Glass Plates Noise Transmission Suppression By Means of Distributed Piezoelectric Composite Actuators Shunted By an Active Circuit

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Abstract: This paper analyzes the possibility of suppression the sound transmitted through glass windows using piezoelectric actuators shunted by an active electronic circuit. We propose a simple way to increase the bending stiffness of the glass plate which results in an increase in reflected acoustic pressure and in a decrease in transmitted acoustic pressure. The method uses Piezoelectric Macro Fiber Composite (MFC) actuators which are distributed on the glass surface. They are shunted by active electronic circuits with a Negative Capacitance (NC) which control the effective elastic parameters of the piezoelectric material. Thus, the actuators are effectively stiffened and the effective bending stiffness of the whole system could be increased. The sound shielding efficiency of the glass plate is measured by the acoustic Transmission Loss (TL). The effect of the shunted NC circuit and glass plate geometry on the TL is analyzed using Finite Element Method (FEM). Results show that it is possible to increase the TL by about 25 dB at both first vibrational mode due to the curved geometry and at the second vibrational mode due to the effect of properly adjusted shunted NC circuit.

Keywords: Glass plate, Acoustic-Structural analysis, Piezoelectric Actuator, Active Electronic Circuit, Acoustic Transmission Loss.

1. Introduction

The noise intensity in cities is steadily increasing which means a quite big problem for the population living there. Glass windows and nowadays also glazed facades are common parts of buildings but very often represent major paths of noise transmission into a building's interior. Because of their "large thin plate" geometry, they have low bending stiffness and therefore it is very easy to make them vibrate by action of incident acoustic pressure wave. Then, non-negligible part of the wave is transmitted through the window (Fig.1a). Unfortunately, passive noise control methods are in this case not much efficient, especially in the low-frequency range (up to 1 kHz). In addition, they can be difficult to apply in the case of large glazed windows or facades because of unacceptable dimensions and weight. At the same time, it is difficult to find a realization of active noise control that would be both efficient in a broad frequency range and financially acceptable. It usually requires robust control algorithms and fast and powerful electronics.

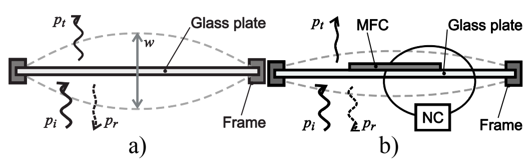

Figure 1. a) Scheme of the sound transmission system – glass plate fixed in a rigid frame at its edges. The sound source located underneath the glass plate generates an incident sound wave of the acoustic pressure p_i that strikes the glass plate. It makes the glass plate vibrate (dashed line), part of the sound wave is reflected (p_r) and a part is transmitted (p_t); b) Scheme of the noise transmission suppression principle. The vibration amplitude is decreased using the effective stiffening of the piezoelectric Macro Fiber Composite (MFC) actuator due to the action of the active shunt circuit with a negative capacitance (NC).

Therefore, in this study, we have focused on the semi-active method – piezoelectric shunt damping, which offers a simple solution and low price approach for reduction of the noise level transmitted through windows in buildings. This method is based on the change of the vibrational response of the structure using piezoelectric actuators shunted by electronic circuits which have a Negative effective Capacitance (NC). The basic idea was introduced by Date *et al*. [1]. It is based on the principle of active control of elastic properties of piezoelectric element embedded in the vibrating structure. Due to the action the active NC circuit, it is possible to increase the effective value of the Young's modulus of used piezoelectrics to a large extent. When piezoelectric actuators are distributed on the glass surface and their elastic properties are controlled by the NC circuit, the vibrational amplitude of the glass plate could be reduced and therefore a greater part of the incident sound wave energy is reflected than transmitted (Fig.1b).

Because of the fragile material of the window, it is suitable to use some flexible piezoelectrics. We use the Macro Fiber Composite (MFC) actuator which was developed by NASA Langley Center [2] and nowadays it is fabricated in Smart Material Corp. [3]. It consists of many thin PZT fibers embedded in an epoxy matrix and covered with interdigital electrodes (IDE) embedded in a polyimid film. Thanks to the use of piezoelectric fibers, the overall strength and flexibility of the actuator are greatly increased. Furthermore, the interdigital electrode pattern offers a much higher force or free displacement than the monolithic piezoceramic devices. As a result, the MFC actuator cannot easily rupture, it has a larger electromechanical coupling factor and it produces a larger force and a free displacements.

To verify the functionality of the sound suppression system outlined above, Finite Element Method (FEM) simulations of sound transmission through a glass plate with attached piezoelectric elements shunted with NC circuits are performed using COMSOL Multiphysics. Next sections present details of the analysis and results.

2. Computational Method

The sound shielding efficiency of the window is measured by acoustic Transmission Loss (TL). The value of *TL* is defined as a ratio, usually expressed in decibel scale, of the acoustic powers of the incident and transmitted acoustic waves, p_i and p_t, respectively. The value of *TL* can be written in terms of the specific acoustic impedance of the window Z_w as it was determined in [4]:

$$TL = 20\log_{10}\left|1+\frac{Z_w}{2Z_a}\right|, \qquad (1)$$

where $Z_a = \rho_0 c$ is the specific acoustic impedance of air, ρ_0 is the air density and c is the sound velocity in the air. The specific acoustic impedance of the glass plate is defined as

$$Z_w = \Delta p / v\ , \qquad (2)$$

where v and $\Delta p = (p_i + p_r) - p_t$ are the normal component of the vibration velocity and the acoustic pressure difference between the opposite sides of the glass plate, respectively. Now, it is clear that, if the amplitude of the window displacement decreases, the values of Z_w and subsequently *TL* increase.

3. Use of COMSOL Multiphysics

3.1. Acoustic – structure analysis

The system of the sound transmission through the glass plate is into COMSOL Multiphysics implemented as Acoustic – structure interaction problem – frequency domain analysis. Let's consider the geometry, shown in Figure 2, of a glass plate, fixed in a rigid frame, of thickness *h* and dimensions *a* and *b* with distributed piezoelectric MFC actuators attached. The presented configuration is selected to allow the suppression of majority of low-frequency vibrational modes.

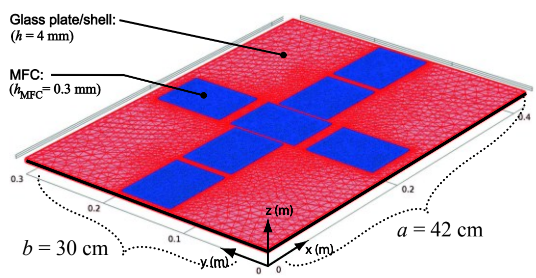

Figure 2. Geometry of the glass plate with 7 attached Macro Fiber Composite (MFC) actuators. The considered coordinate system and basic dimensions are indicated.

Further, we consider that the glass plate with MFC actuators interacts with the acoustic field in the air above and below the shell. Figure 3 presents the whole model geometry. The environment below the glass plate is modeled by the air-hemisphere with a plane incident wave radiation. The wave is transmitted through the glass plate into the air domain above. This domain is surrounded by additional Perfectly

Matched Layers (PML's) to suppress the wave reflections from the outer boundaries of the air domain above.

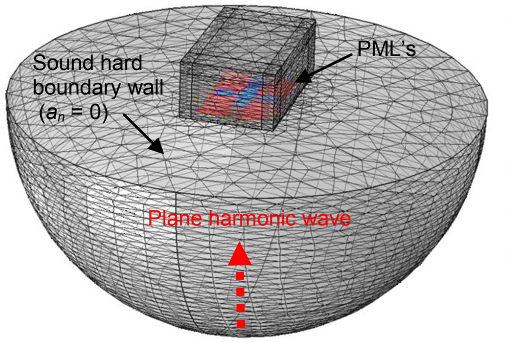

Figure 3. Geometry and mesh of the whole model of the sound transmission through the glass plate with 7 attached Macro Fiber Composite (MFC) actuators. Harmonic plane wave strikes the bottom surface of the glass and is transmitted through it into the air domain above. Perfectly Matched Layers are indicated around the above domain. Finite element mesh size is less than one fifth of the incoming wave length.

The incident acoustic pressure plane wave below the glass plate is incoming in the z axis direction and defined as

$$p(z,t) = Pe^{i(\omega t - kz)}, \quad (3)$$

where k is the length of the wave vector of the incident sound wave. We are interested in the steady-state acoustic pressure distribution, i.e. $p(x,y,z,\ t) = p(x,y,z)e^{i\omega t}$, therefore the pressure p distribution in the air above and below the glass plate is governed by Helmoltz's equation,

$$\nabla \cdot \left(-\frac{1}{\rho_0} \nabla p \right) - \frac{\omega^2 p}{\rho_0 c^2} = 0 \quad . \quad (4)$$

It should be noted that below the glass plate – in the hemisphere domain, the total acoustic pressure is given by the sum of the acoustic pressures of the incident and reflected sound waves, i.e., $p = p_i + p_r$; above the glass plate, thanks to the PML's, the total acoustic pressure is equal just to the acoustic pressure of the transmitted sound wave, i.e., $p = p_t$.

As mentioned above, the calculation of the transmission loss is based on analysis of the interaction between the vibrating glass plate and the surrounding air. First internal boundary condition, which has to be applied in order to couple acoustics with mechanics, is the force caused by the acoustic pressure and applied at the interface of the structure with the air. It can be expressed by the following formula for the force vector,

$$\mathbf{F}_p = -\mathbf{n}p\,, \quad (5)$$

where $\mathbf{n}$ is outward-pointing (seen from the inside of the glass plate) unit vector normal to the surface of the structure "glass plate with the MFC actuators".

The force $\mathbf{F}_p$ works as a boundary load for the calculation of glass plate displacement vector $\mathbf{u}$ distribution, which is governed by the frequency dependent equation of motion,

$$2\rho\omega^2\mathbf{u} - \nabla \cdot \mathbf{C}\left[(\nabla\mathbf{u})^T + \nabla\mathbf{u}\right] = 0\,, \quad (6)$$

where $\mathbf{C}$ is elastic stiffness tensor with appropriate values of Young's modulus for the isotropic glass material and Young's and shear moduli for the orthotropic MFC actuators plates material.

Second internal boundary condition, which bounds structural with acoustic analysis, are the normal accelerations of the glass surface and the air particles which has to be equal at the interfaces of the glass plate and the air:

$$a_n = \mathbf{n} \cdot \omega^2 \mathbf{u}\,. \quad (7)$$

Last boundary condition which wasn't mentioned so far, is the Sound Hard Boundary Wall, i.e. a_n = 0, at the hemisphere plane, meaning that no acoustic pressure is transmitted through this boundary (e.g. the wall of the building), see the Figure 3.

3.1. Control of elastic parameters of the piezoelectric composite

In order to apply the same governing equation (6) to describe the vibrational response of the MFC actuators, it is necessary to consider them as simple plates with some effective elastic parameters. It is reasonable to perform an additional simulation which introduces the effect of the shunt NC circuit on the elastic parameters of the composite.

Composite materials, such as MFC actuator, come under the group of orthotropic materials. Therefore, elastic properties of MFC actuator could be represented by a symmetric stiffness tensor whose components are expressed in terms of Young's and shear moduli, Y_{ii} and G_{ij}, respectively. As introduced in [5], nowadays the common approach to numerically simulate the macroscopic properties of 3D piezoelectric fiber composites is to create a Representative Volume

Element (RVE) or a unit cell that captures the major features of the underlying microstructure. Periodic boundary conditions must be applied – this implies that each RVE in the composite has the same deformation mode and there is no separation or overlap between the neighbouring RVEs. It is assumed that the average mechanical and electrical properties of a RVE are equal to the average properties of the particular composite. The average stresses and strains in a RVE are defined by the formulas:

$$\overline{T_{ij}} = \frac{1}{V}\int_V T_{ij}\,dV; \quad \overline{S_{ij}} = \frac{1}{V}\int_V S_{ij}\,dV, \tag{8}$$

where V is the volume of the periodic representative volume element. Then, after applying specific boundary conditions for each component (presented in detail in [5]), the effective Young's moduli Y_{ii} and shear moduli G_{ij} could be expressed as:

$$Y_{ii} = \frac{\overline{T_{ii}}}{\overline{S_{ii}}}; \quad G_{ij} = \frac{\overline{T_{ij}}}{2\overline{S_{ij}}}. \tag{9}$$

Figure 4 shows the unit cell that is picked from the periodic piezoelectric MFC actuator. It is placed in the coordinate system such that the piezoelectric fibers are oriented along the x axis and polarized in z axis direction.

When the piezoelectric actuator is shunted by the NC circuit, whose electrical scheme is also in Figure 4, the effective value of Young's modulus of the piezoelectrics is a function of the ratio of the shunt capacitance C_{NC} over the static capacitance C_S of the actuator [1]. Since the capacitance of the negative capacitor is frequency-dependent, large effective values of Young's modulus can be obtained only in a relatively narrow frequency range.

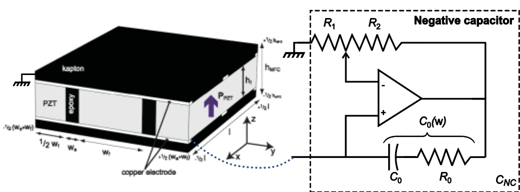

Figure 4. MFC actuator geometry shunted by the active electronic NC circuit working as impedance invertor.

The effect of NC circuit is implemented into COMSOL Multiphysics as Electric Circuit Interface components. The electric scheme is simplified to the simple capacitor parallelly connected to IDE electrodes which create the Terminals for the circuit so the piezoelectric analysis can be coupled with the Electric Circuit Interface. The frequency dependence of the effective Young's modulus of the MFC actuator shunted by the negative capacitor was analyzed in more detail in the recent work by Nováková and Mokrý [6]. Figure 5 presents the typical frequency dependence of the real part and the loss tangent of the effective value of dominant Young's modulus Y_{11} in a broad frequency range. The frequency 890 Hz of the peak values of the real part of Young's modulus Y_{11} is adjusted to the frequency of a particular resonant mode of the glass plate via the particular values of the circuit parameters of the negative capacitor.

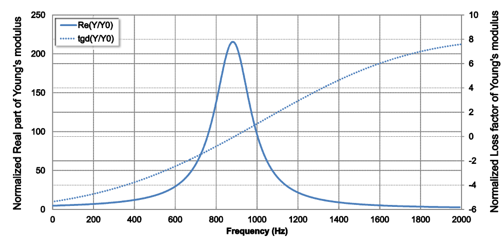

Figure 5. The effective value of the normalized real part and loss factor of the dominant component Y_{11} of the Young's modulus of the Macro Fiber Composite (MFC) actuator with shunted active Negative Capacitance (NC) circuit. Proper adjustment of the NC circuit could increase the value of the Young's in a large extent. The frequency 890 Hz of the peak values of the real part of the Young's modulus is adjusted to the frequency of a particular resonant mode of the glass plate.

4. Results

Calculated frequency dependences of the elastic parameters Y_{ii} and G_{ij} of MFC actuator were applied to the simple MFC patches distributed on the glass surface (according to Fig.2) The frequency acoustic – structure analysis described in Sec. 3.1 was performed. The following numerical parameters were considered in the numerical simulations: Amplitude of incident acoustic pressure $P_i = 0.2$ Pa, corresponding to 80 dB of the sound pressure level. The Young's modulus of the glass is $73.1 \cdot 10^9$ Pa, the Poisson's ratio of the glass is 0.17, and the mass density of the glass is 2203 kg·m^{-3}. The dominant Young's modulus

Y_{11} of the electrically opened piezoelectric MFC actuators equal to ${}^{0}Y_{11} = 30.4{\cdot}10^{9}$ Pa.

Figure 6 shows frequency dependence of the acoustic TL obtained according to the formula (1). Four situations with different geometry of the glass plate and the electrical conditions for the piezoelectric MFC actuators were considered: (solid thick line) planar glass plate with opened MFC actuator, (solid thin line) curved glass plate, according to the shape function

$$z = z_0 \sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{b}\right), \qquad (10)$$

where $z_0 = 5$ mm is the maximal displacement of the glass plate midpoint, with opened MFC actuator, (dashed thick line) planar glass plate with the MFC actuator shunted by NC circuit, and (dashed thin line) curved glass plate, according to the shape function (10), with the MFC actuator shunted by NC circuit. Simulations show that it is possible to increase the TL by about 25 dB at both first vibrational mode due to the curved geometry and at the second vibrational mode due to the effect of properly adjusted shunted NC circuit.

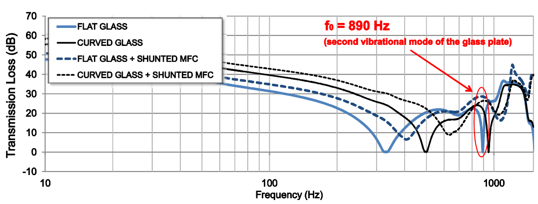

Figure 6. Frequency dependencies of the acoustic transmission loss (TL) through the glass plate with distributed MFC actuators. Comparison of the various glass plate geometry cases and different electrical conditions for attached MFC actuators.

Figure 7 illustrates graphically, that the maximal value of total acoustic pressure above the glass plate is smaller in one order of magnitude when the MFC actuators are shunted by the active circuits with negative capacitance at the adjusted frequency of 890 Hz.

5. Conclusions

We analyzed the possibility of increasing the acoustic Transmission Loss (TL) of sound transmitted through planar or curved glass plates using attached piezoelectric MFC actuators shunted by active circuits with a negative capacitance. The results indicated that that it is possible to increase the TL by about 25 dB at both first vibrational mode due to the curved geometry and at the second vibrational mode due to the effect of properly adjusted shunted NC circuit. The presented method is simple, general as for the broad frequency range and financially acceptable.

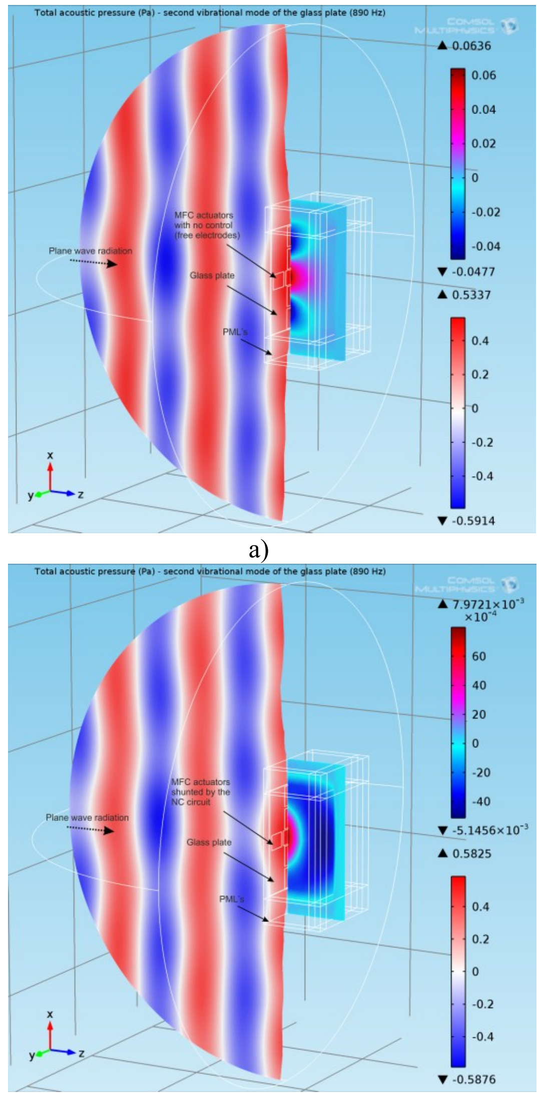

Figure 7. 3D Slice Graph of the total acoustic pressure below and above the glass plate (planar glass plate case); a) MFC actuators without control; b) MFC actuators shunted by NC circuits adjusted to the frequency of 890 Hz.

6. References

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7. Acknowledgements

This work was supported by the Student Grant SGS 2012/7821 Interactive Mechatronics Systems Using the Cybernetics Principles, and the European Regional Development Fund and the Ministry of Education, Youth, and Sports of the Czech Republic in Project Number CZ.1.05/2.1.00/03.0079: Research Center for Special Optics and Optoelectronic Systems (TOPTEC).