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A New Amplified Piezoelectric Actuator for Precise Positioning and Active Damping

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Key Words

Piezoelectric actuator, position control, modeling, experimental results, active damping.

Abstract

Two typical characteristics of direct piezoelectric actuators are displacements of ten micrometers and high stiffnesses. Recently, multilayer actuators have been improved, and they now display strains of approximately 1200 ppm at low excitation levels (less than two hundred volts). Thus, they are well suited to perform precise positioning of optical devices. But for industrial needs, this performance is still insufficient for positioning devices with larger displacements (in the range of several hundred micrometers).

Numerous designs of mechanical amplifier devices based on the use of flexural hinges have been proposed. Due to their low stiffness, these devices cannot be used in space applications because they would not survive during takeoff.

The amplified piezoelectric actuator which we designed and tested, eliminated the low stiffness drawback and ensures good force transmission. Due to the stiffness of the amplifier, the efficiency of the electromechanical transduction is significantly higher than those of conventional amplifier mechanisms.

To design this actuator, we performed a numerical finite element simulation that included the piezoelectric effect. Among other things, this model shows the displacement as a function of the excitation and the electrical admittance. The static and the dynamic behaviors were determined. The main features of the actuator are a no-load displacement of 180 μm and a stiffness of 5 N/m. These characteristics were experimentally verified using an electromechanical test bench including a laser Doppler interferometer, thus confirming the design method. Technological aspects, like the compressive force applied to the piezoelectric material, were considered.

Many applications for this amplified actuator already exist. For example, an active mechanism using this actuator can be used to tilt a mirror. Another application of the amplified actuator is in the field of active damping of structures. In this case, the actuator is connected to a resistive shunt so that electrical damping is obtained through the direct piezoelectric effect. The experimental results show that the actuator is interesting because of its high electromechanical coupling, and, consequently, its ability to perform active damping.

Introduction

Applications of Induced Strain Actuators (ISAs) are increasing in various fields of engineering such as precise positioning [1], intelligent control of shapes [2], and active damping of vibrations [3]. Among the various ISAs, which include piezoelectric, electrostrictive, magnetostrictive, and even shape memory effects, the piezoelectric actuators are the most popular, probably because of their simple and versatile design.

In the past, ISAs performed poorly, mostly because their strain levels were too small and they required high electrical fields. Moreover, deficient designs seldom, if ever, took advantage of the ISAs' high force potential.

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This paper introduces a new type of ISA, the Amplified Piezoelectric Actuator (APA). The APA displays high displacements at low electrical voltage, and it is well suited for applications in precise positioning and active vibration damping. Several aspects of the design are covered: the active material properties, the model of the device which is based on the Finite Element Method (FEM), the equivalent electromechanical circuit representation, and the measurement techniques. The performance of the APA is evaluated and its application in two different mechanisms is discussed.

Active Material Aspects

Piezoceramic material is the most popular active material. It displays strains of approximately 1200 ppm under an electrical field of 2 kV/mm. This corresponds to a charge constant of d_{33} = 600 pC/N, which is found in soft-type materials. However, the high electrical field strongly limits any practical uses of these materials, and it requires the addition of an insulating layer. Some other active materials, like the magnetostrictive alloy Terfenol-D, do not have this problem because they use an external excitation coil. In addition, Terfenol-D can achieve high strains of 2000 to 4000 ppm [4], when it is used correctly. However, the major drawback of Terfenol-D is that it requires the use of both a magnetic bias and a mechanical prestress. This drawback tends to limit the use of Terfenol-D for practical applications.

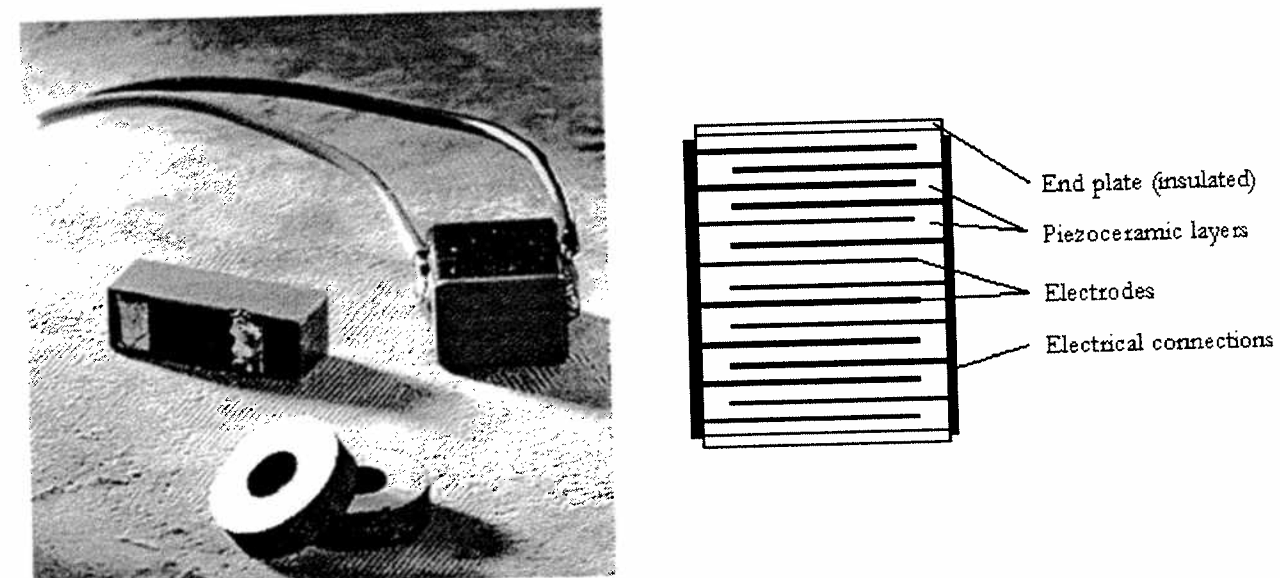

Figure 1: a/ View of various types of CMAs. b/ Schematic of the internal construction of a CMA.

Development of better piezoelectric materials used in the multilayer technique has overcome the aforementioned high voltage drawback, and has lowered the requirements to less than two hundred volts [5, 6]. Although the performance of the Ceramic Multilayer Actuators (CMAs) (Figure 1) has recently improved, their properties differ slightly from those of bulk ceramics because of their internal electrodes and insulating layers. For this reason, CMAs require special characteristic curves (such as the dependency of the stiffness on the mechanical prestress and electrical voltage) which are currently being measured at Cedrat Recherche, France.

Active material	Young's modulus	Coupling coefficient	Mechanical Q	Maximal static induced strain
Bulk hard-type PZT	55 GPa	0.65	300	200 ppm
CMA soft-type PZT	30 GPa	0.75	20	1,200 ppm
Terfenol-D	25 GPa	0.70	10	2,000 ppm

Table 1: Active materials' properties.

One of the objectives of this work is to obtain accurate data that can be used in numerical models. Some of the active material properties that are being measured at Cedrat Recherche are shown in Table 1. Other parameters such as the permittivities, the dielectric loss angle, the Curie temperature, the coercitive electrical field, etc., as well as the material nonlinearities, must also be considered for practical use.

Mechanical Amplifier Structures

The displacement limitation of a piezoelectric actuator can be overcome by using an elastic mechanical amplifier. Various designs, most of them based on flexural hinges, have been proposed in the past [7] (Figure 2). Their low stiffness prevents these structures from being used in space applications because they would not survive during takeoff. They are also subject to fatigue effects because stresses become very high in the hinges during actuation.

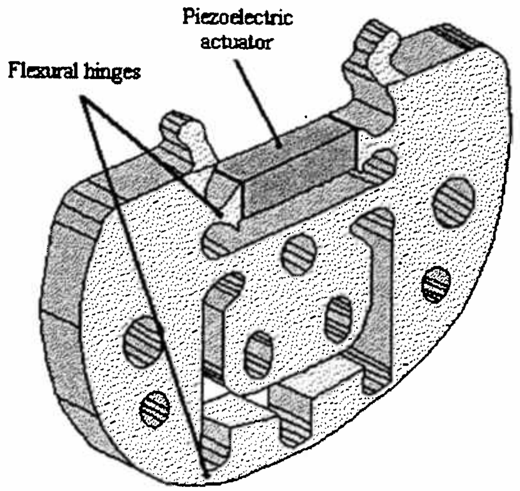

Figure 2: Example of a conventional mechanical amplifier structure using flexural hinges.

To overcome the problems related to the use of flexural hinges, we propose the application of the flexural-extensional principle presented in [8]. Briefly, this principle consists of using a longitudinal piezoelectric actuator and an elliptical shell as seen in Figure 3. Such an actuator presents the following advantages:

- the displacement magnification and the stiffness are functions of the eccentricity of the shell;
- the bending behavior of the shell under the piezoelectric actuation allows for an acceptable distribution of stresses in the amplifier;
- it allows for mechanical impedance matching and a good electromechanical coupling.

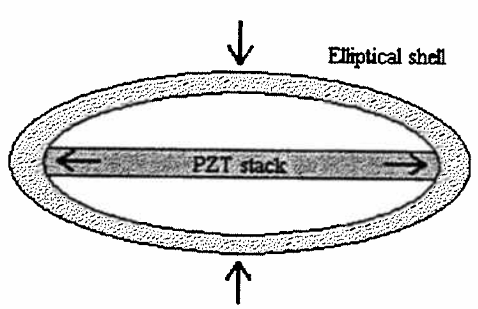

Figure 3: Flexural-extensional principle.

Design and Modeling

We used the FEM software program, ATILA [9], to design this actuator. ATILA is a CAD tool dedicated to modeling structures using piezoelectric, magnetostrictive and electrostrictive materials. Due to the strongly coupled formulation ATILA uses, the mechanical displacements versus electrical excitation and the electrical admittance of the device can be extracted from the model, either in static or in dynamic conditions. A modal analysis of the system gives the resonance frequencies and the corresponding electromechanical coupling coefficients. We also used the results of the FEM computations to derive the equivalent electromechanical ciruit of the actuator.

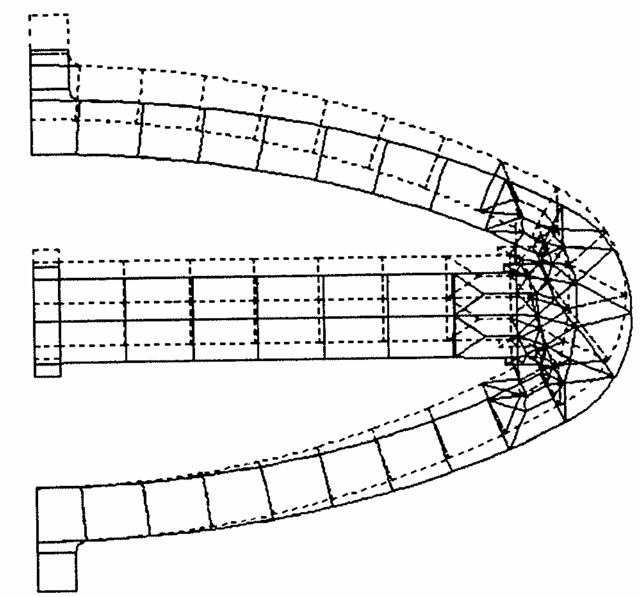

Figure 4: No-load displacements (solid lines are exaggerated for a clearer view) and structure at rest (dashed lines) as computed with ATILA.

We designed several different APAs using ATILA. The strained structure of an APA with a no-load condition was obtained from the FEM computation and is shown in Figure 4. Figure 5 compares the properties of the APAs with those of conventional piezoelectric actuators. When their high levels of displacement are combined with high forces, the proposed actuators achieve displacement amplifications of 2 to 5 and have a high efficiency.

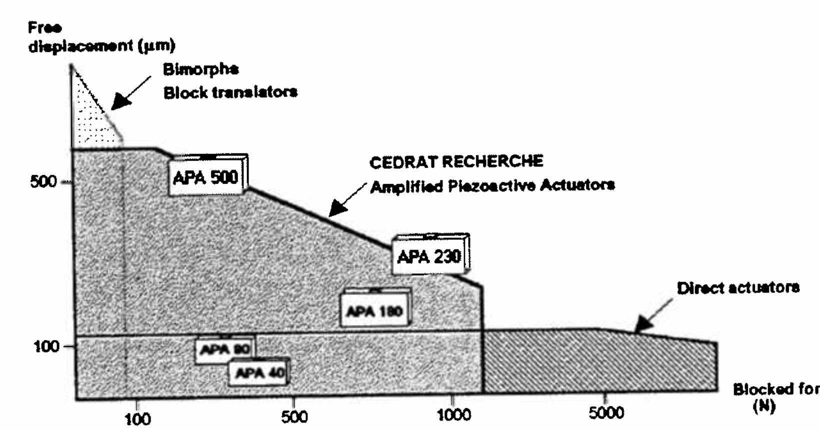

Figure 5: Performance of the APA.

Measurement Setup

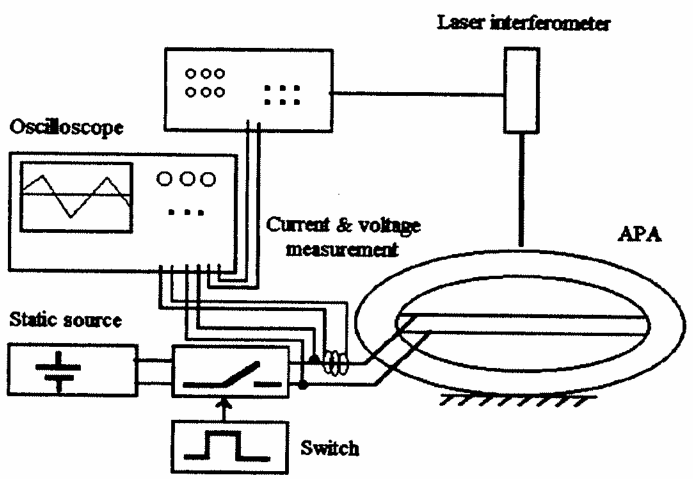

Figure 6: Experimental setup.

The APAs are characterized on a dedicated test bench based on an impedance analyzer HP4194A and a laser interferometer (Figure 6). Figure 7 is a picture of the actuator prototype. The measured admittance curve can be compared to the calculated one (Figure 8). The displacement of the actuator is measured under quasistatic conditions. A low-frequency (e.g. 50 Hz) excitation signal is used to periodically clear the interferometer fringe counter so that unwanted vibrations are avoided in the measurements. The open-loop behavior of the APA is then measured (Figure 9).

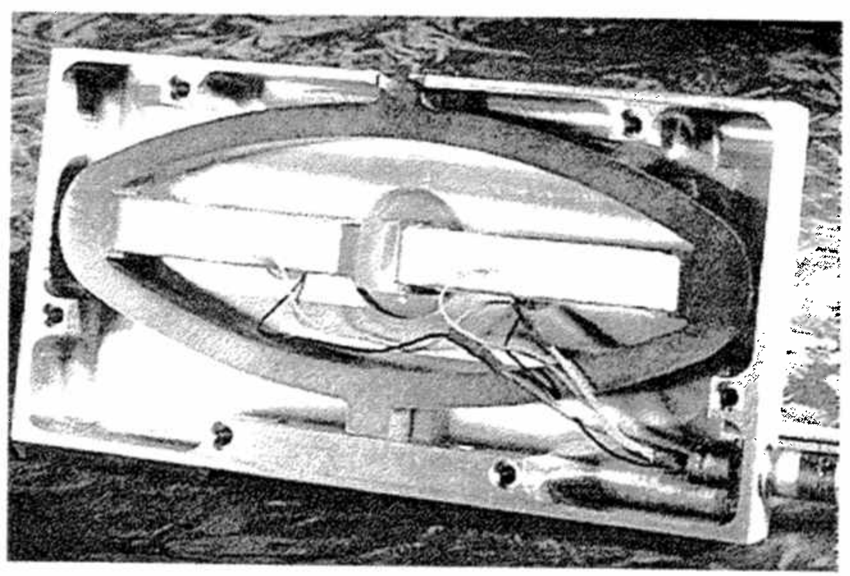

Figure 7: View of the Amplified Piezoelectric Actuator.

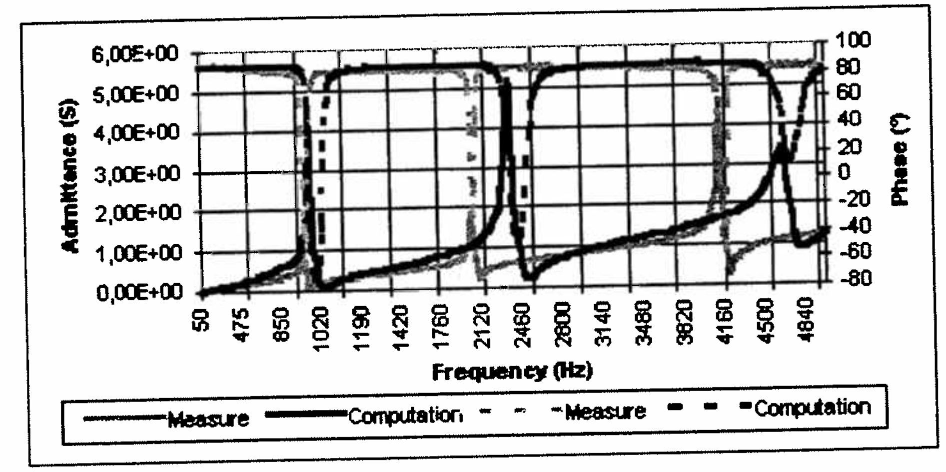

Figure 8: Comparison between measured and computed admittance curves.

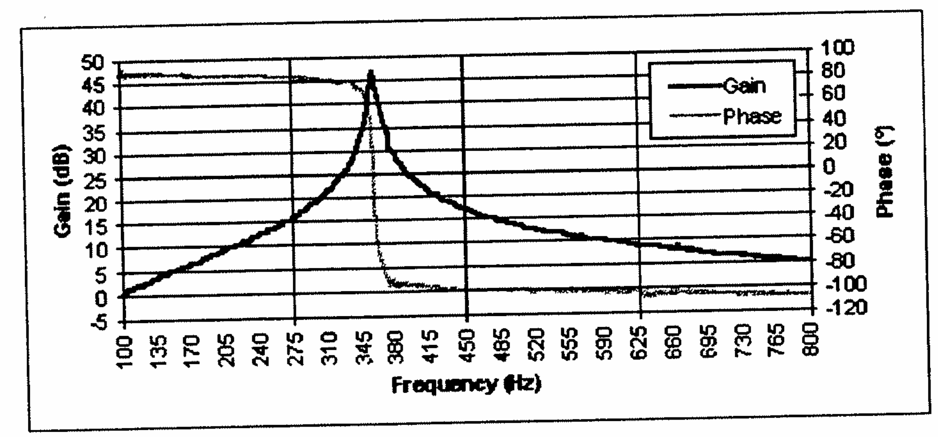

Figure 9: Open-loop behavior of the APA (the inertia load is 1 kg).

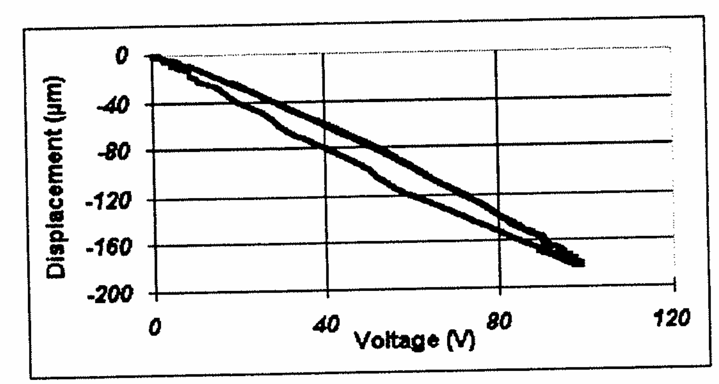

Figure 10: Measured displacement versus voltage, including the hysteresis of the APA.

Precise Optical Pointing Using APAs

The main advantages of piezoactuators are positioning accuracy and low energy consumption. The control loop must be able to remove the hysteresis of the actuator (Figure 10), which is very large in soft-type piezoceramics. The APA can be used to tilt a mirror and/or control its focus. For example, as shown in Figure 11, three degrees of freedom can be controlled in an active mechanism using three APAs.

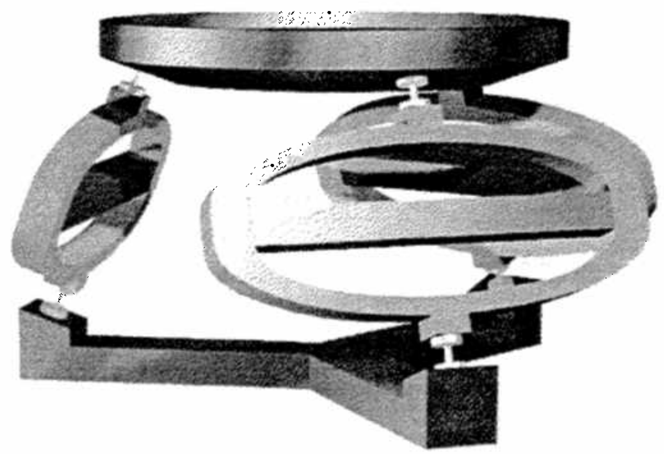

Figure 11: Example of an active mechanism using three APAs.

Semi-Passive Damping of Vibrations Using APAs and Passive Electrical Networks

Another promising field of applications of the APA is vibration damping. In the approach presented hereafter, APAs are tested as 'semi-passive' dampers. We use the term 'semi-passive' because the vibration isolation technique is based on an active material and a passive electrical network (which does not require a power supply). The direct piezoelectric effect of the APA is used to dissipate the vibration energy through a resistive shunt or a tunnel electrical network [10]. This technique is interesting because it does not require a power supply.

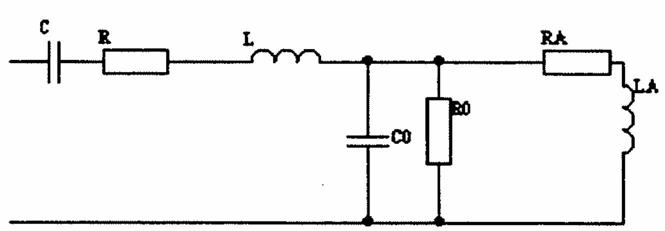

Figure 12: Electromechanical scheme of the 'semi-passive' piezoelectric damping.

The dissipation of the vibration energy can be quantified by considering the electromechanical scheme of the actuator (Figure 12). In such a circuit, the capacitance C accounts for the inverse of the actuator's stiffness; the resistor R represents the mechanical damping; and the inductance L plays the role of the inertia. The capacitance Co is the clamped capacitance of the piezoelectric material, and the resistor Ro accounts for the dielectric losses. The connected electrical network contains a resistor R_A and a matching inductance L_A. It must be noted that the electrical components, when converted into mechanical quantities, are affected by the system's force factor (also called the electromechanical transformer ratio). The force factor is proportional to the electrical coupling coefficient of the actuator. One interesting aspect of the design method is that all the previous parameters can be computed by the Atila software program. For instance, the quality factor of the actuator can be calculated as a function of the actuator's parameters and the value of the resistive shunt. The higher the electromechanical coupling coefficient, the more efficient the resistive damping. Figure 13 compares the computed and measured quality factors as a function of the shunted resistor, and shows that the optimal components have been correctly estimated.

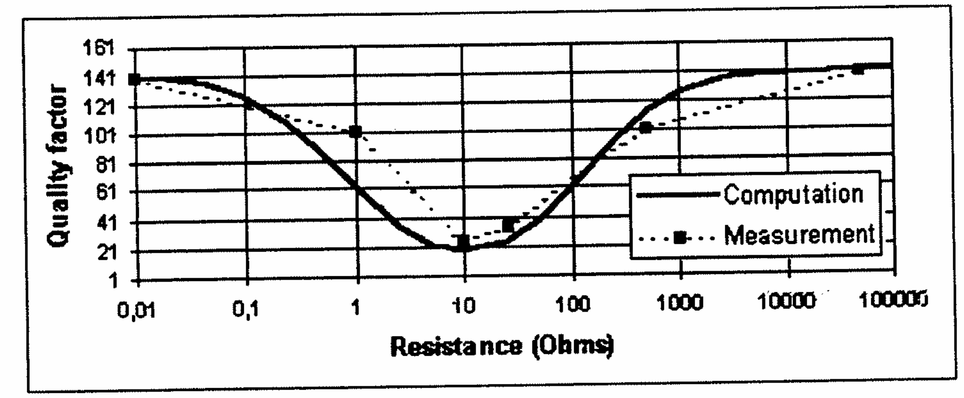

Figure 13: Quality factor versus coupling coefficient and resistive shunt.

We have confirmed these computed results experimentally: Figure 14 displays the transfer function of the APA for two electrical networks. We designed the APA described in Figure 14 for an application in which a high coupling coefficient was a great advantage and where it reduced the vibration level by 28 dB.

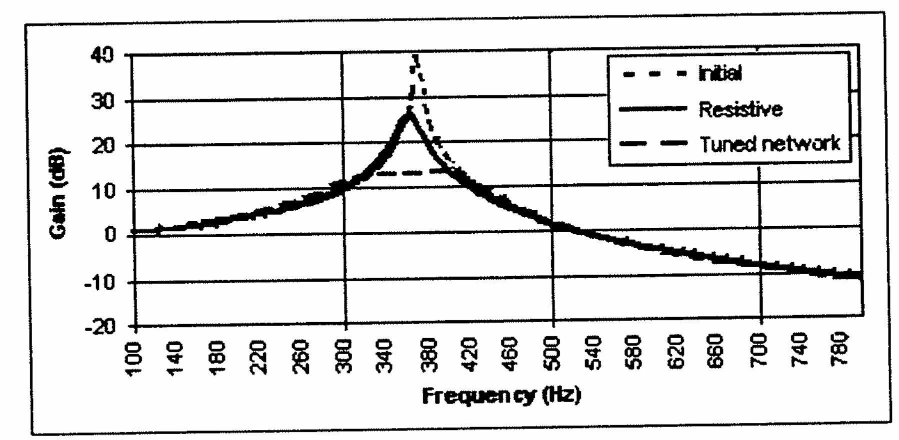

Figure 14: Measured transfer functions of the APA for different resistive shunts.

Conclusion

We have proposed, designed and tested a new Amplified Piezoelectric Actuator. Typical measured values of this actuator are a displacement of 180 µm at no-load condition and a stiffness of 5 N/m. These measured values are very close to the calculated values, and they validate the design models that we developed.

The concept of mechanical amplification allows for a good force transmission and a higher electromechanical transduction efficiency than those of conventional amplifier mechanisms. The APAs are currently being used in two startup applications: fine positioning and semi-passive damping of vibrations. As proven by the 28 dB vibration reduction obtained, the latter greatly benefits from the high electromechanical coupling coefficient of the APA.

Acknowledgment

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