Electrically-Tunable Low-Frequency Miniature Suspension

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Abstract

Optical instruments such as interferometers and optical delay lines are sensitive to external vibrations and require a strong isolation of vibrations. Some products for active, semi active or passive isolation exist but are rather large which makes them much more suitable for lab applications than to embedded applications as meet in Space, Aircraft or Military applications in general, or in the space ICE CNES experiment. These requirements have driven the development of a new type of Electrically-Tunable Low-Frequency Miniature Suspension. The result is a new miniature semi-active single-axis suspension (<10x10x2cm^3) called ETS offering a very low cut-off frequency (<10Hz). Moreover, the ETS can be electrically tuned as a function of the application. Its semi-active control allows better vibration isolation compared to existing voluminous passive low frequency suspensions.

Keywords: Active suspension control, damping, negative stiffness, amplified piezo actuator, tunable frequency.

Introduction

Optical instruments such as interferometers and optical delay lines are sensitive to external vibrations and require a strong isolation of vibration.

A typical situation has been met by Cedrat in the ICE space experiment of CNES, ONERA, SYRTE and LCFIO. ICE stands for "Interférométrie Cohérente dans l'Espace", meaning Coherent Interferometry in Space [1]. This project aims at developing a new type of interferometer in which the coherent source is a Bose-Einstein condensate. This source would allow detecting the phase shift of a single photon by diffraction of a laser source on the Bose-Einstein condensed mater. To make this concept feasible, extremely severe requirement are prescribed for the stability of the inertial reference mirror: 10^{-7} m/s^2.Hz$^{1/2}$ between 0.5 Hz and 1 kHz.

This ICE application is the most severe ever encountered at Cedrat, but it is also representative of a new class of requirements for suspensions offering the following features:

- Structure: One-degree of freedom stackable stage,
- Miniature device: < 10cm x 10cm x 2cm,
- Light weight: < 1kg
- Typical mass payload: 100gr
- Very low cut-off frequency: <10 Hz
- Low power requirement: < 1W
- Compliance with harsh environment (vibrations, vacuum …)

Standard, off the shelve products for active, semi active or passive isolation exist but are rather large which makes them much more suitable to lab applications [2] than to embedded applications as meet in Space, Aircraft or Military applications in spite of some attempts [3]. In particular it has been deemed far too large in the aforementioned space ICE CNES experiment.

These requirements and state of the art have driven the development of a new type of Electrically-Tunable Low-Frequency Miniature Suspension.

Design

The proposed Electrically Tunable Suspension (ETS) is based on the APA patented technology, in particular the APA60SM (fig 1). The APA (Amplified Piezo Actuator) is a mechanically magnified preloaded stack of low voltage piezoelectric ceramics (MLA). The mechanical amplification is obtained thanks to an external elliptical shell made of stainless steel which magnifies along the short axis the MLA deformation occurring along the main axis.

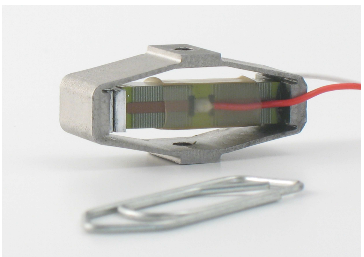

Fig 1 - APA60SM

The ETS system is a semi active suspension, having a very low stiffness provided by a guided spring mechanism, in a principle inspired in part by the tunable damper presented in [2]. This spring stiffness is controlled by the APA60SM piezo actuator. The guidance of the suspension is realized by mechanical flexural blades. In principle, these blades are preloaded by a spring [2] in order to decrease the natural stiffness of the guidance. In theory [5], a blade submitted to compressive force on its longitudinal direction, sees its transversal (flexural) stiffness reduced. Note that this force must be below the buckling force limit of the blade.

Therefore, thanks to the large displacement of the so called APA, it is possible to tune the suspension cut off frequency all along the stroke of the payload.

As the piezo actuator is supplied in static condition, the current demand is very low and can be fulfilled by a small lab amplified such as the standard low noise linear Amplifier CA45 for Cedrat (fig 2). The CA45 is a standalone one channel driver able to control the Electrically Tunable Suspension.

Fig 2 - CA45 Linear Amplifier

The structure of the ETS is a X stage (fig 3). Its size is 89x89x18 mm3 (3.5x3.5x0.7”). It offers a plate for fixing the load to isolate. This plate is mobile along a direction parallel to one of the stage long axis. This structure allows the system to be stacked in order to get a 2 degrees of freedom isolator (XY isolation stage)

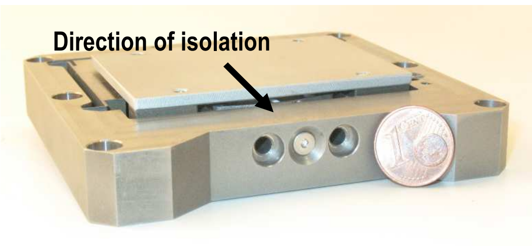

Fig 3 - Views of the new Electrically Tunable Suspension

Simulations

Both mechanical and automatic simulations are used to design the ETS.

<u>Mechanical:</u>

The mechanical design first aims at miniaturizing the suspension. It has to be tiny and includes a long strong linear guidance, a sensor, an actuator and interfaces for preload. The CAD model is shown below (fig.4).

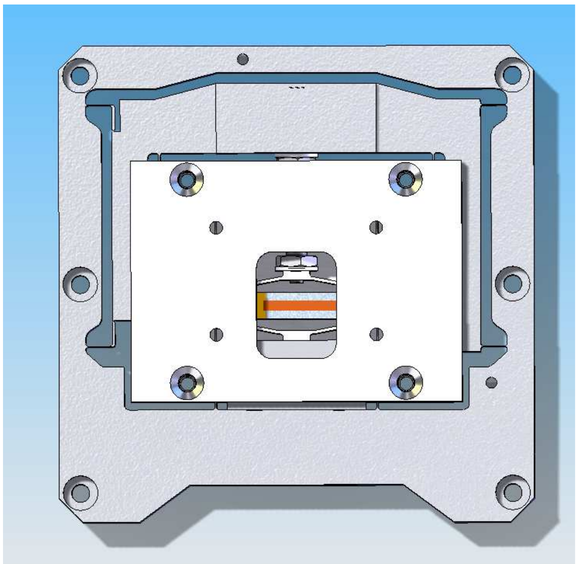

Fig 4 – ETS CAD design

The APA piezo actuator is represented in the middle of the assembly, right in front of the opening.
Once the design is completed a mechanical analysis is performed to ensure the low stresses occur within the mechanism. A dynamic study is useful to simulate the dynamic behavior of such a device in order to get a robust control using automatics. The output of the dynamic calculation is a transfer function to be used in a controller.
The following figure (fig.5) displays the displacement response of the suspension without any use of the controller. It represents the displacement passive response in relation to the frame excitation.

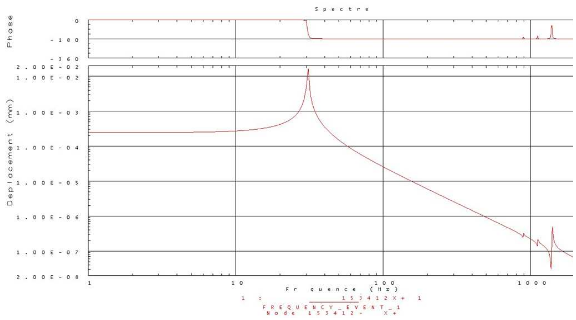

Fig 5 – displacement passive response of the suspension: mechanical simulation

<u>Automatic and control:</u>

An automatic study allows us to set a PID controller. Optimised parameters are implemented into a real time controller such as Cedrat Technologies UC45. The controller is based on FPGA platform form National Instrument. The dynamic response is stable thanks to a low pass filter placed at 30Hz. Phase / Gain margin computation are showed below (fig.6)

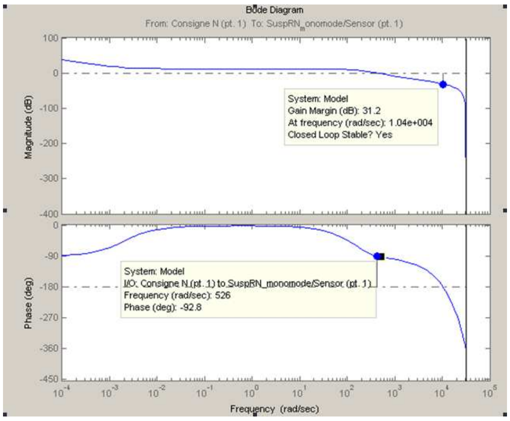

Fig 6 – Controller stability study: Phase / Gain margin

The phase margin is simulated at 90° and the phase margin is computed at 30dB. These values provide low risk of instability of the controller.
Other complex filters have been used to reduce high frequency parasitic modes.

Results

The performances of suspensions are classically evaluated on the base of the transmissibility curve. Actually, this curve represents the fraction between the suspended payload acceleration and the base acceleration excitation level.
An experimental set-up uses a shaker (Fig.10), a spectrum analyzer and two accelerometers to draw the transmissibility curve (fig.7)

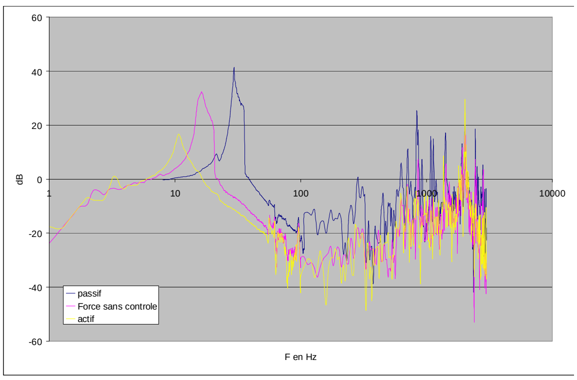

Fig 7 – ETS transmissibility curve:
Blue curve: control Off
Red curve: control On, PID controller
Yellow curve: Control On, optimised controller

All values showed on this curve are not relevant below 5Hz due to accelerometers range limitations.
From the blue curve to the yellow curve, we observe a cut-of frequency reduction from 30Hz to 10Hz. Several controller set up were necessary to optimise the cut off frequency reduction. The semi active nature on this suspension becomes relevant. In addition, another point is the reduction of the quality factor using a semi active control: From the blue curve to the yellow curve we observe a quality factor reduction from 40db to 16dB.

It is possible to measure the quality factor, (i.e magnification at resonance frequency) thanks to simple experimental set-up. The following curve displays the quality factor Q value according to the input controller parameter (fig.8).

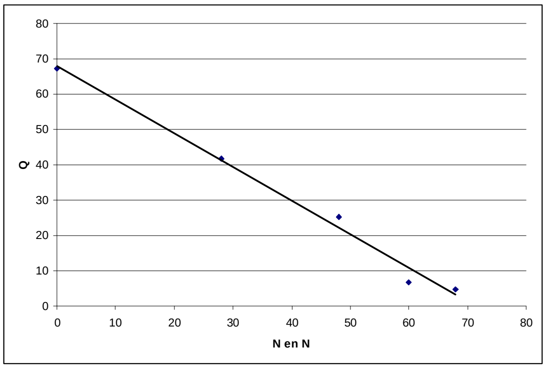

Fig 8 – Quality factor evolution Vs input controller parameter

It appears possible to reduce the magnification at resonance frequency from 68 to 5.

In ICE project [1], the purpose of the isolator it to isolate an optical device from a spectral density of energy at low frequency. The spectral density of energy to be withstood is represented on the following (fig.9) in blue colour.

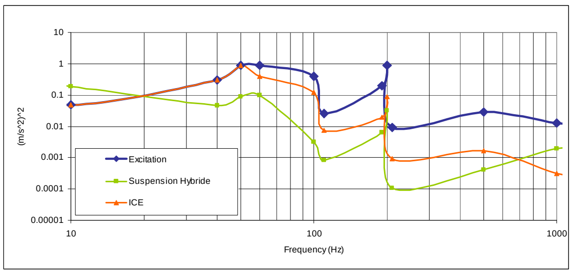

Fig 9 – Spectral density of energy using an active isolator or semi active ETS

According to this graph, the ETS response to the spectral density of energy (represented in green colour) is more efficient than classical active isolator (represented in orange colour).
The use of elastomeric element, in correct proportion, improves the response of the ETS, since it decreases the quality factor

Fig 10 – Dedicated shaker bench

Performances are given in table 1 for an isolated mass of 100gr corresponding to the mobile interface without payload. The added isolated device weight will have a positive effect on the Electrically Tunable Suspension performances.

References	Unit	Performances
Technology	-	Semi-active control based on APA
Resonance frequency	Hz	3.5
Cutoff frequency (-3dB)	Hz	6.5
Attenuation slope	dB per decade	-40
Isolated DOF	-	1 (2 with stacked units)
Stiffness	N/mm	0.050
Dimensions	mm (in)	89x89x18 (3.5x3.5x0.7)
Weight	g	550
Electronics	-	Cedrat Technologies CA45 UC45 controller

Tab 1 – Performance of the new Electrically Tunable Suspension

A comparison with standard existing equipment consisting of a passive mechanically tuned suspension [4] shows the ETS offer lower cut-off frequency which is highly desirable while being much smaller.
The following snapshot (fig 11) shows the ETS final prototype, fully tested.

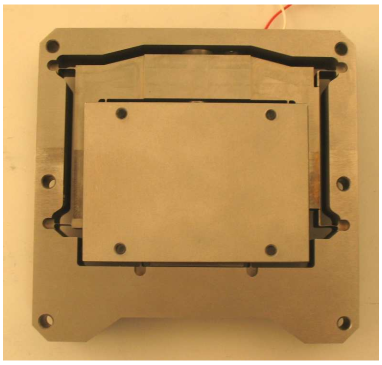

Fig 11 – ETS prototype

The following curve (fig 12) shows the ETS final transmissibility curve and a comparison with conventional passive mechanically tuned suspension performances

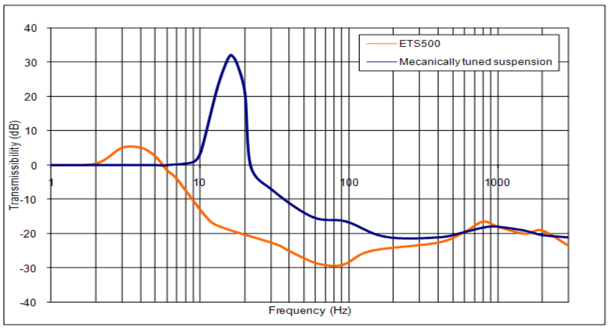

Fig.12 - Comparison of the ETS performances compared to a conventional passive mechanically tuned suspension performances

References

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