Research on Hybrid Absorption Based on Acoustic Impedance

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In this paper, a new hybrid absorption system is posed which is composedof a layer absorbent material and a movable rigid wall. The speed of the movable rigid wall is adjusted in order to make the acoustic impedance of the absorption material match the acoustic impedance of the air, so that the absorption coefficient is maximal. Finally, a numerical calculation and an experiment are carried out, both numerical and experimental results of such a system are presented for a normally incident plane wave. The numerical and experimental results indicate that the absorption effect is effecting at middle and lowfrequencies and imperfect in high frequencies where passive absorption is dominant.

1. INTRODUCTION

The absorption of low frequency sound is difficult with conventional, passive methods, that is to say, passive noise control methods that employ the use of sound absorbing materials are practical and most effective at mid to high frequencies. On the other hand, active noise control techniques are most efficient at low frequencies.[1,2,3] The complementary strengths and weaknesses of passive and active noise control methods have motivated many researchers to develop a system that integrates both methods. One of the first published works on a noise absorption system that comprises both passive and active methods is that of Guicking and Lorenz[2] and then Thenail et al.[3] posed another noise absorption system comprising both passive and active methods which included a fiberglass absorbing layer backed by an air cavity terminated with an active surface.[2-5] In both the control system posed by Guicking and Lorenz[2] and Thenail,[3] the passive component was comprised of a porous material located in an impedance tube a small distance from the open end of the tube which terminated by a loudspeaker, the signal from a microphone in front of the porous plate was sent to the control loudspeaker after it was passed through a suitable amplification scheme, a second microphone controlled the complex amplification factor such that the second pressure at the location was minimized so as to produce a pressure-release condition just behind the plate.[4-8] Based on the published literature about the active absorption and hybrid absorption, in this paper, a new hybrid absorption system is posed in which an absorption material and a mobile rigid wall backed the absorption material are located in an impedance tube, the reflected sound wave is measured by two pieces of PVDF film as the transducer placed in front of the absorption material, according to the reflected sound wave, the mobile rigid wall is moved with controlled speed in controlled time so as to change the acoustic impedance of the absorption material matched with the acoustic impedance of the air, so that the absorption coefficient is maximal. Finally, a numerical calculation and an experiment are carried out, the numerical and the experimental results indicate that the absorption effect is effective at mid and low frequencies and imperfect at high frequencies where passive absorption is dominant.

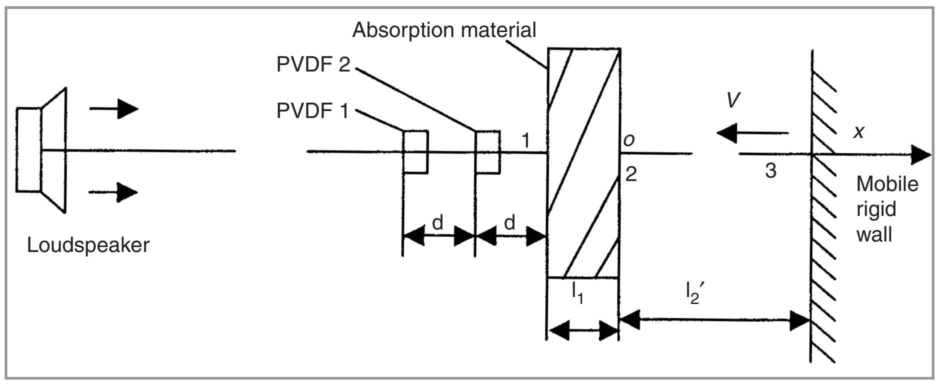

Figure 1 *The arrangement of the hybrid absorption system.*

2. PRINCIPLE OF THE HYBRID ABSORPTION SYSTEM

Based on the hypothesis that the far-field wave is a homogeneous plane wave, the arrangement of two pieces of PVDF film and the absorption material and the mobile rigid wall is shown in Fig. 1.

In Fig. 1, the incident sound pressure is $p_i(t)$, two pieces of PVDF film and the absorption material are arranged with the same distance d shown as Fig. 1, the thickness of the absorption materials is l_1, the depth of the air cavity is l_2', the coordinate origin is located in the place where the back of the absorption material contacts the air cavity, the positions 1, 2 and 3 are shown in Fig. 1. The sound pressure and the particle velocity are given by,

$$\begin{cases} P_1^+ = A_1 e^{j(\omega t - kx)} \\ P_1^- = B_1 e^{j(\omega t + kx)} \\ P_2^+ = A_2 e^{j(\omega t - k'x)} \\ P_2^- = B_2 e^{j(\omega t - k'x)} \\ P_3^+ = A_3 e^{j(\omega t - kx)} \\ P_3^- = B_3 e^{j(\omega t - kx)} \end{cases} \tag{1}$$

$$\begin{cases} V_2^{\pm} = \dfrac{\pm P_1^{\pm}(x,t)}{\rho c} \\ V_n^{\pm} = \dfrac{\pm P_n^{\pm}(x,t)}{\rho_0 c_0} \quad (n = 1, 3) \end{cases} \tag{2}$$

where A_n, $B_n (n = 1,2,3)$ are the amplitudes of the incident and reflected waves respectively, ρc is the characteristic impedance of the absorption material, $\rho_0 c_0$ is the acoustic impedance of the air, ω is the angular frequency, k is the wave number in the air, k' is the propagation constant in the absorption material. At the time $t = 0$, the position of the rigid wall is $x = l_2$, the speed of the rigid wall is v which is positive when the direction is to the right, then at the time t, the position of the rigid wall l_2' is,

$$l_2' = l_2 + vt \tag{3}$$

According to the formulae (1) (2), the following formula is derived,[8]

$$\begin{bmatrix} -1 & 1 & 1 & 0 & 0 \\ \frac{\rho c}{\rho_0 c_0} & 1 & -1 & 0 & 0 \\ 0 & e^{-k'l_1} & e^{k'l_1} & -e^{-ikl_1} & -e^{ikl_1} \\ 0 & e^{-k'l_1} & -e^{k'l_1} & \frac{\rho c e^{ikl_1}}{\rho_0 c_0} & -\frac{\rho c e^{ikl_1}}{\rho_0 c_0} \\ 0 & 0 & 0 & e^{-ik(l_1+l_2')} & -e^{ik(l_1+l_2')} \end{bmatrix} \begin{pmatrix} B_1 \\ A_2 \\ B_2 \\ A_3 \\ B_3 \end{pmatrix} = \begin{pmatrix} 1 \\ \frac{\rho c}{\rho_0 c_0} \\ 0 \\ 0 \\ 0 \end{pmatrix} A_1 + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \rho_0 c_0 \end{pmatrix} v \quad (4)$$

According to the Fig. 1, the acoustic impedance Z of the absorption material in each postion is,

$$Z = \rho c \coth(\xi - jk'x) \quad (5)$$

At $x = 0$, the acoustic impedance Z_2 of the air cavity is,

$$Z_2 = \rho c \coth(\xi) \quad (6)$$

The acoustic impedance $Z_1(x = -l_1)$ of the absorption material is,

$$Z_1 = \rho c \coth(\xi + jk'l_1) \quad (7)$$

According to the formulae (5) (6) (7), the following formula is obtained.

$$Z_1 = \rho c \frac{Z_2 \coth(jk'l_1) + \rho c}{Z_2 + \coth(jk'l_1)} \quad (8)$$

The formulae (1) (2) can lead to the following formulae,

$$V_1 = \frac{P_1^+ + P_1^-}{\rho c} \quad (9)$$

$$P_2^+ = P_1^- e^{jk'l_1} \quad (10)$$

$$P_2^- = P_1^+ e^{-jk'l_1} \quad (11)$$

$$P_2^+ = P_3^+ e^{-jkl_2'} \quad (12)$$

$$P_2^- = P_3^- e^{jkl_2'} \quad (13)$$

Integrating the formulae (1) (2) and (9)–(13), the acoustic impedance Z_2 of the air cavity in the place $x = 0$ can be derived,

$$Z_2 = \rho c \frac{A_3 e^{-jk'l_1} + B_3 e^{jk'l_1}}{A_3 e^{-jk'l_1} - B_3 e^{jk'l_1}} \quad (14)$$

Replacing (14) into (4) and interosculating formula (3) leads to

$$Z_2 = \rho_0 c_0 \frac{\rho_0 c_0 v + 2B_3 e^{jkl_1} \cos(k(l_2 + vt))}{\rho_0 c_0 v + 2B_3 e^{jkl_1} \sin(k(l_2 + vt))} \quad (15)$$

$$B_3 = B_1 e^{jk'l_1} e^{jk(l_2+vt)} \quad (16)$$

Obviously, according to the formula (8) (15) (16), when the controlling time is prescribed, the mobile speed of the rigid wall is designed to make the acoustic

FORCING THE FORCES TO ENFORCE

Mr Llewellyn's neighbour, in Gloucester, Rhode Island, runs a noisy business from his property, involving a substantial number of commercial vehicles – dumper trucks, heavy earth-moving equipment – unusually noisy vehicles. Town authorities did issue an order telling the neighbour, Mr Simas, to cease using his property for this kind of commercial activity. Mr Simas has essentially replied with an 'I was here first' argument. His family have owned the property for over 80 years, before zoning laws existed, and have run all kinds of businesses on it: so current complaints, or court orders, about his noisy activities, can just be ignored. But in the latest twist, Mr Llewellyn is now not only bringing a law suit against Mr Simas for damage to his property and its value by reason of the noise generated from the Simas land; but he is also causing the council to be included in the claim for damages, for its failing to enforce its own order to Mr Simas to cease his nuisance.

impedance of the absorption equal to the acoustic impedance of the air so that the absorption coefficient is maximal.

3. PRINCIPLE OF MEASURING THE REFLECTED WAVE BY PVDF

The incident and reflected wave can be expressed by the following formula for the far-field wave (hypothesed as a homogeneous plane wave)

$$p_i(x, t) = p_i \exp^{j(\omega t - kx)} \tag{17}$$

$$p_r(x, t) = p_r \exp^{j(\omega t + kx)} \tag{18}$$

where k is the wave number, w is the angular frequency. When a force p is applied to the PVDF transducer, a voltage V is generated. The relation between the force and the voltage is,9

$$p = \frac{e_{33} Z_o}{t_p (Z_o + Z_p)} V = SV \tag{19}$$

where e_{33} is the coupling constant of the PVDF, Z_0 is the acoustic impedance of the air, Z_p is the characteristic impedance of the PVDF, t_p is the thickness of the PVDF. The voltage signals in PVDF 1 and PVDF 2 are,

$$V_1(t) = V_i(0,t) + V_r(0,t) \tag{20}$$

$$V_2(t) = V_i(d, t) + V_r(d, t) = V_i(0,t + \tau) + V_r(0,t - \tau) \tag{21}$$

where τ is the propagation time between the two pieces of PVDF, $t = \frac{d}{c}$, c is the propagation speed in the air. If $V_1(t)$ is delayed with τ, then,

$$V_{1\tau}(t) = V_1(t - \tau) = V_i(0,t - \tau) + V_r(0,t - \tau) \tag{22}$$

Here $V_3(t)$ is defined as,

$$V_3(t) = V_{1r} - V_2 = V_i(0,t - \tau) - V_i(0,t + \tau) \tag{23}$$

$V_3(t)$ is delayed by τ, $V_5(_t)$ is attained,

$$V_5(t) = V_3(t - \tau) = V_i(0,t - 2\tau) - V_i(0,t) = 2V_i(0,t)e^{-j(\pi/2 + \omega\tau)} \sin\omega\tau \tag{24}$$

With the same method, $V_2(t)$ is delayed by τ, the following formula can be attained:

$$V_{2\tau}(t) = V_2(t - \tau) = V_i(0,t) + V_r(0,t - 2\tau) \tag{25}$$

Here V4(t) is defined as,

$$V_4(t) = V_{2\tau} - V_1 = V_r(0,t - 2\tau) - V_r(0,t) = 2V_r(0,t)e^{-j(\pi/2 + \omega\tau)} \sin\omega\tau \tag{26}$$

Eq. (24) and Eq. (26) give:

$$V_4{}' = -V_4 + V_4'e^{-2j\omega\tau} = V_r(0,t) \tag{27}$$

$$V_5{}' = -V_5 + V_5'e^{-2j\omega\tau} = V_i(0,t) \tag{28}$$

According to the formulae (27) (28), the incident and reflection sound waves are,

$$p_r(0,t) = SV_4{}' = SV_r(0,t) \tag{29}$$

$$p_i(0,t) = SV_5{}' = SV_i(0,t) \tag{30}$$

$p_r(0,t)$ is the reflected sound pressure at PVDF 1 according to equation (29), so the reflected sound pressure on the surface of the absorption material can be calculated as,

$$p_r = p_r(2d,t) = e^{j2kd}p_r(0,t) \tag{31}$$

According to the formula (31), the amplitude of the reflected sound wave B1 in Eq. (16) is calculated.

The principle of measuring the incident and reflected sound wave with two pieces of PVDF is shown in Fig. 2.

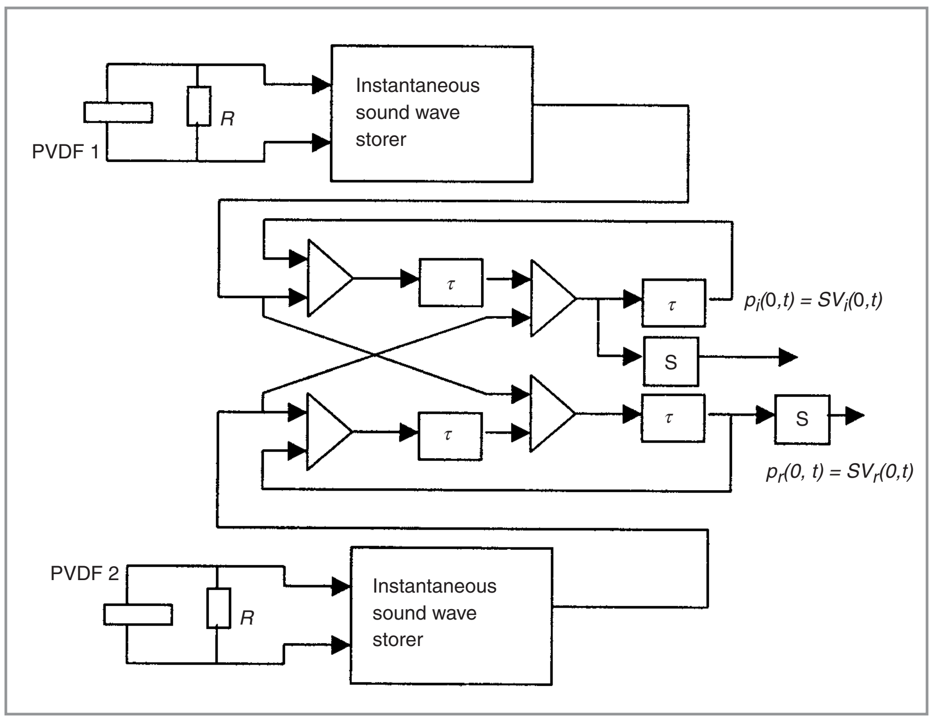

Figure 2 *The principle of measuring the incident and reflected sound wave.*

4. CONTROLLING PRINCIPLE

An error signal can be synthesized from the signals of two pieces of the PVDF located in front of the absorption material. The error signal should have the property that after being minimized by the action of the controller, the acoustic impedance in front of the absorption material matches the desired specification. As the specification is very likely to be made in the frequency domain, a later transformation to the time domain will be required. Using z transforms, the error signal can be defined as,

$$E(z) = H_{12}(z)V_1(z) - V_2(z) \tag{32}$$

where $V_1(z)$ and $V_2(z)$ are the z transforms of the voltage signals of the PVDF and $H_{12}(z)$ is the desired transfer function between them.

The desired transfer function between the outputs and the two pieces of PVDF $H_{12}(z)$ can be related to the desired acoustic impedance at the center of the two pieces of PVDF. For sound consisting only of plane waves, the transfer function is,

$$H_{12}(j\omega) = \frac{\dfrac{Z_A(j\omega)}{\rho_0 c_0} - j\tan\left(\dfrac{\omega\tau}{2}\right)}{\dfrac{Z_A(j\omega)}{\rho_0 c_0} + j\tan\left(\dfrac{\omega\tau}{2}\right)} \tag{33}$$

where ZA(jw) is the desired acoustic impedance. In the particular case when the desired acoustic impedance is $Z_A(j\omega) = r_0 c_0$, corresponding to a perfectly absorption, equation (33) simplifies to a time delay,

$$H_{12}(j\omega) = e^{-j\omega\tau} \tag{34}$$

This can be readily transformed to a digital transfer function if the sampling period is chosen as an integral fraction N of the acoustic time delay, $T_s = \frac{\tau}{N}$, in this case the digital transfer function reduces simply to a delay of N samples,

$$H_{12}(z) = e^{-N} \tag{35}$$

Replacing (35) into (32) gives;

$$e(k) = V_1(k - N) - V_2(k) \tag{36}$$

The controlling principle is shown in the Fig. 3.

The matrix $\begin{pmatrix} G_{11}(z) & G_{12}(z) \\ G_{21}(z) & G_{22}(z) \end{pmatrix}$ is the transmission function between the loudspeaker and the absorption material, H(z) is the transfer function of the controlling filter.

5. NUMERICAL AND EXPERIMENTAL RESULTS

The experimental arrangement is shown in Fig. 4.

A B & K tube is used for this experiment whose diameter is 10 cm and length is 3 m. The primary source is the loudspeaker which located at the end of the tube, the distance between the two pieces of PVDF of 2 cm diameter and 0.2 cm thickness is 5 cm and the distance between the PVDF 2 and the absorption material is 5.0 cm. The density of the air is $\rho_0 = 1.21\ kg/m^3$, the propagation velocity in the air is $c_0 = 343$ m.s^{-1}, the thickness and the density of the absorption material are $l_1 = 20$ mm and $\rho = 1250$ kg.m^{-3} respectively. The propagation speed propagated in the absorption material is $c = 2800$ m.s^{-1}, the frequency of the incident sound wave is 100 Hz ~ 2000 Hz.

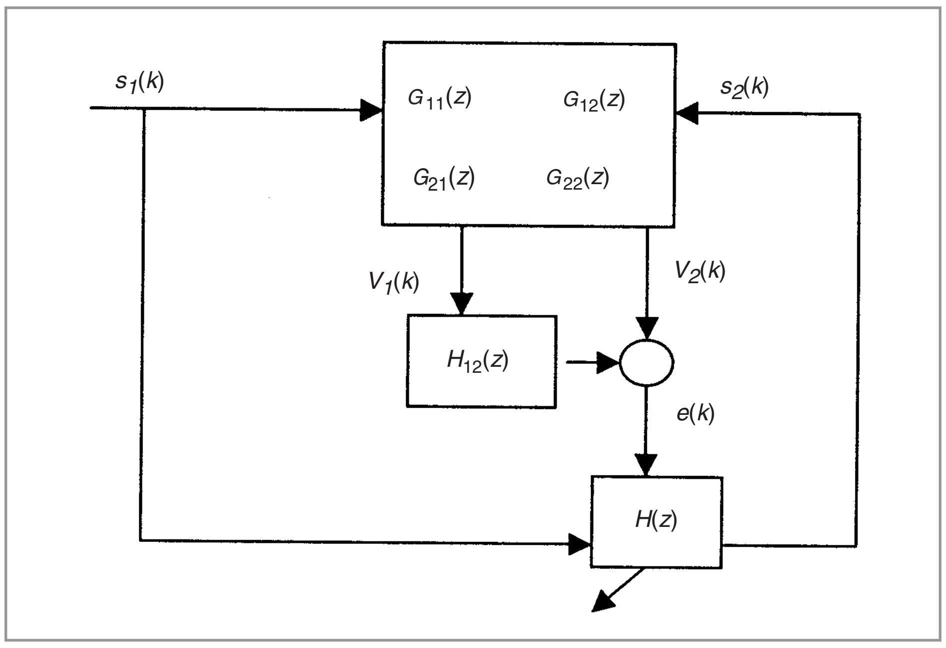

Figure 3 *The controlling system*

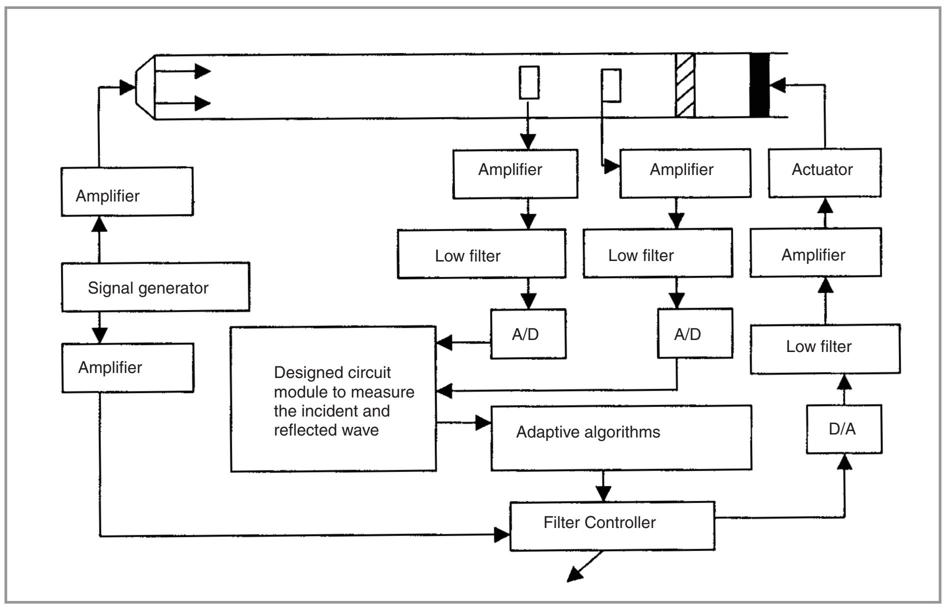

Figure 4 *The experimental arrangement.*

The system investigated is comprised of a 5-cm partially reticulated polyurethane foam layer and an airspace depth of 0-cm (no airspace), the amplitude of the incident sound wave is 1.0 V (the voltage supplied on the loudspeaker), the absorption coefficient of the passive system and the hybrid system as a function of the frequency are shown in Fig. 5.

The result shown in Fig. 5 is the same as that of Beyene and Bardisso by and large.[8] As the Fig. 5 shows, the minimization of the reflected wave in the airspace successfully resulted in a high absorption coefficient over the whole frequency range of interest. Although the absorption peaks at 1350 and 2000 Hz achieved by the passive system were slightly reduced with the introduction of the active component, overall, a consistent high absorption coefficient of 0.87–1.0 was achieved throughout the frequency range of interest. Moreover, the best performance of this hybrid

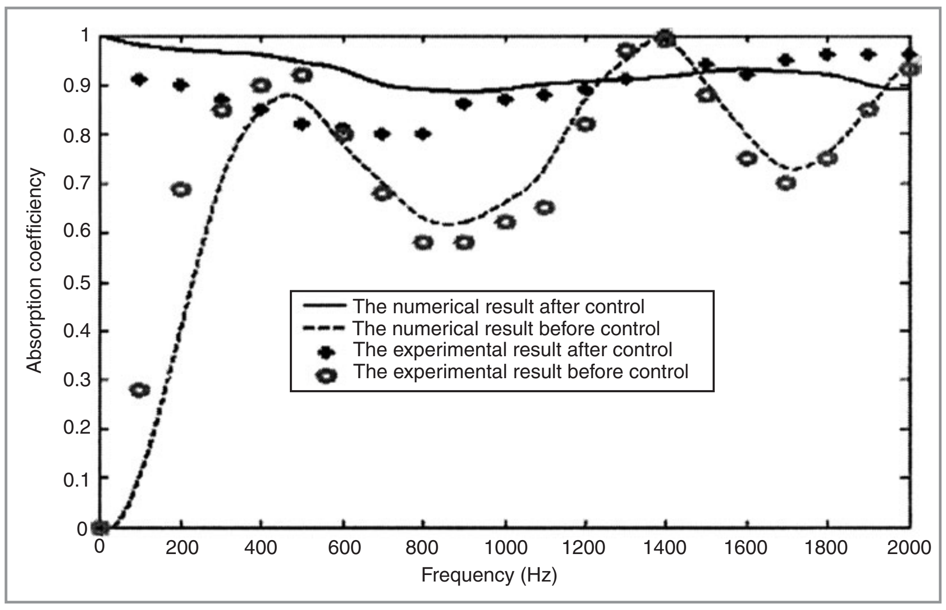

Figure 5 The numerical and experimental absorption coefficient before and after control.

system occurs at frequencies below the first peak of the passive system, i.e., $f < 450$ Hz, where improvement is most desirable.

The experimental results for both before and after control cases are also presented in Fig. 5. As shown in the figure, a high absorption coefficient of 0.78–1.0 is achieved experimentally over the frequency range 100–2000 Hz. At the low frequencies, the experimentally obtained absorption coefficient tends to be lower than the numerical result. The maximum deviation between the experimental and numerical results is an absorption coefficient difference of 0.1. This deviation occurs at the lower frequencies due to a phase mismatch between the two particular pieces of PVDF used. In spite of this problem, the absorption coefficient at 100 Hz is increased from 0.28 to 0.91. Overall, a good agreement between the numerical and the experimental results is observed which validates the proposed approach.

6. CONCLUSION

In this paper, a new hybrid absorption system is posed which is composed of a layer absorbent material and a movable rigid wall. The speed of the movable rigid wall is adjusted in order to make the acoustic impedance of the absorption material match the acoustic impedance of the air, so that the absorption coefficient is maximised. Lastly, a numerical calculation and an experiment are carried out, both numerical and experimental results of such a system are presented for a normally incident plane wave. The numerical and experimental results indicate that the absorption effect is effective at middle and low frequencies and imperfect in high frequencies where passive absorption is dominant.

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noise notes

MUSIC TEACHERS

A study by researchers at the University of Toronto suggests that music teachers are routinely exposed to noise levels that could result in hearing loss. Led by research associate Alberto Behar and electrical and computer engineering professors Hans Kunov and Willy Wong, the team found that while general noise exposure over the course of an average day is marginally acceptable, noise levels during teaching periods could damage the inner ear. “The hair cells of the inner ear simply crumble under the load, and they don’t grow back again,” says Kunov.

A VARIATION ON GOOD VIBRATIONS

The Sound Agency is hoping to increase productivity among office workers by exposing them to the sounds of the gentle rush of wind, the lapping of water and the twittering of birds. Soundscape’s spokesman said that modern working had divorced office workers from the natural sounds and rhythms of life, he said: “Without our natural soundscape we are making ourselves tired, stressed and frightened all at the same time. By starting to pay attention to our natural soundscapes businesses can reduce staff turnover, increase productivity and increase profits.” The Sound Agency can carry out a “sound audit” of an office, identify intrusive noises and then neutralise them with sound absorbers, diffusers and noise cancellation systems normally used in recording studios. Once the building is “sound neutral”, the Agency will create a more conducive working environment by introducing natural sounds like wind, water and birdsong.

WHAT'S GOOD FOR BUSINESS...

In Easton Massachussetts, a foundry run by the aptly named Belcher Corporation is causing grief to the locals. Noise and stink are belching out 24 hours a day. At a public meeting, locals asked the Council what it was going to do about it. On noise, it turns out the Council has no noise byelaw to use to demand a noise reduction from the company. Even if it had such a byelaw it is not likely that it would be effective. The Council has limited jurisdiction over any company. In essence, of Belcher want to run 24/7, there is nothing to stop them. So, as for your complaints about noise and stink, go choke on them.

CHICKEN EARS

Scientists at Washington University School of Medicine in St. Louis have gained new insights into the causes of human deafness and balance disorders by studying the inner ear of chickens. The research provides new clues as to why birds can replace critical cells in the inner ear and humans cannot. Loss of these so-called sensory hair cells in humans is a leading cause of deafness and impaired balance due to aging, infectious disease and exposure to loud noise.

DRIVE SAFELY OR I'LL GROWL

Technology similar to the "black box" recording devices on aircraft is making a marked difference in safety performance for America's largest ambulance service provider. American Medical Response, Inc. (AMR), using event recorders in its ambulance fleet to monitor the driving of its medical crews, is measuring substantial improvements in road safety. Several national studies have noted that ambulance medical crews face substantial risk of injury or death due to vehicle collisions, making the emergency medical service (EMS) profession similarly dangerous to law enforcement or fire fighting. AMR Vice President of Safety and Risk Ron Thackery is presenting the results from nearly two-years of use of the Road Safety 3000 monitors by AMR and its ambulance crews to the Society of Automotive Engineers Conference on June 3 in Washington, D.C. The results, Thackery says, is an industry leading road safety record at AMR, in which collisions and near misses have been reduced, and investigations into collisions produce corrective action based on recorded data. "Data is collected every second the vehicle is on the road," said Thackery. "The driver gets a 10-second grace period in which she hears a growling noise to indicate behaviour outside of the safest parameters. Then it turns into a tone, indicating a penalty." AMR tracks speed in both emergency and non- emergency situations, cornering, acceleration, deceleration, vehicle reverses, and seat belt usage. Company management tracks individual driving performance by its paramedics and emergency medical technicians.