocked - free)	Hz	350	210
Force limit (2)	N	1100	640
> Control & driving			
Voltage Range	V	-20 ... 150	-20 ... 150
Capacitance	µF	77	77
> Dimensions & interfaces			
Height	mm	82	57
Length	mm	220	210
Width incl wires	mm	31	31
Mass	g	650	600
		> See datasheet	**> See datasheet**

Table 4.k Characteristics of APA® XL series

4.3. PARALLEL PRE-STRESSED ACTUATORS PPA

4.3.1. PPA M SERIES

Some applications with PPA M are:

- Vibration assistance
- Needle vibrator in a space Atomic Force Microscope
- Active deformation of mirror in telescopes
- Ultrasonic injection

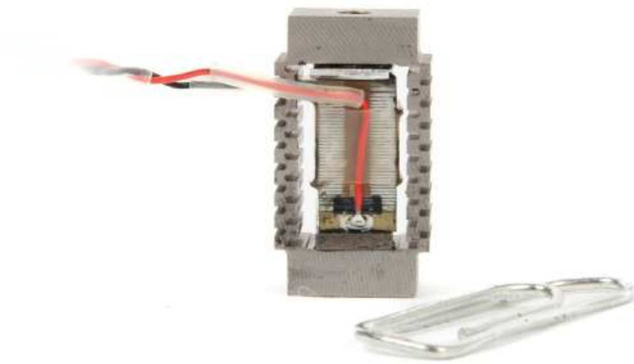


Fig. 4.r: PPA10M

PARAMETER	UNIT	PPA10M	PPA20M	PPA40M
Quasistatic performances				
Nominal stroke	µm	8,3	20	38
Min stroke	µm	7,5	18	34
Resolution (1)	nm	0,47	1,1	2,1
Blocked force	N	850	850	850
Stiffness	N/µm	100	44	22
Dynamic performances				
Resonance Frequency (free - free)	Hz	62000	39000	23000
Resonance Frequency (blocked - free)	Hz	32000	20000	11000
Force limit (2)	N	500	500	500
Control & driving				
Voltage Range	V	-20 ... 150	-20 ... 150	-20 ... 150
Capacitance	µF	0,55	1,1	2,2
Dimensions & interfaces				
Height	mm	18	28	48
Length	mm	10	10	10
Width incl wires	mm	9,0	9,0	9,0
Mass	g	6,0	12	25
		See datasheet	**See datasheet**	**See datasheet**

Table 4.l Characteristics of PPA M series

4.3.2. PPA L SERIES

Some applications with PPA L are:

- Active control of vibration
- Oval piston machining
- Heavy load positioning

Fig. 4.s: PPA80L

PARAMETER	UNIT	PPA40L	PPA60L	PPA80L	PPA120L
Quasistatic performances					
Nominal stroke	µm	44	67	85	130
Min stroke	µm	40	60	77	120
Resolution (1)	nm	2,5	3,8	4,8	7,3
Blocked force	N	3500	3500	3500	3500
Stiffness	N/µm	80	52	41	27
Dynamic performances					
Resonance Frequency (free - free)	Hz	15000	11000	8700	6300
Resonance Frequency (blocked - free)	Hz	8300	6000	4700	3300
Force limit (2)	N	1500	1500	1500	1500
Control & driving					
Voltage Range	V	-20 ... 150	-20 ... 150	-20 ... 150	-20 ... 150
Capacitance	µF	8,8	13	18	26
Dimensions & interfaces					
Height	mm	57	77	97	140
Length	mm	24	24	24	24
Width incl wires	mm	18	18	18	18
Mass	g	92	120	140	190
		See datasheet	**See datasheet**	**See datasheet**	**See datasheet**

Table 4.m Characteristics of PPA L series

4.3.3. PPA XL SERIES

Some applications with PPA XL are:

- Stabilisation of heavy loads in precision machine tool
- Fretting Fatigue testing
- High Frequency Shakers

Fig. 4.t: PPA80XL

PARAMETER	UNIT	PPA40XL	PPA80XL	PPA120XL
> Quasistatic performances				
Nominal stroke	µm	43	90	130
Min stroke	µm	39	81	120
Resolution (1)	nm	2,4	5,1	7,3
Blocked force	N	7000	7000	7000
Stiffness	N/µm	160	78	54
> Dynamic performances				
Resonance Frequency (free - free)	Hz	14000	8700	6200
Resonance Frequency (blocked - free)	Hz	8000	4600	3300
Force limit (2)	N	3300	2900	2900
> Control & driving				
Voltage Range	V	-20 ... 150	-20 ... 150	-20 ... 150
Capacitance	µF	17	34	51
> Dimensions & interfaces				
Height	mm	60	100	140
Length	mm	30	30	30
Width incl wires	mm	30	30	30
Mass	g	250	320	380
		> See datasheet	**> See datasheet**	**> See datasheet**

Table 4.n Characteristics of PPA XL series

4.4. EVALUATION PACK EP120S

Fig. 4.u: Evaluation Pack EP120S:
APA120S actuator & CAu10 amplifier

The Evaluation Pack provides with an easy evaluation of CEDRAT TECHNOLOGIES's (CTEC) piezo offer in quasi static conditions. It includes:

- An Amplified Piezoelectric Actuator APA120S
- A linear amplifier CAu10
- Related cables

The APA120S can bear load up to 0.5 kg over 140 µm, in a compact size.

The CAu10 can deliver a voltage up to 150 V and has 2 channels.

Please refer to the datasheet of APA120S actuator and CAu10 amplifier for technical specifications and drawings.

The typical diagram stroke/frequency of the EP120S is presented in *Fig. 4.v*:

The main features enlightened by the evaluation pack are:

- A high stiffness of the actuator
- A nanometer resolution
- A good repeatability
- An excellent reliability
- An easy implementation
- A low cost of ownership

4.5. CUSTOMISED PIEZO ACTUATORS

CEDRAT TECHNOLOGIES (CTEC) has developed two whole ranges of off the shelf piezo actuators: APA® and PPA.

However, if you are looking for a specific configuration you couldn't find in the previous pages, CTEC design office has the capability to study a new design and realise the new geometry

Customisation may also consist in adding a marking, adapting the mechanical interfaces, withstanding a harsh environment or integrating an actuator in your mechanism.

Don't hesitate to contact us at actuator@cedrat-tec.com for your new development.

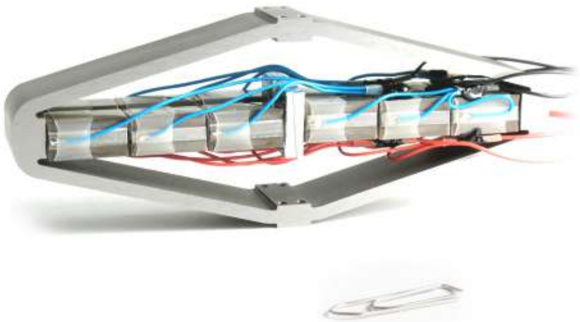


Fig. 4.v: APA500L-Twin with specific interface and wiring

Fig. 4.x: APA200MML-E

Fig. 4.w: APA500L-E-HT

Fig. 4.y: APA500XXL

5. PIEZO MOTORS

CEDRAT TECHNOLOGIES (CTEC) offers piezoelectric motors using the patented Modular Stepping Piezoelectric Actuator (MSPA) technology and inchworm type motor. The MSPA technology allows unique performances through the combination of the Amplified Piezoelectric Actuators (APA®) technology with the inertial motor principle. A piezo motor encompasses an actuator ensuring the performance, a guiding system ensuring load handling and movement precision, and an encoder to operate in closed loop with accuracy.

They operate by accumulation of small steps (see *chapter 2.2, page 30*). Between each step, the motor is held in position and does not need to be powered.

Beside the long stroke mode, they can also be operated in a deformation mode for a fine adjustment. In this case, the stroke is proportional to the applied voltage, thus allowing nanometer resolution and high bandwidth.

In practice, this allows to build a brand of piezoelectric motors offering:

- MSPA: Modular Stepping Piezo Actuators, which provide a linear or rotational stepping motion.
- FSPA: Fine Stepping Piezo Actuators, which is an original variation of the MSPA that allows sub-micrometric stepping resolution combined with large forces in a slow linear motion.

CHARACTERISTIC	MSPA	FSPA
Translation	✓	✓
Rotation	✓	
Integrated guiding		✓
Typical stroke	Infinite	0.1 - 10 mm
High speed	✓	
Micro-positioning	✓	✓
Nano-positioning	Fine mode	✓
Unpowered holding force	✓	✓

Table 5.a: Piezoelectric motors characteristics

Note: fine mode implies continuous driving voltage and is not available when motor is powered off.

Several custom designs are presented at the end of this section. They allow multiple combinations of the various advantages of the piezoelectric motor technology.

5.1. MODULAR STEPPING PIEZO ACTUATOR MSPA

Modular Stepping Piezoelectric Actuators (MSPA) are piezoelectric motors modules that can be easily integrated into already guided mechanisms to drive their mobile part (see application in chapter 6.6, page 89). The MSPA is fixed on one part of the mechanism while a friction track is fixed on the other part. They can accommodate limited guiding quality. This greatly eases their integration in very long stroke applications (>10 cm) and even allows their use for non-linear motion (i.e. friction track is not straight). They can also be operated in a deformation mode for a fine adjustment. In this case, the stroke is proportional to the applied voltage, thus allowing nanometer resolution and high bandwidth.

The MSPA can be supplied with CTEC's standard Linear Amplifier LA75. Other custom Modular Stepping Piezoelectric Actuators can be designed using various APA®.

This motor technology provides:

- Extreme compactness
- High speed
- Holding force at rest
- Nano resolution
- Linear and non linear motion (rotating or even curved motion)
- More than 10km displacement
- Extreme conditions resistance

Fig. 5.a: MSPA35XS

5.1.1. MSPA COUPLED WITH LINEAR MOTION

PARAMETER	UNIT	MSPA30uXS	MSPA35XS	MSPA40SM
Status		Preliminary		
Stepping mode				
Travel range (b.1)	mm	∞		
Nominal speed (b.2) (b.3)	mm/s	5	10	10
Typical step size (b.2) (b.3)	µm	5 … 20		5 … 25
Fine mode				
Stroke	µm	34	52	54
Resolution	bm	<1		
Forces				
Holding force without consumption	N	0.3	3	10
Nominal driving force (b.2) (b.3)	N	0.1	1	2.5
Mechanical properties				
Lifetime (b.4)	km	> 10		
Thickness of module	mm	7.0	10.0	12.0
Width of module	mm	15.0	20.0	40.0
Length (in actuation direction)	mm	20.0	30.0	50.0
Mass of module	g	<10.0	<20.0	50
Environment		Radiation, Temperatue [70K; 90°C]		

Table 5.b: Characteristics of MSPA coupled with linear motion

b.1 Limited by moving part
b.2 Unloaded
b.3 With nominal driver
b.4 Unloaded, nominal speed, 50% duty-cycle, ambient conditions

5.1.2. MSPA COUPLED WITH ROTARY MOTION

PARAMETER	UNIT	MSPA30uXS	MSPA35XS	MSPA40SM-R17	MSPA40SM-R35
Status		Preliminary			
> Stepping mode					
Travel range (c.1)	°	360			
Nominal Speed (c.2) (c.3)	rad/s	0.8	2.5 (c.5)	0.6	0.2
Tangential speed	mm/s	4.8	11.0 (c.5)	10.0	7.0
> Fine mode					
Stroke	nrad	5.7	11.5	3.2	1.5
Resolution	nrad	>1			
> Torques					
Friction radius (c.4)	mm	6.0	4.5	17	35
Holding torque without consumption	N.mm	2.0	13.0 (c.5)	100	500
Nominal driving torque (c.2) (c.3)	N.mm	0.7	4.5 (c.5)	45	100
> Mechanical properties					
Thickness of module	mm	7.0	10.0	12.0	
Width of module	mm	15.0	20.0	40.0	
Length (in actuation direction)	mm	20.0	30.0	50.0	
Mass of module	g	<10.0	<20.0	50	

Table 5.c: Characteristics of MSPA coupled with rotary motion

Fig. 5.b: Rotating motor based on MSPA30uXS

Fig. 5.c: Rotating motor based on MSPA35XS

Fig. 5.d: MSPA40SM-SV

c.1 Limited by moving part
c.2 Unloaded
c.3 With nominal driver
c.4 The friction radius can be adjusted in order to tune the output torque and speed
c.5 Paired with 2 modules in parallel

5.2. FINE STEPPING PIEZO ACTUATOR FSPA

Fig. 5.e: FSPA35XS

Fine Stepping Piezo Actuator (FSPA) is a patented actuator that combines MSPA technology with mechanical reduction. This allows to achieve very small step sizes even down to 10 nm. Typical max speed for FSPA is 200 µm/s.

Another major advantage of FSPA is its ability to maintain its position, while unpowered, even when very large external forces or acceleration are applied.

The main application for this actuator is to accurately position one payload and hold it in extreme environmental conditions such as vibrations and shocks during off- road transportation, space launch or aircraft landing...

PARAMETER	UNIT	FSPA35XS
Status		Preliminary
> Forces		
Actuation force (d.1)	N	20 /100
Holding force (d.2)	N	> 200
Stiffness	N/µm	8
> Stepping mode		
Travel range	mm	5
Typical min step size (d.3)	nm	< 100
Typical max speed (d.4)	µm/s	200
> Mechanical properties		
Typical lifetime (d.5)	Cycles	1000
Dimensions	mm	Ø40 x 62
Total mass	g	160

Table 5.d: Characteristics of FSPA

d.1 Max actuation stall force, no more displacement, depending on the max ouptut peak current of the driver (20N @ 150 mA peak with SPC45 / 100N @ 1.2 A with High power amplifier)

d.2 Unpowered

d.3 Minimum Step size in coarse positioning mode for 50V output voltage step with SPC45

d.4 Maximum speed in coarse positioning mode for 100V output voltage step with SPC45

d.5 1 cycle is +/-5mm at 100µm/s with 10N force. For other loading cases please contact CTEC

5.3. CUSTOMISED PIEZO MOTOR CAPABILITY

5.3.1. LONG STROKE LINEAR STAGE

This linear stage is a demonstrator of an MSPA combined with a basic linear ball bearing guiding. The MSPA has been attached to the moving stage and is then able to travel on more than 100 mm with 20 mm/s. A 5 µm stepping resolution can be achieved.

The customised MSPS35XS stage shown in (see *Fig. 5.f*) is based on fixed MSPA35XS driving a linear guided top plate in motion. The MSPS35XS stage aims at adjusting the focus of a lens payload fixed on the top plate over 17 mm linear stroke in a compact size (~76×56×23 mm) and low mass (~130 grams). The max speed is 8 mm/s, and the driving force is greater than 1 N.

Fig. 5.f: MSPS35XS linear stage

5.3.2. LONG STROKE CURVED STAGE

in this application, the capability of the MSPA to achieve curved motion is demonstrated (*Fig. 5.g*). The MSPA is driving a flat turning track on 90°. Thanks to the robustness of the MSPA technology, the motor can handle variations of friction track radius.

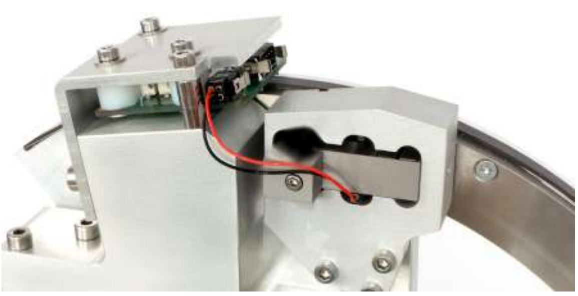


Fig. 5.g: MSPA curved track demonstrator

5.3.3. 3 AXIS CLOSED LOOP MECHANISM

Thanks to their flexibility, MSPA can be combined to achieve direct multi-degrees of freedom movement. In the following mechanism (see *Fig. 5.h*), 3 MSPA are joined to achieve simultaneous Rx, Ry, Tz movement (R: rotation, T: translation).

In that sense the mechanism is similar to a DTT (Double Tip Tilt mechanism). However, using the MSPA35XS stroke capability, the achievable stroke is a hundred times larger (Rx=Ry=+/-2.5°, Tz=+/-2.5mm). Simultaneously, extreme pointing resolution remains available using the fine movement mode.

Additionally, the mechanism includes position sensors to monitor the 3-axis instantaneous position. Closed loop control has then been demonstrated both for speed or position control.

Fig. 5.h: 3 axis closed loop mechanism

5.3.4. ROTARY STAGE

the rotary stage is a demonstrator of an MSPA integration (see *Fig. 5.i*). An MSPA35XS is simply pressed against a common ball bearing. This basic Ø80 mm mechanism achieves 2 rev/min and a 0.2 mrad resolution.

Fig. 5.i: MSPA rotary demonstrator

5.4. CUSTOMISED PIEZO MOTOR REALISATION

5.4.1. NUCLEAR APPLICATION

As part of the ITER project, the development of the In Vessel Viewing System (IVVS) for inspections of the reactor, requires the use of a gimbal in extreme environments (radiations, high temperature, vacuum, non-magnetic). Cedrat Technologies develops 2 custom inertial piezoelectric motor based on the MSPA technology to perform pan and tilt motions. This is a specific and improved version of the MSPA40SM.

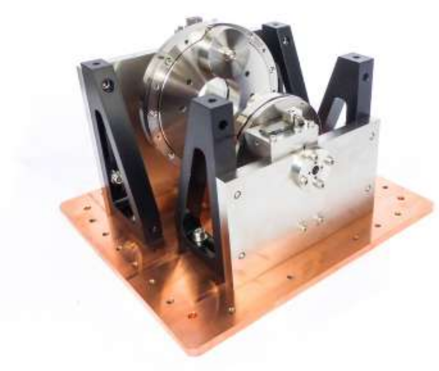


Fig. 5.j: Breadboard models of the gimbal piezo motors.

Thanks to a specific tribological combination of metal and polymer (without outgassing), even if these motors generate friction by using the stick-slip principle, it ensures a high lifetime without maintenance. This project development is challenging in terms of performance taking into account the operating environment.

PARAMETER	PRISM MOTOR	BRACKET MOTOR
Torque	0.026N.m	0.1N.m
Speed	6rpm	2rpm
Travel	360°	180°
Size	60x60x20mm	70x60x20mm
Weight capacity	1.3kg	5.3kg
Operating temperature	+70°C	
Vacuum	4e-4Pa	
Lifetime	2e6 revolutions (30km)	
Magnetic field	5-6.5T	
Gamma radiations	3.8kGy/hr total dose 2.5MGy	

Table 5.e: Rotary inertial motors tested performances

CTEC develops a thermal drain that allows the system to operate continuously in a vacuum at 70°C despite the temperature of the environment and the self-heating of the mechanism. In addition, the tribological materials of the friction parts is improved in order to extend its lifetime.

5.4.2. POWERFUL INCHWORM MOTOR

Within the frame of Cleansky2, project AUDACITY, Cedrat Technologies makes the demonstration of a compact, powerful, and reliable piezoelectric motor for locking applications in the aerospace field. It aims to get rid of the well-established hydraulic actuators in order to comply with System ITD Strategic Objectives in terms of environmental impact and More Electric Aircraft (MAE).

Fig. 5.k: Inchworm piezo motor demonstrator and video

This inchworm motor uses a combination of APA for large step motion and PPA for high locking performance. This is one of the most powerful piezo motors of the world. The actuator functionalities and performances are assessed on a prototype laboratory to achieve a TRL4 demonstration:

PARAMETER	INCHWORM MOTOR
No-load speed	>15mm/s
350N loaded speed	>9mm/s
Holding force	500N
Nominal force	350N
Stroke	>15mm
Operating temperature	-55...+70°C
Parasitic motion	>25µm on perpendicular axis
Mass	2.2kg
Volume	190x116x90mm

Table 5.f: Linear inchworm tested performances

This project enables surpassing previous technological limits in terms of thermal stability, speed limits, and reduction of friction using the inchworm principle, thereby minimizing wear and tear. The power to mass ratio is surpassed without any loss of performance between -55 and +70°.

5.4.3. BSMA

In the frame of the new meteorological satellite METOP-SG, the IASI-NG instrument requires a very precise positioning of an optical blade. In order to meet this need, CTEC designs a sub-micrometer positioning actuator called the Beam Splitter Mechanism Actuator (BSMA). The core BSMA is based on the combination of the following elements:

- Fine Stepping Piezoelectric Actuator (FSPA) that provide a 320µm displacement and a smaller than 50nm resolution,
- Magnetic Clutch,
- Parallel Pre-stressed Actuators (PPA) used to generate the sine oscillations for the vibration mode,
- Eddy Current Sensor (ECS) used to monitor the effective position of the output shaft.

The combination of a piezo actuator and a magnetic drive reduces inrush current and is compatible with voltage/current constraints in the aerospace industry (reduction of inrush current in MSPAs). To achieve cold redundancy, each of these elements must be doubled inside the BSMA. 10 models have been realized in total.

Fig. 5.l: FSPA EM for IASI-NG

Major characteristics of the BMSA are its ability to generate very small steps and its capability to reverse direction without any significant backlash nor step size variation.

PARAMETER	BSMA
Stroke	+/- 40µm
Force	20N
Stepping resolution	30nm
Non powered stability	0.15µm over 24h/1K
	0.30µm over 6 months
	1.4µm long term
Vibration mode	0.8µm, 10-70Hz
Vacuum	10-9 torr
Redundancy	Cold

Table 5.g: BSMA performances

A first lifetime test is performed. The nominal motor performed about 2 000 000 steps, covering about 400 operational ranges (qualification lifetime).

5.4.4. HIGHLY RESOLUTE SPACE MOTOR

An inchworm motor is realized in the frame of space project. A BBM has been built that's currently running tests and has already demonstrated its ability to generate motion with very high resolution, limiting the rejection of micro-vibrations.

The prototype is based on six modules, actuated 3 by 3. Special command including backlash compensation (feedforward profiles), and allowing smooth motion, have been demonstrated in this activity.

Fig. 5.m: Predevelopment motor stage

This motor uses a combination of APA for large step motion and PPA for high locking performance. The actuator functionalities and performances are assessed on a prototype laboratory to achieve a TRL4 demonstration:

PARAMETER	SPACE MOTOR
Power	<1W
Clamp preload force	45N
Stiffness	1.5kN/mm
Maximum force	Back driving force : 39N
	Holding force : 80N
	Maximum load force: 128N
Stroke	>40µm in step mode
	25µm in smooth mode
Max torque	>4N.m
Voltage	<100V
Resolution	<0.8nrad
Temperature	-20°C...+30°C
Rejected micro-vibrations	Low
Vacuum	10-9 torr
Redundancy	Yes

Table 5.h: Rotary inertial motor performances.

5.4.5. MSPA-DTT

At the origin, this 3 DOF mechanism is designed to replace another micro-mechanism that suffered regular failure. The cause is a very close liquid nitrogen blow which at times can spread on the mechanism. Due to the cryogenic capability of MSPA motors, the MSPA-DTT actuator easily supports this event without loss of performance.

Three specifics small (approx. 5x8x13mm3) MSPA35XS piezoelectric motors are assembled in a 120° pattern surrounding a Ø20mm moving element. The three MSPA are driven independently, thus allowing a 3 degrees of freedom movement of the moving element: RX, RY and TZ.

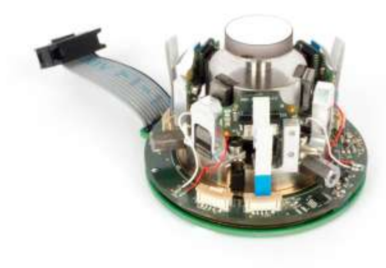


Fig. 5.n: 3 Axis RX, RY, TZ Piezoelectric Motor.

The present configuration is optimized for TZ displacement. In practice, the achievable strokes are ±2.5mm for TZ and ±75mrad for both RX and RY axis.

Based on the sensor feedback, a multi-axis closed-loop control is implemented that mixes pulses to make steps as well as fine positioning mode. The resulting performance is that the mechanism is able to move close to the final position with steps and then achieve a fine positioning. The movement resolution is then mainly limited by the electronic SNR. In practice, TZ resolution is on the order of 1 nm and tilting resolution is 0.1 µrad.

PARAMETER	MSPA-DTT
Linear stroke	+/- 2.5mm
Angular stroke	+/- 2° on 2 axis
Linear stepping resolution	0.5µm
Fine mode resolution	1nm
Angular resolution	0.1µrad
DOF	3 axis in closed loop

Table 5.i: MSPA-DTT performances

5.4.6. MSPA30UXS SHUTTER

A shutter is designed based on the APA30µXS actuator. Since this piezoelectric actuator is the smallest standard product of Cedrat Technologies, it ensures the compactness of the final mechanism.

Indeed, the shutter fits within a Ø26x15mm cylinder (the blade is not considered). It weights 12g since the carter parts are made in aluminum so that the system can withstand external shocks and forces.

The conversion from a linear displacement to an angular rotation is performed using the stick/slip technology. The contact radius between the APA30µXS and the inner shaft was sufficient to avoid the deterioration of the parts due to Hertz pressure being too high. Electromechanical simulations are performed using a dedicated model that combines the mechanical parameters such as stiffnesses, inertia and the piezoelectrical effect. Tribology parameters are also considered such has the static and dynamic friction coefficients.

When the shutter was actuated, the outer blade rotated correctly from 0° to 45° position in open loop:

- By using the embedded electronic, a 1.6 rad/s angular speed is achieved with 1W power consumption resulting in commuting the blade in 500ms.
- By using CTEC electronic designed for SPA, a 2.5 rad/s angular speed is achieved resulting in commuting the blade in 300ms.

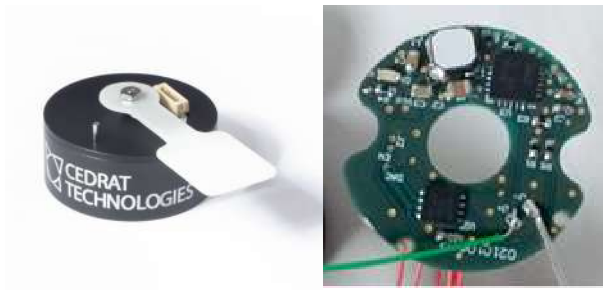


Fig. 5.o: Rotary shutter and its electronic printed circuit board Ø21.5mm

A specific electronic is embedded in the shutter, converting 5Vdc input voltage to high voltage waveforms (-20V/+100V) to drive the actuator.

PARAMETER	ROTARY SHUTTER
Angular speed	2.5rad/s
Angular stroke	45°
Commuting speed	300ms
Dimensions	Ø26x15mm

Table 5.j: Rotary shutter tested performances based on inertial motor

5.4.7. PIEZO MOTORISED SHUTTER

For a new imaging filter development, a nano-positioning device for shutter drive control is realized in order to keep pace with the demanding resolution required by the particles and light beam-based instrumentation. This device allows to create a window with a large and variable opening which can be positioned at different heights. Shutter blades are actuated by inertial piezo motors in order to tune the shutter size in a window of 3mm.

Fig. 5.p: Piezo motorised shutter and dedicated electronic

The challenging aspect of this project is the compatibility of the product with high precision, compact volume, vacuum and non-magnetic environment.

A re-design of the CCB embedded electronic is realized in order to meet both the fine resolution mode and the low-cost target as well as CE marking requirements.

PARAMETER	MOTORISED SHUTTER
Shutter stroke	3mm
Smallest opening	<2.5µm
Resolution	<50nm
Vacuum	2x10-7 torr

Table 5.k: Motorised shutter performances

5.4.8. HIGHSPEED MSPA

The jump spider is a highspeed modular stepping piezo actuator (MSPA). This motor allows a driving motion based on the moving mass inertial force as per classical MSPA, with an optimized stick-slip principle. This generates low wearing and uses a low voltage driving pattern while keeping a highspeed motion. It is a major advantage as high voltage is a concern on many applications such as science spacecrafts, w.r.t optical cleanliness control, and complexity of space drive electronics, having stringent design constrains.

Fig. 5.q: MSPA with active clamp

The advantages of this solution are the following:

- Very low wearing, as the slipping motion is optimized.
- Very high holding force at rest, as the clamping force can be maximized to lock the moving mass during switch off, according to customer requirements
- Very low power consumption as high voltage and current are not required anymore thanks to motion optimization.
- Low driving frequency allowing smaller size and power drive electronics with low design complexity, and featuring voltage and current requirements similar to magnetic actuators

Moreover, the same fine resolution mode as per classical MSPA still can be used, as well as same stepping mode but with driving voltage drastically reduced, without impacting the performances achieved with stick-slip MSPA motors.

PARAMETER	HIGHSPEED MSPA
Holding force	30N
Max actuating force	20N
	6N (with 50V supply voltage)
Speed without loading	8mm/s
	2.5mm/s (with 50V supply voltage)
Linear stroke	< 10 mm (full stroke)
Driving frequency	[70; 110] Hz

Table 5.l: MSPA with active clamp tested performances

5.4.9. MINIATURE SPACE MIEZO MOTOR WITH EMBEDDED ENCODER

In the frame of upcoming space science projects, CTEC is developing a miniature piezo motor concept with embedded compact encoder based on Eddy Current Sensors (ECS). This motor is designed with two motion actuators, and two clamping actuators, allowing either high speed driving based on inertial stick-slip principle (as per MSPA), very low speed walking principle without slipping, or medium speed micro-jumping principle (as per Jump Spider). The motor concept is very compact based on APA30uXS very small actuators and has required the development of a fully embedded encoder, in order to provide a fully controllable positioning over +/- 360° rotational range.

PARAMETER	MINIATURE MOTOR
Rotational range	+/- 360°
Walking frequency range	<10Hz
Micro-jumping frequency range	10Hz - 50Hz
Inertial Slipping frequency range	50Hz - 500Hz
Minimum speed	>15mm
Maximum speed	0,05°/s (walking)
Parasitic motion	10°/s (inertial slipping)
Torque	> 1Nm
Driving resolution (with encoder)	0,01°

Table 5.m: Miniature space motor performances

Fig. 5.r: Piezo motor and encoder assembly

Fig. 5.s: APA30µXS walking clamp

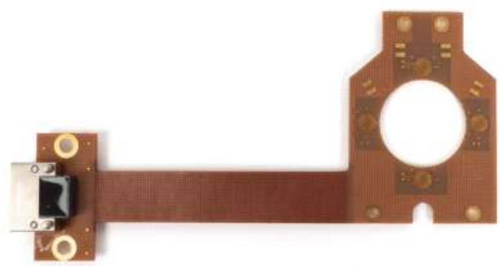


Fig. 5.t: ECS based encoder

6. MAGNETIC ACTUATORS

CEDRAT TECHNOLOGIES (CTEC) has a large heritage in magnetic actuators, sensors and driving electronics. It has been designing, optimising and manufacturing electro-magnetic actuators such as moving iron, voice coil, moving magnet and electromagnet actuators for its customers for more than 20 years.

The MICA™ and BLMM actuators series are standard products. They are powerful, compact, dynamic and precise actuators. Beyond these standard products, CTEC also offers a complete range of engineering services from specifications to custom products: Feasibility, design, optimisation, prototyping, testing, manufacturing and training.

The technical information on this chapter is not contractual and can be changed without prior notice.

6.1. MOVING IRON CONTROLLABLE ACTUATOR MICA™

Moving Iron Controllable Actuators (MICA™) are patented magnetic actuators from CEDRAT TECHNOLOGIES (CTEC). They provide a controllable high force along the stroke.

It is particularly suited for dynamic applications requiring long strokes. MICA™ actuators provide:

- **Large force in a compact design**.
- **High dynamics**, meaning high acceleration.
- **High reliability**.
- **Maintenance free flexure bearing** available
- **High resolution**: MICA™ actuators have a continuous displacement, enabling to reach high resolution. For extreme resolution, frictionless guiding should be chosen (*Fig. 6.a*).
- **Low self-heating**: MICA™ actuators' configuration natively helps in thermal dissipating and of course integrates a temperature sensor to monitor the coil heating. Performances can still be increased thanks to cooling capabilities either passively (heater, thermal interface) or actively (fan, forced air).

Fig. 6.a: MICA300CM-FB with flexure bearing option

MICA™ main features are:

- **Frictionless long life flexure bearings**: Efficient flexure bearing design allows to achieve aerospace and military standard of 30 000 hours at 50 Hz i.e. more than five billions cycles full stroke in continuous operation, friction free (linear behaviour) and tunable natural frequency. Flexure bearings improve the output power capability at resonance frequency (see §2.2.9. Resonant flexure bearing actuators, page 34).
- **Incremental position sensor (option)**: every MICA™ can integrate 15 µm resolution sensor. Higher guiding performances (less than 1 µm) can be achieved upon request.
- **Cooling interfaces (option)**: the unique design of MICA™ allows to easily plug efficient cooling systems when operating and environmental conditions lead to thermal issue management.
- **Accessories**: MICA™ design is also compatible with standard mechanical accessories: brackets, ball joint, supports...

The MICA™ actuators may have a stroke larger than 10 mm, and forces range from 20 N to 550 N.

They are versatile actuators: precise at low speed, efficient at resonance and providing high force above resonance frequency. All those magnetic actuators can be driven with our drive electronics (see for example our MCSA480 switching amplifier).

MICA™ remains also compatible with off the shelf power amplifier existing on the market.

To model the behaviour of magnetic actuators, CTEC provides COMMACT™ software. It is a dedicated tool that draws MICA™ performances (see paragraph §2.2. Tutorial on magnetic actuators, page 27). This tool allows direct exploitable results for the user. It is available upon request.

Standard CTEC magnetic actuators show cylindrical shape and therefore the letter **C** appears in their designation. Actuators are also named with respect to their size: **S** for small, **M** for medium and **L** for large. The designation of MICA™ is then such as:

MICA300CM-FB

Type of actuator | Force in Newtons | Shape Size | Option(s)

Available stroke is defined as the possible mechanical travel between end-stops.

With **dedicated cooling**, the peak force becomes achievable in continuous operation.

MICA™ can be customised and tuned to achieve higher stroke with compromise on the force. For example MICA300CM can extend its stroke from 12 to 20mm when reducing nominal force from 300 to 150 N (see *Fig. 6.b*). See characteristics of cylindrical shapes MICA™ products in *Table 6.a* and *Table 6.b*

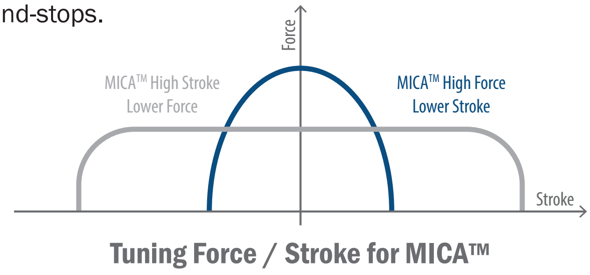


Fig. 6.b: Tuning Force / Stroke for MICA™ C

6.1.1. PROOF-MASS CONFIGURATION

The flexure bearing actuator may be used as proof mass actuator (see equivalent model in *Fig. 6.d*) . The force generated by the actuator on the target structure corresponds to the inertial force.

At frequencies greater than the natural frequency of the actuator, the force magnitude gets constant.

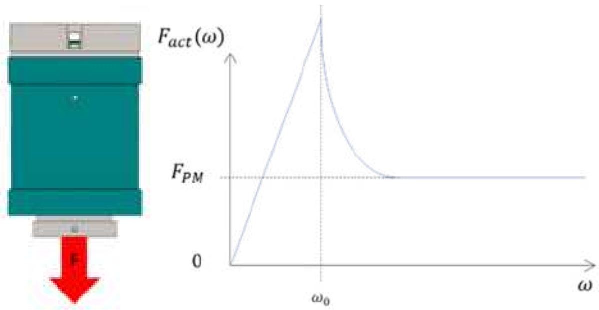


Fig. 6.c: The inertial force is acted on the fixation

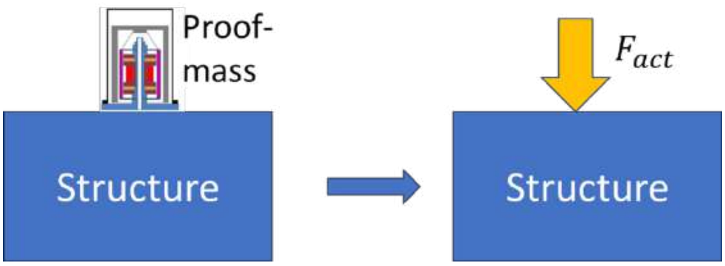


Fig. 6.d: Flexure bearing actuator model

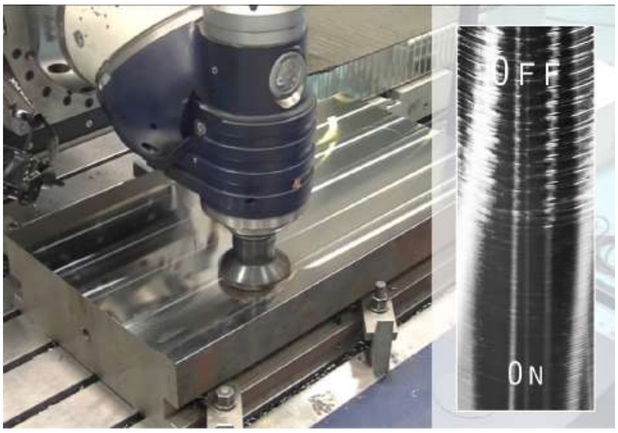


Fig. 6.e: Demonstration of active damping using proof mass MICA actuator

Fig. 6.f: View of MICA20CS-PM

Fig. 6.g: View of MICA300CM-PM

6.1.2. POWER APPLICATIONS

The force response versus frequency is given in *Fig. 6.h*. Then it is of interest to use the actuator at the frequency resonance to benefit from the amplified force given by resonance.

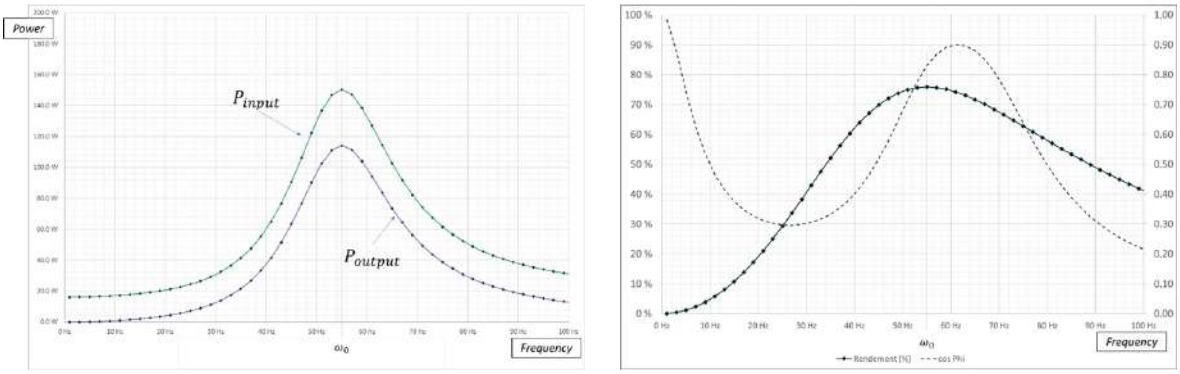


Fig. 6.h: Flexure bearing actuator force response

At the resonance, the yield is maximal. The power supply inputs compensate only the system losses. The stroke is insured by the storage of reactive energy into the system, which means by exchanges between kinetic energy and potential energy, for example the energy stored into the elastic guiding.

The choice of the resonant frequency for power application allows to optimize the yield and thus the efficiency of the system. It implies the minimization of losses, which make it easier to keep acceptable temperature and evacuate the heat out off the system.

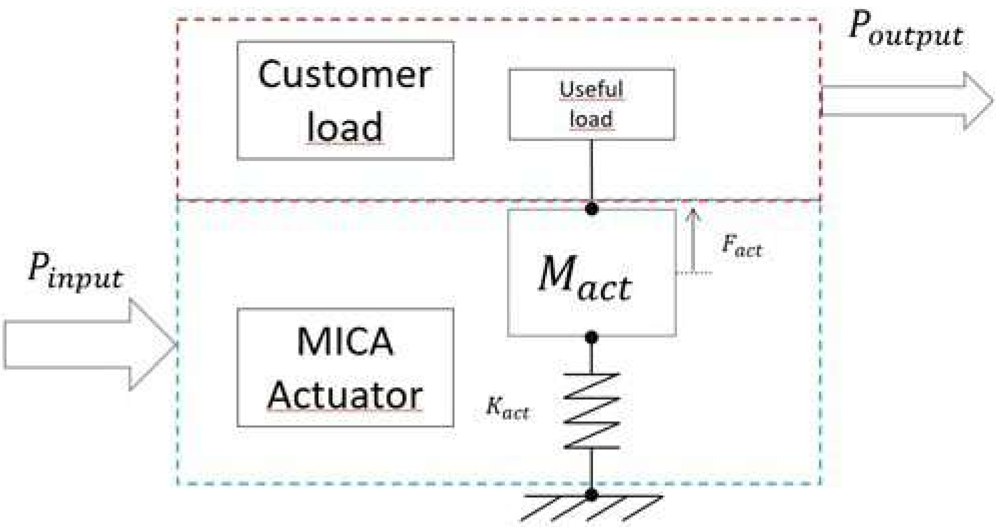


Fig. 6.i: Flexure bearing actuator model

6.1.3. PERFORMANCES

PARAMETER	UNIT	MICA20CS-FB	MICA300CM-FB
Mechanical performances			
Stroke	mm	5	8
Continuous force	N	70	230
Peak force	N	100	650
Actuator constant	N/√W	25	34
Massic actuator constant	N/kg/√W	46	10.6
Force factor	N/A	100	24
Power supply			
DC Resistance	Ohm	15	0.5
Inductance	mH	300	12
Back EMF constant	Vs/m	100	24
Design data			
Resonance frequency	Hz	40	30
Axial stiffness	N/mm	15	21.2
Moving mass	g	230	600
Continuous current	A	0.65	9.0
Peak current	A	5.50	40.0
Dimensions & mass			
Diameter	mm	44	100
Length	mm	70	100
Total mass	kg	0.54	3.2

Table 6.a: Characteristics of FB type of MICA™ actuators

PARAMETER	UNIT	MICA20CS-PM	MICA300CM-PM
Mechanical performances			
Steady state force	N rms	70	230
Peak force	N	100	720
Massic actuator constant	N/kg/√W	46	34
Power supply			
DC Resistance	Ohm	15	0.5
Inductance	mH	300	12
Back EMF constant	Vs/m	100	24
Design data			
Resonance frequency	Hz	30	26
Steady state current	A rms	0.65	9.0
Peak current	A	5.5	80
Dimensions & mass			
Diameter	mm	76	125
Length	mm	87	181
Mass	kg	1.05	4.45

Table 6.b: Characteristics of PM type of MICA™ actuators

6.2. SPECIFIC MAGNETIC ACTUATORS

FIG. 6.J: BLMM1XS production batch

Beyond standard linear magnetic actuators shown in the previous sections, CEDRAT TECHNOLOGIES (CTEC) develops customised solutions to address customer specific requirements in terms of performances and environment. These customised solutions are either built by modification of existing COTS solution or built through engineering develoPMent including design, prototyping and testing phases. The purpose of this section is to give some examples of specific realisations.

6.2.1. BISTABLE LINEAR MOVING MAGNET BLMM

BLMM stands for Bistable Linear Moving Magnet. Those magnetic actuators are based on a permanent magnet moving between two opposite electromagnets.

The main advantage of the BLMM is its holding force without dissipation when not powered. This makes BLMM perfect for applications such as latches devices, locking devices, electro valves, contactors, etc...

FIG. 6.K: BLMM200M.jpg

BLMM Advantages:

- **Holding force at rest**
- **Fast commutation**
- Small size
- Simple current pulse

PARAMETER	UNIT	BLMM1XS	BLMM200M
Status	-	Brique technologique	Prototype
Stroke	mm	> 0.5	7
Holding force at rest (Fh)	N	0.08	200
Commutation time	ms	< 1.7	<90
Nominal commutation current	A	+/- 1.2	+/- 15
Total Mass	g	1.1	1 200
Actuator diameter size	mm	< 6	80
Height actuator (without shaft)	mm	6.8	91
Type of shaft	-	All through shaft	
Diameter Mobile shaft	mm	0.8	8

Table 6.c: Characteristics of BLMM

6.2.2. SPECIFIC MICA™ ACTUATORS

Besides from standards MICA™ actuators, CTEC has also designed customized actuators based on the same technology.

For example, the MICA500L has been designed for medium power and high compacity so to be inserted into a milling head (see *Fig. 6.e*). It is a first generation of actuator used as proof mass actuators.

The MICA 500L is a magnetic actuator using a moving iron mass as mobile part, which is suspended on flexure bearing that allows very high number of cycle and high life time.

Fig. 6.l: View of the MICA500L

6.2.3. MICA™ FOR COMPRESSORS

Specific MICA™ can be developed for compressor application (see *3.2.3, page 69*). This MICA-type linear actuator has been developed to deliver 300W of power with high efficiency (~80%) and virtually infinite lifetime. It has been used in a feasibility project for continuous hydrogen liquefaction for long-duration space missions.

Fig. 6.m: Specific MICA™ developed for hydrogen compressor

6.2.4. VOICE COIL ACTUATORS

Specific linear voice coil actuators have been developped and space qualified for MTG (Meteosat Third Generation) :

- Force homogeneity < 2 % all along the stroke
- Redundant architecture
- Space qualified MCA (Cleanliness, Vibration, Thermal)
- Stroke = 24 mm
- Force constant = 12 N/A

Fig. 6.n: Moving Coil Actuator (MCA): moving part (left) and stator (right)

6.2.5. ROTARY VOICE COIL MOTORS (RVCM)

The RVCM 12d is a rotatory voice coil motor developed for meteorological satellites in the framework of MTG (Meteosat third generation). It belongs to the MCCA (Moving Coil Controllable Actuator) family, with the specificity to drive a rotative move. The application need for high controllability in space application led to develop a specific actuator able to generate constant torque whatever the rotor angle. Additionally the RVCM is equipped with redundant coils to ensure high reliability in space application. As weel the magnetic moment is minimized to reduce EMC interactions with other satellite equiPMent's.

The RVCM 180 degrees is a specific actuator developed for high angular stroke and constant torque versus current.

Fig. 6.p: View of the RVCM 180d

6.2.6. EXTRA FLAT MICA™ STAGES

Fig. 6.q: Flat MICA™ X stage

MICA™ technology allows for making X stage (see *Fig. 6.q*) as well as XY stage (see *Fig. 6.r*). The flat MICA™ X stage offers the following features :

- Integrated proof mass
- Tangential motion (along long dimension)
- Highly dynamic (low mobile mass)
- Peak force = 600 N
- Force constant = 30 N/A
- Stroke = 6 mm

Fig. 6.r: Flat MICA™ XY stage

The XY stage offers a 2D continuous motion in X and Y directions, perpendicularly to the Z axis. A central hole can welcome an optic. Typical application is active stabilisation and antiblur. Key performances are :

- Peak force = 2 N
- Stroke = 2 mm

6.2.7. SPECIFIC ELECTRO-MAGNET ACTUATOR EMA

Fig. 6.s: Electromagnets production batch

Electro-Magnet Actuators (EMA) are suitable when design-to-cost is required. Such an actuator type is deemed relevant when medium to large production is considered. In addition they provide high force in a compact volume. CEDRAT TECHNOLOGIES has the necessary knowledge, equiPMent and experience to provide custom design as well as production batches.

Fig. 7.r shows an example of production batch based on CTEC custom design for the automotive sector. These specific EMA offer the following performances:

- Force = 30 N
- Stroke = 2 mm
- Response time < 10 ms

Fig. 6.t: Electromagnet used as suction cup

6.2.8. SPECIFIC MOVING IRON ACTUATOR

Specific moving iron actuator are necessary for controllable dynamic operations. The special design showed on Fig. 7.s illustrates a moving iron actuator equipped with flexure bearings for long life time purposes. Elsewhere, this actuator works by pair, in a push pull mode, in order to provide high force level at resonance frequency. The customisation includes an embedded drive electronic, one displacement sensor and a closed loop control.

Fig. 6.u: Specific moving iron actuator

This specific moving iron actuator offers the following performances:

- Force = 80 N
- Stroke = 8 mm
- Bandwidth >100 Hz

6.2.9. PIN PULLER FOR LATCH APPLICATION

A Pin puller is an Hold Down and Release Mechanism (HDRM).

A specific electromagnet actuator is integrated into a pin puller of 120g developed for space latch application. This is a secure function that allow to latch equiPMent thanks to a 6mm pin and pulling it in 5ms. The speed of the move is insured by an actuation force that is 8 times higher than the unlocking electromagnetic force. When locked the pin is able to withstand a force of 1500N, which is 10 times greater than the actuation force.

Fig. 6.v: The BRUCE pin puller is an example of pin puller mechanism designed by CTEC

6.2.10. MAGNETOSTRICTIVE ACTUATOR

A specific electromagnet actuator is integrated into drill (see *Fig. 6.w*) to generateaxial vibrations during the drill and allows the natural cut of long chips into small schips. The specificity of the actuator is an axial very high force and high frequency drive applied on the mobile part while rotating. It improves the quality and the speed of drilling operations.

Fig. 6.w: Drilling assistance

7. PIEZO & MAGNETIC MECHANISMS

7.1. SELECTION GUIDE

CEDRAT TECHNOLOGIES (CTEC) offers piezo and magnetic actuators based mechanisms to provide the user with motion over several degrees of freedom as well as advanced mechatronic functions.

These mechanisms integrate position sensors (see chapter 9) for higher positioning accuracy thanks to closed loop control.

These mechanisms are driven and controlled either by the powered rack or OEM controllers from CTEC described in chapter §8. Drive Electronics & Controllers.

Different product lines are available off-the-shelf:

- **X:** single axis X guided stage,
- **XY:** two axis orthogonal XY stage,
- **XYZ:** three axis orthogonal XYZ stage,
- **TT:** single axis Tilt Translator,
- **DTT:** Dual (two axis) Tip Tilt,
- **P-FSM:** Dual axis Piezo based Fast Steering Mirror,
- **M-FSM:** Dual axis Magnetic based Fast Steering Mirror,
- **FPS:** Fast Piezo Shutter.

Please do not hesitate to take a look at our web site, where you can download:

- The technical data sheet,
- The mechanical interface drawing,
- The 3D e-drawings file.

The mechanisms shown in this section can be tuned to your specific requirements: dedicated optical payload, environmental & operating conditions, etc. Please contact us to discuss about your requirements.

7.2. PIEZO STEERING PLATFORMS

The piezo steering platforms are either tilt (single rotational axis) or Tip Tilt (dual rotational axis) mechanisms to move a mirror payload. Each rotational axis includes a pair of APA® driven in push pull. Each platform axis is equipped with a Strain gauge positioning sensor and is combined with OEM controllers like CCBu20 and CCBu40 for an accurate & dynamic motion control.

These piezo steering platform models have a mechanical support to bond different type and size of mirror payload. As an option for COTS Tilt or Tip/Tilt platforms, CTEC can propose to outsource and to integrate a suitable mirror defined in collaboration with the customer. CTEC can even design customized mirrors (Silicon Carbide SiC, Fused Silica SiO2, …).

Their functions and applications include optical & laser communication link, pointing, micro-scanning, D- scanning, anti-blurring, tracking, beam wander correction and line of sight stabilization.

The **TT60SM-SG model** is a single axis steering platform with more than 1° angular motion. The **DTT15XS-SG, DTT35XS-SG & DTT60SM-SG** models have a max angular stroke of 2, 5 & 11 mrad respectively.

Fig. 7.a: View of the Tilt Translator TT60SM

Fig. 7.b: View of the Double Tilt Translator DTT15XS-SG

Fig. 7.c: View of the Double Tilt Translator DTT35XS-SG

Fig. 7.d: View of the Double Tilt Translator DTT60SM-SG

PARAMETER	UNIT	TT60SM-SG	DTT15XS-SG	DTT35XS-SG	DTT60SM-SG
Active axis	-	RX	RX, RY	RX, RY	RX, RY
Angular displacement	mrad (+/-)	24	1,8	4,8	11
Unloaded resonance frequency	Hz	2000	3000	2450	1800
Angular resolution	µrad	0,24	1	5	10
Voltage range	V	-20…150			
Capacitance (per electrical port)	µF	2,8	0,7	0,7	2,8
Dimensions (Ø×Z)	mm	55x35	40x40x24	45x22	65x40
Mass	g	141	110	65	310
Sensor Option	-	SG, ECS	SG	SG	SG

Table 7.a: Characteristics of Steering Platforms

7.3. FAST STEERING MIRRORS

A Fast-Steering Mirror (FSM) is an opto-mechanical solution including a Mirror integrated on a steering platform (Tilt or Tip/Tilt) with positions sensors and a controller. CTEC COTS FSM are either piezo (P-FSM) or magnetic (M-FSM) actuator-based opto-mechanisms. They are controlled with either piezo controllers or magnetic controllers. Their sensors are either Strain Gauges (SG) for P-FSM or Eddy Current Sensors (ECS) for M-FSM.

The **P-FSM150S-SG, M-FSM45, M-FSM45-HPL & M-FSM62 models** have large angular stroke respectively of 18 mrad (>1°), 50 mrad (>2.5°), 90 mrad (>5°) and 140 mrad (>8°). They have SiC mirrors with respectively 15 & 30 mm clear aperture and high reflectivity coating.

The **P-FSM150S-SG model** has been developed and space qualified for both point ahead & fast steering mirror functions inside Optical Communication Terminal (OCT) used for Optical Inter-Satellite Link of space constellations. The P-FSM150S-SG design has been optimized to meet both the harsh environments and low recurrent cost demands of the New-space market.

Fig. 7.e: View of the Fast Steering Mirror P-FSM150S

Fig. 7.f: View of the Fast Steering Mirror M-FSM45

Fig. 7.h: View of the Fast Steering Mirror M-FSM45-HPL

Fig. 7.g: View of the Fast Steering Mirror M-FSM62

PARAMETER	UNIT	P-FSM150S	M-FSM45	M-FSM45-HPL	M-FSM62
Status	-	Standard	Standard	Preliminary	Preliminary
Active axis	-	RX, RY	RX, RY	RX, RY	RX, RY
Angular displacement	mrad (+/-)	18	50	90	140
Loaded resonance frequency	Hz	700	100	80	100
Angular resolution	µrad	20	2	2	20
Dimensions	mm	63x61x30	Ø45x40	Ø45x58	Ø62x60
Mass	g	135	200	400	500
Sensor Option	-	SG	ECS	ECS	ECS

Table 7.b Characteristics of Fast Steering Mirrors

7.4. PIEZO STAGES

Fig. 7.i: View of the X60S stage

Fig. 7.j: View of the XY25XS stage

Fig. 7.k: View of the XYZ200M stage

CEDRAT TECHNOLOGIES (CTEC) piezo stage product line includes models with 1, 2 or 3 translation axis. All the models take advantage from the characteristics of APA® actuators and flexure guiding, in order to offer excellent compactness, robustness, bandwidth and resolution. It can be equipped with strain gauges for very fine positioning or closed loop control. Parasitic translations and rotations as well as cross talk are very limited.

The **X60S & X120S models** are single axis piezoelectric stages. Their moving frame can be custom designed (attachment points, holes...) and 2 stages can be stacked for XY motion.

The **XY25XS, XY200M & XY400M models** are 2 push pull orthogonal axis stages with a centered moving frame for fixing the payload (Optical lens for instance). Thanks to this symmetric design, these XY stages have a self-compensated thermo-mechanical behavior.

These XY stages are usually combined with OEM controllers like CCBu20 or CCBu40.

Their applications include mask, lens or detector positioning, micro scanning, pixel shifting, dithering and line of sight stabilization.

The **XYZ200M model** is actually a 2 axis stage XY200M model with an additional vertical axis based on 3 guided APA200M to provide the user with 200 um motion over the three orthogonal degrees of freedom.

The XYZ200M stage is able to bear loads up to 3 kg.

Applications include confocal microscopy, mask positioning and inspection.

PARAMETER	UNIT	X60S	X120S	XY25XS	XY200M	XY400M	XYZ200M
Status	-	Preliminary	Preliminary	Standard	Standard	Preliminary	Standard
Active axis	-	TX	TX	TX, TY	TX, TY	TX, TY	TX, TY, TZ
Displacement (unloaded)	µm	55	110	25	200	400	200
Stiffness	N/µm	1,2	0,26	2,5	0,59	0,14	0,59
Unloaded resonance frequency	Hz	1840	850	3000	580	260	380
Resolution	nm	5,5	11	3	20	40	20
Voltage range	V	-120...150					
Capacitance (per electrical port)	µF	1,55	1,55	0,5	6,3	6,3	6,3
Dimensions (XxYxZ)	mm	30x30x12	30x30x12	50x50x16	100x100x22	100x100x27	100x100x49
Mass	g	23	23	80	450	500	540
Sensor option	-	SG	SG	SG, ECS	SG, ECS	SG, ECS	SG, ECS

Table 7.c: Characteristics of piezoelectric stages

7.5. FAST PIEZO SHUTTERS

The Fast & Amplified Piezo Shutters (FPS & FAPS) are beam shutter mechanisms using two APA® actuators to open and close a slit, up to 3 mm in less than 10 ms. They are particularly suited to applications requiring low jitter, high repeatability or long lifetime.

Design of FPS & FAPS series is based on either APA200M, APA400M and APA900M actuators. The moving jaw can be made of tungsten to offer very high X-Ray stopping power. The FPS & FAPS embed a Strain Gauge (SG) sensor to feedback the open / close status. Vacuum (VAC) and Ultra High Vacuum (UHV) options are also available on request.

FPS technology, initially developed by CEDRAT TECHNOLOGIES (CTEC) on an initiative of Mr Cipriani from EMBL and qualified at ESRF Grenoble (France), are now used by synchrotron facilities all around the word.

The FPS & FAPS family is driven and controlled by a dedicated electronic rack mounted RK42F3U-LC75B + SP75A-2 + SG75-1.

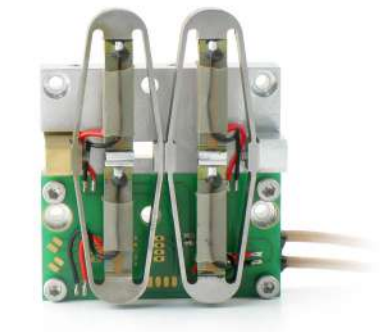


Fig. 7.m: View of the FPS200M (courtesy of EMBL)

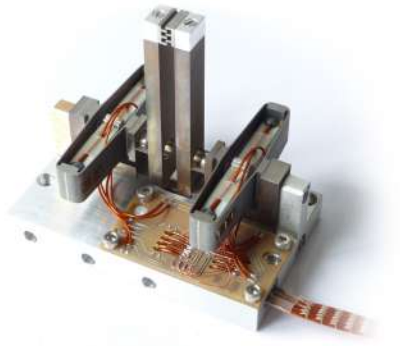


Fig. 7.n: View of the FAPS400M-SIW-SG-UHV

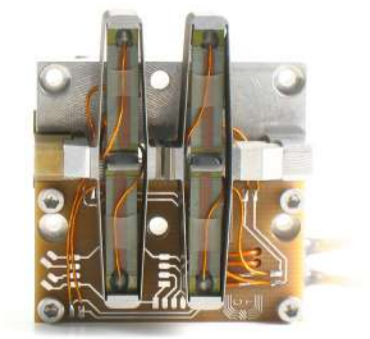


Fig. 7.l: View of the FPS900M

PARAMETER	UNIT	FPS200M	FPS400M	FPS900M	FAPS400M
Max. beam diameter	mm	0,3	0,7	1,1	3
Aperture & closing time	ms	2	4	10	8
Voltage range	V	-20...150			
Capacitance (per electrical port)	µF	3,2			
Dimensions (X x Y x Z)	mm	60x44x21	60x44x21	60x44x23	73x54x65
Mass	g	84	84	82	152
Slit teeth material	-	Tungsten			
Total slit teeth depth	mm	2,4	2,4 / 4,8	4,8	3
Sensor option	-	SG	SG	SG	SG [1]

Table 7.d Characteristics of piezo shutters

a.1 Included, not optional

7.6. CUSTOMISED PIEZO MECHANISMS

The range of Commercially Off The Shelves (COTS) mechanisms shown in the previous paragraphs is indeed the tip of the iceberg in terms of sales revenue and manufacturing volume at CTEC. Usually a COTS product is hardly ready for a friendly plug and play inside the customer system for any application. More and more customer's requests are demanding in terms of integration and functionality. To answer to that reality CTEC has been demonstrating its capability to deliver customized & OEM solutions for more than 25 years.

A customized solution is the possibility for a customer to optimize the performances, the reliability and the cost of ownership for the requested product or function to be integrated inside his system or application. This customized solution is either built from building blocks deriving from existing COTS solution or built through engineering development including design, prototyping and testing phases.

The purpose of this paragraph is to show (without being exhaustive) the diversity of the customized solutions in terms of piezo mechanisms developed and manufactured by CTEC for various industrial field. Some of these customized mechanisms have been delivered together with their controllers in order to provide the customer with a full plug & play integrated function.

Two brochures present the CTEC heritage in customized solutions for Fast Steering Mirrors and XY stages.

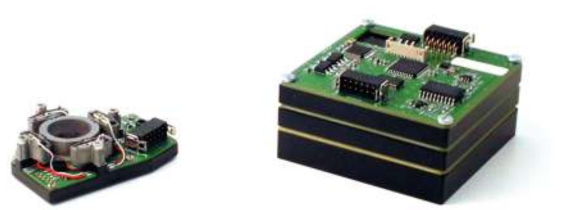


Fig. 7.o: Piezo XY stage (+/- 10 um stroke) and its controller box for Image stabilization

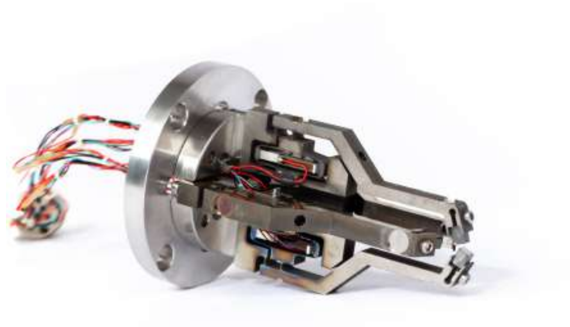


Fig. 7.q: Active slits (> 700 µm aperture) for X ray beam shaper designed with SOLEIL for the SWING beamline

Fig. 7.p: Piezo FSM (+/- 1 mrad stroke) and its controller box for fine laser pointing & stabilization

Fig. 7.r: Micro scanning piezo XY stage (+/- 10 um stroke) and its driver box for image resolution enhancement

Fig. 7.t: Mini P-FSM35XS-SG (angular stoke: 12 mrad) with its CCBu20-SV controller

Fig. 7.s: Piezo activated arms (3 mm stroke for X-ray filter holder 10 ms switching time

7.7. P-FSM150S DEMOKIT

This new demokit has been created to show the implementation of our Piezo Fast Steering Mirror (P-FSM). It utilizes a P-FSM150S, a laser, and mirrors to amplify the laser deflection, making it visible on a screen within a confined space. The electronic used is the Compact Controller Board CCBu20 (see *page 127*) which is an embedded all-in-one controller designed for piezo actuators. It includes everything necessary to drive and control a 2-axis piezo mechanism in a closed loop. As a standard feature, its integrated dual-channel SG conditioner enables the reading of the position of the two axes of the mechanism.

Both axes of the FSM are actuated at different frequencies, creating a visual effect of a rotating rosette due to retinal persistence.

This kit includes:

- A piezo Fast Steering Mirror
- A compact driver CBBu20
- A laser
- 2 static mirrors
- An adjustable mirror
- A screen
- An optical support plate
- A driver power supply
- A laser power supply
- A transport case

Upon request, this demo kit can be adapted and equipped with an alternative tip-tilt mechanism from CTEC.

Fig. 7.u: View of the P-FSM150S demokit

Fig. 7.v: Rosette figure produced by the FSM actuation

Actuator & Sensor
CCBu20
CEDRAT
TECHNOLOGIES
Supervisor I/O
CCBu20 22-031
CEDRAT
TECHNOLOGIES
Fault
Power

8. DRIVE ELECTRONICS & CONTROLLERS

CEDRAT TECHNOLOGIES (CTEC) offers a range of electronic amplifiers and controllers to drive its own range of piezo actuators, magnetic actuators and piezo motors both in open and closed loop, in an optimal manner. These amplifiers & controllers are available either integrated in powered 19" sub-rack (mainly for laboratory & factory use) or integrated in DC powered OEM board & box (mainly for embedded applications).

The range of powered sub-rack mounted & OEM series are further described in the following paragraphs.

8.1. AMPLIFIERS & CONTROLLERS FOR PIEZO ACTUATORS

8.1.1. OEM SERIES

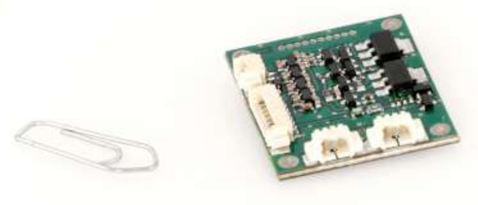


Fig. 8.a: CAU10

The Compact Amplifier CAu10 (*Fig. 8.a*) and Compact Controller Boards CCBu20 & CCBu40(*Fig. 8.b*) are OEM amplifiers and controllers available off the shelf.

The CAu10 is a miniature two-channel amplifier board with both analog and digital (SPI communication) inputs. It is used for driving piezo actuators in open loop, and is able to deliver 5 mA per channel and requires a DC voltage supply of 5 to 12 V.

PARAMETER	UNIT	CAU10 (A.1)
General		
Function		Embedded Driver for piezoelectric actuators
Number of channels		2 + Push Pull
Input		
Analog Control Input voltage	V	0.1 ... +3.3
Digital Input voltage (SPI protocol)	V	3,3
Output		
Typical output voltage	V	+5 ... +150
Permanent output current (a.2)	mA	±5
Power amplifier		
Peak output power (a.3)	VA	1
Gain		
Gain	V/V	45
Dynamic performance		
Small signal bandwidth (-3dB) (a.4)	kHz	2
Noise performance		
Signal to Noise Ratio (a.5)	dB	70
Power Supply		
Main Power supply	VDC	5 ... 12
Options		
Connector interface option for CAU10 2 channels		To connect two actuators

Table 8.a: Characteristics of CAu10

a.1 Guaranteed in labs environment
a.2 Internally limited
a.3 AC+DC apparent power, sine signal.
a.4 Unloaded
a.5 Computed as RMS output signal/ RMS output Noise floor

The CCBu20 and CCBU40 are 2-channel push-pull controller enclosures, designed for driving the XY stages & Fast Steering Mirrors piezo mechanisms developed by CEDRAT TECHNOLOGIES (CTEC).

These controllers can be operated in open loop or closed loop configurations, with up to 2 axes. They combines drivers, sensor conditioners, controllers, and communication modules. The CCBuXX are available in two configurations, depending on whether the gauge conditioner is placed inside (SGIN version) or outside the box (SGEX version).

Fig. 8.b: CCBu20 and CCBu40

PARAMETER	UNIT	CCBU20	CCBU40
General			
Function		All-in-one piezo-driver and controller	
Number of control channels		2	
Digital communication		RS422	
Graphical User Interface		CTEC HDPM	
Digital control			
Control strategy		Tunable PID + Stabilizing filters	
Sampling rate	kSps	20	50
Digital resolution	bits	16	16
Analog inputs			
Number of analog inputs		2	
Analog inputs Voltage range	V	-10 ... +10	
Strain gages (SG) conditioner			
Number of channels		2	
Output voltage range	V	-10 ... +10	
Piezo driver			
Number of channels		2	
Nominal output voltage range	V	-20 ... +150	
Max output current	A	0,2	0,5
Permanent output current	Arms	0,035	0,35
Power supply			
Recommended supply voltage	Vdc	+24 ... +28	+28
Miscellaneous			
Mass	kg	0,25	0,8
Dimensions	mm3	91 × 77 × 35.2	160 × 170 × 36
Operating temperature range [b.1]	°C	-40 ... +70	-40 ... +70

Table 8.b: Characteristics of CCBu20 & CCBu40

b.1 Additional heatsink might be required

8.1.2. PLA SERIES

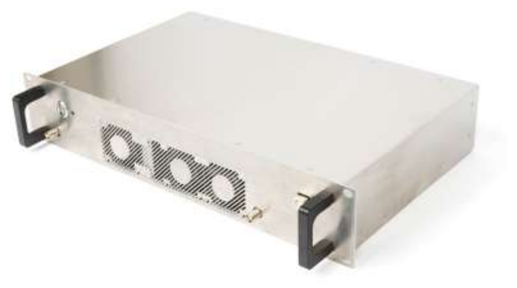


Fig. 8.c: PLa25

The PLa25 is the first model of the PLa piezo amplifier series. It will be CE marked and will help users setup simple, efficient and versatile solutions for their lab or industrial applications. The PLa amplifiers can be integrated into a third-party cabinet or delivered into a tabletop enclosure. The PLa25 driver can be combined in a master / slave topology, to provide multi-channel or push-pull configurations, delivering 2.5 A continuously and 5 A peak, with voltages between -20 V and 150 V. With the PLa series, it is possible to combine drivers, sensor conditioners, controllers, and communication modules. The PLa series modules offers a compact integration while keeping performances, offering a novel output topology with larger transient output current, higher signal to noise ratio and higher communication speed.

PARAMETER	UNIT	PLA25 (C.1)
General		
Function		Driver for piezoelectric actuator
Number of channels		1
Input		
Control Input voltage	V	-1 ... +7.5
Output		
Output voltage	V	-20 ... +150
Permanent output current (c.2)	mA	± 2 500
Max output current (c.3)	mA	±5000
Gain		
Gain	V/V	20
Dynamic performance		
Small signal bandwidth (-3dB) (c.4)	kHz	30
Noise performance		
Signal to Noise Ratio (c.5)	dB	85
Protections		Overcurrent, Overtemperature, Overvoltage
Options		
UC		Controller for position loop See specific datasheet
Piezo cable		Specific length on request Please contact CTEC for more detail

Table 8.c: Characteristics of PLa25

c.1 Guaranteed in labs environement (5 - 40 °C)
c.2 Electronically limited
c.3 With EPC Enhanced Peak Current - During 1,2ms with a max repetition rate of 20ms - Internally limited - see specific application note
c.4 Unloaded
c.5 Computed as RMS output signal / RMS output Noise floor. [1; 200]Hz

8.1.3. POWERED RACK SERIES

The powered mounted series consists of a number of powered 19” sub-rack reference. A powered rack or case includes as standard an AC/DC (either linear or switching) converter board to convert the power from the main electrical power and to deliver it to the other functional boards (amplifier, conditioner & controller) presented in the next paragraphs. The powered 19’’ sub-rack can be inserted in an industrial cabinet.

The powered bench top (*Fig. 8.d, page 130*) and the powered 19’’ sub-rack (*Fig. 8.e, page 130*) allow for various combinations of amplifier, sensor conditioner and controller boards with single or multi channels as well as output power options.

The *Table 8.d* shows the different possibilities to build your configuration.

PARAMETER	RK42F3U-LC75B	RK42F4U-LC75C	RK84F4U-1LC75B	RK84F4U-1LC75C	RK84F4U-2LC75C	RK84F4U-3LC75C	RK84F4U-1SC75D	RK84F4U-2SC75D
> Application								
AC-DC converter topology	Linear						Switching converter	
Max. No. of hosted amplifiers & conditioner boards	2 in total [d.1]	1 of each	6 in total [d.1]	6 in total [d.1]	2 of each [d.1]	3 of each [d.1]	1 of each	2 of each
Max supplied current	0,75 A	2,55 A	0,75 A	2,55 A	5,1 A	7,65 A	20 A	2 x 20 A
> Power supply								
Supply voltage	110/240 VAC							
Supply frequency	50-60 Hz							
> Protections								
Protection type [d.2]	T., OC., HBD.	T., OC., HBD.	T., OC., HBD.	T., OC., HBD.	T., OC., HBD.	T., OC., HBD.	T., OC., OV.	T., OC., OV. [d.3]
> Board compatibility								
LA75A - Up to 3 channels	✓		✓	✓				
LA75B - Up to 2 channels	✓		✓	✓				
LA75C - 1 channel		✓		✓	✓	✓		
SA75A - Up to 2 channels							✓	✓ [d.4]
SA75B - Up to 2 channels							✓	✓ [d.4]
SA75D - 1 channel							✓	✓
SG75 - Up to 3 channels	✓	✓ [d.4]	✓	✓	✓	✓	✓	✓
ECS75 - Up to 3 channels	✓	✓ [d.4]	✓	✓	✓	✓	✓	✓

Table 8.d: Characteristics of powered racks

d.1 Sum should not exceed the max supplied current

d.2 T: Thermal; OC: Overcurrent; HBD: Hosted board default; OV: Overvoltage

d.3 Each SC75 board

d.4 Only 1 channel

Fig. 8.d: RK42 powered benchtop case

Fig. 8.e: RK84F powered 19" sub-rack

The 8 powered rack or case items available off the shelves are listed below:

- **RK42F3U-LC75B**
  Powered benchtop case for LA75A or B amplifier board,
- **RK42F4U-LC75C**
  Powered benchtop case for LA75C amplifier board,
- **RK84F4U-1xLC75B**
  Powered 19'' sub-rack for multiple LA75A or B amplifier boards,
- **RK84F4U-1xLC75C**
  Powered 19'' sub-rack for LA75C amplifier or multiple LA75A or B amplifier boards,
- **RK84F4U-2xLC75C**
  Powered 19'' sub-rack for 2 LA75C amplifier boards,
- **RK84F4U-3xLC75C**
  Powered 19'' sub-rack for 3 LA75C amplifier boards,
- **RK84F4U-1xSC75**
  Powered 19'' sub-rack for 1 SA75A, B or D switching amplifier board,
- **RK84F4U-2xSC75**
  Powered 19'' sub-rack for 2 SA75A, B or D switching amplifier boards.

For driving and/or controlling piezo actuators according to your application, the powered rack can welcome:

- A linear (LA75) or switching (SA75 or SP75) voltage amplifier (see §8.1.3. Linear voltage amplifiers, page 106 and §8.1.4. Switching voltage amplifiers, page 106),
- A sensor conditioning board for monitoring option (see §9. Sensors & Conditioners, page 121 for description),
- A digital controller board for closed loop control option (see §8.1.6. Digital controllers, page 110),

The powered 19'' sub-rack series are more versatile and mainly dedicated for laboratory and factory use.

8.1.4. LINEAR VOLTAGE AMPLIFIERS

The linear voltage amplifier are designed to be compatible with the RK42F and RK84F powered sub-rack series (see chapter *8.1.3, page 129*). The LA75 series of Linear voltage Amplifier board offers the most common solution to drive piezo actuators. The LA75 is designed to drive capacitive loads like piezoelectric actuators with extremely low noise. It can perform amplifying operations in the -20/150 V range. The LA75A-x and LA75B-x can be equipped with the push pull option. LA75A-x is a lowpower amplifier integrated on a 19" board and can have up to 3 independent channels. LA75B-x is a medium power amplifier integrated on a 19" board and can have up to 2 independent channels.

The LA75C has a much higher current capability, suited for high frequency and/or short response time/impulse/ fast applications. It shows the highest continuous output power capability of the linear voltage amplifiers for piezo actuators available on the market.

See *Table 8.e, page 132* for characteristics.

8.1.5. SWITCHING VOLTAGE AMPLIFIERS

The Switching power Amplifiers SA are designed to be compatible with the Switching Converter SC75 powered sub-rack series (see chapter *8.1.3, page 129*). They allow to perform either linear continuous state (SA75) or purely ON/OFF states (SP75) on piezo actuators with extremely short response times. The switching technique allows high current peaks, required by impulse or by high frequency applications on large capacitance piezo actuators.

The SA75A, B and D have max continuous output currents of respectively 5, 10 and 20 Amps.

These amplifier boards can be integrated in either a powered 19" sub-rack RK84F4U-1xSC75 or RK84F4U- 2xSC75 for respectively 1 or 2 board arrangements per rack with optional sensor conditioners and digital controllers.

The switching amplifiers have been developed in collaboration with the G2ELAB of UJF Grenoble (France) in the frame of AVIBUS and PPSMPAB projects. Those 2 projects aimed at driving large piezo actuators for fast machining or helicopter flap actuation.

See *Table 8.f, page 133* for charasteristics.

Fig. 8.f: LA75C, LA75B-2 & LA75A-3 amplifier boards

Fig. 8.h: SA75D amplifier board

Fig. 8.g: Comparison of power bandwidth for LA75A, B, C for Permanent output current

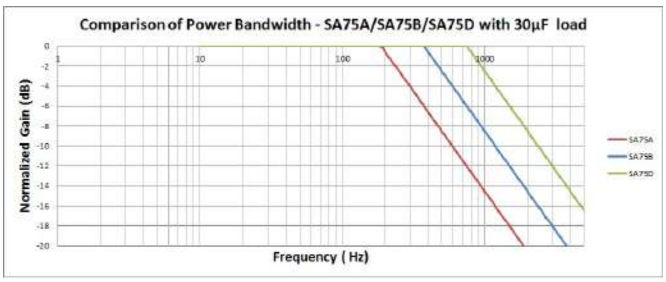


Fig. 8.i: Comparison of power bandwidth for SA75A, B, D for Permanent output current

PARAMETER (E.1)	UNIT	LA75A	LA75B	LA75C
General				
Function		Driver for piezoelectric actuator		
Number of channels		1...3	1...2	1
Input				
Control Input voltage	V	-1 ... +7,5		
Output				
Output voltage	V	-20 ... +150		
Permanent output current (e.2)	mA	±90	±360	±2 400
Max output current (e.3)	mA	-	-	±6 800
Power amplifier				
Peak output power (e.4)	VA	-	-	360
Gain				
Gain		20		
Dynamic performance				
Small signal bandwidth (-3dB) (e.5)	kHz	30		
Signal to Noise Ratio (e.6)	dB	85		
Protections				
Protections	Overcurrent, overtemperature, overvoltage			
Options				
Push pull	Capability to drive push-pull piezo mechanisms			No
UC55	Controller for position loop See specific datasheet			
Piezo cable	Specific length on request Please contact CTEC for more detail			
T LEMO	Able to connect 2 CTEC actuators in parallel Please contact CTEC for more detail			
LEMO -BNC adapter	Converts LEMO to BNC connector			

Table 8.e: Characteristics of LA75A, B & C

e.1 Guaranteed in labs environement
e.2 Electronically limited
e.3 With EPC Enhanced Peak Current - During 600µs with a max repetition rate of 20ms - Internally limited - see specific application note
e.4 Max. instantaneous output power = max(p(t)) = max(u(t) x i(t)), with EPC.
e.5 Unloaded
e.6 Computed as RMS output signal / RMS output Noise floor. [1; 200]Hz

PARAMETER (F.1)	UNIT	SA75A	SA75B	SA75D
General				
Function		Driver for piezoelectric actuator		
Number of channels		1		
Input				
Control input voltage	V	-1 ... +7,5		
Output				
Output voltage (f.2)	V	-20 ... +150		
Permanent output current (f.3)	A	±5	±10	±20
Power amplifier				
Peak output power (f.4)	VA	750	1 500	3 000
Gain				
Gain	V/V	20		
Dynamic performance				
Small signal bandwidth (-3 dB) (f.5)	Hz	3800		
Accuracy				
Signal to noise Ratio (f.6)(f.7)	dB	60		
Protections				
Amplifier protections	Overcurrent, overtemperature, overvoltage			
Actuator protections	Overcurrent, overtemperature			
Options				
UC55	Controller for position loop - See specific datasheet			
Piezo cable	Specific length on request			
Multi outputs LEMO front panel	Allows to connect several actuators in parallel - Please contact CTEC for more details			

Table 8.f: Characteristics of SA75A, B & D

f.1 Guaranteed in labs environment
f.2 Digitally limited, can be increased to -200 ... +200V upon request
f.3 Electronically limited
f.4 AC+DC apparent power. For sine signal with offset, RMS² is (PEAK/√2)² + OFFSET²
f.5 Unloaded. Order = 1Vpp
f.6 With 30µF load. Order = 0V
f.7 Computed as RMS output signal/ RMS output Noise floor. 40 Hz ... 20 kHz

Fig. 8.j: SP75A amplifier board

8.1.6. TWO STATES POWER AMPLIFIER

The Two States Power SP75A amplifier board is a designed two states power driving board.

Only two positions can be obtained:

- OFF position at rest (-20 Volt DC),
- ON position (150 Volt DC).

The two positions are controlled by a TTL signal. The overshoot of the piezo actuator can be reduced after calibrations of the slew rate or the implementation of a signal pre-shaping.

PARAMETER (G.1)	UNIT	SP75A
General		
Function		2 state power driver
Input		
Control Input voltage	V	0 ... +5 TTL signal / CMOS
Output		
Output voltage	V	-20 ... +150
Max output current (g.2)	mA	±480
Type of output signal excitation		Preshaping waveform
Signal to Noise Ratio (g.3)	dB	85
Protections		
Protections	Overcurrent, Overtemperature, Overvoltage	
Options		
RS422 communication	Capability to communicate the two states order with differential pairs	
SG75	Monitoring of the position - See specific datasheet	
Piezo cable	Specific length on request - Please contact CTEC for more detail	
LEMO -BNC adapter	Converts LEMO to BNC connector	

Table 8.g: Characteristics of SP75A

g.1 Guaranteed in labs environement
g.2 Electronically limited
g.3 Computed as RMS output signal / RMS output noise floor. [1;200]Hz

8.1.7. DIGITAL CONTROLLERS

For closed loop applications (see *Fig. 2.z, page 29*), Cedrat Technologies (CTEC) offers different solutions built around digital controllers in order to adapt to the application's requirements. All controllers come with a USB connection for interfacing with a computer. The controllers implement PID real-time control with additional stabilising output filters (low-pass filters, notch filters). They feature analog inputs for the orders and sensors, and analog outputs for the commands to the amplifiers. The different control parameters can be tuned through the USB connection. Dedicated GUI software is provided to allow easy tuning of the control laws and ordering displacements. This software is called HDPM.

Fig. 8.k: UC55 controller board

Under specific request, there is also the possibility to send commands to the controllers over the serial connection instead of the analog inputs. The UC55 control board is plugged as a daughter board into amplifier board and integrates a single channel digital controller that achieves control rate in accordance with CTEC mechanism.

In single channel, the control rate is 30 kSps, in dual channels, 15 kSps, and in triple channels, 10 kSps. The UC55 boards can also be stacked to handle several independent control channels at high frequency (up to 3).

PARAMETER	UNIT	UC55
General		
Function		Digital controller with analog I/Os
Number of control channels		1 ... 3
Digital communication		USB
Graphical User Interface		CTEC HDPM45
Digital control		
Control strategy		Tunable PID + Stabilizing filters
Sampling rate	kSps	10 / 15 / 30 (h.1)
Digital resolution	bits	16
Analog inputs		
Voltage range	V	-10 ... +10
Analog outputs		
Voltage range	V	-10 ... +10
Miscellaneous		
Product compatibility		LA75 and SA75 series

Table 8.h: Characteristics of UC55 controller boards

h.1 10kSps for 3 channels, 15kSps for 2 channels, and 30kSps for 1 channel

8.1.8. CUSTOMISED AMPLIFIERS AND CONTROLLERS

LINEAR CHARGE AMPLIFIER

This linear charge amplifier based powered rack is derived from the linear voltage amplifier board LA75B. The piezo actuator is driven with electric charge instead of voltage in order to reduce the hysteresis effect below 1 % in open loop and dynamic conditions. This charge amplifier option is available for LA75A and B boards under request. (see *Fig. 8.l* and *Fig. 8.m*).

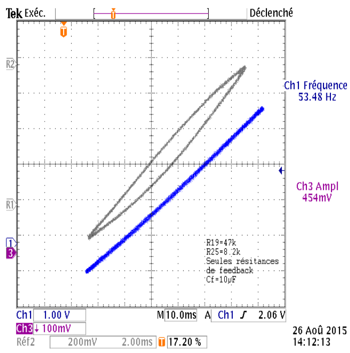


Fig. 8.l: Hysteresis plot of displacement versus input voltage for a linear voltage amplifier (grey curve and for a linear charge amplifier (blue curve)

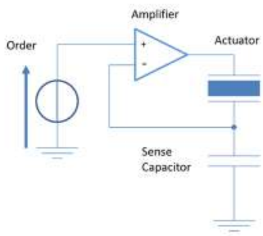


Fig. 8.m: Schematic of a charge amplifier

MULTICHANNEL LA75C POWERED 19'' SUB-RACK CABINET

This combination of 4 LA75C with SG conditioner and digital controller boards is implemented inside a RK84F-9U cabinet in order to drive and to control in push pull configuration some large piezo Tip Tilt, XY stages or fast steering platforms (see *Fig. 8.n*).

Fig. 8.n: Rack cabinet mounted LA75C push pull amplifier channels for driving large capacitance piezo mechanism

HIGH VOLTAGE MULTICHANNEL AMPLIFIER RACK

This 18 channels combination allows to drive simultaneously 18 high voltage piezo actuators (from -200 to +200 V) (see *Fig. 8.o*).

Fig. 8.o: Amplifier channels rack for high voltage piezo actuators

COMPACT CONTROL BOARD FOR NEW SPACE

For a new space mission, CTEC delivered a custom 2-channel CCBu20 controller, designed for piezo mechanisms and qualified for vibrations. To ensure the resistance of the controller, CTEC designed a new reinforced housing and performed vibration tests. This custom CCBu20 design is the first step in the development of a rugged CCBu20 controller that will address new space market requirements.

Fig. 8.p: Custom CCBU20 for new space application

8.2. AMPLIFIER FOR MAGNETIC ACTUATORS

Fig. 8.q: MCLA18

8.2.1. OEM SERIES

COMPACT LINEAR POWER AMPLIFIER MCLA18

The Compact Linear Power Amplifier MCLA18 is a compact size 2 channels push pull controller enclosure with large output power capability. The MCLA18 is relevant for driving & control the motion of either 2 single axes MICA ™ or dual axis magnetic actuators like Magnetic Fast Steering Mirror (M-FSM) along large operating bandwidth.

PARAMETER (i.1)	UNIT	MCLA18
General		
Function		All-in-one magnetic driver and controller
Number of channel		2
Digital communication		RS422, USB
Digital control		
Processor		Floating-point microcontroller
Control strategy		Dedicated control for magnetic mechanism
Sampling rate	kSps	100
Digital resolution	bits	16
Input		
Number of analog inputs		2
Control input voltage (Vin+ - Vin-)	V	-10 ... +10
Output		
Output voltage (with main supply)	V	up to ±11
Output voltage (with optional supply)	V	±2 ... ±32
Permanent output current (i.2)	A	±1
Maximum output load	H	Unlimited
Minimum output load	µH	0
Power amplifier		
Number of channels		2
Max. continuous output apparent power	VA	64
Max. continuous output active power (i.2)	W	64max (2 x 32max)
Gain	A/V	0,1
Protections		
Protections	Reverse Polarity, Current Limitation (Amplifier), Overtemperature (Amplifier)	

Table 8.i: Characteristics of MCLA18

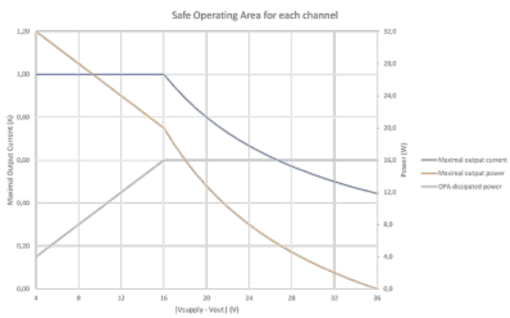


Fig. 8.r: MCLA18 Operating Graph

i.1 Guaranteed in labs environment
i.2 Depending of the output voltage - See next graph

Fig. 8.s: MCSA480

COMPACT SWITCHING AMPLIFIER MCSA480

The Compact Switching Amplifier MCSA480 is a compact size 2 channels push pull controller enclosure with large output power capability (max. 480 VA ~ 48 V × 10 A).

The MCSA480 is relevant for driving & control the motion of either 2 single axis MICA™ or dual axis magnetic actuators like Magnetic Fast Steering Mirror (M-FSM™) along large operating bandwidth (>100 Hz).

PARAMETER (j.1)	UNIT	MCSA480
General		
Function		All-in-one magnetic driver and controller
Number of control channels		2
Digital communication		RS422, Ethernet (optional), USB
Graphical User Interface		CTEC HDPM
Digital control		
Control strategy		Specific Control
Sampling rate	kSps	100
Digital resolution	bits	16
Analog inputs		
Number of analog inputs		4
Control input voltage (Vin+ - Vin-)	V	-10 ... +10
Output		
Output voltage range (*j.2*)	V	-48 ... +48
Permanent output current	A	±7
Power supply		
Supply voltage range	Vdc	24 ... 48
Power amplifier		
Number of channels		2
Protections		
Protections	Overcurrent (Actuator & Amplifier), Overtemperature (Amplifier), Reverse Polarity, Overvoltage (input), Undervoltage (input)	
Options		
Actuator cable	Specific length on request.	

Table 8.j: Characteristics of MCSA480

j.1 Guaranteed in labs environment
j.2 Limited by supply voltage.

LINEAR POWER AMPLIFIER FOR MAGNETIC ACTUATOR CMAμ10

The following linear amplifier is designed to drive inductive loads like magnetic actuators with extremely low noise. The new CMAμ10 is a compact and standalone unit specially designed for driving magnetic products such as MICA20CS actuators. The CMAμ10 includes a current closed-loop control and is ideal for driving small size actuators from CTEC and other actuators such as voice coils and moving magnet actuators, for linear or tilting motion.

Fig. 8.t: CMAμ10

PARAMETER (k.1)	UNIT	CMAM10
General		
Function		Driver for magnetic actuator
Number of channel		1
Input		
Control input voltage (Vin+ - Vin-)	V	-10 ... +10
Output		
Output voltage	V	±32
Permanent output current (*k.2*)	A	±0.5
Minimum output load	μH	100
External power supply		
DC main supply voltage	Vdc	24
DC Additional supply voltage	Vdc	±36
Power amplifier		
Max. continuous output apparent power (*k.2*)	VA	16
Max. continuous output active power	W	16
Gain		
Gain	A/V	0,05
Protections		
Protections	Current limitation, Overtemperature indicator	

Table 8.k: Characteristics of CMAμ10

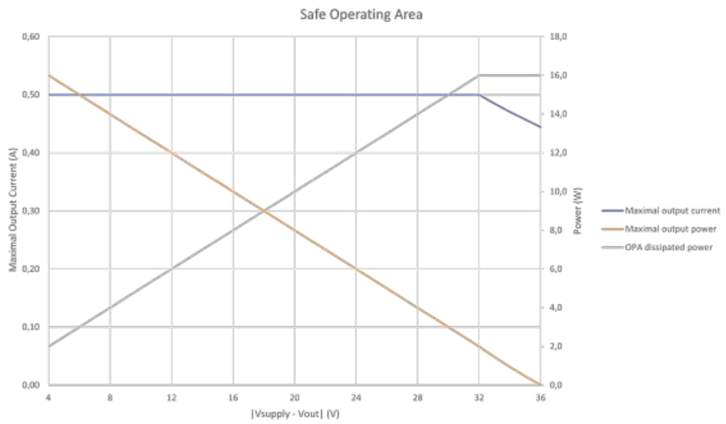


Fig. 8.u: CMAμ10 Operating Graph

k.1 Guaranteed in labs environment

k.2 Depending of the output voltage - See next graph

8.2.2. CUSTOMISED AMPLIFIERS & CONTROLLERS

POWERED CASE CONTROLLER

This powered case includes a DC/DC converter, a linear amplifier, a positioning sensor conditioner and a controller boards in order to control a moving coil based mechanism for high accuracy indent instrument.

Fig. 8.v: Powered case controller for driving moving coil mechanism

OEM COMPACT AMPLIFIER BOARD

This CLAu10 offers a compact linear amplifier board solution to drive magnetic actuators such as MICA™ or Moving Coil Actuators.

Fig. 8.x: OEM amplifier board for driving magnetic actuators

COMPACT SWITCHING AMPLIFIER CSA96

The Compact Switching Amplifier CSA96 is a compact size and large output power amplifier box for driving linear magnetic actuators like Moving Iron Controllable Actuator (MICA™). This CSA96 box is supplied by an External DC power supply up to 96 VDC.

Fig. 8.w: CSA96

8.3. CONTROLLER FOR PIEZO MOTORS

piezo motors always need the combination of a positioning sensor feedback and a controller to be used as accurate positioners or motion providers within mechatronic system. The piezo motor technology developed by CEDRAT TECHNOLOGIES (CTEC) is called Stepping Piezo Actuator (SPA).

8.3.1. CONTROLLER BOARD FOR STEPPING PIEZO ACTUATOR

the Stepping Piezo Controller SPC45 is a versatile, single channel controller board offering an off the shelves solution to control either the Linear Stepping Piezo Actuator LSPA30uXS or the Linear Stepping Piezo Stage LSPS35XS. The SPC45 controller board is included in the developer kit and provide the user with many features in terms of command & control options (step, position), digital or analog I/O connections as well as a user-friendly graphical interface to adjust the motor performances according to the system integration requirements.

Fig. 8.y: SPC45 piezo motor controller board

PARAMETER	UNIT	SPC45
General		
Function		All-in-one driver and controller for stepping piezo-motors and mechanisms
Number of control channels		1
Integated sensor conditioning [I.1]		Quadrature encoder interface
Digital communication		USB
Graphical User Interface (GUI)		CTEC IHM SPC45
Analog inputs		
Number of analog inputs		1
Analog inputs voltage range	V	0 ... 5
Analog outputs		
Number of analog outputs		1
Voltage range	V	0 ... 5
Piezo driver		
Number of channels		1
Nominal output voltage range	V	5 ... 96.5
Max output current	A	0,15
Power supply		
Supply voltage	Vdc	9 ... 24
Supply current	Arms	0.1 ... 0.56
Miscellaneous		
Mass	kg	0,11
Dimensions	mm	91 x 66 x 22

Table 8.I: Characteristics of SPC45

I.1 Sensor gain adjustable through GUI

8.3.2. CUSTOMISED CONTROLLERS FOR PIEZO MOTOR BASED MECHANISMS

Fig. 8.z: Controller box for 2 axis piezo motorised mechanism

Fig. 8.aa: Controller box for 3 axis piezo motorised mechanism

CTEC had already developed from customer specifications some piezo motor based mechanisms with several degrees of freedom requiring multi-channel and complex control features (see chapter §6.6. Customised piezo motor mechanisms, page 89). CTEC custom designed controller boxes in order to meet the functional requirements of the customer system.

Fig. 8.z shows a controller box to drive and to control simultaneously and independently 2 piezo motorised axes with submicron position repeatability & non colliding protocol.

Fig. 8.aa shows a controller box to drive a compact piezo motorised sample along 3 degrees of freedom with accurate tracking & flexibility in motion pattern follow up.

9. SENSORS & CONDITIONERS

9.1. SELECTION GUIDE

Positioning sensors available on the market can hardly keep pace with the accuracy requirements when scaling down the mechatronic system.

That is why CEDRAT TECHNOLOGIES (CTEC) has developed different kinds of sensors for answering to this problematic of accuracy requirements coming from its own compact mechatronic systems.

To monitor actuator displacement or implement a closed loop control, CTEC offers several solutions that allow the customer to build a system corresponding to its requirement.

Two kinds of sensor technologies are mainly integrated in CTEC products:

- **Strain Gauges (SG)** are contact sensors measuring the deformation of the piezo ceramics. They are a standard option in piezo actuators (APA®, MLA, PPA) and in some piezo mechanisms (TT, XY...).
- **Eddy Current Probes (ECP)** are contactless sensors measuring the distance between a probe and a target. They are an option for several types of APA® piezo actuators and in some piezo mechanisms (TT, DTT, XY). They can be used also with magnetic actuators.

A quick tutorial is presented in the § *«Sensor observability», page 58* helping the reader for selecting the well adapted solution. Sensor conditioning boards are available for these two types of sensors. They can be implemented in powered racks in combination with controllers and amplifier's boards to obtain a complete closed loop system.

Both technologies are further presented in §*»9.2. Strain Gauges & associated conditioners», page 146* and *«9.3. Eddy Current Sensors & associated conditioners», page 147*.

CTEC also integrates to its mechanisms other types of sensors from third party manufacturers, such as incremental magnetic sensors, optical encoders, accelerometers, capacitive sensors, end-of-stroke detectors, limit switch sensors, thermal sensors, etc. (see *«9.4. Customised sensors solutions», page 149*).

Independently from actuators and mechanisms, CTEC develops and manufactures non-contact inductive sensors for position measurement in the centimeter range as well as long range magnetic detection systems and acoustic piezo-based Structural Health Monitoring solutions (see *«9.4. Customised sensors solutions», page 149*).

Please contact CTEC by phone or email at actuator@cedrat-tec.com for more detailed information and help in the selection of your configuration.

9.2. STRAIN GAUGES & ASSOCIATED CONDITIONERS

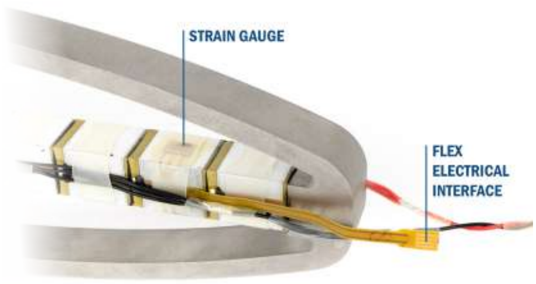


Fig. 9.a: Strain Gauge on MLA on an APA1000XL

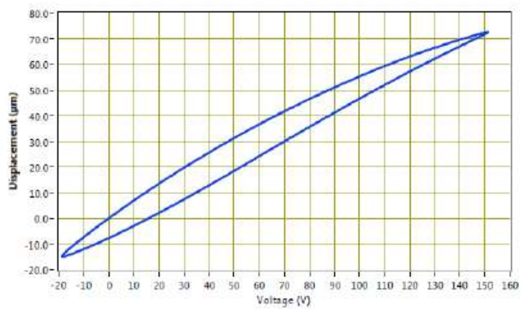


Fig. 9.b: APA60SM-SG stroke versus voltage in open loop

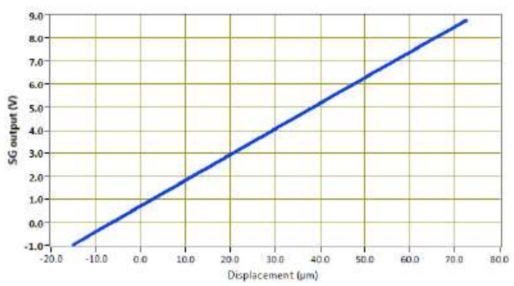


Fig. 9.c: SG output versus APA60SM-SG stroke in closed loop

Fig. 9.d: SG75

9.2.1. STRAIN GAUGE SENSORS

The Strain Gauge (SG) Sensor is a contact sensor which is bonded onto a proof body to in order to measure its deformation. In CEDRAT TECHNOLOGIES (CTEC) piezo actuators, the proof body is generally the Multi Layer Actuator MLA piezo ceramics, although for some cases the APA® shell can also be used as the proof body.

It allows to monitor the displacement of the actuator and to implement a closed loop control.

Measuring principle:

The SG transforms applied strain into a proportional change of resistance. The relationship between the applied strain ε $(\varepsilon = \Delta L / Lo)$ and the relative change of the resistance of a SG is described by the equation:

$$\frac{\Delta R}{R_0} = k.\varepsilon$$

where k is the gauge factor of the SG.

Coupled with a full wheatsone bridge, the induced small variation of resistance is conditionned in small voltage variation. Balanced configuration could be implemented in mechanism to improve the dynamic.

The SG sensor generates a linearisation which is well adapted for applications requiring good resolution and precision. These performances are given with the electronics in the next section (see *Fig. 9.b* and *Fig. 9.c*).

CTEC has performed a Space Qualification of its process of SG Sensor bonded on piezo MLA. This Space Qualification has established a high reliability and an excellent time stability of its SG for piezo actuator.

9.2.2. STRAIN GAUGES CONDITIONERS

The conditionning of the wheastone bridge amplifiies the output of the wheastone bridge with ultra low noise. These amplifiers could be find in the SG75 Strain gage conditioner SG75 or in the CCBµxx-SGxx product where the function is direclty implemented into the OEM product.

Up to date precision specifications (as regard linearity, drift, etc...) are given on the specific product (APA, PPA, XY, DTT...) datasheet on CTEC website.

9.3. EDDY CURRENT SENSORS & ASSOCIATED CONDITIONERS

9.3.1. EDDY CURRENT SENSOR PROBES ECP

Eddy Current Sensing (ECS) is a contactless proximity method for measuring the distance between a probe and a conductive target. As developed in the tutorial *chapter 2.4.3, page 56*, it proposes a better observability of the piezo movement when mounted in a specific arrangement: single or differential.

It requires:

- an Eddy Current Probe (ECP) placed in front of the Target. This probe is designed in regards of the actuator/mechanism.
- an ECS electronic conditioner, as the ECS45 or ECSF45.

The measuring principle is shown on *Fig. 9.e*: the ECP features an induction coil in which an alternating current is applied. It generates an oscillating magnetic field in the conductive target, inside which eddy currents are induced. These eddy currents generate an induced magnetic field the amplitude of which decreases with the distance between the target and the probe. This induced field is then detected by the ECP, giving a signal amplified by conditioner (see *chapter 9.3.2, page 148*).

From its long experience in magnetic devices design, Cedrat Technologies (CTEC) developed a unique ECP which is extremely compact, thanks to the direct integration of the inductive coil inside a PCB. This technology also takes benefit of space qualification, meaning performance and robustness.

The ECP is well adapted for distance measurement requiring higher resolution, high bandwidth and a contactless sensing area.

The ECP is able to sense sub-micron positions in sub-millimeter and millimeter ranges. High precision is obtained when combined with ECS conditioners.

For optimal performances, the target should be preferably made of nonmagnetic conductive materials such as aluminum. Stainless steel is another candidate but with less sensitivity.

Standards ECP are proposed in two versions with a different measurement range: 500 µm for the ECP500 and 1000 µm for the ECP1000. From these items, customized versions can be easily derived and added in mechanisms. CTEC could adapt ECP for specific volume with its proprietary pattern PCB.

From these items, customized versions can be easily derived and added in mechanisms. CTEC could adapt ECP for specific volume with its proprietary pattern PCB. High integration level could be reached to improve the observability of the movement

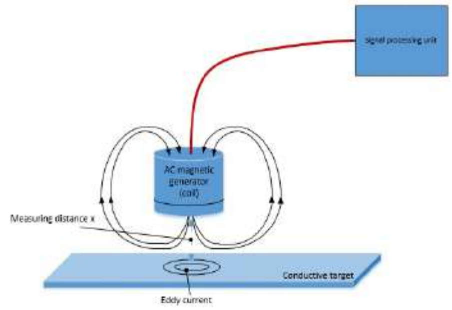


Fig. 9.e: Physical principle of an Eddy Current Sensor probe in front of a target

Fig. 9.f: ECP Probe

Fig. 9.g: TT60SM integrating an ECS sensor and conditioner electronics

Fig. 9.i: ECS45 standalone

Fig. 9.h: ECS25 along with its ESP probe

9.3.2. EDDY CURRENT PROBE CONDITIONERS ECS

CEDRAT TECHNOLOGIES' (CTEC) ECSxx electronics manage the signal from the ECP Eddy Current Probe to provide an information of the probe-to- target distance.

CTEC has developed proper solutions which are able to reduce the inherent thermal drift of such sensor while maintaining a very good resolution and a high accuracy and wide bandwidth.

Two standalone products were proposed:

- The ECS45. Advanced solution with thermal stabilisation
- The ECS25: Technology well adapted for embedded solutions in mechanism. Such conditioner proposes small footprint area which could be integrated in a PCB inside the mechanism.

The ECS45 (Fig. 9.i) is a standalone conditioner. It offers linearized sensing responses. High accuracy is achieved considering low linearity error and low thermal drift.

These electronics linearize the output from the ECP probe with a high order polynomial function programmed in a digital component. The gain of each channel is generally set when the Eddy Current Probe is embedded in the mechanism.

PARAMETER	UNIT	ECS45	ECS25
Status		Preliminary data	Preliminary data
Number of channels		2	1...4
Sensor type		CTEC Eddy Current Probe	
> Electrical characteristics			
Power supply	Vdc	15 +/- 5%	18...36
> Output			
Typical output voltage (a.1)	V	0...10	±10
Bandwidth -3dB (extended on request)	kHz	15	12
> Typical achieved accuracy			
Resolution (BW = 20kHz) (a.2)	% FS (a.3)	0.005	0.012
Linearity (a.4)	% FS (a.3)	±25	±0.2
Thermal drift (a.5)	% FS/ °C (a.3)	0.2	400
> Options			
Differential output (with two probes)		Yes	Yes
MCX to BNC cable		Yes	Yes

Table 9.a: Characteristics of Eddy Current Probe Conditioners ECS

a.1 Set to [-1V ; 7.5 V] on CTEC systems to be consistent with driver input - Could be adjusted with customer specification

a.2 BW: Bandwidth

a.3 FS: Full Scale

a.4 Better linearity can be achieved on request

a.5 Due to temperature change on the probe

9.4. CUSTOMISED SENSORS SOLUTIONS

9.4.1. CUSTOMISED SENSORS INTEGRATION

Besides the SG & ECS positioning sensor technologies described in the previous paragraphs, CEDRAT TECHNOLOGIES (CTEC) have been integrating other type of sensors available on the market inside its customised mechatronic systems for decades. This integration covers mechanical, electronic & control issues.

For instance, CTEC get used to integrate different type of magnetic or optical encoders (see Fig. 9.k) to provide customers with long range (Several mm) & accurate (micron or nano-meter) positioning control.

CTEC also integrates force, gyros, speed or accelerometer sensors (see Fig. 9.l) for various mechatronic functions such like active stabilization, tracking, damping, isolation or control of vibrations.

The selection of the sensor and the control strategy will be made according to the customer specifications and application (payload, mechanical structure, environmental and boarding conditions...).

In the frame of our detection systems' activities, CTEC also integrated various type of temperature and pressure sensors.

On top of this sensors' integration know-how, CTEC develops customised sensor and detection solutions, as shown in the following paragraph to answer to customer's specific needs.

Fig. 9.j: Linear magnetic encoder (hall effect sensor)

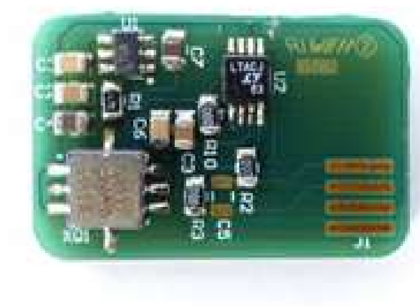


Fig. 9.k: Three axes accelerometer PCB mounted

9.4.2. CUSTOMISED MAGNETIC SENSORS & DETECTION SYSTEMS

Magnetic sensors offer potential for contactless detection techniques. These magnetic sensing technologies are recurrently exploited by CTEC to provide various innovative customized solutions, either as components or as complete systems.

Its Eddy Current Sensors products are used for high precision motion control on distance up to 3 mm. They are used in its actuators or for making customized force & torque sensors as well as top counter sensors.

In machine tool, force feedback systems are requested to measure forces exerted to the workpiece during the cutting operation. To meet this demand, a cost-effective Force Sensing Table with a diameter 100 mm and a height of 70 mm is capable of measuring forces in one direction only with a range of ±20 kN, a resolution of 12 N and accuracy of better than 50 N at 1 kHz.

Following the same approach, three axis force feedback table and Single axis force feedback tool holder are also developed.

Customized Robust & Cost effective Contactless Torque Sensors (CTS) have also been developed for automotive and aircraft. The concept is based on a patented torsion converter and an ECS-based proximity sensor. Different CTS can cover various torques from 1 to 500 N.m, with resolution of 0.1 %.

Fig. 9.l: MC-Suite force sensing table (See cedrat-technologies.com/technologies/engineering/collaborative-projects/)

Fig. 9.m: CTS Contactless Torque Sensor

Using its ECS technology, an accurate contactless top counter sensor has been space qualified for EUCLID-NISP Cryomechanism for CEA. This generates a precise top signal at each rotation with an angular repeatability under +/- 0.25° while operating at 20°K in vacuum.

Fig. 9.n: EUCLID-NISP top counter sensor and associated electronics

To offer cost-effective contactless solutions for tyre thickness measurements, 3 different inductive sensor types have been developed and patented in collaboration with MICHELIN MFP (see *Fig. 9.o*):

- HMP: Hall sensor and Magnet Position sensor
- PCI: Pot shape Coil Inductive sensor
- PCT: Planar shape Coil Transformer

They allows distance measurements up to 40 mm, with power as low as 0.3 mW, weight lower than 6 gr, resolution 0.1 mm.

Fig. 9.o: PCI inductive sensor for MICHELIN MFP

The LES1000 End Stroke Sensor aims to detect the presence of nearby objects without any physical contact, having a linear motion in distance, or closed to be linear. It is based on Eddy Current Sensor (ECS) technology from CTEC (see chapter 9, page xx). This sensor generates an AC magnetic field at high frequency and senses the behavior of the induced magnetic field in regards of a conductive target.

Fig. 9.p: LES1000 microswitch sensor

In the frame of ROXTAR medtec project, CTEC has developed an accurate Magnetic 6 DoF Alignment Localization & Tracking (MALT) system offering a detection range larger than 1 m.

The MALT system is based on 3 sub-systems:

- a magnetic fields emitter and placed on the X Ray emitter
- a sensor systems placed in the X Ray detector plate
- a PC with electronics and a Graphical User Interface (GUI)

Localization resolutions are 0.5mm in horizontal plane, 5 mm along vertical axis, and 0.1° in angle., within a latency of 300 ms.

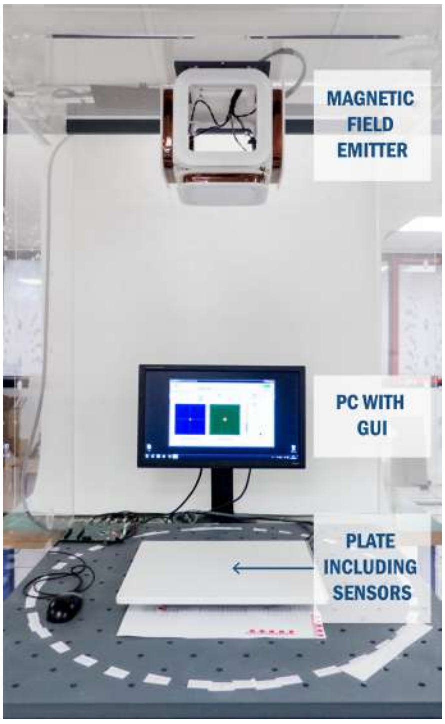


Fig. 9.q: 1 meter range MALT for ROXTAR

9.4.3. NON-DESTRUCTIVE TESTING (NDT) & STRUCTURAL HEALTH MONITORING (SHM)

Non-Destructive Testing (NDT) consists of sensing techniques for material, component or system without causing damage. Among them, Structural Health Monitoring (SHM) is an embedded NDT for detecting damages of a mechanical structure over time.

CEDRAT TECHNOLOGIES (CTEC) has an extensive experience in the field of piezo transducers, magnetic generators and sensors as well as their related electronics (driving, sensing, controlling), which served as a basis to develop powerful NDT or SHM-dedicated electronics solutions.

NDT activities at CTEC consists in developing various acoustic & electromagnetic techniques for dedicated needs, based on:

- Piezo actuators, transducers & sensors
- Strain gages on specific proof bodies
- Specific Eddy Current Sensors
- Reluctance magnetic sensors
- Direct magnetostriction effect (occurring when the magnetic properties are changed with mechanical stress)

These techniques applies on pipelines, ferromagnetic cables, on-line inspection of rolled steel manufacturing, weigh in motion (WIM), etc

One SHM technique developed by CTEC is to emit and receive ultrasonic waves with piezo-electrical transducers attached to the structure. The propagation of the wave is analyzed to evaluate the presence of damages inside the structure. This ultrasonic detection method is particularly appropriate to monitor health of large structures whose systematic inspections are mandatory but costly, such as aircrafts, spacecrafts, boats, bridges, cables, pipes, etc...

The proposed solutions consist in designing piezo patches, driving and sensing electronics, ranging from the pure analog rack to the fully programmable solution delivered with Graphical User Interface (GUI). According to the application, operating frequencies varies from 1 kHz to 1 MHz.

For example in *Fig. 9.r*, a LWDS45 board from CTEC is connected to two piezo patches. A patch is electrically excited to generate a pulse (see *Fig. 9.s*). Then the LWDS switches to a listening mode on both patches (pulse-echo technique). The detected signals are recorded, and compared to previous records. If signal changes are detected, it means a damage has appeared in the plate.

Fig. 9.t shows a 12 channels electronics for piezo patch excitations for SHM.

For more information on customised sensors' solutions, please see:

cedrat-technologies.com/categorie-produit/sensors/eddy-current-sensors-sensors/ and cedrat-technologies.com/technologies/sensors

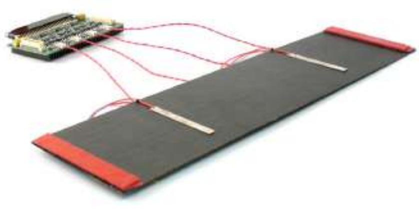


Fig. 9.r: Test bench for SHM : LWDS45 board connected to 2 piezo patches

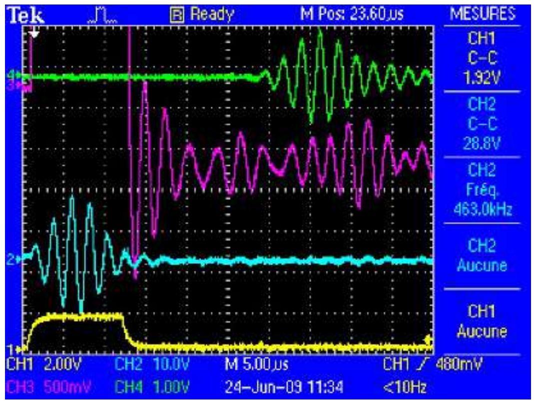
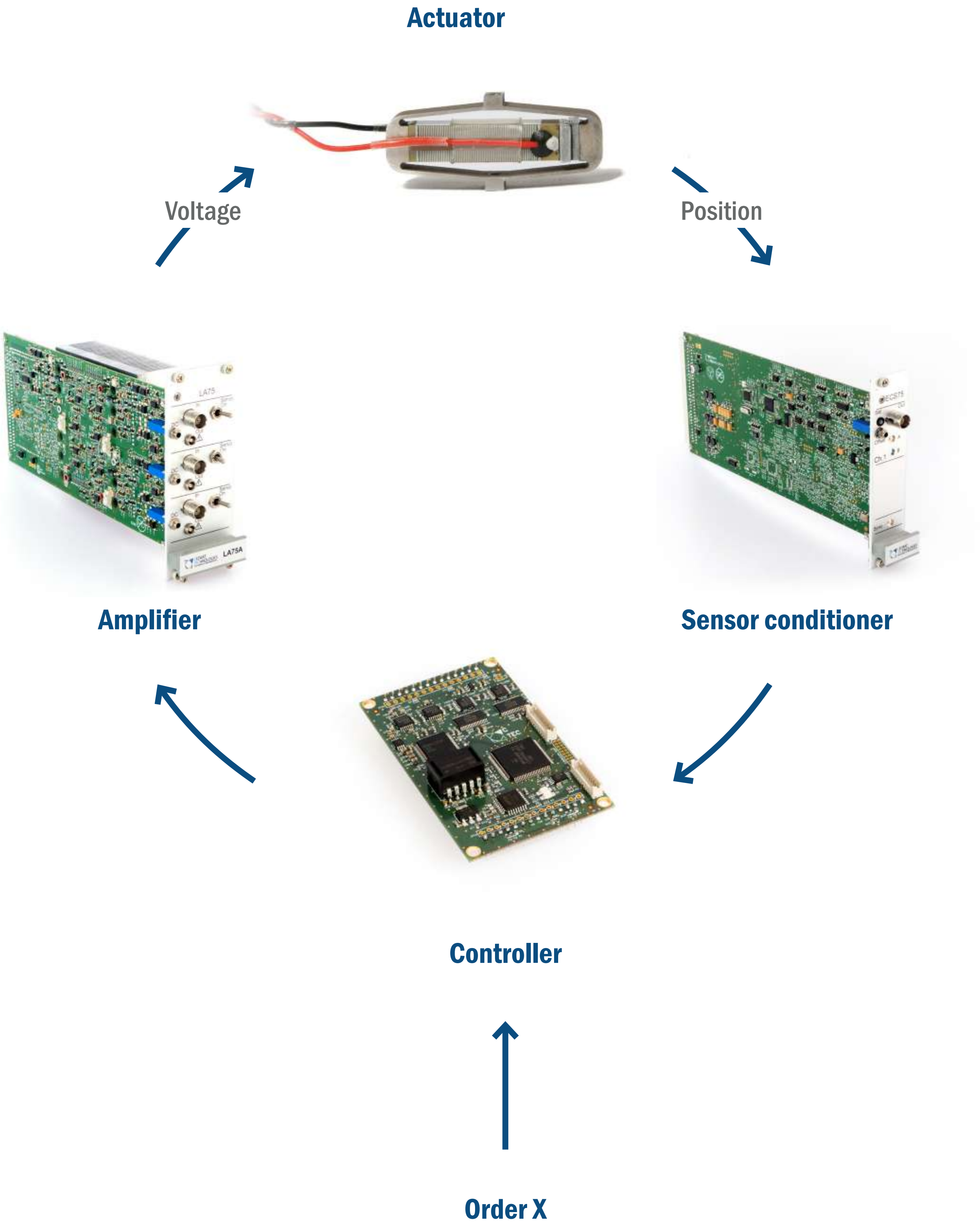


Fig. 9.s: Pulse-echo acoustic signals

Fig. 9.t: 12 channels emission piezo rack

Fig. 9.u: Generation unit


Actuator
Voltage
Position
Amplifier
Sensor conditioner
Controller
Order X

10. APPLICATION NOTES

10.1. YOUR OWN APPLICATION SELECTION GUIDE

CEDRAT TECHNOLOGIES (CTEC) can help you select the right combination of actuator and driver. Try to answer the following questions and share your specifications by email or by phone.

- Maximum **displacement** required for my application
- Required **bandwidth** (At which frequency do I want to drive the actuator ?)
- Required **actuation time**
- **Size** (What volume and dimensions are allowed for the actuator in my application ?)
- **Mass to be moved** by the actuator (What is the inertia ?)
- **Forces acting** on the actuator:
  - Spring loading (Is my actuator loaded by a spring? What is the spring's stiffness?)
  - Presence of other forces like gripping, viscosity, etc...?
- **Position sensor** (Do I need to monitor and/or control the motion/ the position?)
- Motion **resolution** required
- Motion **accuracy** required
- **Environment**:
  - Temperature range
  - Humidity
  - Vacuum
  - Vibration shock
  - Magnetic field compatibility

See Table 11.a and Table 11.b next page for electronic selection.

ELECTRONIC SERIE		CAU10	CCBU20	LA75A	LA75B	LA75C	SA75A	SA75B	SA75D
Continuous peak output current (mA)		5	200	90	360	2 400	5 000	10 000	20 000
Transient peak output current (mA)		-	-	300	1 100	8 000	-	-	-
ACTUATOR SERIE	**CAPACITANCE (µF)**	**CHARGING TIME @ 170 V (MILLISECONDS)** [A.1]							
MLA serie									
MLA 2×5×10	0.25	8.5	0.2	0.14	0.04	0.01	0.15	0.15	0.15
MLA 5×5×10	0.7	24	0.6	0.4	0.11	0.01	0.15	0.15	0.15
MLA 5×5×20	1.55	53	1.3	1.5	0.2	0.03	0.15	0.15	0.15
MLA 10×10×20	6.6	224	6	11.1	1.9	0.1	0.25	0.2	0.18
MLA 14×14×20	12	408	10	21.3	4.4	0.3	0.4	0.27	0.23
APA® serie									
APA - µXS	0.052	1.8	0.04	0.03	0.01	0.001	0.15	0.15	0.15
APA - XXS	0.15	5.1	0.1	0.09	0.02	0.003	0.15	0.15	0.15
APA - XS	0.25	8.5	0.2	0.1	0.04	0.01	0.15	0.15	0.15
APA - S, SM	1.55	53	1.3	1.5	0.2	0.03	0.15	0.15	0.15
APA - M	3.15	107	2.7	4.6	0.5	0.1	0.15	0.15	0.15
APA - MML	10	340	8.5	17.5	3.5	0.2	0.35	0.25	0.22
APA - ML	20	680	17	36.4	8.2	0.4	0.58	0.38	0.28
APA - L	40	1 360	34	74.2	17.7	1.4	1.2	0.67	0.42
APA - XL	110	3 740	94	206	50.7	6.4	4	1.83	0.88
PPA serie									
PPA10M	0.7	24	0.6	0.4	0.11	0.01	0.15	0.15	0.15
PPA20M	1.4	48	1.2	1.2	0.2	0.03	0.15	0.15	0.15
PPA40M	2.7	92	2.3	3.7	0.4	0.1	0.15	0.15	0.15
PPA40L	13.3	452	11	24	5	0.3	0.42	0.29	0.24
PPA60L	20	680	17	36	8.2	0.4	0.58	0.38	0.28
PPA80L	26.6	904	23	49	11	0.6	0.72	0.46	0.33
PPA40XL	24	816	20	44	10	0.5	0.67	0.43	0.31
PPA80XL	48	1 632	41	89	21	2.0	1.52	0.8	0.47
PPA120XL	72	2 448	61	135	33	3.7	2.48	1.2	0.63

Table a : Charging time comparison between drivers [a.2]

a.1 Values computed according to transient peak output current / See EPC application note
a.2 Warning these values are given for electrical limitation. Thermal and mechanical limitations of the actuator are not taken into account

ELECTRONIC SERIE		CAU10	CCBU20	LA75A	LA75B	LA75C	SA75A	SA75B	SA75D
Continuous peak output current (mA)		5	200	90	360	2 400	5 000	10 000	20 000
Transient peak output current (mA)		-	-	300	1 100	8 000	-	-	-
ACTUATOR SERIE	**CAPACITANCE (µF)**	**MAXIMUM FREQUENCY (SINUS) @ 170 VPP (HZ) (B.1)**							
› MLA series									
MLA 2×5×10	0.25	40	300	670	2 700	17 980	- (b.2)	- (b.2)	- (b.2)
MLA 5×5×10	0.7	10	110	240	960	6 420	- (b.2)	- (b.2)	- (b.2)
MLA 5×5×20	1.55	10	50	110	430	2 900	- (b.2)	- (b.2)	- (b.2)
MLA 10×10×20	6.6	1.4	10	26	100	680	1 420	2 840	- (b.2)
MLA 14×14×20	12	0.8	10	14	56	370	780	1 560	3 120
› APA® serie									
APA - µXS	0.052	180	1440	3 240	12 960	- (b.2)	- (b.2)	- (b.2)	- (b.2)
APA - XXS	0.15	62	500	1 120	4 490	29 960	- (b.2)	- (b.2)	- (b.2)
APA - XS	0.25	37	300	670	2 700	17 980	- (b.2)	- (b.2)	- (b.2)
APA - S, SM	1.55	6	50	110	430	2 900	- (b.2)	- (b.2)	- (b.2)
APA - M	3.15	3	20	53	210	1 430	2 970	- (b.2)	- (b.2)
APA - MML	10	1	10	17	67	450	940	1 870	3 740
APA - ML	20	0.5	4	8	34	220	470	940	1 870
APA - L	40	0.2	2	4.2	17	110	230	470	940
APA - XL	110	0.1	1	1.5	6	40	90	170	340
› PPA serie									
PPA10M	0.7	10	110	240	960	6 420	- (b.2)	- (b.2)	- (b.2)
PPA20M	1.4	10	50	120	480	3 210	- (b.2)	- (b.2)	- (b.2)
PPA40M	2.7	3	30	60	250	1 660	3 470	- (b.2)	- (b.2)
PPA40L	13.3	1	10	13	51	340	700	1 410	2 820
PPA60L	20	0.5	4	8	34	220	470	940	1 870
PPA80L	26.6	0.4	3	6	25	170	350	700	1 410
PPA40XL	24	0.4	3	7	28	190	390	780	1 560
PPA80XL	48	0.2	2	3.5	14	90	200	390	780
PPA120XL	72	0.1	1	2.3	9	60	130	260	520

Table b : Maximum frequency comparison between drivers (b.3)

b.1 Values computed according to continuous peak output current

b.2 Please contact CTEC for this configuration

b.3 Warning these values are given for electrical limitation. Thermal and mechanical limitations of the actuator are not taken into account

10.2. BUILDING A GENERAL PIEZOELECTRIC ACTUATOR MODEL

The principal task before controlling a piezo actuator is to build a model integrating the parameters of the actuator from the catalogue. This model allows the tuning of the controller's parameters in advanced processes or for an optimal control. Several parameters are given inside and recalled below:

- **Stroke**: ΔU (m).
- **Voltage**: V (V), output voltage provided by the electronic amplifier on the piezo actuator.
- **Voltage**: V_{max} (V) maximal voltage applied on the piezo actuator to reach the maximal stroke.
- **Blocked force**: F_0 (N), maximum force generated by the actuator with no displacement at maximum voltage V_{max}
- **Force factor**: N (N/V), force per voltage unit:

$$N = \frac{F_0}{V_{max}}$$

- **Stiffness**: K (N/m), displacement ΔU under an applied force F:

$$K = \frac{F_0}{\Delta U_0}$$

Elasticity is the opposite of stiffness:

$$c_m = \frac{1}{K}$$

C_m can be seen as equivalent capacitance in the motional equivalent circuit.

- **Effective Mass**: $M+m$ (Kg) actuator mass plus additional embedded mass
- **Resonant frequency**: f_r (Hz) first mode computed with the stiffness and effective mass:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K}{M+m}}$$

- **Quality factor**: Q indicates a rate of energy dissipation relative to the oscillation frequency:

$$Q_m = \frac{1}{2\pi\ f_r c_m r_m}$$

r_m is the resistance in the motional equivalent circuit. The quality factor of piezo actuators depends on signal amplitude and boundary condition and then can vary from 20 to higher than 100.

From these parameters and as the actuator is driven in voltage the transfer function of this continuous plant can be written:

$$TF(j\omega) = \frac{\Delta U}{V} = \frac{N c_m}{(1 + j\omega r_m c_m - \omega^2 c_m (M+m))}$$

The generic model is a second order filter with high quality factor. When multi mode mechanisms are used, the plant must contain each mode built with the same formulae. Of course, this model is a rough model excluding the nonlinearities of the piezo actuator such as the hysteresis, the creep effect and other non linear effects. Nevertheless, this model can be used to design the control loop.

10.3. EPC: ENHANCED PEAK CURRENT

in the upgraded PLa25 product (see *chapter 8.1.2, page 128*), a new function called Enhanced Peak Current is added to fast charge actuators actuators.

An enhanced peak current capability for PlaXX series allows faster actuator charging thanks to a larger output current during a limited time. This feature increases the power bandwidth as well for low repetition rate signals.

A piezo charge is like a capacitor. Due to this behavior driving at large frequency demands large currents from the specific driver:

$$I_{piezo}(t) = C_{piezo} \times \frac{dV(t)}{dt}$$

CTEC has developed a solution able to provide more current during short time to respond to this problematic. A dedicated Application Note is proposed to understand the details of the behavior of such electronic capability in regards of your need.

See application note on Enhanced peak current for linear amplifiers:

cedrat-technologies.com/downloads/user-manuals/

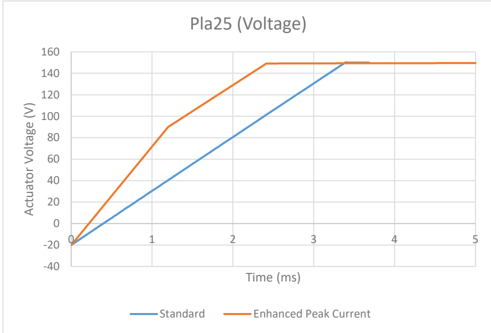


Fig. 10.a: Actuator's voltage with and without peak current capability

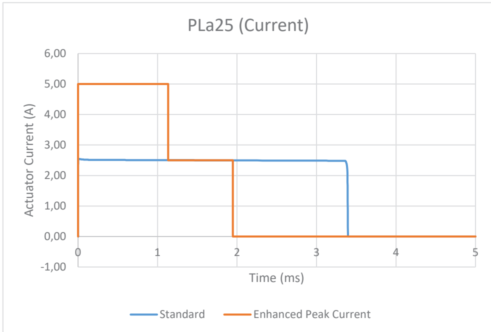


Fig. 10.b: Actuator's current with and without peak current capability

10.4. CURRENT IN PUSH-PULL MODE

In push-pull configuration, actuators work in a complementary motion. The electrical principle of the push-pull motion is given in chapter *«Push-pull mode», page 27.*

Push-pull actuators are driven with complementary voltages, so that they can be attached to the same load: when one actuator is pushing, the other one is pulling, the idle voltage being 65V.

In such a mode, each actuator sees the same voltage range (-20V to 150V), as if it was driven alone.

The equations on the right demonstrate that in push pull mode, the total actuators' capacitance is the sum of each actuator's capacitance.

By using 2 similar actuators with a capacitance "C", the total capacitance becomes "2C" (see equation 5). This means the required current is doubled (see *chapter 2.1.9, page 26*).

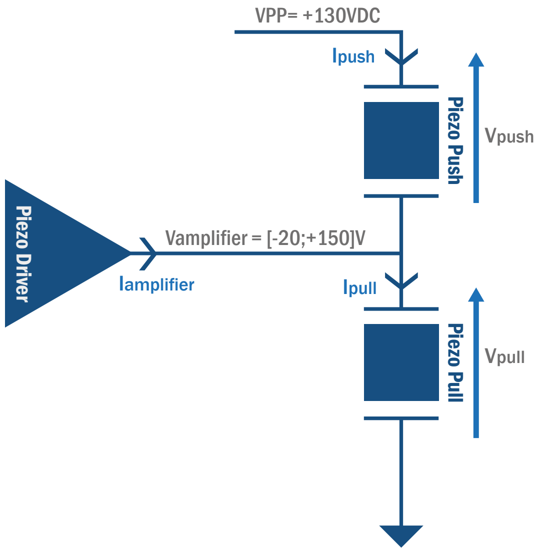


Fig. 10.c: Push-pull operation using one electric driver

$$I_{pull} = I_{push} + I_{amplifier} \ (1) \qquad I_{push} = C\frac{dV_{push}}{dt} \ (3)$$

$$V_{push} + V_{pull} = VPP \ (2) \qquad I_{pull} = C\frac{dV_{pull}}{dt} \ (4)$$

$$I_{amplifier} = I_{pull} - I_{push} \ (1)$$

$$I_{amplifier} = C\frac{dV_{pull}}{dt} - C\frac{dV_{push}}{dt} \ (1)(3)(4)$$

$$I_{amplifier} = 2C\frac{dV_{pull}}{dt} \ (5)$$

CEDRAT TECHNOLOGIES S.A.S. - Meylan, France.

CEDRAT TECHNOLOGIES (CTEC) offers off-the-shelf mechatronics products including piezoelectric & magnetic actuators, motors, mechanisms, transducers and sensors with corresponding drivers & controllers. These mechatronics products are used for scientific and industrial applications requiring fonctions such as: micro and nano positioning, generation of vibrations, micro-scanning, fast & precise motion control, active control of vibrations, and energy harvesting...

Most of the products are available in OEM versions for low cost and high volume industrial applications. CTEC also offers services including, design, R&D under contract and training.

CTEC is a SME located in Meylan, Inovallée, the French Innovation Valley near Grenoble. CTEC is recognised as a highly innovative company and has received several awards.

CEDRAT TECHNOLOGIES

59 Chemin du Vieux Chêne - Inovallée
38246 Meylan Cedex

+33 (0)4 56 58 04 00
www.cedrat-technologies.com
actuator@cedrat-tec.com

CEDRAT TECHNOLOGIES
Innovation in Mechatronics