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DESIGN AND APPLICATION OF A SEMI-ACTIVE ELECTROMECHANICAL VIBRATION ABSORBER

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Abstract
A semi-active tuned vibration absorber based on a shunted piezoelectric transducer is applied to a thin aluminum plate, which forms the front panel of a box made of acrylic glass, in order to reduce its vibrations and sound radiation. In various finite element simulations, varying the position, the size, and the thickness of a piezoelectric patch actuator, an optimal configuration is found that maximizes the generalized electromechanical coupling coefficient. The capacitance of the piezo patch, a resistance, and an inductance form an oscillating circuit that is tuned so as to influence the first vibration mode of the plate. This way, the velocity amplitude of the first vibration mode can be reduced by up to 9 dB and the radiated sound pressure level by approximately 20 dB.

INTRODUCTION

The vibrations of a structure at a certain frequency can be reduced by means of a tuned vibration absorber [1, 5]. Depending on the specific application, such a mechanical vibration absorber can be rather large and heavy. Usually, it is tuned to a specific vibration frequency, so it cannot adapt to changes of the dynamic behavior of the structure due to, e.g., an increase of the ambient temperature. In order to overcome these drawbacks, a semi-active electromechanical vibration absorber based on a shunted piezoelectric patch actuator is designed by means of finite element (FE) simulations, assembled, applied to a rectangular aluminum plate, and successfully tested. This vibration absorber is light and small, it can easily be tuned to a specific frequency by adjusting its resistance and inductance, and it requires only minimum external power supply (±15 V for the operational amplifier) and no control. This paper describes its design and application.

THE GENERALIZED ELECTROMECHNICAL COUPLING COEFFICIENT

In order to find favorable values for the position, the size, and the thickness of the piezoelectric patch actuator, the generalized electromechanical coupling coefficient K_{ij} [2, 4] is calculated by means of FE simulations. This coefficient is a measure for the fraction of mechanical energy that is converted into electrical energy and vice versa, i.e., for the piezoelectric's influence on the system. It is defined as

$$K_{ij} = \frac{\left(\omega^D\right)^2 - \left(\omega^E\right)^2}{\left(\omega^E\right)^2} \quad , \tag{1}$$

where ω^D and ω^E are the natural frequency of the structure with an open circuit piezoelectric and a shorted piezoelectric, respectively. These natural frequencies can be obtained from measurements or FE analyses. The subscripts i and j indicate the direction in which the electric field is applied and in which the mechanical effects are measured, respectively. In this paper, the coupling coefficient K_{31} is used.

FINITE ELEMENT SIMULATIONS

Finite Element Model

The FE model used to determine the coupling coefficient K_{31} of the rectangular aluminum plate with an applied piezo patch according to Eq. (1) is depicted in Fig. 1. The plate has a size of 340 mm × 300 mm × 2 mm. Its lateral dimensions are modeled slightly larger, and the plate is clamped at its edges to model the actual boundary conditions ("stiff rubber frame"). This results in a good agreement between numerical and experimental results.

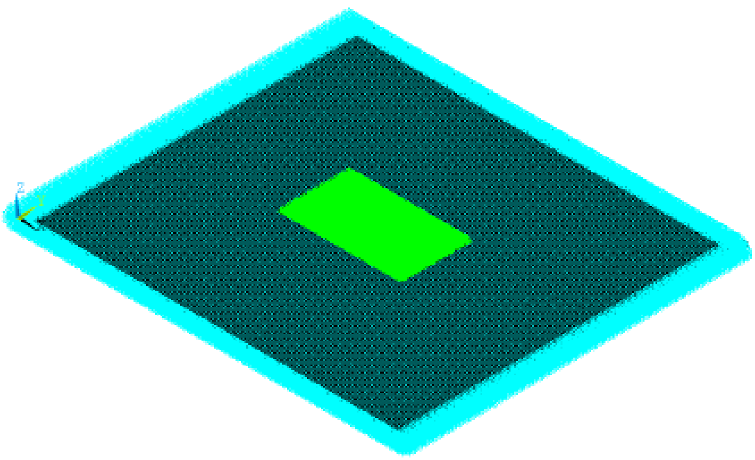

Figure 1: FE model of the aluminum plate with attached piezo patch

The FE model of the piezo patch can be seen in the middle of the plate (green color). The mesh size of the FE model is very small since the piezo patch is quite thin (0.5 mm) and the FE elements should not be too large compared to their thickness. Thus, a piezo element size of 2 mm × 2 mm × 0.5 mm is chosen. During the FE simulations the piezo patch can vary its position, size, and thickness. Two numerical modal analyses are carried out for each set of parameters, one with a shorted and one with an open circuit piezo patch. From the natural frequencies obtained from these analyses the coupling coefficient according to Eq. (1) can be calculated.

Finite Element Analysis Results

First, the position of a piezo patch (96 mm × 48 mm × 0.5 mm) is varied along the *x*-axis in the middle of the plate. Figure 2 shows the coupling coefficient as a function of the patch position. The maximum value is approximately 0.13 for the first vibration mode in the middle of the plate where the strain reaches its maximum value. For modes with an odd number of antinodes along the *y*-axis (mode 1: 1-1; mode 2: 2-1; mode 5: 3-1; mode 6: 1-3; mode 8: 2-3) the curve shape corresponds roughly to the respective mode shape. For modes with an even number of antinodes along the *y*-axis (mode 3: 1-2, mode 4: 2-2, mode 7: 3-2), however, the coupling coefficient is almost zero due to the symmetry of the patch with respect to the centerline of the plate.

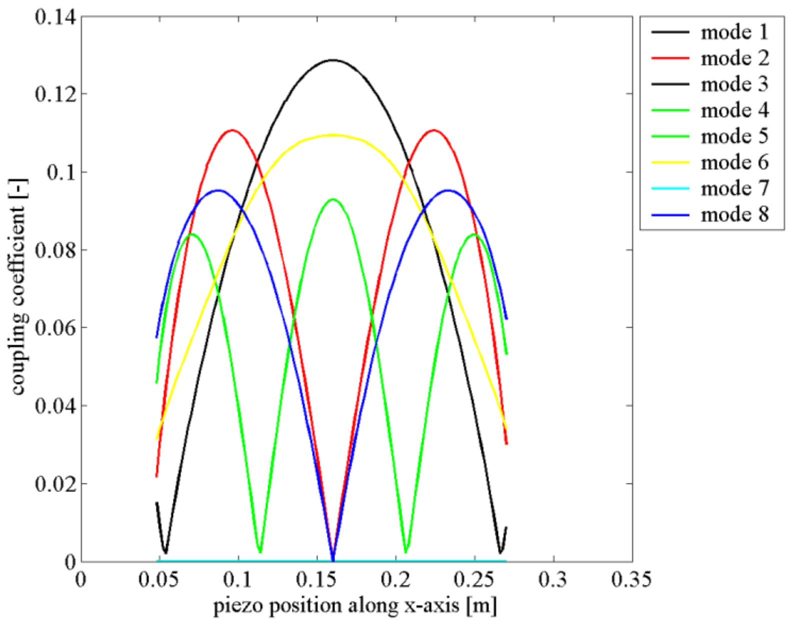

Figure 2: Coupling coefficient as a function of the piezo patch position along the x-axis in the middle of the plate

Next, another piezo patch (48 mm × 24 mm × 0.5 mm) is moved across the plate in both *x*- and *y*-direction. The coupling coefficient for the first vibration mode (1-1; approximately 212 Hz) as a function of the piezo patch position can be seen in Fig. 3. The maximum value is approximately 0.08 in the middle of the plate.

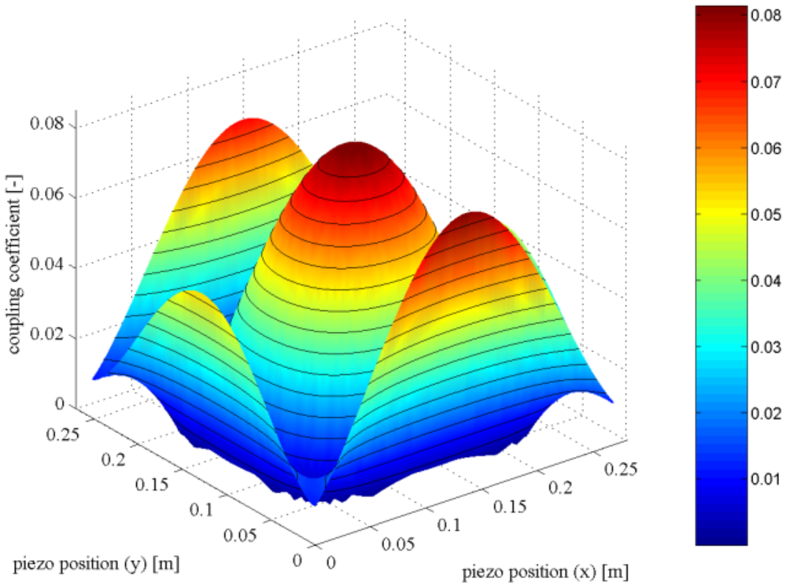

Figure 3: Coupling coefficient for mode 1 (1-1; approx. 212 Hz) as a function of the piezo patch position on the plate

Finally, the size and the thickness of a piezo patch that is located in the middle of the plate are varied. The simulation starts with a piezo area of 48 mm × 24 mm and a thickness of 0.3 mm. The size is increased in steps of 4 mm in both *x*- and *y*-direction until the edge of the plate is reached. The thickness is increased in steps of 0.1 mm up to 1 mm. Figure 4 shows the results of this simulation. The fundamental frequency varies between 180 and 212 Hz due to the mass increase as the piezo patch gets larger

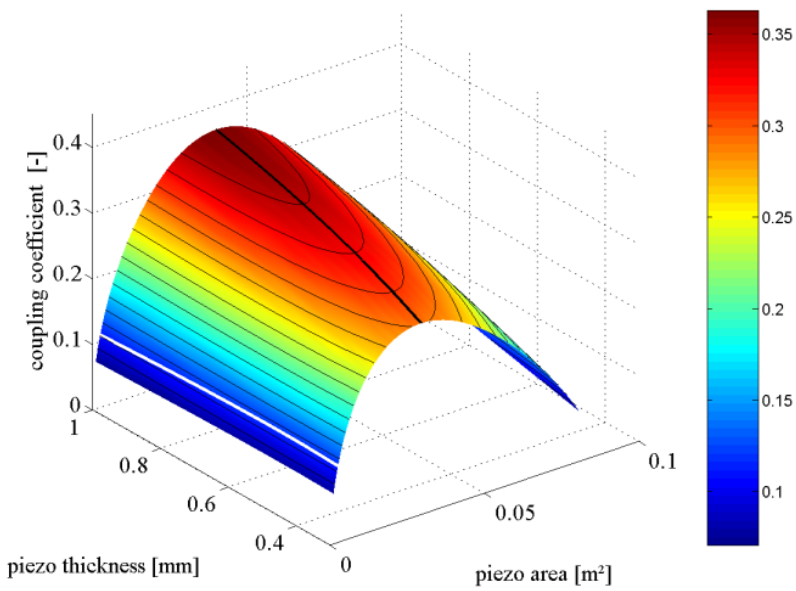

Figure 4: Coupling coefficient for mode 1 (1-1; 180–212 Hz) as a function of the piezo patch area and thickness

and thicker. The coupling coefficient reaches its maximum value 0.36 for a patch size of 210 mm × 190 mm and a thickness of 1.0 mm. The black line in Fig. 4 indicates that the maximum coupling coefficient increases linearly with increasing area as the patch gets thicker.

DESIGN OF THE SEMI-ACTIVE VIBRATION ABSORBER

The FE simulations show that the piezo patch should be placed in the middle of the plate in order to reduce the plate vibrations of the first vibration mode. The maximum coupling coefficient is obtained for a patch area of 210 mm × 190 mm and a thickness of 1.0 mm. However, this would require about 32 patches of the standard size 50 mm × 25 mm. Since this is not very realistic, the number of patches is limited to two, resulting in a total piezo area of 50 mm × 50 mm. The white line in Fig. 4 indicates the relation between the piezo thickness and the coupling coefficient for the aforementioned total piezo area (2500 mm^2). The maximum coupling coefficient of 0.12 is reached for a piezo thickness of 0.5 mm. Thus, total piezo dimensions of 50 mm × 50 mm × 0.5 mm are chosen for the design of the semi-active electromechanical vibration absorber.

The design of the semi-active vibration absorber is based on [2]. The capacitance of the piezo patch can be calculated by

$$C = \varepsilon_0 \, \varepsilon_{33} \frac{A}{d} \quad , \tag{2}$$

where $\varepsilon_0 = 8.854 \cdot 10^{-12}$ As/Vm is the vacuum permittivity, $\varepsilon_{33} = 852$ is the dielectric constant of the piezo material, $A = 0.0025\,\mathrm{m}^2$ is the total piezo area, and $d = 0.005\,\mathrm{m}$ is the piezo thickness. This results in a piezo capacitance of $C \approx 37\,\mathrm{nF}$. Using the equations

$$R_{opt} = \frac{\sqrt{2}\, K_{31}}{\omega^E \, C \left(1 + K_{31}^2\right)} \tag{3}$$

for an optimal resistance and

$$L_{opt} = \frac{1}{\left(\omega^E\right)^2 C \left(1 + K_{31}^2\right)} \tag{4}$$

for an optimal inductance, where $K_{31} = 0.12$ is the coupling coefficient according to Eq. (1), ω^E is the fundamental frequency of the structure with the shorted piezoelectric, and $C \approx 37\,\mathrm{nF}$ is the capacitance of the piezo patch given by Eq. (2), the theoretical values $R_{opt} = 3.29\,\mathrm{k\Omega}$ and $L_{opt} = 15\,\mathrm{H}$ are obtained.

Based on these values, an electrical circuit with a size of approximately 20 mm × 20 mm is assembled (see Fig. 5). A generalized impedance converter is used as a synthetic inductance. Both the inductance and the resistance can be tuned so as to achieve a maximum vibration reduction. This maximum is reached for $R = 220\,\Omega$ and $L = 9.6\,\mathrm{H}$. Although the measured capacitance of the piezo patch matches the theoretical value obtained by Eq. (2) very well, the real resistance and inductance differ greatly from their theoretically optimal values according to Eqs. (3) and (4). Such discrepancies were also observed in [4].

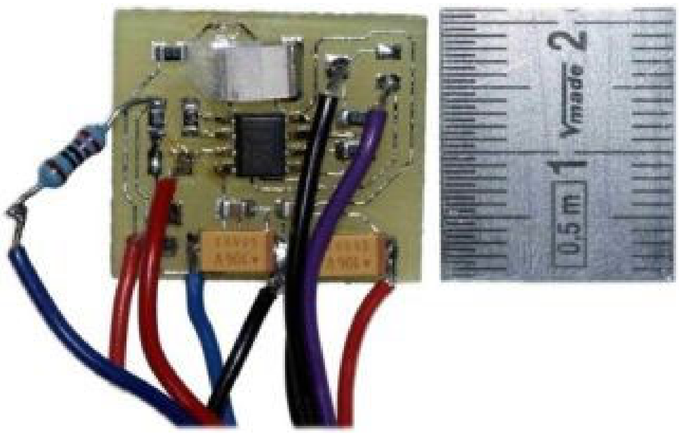

Figure 5: Electrical circuit of the semi-active vibration absorber (approx. 20 mm × 20 mm)

Figure 6 shows the test box made of acrylic glass (right). The abovementioned rectangular aluminum plate forms the front panel of the box, which has a size of 340 mm × 300 mm × 320 mm. The acrylic glass has a thickness of 20 mm. A loudspeaker, which excites the aluminum plate, is suspended in the middle of the box. The piezo transducer, consisting of two piezo patches (see Fig. 6, left), is located in the middle of the aluminum plate on the interior of the test box.

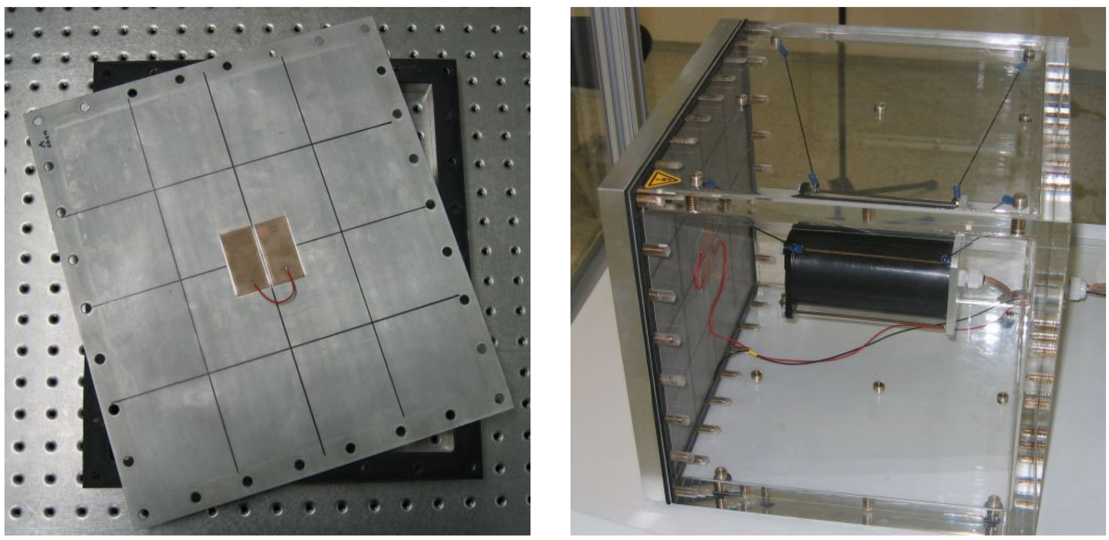

*Figure 6: left: piezo patches attached to the aluminium plate,
right: test box made of acrylic glass (with loudspeaker)*

MEASUREMENT RESULTS

The effectiveness of the semi-active vibration absorber is tested by means of scanning laser vibrometer and nearfield acoustical holography measurements. Both the loudspeaker excitation (see Fig. 6) and the impulse hammer excitation are used.

Figure 7 shows the velocity spectrum at the plate's surface measured with the scanning laser vibrometer using the impulse hammer excitation. The velocity peak at 212 Hz drops by approximately 7 dB as the absorber is switched on. Interestingly, the velocity reduction is slightly larger for the loudspeaker excitation (–9 dB). Those measurement results even show the typical behavior of a vibration absorber, i.e., the amplitude is reduced at the tuning frequency of the absorber, but two new peaks are created in its vicinity. However, this effect is not visible for the impulse hammer excitation (see Fig. 7).

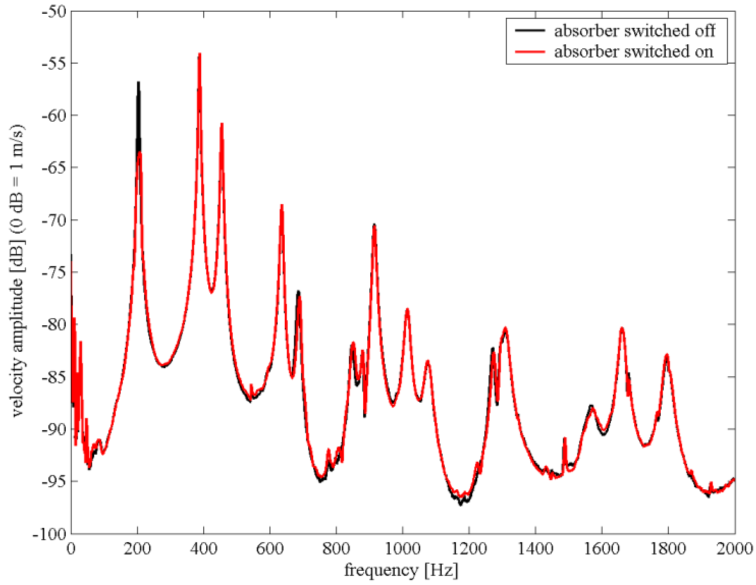

Figure 7: Vibration reduction due to the semi-active vibration absorber (hammer excitation)

The sound field radiated by the aluminum plate at its first vibration mode (loudspeaker excitation) was measured by means of the nearfield acoustical holography. The measurement results are depicted in Fig. 8. The left and right plot shows the sound pressure level distribution in front of the plate with the semi-active vibration absorber switched off and on, respectively. The sound pressure level is reduced by approximately 20 dB due to the semi-active vibration absorber.

SUMMARY

A semi-active electromechanical vibration absorber based on a shunted piezoelectric transducer, consisting of a piezoelectric patch, a resistance, and a synthetic inductance, is designed, assembled, mounted, and tested. Favorable values for the position,

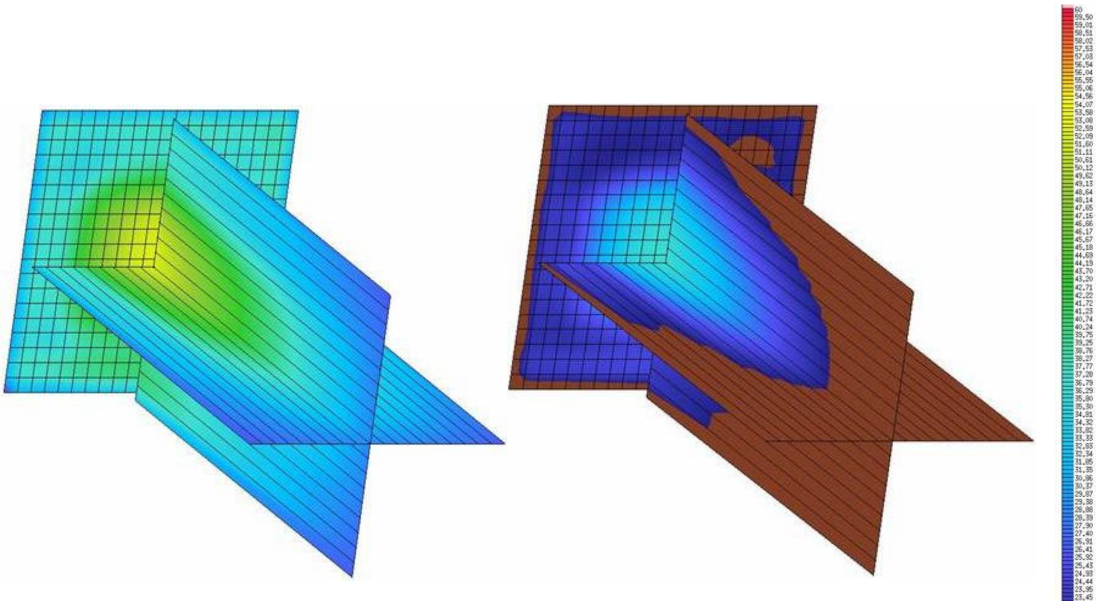

Figure 8: Sound pressure level distribution in front of the aluminium plate (left: absorber switched off, right: absorber switched on)

the size, and the thickness of the piezo patch are determined by means of finite element simulations. An electrical circuit is assembled that constitutes the resistance and the synthetic inductance. The semi-active vibration absorber is then applied to an aluminum plate, which is part of a test box. The velocity amplitude of the first vibration mode can be reduced by up to 9 dB, the sound pressure level by up to 20 dB.

ACKNOWLEDGMENT

The design of the semi-active vibration absorber and the measurements presented in this paper were performed by Martin Heinig as part of his bachelor thesis [3], which was supervised by the authors of this paper.

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