Considerations on the reduction of structure-borne sound radiation using passive and semi-active treatments and active structural actuators and sensors

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Control of structure-borne sound radiation utilising "intelligent materials" is one research topic in EU-funded Integrated Project "Intelligent Materials for Active Noise Reduction" (InMAR). The most obvious method is to damp resonant modes of a structure using passive treatments. More complex methods include treatments with semi-active materials like shape memory alloys, and using active structural actuators like piezoelectric patches to damp the vibration of the structure. If the intention is to control only the sound radiation from the structure (so called Active Structural Acoustic Control, ASAC), more effort must be placed on the identification of modes, which are good sound radiators instead of damping all modes. Also structural sensors are often used as it is a wish to predict the sound radiation from the structure using sensors fixed on the structure itself. In this paper an outline is given of the work done in InMAR Work Area for actuators and sensors (WA 1.2) coordinated by Technical Research Centre of Finland (VTT). Work is mostly oriented for developing different structural actuators to control actively the sound radiation from vibrating structures along with structural sensors for sound radiation prediction. Actuators for high temperature applications are being developed, and investigations on transparent actuator-sensor systems performed. Basic principles of actuator and sensor systems to be developed mainly for plate-like structures will be described and some modelling results are presented.

1 Introduction

This paper gives a short overview of the work done in the Work Area (WA) 1.2 of the European Union funded project "Intelligent Materials for Active Noise Reduction" (InMAR).

Actuator and sensor systems developed in InMAR WA 1.2 can be grouped in structural control and acoustic control.

Most of the work is oriented to control the structural vibrations in order to decrease sound radiation from the structure. Three concepts can be identified:

- Concept for semi-active and active structure borne sound control concentrating in semi-active and active resonant mode vibration damping in structures (including high temperature applications).

- Concept for active structural acoustic control (ASAC) concentrating in active control of well sound radiating structural modes of panels and other structures (including transparent panel applications).

- Concept for active structural barrier control (ASBC) concentrating in developing elastic mass actuator (EMA) elements and their use for active structural sound transmission loss increase and sound radiation reduction.

For acoustic control two concepts can be identified:

- Semi-active and active multilayer structures for sound transmission loss increase and sound radiation reduction.

- Active noise cancellation and active sound quality control utilising acoustic actuators (more traditional ANC-approach).

Some of the concepts and respective applications and actuator and sensor systems are not yet very well defined in InMAR, and in these cases only some perspectives of the future work are given.

2 Structural control

Actuator and sensor systems, which are developed in InMAR WA 1.2 for semi active and active structural control, are primarily meant to decrease the amplitude of the resonant mode vibrations of primary structures. The main effect of structural active systems is to increase the damping of the structure. In ASAC approach, however, the stress is in the control of those modes, which are good sound radiators. From the actuator point of view the systems are more or less identical, but in ASAC approach structural sensors have a very important role in identifying the modes, which radiate sound efficiently.

Both inertial and strain (piezoelectric) actuators are considered for the resonant mode damping and for ASAC approach. Methods and different actuator types
for ASAC are fairly well defined already in literature, e.g. [1]. The newer ASBC concept, based on elastic mass actuator-sensor elements, has not yet been reported in literature, and is described in this paper in some detail.

2.1 Considered actuator and sensor types for resonant mode damping and ASAC approach

For active resonant mode damping inertial actuators and integrated velocity sensors can readily be used for structural control. Different sizes of actuator-sensor units can be found commercially, e.g. [2].

Piezoelectric actuators and sensors, even if available commercially, need further considerations in structural noise control. All main designs: unimorph, bimorph (trimorph) and stacked actuators for different applications will be studied and special actuator configurations will be developed. An overview of possible configurations to be used also in InMAR is given in [3].

A special attention will be paid to low profile composite actuators, both to wafer composites manufactured by German Aerospace Center (DLR) and to fibre composites manufactured by Smart Material GmbH (SMG). Also new developments based on the shear effect (d15-effect) of the piezoelectric will be considered. Combining different actuator designs complex shape change actuators (3-D elements) producing twisting and tilting actuation in addition to traditional elongation (d33-effect) and contraction (d31-effect) will be developed, especially by Fraunhofer Institut für Keramische Technologien und Sinterwerkstoffe (FhG-IKTS). All three institutes are partners of InMAR WA 1.2. Designs to be used in practical applications are, however, still under consideration, because only very few final applications have been defined so far.

There are also two special cases to be studied in InMAR WA 1.2 context:

- high temperature material based piezo actuator and sensor systems with the ability to withstand high temperatures, e.g. for car oil sump and power train sound radiation reduction and
- transparent actuator-sensor systems to be used in applications (e.g. car wind shield vibration damping) in which transparency of the sound radiating structure is essential.

There seem to be possibilities to develop both high temperature and transparent piezo actuator systems for car applications. Different actuator, electrode and packaging materials are studied by FhG-IKTS and DLR for these applications.

For resonant mode damping and ASAC approach, one essential challenge is to develop actuator-sensor pairs for decentralised local control. Direct velocity feedback (DFVB) control is simple and can be very effective. If the sensor and actuator are collocated and dual, then the sensor-actuator response function is real and positive so that the feedback control loop is unconditionally stable and large control gains could be implemented with high levels of damping [4]. This kind of systems are studied and developed at ISVR. A special sensor type, which is developed for ASAC approach, is sound radiation (modal) sensor (spatially distributed PVDF sensor) with porous electrode design. Prototypes have been fabricated by Université Libre de Bruxelles (ULB). Volume velocity sensor outputs have been compared with the real volume displacement measured using scanning laser vibrometer. The results show a very good agreement.

2.2 Considered actuator and sensor type for active structural barrier control

For active structural barrier control a special large surface elastic element is being developed by Panphonics Ltd. and VTT. The principle of the element structure with local control system is described in Figure 1. This element can be used as general structural vibration damping element also for the load carrying part of the structure, but is mainly intended to be attached to trim part (sound radiating part) of the sound insulating double wall structure.

![Figure 1: Basic design of Elastic Mass Actuator (EMA) element for active structural barrier control.](image_url)
\begin{align*}
A_n p_n - A_p p_t = m_1 \ddot{x}_1 + R_1 \dddot{x}_1 + \frac{1}{C_1} (\dot{x}_1 - \dot{x}_2) + \frac{1}{C_2} (x_1 - x_2) \\
A_p p_t = m_2 \ddot{x}_2 + R_2 \dddot{x}_2 + R_4 (\dot{x}_1 - \dot{x}_2) + \frac{1}{C_4} (x_2 - x_3)
\end{align*}

where (see Figure 2):

- $A_n$ = surface area over which electric pressure is effecting [m$^2$]
- $A_m$ = surface area over which acoustic pressure is effecting [m$^2$]
- $p_s$ = electric pressure between mass element and the primary structure [Nm$^{-2}$]
- $p_m$ = acoustic pressure on the primary structure [Nm$^{-2}$]
- $x_1$ = location of the primary structure [m]
- $m_1$ = mass of the primary structure [kg]
- $C_1$ = elasticity of the primary structure [m/N]
- $R_1$ = losses related to elasticity [Ns/m]
- $x_3$ = location of the mass element [m]
- $m_3$ = mass of the mass element [kg]
- $C_k$ = elasticity of the mass element fixing [m/N]
- $R_k$ = losses related to elasticity [Ns/m]
- $R_s$ = losses related to the air flow [Ns/m]

Figure 2: Motion of the structure when active EMA-element is attached to it [5].

Net force on the mass element is (see Figure 3):

$$P_z = \frac{1}{2} E_0 (E_z^2 - E_{\delta_z}^2)$$

where

$$E_z = \frac{h_0 \sigma (\varepsilon_0 \varepsilon_r)}{h_0 + x_1 + x_3 + h_0 / \varepsilon_r}$$
$$E_{\delta_z} = \frac{h_0 \sigma (\varepsilon_0 \varepsilon_r) - V}{h_0 + x_1 + x_3 + h_0 / \varepsilon_r}$$

and

- $\varepsilon_0$ = dielectricity coefficient of the actuator
- $\varepsilon_0$ = dielectricity coefficient of vacuum
- $\delta_0$ = thickness of the actuator [m]
- $\sigma$ = surface charge on the actuator surface [Cm$^{-2}$]
- $V$ = control voltage [V]
- $h_0$ = initial distance between mass and surface plates [m].

3 Acoustic control

For acoustic control two different actuator types are being developed in InMAR: polymer material based large surface actuators and large stroke piezo actuators. These would be used for two different concepts: for active acoustic barrier control (AABC) and for more traditional active sound quality control in car interior.

The most important part of the development in both actuator types is to get large amplitudes at low frequencies (50 - 500 Hz) with thin actuator structures. Actuators should be thin and high amplitude enough, so that they can be integrated in the sound package of a car, but could produce about 100 dB sound pressure level at 100 Hz.

3.1 Considered actuator and sensor type for active acoustic barrier control

The basic idea behind the active acoustic barrier control is that the actuator-sensor system does not try to influence the vibration behaviour of the load carrying (primary) structure, but only on the "sound package" layers on top of the load carrying structure.

The actuator-sensor systems, which are developed in InMAR are primarily polymer foil material based large surface elements, which are integrated in the sound package or attached to trim panel structure.

Following actuator and sensor systems are considered:

- revised elastic mass actuator element comprising of Panphonics G1 element based actuators and sensors, optimised local mass, and local control system, but contrary to the EMA-element (see section 2.2), do not necessarily have cover plates
- active hybrid sound absorbing (AHA) and sound insulating elements based on existing Panphonics G1 actuator element with specialised local control electronics.
In Figure 4 is described a principle of active hybrid absorber. Several independent units can be used on a wall structure to absorb incoming sound and insulate the sound due to the vibrations of the back plate. Same element can also be used as a loudspeaker of an audio system.

![Principle of the active hybrid absorbing (AHA) element.](image)

3.2 Considered actuator and sensor types for active noise cancellation and for active sound quality control

Also more traditional acoustic active noise cancellation (ANC) systems will be studied in InMAR and some new actuators will be developed for these applications. Main actuator development for the ANC applications will be based on existing large surface Panphonics G1 actuators. New development is oriented to increase sound output of G1 actuators at low frequencies. Also new large stroke acoustic actuators will be developed based on low profile piezo composite driving units. These elements can be used as low frequency acoustic actuators instead of traditional dynamic loudspeakers or Panphonics G1-panels, if the development work is successful.

4 Principles of structural control

The most important structural control applications in InMAR will be plate like structures in vehicles (cars and trains) and infrastructure (buildings and bridges).

In ASAC approach the control is oriented to attenuate those structural modes, which radiate sound well. This approach needs sophisticated control algorithms and sensors to identify the modes to be attenuated.

In InMAR applications, however, the development work in most cases is oriented to reduce the sound radiation from the structure using decentralised local control units with simple feedback control producing broad band vibration attenuation of all resonant modes rather than to apply more complex ASAC approach.

4.1 Comparison of different control strategies

The most obvious application of the active control is to reduce the sound radiation on plate like structures by damping the structural modes of the structure. In decentralised control several actuator - sensor - local feedback control loop units are attached to the structure to be attenuated.

In Figure 4 is presented the core results from the theoretical work at ISVR comparing different control approaches for plate like structures.

![Expected radiated sound power vs. frequency for different controller types](image)

The most important conclusion is that for the studied excitation and control locations similar sound radiation reductions can be achieved despite of the control configurations [6]. Thus the most simple and robust systems should be chosen for the practical applications.

4.2 Active structural barrier control applications of building walls

One of the most straight forward applications of ASBC concept is to improve sound insulation of light weight internal walls in buildings. The concept described in section 2.2 can be readily applied for this. Light weight walls are often the most important reason for poor sound insulation between rooms.
First simulations show that considerable increase of sound transmission loss can be achieved depending on the weight ratio of the Elastic Mass Actuator and the structure to be controlled, and the control type (Figure 5). Practical demonstrations are, however, needed to confirm the simulation results.

5 Applications of acoustic control in InMAR project

5.1 Active acoustic barrier control

Active acoustic barrier control will be applied in car sound package. The intention is to increase the sound transmission loss of the sheet metal structure against broad band tyre-road noise. Depending on the chosen application the demonstration system may be constructed based on EMA-element integrated in the car sound package, as sketched in Figure 6, but more obviously on slightly revised EMA concept utilising existing Panphonics G1-type panel actuators inside car sound package as an acoustic actuator-sensor system.

![Figure 6: Sketch of a car sound package application using EMA-element, where active element (EMA) is inserted inside the porous sound absorber between the sheet metal of the car (bottom layer) and the car floor mat (top layer).](image)

5.2 Active control for sound quality

A more traditional active control application in InMAR, for which special high power low frequency acoustic actuators are needed, is sound quality control (or sound profiling) in car interior. If the noise level inside the car is low enough (meaning especially the attenuation of broad band tyre-road and aerodynamic noise), the subjective experience of sound in car interior is determined purely by the engine order sound profile. The sound profile can be created and adjusted by active means utilising feed forward control of periodic sound components for which the reference is taken from the engine rotation. [7]

The control algorithm can be relatively simple, the main problem being to get enough sound power from the secondary sound sources to compensate the low frequency engine order sound. A special problem is so
called "booming noise", where the second engine order frequency coincides with the acoustic mode of the car interior cavity. The most disturbing noise is normally at low frequencies below 100 Hz, but can also be at higher frequencies at high driving speeds, so called "high-speed boom".

The first InMAR demonstration has been constructed, however, using conventional dynamic loudspeakers, as the development work for thin low frequency piezo composite or polymer loudspeakers have not yet been completed.

The target levels of the test car for the active control at different frequencies compared with the achievable levels from present panel loudspeaker elements are shown in Figure 7.

Figure 7: Requirement from the test car (solid red area) compared with sound output from different Panphonics G1-element based actuator configurations [8].

6 Summary

An overview of the actuator and sensor development work in European Union Integrated Project InMAR is given.

Most of the work on actuators and sensors is oriented for developing structural actuator-sensor pairs with decentralised local feedback control in each pair. The main effect of the active systems is similar to the increase of passive damping of resonant modes of the structure. The sound radiation reduction is due to "broad band" damping of all resonant modes rather than more sophisticated Active Structural Acoustic Control of only well sound radiating modes.

New concepts called Active Structural/Acoustic Barrier Control (ASBC and ASBC respectively) are also being developed based on polymer material based large surface actuators. Also some more traditional active control of sound for sound quality in car interior is a research topic in InMAR.

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