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An actively controlled triple-glazed window

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Abstract [404] In recent years were investigated actively controlled double-glazed windows with loudspeakers installed inside the cavity between the window panes. The loudspeakers tried to cancel the sound field inside the cavity in order to improve the transmission loss of the window. Improvements of more than 10 dB in the region of the mass-spring-mass resonance frequency were measured. For usual double-glazed windows the distance of the panes is too small for the installation of loudspeakers between them. On the other hand, a low pane distance is important for the thermal isolation. Thus, here a new approach is investigated. A third window pane with a larger distance is applied to the ready made double-glazing. Now, the loudspeakers are installed in the second cavity. In this paper numerical results obtained from an analytical model of the actively controlled triple-glazed window are discussed.

1 INTRODUCTION

In recent years actively controlled double-glazed windows were investigated theoretically as well as practically (cf. [1–9]). In terms of improvements the most promising approach for actively controlled double-glazed windows is to use secondary loudspeakers and error microphones inside the windows air-cavity. Under certain circumstances improvements of more than 10 dB(A) are achievable. The improvements occur mainly around the mass-spring-mass resonance frequency of the double-glazing, which is usually the weak spot of double-glazed windows.

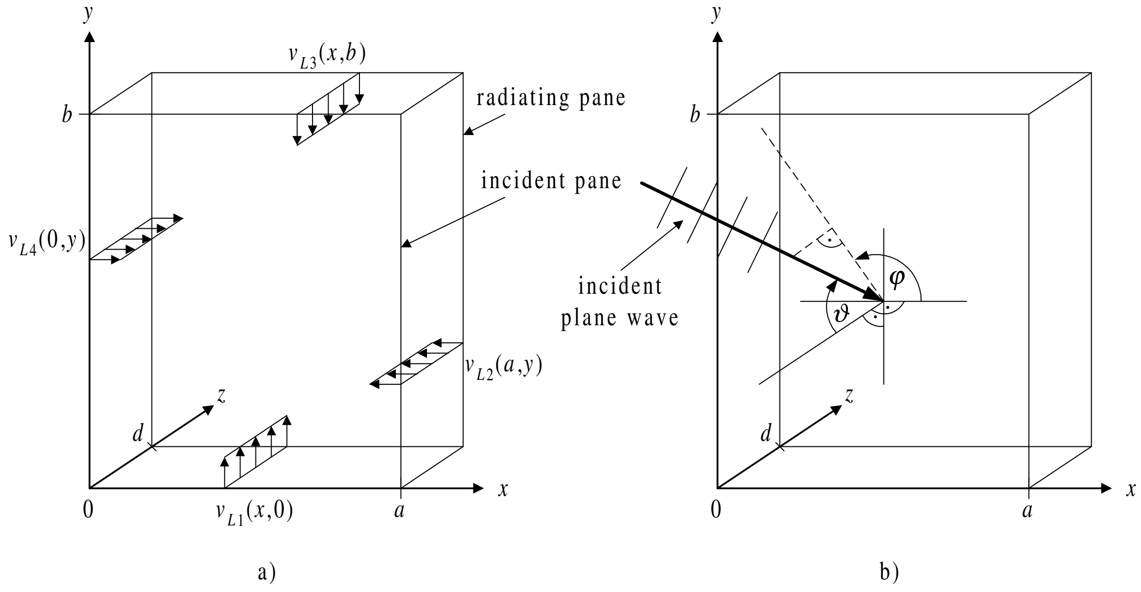
One major Problem of actively controlled double-glazed windows is the necessary relatively large distance of the panes due to the loudspeakers inside the cavity. For example, our first experimental setup contained rather large loudspeakers resulting in a pane distance of approximately 20 cm [3–7]. Other researchers used smaller loudspeakers resulting in a pane distance of 8.4 cm [8]. In our later work [9] we showed experimentally that is is possible to use even smaller — and very cheap — loudspeakers resulting in a pane distance of only 4 cm.

But even that low distance still is not accepted by window manufacturers. The reason is, that the optimal pane distance for thermal isolation is in the order of 16 mm. At that distance no convection of the air inside the cavity occurs, and thus thermal isolation is best. Another potential problem is, that the manufacturing facilities for double-glazings are rather complex. The double-glazing has to be sealed, i.e. the cavity has to be airtight otherwise the window would let condensation in and gets mist. In summary, the inclusion of loudspeakers in the sealing may decrease thermal isolation, it means a high effort in changing the manufacturing facilities and, additionally, it may result in problems in making the sealing airtight.

To solve these problems here an actively controlled triple-glazed window is proposed. A window with a conventional double-glazing — airtight and with a low pane distance — is extended with a third single glass pane — preferably at the side of the room, which shall be protected from sound. This third glass pane can be mounted in a distance from the double-glazing as large as needed for the loudspeakers to be built inside this new cavity. Additionally this cavity does not need to be airtight. The resulting setup is an actively controlled triple-glazed window with three panes and two different large cavities between them.

The aim of this paper is to give some numerical results for the actively controlled triple-glazed window. First, the model used is summarized briefly. Secondly, some numerical results are discussed.

Recently a modal model for an actively controlled double-glazed window was introduced [1]. The main underlying assumptions are: The double-glazed window is modelled in cartesian coordinates as a rectangular box with glass panes at two opposite sides, both in x-y-planes, cf. Figure 1. The primary pane, i.e. pane 1, is set to be at $z = 0$ and the radiating pane, i.e. pane 2, at $z = d$. The panes are assumed to be flexible plates and to be simply supported at the boundaries. The window frame is modelled as four rigid walls in the x-z and y-z planes respectively.



a) b)

Figure 1: *Schematic of the model of the actively controlled double-glazed window.*

Each sub-system is modelled by a sum of infinite modes, i.e. sine-functions for the velocities of the plates and cosine-functions for the sound pressure inside the cavity. The cavity sound field is assumed to be constant in the direction perpendicular to the panes, i.e. in z-direction, because of the relatively short pane distances. These three differential equations, describing the panes and cavity are coupled to yield a set of system equations resulting in a linear set of equations with as many unknowns as modes of plates and cavity considered.

The primary excitation is modelled as an incoming plane wave at an arbitrary angle of incidence. The control loudspeakers are modelled as line sources along the z-direction and, are to be controlled by some complex control coefficients.

The whole set of equations is brought into 'Hermitian Quadratic Form' such that the complex control coefficients can be obtained in an easy manner depending on the cost function to be minimized. The cost functions are some quadratic measures describing which field quantity is to be minimized, e.g. global cost functions like the mean square velocity of one or both of the panes, the radiated sound power or the mean square sound pressure inside the cavity. Also investigated are local cost functions simulating samples of the fields registered by means of microphones or accelerometers.

With this modal model a parameter study was performed and the detailed results can be found in [2]. The main findings are:

- The ranking of the global types of minimization from best to worst is: minimization of the radiated sound power, minimization of the mean square velocity of pane 2, minimization of the mean square sound pressure inside the cavity, minimization of the mean square velocity of pane 1.
- Local minimization of the sound pressure inside the cavity performs better than local minimization of the velocity of pane 2, due to the lower modal density of the cavity sound field.
- Loudspeakers as control sources perform better than forces as control sources.
- Forces applied to pane 1 as control sources perform better than forces applied to pane 2.
- Mixed control schemes using loudspeakers and forces simultaneously is not advantageous.
- A square window is easier to control than a rectangular window due to the degenerated modes.
- Different pane thicknesses are advantageous.
- A large pane distance improves the success of active control.
- For local minimizations, the number of secondary sources should be less than the number of error sensors.

2 A MODAL MODEL FOR ACTIVELY CONTROLLED TRIPLE-GLAZED WINDOWS

The modal model for actively controlled triple-glazed windows given here, is a straightforward extension of the modal model for actively controlled double-glazed windows given in [1]. Thus, here only the basic assumptions for the model and the underlying equations are given rather briefly. For a detailed derivation the reader is kindly asked to refer to [1].

Figure 2 shows a schematic of the triple-glazed window. The distances between the panes are d_1 and d_2 respectively. The velocity distributions on the panes are — from the side of sound incidence to the side of sound radiation — denoted with $v_1(x, y)$, $v_2(x, y)$ and $v_3(x, y)$ respectively. The sound field between pane 1 and 2 is given by $p_{12}(x, y)$ and, the sound field between pane 2 and 3 is given by $p_{23}(x, y)$. The control loudspeakers are assumed to be mounted between pane 2 and 3, i.e. between the middle pane and the radiating pane.

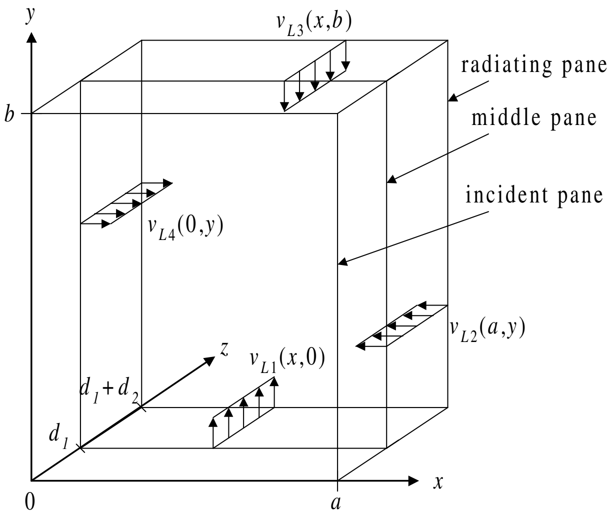


Figure 2: *Schematic of the model of the actively controlled triple-glazed window.*

Five differential equations can easily be stated describing the vibrational behavior of the triple-glazed window:

$$\Delta\Delta v_1(x,y) - k_{B1}^4 v_1(x,y) = \frac{jk_{B1}^4}{m_1''\omega}\left(p_1(x,y,z=0) - p_{12}(x,y)\right) , \tag{1}$$

$$\Delta p_{12}(x,y) + k_0^2 p_{12}(x,y) = \frac{j\omega\rho}{d_1}\left(v_2(x,y) - v_1(x,y)\right) , \tag{2}$$

$$\Delta\Delta v_2(x,y) - k_{B2}^4 v_2(x,y) = \frac{jk_{B2}^4}{m_2''\omega}\left(p_{12}(x,y) - p_{23}(x,y)\right) , \tag{3}$$

$$\Delta p_{23}(x,y) + k_0^2 p_{23}(x,y) = \frac{j\omega\rho}{d_2}\left(v_3(x,y) - v_2(x,y)\right) , \tag{4}$$

$$\Delta\Delta v_3(x,y) - k_{B3}^4 v_3(x,y) = \frac{jk_{B3}^4}{m_3''\omega}\left(p_{23}(x,y) - p_3(x,y,z=d_1+d_2)\right) . \tag{5}$$

Equations (1), (3) and (5) are bending wave differential equations describing the velocity distributions on the panes. Each pane is excited by the two sound fields adjacent to it, e.g. pane 2 (cf. Equation (3)) is excited by cavity sound fields $p_{12}(x,y)$ and $p_{23}(x,y)$. Equations (2) and (4) are differential equations for sound in air describing the cavity sound field distributions between the three panes. Each cavity sound field is excited by the vibration of its two adjacent panes, e.g. the cavity between pane 1 and 2 (cf. Equation (2)) is excited by the velocity distributions $v_1(x,y)$ and $v_2(x,y)$.

In Equation (1) $p_1(x,y,z=0)$ is the sound field distribution on the incident pane 1 due to the incoming wave (cf. [1]). In Equation (5) $p_3(x,y,z=d_1+d_2)$ is the external sound pressure reacting on the radiating pane due to the radiated wave, i.e. the fluid loading. The fluid loading has a negligible effect and can be omitted, cf. [10]. Δ is the Laplace operator $\Delta = \nabla\nabla$.

k_0 is the free wave number in air. The bending wave numbers of the panes are defined by

$$k_{Bu}^4 = \frac{m_u''}{B_u'}\omega^2 \qquad \text{with} \qquad B_u' = \frac{E_u}{(1-\gamma^2)}\frac{h_u^3}{12} \qquad \text{and} \qquad E_u = E_{0u}\cdot(1+j\eta_u) , \tag{6}$$

where $u = 1,2,3$ and $m_u'' = \rho_u h_u$ are the masses per unit area of the panes of densities ρ_u and thicknesses h_u respectively. B_u' are the bending stiffnesses (cf. e.g. [10,11]) with Poisson's ratio

γ and complex Young's moduli E_u taking the dissipation of the panes into account via the loss factors η_u.

As in the case of the double-glazed window, for the triple-glazed window the panes are assumed to be flexible plates and to be simply supported at the boundaries. The two window frames each are modelled as four rigid walls in the x-z and y-z planes respectively. Thus for the velocities of the panes modal functions in the form

$$v_u(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} V_{unm} \sin\frac{n\pi x}{a} \sin\frac{m\pi y}{b} \tag{7}$$

are chosen with modal amplitudes V_{unm} where $u = 1, 2, 3$. For the cavity sound fields modal functions in the form

$$p_w(x,y) = \sum_{p=0}^{\infty}\sum_{q=0}^{\infty} A_{wpq} \cos\frac{p\pi x}{a} \cos\frac{q\pi y}{b} \tag{8}$$

are chosen with modal amplitudes A_{wpq} where $w = 12, 23$.

The next step is to insert the modal functions (7) and (8) into Equations (1) to (5). After a lot but simple manipulations, taking advantage of the orthogonality of the mode shape functions, one can state a linear set of equations with as many equations as modes considered, i.e.

$$\frac{m_1''\omega ab}{j4k_{B1}^4}\left\{H_{1nm} - k_{B1}^4\right\} V_{1nm} + \sum_{pq} J_{np}J_{mq}A_{12pq} = 2p_0 I_n I_m \tag{9}$$

$$\frac{j\omega\rho}{d_1}\sum_{nm} J_{np}J_{mq}V_{1nm} + k_{pq}^2 M_p M_q A_{12pq} - \frac{j\omega\rho}{d_1}\sum_{nm} J_{np}J_{mq}V_{2nm} = 0 \tag{10}$$

$$-\sum_{pq} J_{np}J_{mq}A_{12pq} + \frac{m_2''\omega ab}{j4k_{B2}^4}\left\{H_{2nm} - k_{B2}^4\right\} V_{2nm} + \sum_{pq} J_{np}J_{mq}A_{23pq} = -\sum_i L_{nm}^{(i)}\alpha_i \tag{11}$$

$$\frac{j\omega\rho}{d_2}\sum_{nm} J_{np}J_{mq}V_{2nm} + k_{pq}^2 M_p M_q A_{23pq} - \frac{j\omega\rho}{d_2}\sum_{nm} J_{np}J_{mq}V_{3nm} = 0 \tag{12}$$

$$-\sum_{pq} J_{np}J_{mq}A_{23pq} + \frac{m_3''\omega ab}{j4k_{B3}^4}\left\{H_{3nm} - k_{B3}^4\right\} V_{3nm} = +\sum_i L_{nm}^{(i)}\alpha_i \tag{13}$$

where the infinite sums $\sum\limits_{nm}$ and $\sum\limits_{pq}$ are truncated to yield a finite number of equations. The variables of the set are the modal amplitudes V_{unm} and A_{wpq}. A more detailed derivation of Equations (9) to (13) is easy to obtain with the help of [1], as is the inclusion of the secondary loudspeakers leading to the terms $L_{nm}^{(i)}\alpha_i$ on the right side of Equations (11) and (13) and all the other abbreviations.

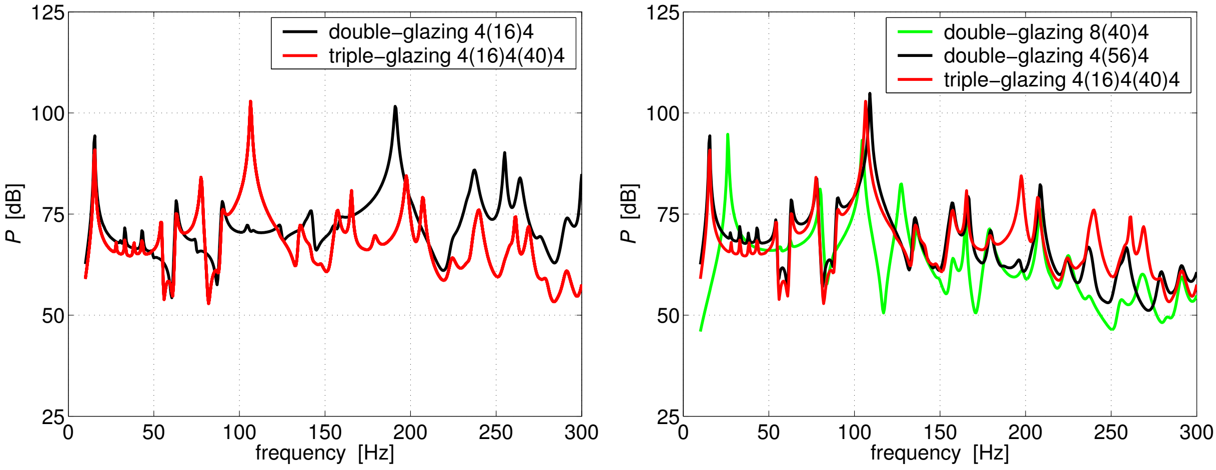
The α_i are some complex coefficients controlling the secondary loudspeakers. If the loudspeaker control coefficients α_i are set to zero, one can simulate the passive triple-glazed window. The goal of this work, however, is to minimize some cost function, e.g. the mean square velocity of the radiating pane, by a suitable choice of the loudspeaker control coefficients α_i. This can be done by the same procedure given in [1] making use of the well-known 'Hermitian quadratic form'. Thus it is not further carried out here.

3 NUMERICAL RESULTS

Some first numerical calculations with the model for the triple-glazed window given in the previous section are performed and comparisons are made with the double-glazed window.

Figure 3a) compares two windows without active control, i.e. a double-glazed window with two 4 mm glass panes and an air gap of 16 mm (often called a 4(16)4-window) and a triple-glazed window with an additional air gap of 40 mm and an additional 4 mm glass pane (resulting in a 4(16)4(40)4-window).

As can be seen from Figure 3a) the mass-spring-mass resonance frequency of the double-glazed window is somewhat below 200 Hz. When applying the third glass-pane at a distance of 40 mm the peak below 200 Hz is lowered substantially and shifted somewhat higher in frequency and a new peak somewhat above 100 Hz appears. This new peak is at nearly the same frequency at which a double-glazed window with an air gap of 56 mm and panes both 4 mm thick would have its mass-spring-mass resonance frequency. Thus, at this low frequency range the triple-glazed window acts as a double-glazed window with the distance of the outer panes. The influence of the middle pane can be neglected in this case [12]. The original mass-spring-mass resonance frequency of the double-glazed window is isolated from the sound radiation into the room due to the application of the second pane at a larger distance. Thus in the frequency range considered here, the passive 4(16)4(40)4-triple-glazed window behaves almost like a 4(56)4-double-glazed window (cf. Figure 3b)). It is interesting to note, that the window does not behave as a 8(40)4-double-glazed window, except the fact that the mass-spring-mass resonance frequency of this window is nearly the same. The differences are mainly due to the fact that a 8 mm pane has, of course, different structural resonance frequencies than a 4 mm pane (cf. Figure 3b)).



a) b)

Figure 3: *Comparison of double- and triple-glazed windows without control.*

Applying active control with four secondary loudspeakers (cf. [1] for the exact positions) yields the results illustrated in Figure 4. In the upper diagram of Figure 4 radiated sound powers vs. frequency are displayed with and without control and, in the lower diagram of Figure 4 are displayed the differences in radiated sound power with and without control. Four cases are shown, i.e. minimization of the radiated sound power, minimization of the mean squared velocity of the (radiating) pane 3, minimization of the mean squared sound pressure inside cavity 23 and, control off.

The ranking of the three types of minimization is clearly visible. Minimization of the radiated sound power naturally yields the highest improvements in the whole frequency range regarded. In the ranking order sound power minimization is followed by velocity minimization of the radiating pane which itself is followed by sound pressure minimization of cavity 23.

Sound power minimization and velocity minimization yield the highest improvements in the very low frequency range, where only a few modes contribute to the vibration of the radiating pane. In this frequency range the passive triple-glazed window (as well as any double- or single glazed-window) vibrates as a whole with all panes in phase. Only very small sound pressure is produced inside the cavities and, nearly no sound pressure can be minimized, thus the control loudspeakers remain almost inactive.

Besides the very low frequency range the range around the mass-spring-mass resonance frequency is mainly affected. In this range sound pressure minimization achieves its highest improvements.

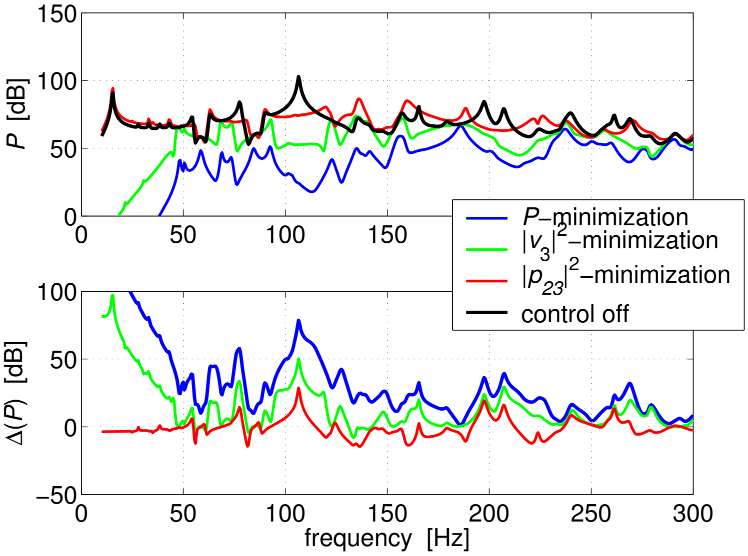


Figure 4: *Actively controlled triple-glazed window 4(16)4(40)4.*

4 SUMMARY AND CONCLUDING REMARKS

A modal model for actively controlled triple-glazed windows is presented, which is a straightforward extension of a previous presented modal model for actively controlled double-glazed windows. It is known from literature, that the passive triple-glazed window behaves like a double-glazed window with overall distance of both cavities at low frequencies. In the special case considered here, with one rather small and one rather large pane distance, a reasonable assumption to explain the behavior around the mass-spring-mass resonance frequency is to think of the triple-glazed window as a double-glazed window with one pane as thick as the two near panes together. The near panes in that frequency range vibrate in phase acting as one thick pane but with structural properties of a thin pane. Thus the behavior of this special actively controlled triple-glazed window seems to be the same as an actively controlled double-glazed window.

Nevertheless, a detailed parameter study is still necessary with varying pane distances and pane thicknesses, e.g. to understand what happens if the magnitude of both pane distances are in the same order. It is expected that in that case the triple-glazed window cannot be regarded as a double-glazed window and, active control might behave differently. Additionally it might be interesting what happens if the loudspeakers are mounted in cavity 12, because from the actively controlled double-glazed window it is known, that it is best to apply the secondary sources as near to the side of the noise source as possible. In that context it could also be interesting to apply forces on one of the panes rather than loudspeakers.

Further simulations will be carried out in the future showing the effects of varying the parameters as mentioned above. Additionally, measurements with a real time controller will be performed to validate the numerical findings.

REFERENCES

[1] A. Jakob, M. Möser: A modal model for actively controlled double-glazed windows, Acta Acustica united with Acustica, 89(3), 2003, 479–493.

[2] A. Jakob, M. Möser: Parameter study with a modal model for actively controlled double-glazed windows, accepted for publication in Acta Acustica united with Acustica, 2004.

[3] Jakob A, Möser M. Enhancement of the transmission loss of double panels by means of actively controlling the cavity sound field, Proceedings Active 99, Ft. Lauderdale, FL, USA, 1999, p. 363–374

[4] Jakob A, Möser M. Active control of the cavity sound field of double panels with a feedback controller, Proceedings 7th International Congress on Sound and Vibration - ICSV7, Garmisch-Partenkirchen, Germany, 2000, p. 281–288

[5] Jakob A, Möser M. Active control of double-glazing windows: an experimental comparison between feedback and feedforward controllers, Proceedings 17th International Congress on Acoustics - ICA, Rome, Italy, 2001

[6] Jakob A, Möser M. Active control of double-glazed windows. Part I: Feedforward control, Applied Acoustics, 64(2), pp. 163-182, 2003

[7] Jakob A, Möser M. Active control of double-glazed windows. Part II: Feedback control, Applied Acoustics, 64(2), pp. 183-196, 2003

[8] O.E. Kaiser, S.J. Pietrzko, M. Morari: Feedback control of sound transmission through a double glazed window, Journal of Sound and Vibration, 263, 775–795, 2003

[9] Jakob A, Möser M. An actively controlled double-glazed window with small pane distance, Forum Acusticum, Sevilla, 2002

[10] Fahy F. Sound and Structural Vibration, Academic Press, 1985

[11] Cremer L, Heckl M. Körperschall, Springer-Verlag, Berlin, 1996

[12] Brekke A. Calculation methods for the transmission loss of single, double and triple partitions, Applied Acoustics, 14, pp. 225-240, 1981