noise
notes

Research on active absorption using piezoelectric ceramic

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Piezoelectric ceramic (PZT) is used as the main material of the transducer, energy exchanger, arrester etc. and used in a control system in sound and vibration because of its excellent mechanical and electrical coupling performance, based on which, in this paper, a new active absorption system is designed in which the piezoelectric ceramic is used as the absorption material. Two equal distance microphones are placed in the front of the piezoelectric ceramic in order to measure the incident plane wave. Then, a voltage is applied on the piezoelectric ceramic in order to make the reflected wave zero using the adaptive controlling. Finally, an experiment is carried out and a good absorption effect attained. The experimental results denote that the theory is correct and practical.

1. INTRODUCTION

In general, passive noise control is most effective at mid and high frequencies and ineffective at low frequencies.[1] Furthermore, the mass of the primary structure must be increased, which augments the analysis difficulty. With the development of science and technology, active absorption has become of importance. So active noise control is the most effective and has the advantage of a good system, light mass and easy control. With the development of modern controlling technology, active absorption is becoming a research "hotspot".

Active noise control (ANC) is attained by introducing a cancelling "anti-noise" wave of equal amplitude and opposite phase using a secondary source,[2] which was posed by Paul Lueg.[3] Early work on ANC used analogue techniques. Much work on ANC has been published; adaptive feed forward control is the most popular and successful approach. Feed forward control involves feeding a signal related to the disturbance input (called the primary noise) into the controller which then generates a signal to drive a speaker in such a way as to cancel the disturbance. This signal related to the primary noise is called the reference signal. [4][5][6][7][8] Results on many successful feed forward ANC systems have been published. However, the major limitations of ANC systems must be noted. First, large secondary sources are needed in ANC. Secondly, other noise can emerge with the secondary source. Third, the transducer, controller and actuator must be external to the structure of ANC system so that the structure is large, with additional mass and high cost, and the acoustic characteristics are changed. In order to overcome the shortcomings mentioned above, active absorption has brought interest to the topic. A common active absorption system consisted of a fibreglass absorption layer backed by an air cavity terminated with an active surface [9]-[12], but it is impractical in some conditions such as submarines. There has been earlier work using active loudspeakers for active absorption [13]. In this paper, a new active absorption based on piezoelectric ceramic is proposed.

Piezoelectric ceramic can be used as

the main material of the transducer, energy exchanger, arrester etc. and used in the control system for sound and vibration due to its excellent mechanical and electrical coupling performance. Some researchers have researched the sound and electrical characteristic of piezoelectric ceramic, which have not been applied in active absorption [14][15]yet. In this paper, the piezoelectric ceramics are applied as the absorption material in active absorption, two equal distance microphones are placed in the front of the piezoelectric ceramic in order to measure the incident plane wave and the reflected wave, a voltage is applied to the piezoelectric ceramic in order to make the reflected wave zero using adaptive controlling. Finally an experiment was carried out with different frequency plane waves and a good absorption effect attained, the experimental results denote that the theory is correct and practical.

2. THEORY OF ACTIVE ABSORPTION

The arrangement of two microphones and the piezoelectric ceramic is shown in Fig. 1,

In Fig.1, the incidence sound pressure is $p_i(t)$, two microphones and the piezoelectric ceramic are arranged as shown.

2.1 MEASUREMENT THEORY OF THE INCIDENT AND REFLECTED WAVE

In this paper, the delay method is used to measure the incident and reflected wave, the principle of which is shown in Fig.2,

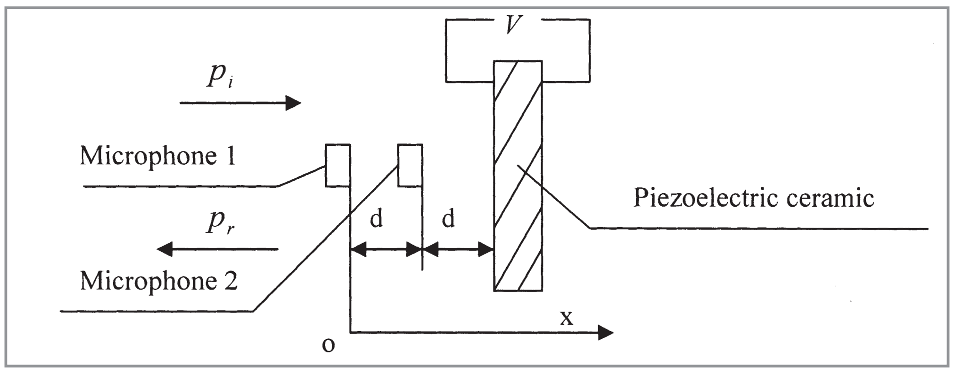


Fig. 1 *The arrangement of two microphones and the piezoelectric ceramic*

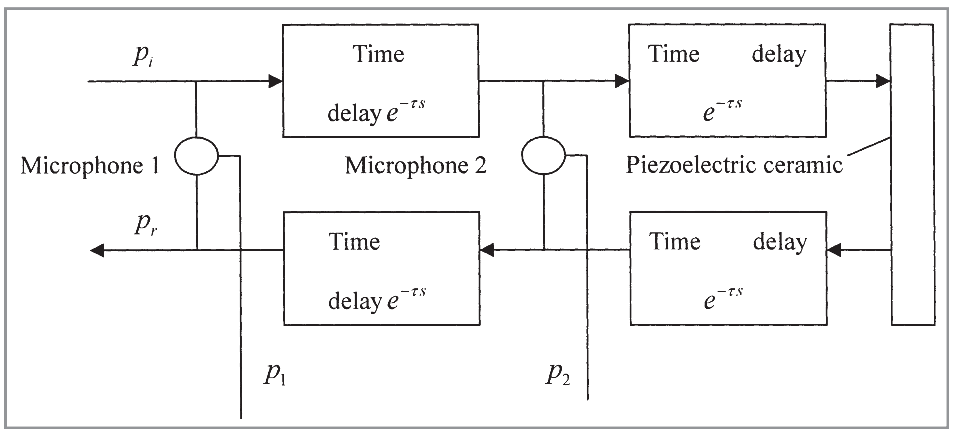


Fig. 2 *The delay method for wave separation*

As can be seen in Fig.2, the signals p_1 and p_2 can be separated into two parts: incident wave and reflected wave. For a plane wave, the difference between p_{1i} and p_{2r} is a pure time delay. Likewise, the difference between p_{2i} and p_{2r}, is another time delay multiplied by *R(s)* which is the reflection coefficient. The delay between the microphone 1 and microphone 2 is τ, $\tau = \tau \frac{d}{c}$, c is the propagation velocity of the wave in the air. Considering these relationships, we get

$$p_1(S) = p_i(s) + p_r(s)e^{-4\tau s} \quad (1)$$

$$p_2(S) = p_i(s)e^{-\tau s} + p_r(s)e^{-3\tau s} \quad (2)$$

Let

$$x(t) = p_2(t) - p_1(t-\tau) \quad (3)$$

and

$$y(t) = p_1(t) - p_2(t-\tau) \quad (4)$$

Eq.3 and Eq.4 are Laplace transformed, and the following equations are obtained,

$$X(s) = p_2(s) - p_1(s)e^{-\tau s} \quad (5)$$

$$Y(s) = p_1(s) - p_2(s)e^{-\tau s} \quad (6)$$

Substituting Eq.1 and Eq.2 into the Eq.5 and Eq.6, we get

$$X(s) = p_r(s)e^{-3\tau s} - p_r(s)e^{-5\tau s} = p_i(s)\,(1-e^{-2\tau s}) \quad (7)$$

$$Y(s) = p_i(s) - p_i(s)e^{-2\tau s} = p_i(s)\,(1-e^{-2\tau s}) \quad (8)$$

Combining the Eq.7 and Eq.8 gives

$$p_r(t) = L^{-1}(p_r(s)) = L^{-1}\left(\frac{X(s)}{1-e^{-2\tau s}}e^{3\tau s}\right) \quad (9)$$

$$p_i(t) = L^{-1}(p_i(s)) = L^{-1}\left(\frac{Y(s)}{1-e^{-2\tau s}}\right) \quad (10)$$

where, $L^{-1}(x)$ is the adverse Laplace transform of the function x.

2.2 THEORY OF ACTIVE ABSORPTION WITH PIEZOELECTRIC CERAMICS

The structure of the piezoelectric ceramic used in this paper is shown in Fig. 3,

In Fig.3, b is the thickness of the piezoelectric ceramic, u_1, u_2 are the vibration velocities in the direction of thickness. F_1, F_2 are forces pressing on the piezoelectric ceramic. V is the voltage. According to the structure of the piezoelectric ceramic, the equivalent circuit figuration is as shown in Fig.4, [14][15]

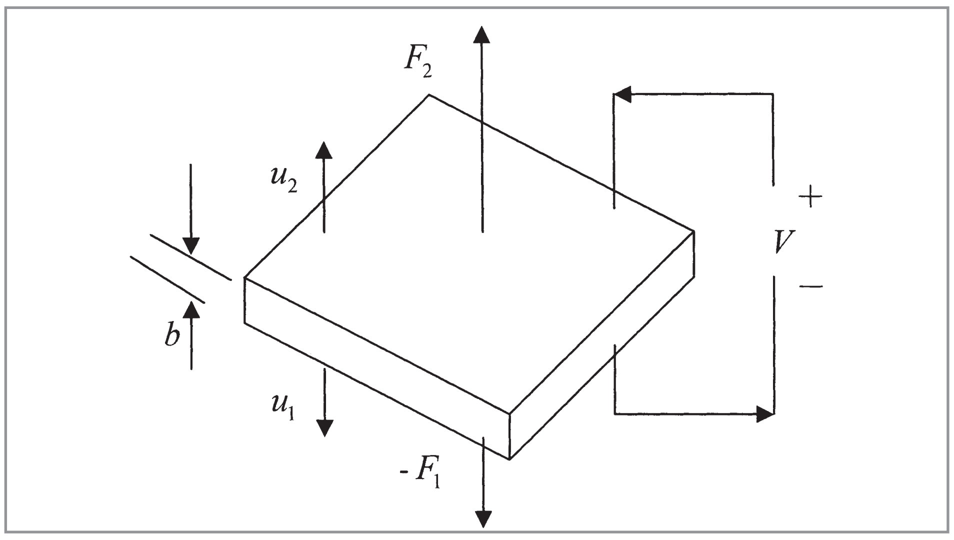


Fig. 3 Structure of the piezoelectric ceramic

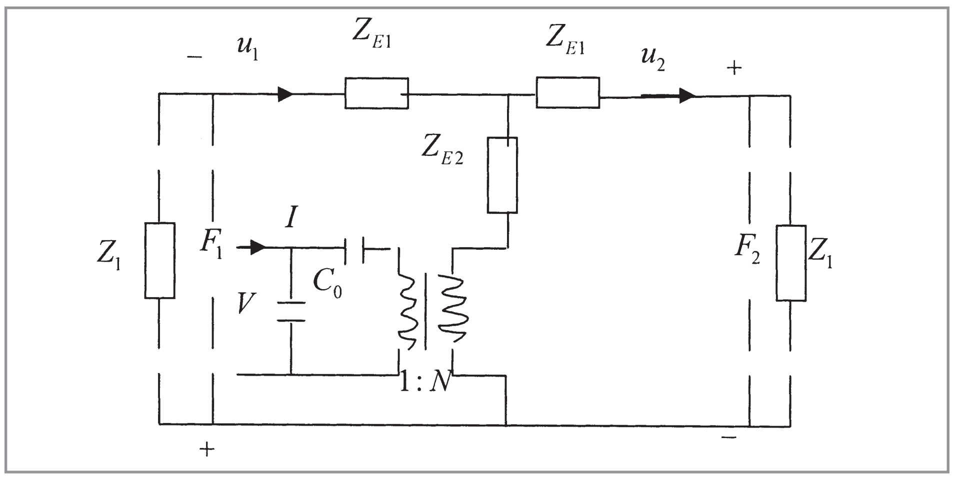


Fig. 4 *The equivalent circuit figuration*

In the Fig.4, $Z_{E1} = j\rho C_t^{\,D} \tan\frac{kt}{2}$, $Z_{E1} = \frac{-j\rho C_t^{\,D}}{\sin kt}$, $C_0 = \frac{\varepsilon_{33}^{\,S}}{t}$, $N = \frac{e_{33}}{t}$,

t, ρ, C_t^D, ε_{33}^S, ε_{33} are thickness, density, elastic coefficient, dielectric constant, coupling constant of the piezoelectric ceramic respectively. The following equations can be derived accordingly from circuit theory.

$$F_1 = -(Z_{E1} + Z_{E2})u_1 + Z_{E2}u_2 - \frac{N}{j\omega C_0}I \tag{11}$$

$$F_2 = -(Z_{E1} + Z_{E2})u_2 + Z_{E2}u_1 + \frac{N}{j\omega C_0}I \tag{12}$$

$$V = \frac{N}{j\omega C_0}u_1 - \frac{N}{j\omega C_0}u_2 + \frac{1}{j\omega C_0}I \tag{13}$$

The reflected sound pressure P_r, velocity u_1 and the transmission sound pressure p_t velocity u_2 satisfy the following relations:

$$F_1 = (P_i + P_r)A_0 \tag{14}$$

$$F_2 = P_t A_0 \tag{15}$$

$$\frac{p_i - p_r}{Z_1} = u_1 \tag{17}$$

where Z_1 is the characteristic impedance of the air, A_0 is the cross-sectional area of the piezoelectric ceramic. According to the equations (14) to (17), the following equations can be derived

$$(A_0 + \frac{Z_{E1} + Z_{E2}}{Z_1})p_i + A_0 - \frac{Z_{E1} + Z_{E2}}{Z_1})p_r - \frac{Z_{E2}}{Z_1}p_t - \frac{N}{j\omega C_0}I = 0 \tag{18}$$

$$\frac{Z_{E2}}{Z_1}p_i - \frac{Z_{E2}}{Z_1}p_r + (\frac{Z_{E1} + Z_{E2}}{Z_1} - A_0)p_t + \frac{N}{j\omega C_0}I = 0 \tag{19}$$

$$\frac{N}{j\omega C_0 Z_1}p_i - \frac{N}{j\omega C_0 Z_1}p_r + \frac{N}{j\omega C_0 Z_1}p_t - V + \frac{1}{j\omega C_0}I = 0 \tag{20}$$

In the Eq.18, Eq.19, Eq.20, there are five complex amplitudes p_i, p_r, p_t, V, I. If two of these amplitudes are specified, the equations may be solved for the remaining three. For example, if p_i is set to a desired incident wave amplitude and p_r is set to zero, the following equations can be obtained.

$$(A_0 + \frac{Z_{E1} + Z_{E2}}{Z_1})p_i = \frac{Z_{E2}}{Z_1}p_t - \frac{N}{j\omega C_0}I \tag{21}$$

$$\left(\frac{Z_{E1}+Z_{E2}}{Z_1}-A_0\right)p_t+\frac{N}{j\omega C_0}I=-\frac{Z_{E2}}{Z_1}p_i \qquad (22)$$

$$\frac{N}{j\omega C_0 Z_1}p_t-V+\frac{1}{j\omega C_0}I=-\frac{N}{j\omega C_0 Z_1}p_i \qquad (23)$$

From Eq.21~Eq.23, the voltage V of the piezoelectric ceramic is obtained

$$\begin{pmatrix} p_t \\ V \\ I \end{pmatrix}=\begin{pmatrix} \frac{Z_{E2}}{Z_1} & 0 & -\frac{N}{j\omega C_0} \\ \left(\frac{Z_{E1}+Z_{E2}}{Z_1}-A_0\right) & 0 & \frac{N}{j\omega C_0} \\ \frac{N}{j\omega C_0 Z_1} & -1 & \frac{1}{j\omega C_0} \end{pmatrix}^{-1}\begin{pmatrix} A_0+\frac{Z_{E1}+Z_{E2}}{Z_1} \\ -\frac{Z_{E2}}{Z_1} \\ -\frac{N}{j\omega C_0 Z_1} \end{pmatrix}p_i \qquad (24)$$

According to Eq.24, the voltages applied to the piezoelectric ceramic can make the reflected wave zero and the aim of active absorption is achieved.

The density, the acoustic impedance, the dielectric constant and the coupling constant of the piezoelectric ceramic respectively are $\rho = 2430 kg.m^{-3}$, $\rho C_t^D = 7.6 \times 10^6\,kg(m^2.s)^{-1}$, $\varepsilon_{33}^S = 174.3\varepsilon_0$, $\varepsilon_{33} = 3.95 C.m^{-2}$. The diameter of the piezoelectric ceramic is d = 100mm and the thickness is t = 1.5mm. If the amplitude of the incident wave is 1.00Pa, the theoretical calculated amplitude and phase of the piezoelectric ceramic according to the Eq.24 are shown in Fig.5,

For the same piezoelectric ceramic, the thickness is t = 2.5mm. If the amplitude of the incidence wave is 1.00Pa, the theoretical calculated amplitude and phase of the piezoelectric ceramic according to Eq.24 are shown in Fig. 6,

For the same piezoelectric ceramic, the thickness is t = 3.5mm. If the amplitude of the incidence wave is 1.00Pa, the theoretical calculated amplitude and phase of the piezoelectric ceramic according to the Eq.24 are shown in Fig.7,

According to the Fig.5-Fig.7, the conclusion can be drawn:

(1) For the piezoelectric ceramic of the same thickness, the amplitude and the phase of the voltage are reduced when the incident frequency is increased.

(2) For the same frequency of the incident wave, the amplitude of the voltage is increased and the phase is reduced when the thickness of the piezoelectric ceramic is increased.

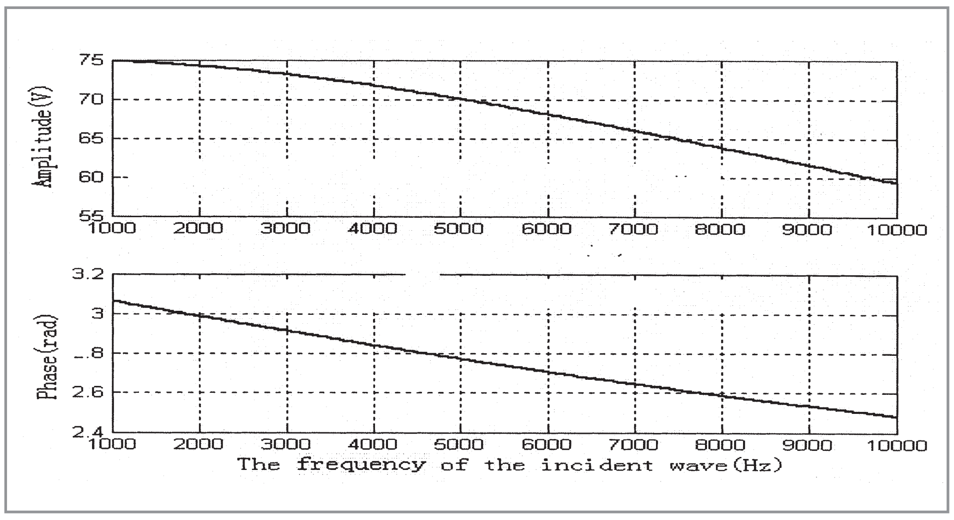


Fig. 5 *The theoretical calculated amplitude and phase of the piezoelectric ceramic*

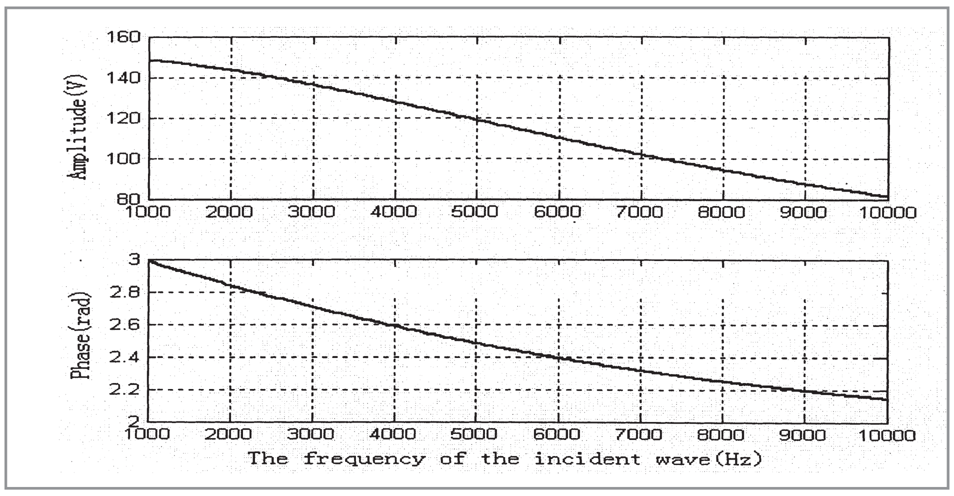


Fig. 6 The theoretical calculated amplitude and phase of the piezoelectric ceramic

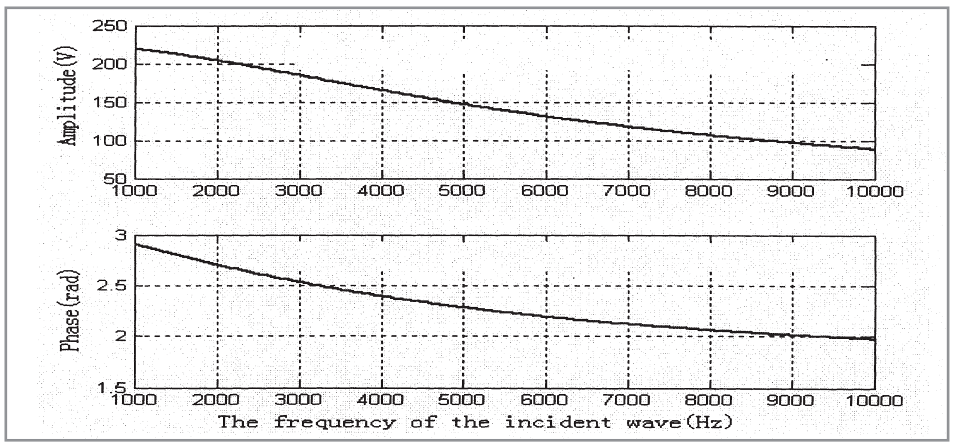


Fig. 7 The theoretical calculated amplitude and phase of the piezoelectric ceramic

3. CONTROL THEORY

An error signal can be synthesized from the signals of a pair of microphones located in front of the piezoelectric ceramic. The error signal should have the property that after being minimized by the action of the controller, the acoustic impedance in front of the piezoelectric ceramic matches the desired specification. As this 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

$$E_1(z) = H_{12}(z)p_1(Z) - p_2(Z) \quad (25)$$

where p_1 (z) and p2 (z) are the z transforms of the signals from the microphones and H_{12} (z) is the desired transfer function between them.

The desired transfer function between the outputs from the microphones H12 (z) can be related to the desired acoustic impedance at the center of the microphone pair. For sound consisting only of plane waves, the transfer function is

$$H_{12}(j\omega) = \frac{\dfrac{Z_d(j\omega)}{\rho c} - j\tan(\dfrac{\omega\tau}{2})}{\dfrac{Z_d(j\omega)}{\rho c} + j\tan(\dfrac{\omega\tau}{2})} \quad (26)$$

where Z_d $(j\omega)$ is the desired acoustic impedance. In the particular case when the desired acoustic impedance is Z_d $(j\omega)$ = ρc, corresponding to perfect absorption, Eq.26 simplifies to a time delay,

$$H_{12}(j\omega) = e^{-j\omega\tau} \quad (27)$$

This can be readily transformed to a digital transfer function if the sampling period is chosen as an integer 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,

$$H_{12}(z) = e^{-N} \quad (28)$$

In the time domain, the error signal is then calculated as

$$e_1(k) = p_1(k - N) - p_2(k) \quad (29)$$

where k is the digital time index and lowercase letters denote the time signals corresponding to the z transforms in capitals. This simple form is amenable to a highly efficient real time implementation in a microprocessor. The control system is shown in Fig.8:

4. EXPERIMENT

A Kundt impedance tube 4002 is used for this experiment whose diameter is 10cm and length is 3m. The experimental arrangement is shown in Fig.9.

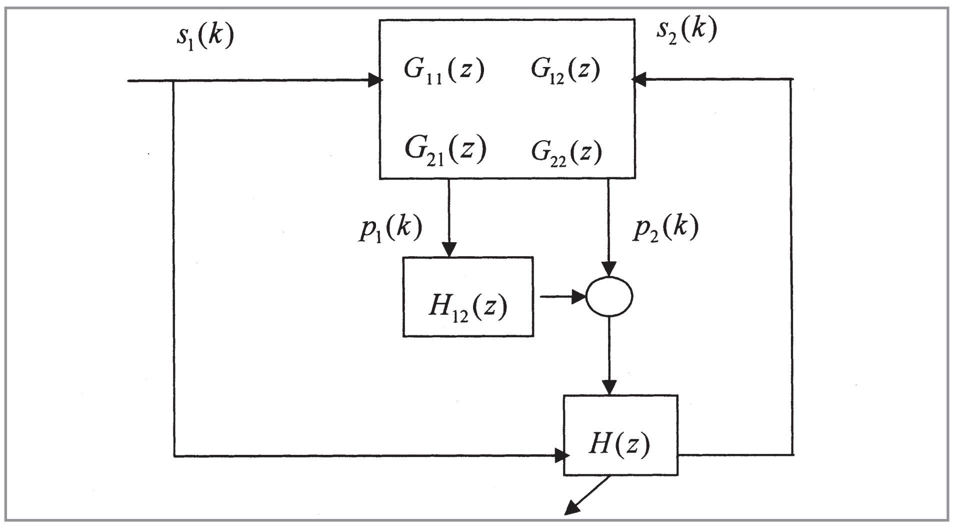


Fig.8 *the control system*

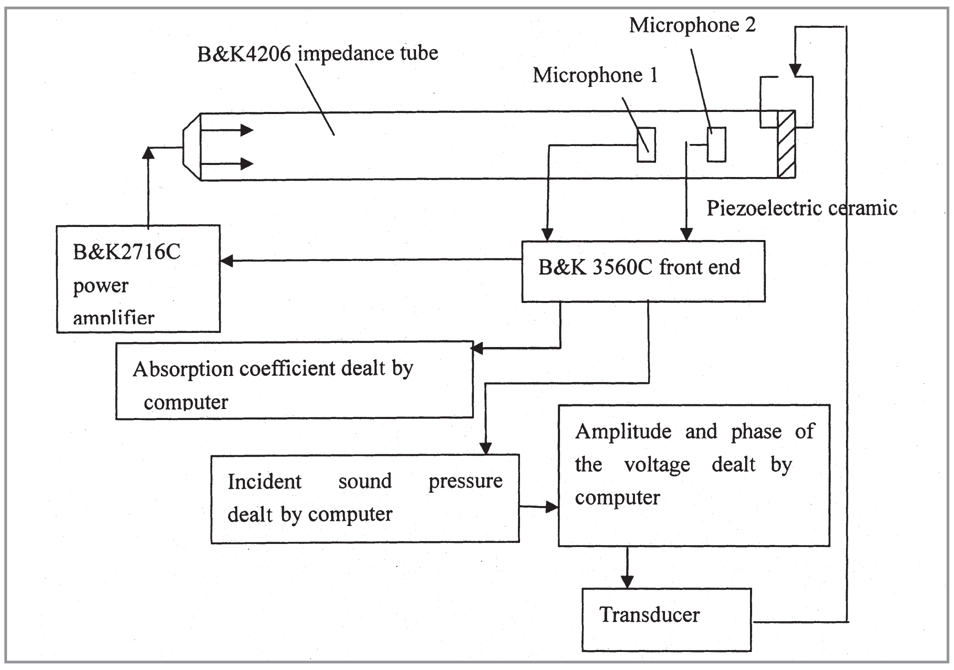


Fig. 9 *The experimental arrangement*

Fig. 10 *The practical experimental arrangement*

The practical experiment arrangement is shown in Fig. 10.

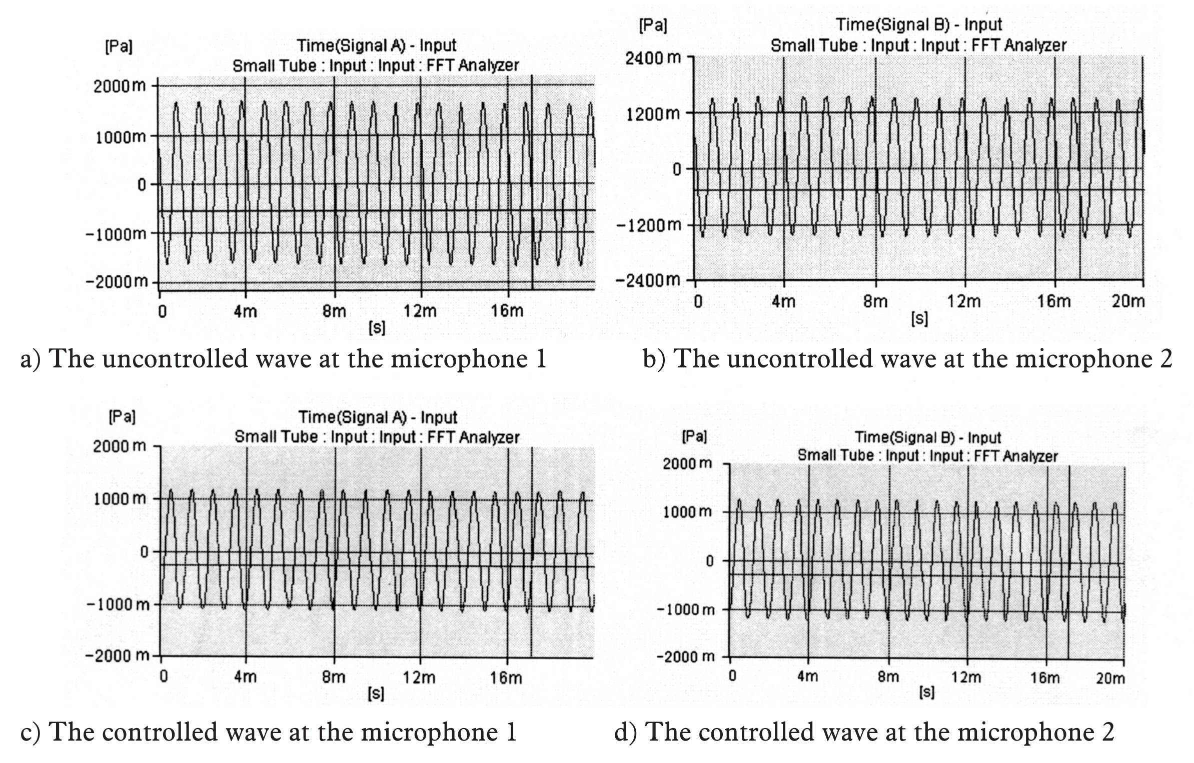
The primary source is a loudspeaker which is located at the end of the tube, the distance between the two microphones is 5cm and the distance between microphone 2 and the piezoelectric ceramic is 5cm. The density of the air is $\rho = 1.21\text{kg} / \text{m}^3$, the propagation velocity in the air is c = 343m.s^{-1}, the thickness, the density, the acoustic impedance, the dielectric constant, coupling constant respectively are t = 1.5mm, $\rho = 2430\text{kg}.m^{-3}$, ρC_t^D = $7.6 \times 10^6 \text{ kg}(\text{m}^2.s)^{-1}$, $\varepsilon_{33}{}^S = 174.3\varepsilon_0$, ε_{33} = $3.95C.m^{-2}$. If the loudspeaker emits a plane wave, the signals of the two microphones are passed by the circuit module designed for measuring the incidence and the reflection sound pressure to the computer, so that the reflection pressure is obtained. At the same time, the voltage is applied on the piezoelectric ceramic passing the filter controller. The function of the two microphones is not only to measure the incident and reflection wave, but also to adaptively control as error transducers. The experimental frequency ranges from 1000*Hz* to 4000Hz. Although the second mode of the 100mm diameter tube is close to 2000Hz, another experiment as arranged in Fig.9 is carried out in an anechoic chamber. The last measured absorption coefficient is little different from the absorption coefficient measured in the tube mentioned in Fig.9. Thus the last result measured in the tube is used in this paper.

The frequency and the amplitude of the incident wave are 1000Hz and 1.00Pa respectively. The uncontrolled and controlled wave at microphones 1 and 2 are shown in Fig.11. In Fig.11, the symbol m is milli and s is second.

The frequency and the amplitude of the incident, wave are 2000Hz and 1.00Pa respectively. The uncontrolled and controlled waves at the microphone 2 are shown in Fig. 12.

The frequency and the amplitude of the incident wave are 3000Hz and 1.00Pa respectively. The uncontrolled and controlled wave at the microphone 1 and 2 are shown in Fig. 13.

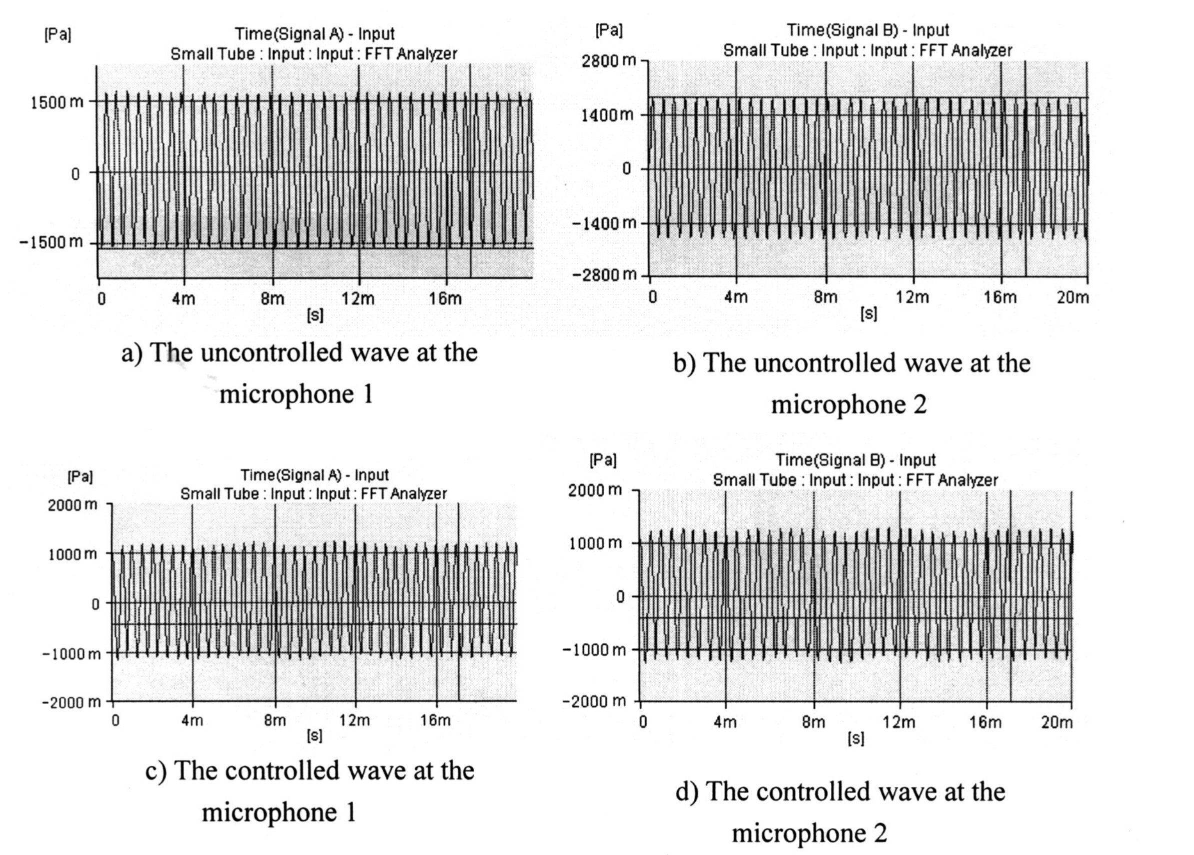
The frequency and the amplitude of the incident wave are 4000Hz and 1.00Pa respectively. The uncontrolled and controlled wave at the microphone 1 and 2 are shown in Fig. 14.



a) The uncontrolled wave at the microphone 1 b) The uncontrolled wave at the microphone 2

c) The controlled wave at the microphone 1 d) The controlled wave at the microphone 2

Fig. 11 The uncontrolled wave at the microphone 1 and microphone 2 with the incident frequency 1000Hz



a) The uncontrolled wave at the microphone 1

b) The uncontrolled wave at the microphone 2

c) The controlled wave at the microphone 1

d) The controlled wave at the microphone 2

Fig. 12 The uncontrolled and controlled wave at the microphone 1 and microphone 2 with the incident frequency 2000Hz

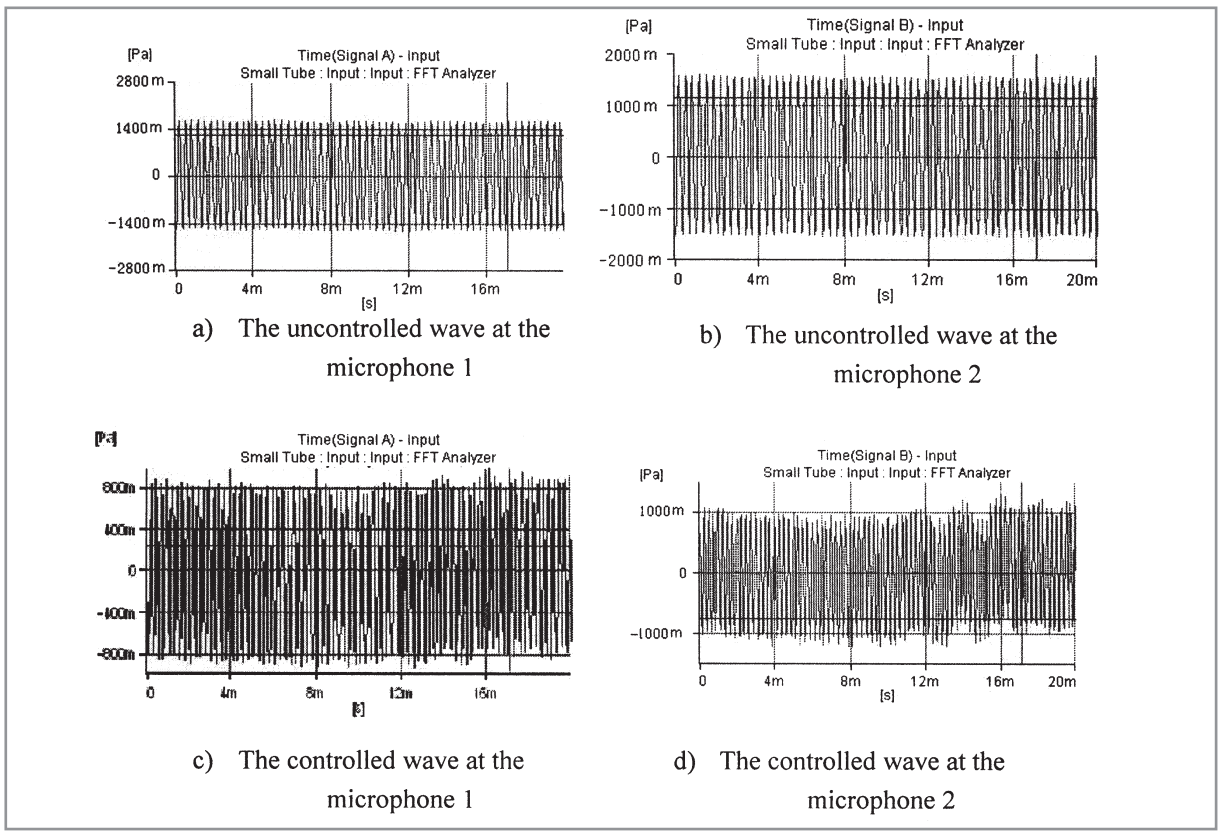


Fig. 13 *The uncontrolled and controlled wave at the microphone 1 and microphone 2 with the incident frequency 3000Hz*

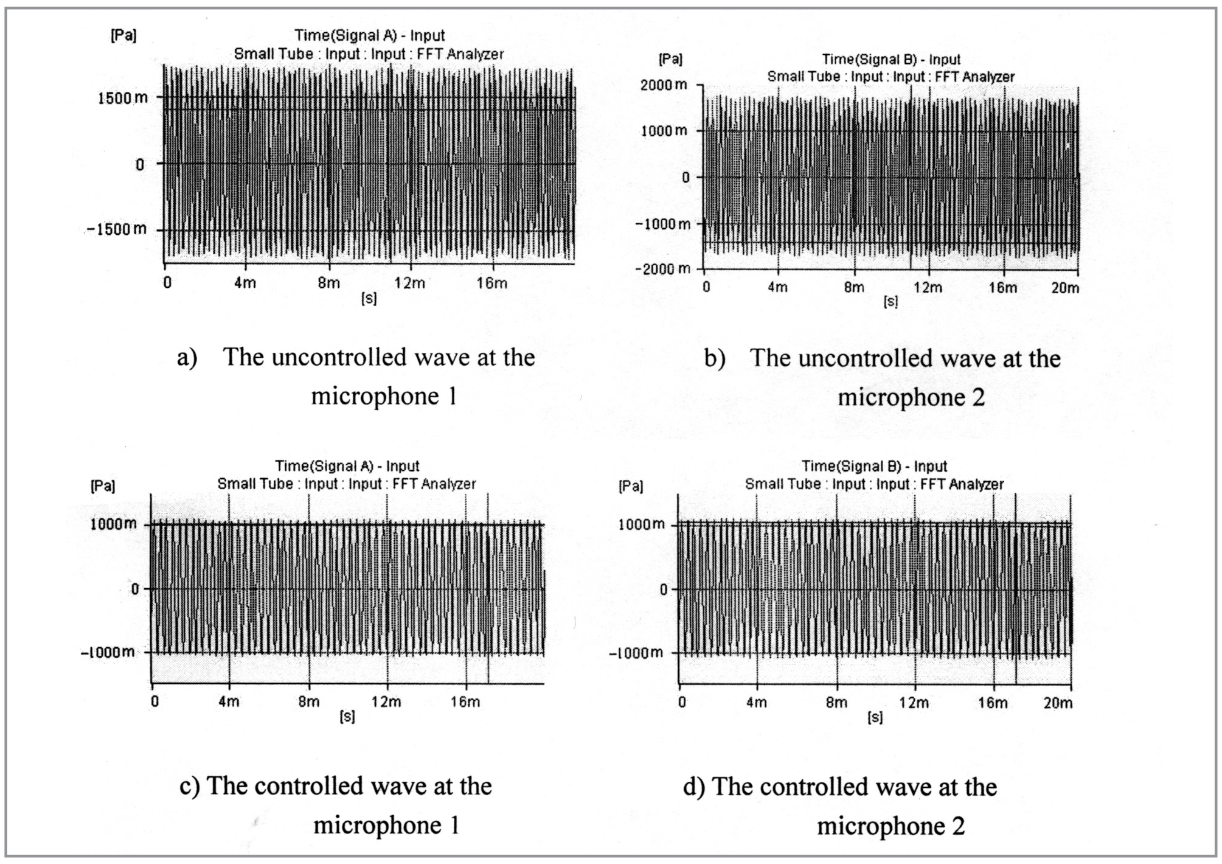


Fig. 14 *The uncontrolled and controlled wave at the microphone 1 and microphone 2 with the incident frequency 4000Hz*

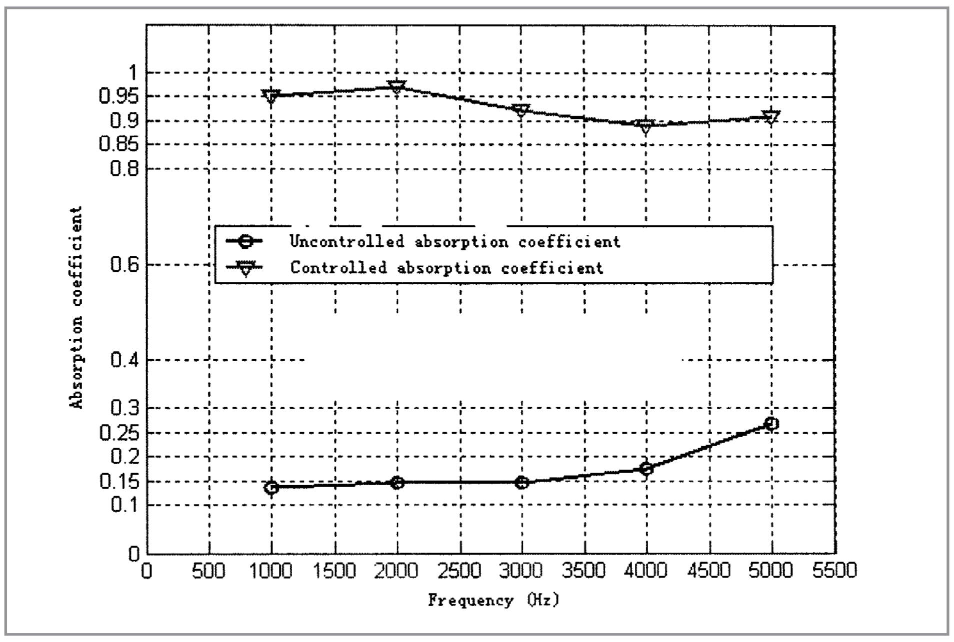


Fig. 15 *The absorption coefficient uncontrolled controlled*

The absorption coefficient before and after control are shown in Fig. 15

According to the Fig. 11, the absorption coefficient before control is lower than 0.3, after control, the absorption coefficient reaches 1.0 at all measured frequencies. So the experimental results denote that the absorption theory is correct and feasible.

5. CONCLUSION

Unlike the active noise control systems that cancel sound at a point in space, this active absorption method mentioned in this paper causes sound reduction along an acoustic boundary. This active surface of the piezoelectric ceramic is controlled in a manner similar to active vibration actuators, which cancel unwanted vibrations along the surface of the actuator. The signal into the actuator causes its surface wave with equal amplitude and opposite phase to the disturbance. This technique is also used for sound reduction of the propagation disturbance and the active actuator surface.

Another way to view this is that the acoustic impedance of the active surface is displaced to match the dynamic incident acoustic pressure wave. This means that the incident pressure travels into the boundary as if it is an infinite medium. This concept is different from many traditional and commercial active acoustic systems approaches in that it matches the impedance of an acoustic boundary surface such that an incident disturbance will not reflect from the boundary. The energy associated with the disturbance is removed from the acoustic medium and dissipated through the electrical resistance dissipation in the power amplifier.

The experiment results denote that the absorption theory is correct and feasible. Other research is being carried out under the condition that oblique incidence plane wave and random incidence wave replaced the normal incidence plane wave and PVDF film replaced the two microphones as transducers.

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BRITS FLEE

A million Britons may have moved house to escape from noisy neighbours, according to new research. The survey by Ipsos MORI of 2,000 adults found that two per cent said that the noise was so bad that they had moved out, while 70 per cent said they were bothered by noise in their neighbourhoods One in five people said motorcycles and cars are the most common irritants.

RACIST COMPLAINTS?

Noise complaints have been lodged since late 2004, when Chesapeake's Holy Temple church moved to its spot at 740 Great Bridge Blvd. Some residents conducted a failed petition drive to block construction of the church there, saying they wanted the area to remain residential. Members of the predominantly black congregation have said they think the noise complaints are racially motivated. Nearby neighbourhoods are mostly white.