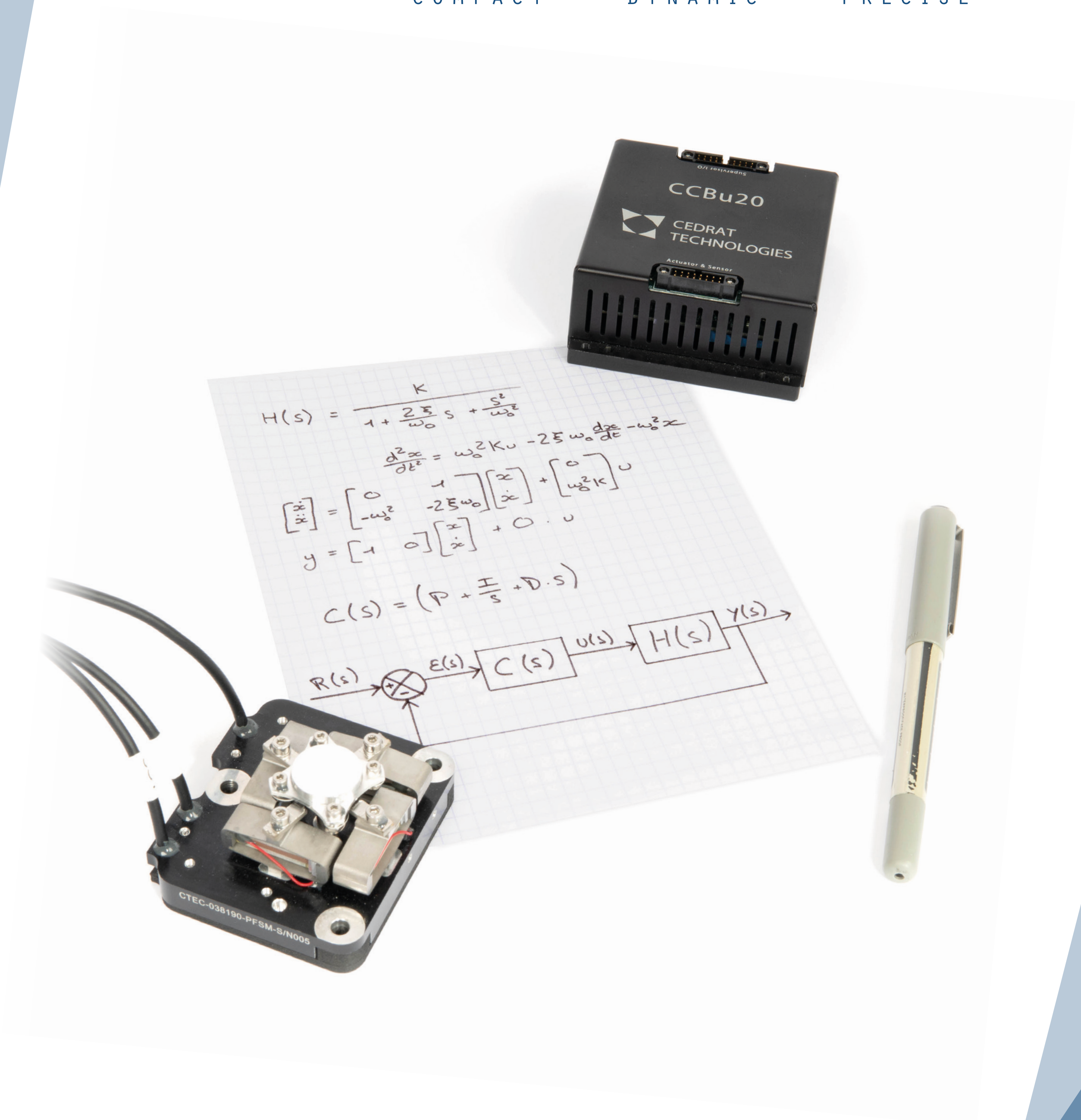
ADVANCED CONTROL FOR

MECHATRONIC APPLICATIONS

COMPACT - DYNAMIC - PRECISE



CEDRAT TECHNOLOGIES
Innovation in Mechatronics

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CEDRAT TECHNOLOGIES ADVANCED CONTROL FOR MECHATRONIC APPLICATIONS

The objective of this document is to briefly present the definition, the achievement, the key parts & laws as well as the setup at Cedrat Technologies (CTEC) to perform advanced control of its piezo & magnetic actuators.

From any fixed actuator mechanical design & characteristics, the dynamic performances will mainly rely on both the driver and the controller performances. The driver is responsible for providing the required output electric power to the actuator and the controller for providing the best actuator response with respect to a signal input order. At CTEC, the driver and the controller parts are always combined in the same single box or rack and named “The controller”. The controller is based on microprocessor hardware with implemented digital control laws to allow fast, accurate and reliable computations.

1. GLOSSARY

Before providing with performances in advanced control, it is important to go through the basic lexical field and to define the vocabulary used in control engineering.

- Resolution: the smallest displacement achievable
- Accuracy: static and dynamic, the accuracy can be seen as the total budget of error between the response and the order considering the full operating and environmental conditions.
- Precision: Precision is the ability of a system to reproduce the same response with respect to an identical series of orders in given operating and environmental conditions, covering both repeatability and reproductibility. The figures A & B below shows the difference between Accuracy and Precision

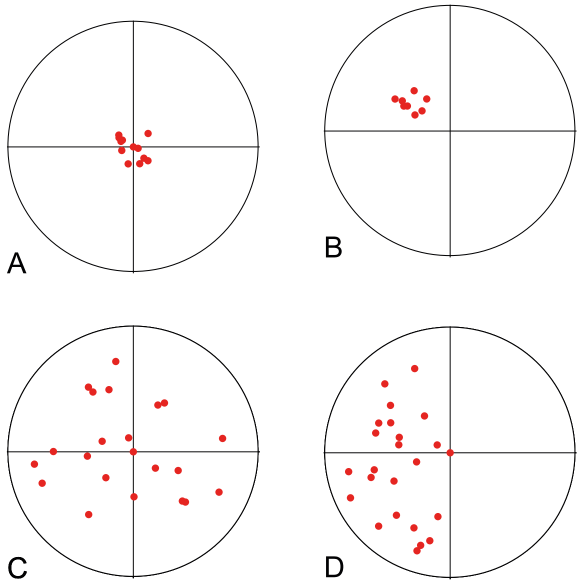


Fig. 1 : Definition of terms: A : precise and accurate ; B : Precise but not accurate ; C : Accurate but not precise (average is centered); D : Not accurate and not precise

- Position stability: Ability of the control loop to converge to a finite value given a finite command with respect to a certain time period
- Gain and phase margin : parameters which describe the ability of the closed to be stable. The gain /phase margin is currently defined as the amount of gain and phase in change in open loop needed to make the closed unstable. +3dB and 45° is considered as acceptable.
- PID: Proportional Integral Derivative scheme; Control strategy using a feedback measure of the useful quantity.

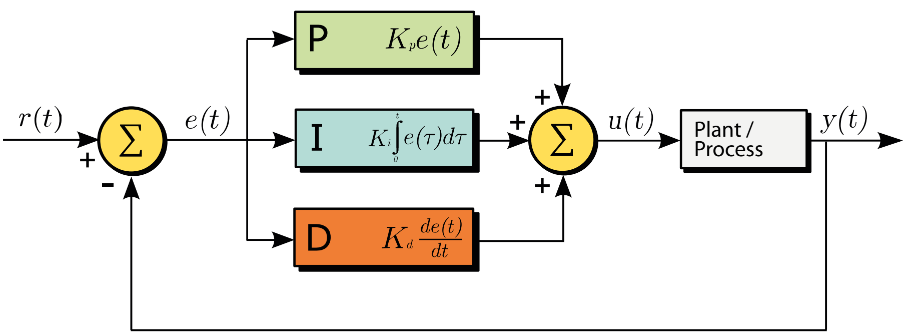


Fig. 2 : Diagram of a PID control scheme

2. DEFINITION OF CONTROL PERFORMANCES

The role of a controller is to reduce the error of an actuator response vs an input order for a given application.

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
Application	Fig. 14a	Fig. 12 Fig. 14b	Fig. 13 Fig. 15 Fig. 16	Fig. 19 Fig. 21

Table a : Analysed parameters in regards of the application

2.1. CLOSED-LOOP PERFORMANCES

The performance of a closed-loop controlled system is defined according to several indicators:

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

Those parameters are illustrated below.

The bandwidth and the rising/settling time are intimately linked. The largest the bandwidth the smallest the rising/settling time.

2.2. RISING TIME/SETTLING TIME/OVERSHOOT/DELAY TIME

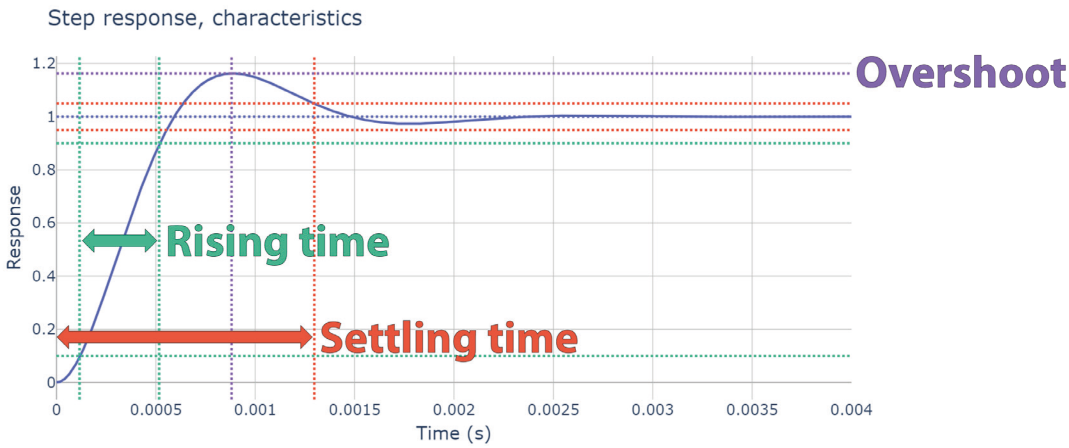


Fig. 3 : Step response and associated parameters

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 (or falling) time is the time needed for the system to go from 10% to 90% of its final value.

2.3. CLOSED-LOOP BANDWIDTH AND FLATNESS/DELAY

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

The cutoff frequency is the frequency where the gain loop crosses 0.707 (assuming the static gain of the sensor vs the reference $\frac{y(t)}{r(t)}$ is equal to 1)

The flatness is the maximum frequency such as the gain stays in a +/-x% band around 1 below this frequency.

The delay or phase which represents the delay between the command and the position.

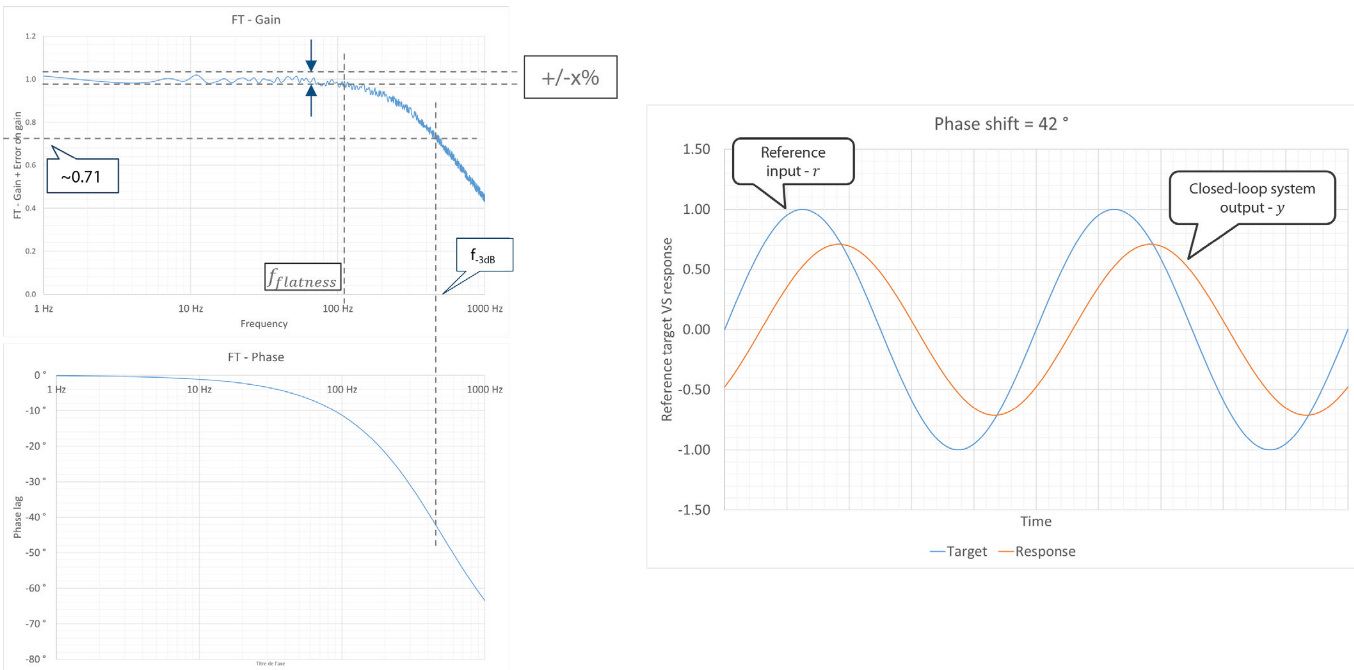


Fig. 4 : Control loop bandwidth , flatness and delay

2.4. DEFINITION OF ERRORS

The definition of the accuracy could be seen as the total error budget as several types of error can be identified in a dedicated application.

The error is defined between the reference requested by the operator r and the output of the closed-loop system y.

The error can be defined in several ways. The following paragraphs distinguish between the main approaches (in amplitude and in phase).

For instance, the "combined error" includes the amplitude error and the phase error addressed in dynamic applications to define the trajectory of the motion.

In practice, it is the combination of the different errors that gives the overall accuracy of the appropriate Closed-Loop strategy.

However, it is important to distinguish the relative influences of each of these parameters to prioritize the effort required for the improvements deemed relevant.

2.5. COMBINED ERROR

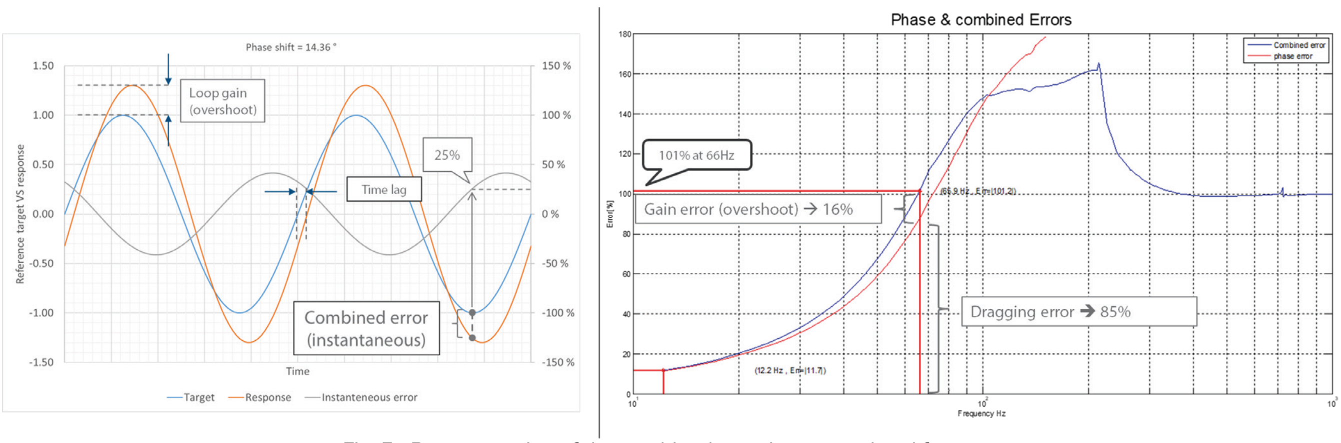


Fig. 5 : Representation of the combined error in temporal and frequency

2.6. CROSS COUPLING

Axes cross coupling is an important parameter which defines the error generated by one active axis on the other passive axes.

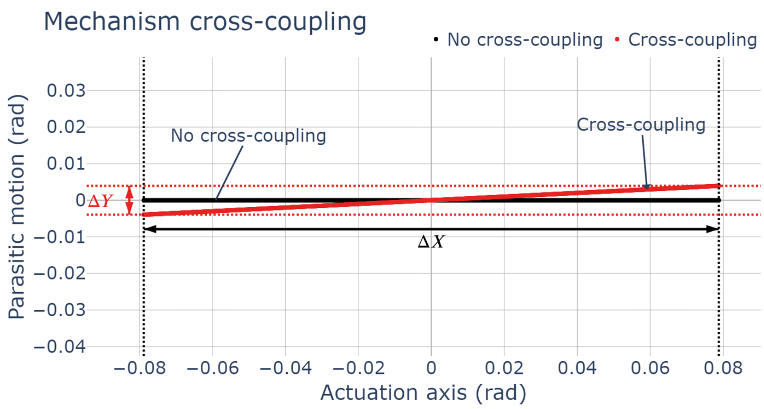


Fig. 6 : Representation of the Axe cross coupling

The cross-coupling is defined as the ratio $\frac{\Delta Y}{\Delta X}$.

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

CTEC digital controllers are characterised with their capability to compute in a few microseconds the designed control law for several channels. Additionally, they are more versatile and allow calibration, look up table correction, 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.

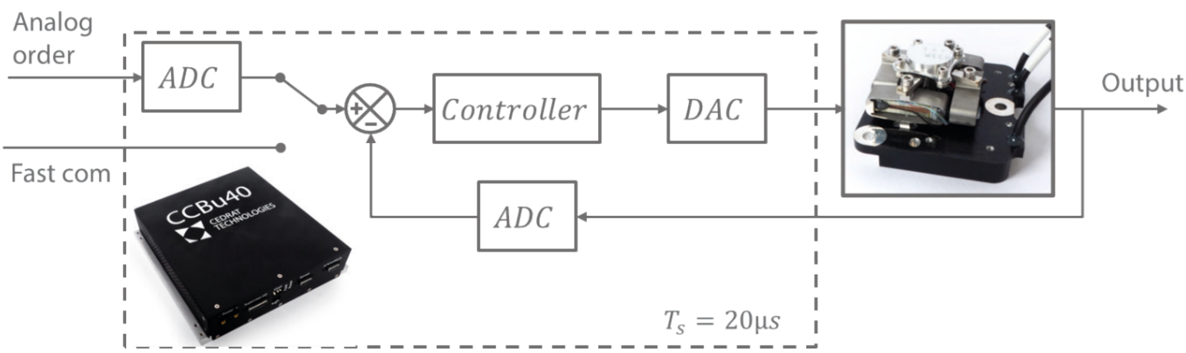


Fig. 7 : Synoptic of numeric control processing from CCBu40 for piezo mechanism P-FSM150S-SG

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

As a matter of fact, USB/ Ethernet communications are not deterministic and cannot be used to send position commands or read real time sensor sensors.

Nevertheless, serial communication protocols like RS422 and SPI are deterministic and can be used to write and to read data at different speeds.

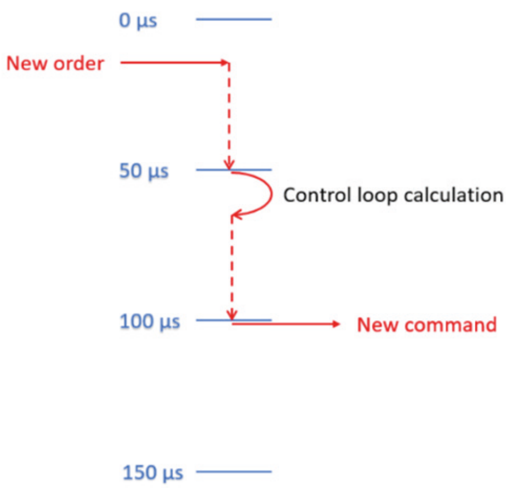


Fig. 8 : Deterministic control computation and associated delay

This delay could be added in the global performance of control (i.e. the faster, the better).

3.1. CONTROL IN OPEN LOOP : FLATNESS-BASED TRAJECTORY PRESHAPING + HARMONIC PRESHAPING

Control loop is often associated with closed loop. In some cases, open loop is sufficient to improve some categories of non-linearities (hysteresis excluded) or reduce excitation level of resonant frequencies. This kind of open loop control is particularly relevant for periodic signals. Obvious advantage of open loop control is the absence of numerical control, leading to a reduced cost compared to a close loop.

HARMONIC PRESHAPING

This technique relies on an iterative optimization in the frequency domain. The input signal of the actuator is optimized to decrease the unwanted harmonics in the output motion generated by the actuator.

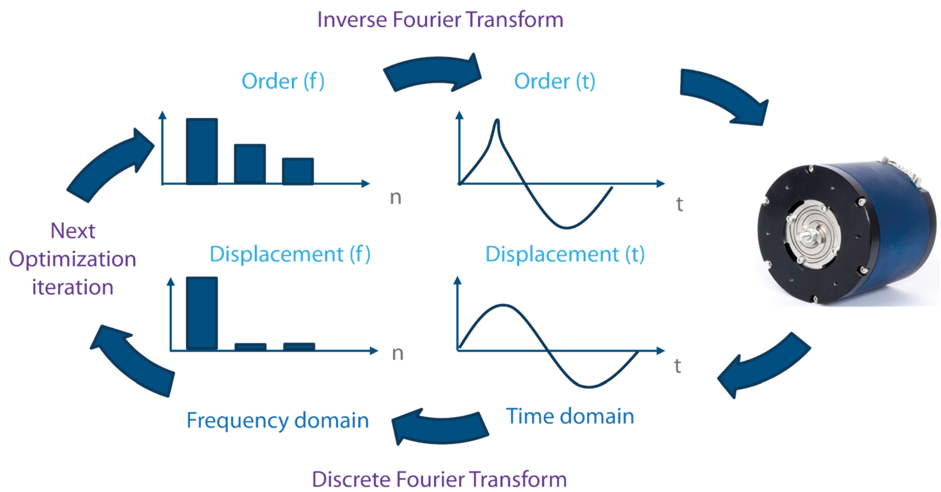


Fig. 9 : Harmonic preshaping representation for a MICA300CM actuator

In the following example, the order Fourier series have been enriched with higher harmonics to obtain a sinusoidal displacement of the actuator.

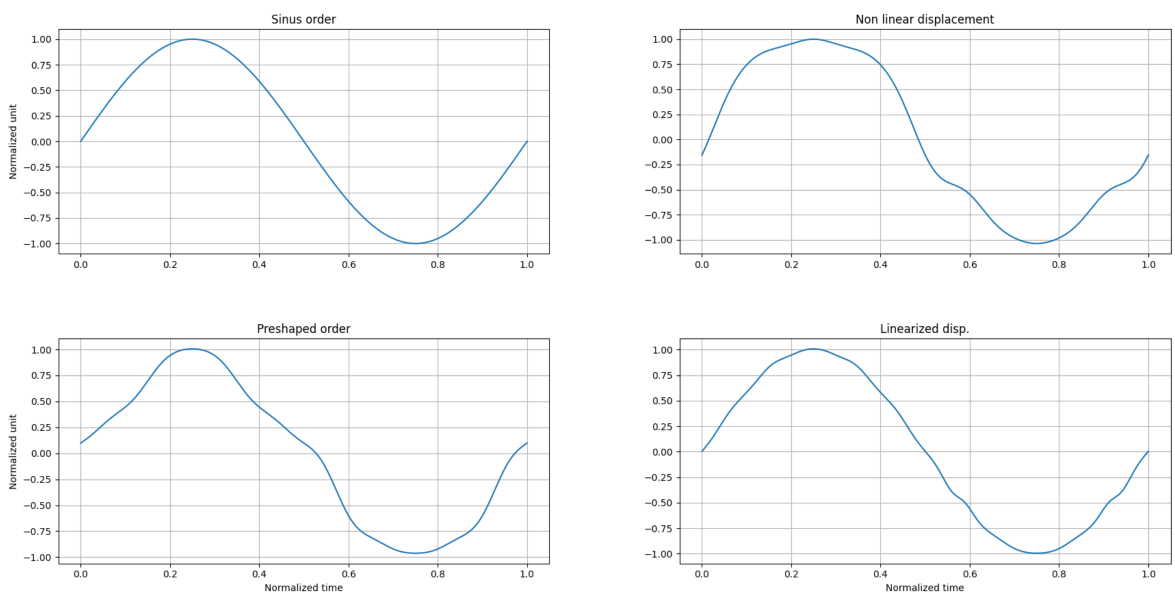


Fig. 10 : Normalized results on MICA300CM device

TRAJECTORY PRESHAPING

To avoid ringing on a fast step response due to large Q factor at the actuator resonant frequency, CTEC develops specific trajectory command able to reduce the overshoot.

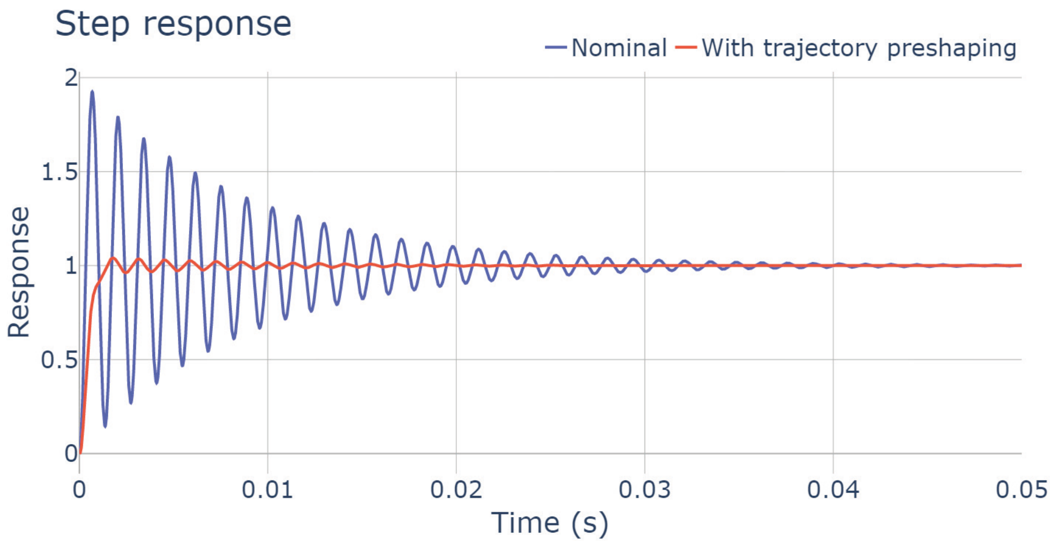


Fig. 11 : Comparison of step response in open loop without and with trajectory preshaper

Applications:

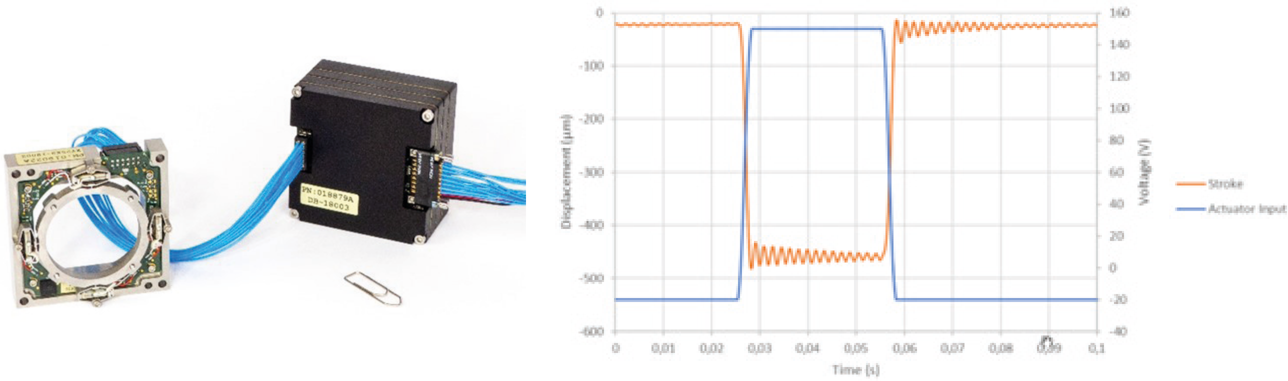


Fig. 12 : Example of trajectory preshaping for microscanning with XY piezo stage

3.2. PID CONTROL

In most of the cases, the previous open loop preshaping solutions do not have sufficient robustness & efficiency to reach the ultimate & required accuracy. In those cases, a closed loop control shall then be implemented.

At first, CTEC provides control laws based on PID regulator& filters (such as low pass or Notch filters) with the following advantages:

- Versality of the control law built around the standard industrial PID controller
- Easy adjustment by the customer of different parameters depending on its application.

This approach is effective as long as the control bandwidth remains significantly below the resonant frequency of the system.

In fact, the principle of these controllers relies on the suppression of the resonant frequency with notch filters.

These filters reduce drastically the peak gains due to natural frequencies over the frequency range, and therefore avoid overshoot for low frequency bandwidth (*Fig. 13a*).

However, an overshoot can arise when the frequency bandwidth of the control loop approaches the natural frequency of the system. In this situation, the controller cannot help for stabilizing the mode and it can induce a significant overshoot (*Fig. 13b*).

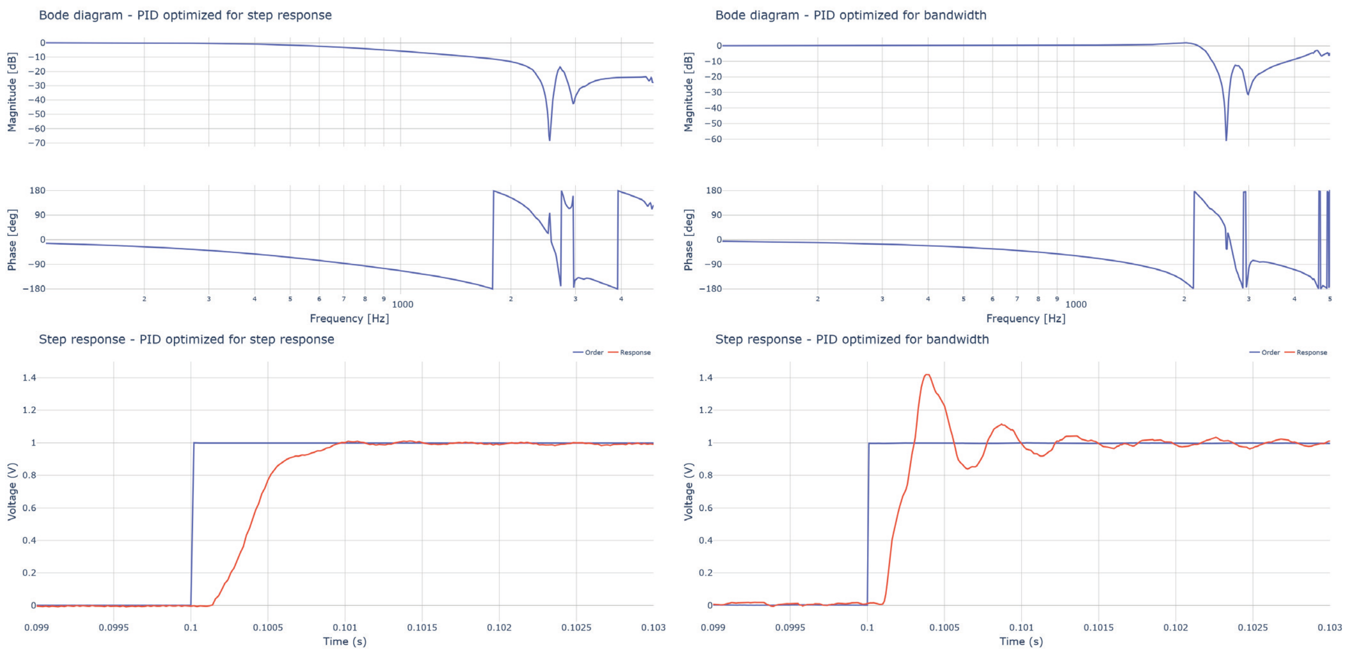


Fig. 13 : Improvement of the PID terms on the global closed loop bandwidth: a- optimised for step response: low overshoot response , b- optimised for bandwidth

Typical Applications:

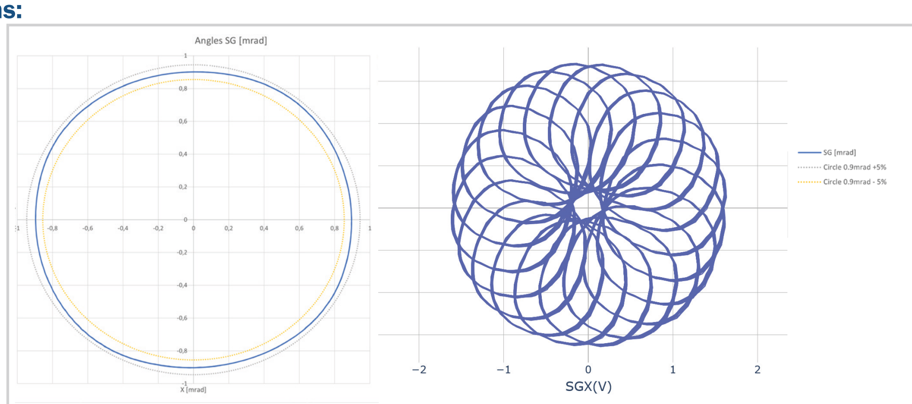


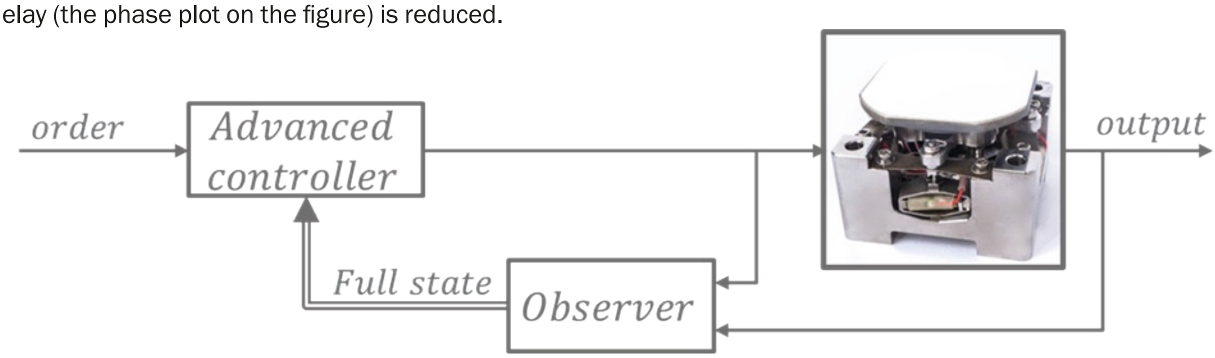
Fig. 14 : Fast Steering Mirror applications: optimised for large bandwidth a-circular dynamic pattern, b-Scanning mode Rose type pattern

3.3. ADVANCED CONTROL USING FULL STATE FEEDBACK

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 and the system response time is shorter. A comparison between such advanced control and standard PID is given in the next figure. The trajectory is improved because the delay (the phase plot on the figure) is reduced.



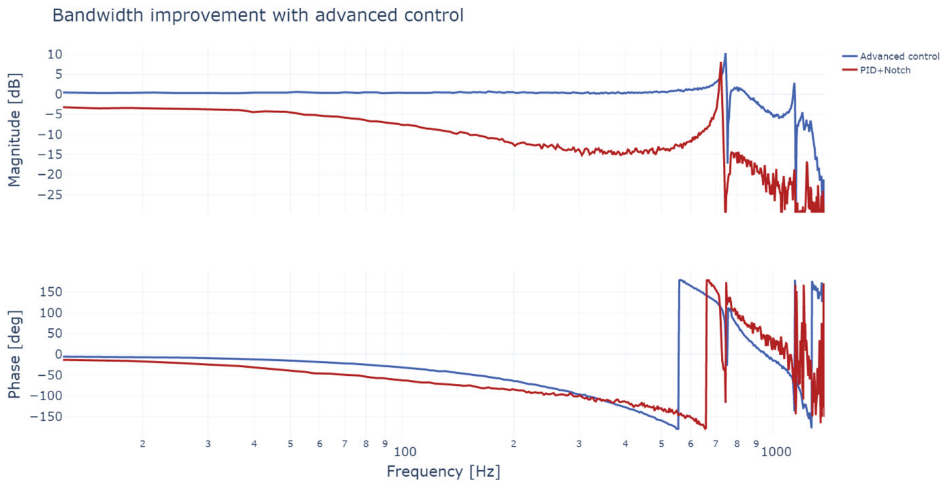


Fig. 15 : Comparison between standard PID + Notch and advanced full state feedback controls

Application:

Improvement of dynamic precision with advanced control versus PID is also clearly visible on the fast sawtooth of a FSM scanning function (*Fig. 16*).

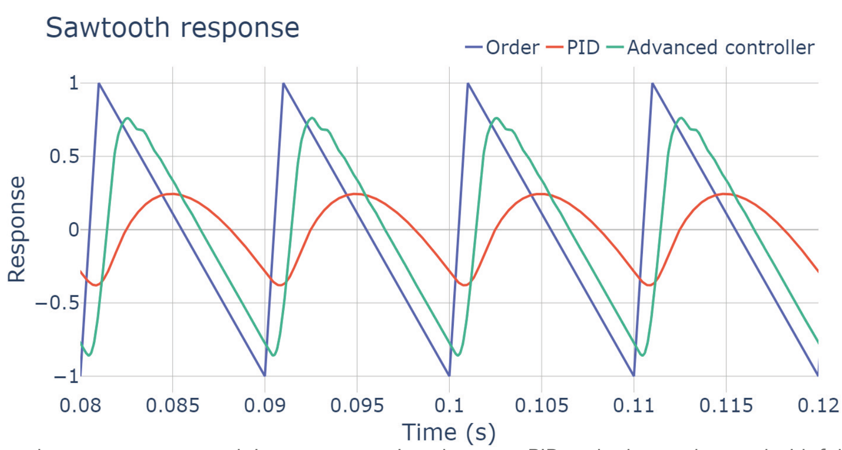


Fig. 16 : Temporal response to sawtooth input – comparison between PID and advanced control with full state feedback

3.4. REJECTION OF VIBRATION

Vibration rejection is a key element for many industrial applications (machining, imaging , etc....)

CTEC mechanisms (such as Fast Steering Mirrors) are integrated into observation & optical communication satellites where pointing accuracy is a fundamental requirement.

Active vibration rejection in the closed loop control is a key capability to achieve this pointing accuracy requirement, as the spectrum of perturbation frequencies can be broad or variable over time.

In the machining industry, especially for cutting process, where vibrations at the tip of the cutter degrade the surface finish of the machined part, active vibration rejection allows for better surface finish and better machining accuracy.

VIBRATIONS DAMPING WITH ACTIVE PROOF MASS :

This control strategy consists in dissipating the energy introduced in the structure (M) by the unknown disturbance (F_{dist}).

The active proof-mass is fixed in a Skyhook configuration to the structure (M) and generates actuation allowing efficient vibration rejection.

The control law is designed in order to achieve $\frac{\ddot{x}_M}{F_{dist.}} \approx 0$

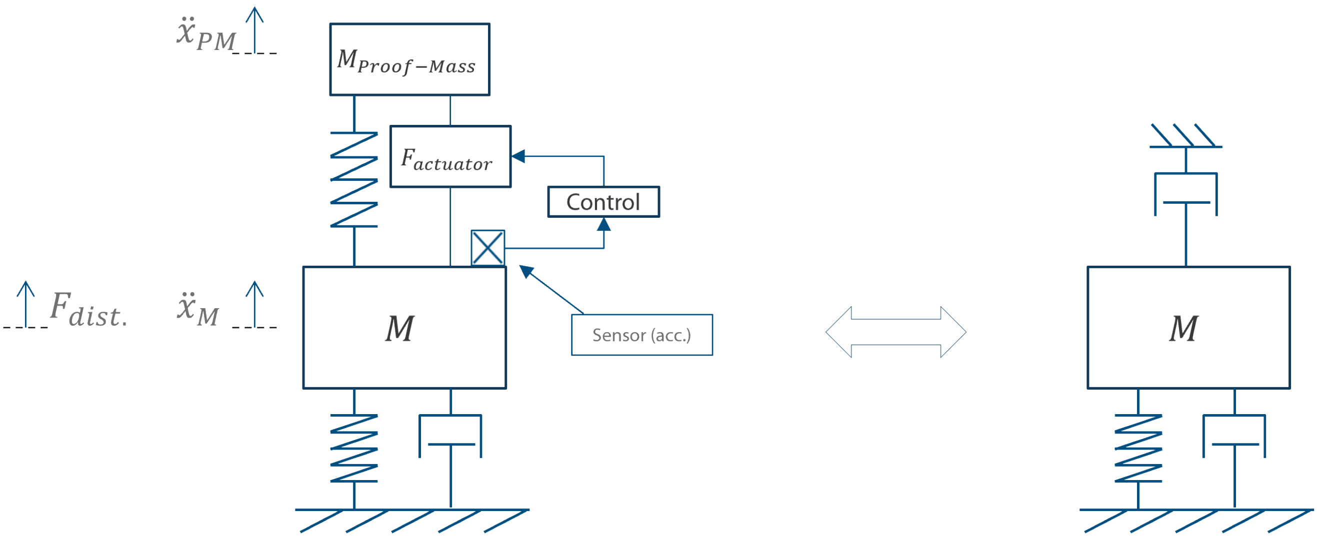


Fig. 17 : Principle of an active proof mass for damping structure i.e. Sky hook damper

Proof Mass damping application:

An active proof mass damper application in two directions is represented hereafter for a boring bar based machining process. CTEC has developed specific actuators coupled with embedded accelerometers as well as a specific control laws.

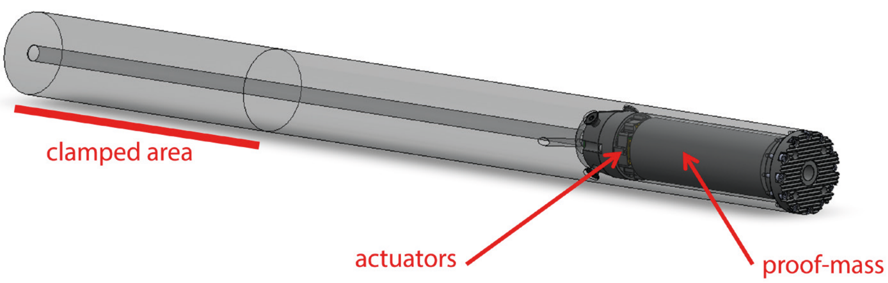


Fig. 18 : Boring bar equipped with 2 internal axes Proof mass damper

The response of the boring bar to a hammer impact is plotted on the next figure. The damping of oscillations vs time is significantly higher with active proof mass than without.

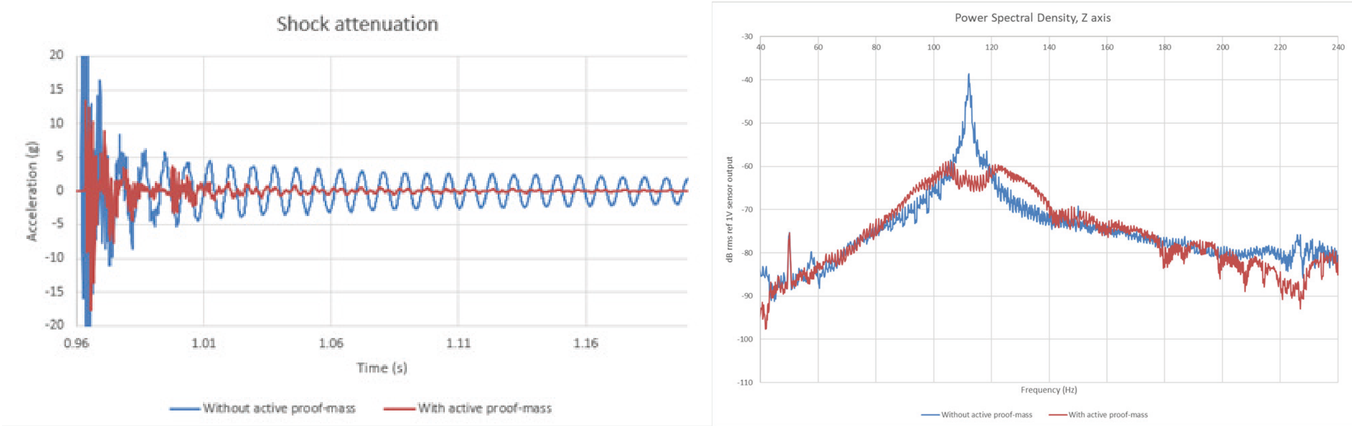


Fig. 19 : Response of Active proof mass damping in boring bar: a- transient and b-frequential

ACTIVE ISOLATION

Active vibration isolation consists in dissipating the energy introduced in the structure (M) by the unknown disturbance coming from a moving support $\ddot{x}_{dist}$.

The actuation allows efficient vibration rejection without the need to clamp the actuator to an external support.

The control is designed in order to achieve $\frac{\ddot{x}_M}{\ddot{x}_{dist.}} \approx \mathbf{0}$.

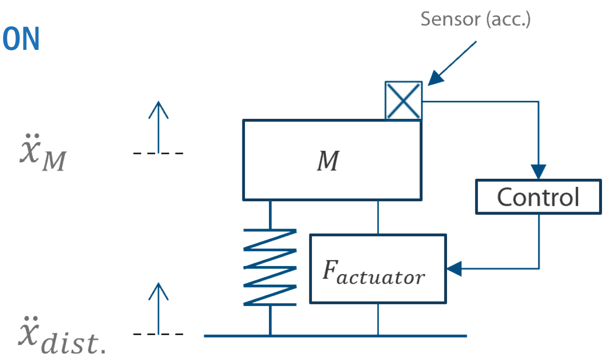


Fig. 20 : Principle of the active suspension

A dedicated adaptive controller can be used to reduce external perturbations.

With this approach, the controller is always finding the optimal way to reject perturbations, and a variation of the perturbation frequency can be compensated. The drawback is that the filter needs time to converge to the optimal perturbation rejection. With a fine tuning, a rejection of more than 20dB can be practically obtained.

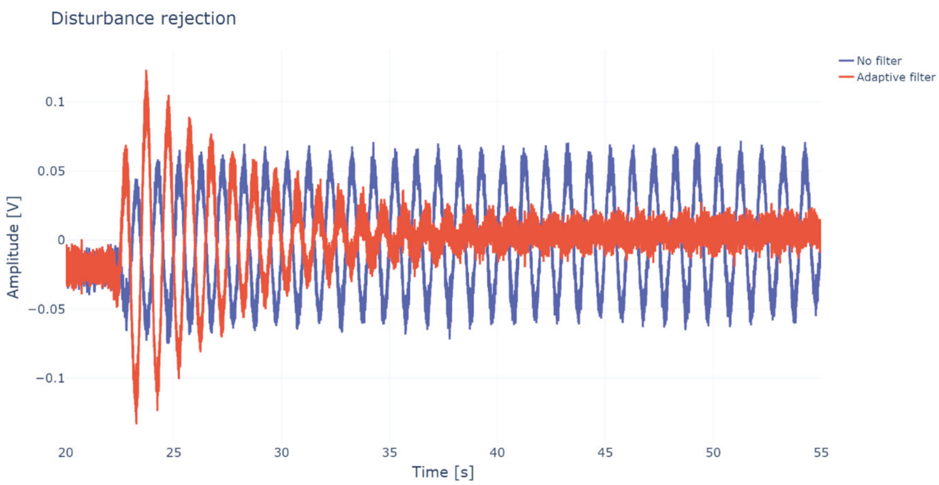


Fig. 21 : Results from active suspension with and without control

4. SENSORS

The CTEC actuators may include positioning sensors options in a compact design.

Strain gage (SG) sensors are well adapted for this compacity purpose, thanks to their small volume and accurate response. SG sensor is an indirect motion measurement because it is implemented onto the piezo ceramics and not directly at the tip of the motion mechanism. Controlling such systems may demand a specific law to take into account the transfer function between the SG sensor and the tip of the mechanism. This observability is fundamental in all the control loops.

Nevertheless, for specific mechanism, such solution is not efficient enough and specific contactless metrology should be addressed to improve the sensor observability.

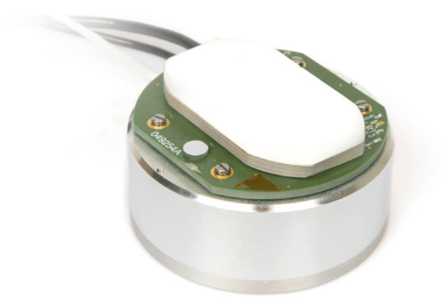


Fig. 22 : Contactless Eddy Current Sensor embedded on a TT60SM

CTEC has already implemented such sensors directly inside their mechanisms (like Eddy current sensor PCB built or accelerometers) or in a specific optical bench (like Photodiode Sensing Detectors).

A main advantage is the control of the real position of the payload. This leads to a more efficient control with larger capabilities in term of performances.

Application : TT60SM equipped with ECS sensor

On *Fig. 23*, the ECS response above the first resonance frequency is more detailed and accurate than with SG sensors. This allows to implement advanced control as defined in previous paragraphs.

Additionally, when contactless sensors are not implementable in mechanism, Cedrat Technologies is able to compensate partially the lack of observability of the integrated sensors, by feeding observability knowledge into the controller during the tuning process. This allows to achieve higher bandwidth and controllability without any additional sensors during operational use of the mechanism (see Fig 24).

The introduction of more complex observer in the control improves the flatness of the bandwidth.

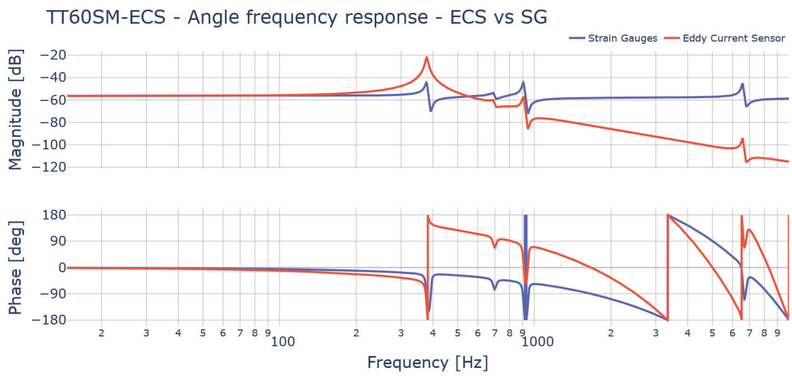


Fig. 23 : Comparison of electromechanical model for a TT60SM mechanism with SG and ECS

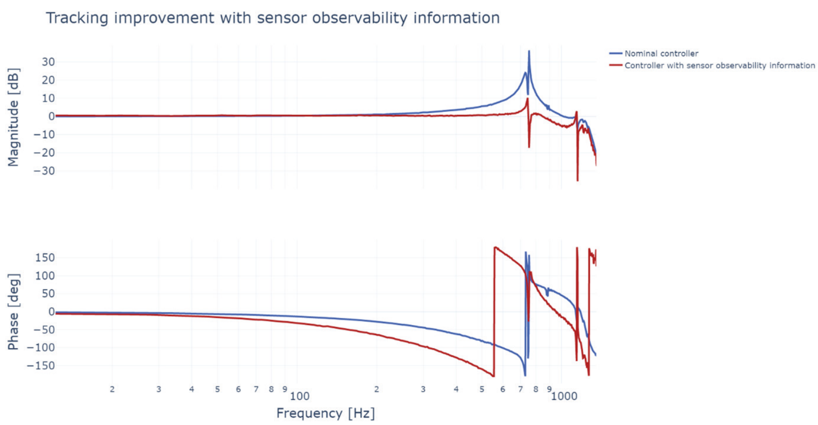


Fig. 24 : Comparison of a control loop performance with and without modified observers

5. AVAILABLE EQUIPMENT'S

Facing to these global interactions, CTEC is able to design test benches such optical benches with electro-optical instrumentations to measure such performances.

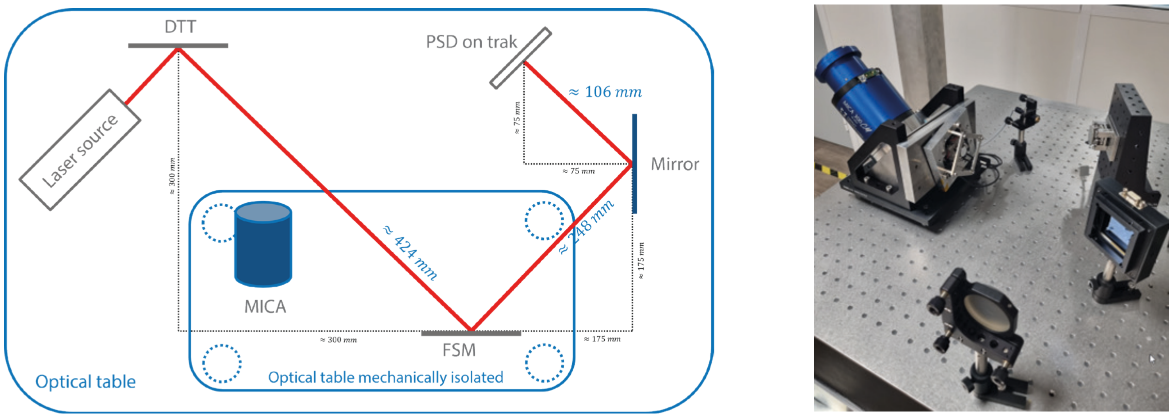


Fig. 25 : Optical test bench for vibration rejection using MICA300CM proof mass and PFSM150S associated to PSD

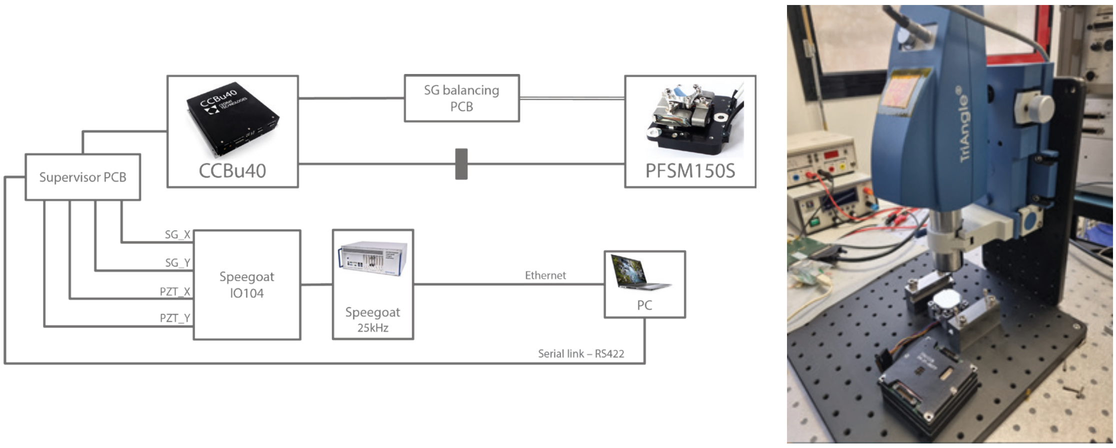


Fig. 26 : Angular measurement of DTT using electronic autocollimator to measure tracking error

Coupled with power full simulations and hardware in the loop platforms, CTEC is able to design efficient algorithms to control your mechanisms.

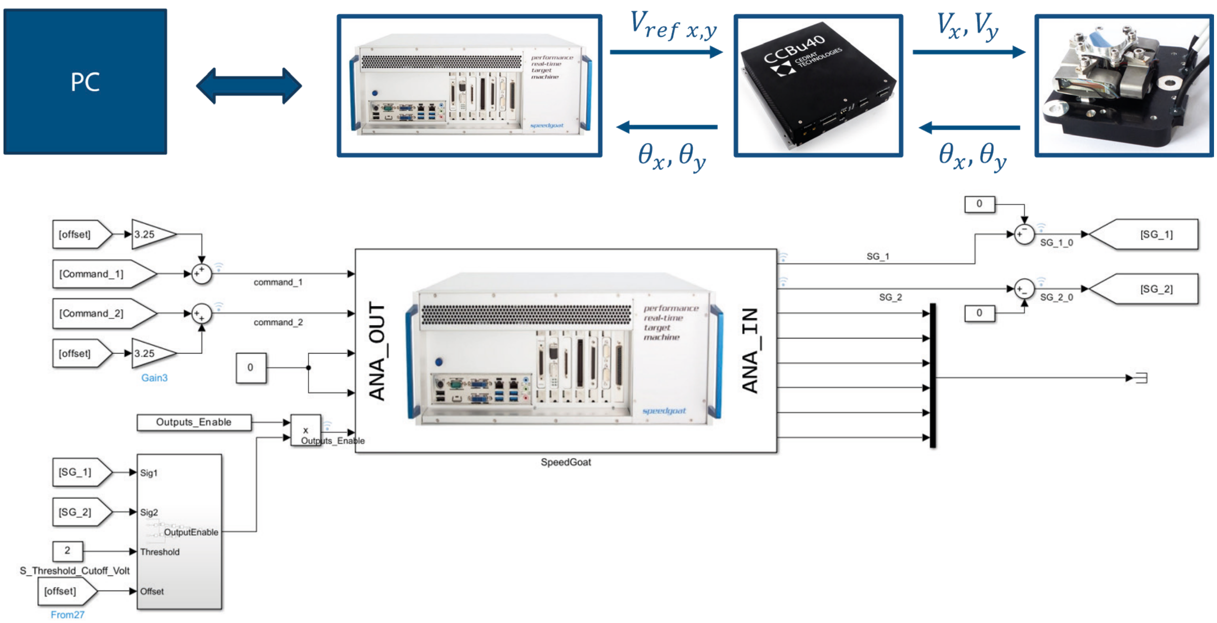


Fig. 27 : Implantation of HIL platform coupled with associated simulations

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

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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

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