Hybrid Passive-Active Multilayer Sound Absorbers

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A two-layer passive/active system to provide broadband absorption, including low frequencies, is described. The passive system consists of a fibrous layer in front of an air layer. Absorption at low frequencies is achieved by an active controller which drives an actuator in the back of the system that minimizes the pressure measured by a sensor in the air layer. The passive/active system is modelled considering plane waves propagating at oblique incidence. The absorbing layer is characterized by empirical equations of the nondimensional parameter $E_n=\rho_0 f/\sigma_n$, σ_n being the flow resistivity, f the frequency, and ρ_0 the air density. The model predicts high performance of the hybrid passive-active system for values of $R=\sigma_n\, d/Z_0$ close to 1.2, d being the thickness of the absorbing layer and Z_0 the air impedance.

1. INTRODUCTION

Passive control solutions to broadband noise problems including low frequencies may become too bulky. Active control offers techniques to attenuate the low frequency contents of such a problems [1], so that the complete solution to the broadband noise needs to be hybrid passive-active. Multilayer absorbers used to reduce reverberation in halls are an example of a passive system with a lack of performance at low frequencies [2]. Beyene and Burdisso [3] proposed an active system to complement the low frequency contents of a two-layer absorber. This system consisted of an actuator at the backing of the air layer, an error sensor at the air layer, and a feedforward controller. The error sensor could be either a unique microphone (pressure-release condition) or a couple of microphones connected to a deconvolution filter (impedance-matching condition). In this paper, a simple plane-wave two-layer model including the properties of the absorbing material is presented which allows predicting the behaviour of the hybrid system under the assumed active control condition. Experimental results are given that validate the theoretical model.

2. THEORETICAL MODEL

The passive system consists of a first absorbing layer of thickness d, acoustical impedance Z_a, and propagation constant Γ_a, in front of an air layer of thickness t, acoustical impedance Z_0, and wave number k_0, Fig. 1. The plane-wave absorption coefficient against frequency and incidence angle of this two-layer system is

$$\alpha(f,\theta)=1-\left|\frac{Z_1(f,\theta)-\dfrac{Z_0}{\cos\theta}}{Z_1(f,\theta)+\dfrac{Z_0}{\cos\theta}}\right|^2 \qquad (1)$$

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where

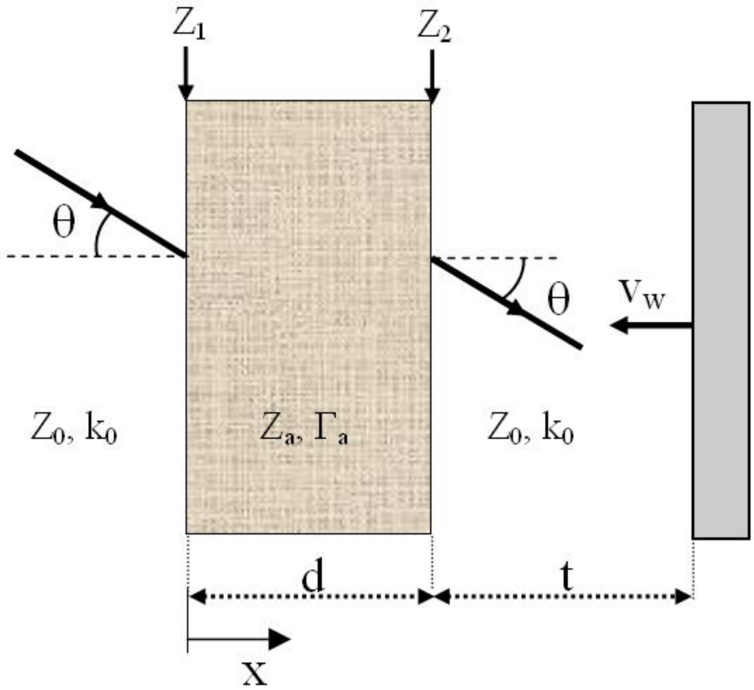

Figure 1. *Setup of the two-layer passive-active absorption system.*

$$Z_1(f,\theta)=\frac{Z_n\Gamma_n}{q}\frac{Z_2(f,\theta)\cosh(qd)+\frac{Z_n\Gamma_n}{q}\sinh(qd)}{\frac{Z_n\Gamma_n}{q}\cosh(qd)+Z_2(f,\theta)\sinh(qd)}, \tag{2}$$

is the input impedance to the two-layer system, and

$$q=\Gamma_n\sqrt{\frac{\Gamma_p^2+k_0^2\sin^2\theta}{\Gamma_p^2}}, \tag{3}$$

Γ_n and Γ_p being the propagation constants through the absorbing layer in the perpendicular and planar directions, respectively. For the active case, an actuator moving rigidly with velocity V_w substitutes the impervious wall at the back of the system. The acoustic impedance at the input of the air layer is therefore

$$Z_2(f,\theta)=\frac{Z_0}{\cos\theta}\frac{V_w\frac{Z_0}{\cos\theta}+2B_3e^{jk_0d\cos\theta}\quad\cos(k_0t\cos\theta\ )}{V_w\frac{Z_0}{\cos\theta}+2jB_3e^{jk_0d\cos\theta}\quad\sin(k_0t\cos\theta\ )}. \qquad (4)$$

Note that Eq. (4) reduces to $Z_2=-j(Z_0/\cos\theta\ )\cot(k_0t\cos\theta\ )$ when $V_w=0$ (passive case [2]).

To complete the hybrid passive-active model, the acoustic impedance and the propagation constant of the absorbing material must be specified. Empirical equations against the nondimensional parameter $E_n=\rho_0 f/\sigma_n$, offer precision enough for the purpose of this model. Due to the low frequency contents involved in active control, the empirical equations of Allard and Champoux [4] are considered

$$\begin{aligned}\Gamma_a &= j2\pi f\sqrt{\rho(f)/K(f)}\\ Z_a &= \sqrt{\rho(f)K(f)}\end{aligned}\ , \qquad (5a)$$

where

$$\begin{aligned}\rho(f)&=1.2+\left[-0.0364E_n^{-2}-j0.1144E_n^{-1}\right]^{1/2}\\ K(f)&=101320\frac{j29.64+\left[2.82E_n^{-2}+j24.9E_n^{-1}\right]^{1/2}}{j21.17+\left[2.82E_n^{-2}+j24.9E_n^{-1}\right]^{1/2}}\end{aligned}\ . \qquad (5b)$$

Similar equations can be set for the planar nondimensional parameter $E_p=\rho_0 f/\sigma_p$. For fibrous materials, the anisotropy factor $s=\sigma_p/\sigma_n$ is often defined. A statistical absorption coefficient can be calculated by [5]

$$\alpha_{st}(f)=\int_0^{\pi/2}\alpha(f,\theta)\sin 2\theta d\theta\ . \qquad (6)$$

Equations (1)-(6) permits to calculate the plane absorption coefficient as a function of geometrical (thicknesses of the two layers), constitutive (flow resistivity and anisotropy factor) and acoustical (frequency, control condition) parameters. Mechel [5] showed that physical insight on the performance of multilayer absorbers is gained when the absorption coefficient is plotted against the nondimensional variables $F=f\,d/c_0$ and $R=\sigma_n d/Z_0$. Figure 2 shows such charts for a two-layer system with $t=2d$, in the passive (a) and active (b) cases, at normal incidence. The control condition for the active case considered in Figure 2b is pressure-release ($Z_2=0$). Figure 2c shows the excess of absorption of the active-over-passive case (α_a-α_p). As can be expected, under the pressure-release condition, almost maximum absorption is obtained when the flow resistance of the absorbing layer ($\sigma_n d$) is close to the acoustical impedance of air (Z_0)[6]. Thus, a highly absorbent hybrid passive-active two-layer system can be designed with a passive porous layer with $R\approx 1$ in front of an air layer complemented with an active pressure-release control. Figure 2d shows the normal incidence passive and active absorption curves corresponding to a 4-cm thick layer of porous material with σ_n=12 500 N s m^{-4} and s=1, spaced 8 cm from the active wall. Since the passive system affords high absorption at frequencies above 700 Hz, the active system could be low-pass filtered below this frequency.

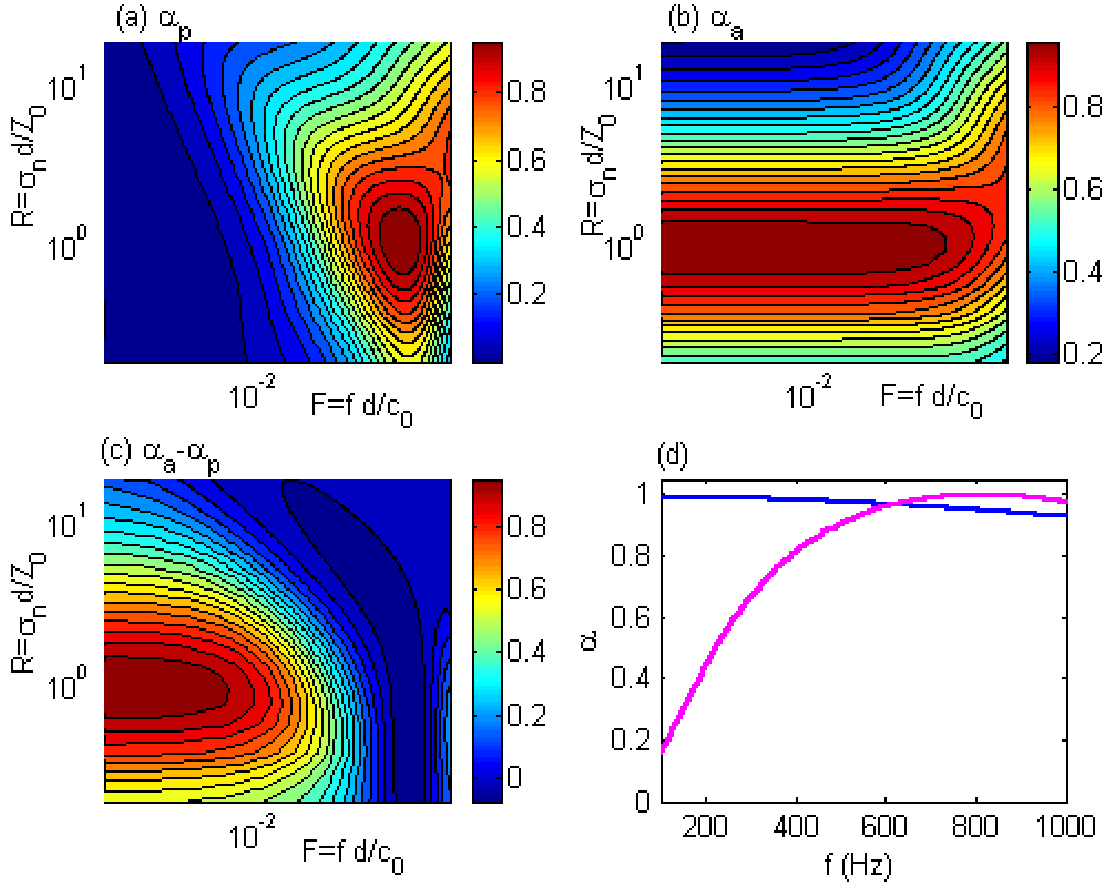

Figure 2. *Contour maps showing the absorption coefficient at normal incidence for the passive (a) and active (b) cases of a two-layer system with t=2d. (c) Absorption excess (α_a-α_p) of the active over the passive control. (d) Passive (—) and active (—) absorption curves of a 4-cm thick layer with σ_n=12 500 N s m^{-4} in front of a 8-cm thick air layer.*

3. EXPERIMENTAL RESULTS

Experiments were carried out in a standard impedance tube (normal incidence). The passive system consisted of a 4-cm thick layer of melamine foam with σ_n=12 000 N s m^{-4} and s=1, spaced 7 cm from the ending cap. Figure 3 shows overlapped the theoretical and experimental passive absorption coefficients. For the active case, a secondary loudspeaker substitutes the ending cap and a commercial controller is configured to yield maximum absorption. Figure 3 shows also the theoretical and measured active absorption curves in the frequency range 100-800

Hz. The hybrid passive-active two-layer system provides absorption close to 1 in the considered frequency range.

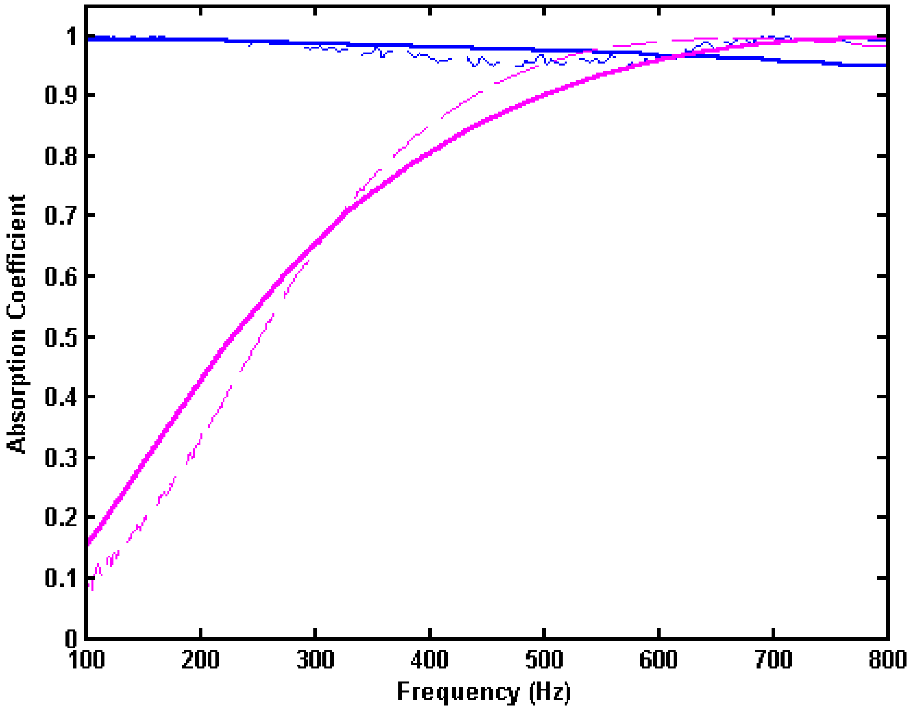

Figure 3. *Absorption coefficient of a melamine foam 4-cm thick in front of a 7-cm air layer. (—) passive theory, (- - -) passive experiment, (—) active theory, (- - -) active experiment*

Figure 4 shows the time-frequency spectrogram of the broadband noise in the standard impedance tube before and after the active noise controller is switched on. Before connecting the controller, the passive system affords absorption at frequencies above 700 Hz. The active controller attenuates the broadband noise in the low frequency range. The hybrid passive-active system provides absorption in the whole frequency range.

4. CONCLUSIONS

Active control allows complementing the lack of absorption of classical multilayer passive absorbers. Hybrid passive-active multilayer systems may provide broadband noise absorption including low frequencies. The passive system may consist of a layer of porous material in front of an air layer. The active system needs additional actuator and error sensor as well as a controller. Under the pressure-release control condition, maximum absorption is obtained when the flow resistance of the porous layer is close to the acoustical impedance of air. The cutoff frequency between passive and active absorption is set by the thickness of the air layer.

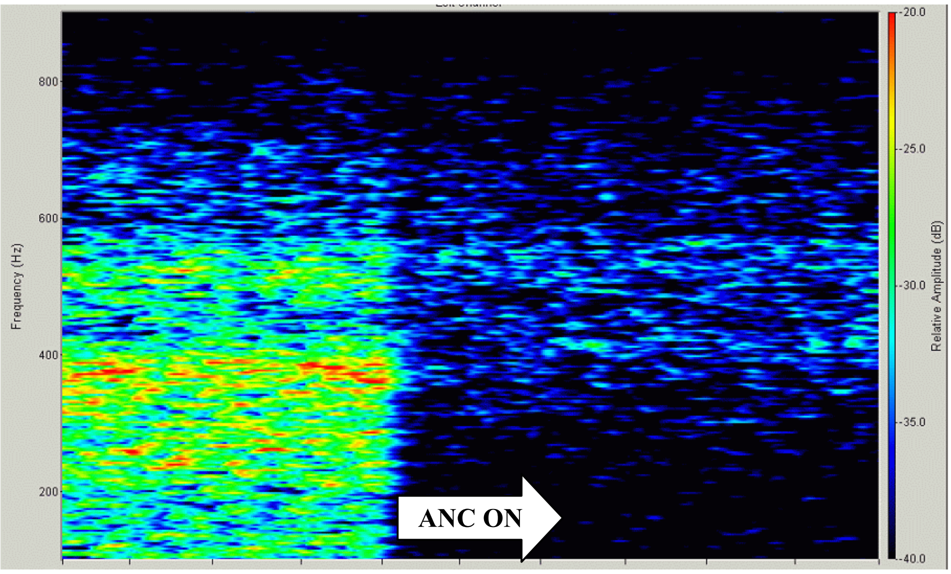

Figure 4. *Spectrogram of the noise showing the broadband cancellation after the active control system is switched on.*

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REFERENCES

1. P. Cobo, Control activo del ruido. Principios y aplicaciones. CSIC, Colección Textos Universitarios Nº 26, Madrid 1997.
2. L.L. Beranek and I.L. Ver, Engineering sound and vibration control. Principles and applications. Wiley Interscience, N.Y 1992
3. S. Beyene and R.A. Burdisso, A new hybrid passive/active noise absorption system, *Journal of the Acoustical Society of America* **101**, 1512-1515, (1997).
4. J.F. Allard and Y. Champoux, New empirical equations for sound propagation in rigid frame fibrous materials, *Journal of the Acoustical Society of America* **91**, 3346-3353, (1993).
5. F.P. Mechel, Design charts for sound absorber layers, Journal of the Acoustical Society of America, 83, 1002-1013, (1988).
6. M. Furstoss, D. Thenail, and M.A. Galland, M.A., Surface impedance control for sound absorption: direct and hybrid passive/active strategies, *Journal of Sound and Vibration*, **203**, 219-236, (1997).