Active control of sound transmission loss through a single panel partition using distributed actuators. Part I : simulations

K. Henrioulle W. Dehandschutter P. Sas
Department of Mechanical Engineering, division PMA, K.U.Leuven, Belgium
e-mail : kris.henrioulle@mech.kuleuven.ac.be

Abstract

A new acoustic actuator is designed and optimised to be used for active noise control. The active element is a flat acoustic actuator, consisting of two PVDF elements bonded on a honeycomb structure, and driven in opposite phase. The actuator can be useful in many applications. One of these, as illustrated in this article, is an active control system, designed to increase the sound transmission loss through a single panel partition in the low frequency range. Simulations make use of an analytical model for the actuator, for the fluid-structure coupled model, and for the controller. The transmission loss can be increased considerably below 250Hz, and with a small modification to the actuator, the system can increase the transmission loss up to 500 Hz. Special attention is paid to a configuration suitable for an industrial application of this control technique, where the actuator is shielded from the environment by the passive plate, and using accelerometers on the passive plate as error sensors.

1. Introduction

In many active noise and vibration control applications, it is impossible to use conventional point actuators or sensors due to the limited space available like in sound encapsulations, aircraft fuselages etc. Piezoelectric elements are a promising alternative, because they are very thin and thus space efficient, light, easily shaped and bonded to or embedded in a variety of structures. Most used piezoelectric materials are PZT (Lead Zirconate Titanate) and PVDF (Polyvinylidene Fluoride). PVDF has some advantageous properties; it can easily be produced in large sheets to cover large surfaces, it has low Young's modulus and low density, and it can withstand an electrical field which is 100 times larger than for PZT (Sessler [1]). In most applications however, the maximum electrical field in the PVDF film is limited by the voltage that the amplifier can produce. A disadvantage is that, compared to PZT, PVDF has smaller piezoelectric constants.

This paper presents an acoustic actuator based on PVDF piezoelectric material, that can be an alternative for conventional loudspeaker systems used in active control systems. The actuator is very thin and can be placed in the cavity of a double wall structure. The actuator was not designed for a specific application, but was meant to be used as a sound source or vibration controlled element in a variety of applications. Its use will be demonstrated in a configuration where the sound transmission loss through a single panel partition will be increased by an active control system based on the acoustic actuator.

2. Modelling and optimisation of a distributed actuator

2.1 Analytical actuator model

The analytical model for the actuator, relating the voltage applied to the actuator, to the resulting displacement, is based on the work of Sutton *et al.* [2] and Lee [3], and will be briefly recalled here.

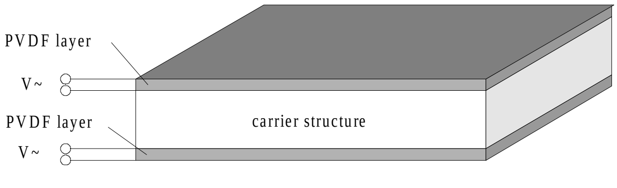


Figure 1 : Schematic view of the acoustic actuator

The actuator (fig. 1) consists of a rectangular plate, which will be referred to as the carrier structure, covered on its entire upper and lower surface with a piezoelectric PVDF-layer. It is assumed that the actuator's boundary conditions are simply supported. Therefore their action on the carrier structure is equivalent to external line moments acting along the boundaries of the piezoelectric elements, as shown by Dimitriadis *et al.* [4]. As a result, the PVDF elements can only excite the odd-odd bending modes in the actuator.

In the model, the strain in the actuator is supposed to vary linearly over the actuator height, including the piezoelectric elements. The stress in the PVDF-layers can be described by the piezoelectric constitutive equations (1).

$$[\sigma]=[c][\varepsilon]-[c]P(x,y)\begin{bmatrix}d_{31}\\ d_{32}\\ d_{36}\end{bmatrix}E_3 \qquad (1)$$

σ is the mechanical stress matrix, c is the stiffness matrix, ε is the strain matrix, P(x,y) is the piezoelectric sensitivity function which equals 1 on the surface where the PVDF is covered by an electrode, and equals zero where the PVDF is not covered by an electrode, d_{31} d_{32} and d_{36} are the piezoelectric constants and E_3 is the electric field across the actuator's thickness.

From this equation, the moment per unit length and the twisting moment can be calculated and substituted in the plate equation for thin plates, yielding :

$$m_a\frac{\partial^2 w}{\partial t^2}+(D_{ca}+D_p)\left\{\frac{\partial^4 w}{\partial x^4}+2\frac{\partial^4 w}{\partial^2 x\partial^2 y}+\frac{\partial^4 w}{\partial y^4}\right\}=\ell(x,y,t) \qquad (2)$$
$$-C_pV_3\left\{(d_{31}+v_pd_{32})\frac{\partial^2 P(x,y)}{\partial x^2}+(d_{32}+v_pd_{31})\frac{\partial^2 P(x,y)}{\partial y^2}\right\}$$

in which m_a is the mass per unit area of the actuator, w the out-of-plane displacement, D_{ca} and D_p the bending stiffness of respectively the carrier structure and piezoelectric elements, η_p the piezoelectric Poisson coefficient, C_{pe} the piezoelectric actuation term, and V_3 the voltage applied across the thickness of the piezoelectric layer. This equation is solved by decomposing the plate's normal displacement in a finite sum of bending modes.

This actuator was built and measurements prove that this analytical model describes quite accurately the behaviour of the acoustic actuator [5].

2.2 Optimisation of the actuator properties

The analytical actuator model was used to optimise the actuator properties, aiming at the highest acoustic power output in a frequency range from 30 to 500 Hz [6]. The actuator's length and width are 300 mm x 400 mm, which is small enough to ensure that the actuator be integrated in existing structures. The parameters that have to be optimised are the specifications for the piezoelectric elements and the carrier structure. They were determined taking into account the following considerations.

To operate as an acoustic source, the actuator should produce a high momentum on a light and flexible structure.

The PVDF film should be as thin as possible for two reasons. Firstly, a high sound power output is achieved with a high bending moment on a flexible actuator. A thin PVDF layer yields a flexible actuator. Secondly, the strain in the PVDF depends linearly on the electric field, which is inversely proportional to the PVDF thickness. A thinner PVDF film results in a larger electric field in the actuator, and a higher displacement. For manufacturing reasons, the thickness of the PVDF film is chosen to be 0.5 mm.

The main function of the carrier structure is to maintain a distance between the piezo elements, and couple the movement of the piezo elements to assure a bending motion in the actuator, preventing the actuator to deform due to shear strain. The larger the distance between the PVDF elements, the larger the momentum applied to the actuator will be, but also the higher the actuator's stiffness will be. A honeycomb carrier structure was chosen, which is a light and flexible structure that guarantees a bending motion in the actuator. This means that the mass and stiffness of the actuator assembly are almost completely determined by the PVDF elements, and not by the carrier structure, resulting in a very light actuator.

A honeycomb carrier structure thickness of 6.4 mm was chosen, because over the frequency range considered here, the actuator has two resonance frequencies, and a sufficiently high sound power output can be expected over the whole frequency range.

Finally, the actuator will be denoted as honeycomb-PVDF actuator.

2.3 Analytical fluid-structure coupled model

In order to study the behaviour of the acoustic actuator in an active control system, an analytical fluid-structure coupled model was implemented in MATLAB [6], describing the behaviour of the system shown in figure 2. This system can be part of a transmission wall for instance as used for machine encapsulations. This single panel partition consists of a simply supported passive steel plate placed in parallel with the honeycomb-PVDF actuator. The passive plate has the same dimensions as the honeycomb-PVDF actuator (300 mm x 400 mm), and a thickness of 1 mm. Between the passive plate and the actuator is a cavity of 70 mm. The honeycomb-PVDF actuator can be placed at both sides of the plate; at the side where the disturbance field is incident, referred to as the incident side, or at the side where the sound is radiated into the free space, referred to as the radiating side.

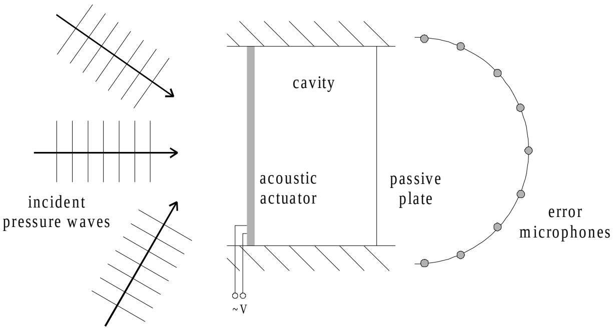


Figure 2 : Simulation set-up

The system is excited by a number of plane waves, each incident to the actuator under a certain angle and with a certain phase difference, to approximate a diffuse sound field excitation. The control input is the voltage applied to the actuator. The output of the model is the resulting displacement of the passive plate and the actuator, and the resulting sound pressure in the cavity. With this information, the sound pressure in a point outside the single panel partition can be calculated, as well as the total radiated sound power into the far field.

The analytical model for the single panel partition is extended with a model for the controller. The controller calculates the voltage applied to the acoustic actuator, to minimise the cost function, being the squared moduli of the outputs from the error signals [7]. The best practical realisation [7] of this exact least squares solution is a filtered-X LMS feed forward algorithm [8], which will be used for later experiments. The best choice of error sensors, to realise a minimum sound power transmitted through the double panel partition, is a number of error microphones located at the radiation side of the double panel system. Other possible error sensors are accelerometers on any of the structural components, or microphones inside the cavity.

3. Simulation of an actively controlled single panel partition

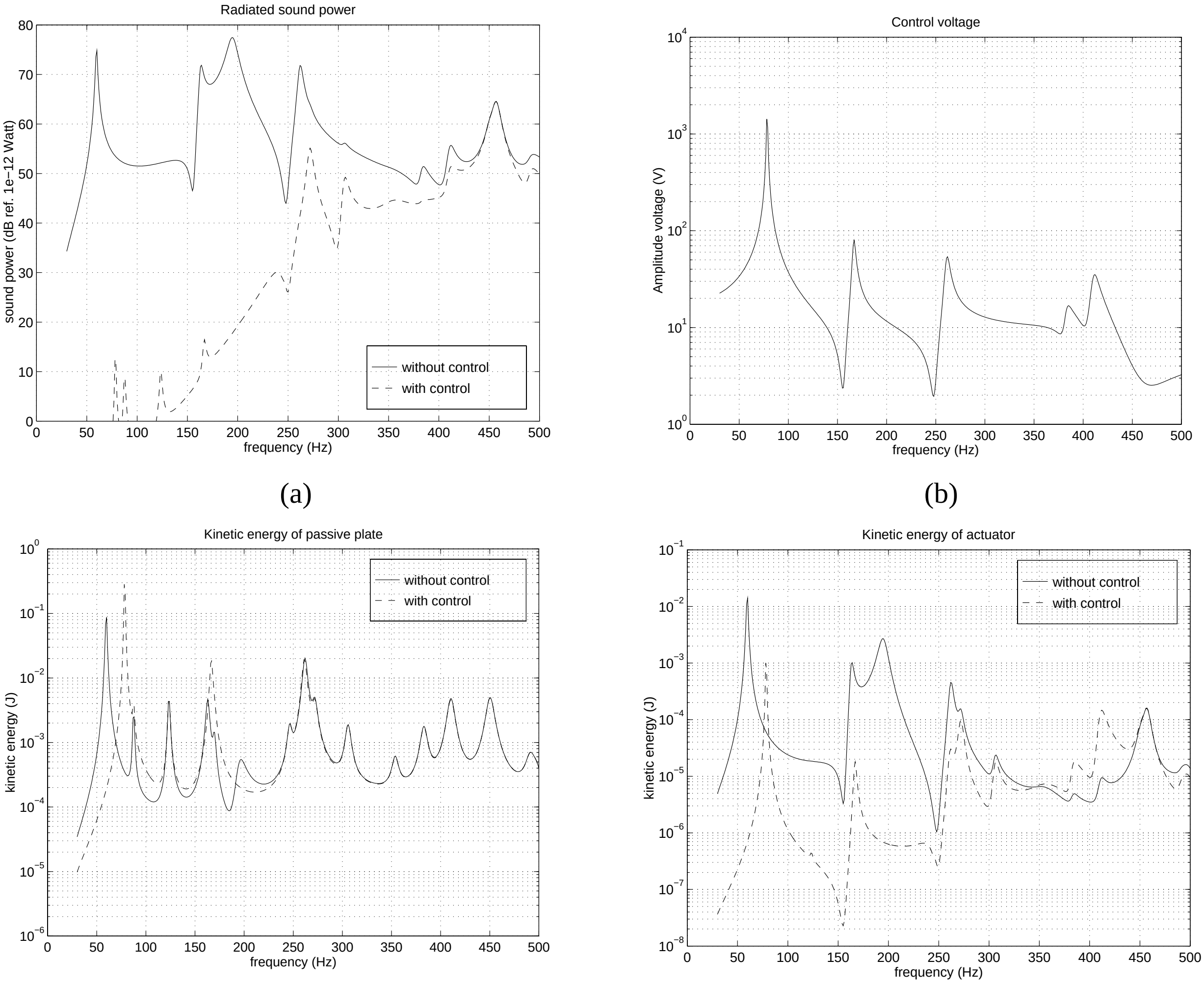
Based on the simulation results, the configuration for the panel partition and the controller will be selected. The first question that arises is at which side of the passive plate the acoustic actuator should be placed, at the incident or at radiating side? The simulations described in paragraph 3.1 deal with this question. Paragraph 3.2 examines the use of accelerometers as an alternative for the microphones as error sensors. Based on the conclusions from the simulations; an improved design is proposed for the honeycomb-PVDF actuator.

3.1 Selection of the single panel configuration

3.1.1 Actuator at radiation side

Figure 3 presents the simulation result for an actively controlled single panel partition with the actuator placed at the radiation side using microphones as error sensors. Figure 3.a shows the sound power with and without control. The solid line is the sound power produced by the primary sound field. The dashed line is the sound power resulting from a superposition of the primary field and the sound power due to the applied control voltage. Because of the small dimensions of the cavity, there is a strong the coupling between the steel plate and the actuator, and the behaviour of the system is quite complex.

Below 250 Hz, the transmission loss through the panel partition is increased considerably by the control action, which is not the case above this frequency. Figure 3.c shows that the control system achieves this result by increasing the vibration level of the actuator in the frequency range from 350 Hz to 450 Hz and around 78 Hz. In this frequency range, the sound power radiated by the actuator is controlled by generating a secondary sound field, which interferes destructively with the primary sound field. In the other frequency band, the sound power transmitted through the panel partition is reduced by decreasing the vibration level of the passive plate. The control voltage, given in figure 3.b, shows that at frequencies where the vibration level is increased, the control voltage required is much larger than in the case where the vibration level is decreased by the controller. Standard amplifiers can give an output voltage of 200 V amplitude, a value which is exceeded only around 78 Hz, where the vibration level of the actuator is increased considerably.



(a) (b)

(c) (d)

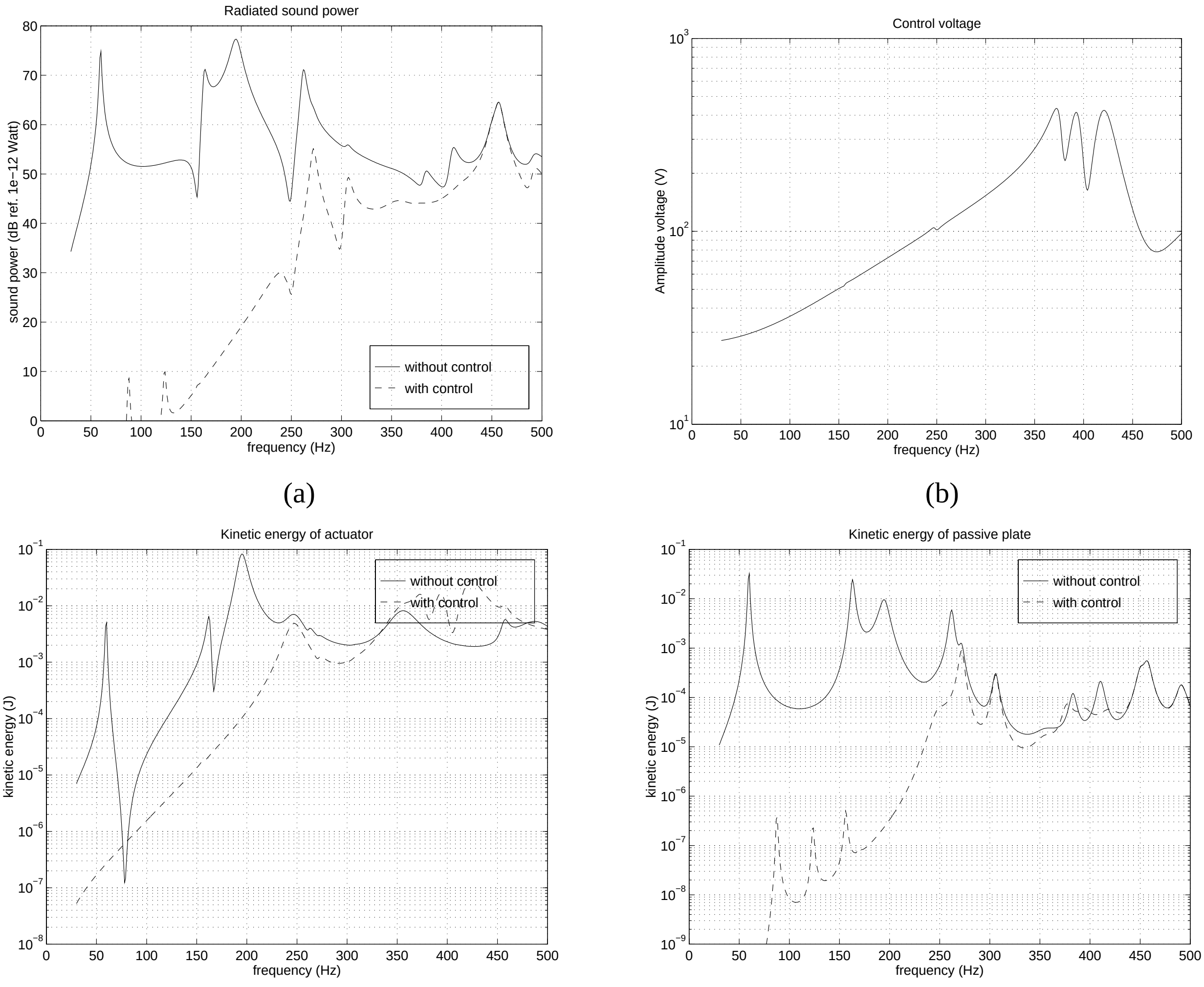
Figure 3 : simulation of a single panel partition with the standard acoustic actuator placed at radiation side, and error microphones as error sensors.

Figure 3.c shows that the control action has an effect on the passive plate as well. The insertion loss by the active control system, averaged over the frequency range from 30 to 500 Hz is 14.2 dB (ref. 10^{-12} W)

The reason for the worse control performance above 250 Hz is twofold.

Firstly, due to the design of the actuator, it can excite only the odd-odd structural bending modes. As mentioned before, the action of the PVDF elements on the carrier structure is equivalent to external line moments bending moments acting along the boundaries of the piezoelectric elements. The primary field however will also excite the even structural modes in the actuator, which is the case f.i. at 307 Hz. The control system can reduce the sound radiated by the odd-odd modes, but is unable to influence the vibration level of these even modes. Although the even modes are less efficient sound radiators, they will contribute to the sound power radiated by the panel partition after control.

The phenomena involved can be explained by introducing the notion ‘radiation modes’ [9]. The sound power radiated by a vibrating structure can be decomposed into radiation modes, which are a set of velocity contributions on the structure whose sound power radiation is independent of the amplitudes of the other velocity contributions. This was also recognised by Pan et al. [10], who simulated a PVDF volume velocity sensor and actuator. This actuator-sensor pair was designed to control only the first radiation mode, preventing spillover to other radiation modes. They showed that controlling only the first radiation mode is effective below a certain frequency, which depends on the dimensions of the panel partition. For their configuration, this frequency is located around 400 Hz, for the configuration in this study it is located around 250 Hz. The honeycomb-PVDF excites besides the first radiation mode also other radiation modes consisting of a set of odd-odd vibration modes. The main reason for the poor active transmission loss



(a) (b)

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Figure 4 : simulation of a single panel partition with the standard acoustic actuator placed at incident side, and error microphones as error sensors.

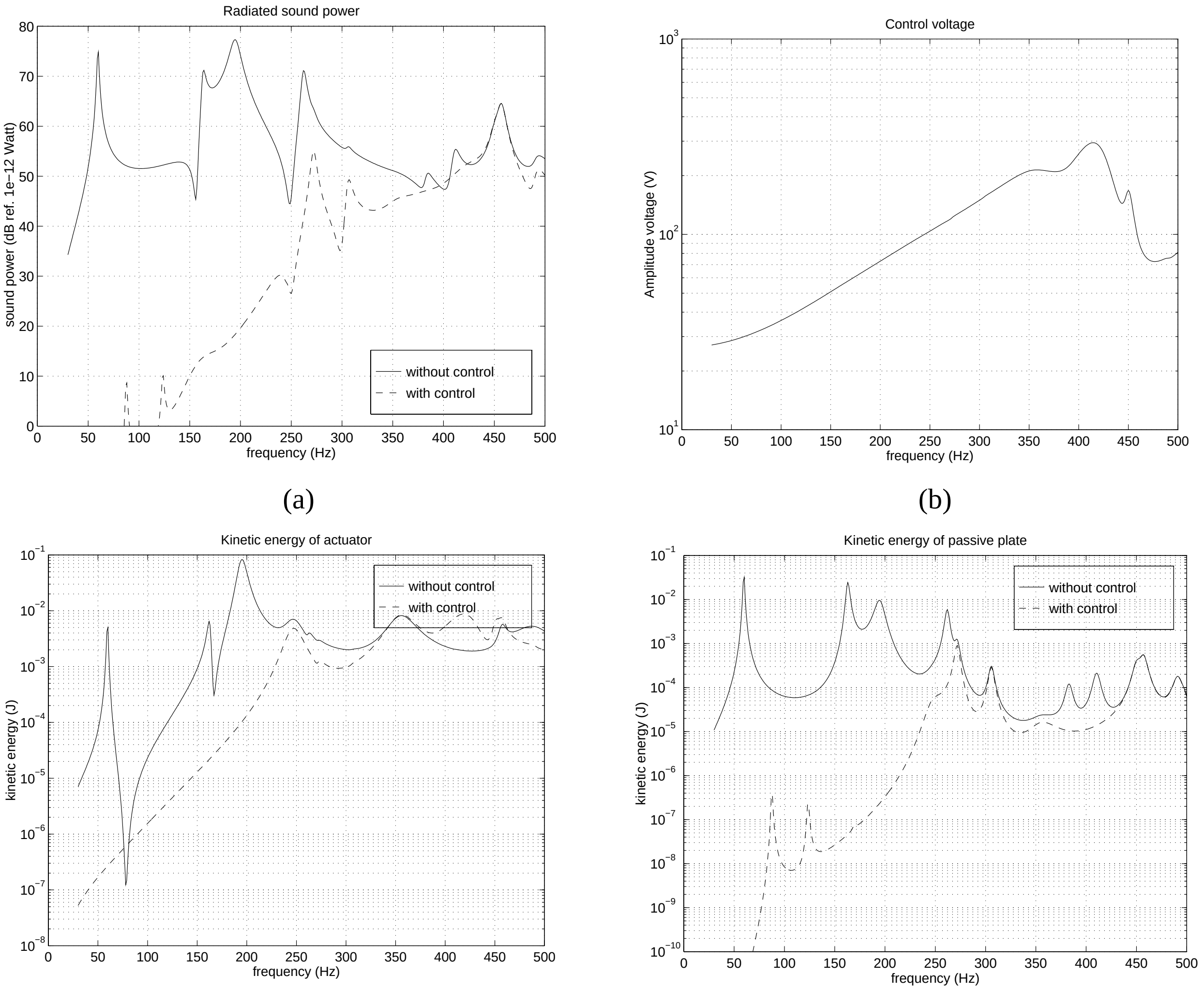
above 250 is the impossibility to control some of the higher order radiation modes, which applies to the PVDF-honeycomb actuator as well to the volume velocity actuator.

Secondly, due to the high damping of the actuator modes, more than one mode will contribute to the sound power radiated by the panel partition. As the actuator has only one control input, only one mode can be controlled independently at one frequency by the control system. The control system cannot reduce the vibration level of one mode at one frequency without increasing the vibration level of other modes at the same frequency. The only alternative is to increase the vibration level of a certain set of modes, and adjust their phase such that the sound field that they produce will interfere destructively with the primary sound field. For both problems, a solution will be suggested in paragraph 3.2.

3.1.2 Actuator at incident side

Figure 4 groups the simulation result for a similar configuration as the previous paragraph, but with the actuator placed at the incident side, again using microphones as error sensors. The conclusions are very similar. Note that the actuator’s vibration level (figure 4.c) is increased at some frequencies to decrease the vibration level of the actuator, and is decreased at other frequencies to obtain the same effect. Comparison of figure 3.a and 4.a learns that the increase in transmission loss is almost the same, and when averaged over the frequency band from 30 to 500 Hz differs only by 0.1 dB.

The most important difference is the required control voltage. When the actuator is placed at radiation side, the primary sound field is already weakened by the passive plate, and the control voltage is lower (figure 3.b) than in the case where



(a) (b) (c) (d)

Figure 5 : simulation of a single panel partition with the standard acoustic actuator, error sensors are accelerometers placed on the passive plate

the actuator is placed at the incident side, as shown on figure 4.b. The conclusions concerning the control mechanisms and the worse control performance above 250 Hz are the same as in the previous paragraph

3.1.3 Conclusion

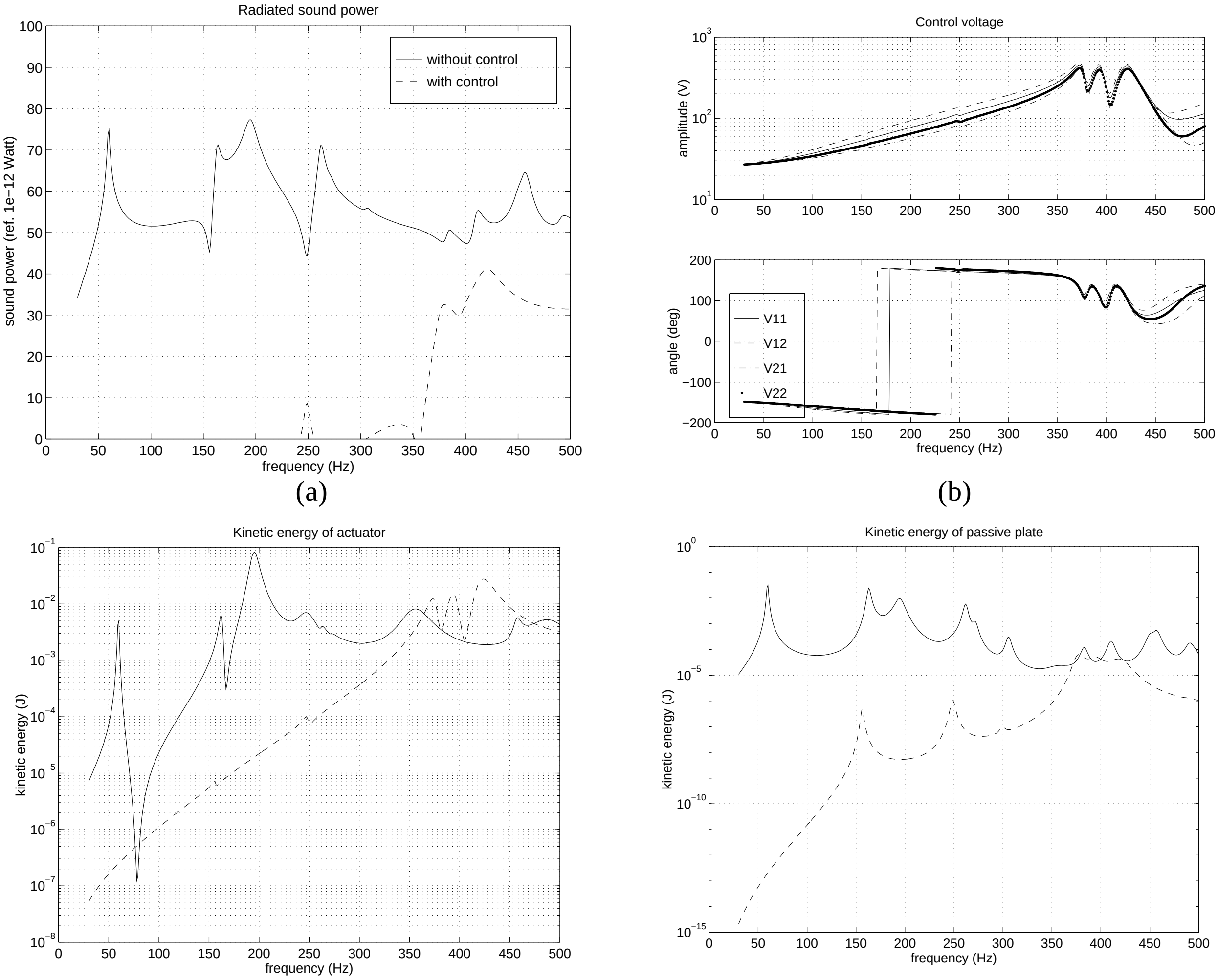
As the control performance is comparable for both configurations; the best configuration is to place the actuator at the radiating side, because in that case a lower control voltage is required.

However, for a practical implementation; it is more interesting to shield the actuator from the environment. Therefore, the configuration where the actuator is placed at the incident side will be used for the next simulations. This configuration is similar to existing (passive) machine enclosures, where absorbing material is used to increase absorption of the sound inside the enclosure. The outside of the enclosure comprises a steel plate. In such an enclosure, the flat actuator can be included in the absorbing material.

3.2 Selection of control configuration

3.2.1 Accelerometers on the passive plate as error sensors

Figure 4.d already indicated that the optimal control strategy - minimising the sound pressure in the error microphones - consists of decreasing the vibration level of the passive plate. It can be expected that a control performance, close to the optimal performance, can be obtained using accelerometers as error sensors placed on the passive plate, so that the control system will reduce its vibration level.



(a) (b)

(c) (d)

Figure 6 : simulation of a single panel partition with the acoustic actuator with four control inputs, and error microphones as error sensors.

Figure 5 gives the result for this simulation. The active increase in transmission loss is only 0.6 dB less than in the optimal case. Only at those frequencies, where the optimal control strategy was to increase the vibration level, this control strategy will show a worse control performance.

3.2.2 Honeycomb-PVDF actuator with four control inputs

The frequency region where the actuator can increase the transmission loss can be extended to 500 Hz by dividing the PVDF sheets in four independent elements. A schematic view of this actuator is given in figure 7. When all four elements are driven in phase, the odd-odd modes will be excited. To excite the (1,2) mode, V_{11} and V_{12} are driven in phase, and V_{21} and V_{22} in opposite phase. In a similar way, modes (2,1) and (2,2) can be excited. It should be noted that still not all bending modes can be excited. To be able to excite a certain mode requires at least 1 element per half wavelength for this mode shape. However, in the frequency region considered here, most of the modes contributing to the sound power output can be controlled with this actuator. As there are four control inputs, four modes can be controlled at one frequency independently. Figure 6 shows that the sound power after control is considerably lower than for the standard honeycomb-PVDF actuator. At all frequencies, the controller is capable of increasing the transmission loss. Figure 6.b shows how the control system can optimise the phase of the voltage

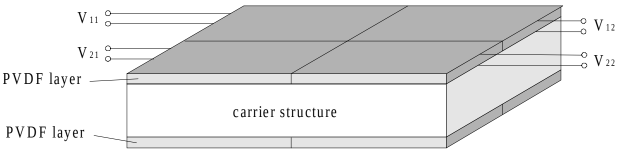


Figure 7 : schematic view of the PVDF-honeycomb actuator with 4 independent PVDF elements

applied to the different PVDF elements. The vibration level of the plate is decreased over the whole frequency band from 30 to 500 Hz.

A disadvantage is that this configuration requires four amplifiers, and four control outputs.

4. Conclusions

An flat acoustic actuator was designed, consisting of two PVDF sheets, bonded at each side of a honeycomb carrier structure. The analytical model for the actuator allowed the optimisation of the design, yielding the highest acoustic power output.

One application for the actuator was illustrated, i.e. the active increase of transmission loss through a single panel partition. A fully coupled fluid-structure analytical model was derived for the single panel partition, extended with a model for the controller.

It was shown that the transmission loss can be increased considerably in the low frequency region when the actuator is placed in the parallel with the passive plate of the single panel partition, and driven by a control system.

A study of the performance of the active control system learned that the optimal configuration consists of the actuator placed at the outside of the panel partition, where the sound is radiated to the environment, and using microphones as error sensors. However, a configuration with the actuator placed at the incident side, and using accelerometers placed on the passive plate as error sensors gives good results, which do not differ much from the optimal performance.

Finally, where the simulations showed a worse control performance at some frequencies, these problems can be overcome by dividing the PVDF elements, covering the honeycomb carrier structure, into four independently driven elements. Simulations showed a much improved control result for this modified design of the actuator.

Acknowledgements

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