Semi-Passive Vibration Control Technique via Shunting of Amplified Piezoelectric Actuators

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Abstract:
The objective of this paper is to provide results of an experimental and analytical investigation of Amplified Piezoelectric Actuators (APA) as vibrational isolator in a configuration of a mechanical Single Degree of Freedom system. The investigation is aimed at assessment of the mechanical properties modification ability via shunting techniques. The investigation consist of a phenomenological modelling of the APAs considered as generators and experimental verification of the vibrational energy dissipation ability in frequency domain.
The results obtained during this investigation reveal that it is feasible to receive more than 20 dB reduction of the displacement amplification in the resonant range. Moreover, three tested examples of APA reveal up to 9 % of resonant frequency shift due to proper adjustment of the electronic shunting circuit, which is an encouragement for further analyses towards application of the APAs in semi-passive vibration control applications.

Keywords: Vibration, Dissipation, Adaptive, Piezoelectric

Introduction

Mechanical structures dedicated to aeronautic or space applications need to be developed with regard to strict weight limitations. These requirements lead to development of slender structures with limited internal stiffness and therefore being susceptible to externally excited vibrations. These require dedicated engineering solutions. Since the beginning of 1980s, there is a technique developed with utilization of shunted piezoelectric patches adhered on the structural elements which increases the damping properties of structures in a controlled way [1]. The tested applications reveal the efficiency of that method [2] but a significant drawback of that technique is that it should be introduced on an early design stage and embedded in the structural material.

In the engineering practice, there is often a necessity of application of a vibration control treatment in an advanced phase of the design process, when each modification of the principle structure generates high costs and therefore it is difficult to introduce any embedded system. In such situations vibration energy absorbers like Tuned Mass Dampers (TMD) [3] are often utilized in order to meet the technical specification of the design.

However, the classical TMDs [4] are narrow-band devices that need to be tuned for a particular operational frequency. This is not well fitted to the requirements of the aeronautic structures where it often happens that the dominant excitation frequency changes in reference to the flight stage. The bandwidth of the passive TMD may be widen by increasing the mass of the device but this solution stays in contradiction to the weight limitations of the aeronautic or space applications.

Therefore, a solution is required which would provide an ability of adaptation of the mechanical properties of the vibration attenuation device to the recognized frequency of the vibrational excitation. There are known results of investigations dedicated to analysis of modification of the mechanical stiffness and damping of piezoelectric ceramics via shunting methods [2]. Most of them are focused on piezoelectric patches or piezoelectric stacks. However, the first group of the solutions is strictly dedicated to the applications embedded in the structural elements and the second group of materials reveals high values of stiffness which eliminates them from the prospects of practical application due to high quality factor.

The mentioned limitations drive us to an idea of utilization of Amplified Piezoelectric Actuators (APA) [5] as mechanical fuses of modifiable stiffness and damping properties by means of the shunting technique. Due to utilization of a geometric lever in the APA design, the effective stiffness of the element with the piezoelectric stack can be reduced. Therefore, the operational frequency range can be adjusted and suited to the requirements of an application in the aeronautical or space industry.

The objective of this paper is to provide results of a preliminary experimental and analytical investigation of the APAs as vibrational isolator in a configuration of a mechanical SDOF system. The investigation is aimed at analysis of the APAs mechanical properties with ability of modification via shunting techniques. The investigation consists of an experimental verification of the vibrational energy dissipation ability in frequency domain and a phenomenological modelling of APA considered as generator.

State of the art

The presently observed rapid development in the domain of material technologies, which include introducing a class of new innovative functional materials, allows engineers to redefine their approach to the classical problem of the vibration attenuation. The utilization of the unique features of the newly engineered materials opens new perspectives in design of more efficient and versatile vibration control devices.

Widely developed advanced vibration control systems are based on active or semi-active principles. A typical active control is very effective but its implementation requires a complex system consisting of: a sensing system, a power amplifier (for the actuator) and a signal conditioning system for the controller, which make the system expensive and less reliable [7]. On the other hand, a semi-active control system requires all the same components with the exception of the power amplifier. This makes it less power consuming. However, also less effective and still expensive.

The utilization of the expanded mechano-electric devices may be impractical in many applications and a reasonable trend occurs, which is aimed at minimization of complexity and power requirements in the vibration control systems. In accordance with this philosophy the most reliable and the least expensive are passive solutions. However, those usually exhibit a limited effectiveness in applications of varying frequency content in excitation (e.g. rotorcrafts).

The versatility of the passive systems may be improved by utilization of functional materials like shunted piezoelectric ceramic. The material exhibits a change in mechanical properties in response to modification of the parameters of electronic circuit connected to the electrodes [6]. The demand of adaptivity motivates the use of semi-passive systems where the parameters of the electrical circuit are modified in accordance with the recognized mode of vibration. The principle of the application is to use only a small amount of electrical energy in order to fit the parameters of the electronic circuit to recognized frequency of vibration and to dissipate energy via passive response of the vibration atenuator. In this configuration, the transducer (e.g. piezo) acts as an energy converter: it transforms mechanical (vibrational) energy both into electrical energy and heat. The electrical energy is in turn dissipated in the shunt circuit by further conversion to heat. Since the system operates mainly as passive one with adjustable mechanical parameters it is called semi-passive. The power consumption of the described system might be minimal since the external energy is required only for supply of an electronic device that modifies the passive electric parameters of the system and the operation itself takes place in a passive mode.

The semi-passive solutions are based on the primary feature of the piezoelectric elements, which is an ability of transduction the mechanical energy (strain) into electrical charge. The piezoelectric shunt damping techniques have become a widespread branch for vibration suppression in intelligent systems since it first proposed by Forward in 1979 [1]. Lesieutre [8] primarily categorized the shunt circuits as four basic kinds: resistive, inductive, capacitive and switched circuits based on their different dynamic behaviours. The method offers the benefits of stability, robustness and performance without the need of complex digital signal processors [9].

Investigation methods

The objective of the conducted investigation was verification of a concept for utilization of Amplified Piezoelectric Actuators (APA) as semi-passive vibrational energy dissipaters. Specifically, the possibilities to control of the piezo ceramics' stiffness and damping parameters under mechanical excitations were examined.

In order to conduct a comparative study of the APA mechanical response, an experimental session for three types of them was defined. Each of the tested APA (Table 1) was subjected to the kinematic excitation and an inertial load on a dedicated mock-up. The mock-up of the vibratory system was prepared as a proof mass (m = 205 g) fixed on the APA actuator under kinematic excitation provided by a PPA actuator (PPA20M; C = 1.39 uF, k = 40 e-6 N/m) supported on a stiff base as depicted in Fig. 2. The experiments were defined in order to acquire Frequency Response Functions (FRF) in displacement domain between the excitation point of the system and the vibrating mass. The frequency range of the analysis that was taken into consideration was determined by the resonant frequency of the tested system and the range of its variability. The resonant frequency of the system was determined by the stiffness of the APA.

Table 1: *Types of APA tested*

Type	Technical data
APA400M	C = 2.5 uF, k = 0.06e-6 N/m
APA60SM	C = 1.27 uF; k = 1.45e-6 N/m
APA40SM	C = 1.33 uF; k = 3.73e-6 N/m

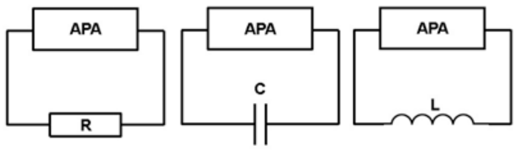

Fig. 1: Shunting circuits

The mechanical properties of the APA were influenced by passive electrical circuits connected to the electrodes of the piezoelectric material. Three types of the shunting circuits were taken under consideration: resistance, capacitive and inductive connected in accordance to the schemes depicted in Fig. 1.

The experimental setup was composed of:

- mechanical SDOF setup with piezoelectric actuator APA and proof mass,
- mechanical excitation with actuator PPA20M and amplifier LA75A by CEDRAT-TEC,
- shunting setup that consisted of passive electronic elements used for shunting the APA actuator considered as electro-mechanical generator,
- data acquisition setup consisted of Dynamic signal analyser and a laser vibrometer.

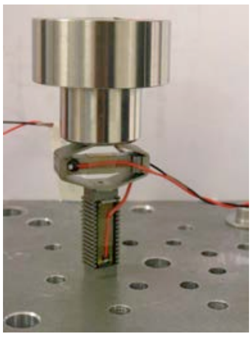

Fig. 2: Experimental setup

The experimental mock-up was excited with a method of frequency sweep. The range of the frequencies was determined in the direct neighbourhood of the recognized resonant frequency. The amplification of the vibration amplitude was defined as:

Amp [dB] = 20 log(s_{out} / s_{in}) [um/um],

where s_{out} – displacement of the proof mass, s_{in} – displacement of the excitation provided by the PPA actuator.

Results

The conducted experiments were divided into groups dedicated to examination of the following types of shunting circuits: resistance, capacitive, and inductive. The influence of the resistance circuit on the mechanical response of the experimental system is depicted in Fig. 3. The range of the resistance was chosen from 0 Ohm to very high value, which was realized by testing the system with open and short circuit. In between the extreme cases, the tested resistance values are given in Fig. 3. Two phenomena were observed as the effect of the resistance shunting: stiffness modification of the APA actuator, which was demonstrated by shift in the resonant frequency; and damping modification that was demonstrated in reduction of the vibration displacement amplitude. The magnitudes of the modifications were tabelarized and presented in Tab. 2.

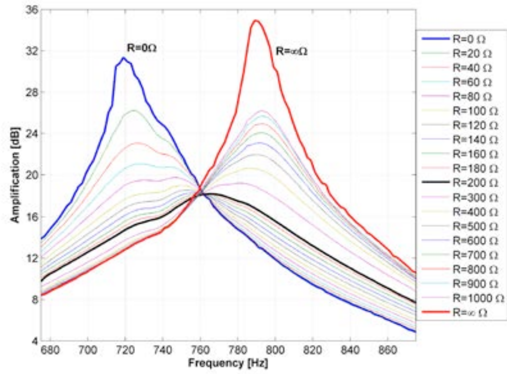

Fig. 3: FRF function, resistance shunting, APA40SM

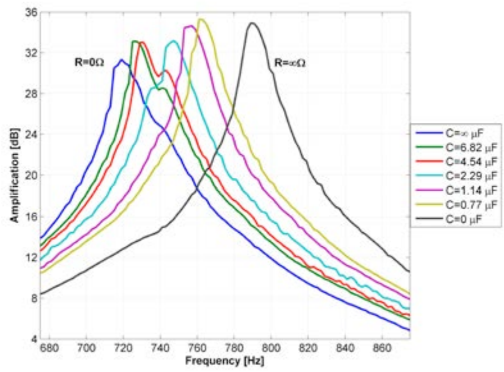

Fig. 4: FRF function, capacitive shunting, APA40SM

The second type of tested circuit was the capacitive shunt. The magnitudes of the capacitors utilized in the circuit were given in the Fig. 4. The dominant phenomena observed as the result of the capacitive shunt was modification of the system stiffness, which was demonstrated in resonant frequency modification. The modification of the damping in the system was a minor effect since the amplitudes of the resonances were not influenced significantly as the response to the capacitive shunt.

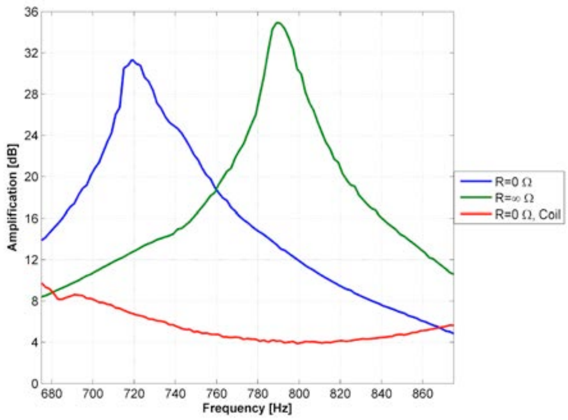

Fig. 5: FRF function, inductive shunting, APA40SM

Table 2 Mechanical response modifications

	APA400M	APA60SM	APA40SM
Resonance shift – resistance shunt	7 %	8 %	9 %
Amplification reduction – resistance shunt	10.5 dB	15.5 dB	17 dB
Amplification reduction – inductive shunt	31 dB	-	31 dB

The third type of the tested circuits was inductive shunt, which was characterized by a resonant type of the electrical response. The parameters of the circuit were determined to receive a fit between the resonant frequencies of the electrical and mechanical systems. By this way it was received an effect of improved reduction of the amplitudes in the resonance of the mechanical system. The effect of the the inductive shunt utilization on the example of APA40SM is depicted in Fig. 5. The vibration displacement amplitudes in the resonance range were reduced of 31 dB.

Phenomenological modelling

The piezoelectric actuators were mathematically described with a model of a piezoelectric transducer considered as generator. The scheme of the adopted model is presented in Fig. 6. The model assumptions were that the mock-up with the APA actuator was treated as homogenized object characterized by mechanical stiffness, damping and inertia, which were reflected in a phenomenological routine. The parameters of the model were determined on the basis of a model identification procedure implemented in a laboratory impedance analyser. The model did not take into account the geometrical specific details of the examined APA actuators. An exemplary results of modelling the system with the resistance shunts is depicted in Fig. 7. The results reflect a FRF of the mock-up in the domain of velocities. The presented curves reflect properly the character of the phenomenon that was observed in the experiments. However, the adapted simplification (homogenization of the object) did allow to reveal qualitative results more than quantitative.

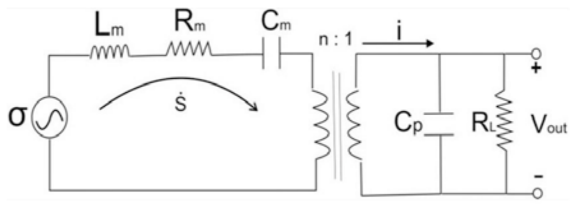

Fig. 6: Equivalent circuit of a piezoelectric generator

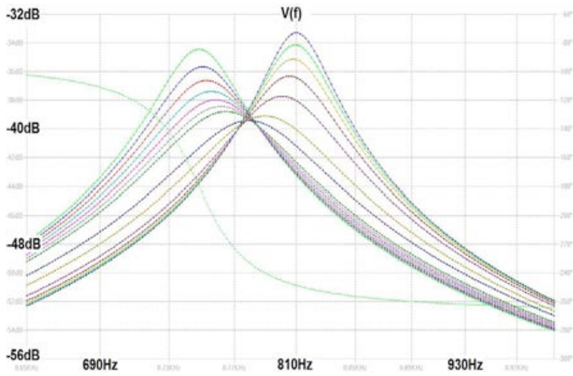

Fig. 7: Results of the resistance shunt modelling

Discussion

The experimental investigation of the APA mechanical properties modified with the passive linear shunting circuits revealed that it is feasible to control the stiffness and damping effectively. The presented study had a preliminary character and it was conducted in order to test an influence of utilization the mechanical lever in the application of the piezoelectric stacks with shunting circuits. Both, the methods of modelling the phenomenon and the analysis of technical issues connected with potential applications require further studies.

Conclusions

The results obtained in the presented investigation reveal that it is feasible to receive more than 20 dB reduction of amplification in the resonant range of the structure vibration by utilization of APA as structural fuses. Moreover, the three tested examples of APA reveal up to 9 % of resonant frequency shift due to proper adjustment of the electronic shunting circuit. The presented results might be encouraging to utilize the reported features of the APAs in design of adaptive semi-passive TMDs or vibration isolation systems dedicated to aeronautical or space applications.

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References

[1] R. L. Forward and C. J. Swigert, Electronic Damping of Orthogonal Bending Modes in a Cylindrical Mast-Experiment, Journal of Spacecraft and Rockets, vol. 18, pp. 5–10, Jan. 1981

[2] T. Delpero, Design of adaptive structures with piezoelectric materials, PhD Thesis, Zurich, 2014

[3] M. Luu, Structural control systems in high-speed railway bridges, PhD Thesis, Bauhaus-Universitat Weimar, 2014

[4] S. Nagarajaiah, E. Sonmez, Structures with semiactive variable stiffness single/multiple tuned mass dampers, Journal of Structural Engineering, 2007

[5] www.cedrat-tec.com, 2015

[6] B. Mokrani, R. Bastaits, M. Horodinca, A. Premount, Parallel Piezoelectric Shunt Damping of Rotationally Periodic Structures, Advances in Materials Science and Engineering, Volume 2015 (2015), Article ID 162782

[7] B. de Marneffe, “Active and passive vibration isolation and damping via shunted transducers,” PhD, Universite Libre de Bruxelles, 2007

[8] G. A. Lesieutre, “Vibration damping and control using shunted piezoelectric materials,” The Shock and Vibration Digest, vol. 30, no. 3, pp. 187 – 195, 1998

[9] S. O. R. Moheimani and A. J. Fleming, Piezoelectric transducers for vibration control and damping. Springer, 2006