Experimental assessment of the performance of a 'smart foam' absorber

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The signal processing implementation of a hybrid passive/active absorber (smart foam) made up from the combination of a passive absorbent (foam) and a bonded, curved PVDF film, to enhance low frequency performance is considered. Three methods for obtaining the control signal are experimentally compared in the case of a plane wave excitation. Three prototypes of such smart foam have been built and tested in a waveguide (rectangular impedance tube) at frequencies between 100 Hz and 1500Hz. The performances in term of the absorption coefficient and the control input normalized by the incident pressure are presented and discussed, comparing the three methods. The first method uses estimations of the transfer functions between the sources and two microphones in the tube to calculate off-line an optimal filter in the frequency domain. The two other methods are based on a real-time adaptive control using a nFXLMS algorithm, a unidirectional microphone as error sensor, and the primary source signal as reference signal. The control filter is obtained after the initial convergence, using either pure tone disturbance (2nd method) or broad band disturbance (3rd method).

1 Introduction

Improving low frequency absorption is an important topic in acoustics. Passive materials generally provide adequate absorption at medium and high frequencies whereas active control is effective to cancel low frequency sound waves. Many devices combining sound absorbing passive materials and active absorption properties have been studied. One can distinguish between two main approaches. The first approach consists in associating a passive porous layer with an active surface separated from the rear face of the porous layer by an air gap. There are here two different control strategies. The first strategy is to impose a zero pressure on the back surface of the porous layer [1, 2]. The second strategy consists in controlling the surface impedance of the active surface in order to cancel the reflected sound wave [3, 4]. These two strategies have proved to be effective for a broad frequency range but imply a weight and space penalty that may limit their application in industrial sectors such as aerospace. To overcome these limitations, the second approach, called "adaptive foam" or 'smart foam', consists in a control actuator (generally a piezoelectric polyvinylidene fluoride (PVDF) membrane) directly embedded in a foam layer [5, 6, 7]. Smart foams can be used for radiation control and for absorption control depending on the type of noise source (structural and/or acoustic). They have been mostly studied for radiation control. In comparison less work was done for absorption.

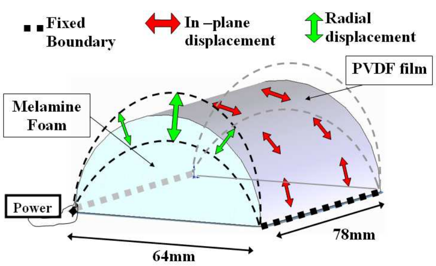

Figure 1: Schematics of the smart foam and actuation mechanism

In this paper, three smart foam prototypes based on the configuration described in figure 1 are tested in an impedance tube under plane wave propagation condition. Three control cases are tested. The first case uses estimations of the transfer functions between the sources (smart foam and primary source) and a unidirectional microphone in the tube in order to calculate off-line an optimal filter in the frequency domain. The two other methods are based on a real-time adaptive control using the nFXLMS algorithm, a unidirectional microphone as error sensor, and the primary source signal as reference signal. The control filter is implemented, using either a pure tone disturbance (2nd case) or a broad band disturbance (3rd case).

2 Material and method

2.1 Introduction

The study takes place in a closed waveguide at frequencies low enough so that plane waves dominate (figure 2). The cut-off frequency of the tube is 2200Hz. The primary source is composed of two speakers placed face to face perpendicularly to the direction of the tube. The minimization criterion is the acoustic pressure reflected by the smart foam. The reflected plane wave estimated using a unidirectional microphone positioned in the tube at 200mm from the surface of the smart foam. The effectiveness of the control is evaluated by measuring the absorption coefficient, using four microphone pairs. Three smart foam prototypes with different shapes have been tested in three control cases.

2.2 Absorption measurement

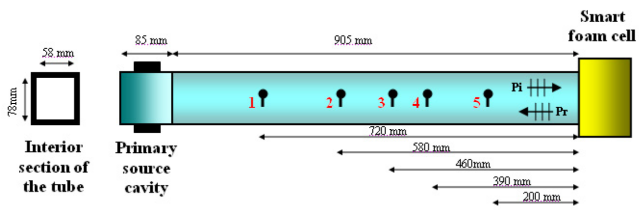

Figure 2: Closed waveguide for active absoption experiments, with microphone positions

The two microphone method is used to measure the absorption coefficient [8, 9].

Knowing the transfer function between the two microphones ($H21 = \frac{P2}{P1}$), the distance separating these two microphones (d12) and the distance (L1) separating the sample's surface and the first microphone, it is easy to calculate the reflection coefficient with the following relation using the $e^{j\omega t}$ convention:

$$R = \frac{H_{21} - e^{-i.k.d_{12}}}{e^{i.k.d_{12}} - H_{21}}.e^{2.i.k.L_1} \quad (1)$$

Where k is the wave number. The absorption coefficient is directly obtained :

$$\alpha = 1 - |R|^2 \quad (2)$$

In order to obtain a satisfactory precision in the frequency range of interest [100Hz-1500Hz][9], four pairs of microphones have been used (table 1).

Pair	d(cm)	Fmin(Hz)	Fmax(Hz)
$1-2$	14	50	1200
$2-3$	12	60	1400
$3-4$	7	100	2400
$4-5$	19	35	900

Table 1: Four microphone pairs. d is the distance between the microphones, Fmin et Fmax are the minimum and maximum usable frequency of the pairs, respectively

2.3 Smart foam prototypes

Three smart prototypes with different shapes have been built (figure 3). They are made of melamine foam covered with PVDF. The PVDF is bonded on the foam and fixed in a small cavity provided with electric jaws able to feed the PVDF and to ensure a correct embedding for the PVDF. Plexiglass flasks are placed on the side of the smart foam to ensure the tightness and the sealing with the back cavity and thus to avoid acoustic short cut. The unit smart foam + cavity constitute what we call active cell (figure 3). The three smart foam prototypes have different foam volume related to shape and mean thickness, PVDF surface related to electric capacity and back cavity volume (table 2). The foam volume, mean thickness and the PVDF surface increases with the smart foam number. Foam volume and mean thickness should directly affect the passive absorption. PVDF surface should affect the transducer effectiveness.

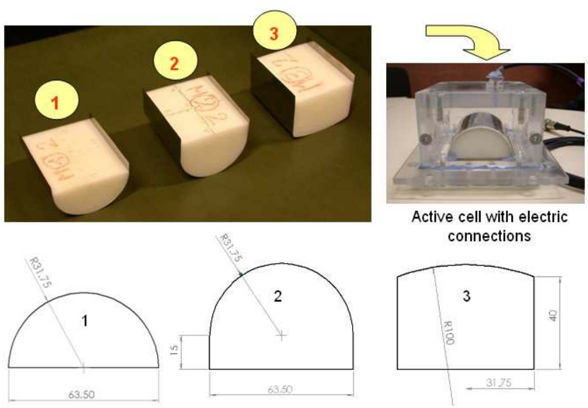

Figure 3: 3 smart foam prototypes (dimensions are given in mm)

Characteristics	SF 1	SF 2	SF 3
Foam volume (cm^3)	125	200	225
Mean thickness (cm)	2.5	4	4.4
PVDF surface (cm^2)	78	101	115
PVDF capacity (nF)	31	38	41
PVDF radius of curvature (cm)	3.2	3.2	10
Back cavity volume (cm^3)	360	271	245

Table 2: Smart foam prototypes characteristics

To correctly bond the PVDF onto the surface of the melamine foam, the latter is conditioned with a heat-reactivatable membrane and a double-sided scotch tape is used to bond the PVDF. For a positive voltage the PVDF shrinks and for a negative voltage it expands.

2.4 Off-line control with a sum of cosines

The hypothesis of the linear superposition of the sources is used. Since all governing equations are linear, it is possible to divide the complete system (primary source and smart foam) into the sum of two excitation states: "primary" (primary source active and smart foam passive, denoted by the letter p) + "secondary" (primary source passive and smart foam active, denoted by the letter s). The primary and secondary sources are driven in turn with pure tones between 100Hz and 1500Hz. The Frequency Response Function (FRFs) between the error microphone (reflected pressure) and the voltage applied to the considered source (H^p and H^s)are measured for each excitation state. It is therefore possible to evaluate the control filter (figure 4). The control filter (H^c)

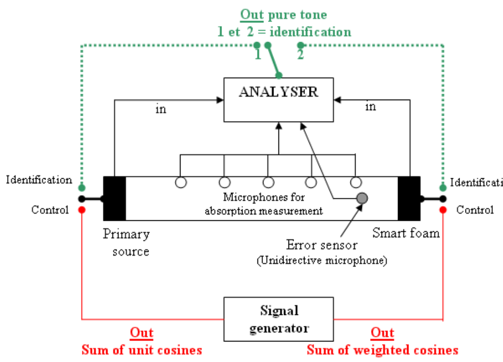

Figure 4: Experimental setup-up for off-line control

represents the ratio between the secondary and primary sources and is calculated in the frequency domain as follow:

$$H^c(\omega) = -\frac{H^p(\omega)}{H^s(\omega)} \quad (3)$$

In the control situation, a combination of unitary cosines is sent to the primary source and a combination of cosines each weighted by the control filter of (3), is sent to the smart foam The combination involves frequencies between 100 Hz and 1500 Hz with a 10 Hz increment.

2.5 Adaptive control

The nFXLMS algorithm used for the adaptive control, is derived from the classical FXLMS [10, 11, 12]. The nFXLMS algorithm tends to minimize an error signal using a reference signal of the perturbation. In this paper the nFXLMS algorithm is used to minimize the reflected pressure estimated by a unidirectional microphone.

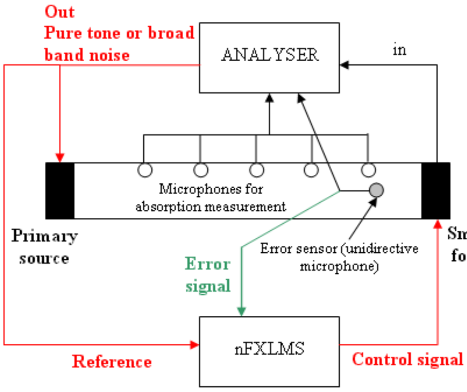

Figure 5: Experimental set-up for adaptive control experiments

Two types of disturbances are used. The first is a pure tone in the frequency range [100-1500Hz]. The second is a white noise in the frequency range [0-1500Hz](figure 5).

The sampling frequency of the controller is 4069Hz and the cut-off frequency is 1590Hz. The algorithm uses 400 coefficients for the identification of the control path. The control filter (FIR) uses 20 coefficients for pure tone and 300 for white noise.

3 Results

For each smart foam, the passive and active absorption coefficient (figures 6,8 and 10) and the normalized control input (figures 7,9 and 11) are shown. The normalized control input is defined as the ratio between the applied voltage to the PVDF and the amplitude of the incident pressure amplitude on the smart foam surface.

3.1 Smart foam 1

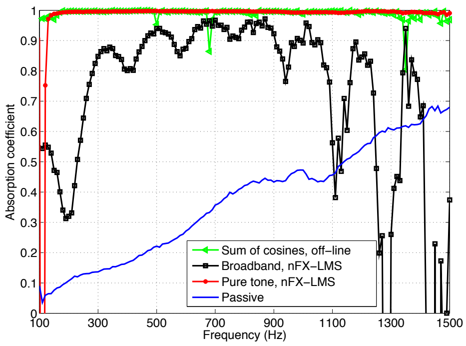

Figure 6: Passive and active absorption coefficient of the smart foam 1

The absorption coefficient is almost equal to 1 from 100Hz up to 1500Hz for off-line control with a sum of sine and adaptive control with a pure sine (figure 6).

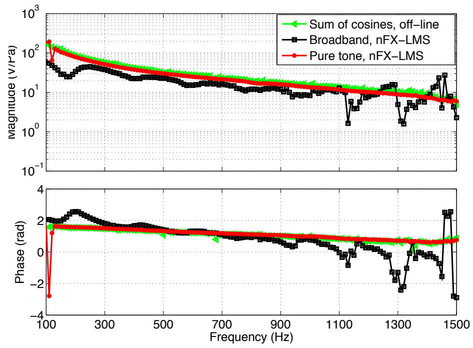

Figure 7: Normalized control inputs of the smart foam 1

The control inputs for these 2 cases are almost identical (figure 7). Adaptive control with a white noise leads to the worst result. The absorption coefficient is close to 0.9 in the frequency range [300-1000Hz] but is smaller under 300Hz and above 1000Hz (figure 7). The angle of the normalized control input is around $\pi/2$ in the low frequencies and decrease a little with the frequency.

3.2 Smart foam 2

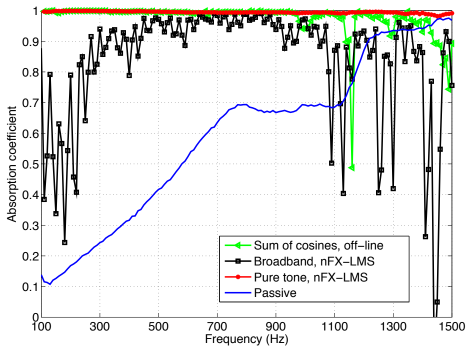

Figure 8: Passive and active absorption coefficient of the smart foam 2

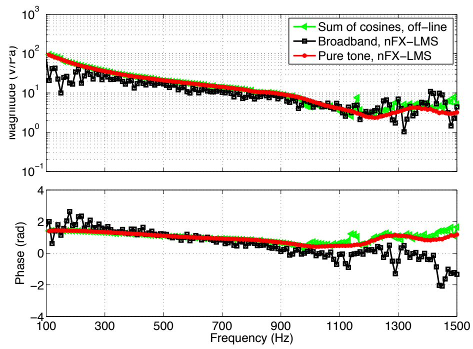

Figure 9: Normalized control inputs of the smart foam 2

The observations made for the first smart foam remain valid. However, the off-line control of the sum of cosines is a little bit degraded above 1000Hz, particularly around 1150Hz (figure 8). Adaptive control with white noise seems to be slightly better than in the case of the smart foam 1, despite the absorption coefficient and normalized control input are slightly less stable due to measurement instabilities (figure 9).

3.3 Smart foam 3

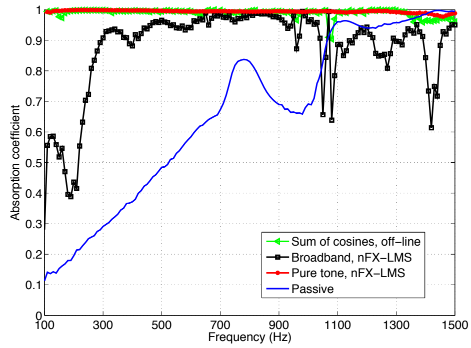

Figure 10: Passive and active absorption coefficient of the smart foam 3

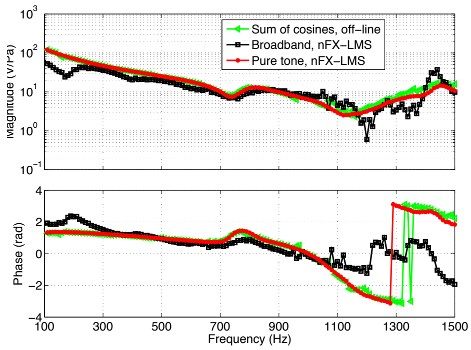

Figure 11: Normalized control inputs of the smart foam 3

Adaptive control with white noise seems to give better results compared to smart foams 1 and 2. The corresponding normalized control input is closer to the other filters excepted for frequencies higher than 1100Hz, especially for the phase. In the low frequencies, the phase is still close to $\pi/2$. Adaptive control with white noise is interesting for this smart foam because it joins passive absorption towards 1100Hz, where passive absorption is higher than 0.95. Stopping control at this frequency, the active/passive absorber would have an absorption coefficient higher than 0.9 starting from 300Hz.

3.4 Comparison

The normalized control input obtained with the adaptive control using pure tone excitation is compared for the three smart foam prototypes (figure 12). The pure tone adaptive control case has been chosen for the comparison because the absorption coefficient is close to 1 all over the frequency range [100-1500Hz].

In the best control situation (adaptative control with pure tone excitation), the normalized control input of the smart foam 2 is less important than the smart foam

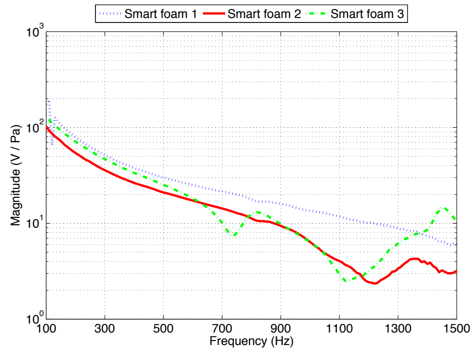

Figure 12: Normalized driven voltages obtained with the thee smart foam prototypes for the adaptative control using a pure tone as excitation

3 that is less important than the smart foam 1 (figure 12).

4 Discussion

For each smart foam prototypes, there is good agreement between the normalized control input of the three cases when the control is effective, i.e. when the absorption coefficient is close to 1. For a perfect control, the normalized control input does not depend on the disturbance and the mode of control.

The passive absorption is a very important parameter because it determines the frequency range in which the control have to be effective. So the higher the passive absorption is and the lower the cut-off frequency of the control will be. Even if the smart foam 3 is less efficient than the smart foam 2 as a transducer in the low frequencies, this prototype has the advantage of having an absorption coefficient close to one starting from 1100Hz. Mean thickness and foam volume is the important parameter for the passive absorption.

The adaptive control for the white noise is not efficient for frequencies lower than 300Hz and higher than 1100Hz. This can be explained by two main facts. The first is that the smart foam prototypes have a very high distorsion level for frequencies lower that 300Hz. The control of the low frequencies would involve many harmonics for higher frequencies that cannot be controlled because they are not in the reference signal. The other fact is that the anticipation time of the reference signal is around 4ms. Only about fifteen coefficients of the adaptive filter are used which are not not sufficient. Some other results, that are not presented here, show that it is possible to enhance the control efficiency above 300Hz by adding a delay between the primary source and the reference signal. With an added delay of 10ms, corresponding to an addition of 45 coefficients to the previous adaptive filter, it is possible to obtain a perfect absorption from 300Hz to 1500Hz.

The angle of the normalized driven voltage is close to $\pi/2$, excepted for the smart foam 3 above 900Hz where the modal behavior has a great influence. The normalized control input phase represents the angle between the control input of the smart foam and the incident pressure on the foam surface. There are many elements influencing this phase. The group delay of the smart foam transducer and the propagation into the foam take a part in the phase. The displacement of the PVDF is proportional to the driven voltage. The PVDF shrinks for a positive applied voltage. The angle $\pi/2$ for the phase of the normalized control input indicates that the control input has a advance of $\pi/2$ on the incident pressure, so that the PVDF speed is in phase with the incident pressure. This illustrates the fact that the displacement of the PVDF is in phase with the particule displacement of the air in front of the smart foam. This is the active mode of absorption of the smart foam. Indeed, the incident pressure is proportional to the particule speed and in phase quadrature with the particule displacement of the air. The phase angle is not exactly $\pi/2$ and decrease with the frequency. This can be explained by two facts. The first is that the propagation time of the pressure between the surface of the foam and the PVDF is not taken into account in the normalized driven voltage. The other fact is that the smart foam has certain a group delay, i.e. a delay between the voltage and the PVDF membrane displacement. This group delay is not taken into account in the normalized control input.

The comparison of the three prototypes shows that the smart foam 2 is the best in term of the ratio of the control input to the incident pressure. The important parameter in term of radiation effectiveness seems to be the shape more than the PVDF surface. The smart foam 3 has a greater PVDF surface than the smart foam 2 but it is less effective. The maximum voltage that can be applied to the PVDF is around 300 Vrms. As the smart foam 2 needs 100Vrms to absorb an incident pressure of 1 Pa rms at 100Hz, the highest pressure level that this smart foam could absorb is 103dB. This level could be 114dB at 300Hz. This is quite an important level however it remains insufficient for industrial applications where the noise is very high. Under 100Hz, the active absorption becomes very low because of the very bad radiation efficiency of the smart foam for those frequencies.

5 Conclusion

This experimental study is exploratory and aims at understand main tendencies and to select suitable prototypes of smart foam. The geometrical configuration has a great importance on the driven voltage. The passive absorption coefficient relating to the shape and the thickness of foam determines the high limit frequency of the control. The configuration 2 seems to be very efficient for active and passive sound absorption. It is however certainly possible to optimize the design of smart foam further. We have shown that it is possible to absorb an incident pressure of 103dB at 100Hz. The efficiency of the smart foam is limited in the very low frequencies because of the high distorsion level due to the PVDF limitation. The displacement of the actuator is almost in phase with the incident wave particular displacement. The acting mechanism results in transferring in the actuator the energy of the incident sound pressure that is not passively dissipated.

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