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The verification of a piezoelectric vibration-suppression system with a multimode basic RLC shunt circuit and its comparison to a multi-mode current-flowing shunt circuit

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Abstract

One of the modern methods of reducing vibrations of plates and beams is using piezoelectric materials in the form of distributed elements or patches (applied in a passive or an active system). However, for the multimodal response of a structure, there is no possibility to place the actuators in exactly the areas with maximum curvature values for each mode. Additionally, in the case of passive multimodal suppression systems – in which energy is needed to be supplied to the system – there is the necessity to create a complicated electrical circuit. The particular electrical shunts of the circuit are tuned to the specific vibration forms which require damping. The main objective of this article is to show the possibility of creating a multimodal vibration suppression system with typical resonant shunts and proposed second slightly modified.

Keywords: piezoelectric materials, piezoelectric effect, passive methods, vibration damping

1. Introduction

Piezoelectric materials have received a great deal of attention over the last few years, especially as components for passive and active vibration suppression systems.

Piezoelectricity is a form of coupling between the mechanical and the electrical behaviours of ceramics and crystals belonging to certain classes. These materials exhibit a specific effect which is known in literature as the piezoelectric effect; this can be divided into the direct and the converse piezoelectric effect. The principle behind the application of piezo-material is that when it is mechanically strained, electric polarisation proportional to the applied strain is produced (the direct piezoelectric effect). Moreover, when the same material is subjected to an electric polarisation, it becomes strained and the amount of strain is proportional to the polarising field (the converse piezoelectric effect). Both effects usually coexist in piezoelectric material.

Active vibration reduction is an interdisciplinary challenge and combines such fields as mechatronics (mechanics and automation) and informatics (numerical methods). The use of piezoelectric transducers, arranged in the proper manner on the external surface of a structure subjected to vibration is one of the currently employed vibration reduction methods. An important issue is multimodal vibration control. The problem comes down to the proper arrangement of piezoelectric elements on external surfaces in such a way as to ensure their settings in the areas of most curvature, depending on the vibration form; they cannot be placed in nodes.

Other interesting ways of creating a functional vibration suppression system which are naturally orientated towards single-mode usage are passive methods in which a properly tuned electrical circuit is used for obtaining vibration reduction. Piezoelectric transducers (passive method) are very popular in the suppression systems of smart structures. This technique is described as the connection of electrical impedance with a piezoelectric transducer connected to the structure. The easiest way to create a passive vibration suppression system is to connect a resistor R (Batra, Dell'Isola, Vidoli, Vigilante, 2005; Ahmadian, Jeric, 2001) with a piezoelectric element. Mechanical energy is changed to electrical energy by a piezoelectric transducer and is dissipated on the resistor. A different method to assure passivity is to connect the transducer electrodes with a resistor R and an inductor L in series; together with the internal capacity of the piezoelectric element Cp, they create a resonant electrical circuit (Granier, Hundhausen, Gaytan, 2002; Hagood, Von Flotow, 1991). The circuit is tuned to the resonant frequency of the system using a properly selected inductance and the resistance is selected so that the whole electrical energy is changed into heat. By adding more piezoelectric transducers, specific vibration modes can be dampened; however, a better solution is to use one piezoelectric transducer which is connected to the circuit with the possibility to dampen the vibrations of many modes. An example of such a system is that which is presented by Hollkamp, which consists of many parallel connections of a series of RLC circuits and the first branch of a RL circuit (Hollkamp, 1994). Many other circuits have been discussed in which additional LC circuits with current blocking or LC circuits without blocking were used (Yi, Ling, Ying, 2000).

Monograph (Moheimani, Fleming, 2006) is devoted to the problem of both passive and active vibration suppression in continuous structures.

Piezoelectric transducers have been extensively used in structural vibration control applications. Their wide-ranging utilisation in this specific application can be attributed to their excellent actuation and sensing abilities, which stem from their high electro-mechanical coupling coefficient as well as their non-intrusive nature. Piezo-elements can be implemented for both passive (Kozień, Wiciak, 2010; Khorshidi, Rezaei, Ghadimi, Pagoli, 2015; Kozień, Ścisło, 2015) and active (Kozien, Koltowski, 2011; Hansen, 2013) vibration reduction.

In the case of passive methods, one of the most promising damping methods is the so-called piezoelectric shunt damping. The technique is characterised by

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the connection of electrical impedance to a structurally bonded piezoelectric transducer. Such methods do not require an external sensor and, if properly designed, may guarantee the stability of the shunted system (Granier, Hundhausen, Gaytan, 2002; Hagood, Von Flotow, 1991; Moheimani, Fleming, 2006; Goldstein, 2011). Additionally, modern shunt circuit designs require impractically large inductance values (Lossouarn, Aucejo, Deü, Multon, 2017).

In the case of the active method, the real problem lies in the placement of piezoelectric elements on the surface (Żołopa, Brański, 2014), the selection of a control parameter (Kozień, Ścisło, 2015) and the problem of multimodal vibration suppression (Ścisło, Kozień, 2014; Berardengo, Manzoni, S., Conti, 2017).

2. A piezoelectric vibration suppression system with a multi-mode basic RLC shunt circuit compared to a current-flowing multi-mode shunt circuit

For the problem introduced in the previous section, the approach to finding a solution consists of two strategies:

- a finite element method (FEM) simulation of the problem for a model of a steel beam which was created for the testing of the authors' algorithms mentioned in previous papers (Kozień, Ścisło, 2015; Ścisło, Kozień, 2014);
- laboratory verification of the vibration reduction method for the laboratory test beam (because of good coupling effect).

Three conditions were investigated:

- a system with an open circuit between electrodes of the piezoelectric transducer;
- a system with a tuned, branched RLC shaft (Fig. 1a);
- a system with a multimode current-flowing shunt circuit (Fig. 1b).

The multimode current-flowing shunt circuit (Fig. 1b) was designed to simplify the implementation of high-order multimode shunts (Behrens, Moheimani, Fleming, 2003). Such a shunt circuit requires one parallel branch for each mode which is required to be controlled. The current-flowing network $L_i^*C_i$ in each branch is tuned to approximate a short circuit at the target resonance frequency whilst approximating an open circuit at the frequencies of adjacent branches, i.e. the amplitudes of the free end of the beam (control point) were observed for all cases with a significant reduction of the amplitude for the beam with a tuned electrical shunt. Additionally, during FEM simulation, it was possible to determine the level of acoustic pressure for which the system with damping was around 10–16 dB lower than for the system with no damping. This value may continue to an increase of dB; however, further optimisation of the number of elements is required as is optimisation of the placement of the element.

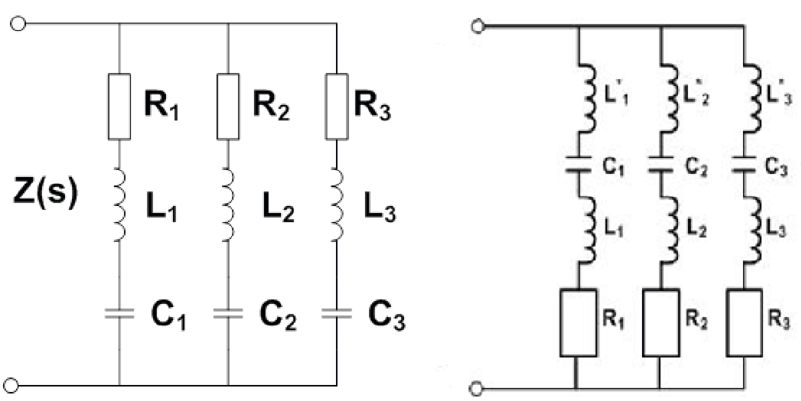


Fig. 1. a) Equivalent RLC circuit for multimodal vibration damping system for three arbitrarily chosen modes (left); b) equivalent current-flowing circuit for multimodal vibration damping system for three arbitrarily chosen modes (right)

2.1. FEM simulation test results

Table 1 shows the result of the FEM simulation – performed using the Ansys software program – of the displacement of the free end of the beam with and without activation of the multimode passive circuit (Fig. 1a). The FEM method used to solve the differential equations was described in detail in previous works by the author (Ścisło, Kozień, 2010; 2011) and other scientists (Wiciak, 2008).

Table 1. Displacement of the free end of the beam both with and without piezoelectric shunt damping

Arbitrarily chosen modes of vibration	Displacement (without shunt activation) [m]	Displacement (with damping-shunt activated) [m]
3	21E-06	16E-06
5	7.3E-06	4.4E-06
6	4.8E-06	2.9E-06

Despite the above results, while the implementation of the proposed system turned out successfully, the main problem of the proposed system was the optimisation required for the circuit branches. It was required that they turn to a specific frequency, which is problematic for large numbers of modes. Together with the issue of circuit construction, the proposed multi-mode shunt is extremely difficult for real-life implementation.

The main problem of the RLC multi-shunt technique mentioned in the previous section is the requirement for n-mode branches of RLC circuits (every branch dedicated and tuned to one specific frequency). This causes complications in creating such a circuit. The other significant problem is the optimisation of every branch so that it can be precisely tuned to the resonant frequency.

One of the possible simplifications of the shunt, especially for high-order multi-mode damping, is the implementation of the so-called piezoelectric passive current-flowing shunt circuit (Fig. 1b). This circuit can be also tuned to the corresponding frequencies due to vibration form which is chosen for dumping.

This approach was examined and compared with previous results in the following investigations.

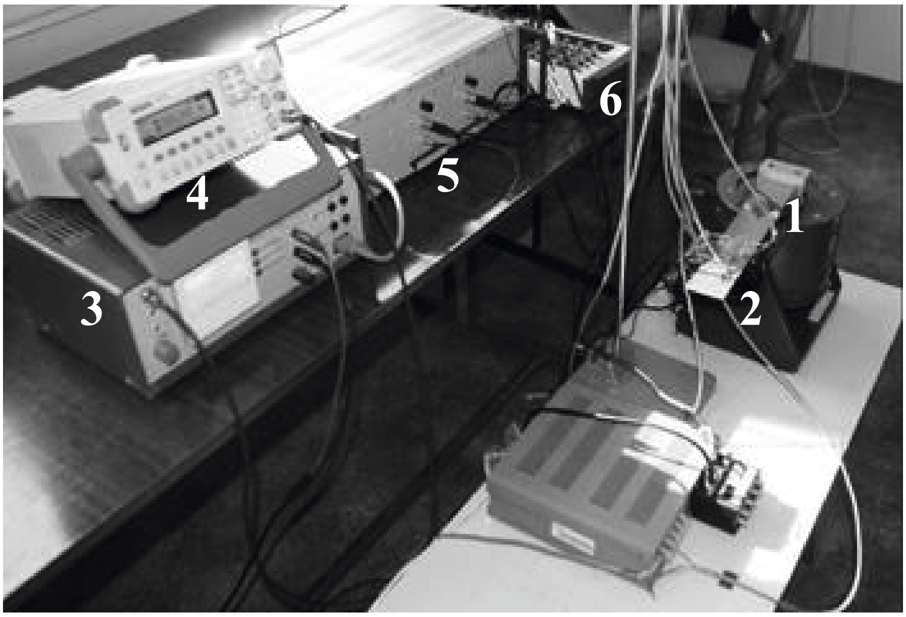
2.2. Laboratory verification

The laboratory test station was built at the Faculty of Mechanical Engineering, Cracow University of Technology. The laboratory station is shown in Fig. 2.

The experimental verification of the proposed vibration suppression system was performed on a cantilever beam made of a typical composite board for printed circuits. The dimensions of the beam were 330 x 55 x 2 mm. The piezoelectric elements were 10 x 10 x 1 mm. Figure 2 shows the tested beam. The beam is forced to oscillate kinematically by the movement of the core of the electrodynamic driver, which is attached at the fixed end of the beam. The forcing signal fed to the inductor enables the implementation of various beam responses, including multimodal responses.

During laboratory tests, the results demonstrated the effectiveness of the passive shunt damping technique for the examined circuit system. Unfortunately, due to the fact that different types of beam were used

Fig. 2. Laboratory test station



1. Test object with required circuits
2. Electrodynamic shaker
3. Amplifier
4. Waveform generator
5. Modular Piezo Controller
6. NI USB – 6259

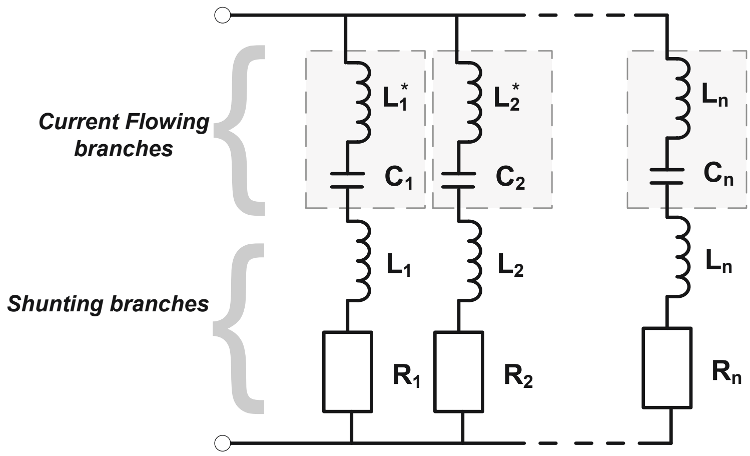


Fig. 3. The equivalent of a current-flowing shunt circuit

for numerical and laboratory verification of the method, the solutions are not appropriate for full comparison. However, in both cases, a significant reduction of displacement can be observed.

Figure 4 shows that the current-flowing shunt circuit requires one circuit branch for each structural mode chosen to be controlled. The current-flowing L_n^*–C_n network in each branch is tuned to approximate a short circuit at the target resonance frequency whilst approximating an open circuit at the adjacent branch frequencies. The remaining inductor and resistor in each branch L_n–R_n is tuned to dampen the n-th target structural mode in a manner comparable to that performed during the single-mode design. The current-flowing shunting network decouples the multi-mode problem into a number of independent single-mode designs. Unlike current blocking techniques, the order of each current-flowing shunting branch does not increase as the number of modes to be shunt-damped increases. This design greatly limits the number of required electrical components. Moreover, it widely extends the possibility to damp a large number of modes simultaneously, e.g. five modes of a simply supported beam. An additional practical advantage is realised when implementing the circuit – only a single non-floating inductor is required per branch.

For testing the current-flowing shunting circuit vibration suppression system, the second and third structural modes were chosen for testing. For the proper selection of circuit parameters, the natural frequencies needed to be specified. This was achieved with the LabView software application and the Rigol1022 waveform generator, which was used scanning across the frequency spectrum. Table 2 shows the first five natural frequencies of the examined beam.

Table 2. Identified natural frequencies of the examined structure

Mode	Measured frequency [Hz]
1	9.08
2	50.76
3	134.23
4	179.22
5	205.12

Using the natural frequencies (ω_1, ω_2) and the equations for the current--flowing equivalent shunt circuit (visible in Fig. 4), the proper values of L_n, L_n^*, C_n and R were calculated (circuit elements description in (Moheimani, Fleming, 2006)).

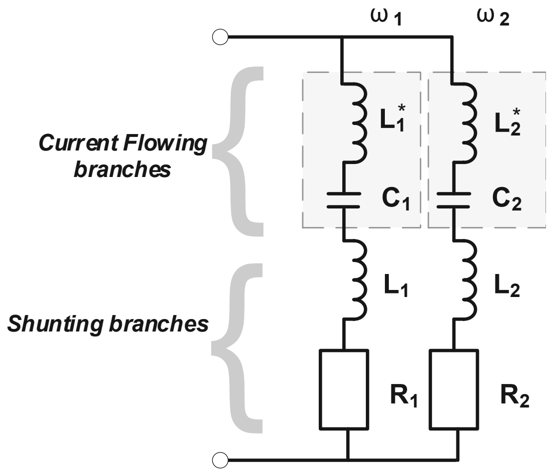


Fig. 4. Proposed two-mode current-flowing shunting circuit

Table 3. Laboratory verification of the passive current-flowing circuit method for the vibration suppression system utilising piezoelectric elements

Method	Vibration form number	Maximal displacement [m]
SINGLE FORM		
WITHOUT DAMPING	2	5.17E-03
CURRENT-FLOWING CIRCUIT ACTIVATED	2	4.13E-03
SINGLE FORM		
WITHOUT DAMPING	3	6.32E-03
CURRENT-FLOWING CIRCUIT ACTIVATED	3	4.98E-03
MULTIMODAL		
WITHOUT DAMPING	2 and 3	2.30E-03
CURRENT-FLOWING CIRCUIT ACTIVATED	2 and 3	1.70E-03

3. Conclusions

One of the most interesting damping suppression techniques is the so-called piezoelectric shunt damping in which a piezoelectric shunt circuit is tuned to the resonant frequency of the structure; after this occurs, an antiresonant effect can be observed for which amplitudes of vibrations are greatly reduced. Structural vibration can be reduced by shunting an attached PZT with an electrical impedance. Modern shunt circuit designs require impractically large inductance values.

This paper has presented numerical modelling and the laboratory verification of the multimodal vibration control system using the finite elements method. Special attention has been paid to the problem of passive multimodal damping. The size of single and multi-mode shunt circuit inductors can be reduced by placing an additional capacitance across the terminals of the PZT or by simplifying the circuit itself.

The simulation demonstrated a reduction of the displacement of the free end of the beam, which proves the efficiency of the method. The proposed class of multimode impedances can be tuned to dampen a small number of modes in an effective manner. Larger reduction rates can be obtained by using different, more complicated types of electrical shunts, such as a multimode current-flowing shunting circuit (discussed in the paper) and a series-parallel shunt circuit. In the case of the current-flowing shunt, it is possible to obtain a similar rate of vibration reduction with significant simplification of the circuit. The main disadvantage of the passive shunt vibration suppression system is the necessity for creating a large and complicated circuit. The author concludes that it is appropriate to use the proposed methods only for an objectively small number of modes (the multimodal case). For even higher vibration reduction rates and the elimination of a complicated electrical circuit, active methods of vibration reduction with a control system must be considered (Kozień, Ścisło, 2015; 2018).

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Weryfikacja laboratoryjna piezoelektrycznego multimodalnego systemu redukcji drgań z obwodami RLC w porównaniu do prądowego multimodalnego obwodu bocznikującego

Streszczenie

Jedną z metod redukcji drgań jest wykorzystanie elementów piezoelektrycznych w postaci przyklejonych warstw elementów lub rozłożonych na powierzchni struktury plastrach (w systemie pasywnym lub aktywnym). W przypadku tłumienia wielomodalnego nie jest możliwe znalezienie najlepszego miejsca dla wszystkich form jednocześnie. Dodatkowo w przypadku tłumienia pasywnego, gdzie wymagane jest dostarczenie energii do systemu, dla tłumienia wielomodalnego istnieje konieczność stworzenia skomplikowanego obwodu elektrycznego dostrojonego do częstotliwości rezonansowej konkretnych form drgań własnych. W artykule poruszono temat pasywnego tłumienia wielomodalnego belek. Zaprezentowano typowy sposób stworzenia obwodu eklektycznego oraz porównano z przypadkiem zmodyfikowanego obwodu.

Słowa kluczowe: materiały piezoelektryczne, efekt piezoelektryczny, metody pasywne, tłumienie drgań