APPLICATION NOTE

POSITION CONTROL OF PIEZO ACTUATORS

INTRODUCTION

The aim of this note is to help a piezo actuator user to control its system using Cedrat Technologies' drivers, sensors and controllers.

Facing various application cases, basic rules are given in order to stabilize and to optimize PID based control parameters of your system.

For advanced readers, theoretical contents are given in the last part of the document in order to explain the basic rules in positioning control of piezo actuators with a PID regulator and associated filters.

In this guide, some items will allow you to quickly get information on:

Warning

For your own safety and for your system security, be sure to carefully respect that information.

Good practices

This information gives you the best way to do.

Warning

Before stating, the user should read carefully the dedicated user's manual of each part constituting the entire control loop.

TABLE DES MATIÈRES

I. I WANT TO BE SURE TO FULLY UNDERSTAND WHAT I HAVE IN MY HANDS

I. 1. ACTUATOR CLOSE-UP

Amplified Piezo Actuators (APA®) and Parallel Prestressed Actuators (PPA) are active components which will perform a displacement proportional to a voltage. Those actuators are composed of active parts made from piezoelectric ceramics and passive parts allowing preload and amplification of piezo displacement (in case of APA®). Some actuators are also integrating Strain Gages sensors. In this application note, this kind of actuators is considered, due to their capability to be part of a closed-loop solution.

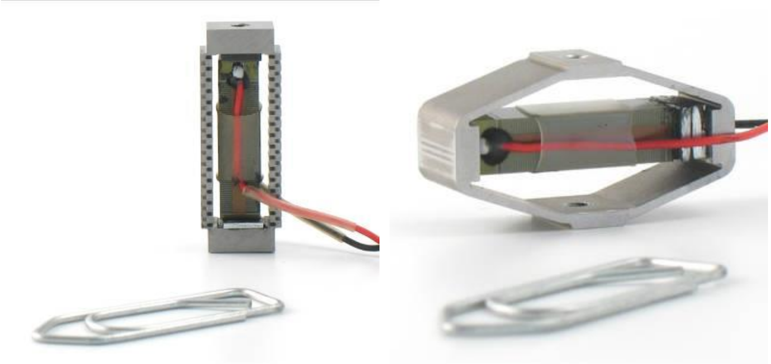


Figure 1: PPA20M and APA40SM actuators

Piezo actuators are connected to supply voltage amplifier using banana plugs. Those have to be correctly plugged in order to allow actuators to be powered.

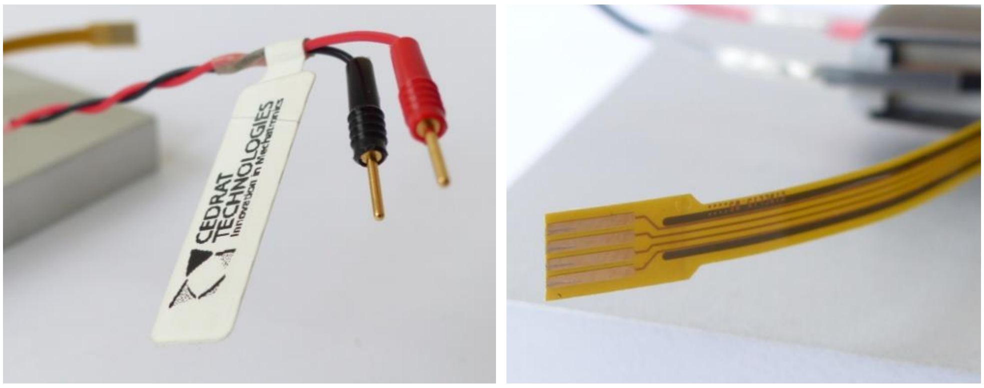


Figure 2: Actuators banana plugs and stain gage connection

Warning

Completely plug bananas in order to avoid any visible metal part of the connector. This would lead to high voltage risk. Do not invert red and black wires when plugging in piezo actuators. This will lead to unexpected behaviour of the system due to depolarization risk of piezo ceramics.

The flex connection should not be bent with min radius of 5 mm to avoid disruption of printed wires

I. 2. VOLTAGE AMPLIFIER CLOSE UP

Actuators are driven and controlled using dedicated electronic boards, typically set in a rack. Each electronics rack is mainly composed of:

- AC-DC converter (LC75 or SC75) providing stabilized voltage

- Voltage electronic amplifier (LA75 or SA75) supplying appropriate voltage to the actuator by amplifying with x20 V/V gain factor.
- If actuators are equipped with a position sensor, sensor conditioner board is also integrated inside the rack (SG75 for Strain gage conditioner or ECS75 for Eddy current conditioner).
- When a closed loop control is required, a control board is finally integrated.

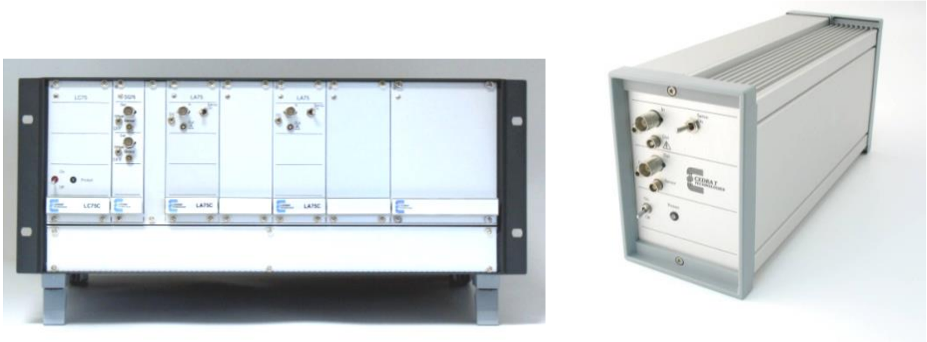


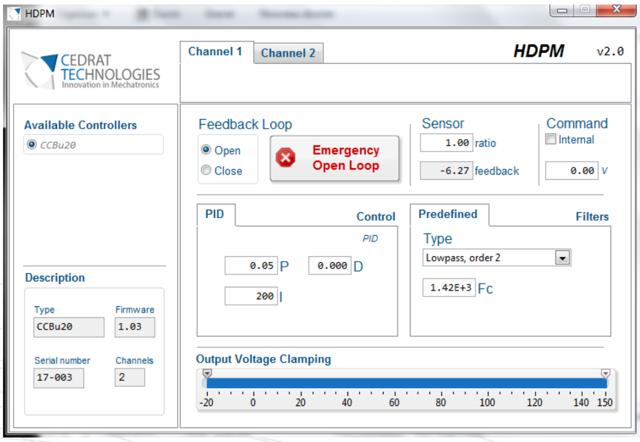
Figure 3: Typical rack with several boards and Compact Amplifier CA45

Warning

Do not plug your piezo actuator to the rack until your setup is completed. This will avoid any risk of electrical shocks.

I. 3. SOFTWARE

Closed-loop is driven by parameters that are integrated into the controller. Those parameters may be changed using a dedicated Graphical User Interface (GUI) called HDPM which impacts directly the essential parameters of real time firmware inside the controller. See your driver user manual to learn how to install the GUI on your laptop.



● CCBu20

● Open
○ Close

Sensor: 1.00 ratio
-6.27 feedback

Command: ☐ Internal
0.00 V

PID: 0.05 P
0.000 D
200 I

Type: Lowpass, order 2
1.42E+3 Fc

Description
Type: CCBu20
Firmware: 1.03
Serial number: 17-003
Channels: 2

Figure 4: HDPM GUI main window

I. 4. SYSTEM EXAMPLE

In the following pages, we review several situations that you may encounter with our closed loop system. In order to give a practical context, we will use the example of the position control of an APA600M piezo actuator with a strain gage position sensor. The next figure represents the considered actuator:

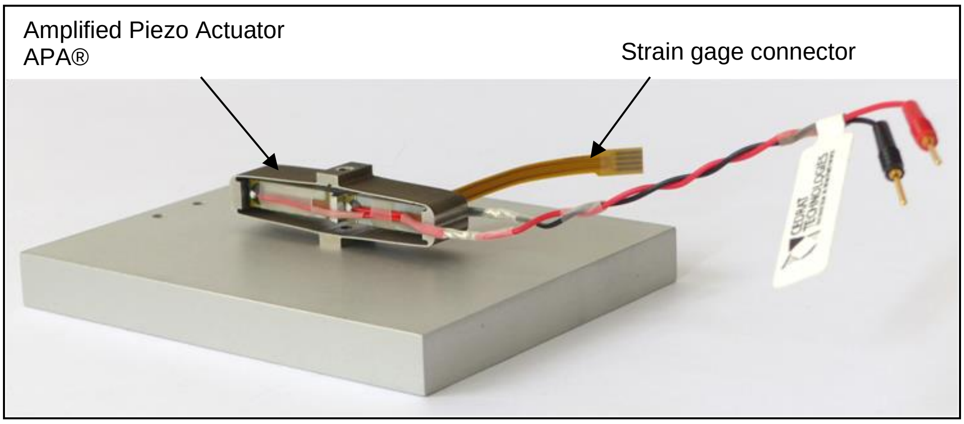


Figure 5 Considered actuator equipped with strain gages

The actuator is driven with a LA75A amplifier coupled to a UC45 controller. Strain gage sensor is conditioned using a SG75 board. A USB port allows the user to adjust the controller parameters with its own computer through the GUI “HDPM”. Those components are gathered in a signal rack (Figure 3).

The strain gage sensor converts strain on piezo ceramics into voltage with sensitivity in µm/V. In this case, the closed loop works with voltage and the supervisor/controller will compare these voltages to control the position of the actuator.

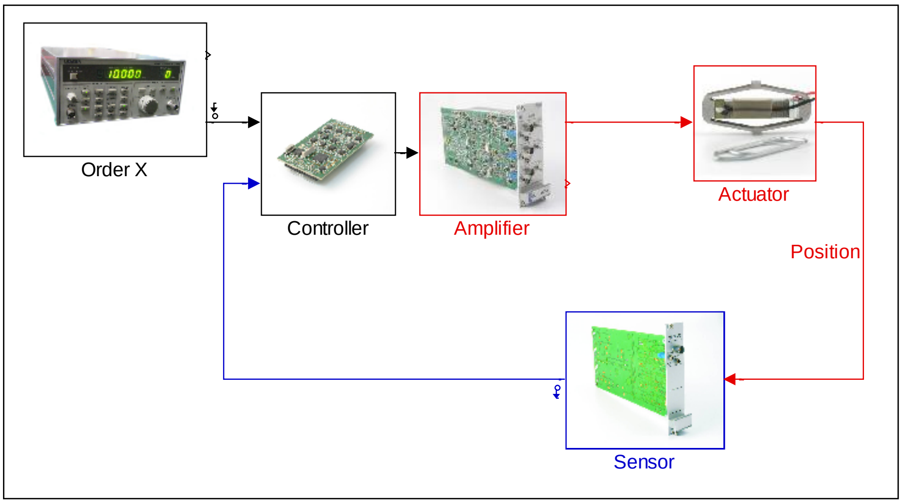


Figure 6: Closed loop components schematics

II. I JUST PLUGGED EVERYTHING. I WANT TO BE SURE THAT EVERYTHING IS CORRECT

You strictly followed the instruction manual that has been provided and want to be sure that the results you are obtaining are correct? Please follow the next steps to get your answer.

PID controller parameters of UC45 are set to default values. Those parameters are made to give stable results for a very large set of installations. They provide a safe configuration, with low speed but high stability margins. Following values are pre-programmed. These parameters are not optimized for your application and you will have to tune each and every to answer to your requirement (accuracy, settling time, bandwidth…).

- P=0.05
- I=200
- D=0
- Filter= Lowpass@100 Hz

Following graph presents the actuator response to a step through the integrated sensor. Open loop response is visible in red curve, showing oscillating response, related to the main structure mode. Green curve is the closed-loop response. It highlights slower but smoother and more stable response. Therefore, if you encounter this kind of response, you may consider that the current control setting configuration and the implementation of each function are correct.

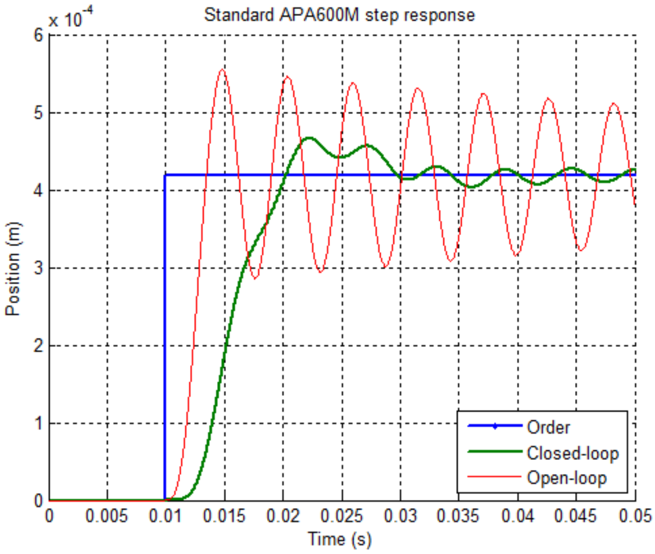
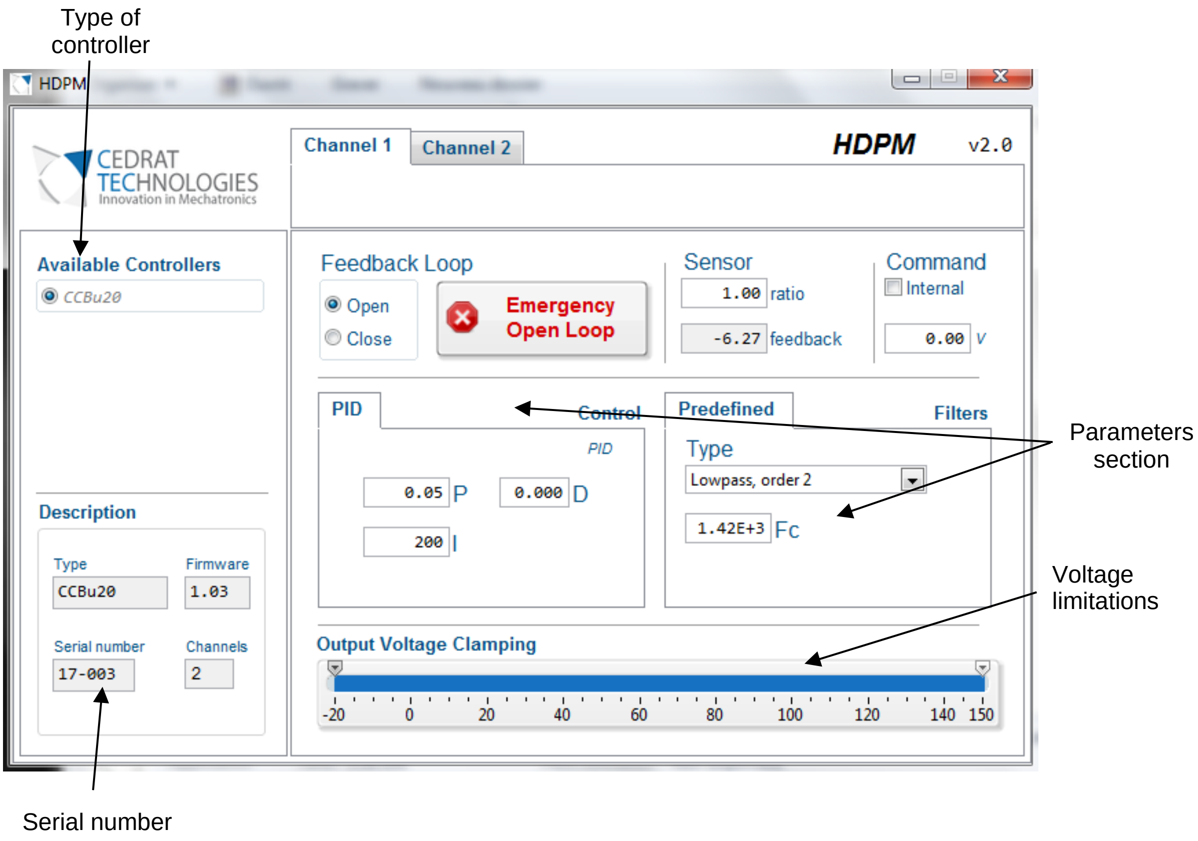


Figure 7 System typical response in Open and Closed-loop

Good practices

Please use low level signals (<0.5 Vpp before amplifier) for first tests in order to avoid any damage if setting is not correct. You could also limit the output voltage with two parameters in the GUI (see next Figure 8)

In order to be sure that the correct parameters are implemented into the controller, you have to use the GUI.



Type of controller

Parameters section

Voltage limitations

Serial number

Available Controllers
● CCBu20

Description
Type: CCBu20
Firmware: 1.03
Serial number: 17-003
Channels: 2

Feedback Loop
● Open
○ Close

Sensor
1.00 ratio
-6.27 feedback

Command
☐ Internal
0.00 V

PID
0.05 P
0.000 D
200 I

Predefined
Type: Lowpass, order 2
1.42E+3 Fc

Figure 8: HDPM45 GUI parameter sections

After a few seconds, the current setting configuration of the controller is printed on GUI. Serial number is visible on the left, PID and filter parameters are accessible.

Warning

If the actuator is whistling, quickly shut down the power of the driver. This is certainly because it came to resonance due to instability. Check the control parameters and restore default values if this is not the case.

III. WHAT ARE THE KEY CRITERIA TO DEFINE A STABLE & RESPONSIVE SYSTEM?

Every closed-loop system is defined by several criteria like stability and speed (bandwidth). Those criteria shall be studied to optimize the performances of the system in control loop.

III. 1. STEP RESPONSE

The step response is one of the most interesting tests in term of control characterization. Indeed, rise time, overshoot, settling time and steady-state error can be measured.

Each of those characteristics is explained on following graphs on Figure 9 and Figure 10.

III. 1. 1. RISE TIME

Rise time refers to the time required for a signal to typically change from 10% to 90% of the step order value. There is often a trade off to make between "Rise Time" and "Settling Time" during the calibration of a closed loop.

III. 1. 2. OVERSHOOT

Overshoot is the maximum value reached above the desired target. Reduction of this overshoot may be a strong objective on several specifications due to mechanical hard stops, or other physical limits.

III. 1. 3. SETTLING TIME

Settling time is the time elapsed from the application of an ideal instantaneous step input to the time at which the output has entered and remained within a specified error band. Typically, 100%+/-5% is considered. On Figure 10, it can be seen that settling time is the same for both configurations.

III. 1. 4. STEADY-STATE ERROR

This is the difference between the desired final output and the actual one when the system reaches a steady state. One of the most common aims of closed-loop control is to make this error null.

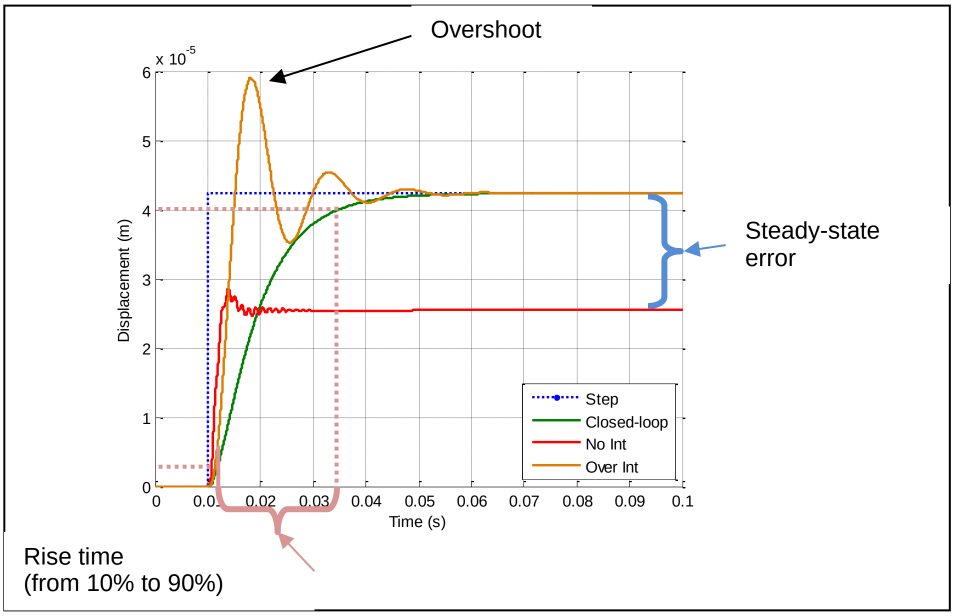


Figure 9 Step response for the example system

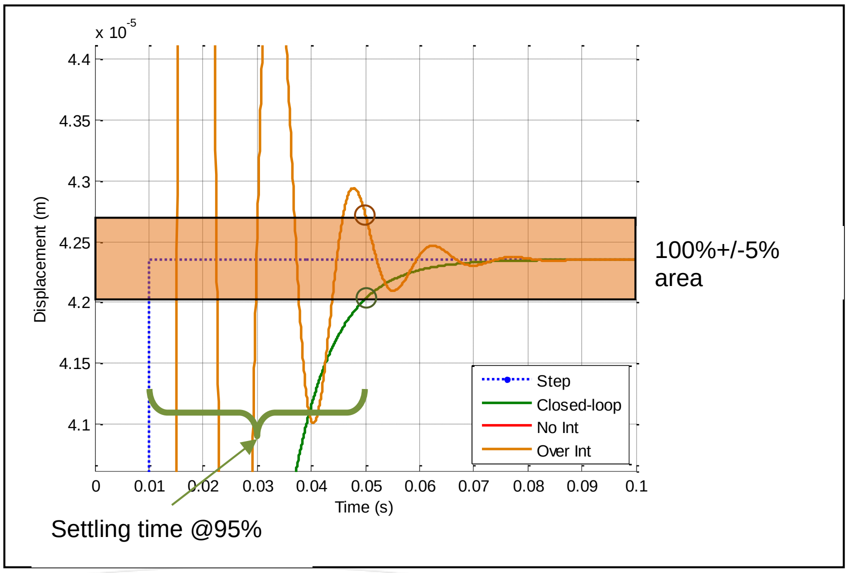


Figure 10 Step response, close-up on steady state

In the standard case, considering our reference case, there is no overshoot, response is damped. With no integrator, the steady-state position is far from desired position. This error is canceled when integrator is added to the controller (the integral term has the effect of static error cancelation). However, this controller may introduce overshoot.

III. 2. SINE RESPONSE OR BODE DIAGRAM

In addition, the sine response is interesting to validate the bandwidth of the control when the amplitude error and phase lag could be acquired. In parallel as the transfer function in open loop is not measurable, the Bode diagram is able to give information in regards of the stability of the loop. These measurements demand more complex instrumentation to trace a Bode diagram between sensor output and order.

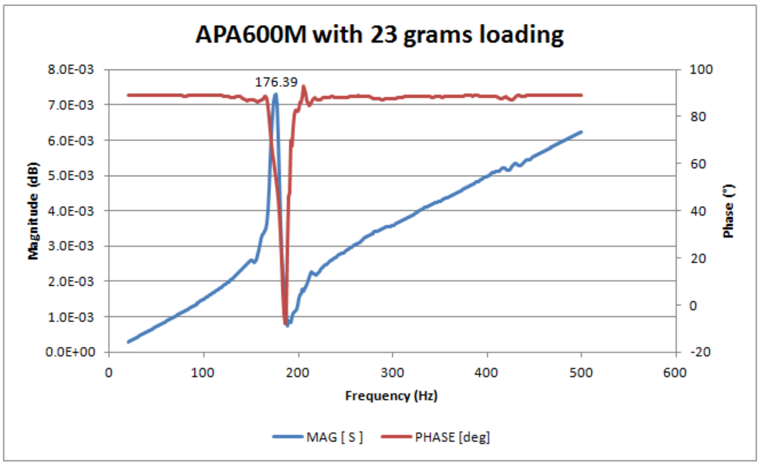


Figure 11 Frequency typical response in gain and phase

Amplitude is characterizing level of deformation facing input order. This can be done on electrical response, through impedance measurement, or using external sensor. Phase is representing lag between order and response. This is one of the main sources of instability (see below). Finally, each actuator is presenting at least on major frequency resonance. This frequency is characterized by a large magnification of displacement. This is source of risk for actuator security. Full input amplitude shall never be applied at such frequency.

III. 3. STABILITY MARGINS

The stability of a control loop is a major preoccupation of controller designers. Indeed, this characteristic is the most important to ensure the performances of the control. However, in order to give a quantitative feedback on the stability (instead of talking about stable or instable systems), notion of stability margins has been introduced. Those margins are expressed in terms of Gain margin and Phase margin. Both of these characteristics could be extracted from the Bode Diagram. This diagram is the graphical representation of displacement magnitude of displacement (for example) and phase (difference versus excitation and actual displacement) versus frequency. The combination of this information is so called Open Loop Transfer Function (OLTF) or Closed Loop Transfer Function (CLTF). Stability margins are only analyzed using OLTF. Experts will find details on control theory on driver user manual.

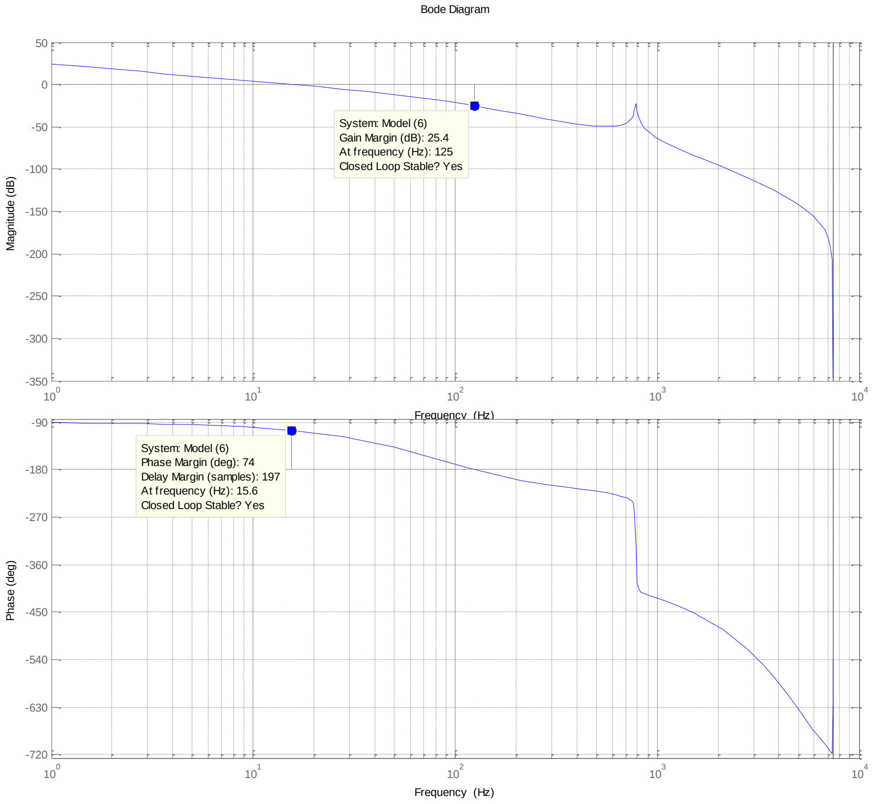


Figure 12 Bode diagram for the example system

III. 3. 1. GAIN MARGIN

Increasing the gain typically allows reaching the final position faster. The gain margin characterizes the possibility to increase the gain of the loop before becoming instable. It is determined by measuring the gain when the phase is crossing the “180°” level. If the gain is negative, it means that every contribution from the controller that may be in the wrong direction (phase >180°) have a less than 1 magnitude impact. This low impact won’t be able to make the system instable. In the previous example, the gain margin is 25.4 dB.

Typically, a gain margin of 3 or 5 dB can be considered to be sufficient for piezo actuator.

III. 3. 2. PHASE MARGIN

The phase characterizes the delay between the order and the output of the system. The risk in terms of phase is that the controller may apply an order with too much delay so this order is occurs too late. If the magnitude of this order is amplified (magnitude > 0dB), therefore the system will start to amplify the “wrong direction” order, so and it makes the system instable. That is why a phase margin, determined when magnitude is crossing the 0dB magnitude level can be pointed out. In the previous example, the phase margin is 74°.

Typically, a phase margin of 45° can be considered to be sufficient, depending on the application.

Mathematically, the stability margins study is built around the next formulae:

The closed loop could be written as $\frac{T(j\omega)}{1+T(j\omega)}$ with $T(j\omega)$ the transfer function of the entire loop corresponding into the transfer functions of the controller + the sensor + the driver, i.e. $T(j\omega) = TFcontroller(j\omega) \times TFsensor(j\omega) \times TFdriver(j\omega)$

The study of the denominator $1 + T(j\omega) = 0$ or $T(j\omega) = -1$ demands the study of phase and gain. Poles could be:

- Real negative -> the system is stable
- Complex and real negative -> the system is stable
- Imaginary complex -> the system is unstable

This study could be analytically complex and plot diagrams are used to facilitate the analysis coupled with specific software. The engineers should analyze the impact of the controller in term of stability.

IV. Can I change the P, I and D parameters, as well as filter, as I want?

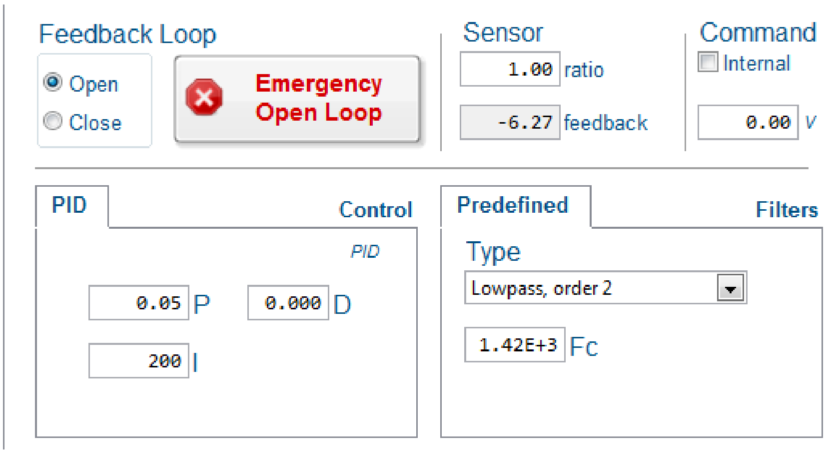
Before going into the details, let’s explain why CTEC proposes a PID + filter structure for the open platform. PID controller is the most popular controller in the world. This is an easy real time controller with the possibility to adjust the different parameters in real time [in view of the real performances]. In other term, it is simple to adjust the parameters by the following manual tuning method.

In the other hand, this is not the best in term of performance and other laws such as state feedback regulator could be implemented without the same versatility.

Coming back to the question, the answer is YES and NO

IV. 1. Yes, PID parameters can be changed easily

Using the provided GUI, it is possible to change the PI&D parameters on a large band. The available parameters ranges are described below.



● Open
○ Close

1.00 ratio
-6.27 feedback

☐ Internal
0.00 V

0.05 P
0.000 D
200 I

Type: Lowpass, order 2
1.42E+3 Fc

Figure 13: GUI parameter section

Example of parameter ranges:

- P Є [0 : 10]
- I Є [0 : 32000]
- D Є [0 : 0.01]

Over these ranges, the parameters admit no physical limitations except instability. Instability of a closed loop control can lead to damages. That is why PID parameters shall be changed with precautions.

IV. 2. But NO, P-I-D should not be changed in a random way

As it has been seen previously, instability is ruled by values of PID parameters. Impact of each of them is not easy to catch. However, following major rules are generally admitted:

	Rise Time	Overshoot	Settling time	Steady-state error
Gain ↗	↘	↗	-	↘
Integral ↗	↘	↗	↗	Ø
Derivative ↗	-	↘	↘	-

Table 1 Main PID rules

Good practices

When you are looking for best performances parameters, keep the last best configuration in mind in order to go back to a well known starting point. Don't forget that: "The best is the enemy of good"

V. I WANT MY ACTUATOR TO REACH THE ORDER FASTER

As it has been presented, the definition of “reaching the order position” can be quantified using rise time, settling time and steady-state error. Those characteristics can be specified over a step signal closed-loop response. In the presented solution, adapted PID parameters and filter are presented in order to increase performances of the solution.

The main goal of this part is to show the influence of PID parameters and filter type on performances in order to obtain a “faster control”.

V. 1. SIMULATION: DEFAULT AND PROPOSED OPTIMIZED VALUES

I. 1. 1. INITIAL PERFORMANCES

PID parameters of UC45 controller are initially set to default values. Those parameters are giving performances that are summarized on following table.

P	0.05
I	200
D	0
Filter	Low pass 2nd order 100 Hz
Rise time (10-90 %)	14.6 ms
Settling time (@ 5 %)	21.8 ms
Overshoot	1.2 %

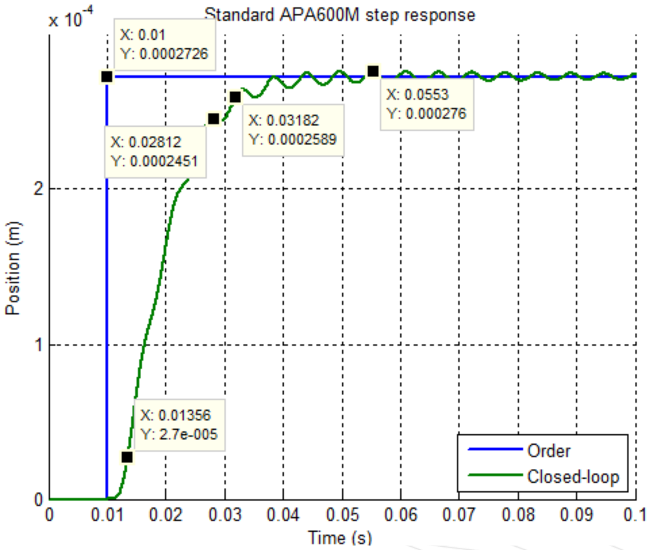


Figure 14: Standard initial performances

This response is conservative but relatively slow and may be not sufficient if your application needs high bandwidth. Therefore we will discuss influence of PID parameters to make it faster.

V. 1. 1. PID EVOLUTION

The PID controller is mainly ruled by Table 1. In order to accelerate the response, it is possible to:

- Look for a smallest rise time: increase P & I parameter.
- Look for a smallest settling time: adjust I parameter.

According to these both case, we will see impact of P and I parameters on step response.

GAIN IMPACT

When increasing the value of P gain, the rise time is reducing. This is clearly visible on Figure 15. It is visible that this fast response does not allow reaching the final position and it takes too much time. For high P values, it is also visible that oscillations appear. It shows that the stability margins are reduced.

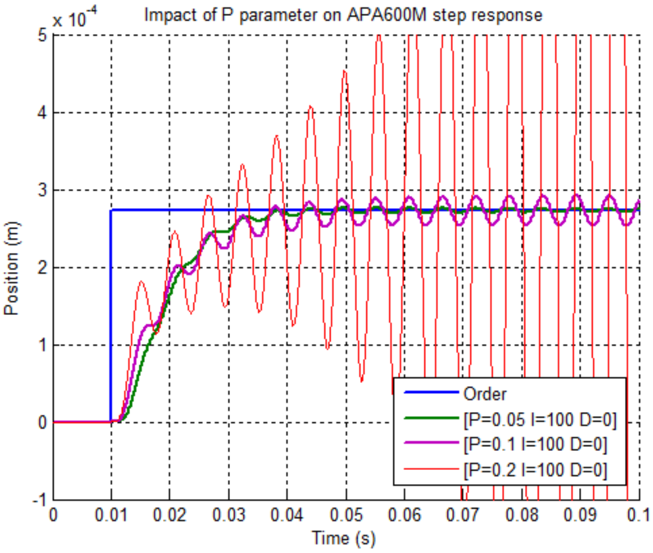


Figure 15 Impact of P parameter increase

INTEGRAL GAIN IMPACT

The integral gain I has impact on rise time because it accelerates response of the controller by wanting to cancel steady-state error. This is done to the detriment of settling time because it makes oscillations appearing. Large overshoot is observed. This behavior is visible on Figure 16.

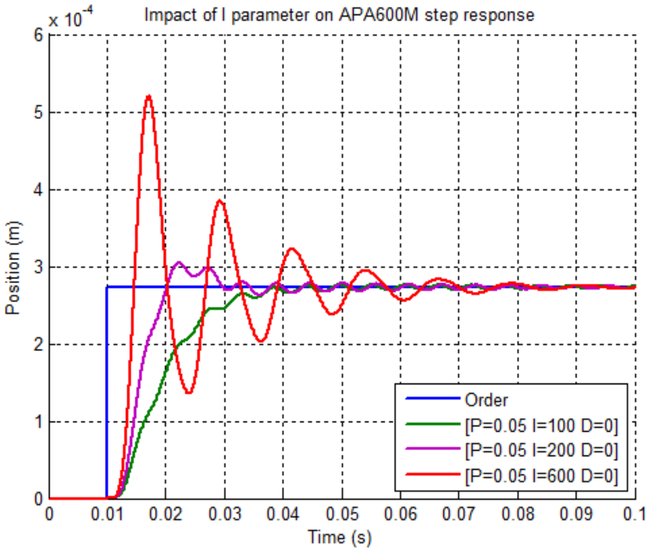


Figure 16 Impact of I parameter increase

Every PID configuration proposed so far have limitations facing the need in speed improvement. We see in the next chapter the impact of filtering to improve the speed while keeping stability in the control loop.

V. 1. 2. INTEREST OF FILTERING

It has been seen that PID parameters are ruling the response speed but they also introduce energy into system modes. Those modes are bad/negative contributors to system stability and performances. Therefore, a control strategy consists in adding a filter to the PID controller in order to diminish the impact of modes.

The first type of filter that has been implemented so far as a default value is a 2nd order low pass filter. This kind of filter is able to cut high frequencies but is not very efficient when a strong and precise mode is close to working frequencies. A solution may consist in reducing the cut-off frequency of this filter, but it would also slow down the system response. Another solution is to use another type of filter called “notch filter”.

A Notch filter is a stop band filter dedicated to a specific frequency. Cedrat Technologies controllers are compatible with 2nd and 4th order notch. Those present the advantages not to change gain and phase far from the cut-off frequency. This leads to potential larger stability margin.

Next figure is showing system response using [P;I;D]=[0.05;100;0] parameters. It is visible that the small frequency of low pass filter is reducing performance of the control because it makes it too slow. A 75 Hz cut-off frequency allows reaching best performances. As a complement, Notch of 2nd order and 4th order are presented, showing good results.

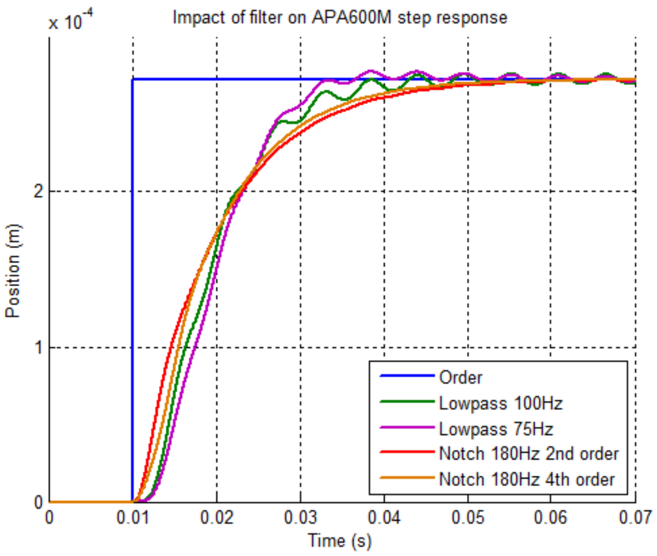


Figure 17 Impact of filter type

Difference in terms of Bode diagram between standard 100 Hz filter and 4th order Notch is presented on Figure 18. It is easily seen that green curve (Notch filter) is strongly reducing magnitude of mode and increase the stability margins in phase and gain.

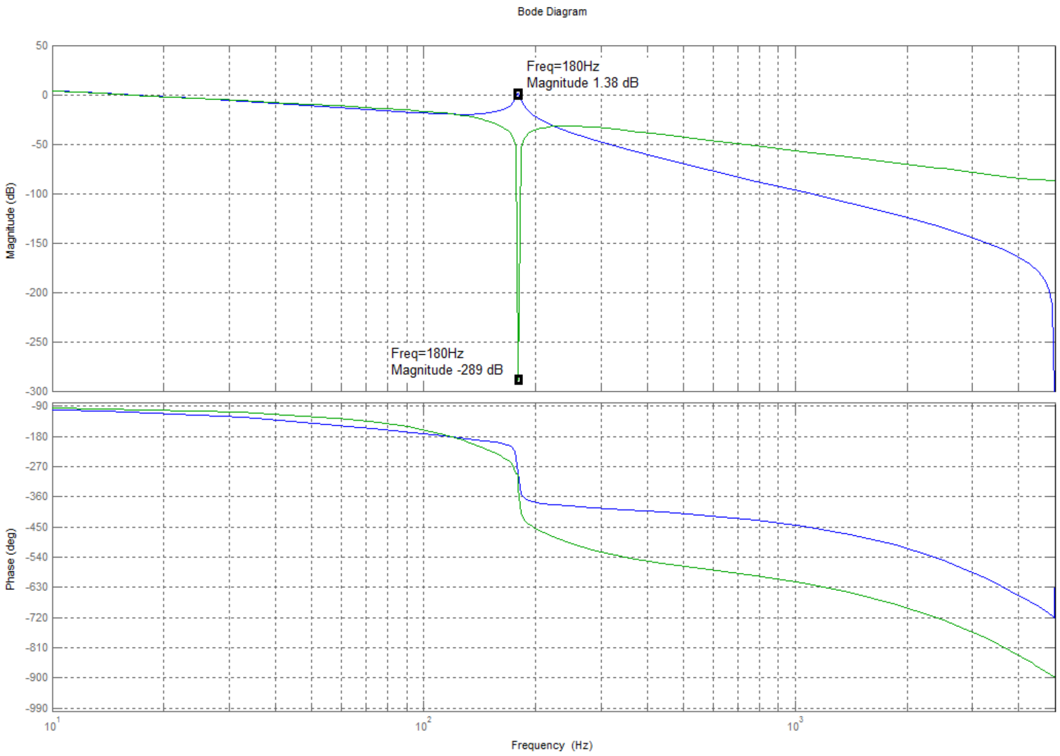


Figure 18 Comparison between standard and Notch filter

V. 1. 3. FINAL CONFIGURATION

An efficient control configuration can be found when combining PID optimization and filtering. In a general process, it may be easier to fit the filter according to the parasitic mode before changing the PID parameters. In the considered example, retained parameters are summed-up in Table 2.

	Optimised	Initial
P	0.27	0.05
I	310	200
D	0	0
Filter	Notch 4th order 180 Hz	Low pass 2nd order 100 Hz
Rise time (10 - 90 %)	3.3 ms	14.6 ms
Settling time (at 5 %)	5.3 ms	21.8 ms
Overshoot	2.5 %	1.2 %

Table 2: Optimised parametres examples and performances

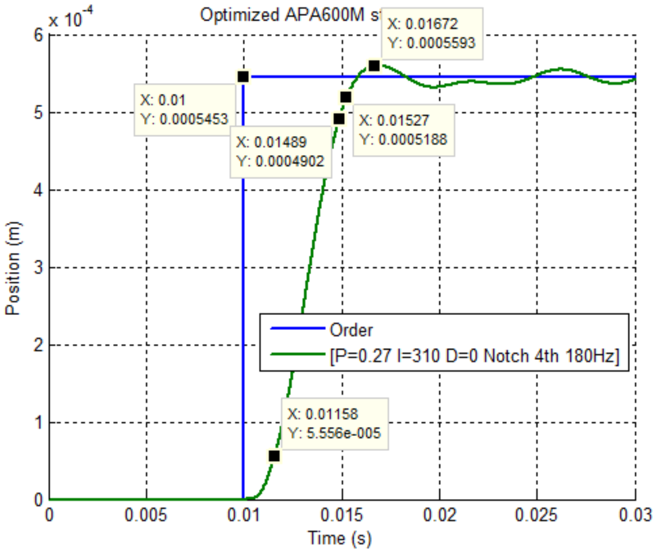


Table 1 Optimized proposed configuration performances

V. 2. EXPERIMENTATION: DEFAULT AND PROPOSED OPTIMIZED VALUES

Now that simulation helped us to determine interesting results, it is necessary to apply those parameters to real system. In our case, example system (presented in page 7) is used.

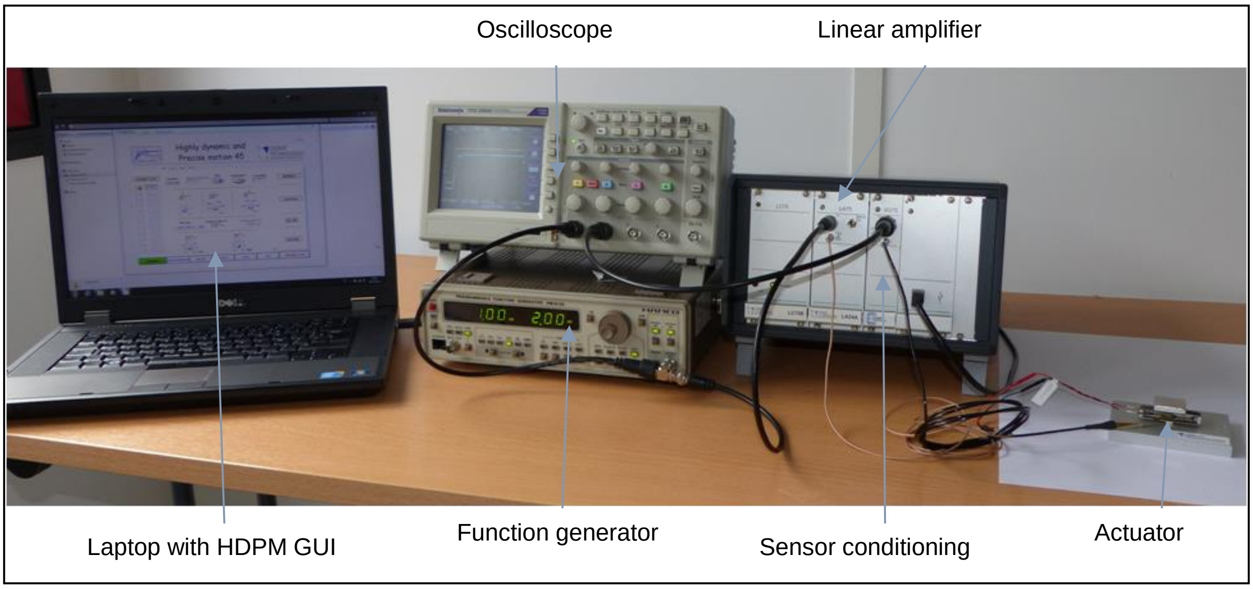


Figure 19 Full control setup

V. 2. 1. FREQUENCY RESPONSE

Before applying any advanced order, it is recommended to check the modal landscape of the considered actuator. In our example, main frequency has been predicted to be at 180Hz. A 176.4Hz mode is measured, which is very satisfying.

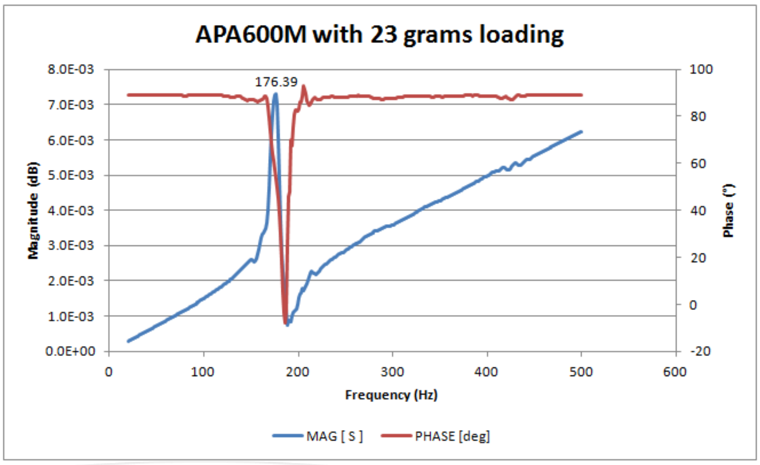


Figure 20 Impact of notch filter frequency on Closed-loop transfer function

V. 2. 2. OPEN LOOP RESPONSE

System is firstly tested in open loop. This response is the very basic way to drive piezo, without any feedback about actuator behaviour. Result is plotted below.

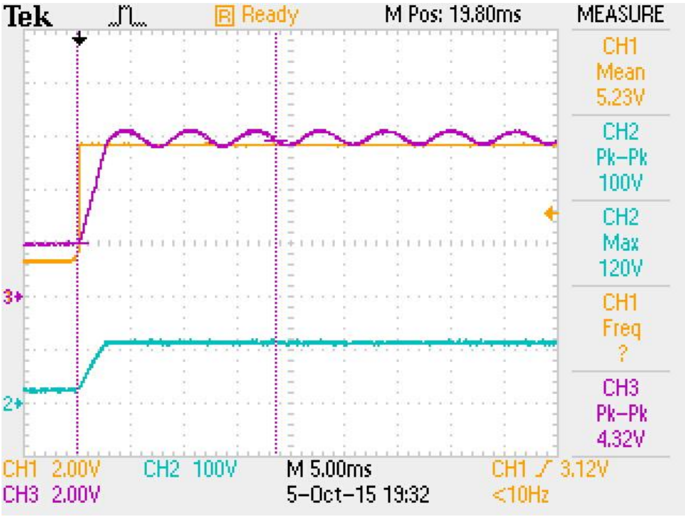


Figure 21 Open loop response

It can be seen that oscillations are appearing after the voltage increase. Voltage increases linearly because of driver current limitation.

Note: Do not mix up the open loop response with the open loop analysis during the analysis of stability.

V. 2. 3. Closed-loop response

Initial parameters

The measured response is slightly different compared to modelled one (See Figure 7). Major difference comes from low oscillations that are not visible on acquired data.

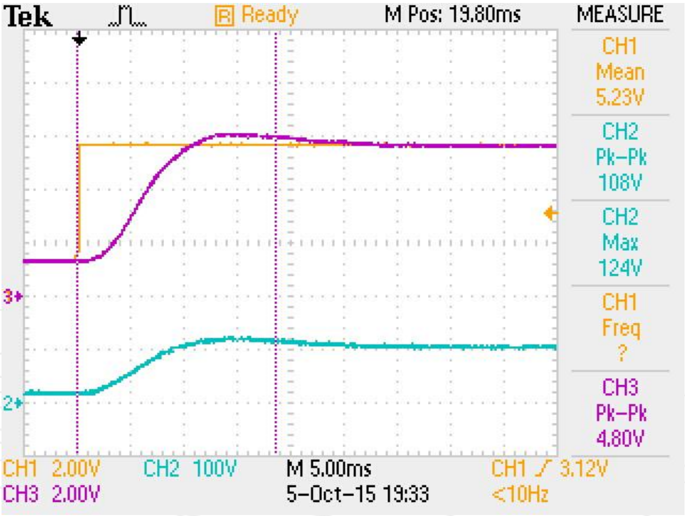


Figure 22 Step response with initial parameters

Predicted parameters

Using the model, some adapted parameters are predetermined, in order to reach faster response time.

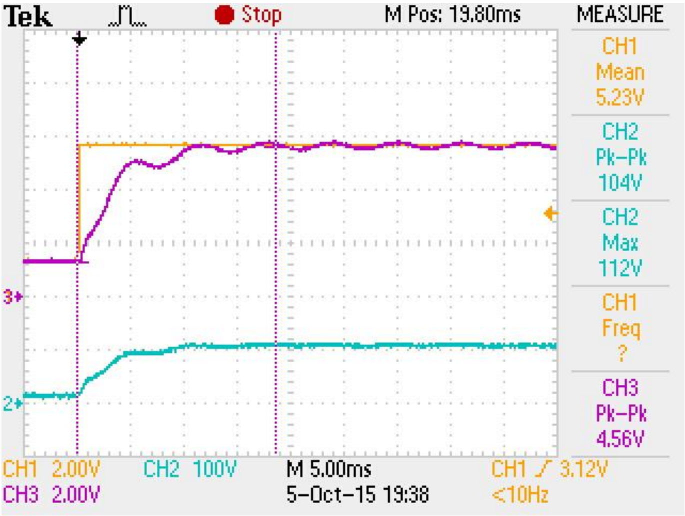


Figure 23 Step response with predicted parameters

EXPERIMENTAL PARAMETERS

Difference between model and experiment setup is leading to non-optimal results using the predicted parameters. Therefore, a local optimization is made in order to reduce response time. Parameters are changed to

[P=0.3, I=400; D=0, Filter=Notch 4th order, 140 Hz]

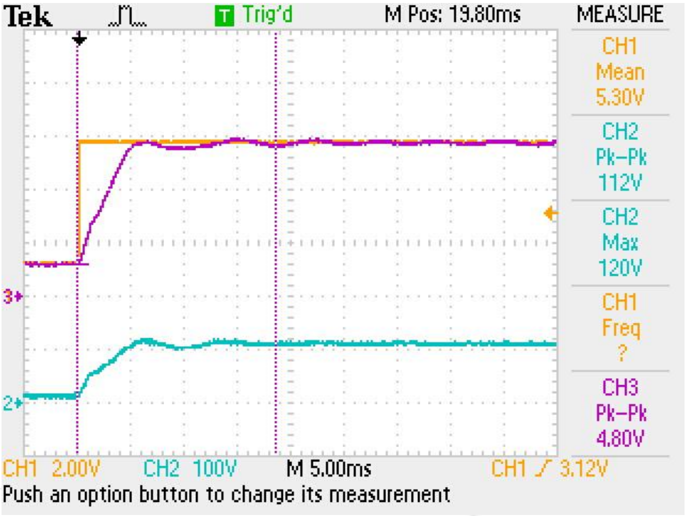


Figure 24 Step response with optimized parameters

Using those parameters, a 5 ms response time is obtained. This 5 ms value corresponds to 1/Fr period. This response time is satisfying facing system overall dynamic.

VI. I WANT TO REACH A STATIC POSITION WITH A VERY FLEXIBLE SYSTEM/SOFT STRUCTURE

In the case where high precision static positioning is the only aim of the closed-loop, a few rules may be applied to obtain a fully satisfying behaviour. Sometimes, very flexible/soft (low stiffness) structures are involved, leading to low resonance frequencies. This is the case when large lever arms are used, for example.

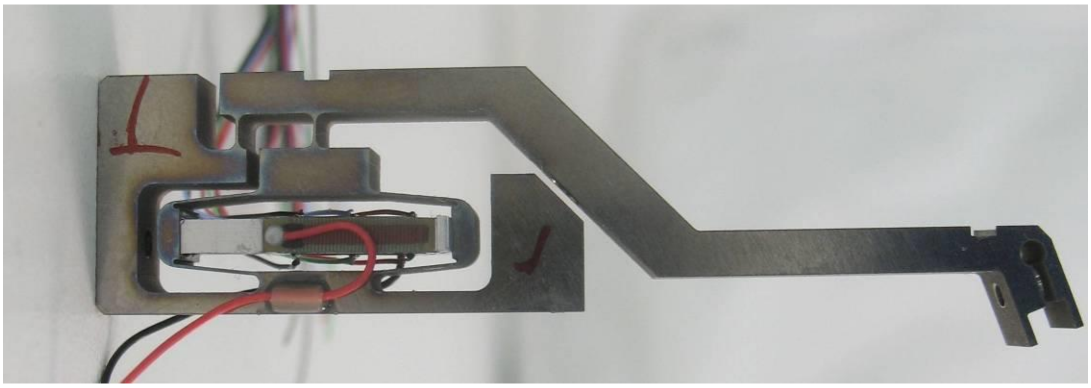


Figure 25 Example of a highly amplified mechanism, with lower resonance frequency

In the standard case, with initial parameters, closed-loop may be instable if the resonance frequency is very low. In the following example (Figure 26), a 55 Hz resonance frequency system is considered. Whereas the open loop response shows large oscillations (red curve), the actuator finally reaches its target position. On the contrary, the closed-loop response increases with no visible limit. The controller is not able to compensate the system dynamic, it becomes instable.

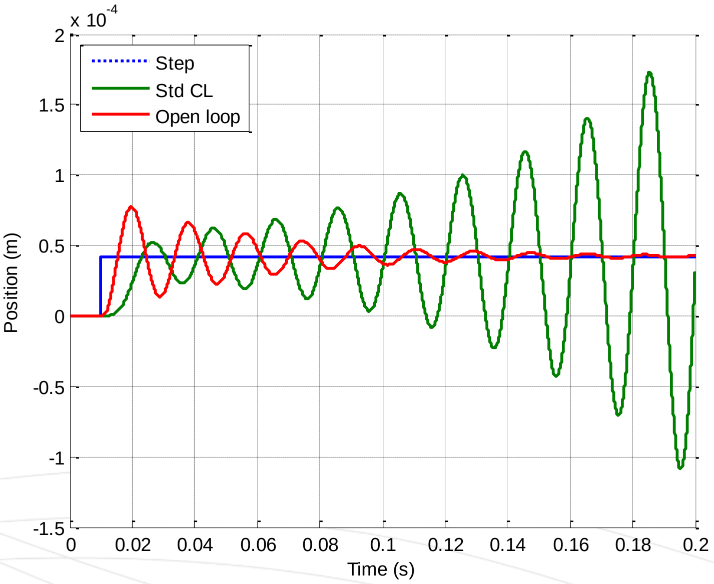


Figure 26 Low resonance frequency system responses

In order to restore stability, it is necessary to adapt the parameters to system characteristics. The low resonance frequency is easily damped using a lower cut-off frequency for the low-pass filter. However, as overshoot remains, see Figure 27, we slightly decrease the integral term of the controller (from 100 to 30). This final I adjustment leads to an attenuation of the slope and a good fitting to the order.

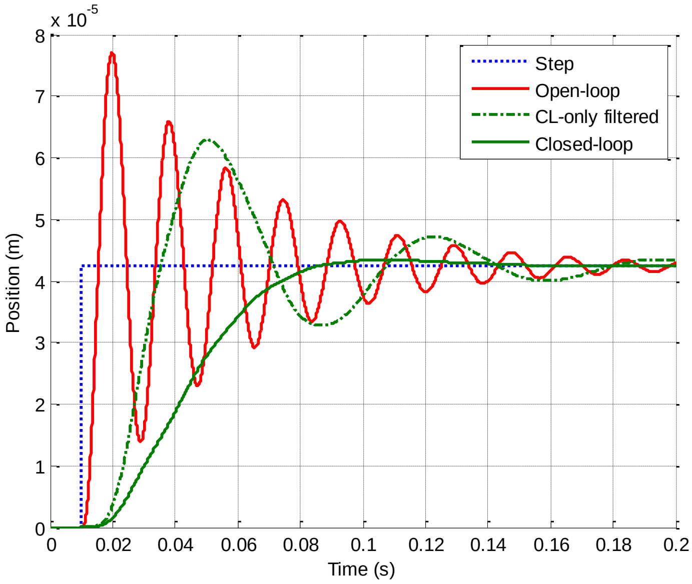


Figure 27 Low resonance system solution proposal

Warning

If the actuator is strongly whistling, shut down the power immediately. This sharp noise comes from resonant modes of the system that are excited due to loss of control stability. Check the control parameters and restore default values if this is not the case.

VII. How can I Build a model for performing simulation?

VII. 1. System models

VII. 1. 1. The different functions

The basic scheme of one channel control loop includes the following blocks (see figure 20):

- The Actuator
- The Amplifier
- The Sensor and its conditioner
- The Controller including:
  - Two analogue-to-digital converters (ADC) including the anti-aliasing filters. These blocks are characterized by sample and hold and quantization functions (the quantization is function of the resolution of the A/D converter, typically 16 bits). Those converters are used to sample the analogue orders and feedback signals.
  - A digital-to-analogue converter (DAC) with 16 bits resolution to convert the digital command to an analogue command applied on the actuator. This block is generally characterized with the maximum range and the resolution in terms of bits.
  - The regulator which computes the error between the command and the real position monitored by the sensor. The controller is calculated to maintain a closed loop which is stable with the desired performances (accuracy, speed…). It includes some regulators based on analogue/digital converters and a robust PID controller.

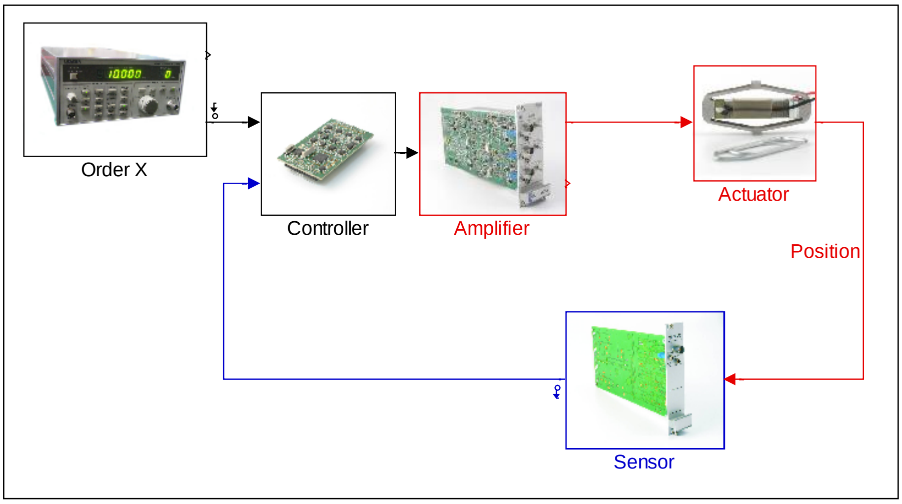


Figure 28: Schematic of a basic digital control loop

Each block is represented with an input and an output to model their behaviour.

VII. 1. 2. Actuator model

Before analysing the behaviour of the loop, a first step is the definition of the model and its accuracy. In quasi-static condition, a model of the piezo actuator with its fundamental mode can be used (see equation 1).

$$H(j\omega)=\frac{u}{V}=\frac{Nc_m}{1+r_m c_m j\omega+m_m c_m (j\omega)^2}$$

Equation 1: Actuator transfer function

This transfer function represents the displacement of the actuator as a function of the applied voltage on the ceramics. This transfer function of course is linear and doesn't take into account the creep effect or the intrinsic hysteresis. (If necessary we suggest using simulation software to include these nonlinearities). In a first order the hysteresis is closed to 10% for piezo actuator and we assume that a linear controller is able to correct this effect effectively. In a more accurate model, the reader could take into account this non linearity with specific model. Keep in mind the model is representative for one behaviour. Then a parametric model should be used when the environment has an impact on the characteristics of the specified model.

Additionally, when dynamic performances or when using mechanisms are required, the actuator should be modelised with more than its first mechanical mode. In this case, only FEM modelisation coupled with electromechanical elements extraction could give the overall transfer function of the mechanism.

Good practices

When short settling time is required, the Lumped model (based on a single mode) may not be accurate enough to tune the control loop due to spurious modes in the system. We strongly recommend a modal identification / analysis from Finite Element Model software of the mechanism or a hardware-in-the loop identification process to take into account the other modes at higher frequency.

VII. 1. 3. AMPLIFIER MODEL

In first approximation (for quasi-static application), the driver is a pure gain. You shall integrate the output current limitation, the cut-off frequency of the driver when the system requires bandwidth or the non linearities like the output voltage limitations.

$$Driver(j\omega)=\frac{Out}{In}=20$$

Equation 2 : Amplifier transfer function

Note: Don't mix-up the power bandwidth with signal bandwidth. The first one is characterized by the current limitation and the max frequency sine wave could be written as $Fmax=\frac{Imax}{Vpp\times\pi\times Cpiezo}$

VII. 1. 4. SENSOR MODEL

A sensor can be represented with a gain coupled to a first order low pass filter. If you use a strain gages sensor from Cedrat Technologies (SG75 board), this gain is defined as:

$$Sensor(j\omega) = \frac{Out}{In} = \frac{Maximal\_stroke}{Maximal\_input\_voltage}$$

Equation 1 Sensor transfer function

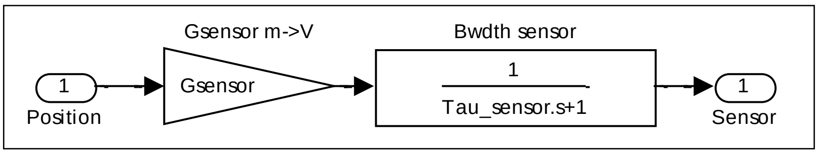


Figure 29 Sensor model

Numerical application: For an APA120ML, the maximum stroke is 120 µm and the maximum voltage order is 8.5 V: The gain is 70833 V/ma

VII. 1. 5. CONTROLLER MODEL

The controller includes a PID regulator in series with a dedicated filter. A filter is placed in line to limit the effect of the resonant frequency of the actuator. If the actuator has a low quality factor or if the bandwidth is very low, this filter can be bypassed and only an adjustment of the PID parameters will then optimize the behaviour of the loop by reducing the Integral parameter (play the role of integrator, i.e. low pass filter).

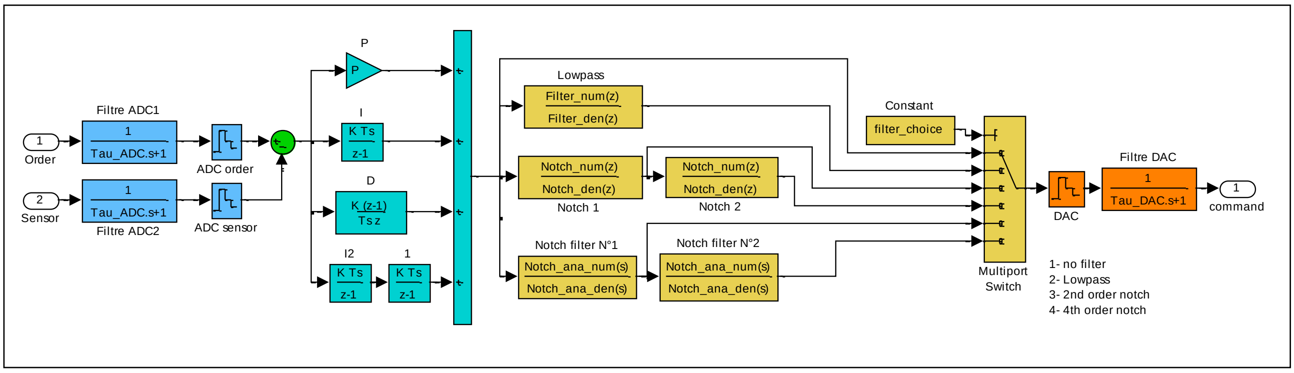


Figure 30 Controller model

A PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly.

It is used to ensure an optimum response behaviour of the actuator to its order- reducing error in velocity, in acceleration and mainly in position.

Finally, the controller is built in digital domain then discrete transfer function should be used to implement the P, I, D bloc functions.

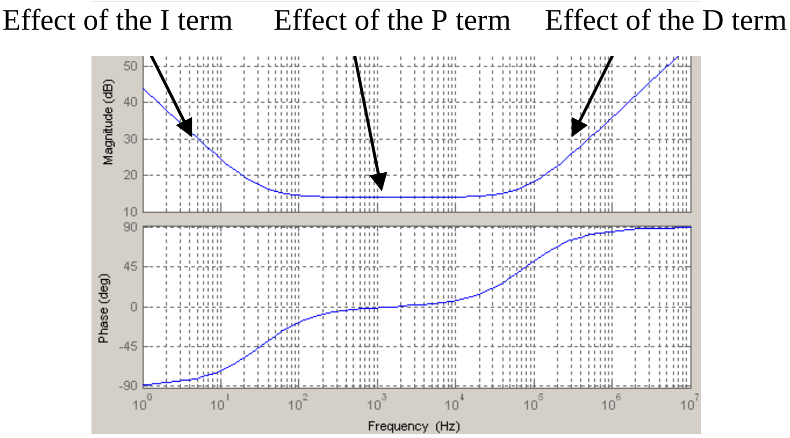


Figure 31 Controller frequency response, effect of P, I and D

VII. 2. MODEL PARAMETERS

VII. 2. 1. MECHANICAL PARAMETERS

System mechanical parameters can be determined using few different methods. The goal of this step is to obtain system frequency behaviour for the first mode.

First of all, theoretical values can be applied in first approach. Those parameters can be found in the catalogue (see Figure 32). Stiffness K, stroke, quality factor Q and capacitance Cpiezo are the main properties to be considered. Resonance frequency fr0 in blocked-free condition is also used in order to determine effective mass m of the actuator. The payload mass of the object M to be positioned takes major role on the system behaviour. Stroke gives information on static gain Gstatic of the actuator, by dividing stroke by the maximum voltage amplitude (typically 170 Vpp).

PROPERTIES	STANDARD TECHNICAL CONDITIONS	UNIT	NOMINAL VALUES
Notes		-	0
Max. no load displacement	Quasistatic excitation, blocked-free	µm	618
Blocked force	Quasistatic excitation, blocked-free	N	26.3
Stiffness	Quasistatic excitation, blocked-free	N/µm	0.043
Resonance frequency (free-free)	Harmonic excitation, free-free, on the admittance curve	Hz	1306
Response time (free-free)		ms	0.38
Resonance frequency (blocked-free)	Harmonic excitation, blocked-free, on the admittance curve	Hz	318
Response time (blocked-free)		ms	1.57
Capacitance	Quasistatic excitation, free-free, on the admittance curve	µF	3.15
Max. no load displacement at resonance	Max. harmonic excitation, free-free	µm p-p	289
Max. voltage at resonance	Max. harmonic excitation, free-free	Vrms	9.00
Force limit (0-pk)	Max. harmonic excitation, free-free	N	6.83
Resolution	Quasistatic excitation	nm	6
Height (in actuation direction)		mm	14.60
Length		mm	48.50
Width (excl. wedge & wires)		mm	10.00
Width (incl. wedge & wires)		mm	12.00
Mass		g	14.2

Figure 32 Catalogue extract with actuator parameters

Transfer function of the actuator is characterized by the spring-damper-mass system as follow:

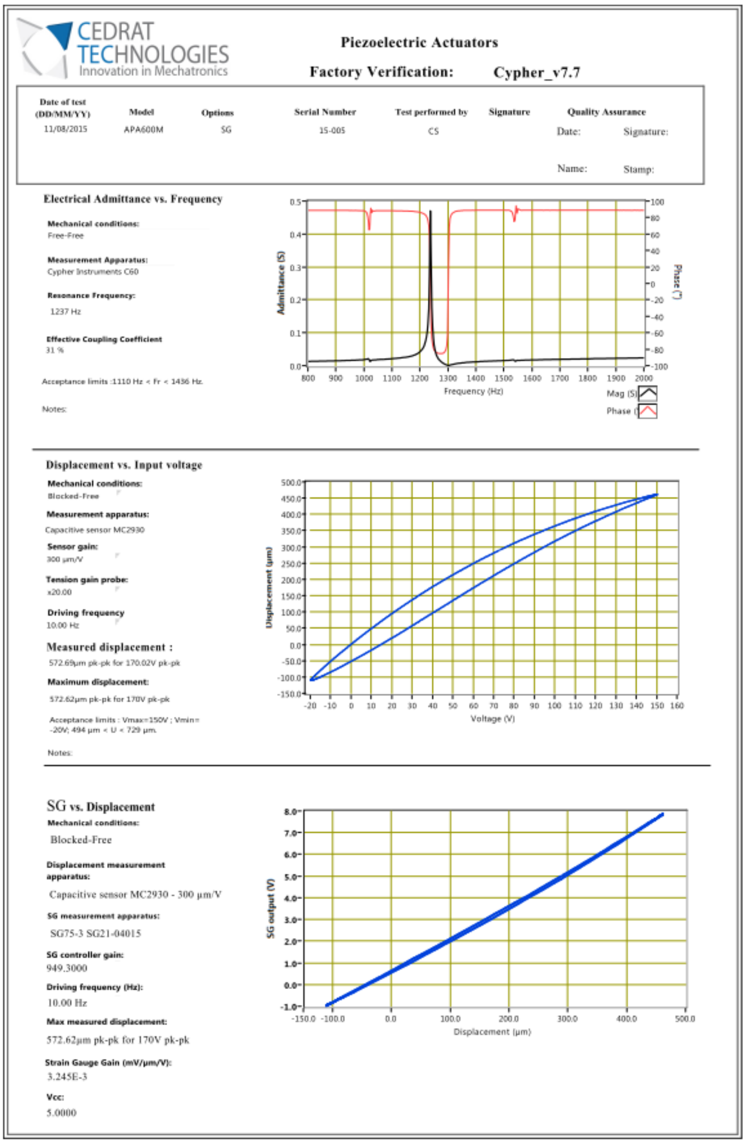
Effective mass m determination	$f_{r0} = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \Leftrightarrow m = \frac{K}{(2\pi.f_{r0})^2}$
System resonance frequency	$f_r = \frac{1}{2\pi}\sqrt{\frac{K}{M+m}}$
Quality factor	Q= 100 arbitrary and by experience or measurements
Transfer function	$FT(j\omega) = \frac{G_{static}}{(\tau.j\omega)^2 + \tau/Q.j\omega + 1}$ where $\tau = \frac{1}{2\pi.f_r} = \sqrt{\frac{M+m}{K}}$

Equation 2 Resonance frequency and transfer function

The mechanical parameters used are summed-up into following table. Those values can be generally found inside the catalogue, or on factory verification sheet provided with your actuator.

Parameter	Value	Units	Note
Actuator (APA600M)			
Stroke	618	µm	
Stiffness K	0.04349	N/µm	
Resonance frequency fr0	318	kHz	Blocked-free condition
Capacitance Cpiezo	3.15	µF	
Quality factor Q	100	-	Typical value @ low level @ full range, the Q factor is reduced around 30-50
Effective mass	11.8	gr	Using Equation 2

Table 2 Actuator characteristics



Piezoelectric Actuators

Factory Verification: Cypher_v7.7

Date of test (DD/MM/YY)	Model	Options	Serial Number	Test performed by	Signature	Quality Assurance
11/08/2015	APA600M	SG	15-005	CS		Date: Signature: Name: Stamp:

Electrical Admittance vs. Frequency

Mechanical conditions:
Free-Free

Measurement Apparatus:
Cypher Instruments C60

Resonance Frequency:
1237 Hz

Effective Coupling Coefficient
31 %

Acceptance limits :1110 Hz < Fr < 1436 Hz.

Notes:

Displacement vs. Input voltage

Mechanical conditions:
Blocked-Free

Measurement apparatus:
Capacitive sensor MC2930

Sensor gain:
300 µm/V

Tension gain probe:
x20.00

Driving frequency
10.00 Hz

Measured displacement :
572.69µm pk-pk for 170.02V pk-pk

Maximum displacement:
572.62µm pk-pk for 170V pk-pk

Acceptance limits : Vmax=150V ; Vmin=
-20V; 494 µm < U < 729 µm.

Notes:

SG vs. Displacement

Mechanical conditions:
Blocked-Free

Displacement measurement apparatus:
Capacitive sensor MC2930 - 300 µm/V

SG measurement apparatus:
SG75-3 SG21-04015

SG controller gain:
949.3000

Driving frequency (Hz):
10.00 Hz

Max measured displacement:
572.62µm pk-pk for 170V pk-pk

Strain Gauge Gain (mV/µm/V):
3.245E-3

Vcc:
5.0000

Figure 33 Factory verification sheet delivered by CTEC

In the blocked-free condition that is considered in our case, the frequency behaviour is analysed using an admittance analyser. This kind of apparatus is useful in piezo mechanism identification because it allows getting information about piezo excited modes of the structure.

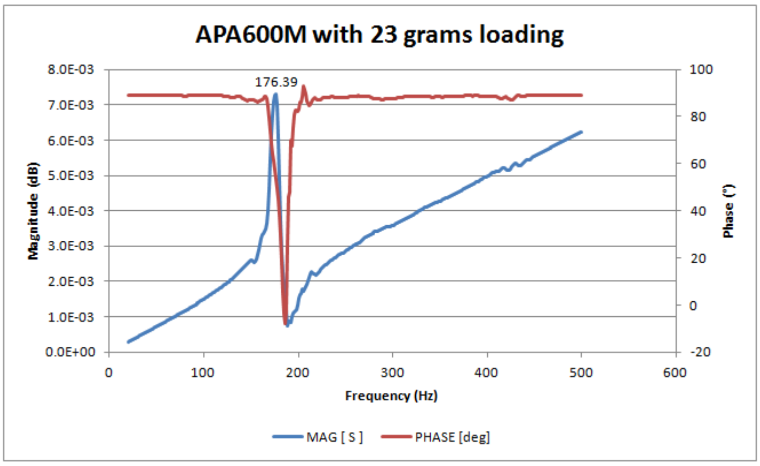


Figure 34 Admittance measurement on considered system

For more complex or detailed systems, the elementary model may not be enough. A modal identification from Finite Element Model software of the mechanism or a hardware-in-the loop identification process may be necessary to take into account other modes at higher frequencies in order to better fit the real application behaviour.

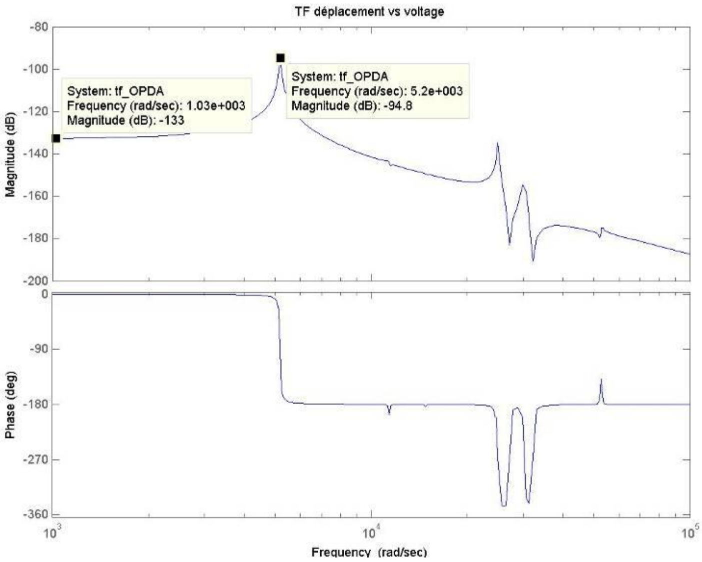


Figure 35 Modal identification on a multi degrees of freedom mechanism

VII. 3. ELECTRICAL PARAMETERS

Electrical parameters are decomposed into 2 categories: signal and power. Signal data concerns ADC and DAC converters, sensor bandwidth and gain for example. Power data is about current limitations, voltage saturation. Those parameters are mainly ruled by hardware (Typical values are given in Table 5). The control limitations induced by these data vary from one configuration to another.

Parameter	Value	Units	Note
Controller (UC45)			
Sampling frequency			
ADC filter frequency	100	kHz	1st order low pass
DAC filter frequency	5	kHz	1st order low pass
P, I, D	-		See §XXXX
Filter	-		See §XXXX
Amplifier (LA75A)			
Gain	20		
Cut-off frequency – small signal	33	kHz	1st order low pass
Max voltage saturation	+150	V	
Min voltage saturation	-20	V	
Current limitation	90	mA	Refer to CTEC catalogue to obtain current limitation of various amplifiers (the power bandwidth). Example for LA75A.
Sensor (SG75)			
Gain	8.5/stroke		Gain is adapted to entire deformation stroke real value can be extracted from factory verification sheet
Cut-off frequency	15	kHz	1st order low pass

Table 5 Typical electrical parameters values