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# Piezoelectric solutions: Absorbers and Suspensions

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## ABSTRACT

Most industrial machines present vibrations. These vibrations can lead to premature aging, mechanical failure, local noise pollution or discomfort for people working nearby vibration sources. In particular, in the naval industry, vibrations can lead to several problems such as the deterioration of acoustic stealth for military applications, non-respect of the norms limiting the radiated noises on ships or the deterioration of underwater acoustic measurements on scientific ships.

To offer efficient vibration damping solutions, PYTHEAS Technology has developed several devices based on piezoelectricity materials seeking to address the weaknesses of traditional solutions. Currently, the most commonly used solution consists of adding dissipative materials, often viscoelastic ones, which convert vibrations into heat. This solution has the advantage to be simple and cheap. However, its vibration damping performances are limited and its lifespan is often reduced due to creep. Active devices form the second main solution. They present better vibration damping performances, but their cost and complexity are obstacles to their deployment.

PYTHEAS Technology has developed and tested several concepts of absorbers and suspensions which allow to reach a damping coefficient ( $\xi$ ) equivalent to the one of active systems ( $\xi > 10\%$ ), while remaining simple and having more than ten years of lifetime. Furthermore, the electromechanical conversion provided by the piezoelectric effect brings additional advantages : vibration frequency tracking if it varies over time, damping of several modes simultaneously using only one device (gain in terms of added mass and size), device's fine-tuning using the electronic (reduction of manufacturing costs),...

This paper is an overview of the concepts developed by PYTHEAS Technology and their potential applications.

## 1. INTRODUCTION: PIEZOELECTRICITY AND VIBRATION

Piezoelectricity was discovered in 1880 by the Curie brothers in quartz and other crystals [1]. Piezoelectricity is the property of some materials to convert a mechanical stress into an electric displacement (direct effect) and an electric field into a mechanical strain (reverse effect). Today, the most commonly used piezoelectric materials are PZT (ceramics), Quartz (single-crystals) and PVDF (electroactive polymers).

Sonar systems were the first application and were developed during the first and the second World Wars by Paul Langevin for water communication and surveillance [1]. Nowadays, piezoelectric materials are used for a wide range of applications: underwater acoustics, medical imaging, actuators, sensors, etc.

PYTHEAS Technology is specialized in the design and manufacturing of innovative piezoelectric devices and seized the opportunity, through research collaborations [2], to use the piezoelectric effect for vibration damping. Piezoelectric materials are used to convert the mechanical vibration energy into electricity. The electrical energy is dissipated using the Joule effect in an electronic circuit. By coupling piezoelectric components with smart electronic shunts, the damping performances are largely improved compared to usual passive solutions (elastomers, etc.). The piezoelectric solutions developed by PYTHEAS Technology are passive or semi-passive and their performances reach the ones of active systems, while being much more robust.

To solve vibration issues, it is important to choose the systems according to their function and their location on the structure. We differentiate systems that act directly on the structure and control its vibrations (see paragraphs 2 and 3) and systems that act at the interface between two structures to isolate one from the other (see paragraphs 4 and 5).

## 2. BROADBAND ABSORBER: TUNED MASS DAMPER

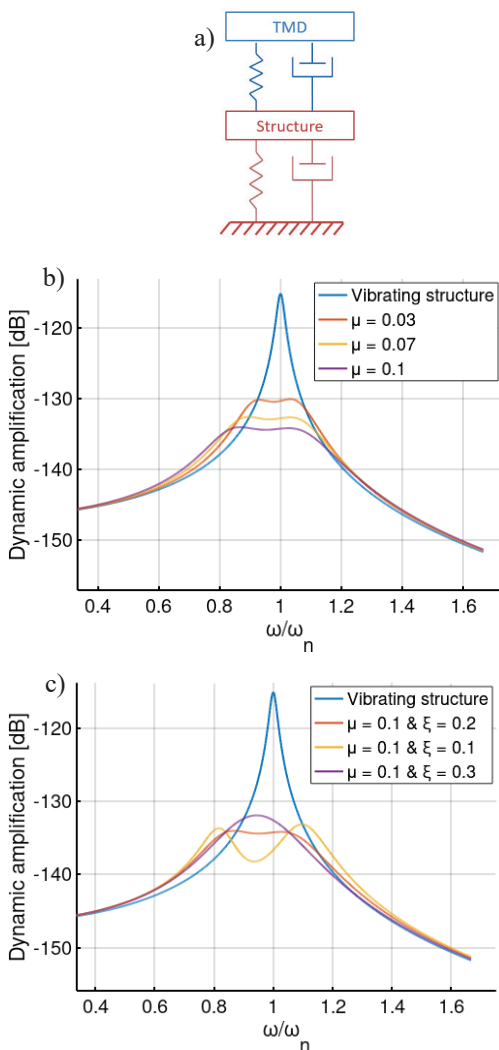
### 2.1 State of the art

A tuned mass damper (TMD) is a device mounted onto a structure to reduce its mechanical vibrations. Originally, it was used in buildings to prevent vibration discomfort, structural damage, as well as for acoustic stealth [3].

The TMD is an oscillator tuned at a frequency close to the resonance of the structure it is attached to. Its oscillations have a 180° phase shift with the structure, which allows to « pump » the vibration energy. The resulting damping depends on the mass ratio between the TMD and the structure ( $\mu$ ), as well as its own damping coefficient ( $\xi$ ) (see Figure 1). Several rules exist for the design of TMDs and the most common one aims to reduce the maximal dynamic amplification level of the structure - also known as equal peak design [4].

Today, the most common TMDs are composed of a mass mounted on an elastomer spring. They present the advantage to be cheap and easy to implement. However,

they present several limits: they are subject to creep, their damping coefficients are low, their characteristics vary with temperature, and their damping frequency is fixed.



**Figure 1.** (a) Principle of a TMD, (b) Dynamic amplification using a TMD with different mass ratios, (c) Dynamic amplification using a TMD with different damping coefficients.

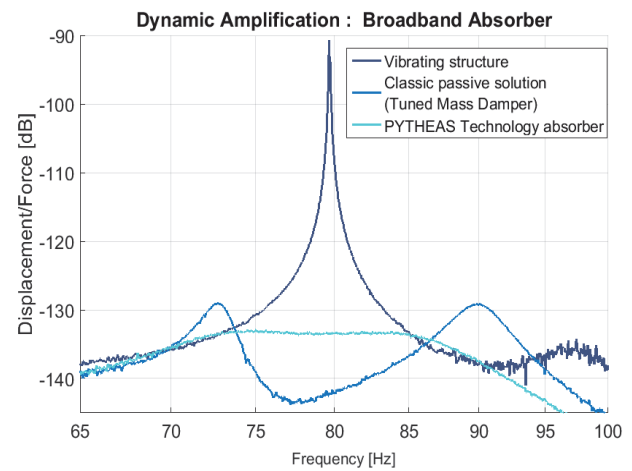
### 2.2 Piezoelectric TMD

As part of its activities, PYTHEAS Technology has developed a piezoelectric tuned mass damper. A proof of concept (POC) was manufactured and tested. The goal of this POC was to damp the first mode of a structure around 80 Hz with a final damping coefficient ( $\xi_{tot}$ ) superior to classic passive solution (3%). The manufactured piezoelectric TMD is a semi-passive device, much more robust and simple than active systems but with equivalent performances : a damping coefficient of 12% was measured, as shown in Figure 2.

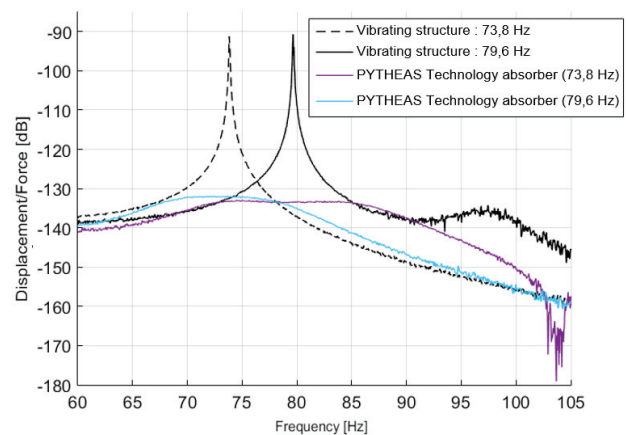
Another advantage of using the piezoelectric effect, in addition to obtaining a high damping coefficient, is the capability to tune electronically the damping frequency of the TMD. Experimentally, an adaptability of 10% has been proved (see Figure 3). An analytical study showed that a

frequency adaptability of 40% is reachable, but experimental test bench conditions limited the range of adaptability to 10%.

This adaptability offers two advantages: first, if the frequency of the structure is modified due to environmental conditions (temperature, fixation, etc.), the TMD is able to follow the system's frequency by using simple control electronics. A second advantage is the reduction of cost: resonant frequency differences caused by manufacturing variations between structures built in series can be compensated by one single tunable TMD instead of custom TMDs for each of these resonant frequencies.



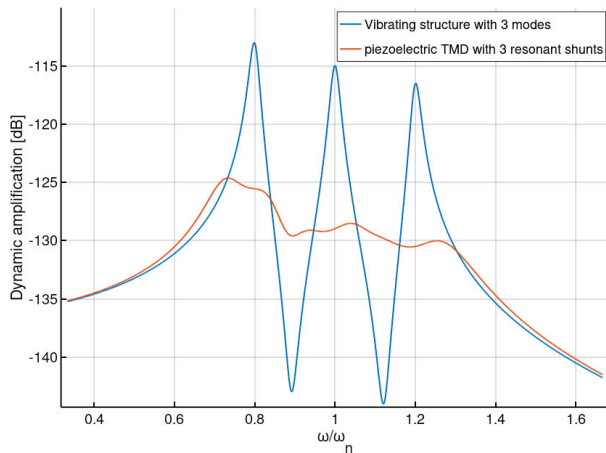
**Figure 2.** Experimental dynamic amplification measurement. Comparison between the vibrating structure without absorber, the structure coupled to a classic passive absorber using elastomer ( $\xi_{tot} = 3\%$ ) and the structure coupled to the piezoelectric TMD designed by PYTHEAS Technology ( $\xi_{tot} = 12\%$ ).



**Figure 3.** Frequency tuning experimental test. The same piezoelectric TMD was used in both cases, only the electrical shunt was modified.

To finish, one unique piezoelectric TMD could be used to damp several modes if they are in a frequency range of 40% as illustrated in Figure 4. It is a very important advantage since it allows to use a unique mechanical device to damp several modes, which provides a

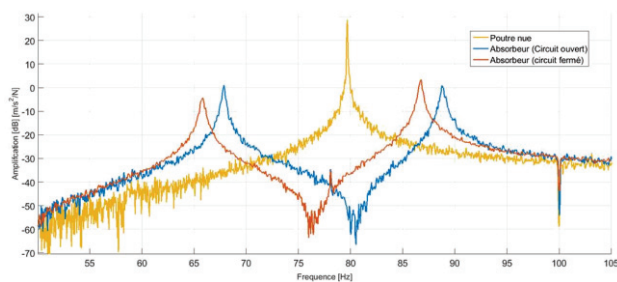
significant mass reduction. The theoretical principle rests on the use of a multi-resonant shunt. This method was developed by Gardiono et. al. [5] for piezoelectric patches and has been adapted to piezoelectric TMDs by PYTHEAS Technology.



**Figure 4.** Damping of the three modes of a structure using one piezoelectric TMD coupled to a multi-resonant shunt. These results were obtained through numerical simulations.

### 3. HARMONIC ATTENUATOR: DYNAMIC VIBRATION ABSORBER

In the case where a harmonic attenuation is needed, a piezoelectric transducer can also be used. In this case, following resonant frequency variations electronically is critical, as a slight mismatch in frequency can make the device useless or even amplify the original vibration. The tunability can reach a frequency range of 40%, as calculated for a TMD. This capability was tested in laboratory and was limited to 5% of tunability because of experimental conditions, as shown in.

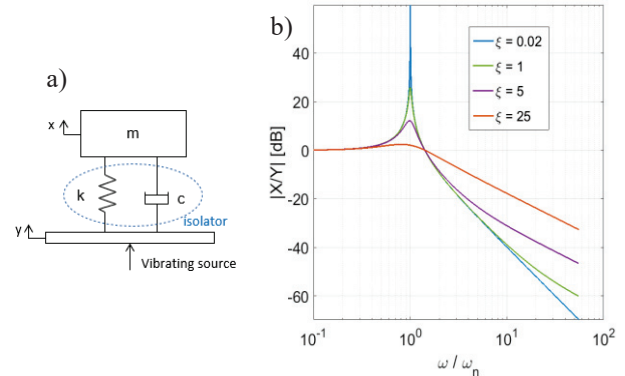


**Figure 5 :** Piezoelectric dynamic vibration absorber with 5% tunability.

### 4. SEMI-PASSIVE ISOLATOR

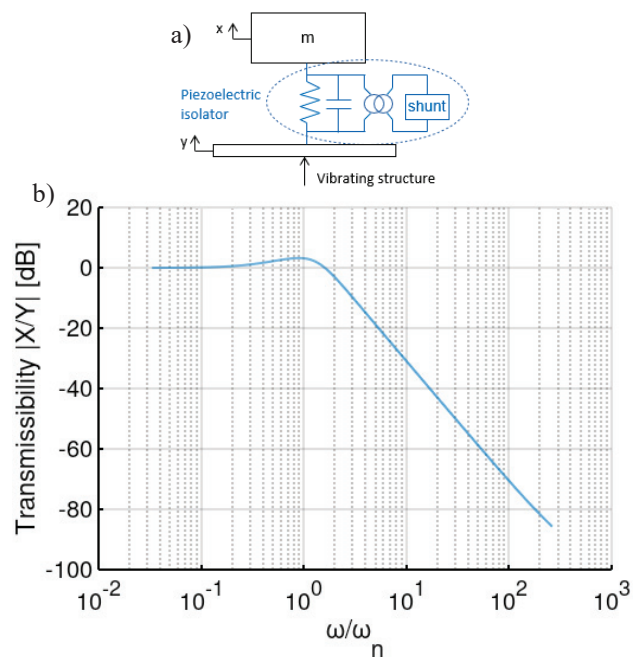
When the vibrations of a structure cannot be treated directly, systems known as isolators can be used at the interface between two structures to isolate one from the other. Currently, the most commonly used solution consists of adding dissipative materials, often viscoelastic ones (elastomer, etc.), which convert vibrations into heat. The performances of an isolator are quantifiable in terms

of transmissibility, which represents the transmission of vibrations through the isolator, as described in Figure 6. The transmissibility should have two main characteristics: a low overshoot at the resonance frequency and a -40 dB per decade decay rate at higher frequencies. With viscoelastic solutions, it is impossible to combine these two properties, as shown in Figure 6.



**Figure 6.** (a) Principle of an Isolator. (b) Transmissibility of viscoelastic isolators of different damping coefficients ( $\xi = \frac{c}{2\sqrt{km}}$ ): with low damping ( $\xi < 1$ ), the decay rate is -40 dB/dec but the overshoot is critical and with high damping ( $\xi > 1$ ), the overshoot is reduced but the decay rate is only -20 dB/dec.

By using a piezoelectric isolator coupled to an optimized shunt [2], both effects can be combined, as shown in Figure 7. In addition to improving the transmissibility compared to viscoelastic solutions, the piezoelectric isolator offers other advantages: high lifespan, good resistance to creep and static load, unchanged behavior at low temperatures, etc.

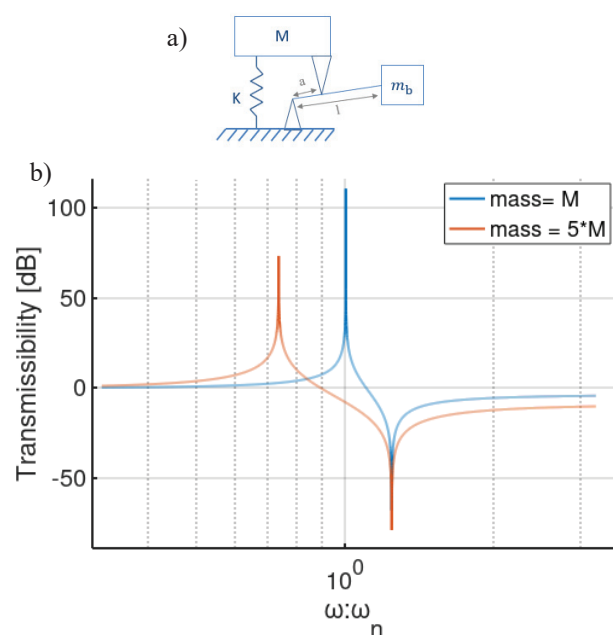


**Figure 7.** (a) Principle of a piezoelectric isolator, (b) Transmissibility of a piezoelectric isolator: the

overshoot is below 3 dB and the decay rate at high frequency is -40 dB/dec.

## 5. PIEZOELECTRIC DYNAMIC ANTIRESONANT VIBRATION ISOLATOR (DAVI)

To achieve proper isolation of one harmonic frequency, a system known as DAVI (Dynamic Antiresonant Vibration Isolator) was designed. In this system, a flapping mass is added to the isolator and placed at the interface between the two structures to isolate. It is designed to generate inertial effect on the support structure in order to obtain a zero of transmissibility, also called « antiresonance ». This antiresonance frequency is independent of the mass to isolate, as shown in Figure 8. A good application example is the isolation of a helicopter seat, where a precise frequency (due to a rotor rotation for example) must be filtered regardless of the mass of the operator [6].



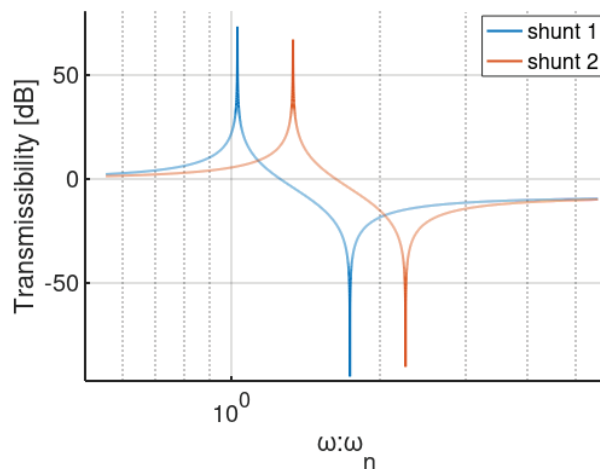
**Figure 8.** (a) Principle of a DAVI, (b) Transmissibility of a DAVI with two different masses ( $M$ ) to isolate.

If the stiffness of the DAVI is piezoelectric, its antiresonance frequency can be tuned. Numerical simulations showed that a 30% tunability can be achieved (see Figure 9). This property is a real advantage if the undesired frequency can vary with time. The helicopter case is still a good illustration, since when the rotor regime is modified, the frequency to filter changes.

## 6. CONCLUSION

Several vibration solutions developed by PYTHEAS Technology were presented in this article. They all combine the advantages to be passive or semi-passive, easy to implement and very robust. Their damping performances are improved compared to classic solutions and the piezoelectric effect brings additional advantages: the vibration frequency can be tracked electronically if it varies over time, several modes can be damped

simultaneously using only one device, lifespan, static load and creep resistance are improved compared to classic solutions, and their behavior is unchanged even at low temperatures, etc.



**Figure 9.** Tunability of a DAVI using a piezoelectric stiffness. These results were obtained through numerical simulations.

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