DRIVING AND CONTROL ELECTRONIC OF PIEZOELECTRIC ACTUATORS FOR SPACE APPLICATIONS

Olivier Sosnicki
CEDRAT TECHNOLOGIES
10 Chemin de pré carré 38246 MEYLAN, France
Phone: +33 04 76 90 50 45- Fax: +33 04 76 90 16 09
Email:Olivier.sosnicki@cedrat.com
URL: http://www.cedrat.com

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Keywords

Piezo actuators, motion control, Power conditioning, Linear drives, Servo drives

Abstract

Piezoelectric mechanisms are more and more used in space applications requiring precise positioning functions for scientific payloads or optical functions. Indeed, piezoelectric actuators are generally deemed of being good candidates for driving and control compact mechanisms. They offer advantages like:

- fine precision,
- low power consumption,
- fast time response,
- and easier implementation.

For the application of these new components, an adapted electronic must be used to obtain the command of the actuators. The use of an unsuited driver can ruin the accuracy of the mechanism.
To comply with the space applications needs, the "**FB-LA75 SPACE**" has to comply with many requirements besides the functional ones: space environment in terms of vibration, radiation and thermal vacuum, but also in terms of quality of design and reliability.
After a brief recall about the original "Amplified Piezo Actuators" family and the qualified actuators designed by Cedrat Technologies, a high accuracy driving electronic development is proposed in order to obtain the full characteristics of the mechanism.

The study and the accuracy budget are also described: phase stability, thermal stability, noise budget.

The paper will conclude with:

- a discussion of these new performances,
- estimated capabilities for the future,
- application perspectives.

1. Introduction

Piezo actuators [1] display attractive features for space application, such as precise positioning, unlubricated, non magnetic behavior, and leading to small mechanisms. However, the performances of piezo mechanisms cannot be considered separately from their driving and control electronic. Starting

with a multilayered component, which has been space evaluated in the frame of French Space Agency (CNES; DTS/AE/MT/ME and DTS/AE/SEA/ACE)) contract [2], it is possible to build Parallel Pre-stressed Actuators or Amplified Piezo Actuators.
To use these mechanisms, we have studied electronic functions and realized a sub-system (named FB-LA75 SPACE) which include the whole of the parts to drive the different mechanisms with fine precision and high accuracy
It can be interfaced with an other sub-system which scans the TMs and commands the TCs.

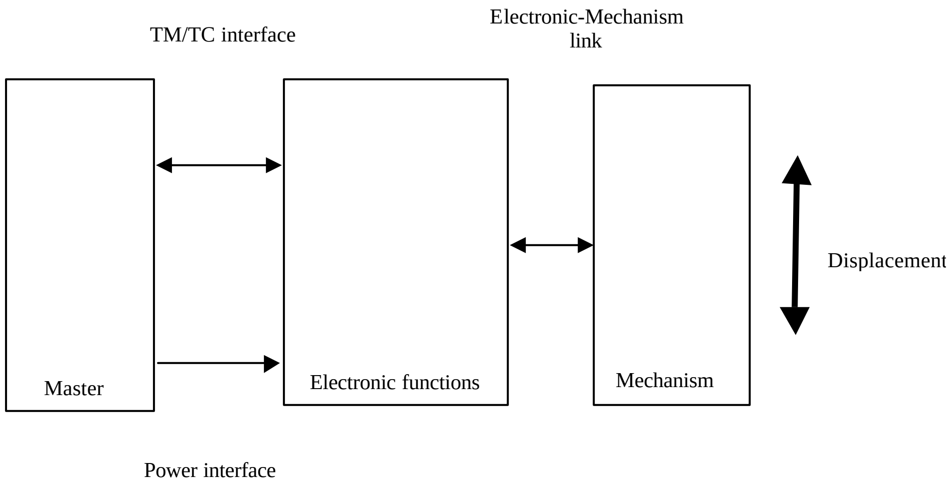
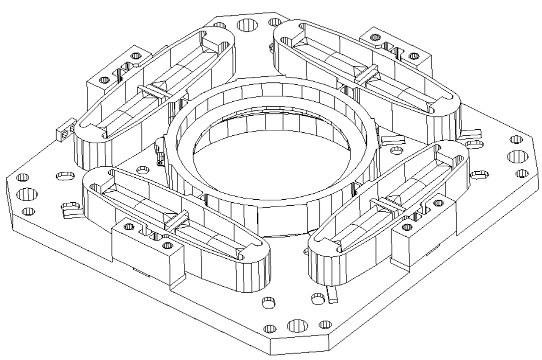


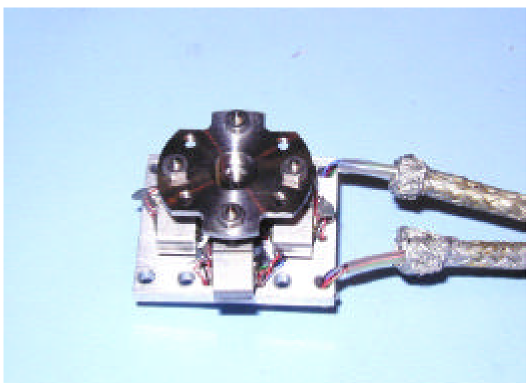
Fig 1 : Overview of the driving and control electronic

2. Considerations on the mechanism

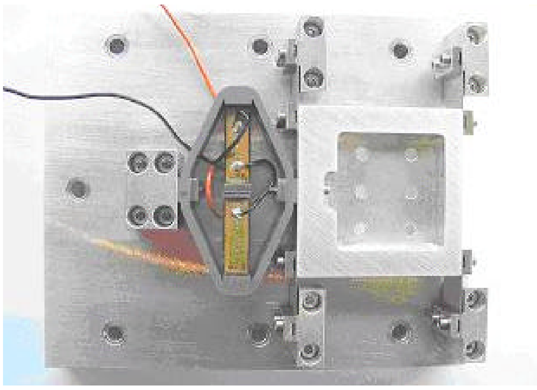
The development of the control electronic for space applications is directly connected to the use of a qualified piezoelectric actuator. The selected actuator is the APA120ML, which is designed for space instruments.
We notice that Cedrat Technologies have designed other actuators for space environments like the XY 200M stage, based on APA200M [1], the Midas stage (Rosetta mission), based on APA50S [2] or the Pharao double tilt tip mechanism, which uses APA35XS. All these devices may be connected to the new electronic described in the following lines without modifications of the PCB layout.



Normally centered stages ↑



Pharao DTT↑



← *Mechanism with APA120ML*

Fig 2 : Mechanisms that the standard electronic can drive

The XY stages are normally centered. To obtain a normally centered design, a symmetric design and a driving in push-pull mode are used. (Figure 2). A key advantage of this design is that the two channels display a low cross coupling and therefore allows the use of two independents drivers and controllers. This aspect dramatically simplifies the driving control.

The ML series are especially designed to obtain stiff actuators and to produce higher displacements than direct actuators. Consequently, they have a high bandwidth and can be used in several dynamic applications. The APA120ML gives the following characteristics: 120µm displacement, 1750Hz blocked-free resonant frequency, 1400N blocked force, -20..150V voltage range and 20µF electric capacitance. Its mass is 160 grams.

3. Design of the driving and control electronic

A piezo driving electronic requires several features:

- a large gain to provide the high voltage to the mechanism,
- a high signal to noise ratio to improve a high accuracy and a fine resolution,
- a low quiescent current to decrease the power consumption
- protections (against short circuit,…) to have a high reliability system.

Although piezo actuators have "infinite" resolution, features such as accuracy, stability can only be improved by using a closed loop involving a position sensor. The performances therefore become dependent on the driving and control electronic.

And thus, the electronic control is composed of:

- a DC-DC converter,
- a post regulation stage,
- an additional TM/TC interface
- a linear amplifier,
- a sensor conditioner,
- a filtered Proportional-Integral controller.

The first three stages allow to supply and to scan the different functions of the electronic board and the three others one allow to drive the actuator in closed or in open loop.

As the electronic board is able to drive a XY stage like the XY 200M stage or the Amplified Piezo Actuators like the APA120ML mechanism, the driving and control functions are duplicated and the DC-DC converter is designed to provide the high voltages for two channels.

The topology chosen allows to multiple the number of the channel by adding control and driving electronic boards. The DC-DC can be redesigned to increase the output power consumption.
The whole of the electronic is designer to be modular: If the application requires an multi channel control, the DC/DC converter and the TM/TC can be kept and the driver functions including the controller and the linear power amplifier are multiplied. Of course, if the redundancy philosophy requires it, the electronic can be designed with only one DC/DC converter and TM/TC and its driver function.

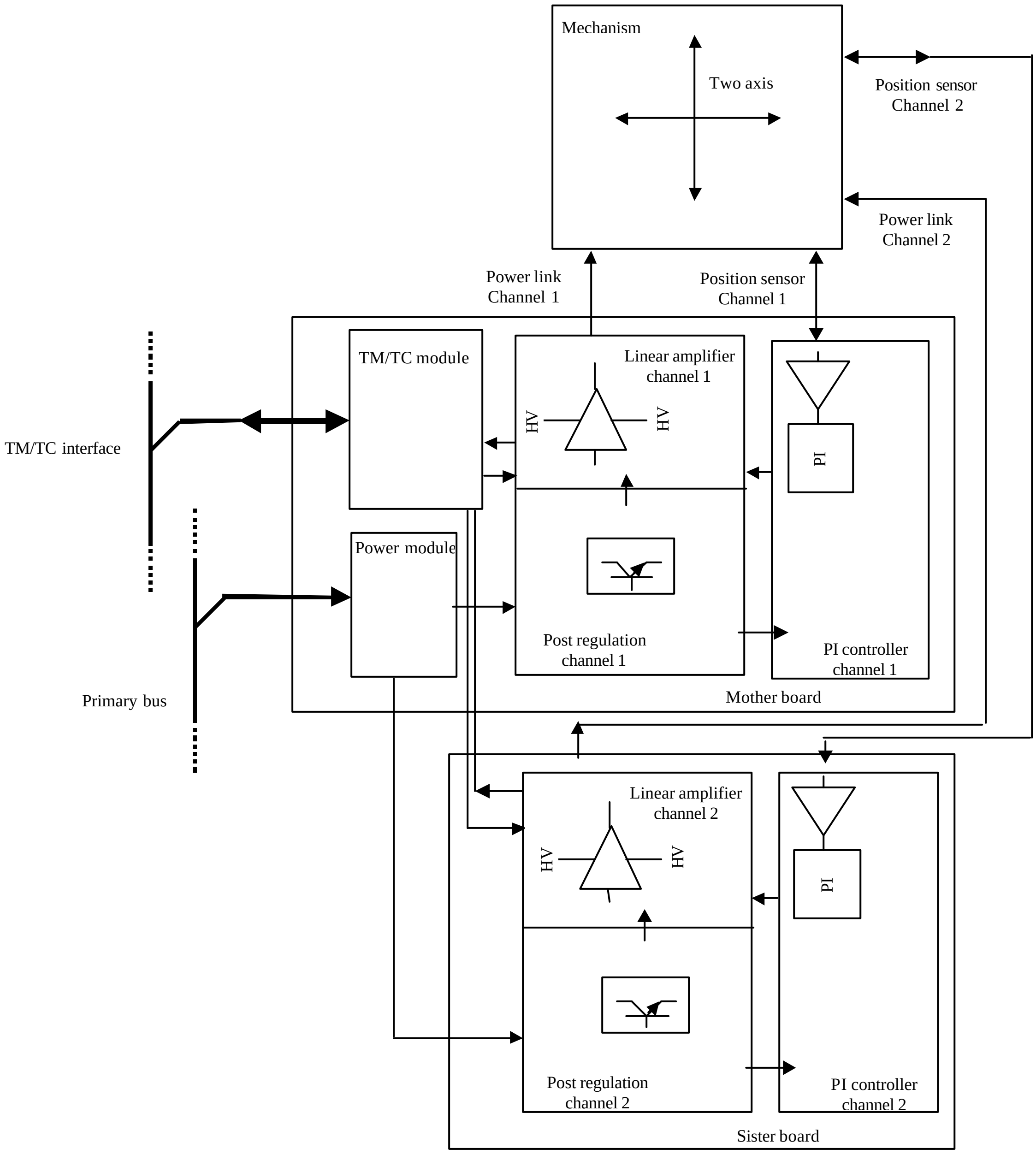


Fig 3 : Architecture of the FB+LA75 SPACE

3.1. Power stage

The power stage is able to drive the mechanism in open loop. It provides the asymmetric high voltage (regulated), auxiliary voltages (regulated) to the linear amplifier described hereafter.
The DC-DC converter is isolated from the main primary bus. As the actuator is supplied with high voltages, the DC-DC converter is able to provide +165V and –30V from the primary bus. The topology chosen is a fly-back converter which can be switched on or off via a TC and synchronized by an external clock. It is protected in current and voltage. In add, we have an In—rush current filter to minimize the overshoot at the start of the DC-DC converter.

The secondary output voltage varies with the load, so regulators are used to stabilise all the secondary voltages. For high voltage (>40V), pre-cabled regulators do not exist. That is why the 160V linear regulator is made with discrete components and is protected against over current.
The choice between linear or switching regulators is made to have a ratio Signal to Noise better.

The power amplifier is a linear type built around the topology of class AB power amplifier. It allows to drive the mechanism with very low noise. The power stage is protected against over current and the current limits are fixed to +/-30 mA (see §5 for the perspectives).
A special care is taken to ensure the stability of the amplifier. Indeed, the mechanism behaves at first approximation in a pure capacitate depending of the type of actuator. The phase margin in open loop is higher than 45° which is very stable on all loads.

3.2. Control stage

To minimize the disturbances (creep effect, thermal drift, …) and the hysteresis of the actuators, the electronic includes an analog control loop which allows to operate the piezo actuator in open or closed loop.

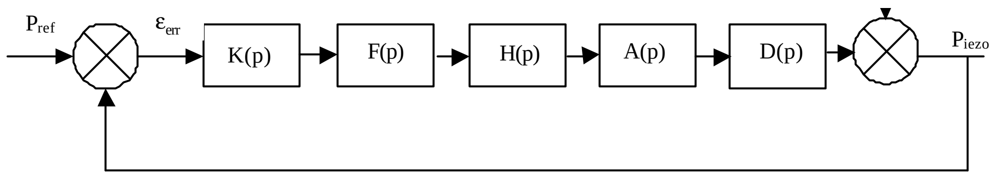


Fig 4 : Bloc diagram of the position control loop

With: P_{ref}*, the displacement consign,*
$P_{drift,}$ *the disturbance,*
P_{piezo}*, the corrected position of piezoelectric actuator,*
$e_{err,}$ *the error between the consign and the real position of the actuator,*

The control loop is composed of:
- a position sensor (transfer function: K(p)), which includes a 2nd order low pass filter,
- the corrector (transfer function: F(p)), which includes the PI controller,
- and a 4th order low pass filter (transfer function: H(p)).

The order is sent to the actuator (transfer function: D(p)) through the power amplifier (transfer function: A(p)).

So, the control loop is described in open loop with the following formulae:

$$T(p) = K(p) \times D(p) \times H(p) \times A(p) \times F(p) \quad \text{[Eq. 1]}$$

And the control loop is described in closed loop with the following formulae :

$$P_{piezo}(p) = \frac{T(p)}{1+T(p)} \times P_{ref}(p) + \frac{1}{1+T(p)} \times P_{drift}(p) \quad \text{[Eq. 2]}$$

In many applications, the functional mode is a quasi static operation (position under a static consign), also the corrector is a Proportional-Integrator for a high static and dynamic accuracy.

The study of the control loop was about the stability of the loop, the accuracy and the response of a position step.
The criteria to obtain a good response to a step is a fast response with an overshoot below 5%. So, we improve the high accuracy of the position.

Two kinds of sensors have been implemented:

- strain gauges sensors,
- capacitive sensors.

The sensors can be either strain gauges in a full bridge or capacitive sensors. If the position sensors are strain gauges, the conditioners are implemented on the electronic board and the sensor can be calibrated with the offset and the gain adjustment. If the second types of sensor are used, the conditioners are not yet on-board and the calibration are made on an external board.

The choice of an capacitive sensor or a strain gauges sensor is done principally by the fact than the capacitive sensor is an absolute sensor for the mechanism. Indeed, the strain gauges sensors are mounted on the ceramic of the mechanism and so, the ceramic thermal coefficient is different ofmechanical frame thermal coefficient. The choice of the position sensor depends of applications.

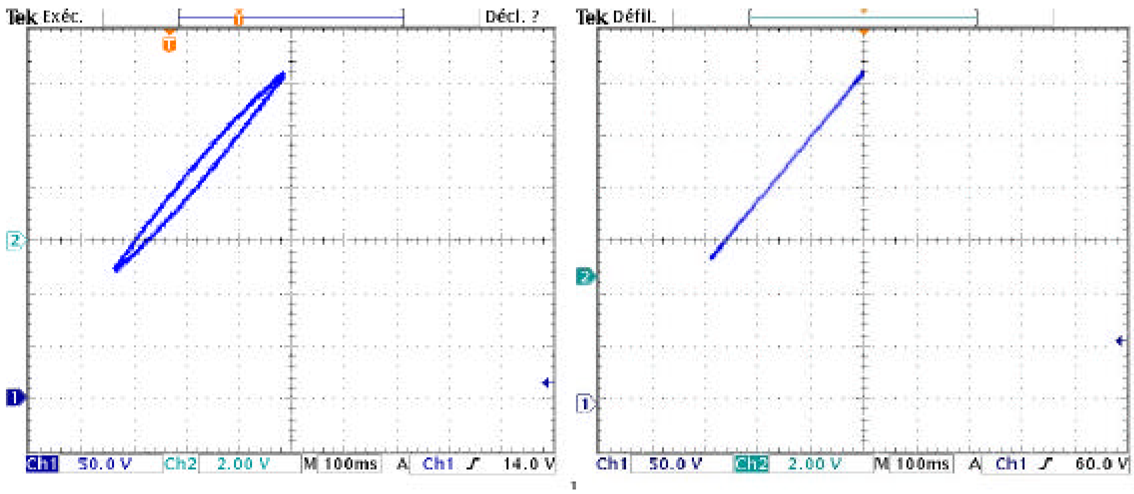


Fig 5 :Mechanism response to a sine order in open and closed loop

We can see the reduction (with strain gauges sensor) of the hysteresis effect when the controller is switched on.

The study of the global accuracy budget is given in the table 1. The principal effect is the thermal drift on the electronic sub-functions. For the analyse, the hypothese are a stability of the temperature of +/-2°C with a full range displacement of the mechanism. The principal contribution in closed loop is the position sensor.

Functions	Thermal stability by analyze @+/-2°C	Thermal stability by tests @+/-5°C	Noise@100Hz	Remarks
Strain gauges sensor	+/-32 nm	Non processed	3-4 nm	In closed loop
Capacitive sensor	+/-50 nm	Non processed	4 nm	In closed loop
Power linear amplifier	+/-25 nm	Non processed	0.65 nm	In open loop only
Error signal conditioner	+/-3 nm	Non processed	7 pm	In closed loop
PI controller	+/-9.3 nm	Non processed	10 pm	In open loop only
Low pass filter	+/22 nm	Non processed	43 pm	In open loop only
Total budget	**8.75 nm/ °C in the case of strain gauges sensor**	**5 nm/ °C**	**4.05 nm**	**In closed loop**

Table I : Analyze of the accuracy budget

The tests consist to place the mechanism in an stable thermal environment and the electronic unit in a thermal chamber with a gradient of +/-5 °C. The total contribution (after a stabilization time) is lower than 5 nm/°C (by tests) with a drift of the temperature of +/-5 °C and in a full range displacement (i.e: 120 µm). The different contributions aren't measured but only the final drift (on the displacement) is performed. In the case of the analyze, it's a worst case analysis. The resolution is fixed by the noise in a 100Hz equivalent noise band.

3.3. TM/TC interface

the TM/TC interface allows to connect the FB-LA75A SPACE to the master unit. As the applications can be very different, the design of the TM/TC module is not especially characterized because many protocols are specific to platforms.
The standard protocol to read the different TMs and to command the different TCs is a passive interface without intelligent components as ASIC or µ-processor:

- ML16/DS16 protocol to send words of 16 bits,
- SBDL link to send analog or digital signals,
- Temperature acquisition to send the monitoring of different temperature (mechanism, electronic unit).

4. Space constraints

Different analyses are made to obtain the electronic board able to withstand space environments:

- radiation analysis,
- thermal analysis,
- Electro-Magnetic Compatibility analysis.

The results of the radiation analysis show that the cumulated dose on the components is 10 krad at level components (for the linear amplifier, the total dose is 5krad). The power amplifier is composed of MOSFET transistors sensitive to Single Event Burn out and Single Event Gate Rupture. To minimize these effects, a derating factor of 50 % on the Vdsmax parameter is take into account (see §6 to increase the cumulated dose).

The thermal analysis shows an elevation of temperature of 25 °C max versus the ambient temperature (only by conduction) at level of the junction with the additional conduction under the dissipating components.

The EMC design is compatible with the rules in space environment: Filters connectors and ground and power plans to reduce the conducted emission and the conducted susceptibility, Connection by RF joint and screws between different mechanical interfaces in order to reduce the radiation emission and the radiation susceptibility.
The reduction of the cross-talk between the different electronic functions is realized with the integration of the different functions (post regulation, low power and high power level) in mechanical cells.

The mechanical design allows to maintain the electronic board in vibration environments. The printed board is fixed in many points to remove the risks of destruction (with a framework).

From a point of view of space reliability, the electronic board is designed with the state of the art in the space industries. The choice of the electronic components, material parts and process is made with the respect of the different ESA and CNES rules: the printed board is routed to receive some Hi rel components. The mechanical parts are chosen to be compatible with the space surface treatments.

5. Architecture

The figure 7 shows an elegant breadboard model for the axis number 1.

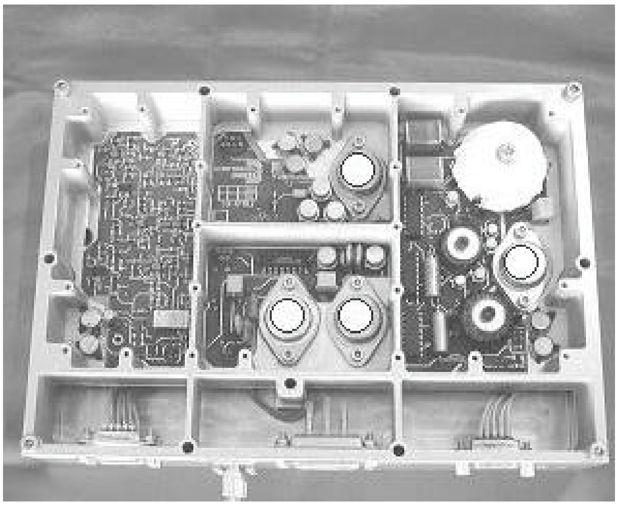


Fig 6 : View of an elegant breadboard model of the driving and control electronic

The different parts are located in mechanical cell to isolate the electronic functions. We find the DC-DC converter cell (on the right of the picture), the regulation and the power amplifier cell (on the middle of the picture, and the controller cell (on the left of the picture). Five connectors are used for the electrical interfaces: one for the connection with the primary bus, two for the link with the actuator 1 and actuator 2, two for the link with the position sensor of the actuator 1 and actuator 2.
This mechanical design allows to stack the different axis. If we use more than two axis, we can stack the mechanical box.
The mechanical parts allow to robustify the printed board under vibrations and allow to evacuate the heat to the plate. The dimensions are 220mm*150mm*50mm and the weight is 1300 grams for one axis and 1600 grams for two axis.

6. Performance summary of the driving electronic FB-LA75 space

The performance are summarized in the following table II.

Performances	Levels
DC-DC converter :	
Primary bus connexion	Yes/ isolated
Primary bus voltage range	18V 38V
Switching frequency	~30kHz
Secondary ouputs	+160V, +/-20V, -30V
Current/ voltage limiters	Yes
Soft start	Yes
Noise level	<1V rms
Regulated voltage	
output +/-15V	+/-15V +/-5%, +/-100mA max.
output -30V	-23V min→ -28V max, -35mA
output +150V	155V min.→165V min, +35mA
auxiliary output	130V +/-1%, +35mA
Noise rejection for the high voltage	<0.2V
Current protection	Only for high voltages
Linear amplifier	
Input voltage,	-1 →+7.5V
Output voltage,	-20 → +150V
bandwidth,	0-10Hz depending of the load
output current,	+/-30mA

phase margin in open loop load	45° mini capacitive :de 200nF à 40µF
Controller : Proportional Integral type, adjustment Position sensors: Consign Frequency	 Yes, parallel Yes Capacitate sensor or strain gauges sensor -1.6 → 8.5V <10 Hz. function of the load
Environment Vacuum Radiation level High reliability Push pull mode Number of axis	 Yes 10krad but for the linear amplifier devices<5krad hi rel components Yes Two (modular)

Table II : Performances summary of the FB-LA75 SPACE

Many evolutions are described in the following paragraph.

7. Conclusion and perspectives

In conclusion, Cedrat Technologies has designed a new driving and control electronic for space piezo qualified actuators. This driver operates in open or closed loop with two types of sensor: strain gauges or capacitive sensor. The complete range of the actuators can be drive without electronic modification.

The performances of the electronic allow to obtain the full characteristics of the mechanisms: 120µm displacement with a 4.05 nm resolution and 5 nm/°C thermal stability (in full range). The selected design is fully compatible with space environments and with a quality and a reliability concept. It can be connected directly from the primary bus, and generates the high voltage used for the actuators and the correction function to minimize some disturbances. This sub system can drive all the qualified actuators developed by Cedrat Technologies but it can also be used in an industrial application with very good accuracy performances.

The evolutions in progress are multiples:

- the choice of the topology to scan and command the FB-LA75 SPACE via the TM/TC interface,
- the decrease of the weight of the mechanical frame: At the moment of the study, the Bread Board Model is realized to verify the different analyses. A reducing treatment of the weight can be done,
- the increase of the bandwidth. We are developing a new generation of linear amplifier with an output current higher than 300mA. The design is realized in discrete components to improve the performances of the power amplifier. This perspective will allow to use the mechanisms in scan applications or in application where the time response is very high. In the same way, the Total Cumulated Dose is increase by chosen hard-rad MOSFET.
  The topology is the same as the first linear amplifier to minimize the noise in the control loop and increase the accuracy of the displacement.

With these evolutions, the perspectives of uses of this electronic unit with different mechanism are shutters, optical refocus, fine pointing, active control of vibration…

8. References

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