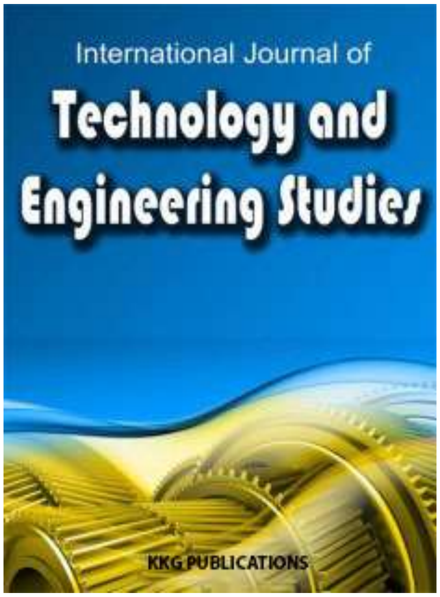

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DESIGN OF ACTIVE NOISE CONTROL SYSTEMS USING ULTRASONIC TRANSDUCERS AND ACOUSTIC HOLOGRAPHY TECHNIQUES

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Microphone Array
Desired Quiet Zone

Abstract. This paper presents an active noise control system design using ultrasonic transducers and spatial transformation of sound fields in acoustic holography. In the active noise control field, most of the researchers used traditional loudspeakers as secondary sources. However, ultrasonic transducers are used as secondary sources to control the noise. Recently, only a few of the studies used ultrasonic transducers as secondary sources. The microphone array is used to measure the sound pressure within the desired quiet zone in the active noise controls. However, there is no need to measure the sound pressure within the desired quiet zone using the microphone array in this study. The spatial transformation of sound pressure was used to estimate the sound pressure within the desired quiet zone. Also, the ultrasonic transducers were used to control the noise within the desired quiet zone. The results showed that larger quiet zones were obtained using the ultrasonic transducers and acoustic holography in the active noise control system.

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INTRODUCTION

In the last decade, Active Noise Control (ANC) has been developed significantly to deal with low-frequency noise, mostly using traditional loud speakers to reduce noise [1], [2], [3] and [4]. The ANC method works very well especially against low-frequency noise, which is hard to attenuate by passive methods [5]. The most desirable noise control result would be the attenuation of sound pressure in all directions in space. However, such global control can only be achieved when primary sources and control sources are closely located. Under these circumstances, to cancel the sound pressure in restricted regions and to achieve quiet zones seem to be the only choice for active noise control in free space. This control strategy is called local control. Local active noise control can be applied inside automobiles and aircraft to cancel the noise near a listener’s ear. It is called the active headrest system.

This paper used ultrasonic transducers as secondary sources to control the noise. Also the acoustic holography technique has been used to predict the sound pressure in the desired quiet zone area. Therefore, there is no need to use the microphone array to measure the sound pressure in the desired quiet zone area. T he results showed that the performance of the active noise control system using ultrasonic transducers was better than that using conventional loudspeakers.

THEORY

The fundamental theory of acoustic holography techniques dates back around 100 years. Invented by Strutt from Great Britain, this technique had only a preliminary concept [6]. In the late 1960s, it was Graham who was first dedicated to the question of plane-acoustic-field radiation of long waves [7,8,9,10].

In the three-dimensional acoustic field, there is a measuring plane S at r' (x', y', z'), and the acoustic pressure of which is P(r'). When looking to the direction of a measuring plane outwards, there is a plane at r (x, y, z). To satisfy the sound wave equation, the homogeneous acoustic wave equation can be expressed as follows:

$$\Delta p(r,t) = \frac{1}{c^2}\frac{\partial^2 p(r,t)}{\partial t^2}$$

Where $p(r,t)$ acoustic pressure in time domain is, Δ is Laplace operator and c is the speed of sound. Because measuring of acoustic holography indicates the frequency area, equation (2) is expressed in the frequency domain. Also, in order to show how Fourier transformation can be used to transfer the function from the time domain to the frequency domain, the equation (1) can be written as follows:

$$P(r,\omega) = \int_{-\infty}^{+\infty} p(r,t)e^{j\omega t}dt$$

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The acoustic Helmholtz equation can be expressed as follows.

$$\Delta \mathrm{P}(\mathrm{r},\omega)+\mathrm{k}^2\mathrm{P}(\mathrm{r},\omega)=0 \qquad (3)$$

Where $\Delta P(r,\omega)$ is acoustic pressure of frequency domain, and k is wave number.

Equation (1) can also be rewritten as follows:

$$S(k_x,k_y,k_z)=S(k_x,k_y,z')g_d(k_x,k_y,z-z') \qquad (4)$$

$S(k_x,k_y,k_z)$ means to transfer the measurement of plane *z'* from a sound source to a new predictive plane *z*, which is, so-to-speak, the spatial transformation of the pressure field. g_d means the so called spatial transform of Green's function. Supposing that the measurement plane of sound pressure is at *z'*, and new predictive measurement plane is at *z* - that is, the forward propagation: $z \geq z'$ the equation can be written as equation (5), and g_d can be demonstrated as following:

$$g_d=e^{jk_z(z-z')} \qquad (5)$$

Again, to presume that measurement plane is at *z'*, a new predictive measurement plane is at *z*, that is, the back propagation: $0 \leq z \leq z'$, which shifts from one plane z' to new predictive plane *z* of spatial transformation of the pressure field and can be expressed as the following equation:

$$k_z=\sqrt{\left(\frac{\omega}{c}\right)^2-({k_x}^2+{k_y}^2)}$$

$$g_d=e^{jk_z(z-z')}=e^{-jk_z(z'-z)}=\frac{1}{e^{jk_z(z-z')}}$$

$$S(k_x,k_y,k_z)=S(k_x,k_y,k_z')\frac{1}{e^{jk_z(z-z')}} \qquad (6)$$

The sound pressure in the reconstructive surface can be expressed as:

$$P_{AH}(x,y,z)=\xi^{-1}\left\{S(k_x,k_y,k_z')\left\{\frac{e^{jk_z(z-z')},k_x^2+k_y^2\leq k_0^2}{e^{-k_z(z-z')},k_x^2+k_y^2>k_0^2}\right\}\right\} \qquad (7)$$

This study used ultrasonic transducers as the secondary sources. The audible sound pressure of ultrasonic transducers does not decay rapidly with distance. Applied to active noise control, larger quiet zones can be obtained than those with conventional loudspeakers. The secondary field of ultrasonic transducers at the field point away from the secondary monopoles can be expressed as [8].

$$P_s(r,\theta,t)=P_0{}^2Z_s$$

$$Z_s=\frac{p_0^2\beta m\omega_s S}{4\pi\rho_0{c_0}^4}$$

$$\int_0^l\frac{e^{-a_s r_q}e^{-2a_p x}\left(sin\left\{\omega_s\left(t-\frac{r_q}{c_0}\right)-k_s x\right\}-mcos\left\{2\omega_s\left(t-\frac{r_q}{c_0}\right)-k_s x\right\}\right)}{\gamma_q}dx \qquad (8)$$

where P_0 is sound pressure amplitude, β is the nonlinear factor, ω_s is the angular frequency, S is the opening area, ρ_0 is the air density, c_0 is the sound speed, α_p is the absorption coefficient of the carrier wave, and k is the wave number.

Then, the total sound pressure of random point in space is the sum of primary sound field pressure of noise sources and the secondary sound field created by ultrasonic transducers and can be expressed as follows.

$$P_T(x,y)=P_P(x,y)+P_S(x,y) \qquad (9)$$

This study used 2-norm pressure minimization method to control the primary source. The optimal secondary field, which minimizes the 2-norm of the total pressure in a given area can be calculated by minimizing the sum of squared pressure as follows:

$$\min_{ps}\|P_T\|_2^2=\min_{ps}\left\|P_p+P_s\right\|_2^2=\min_{ps}\sum_{i,j,k}\left|P_{AH}(x_i,y_j,z_k)+P_S(x_i,y_j,z_k)\right|^2 \qquad (10)$$

RESULTS

This section presents the performance of active control systems using the ultrasonic transducers and the acoustic holography technique. The primary noise frequency is set with 108 Hz. The primary noise source was located at the origin. The microphone array was 0.1m away from the origin, and the reconstructive surface was 0.2m away from the origin. The quiet zones created by using ultrasonic transducers were compared to those created by using conventional loudspeakers.

Fig. 1 is the 2-D attenuation contour using one ultrasonic transducer and the acoustic holography technique for 108Hz. The ultrasonic transducer was located at the point 0.05m away from the origin. The blue line represents the 10 dB quiet zone, and the green line represents the 5 dB quiet zone. Fig. 2 is the 3-D attenuation contour using one ultrasonic transducer. From the figures it can be seen that the quiet zones are circles and the diameter of the 10dB quiet zone is about 0.65m. Fig. 3 is the 2-D attenuation contour using one conventional loudspeaker located at the point 0.05m away from the origin. Fig. 4 is the 3-D attenuation contour using one conventional loudspeaker. From the figures we can see that the diameter of the 10dB quiet zone is about 0.4m. As can be seen from figures 1, 2, 3, and 4 the 10dB quiet zone created by using the ultrasonic transducer was larger than that created by using the conventional loudspeaker.

This is because the sound pressure of the ultrasonic transducer does not decay rapidly with distance. However the sound pressure of the conventional loudspeaker decays rapidly with distance. Therefore the secondary field created by the ultrasonic transducer can fit the primary filed well and the larger quiet zone could be obtained.

Figure 5 shows the 2-D attenuation contour using one ultrasonic transducer for 216Hz. Fig. 6 shows the 3-D attenuation contour using one ultrasonic transducer for 216Hz. From the figures it can be seen that the quiet zone became smaller. This is since the frequency of the primary field is increased and primary field becomes more complicated. Therefore the quiet zone became smaller. Fig. 7 shows the 2-D attenuation contour using one conventional loudspeaker for 216Hz. Fig. 8 shows the 3-D attenuation contour using one conventional loudspeaker. From figures 5, 6, 7, and 8 we can see that the quiet zone created using one ultrasonic transducer was still larger than that created using one conventional loudspeaker when the frequency of the primary field was increased.

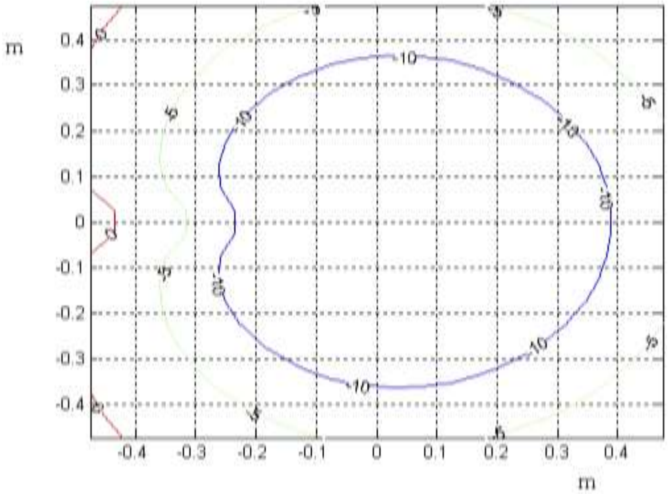

Fig. 1. Attenuation contour (2-D)-one secondary source (ultrasonic transducers)–108 Hz

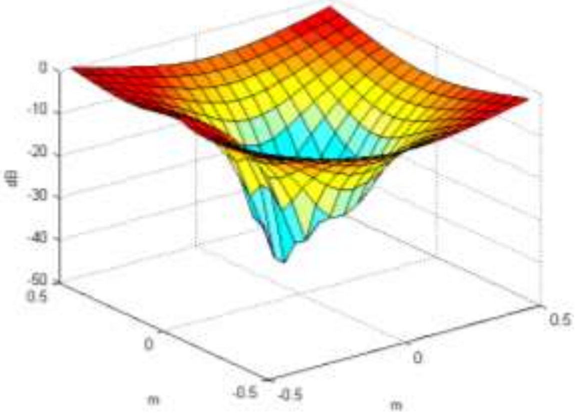

Fig. 2. Attenuation (3-D)-one secondary source (ultrasonic transducers)–108 Hz

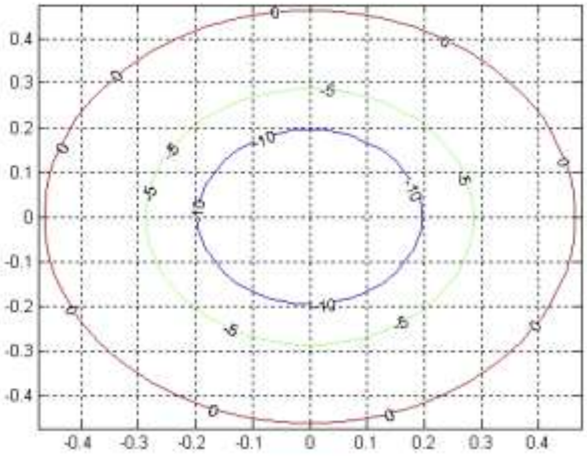

Fig. 3. Attenuation contour (2-D)-one secondary source (loudspeaker)–108 Hz

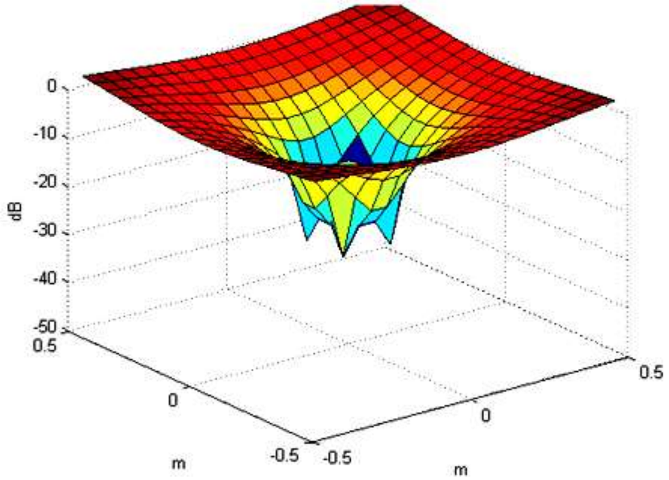

Fig. 4. Attenuation (3-D)-one secondary source (loudspeaker)-108Hz

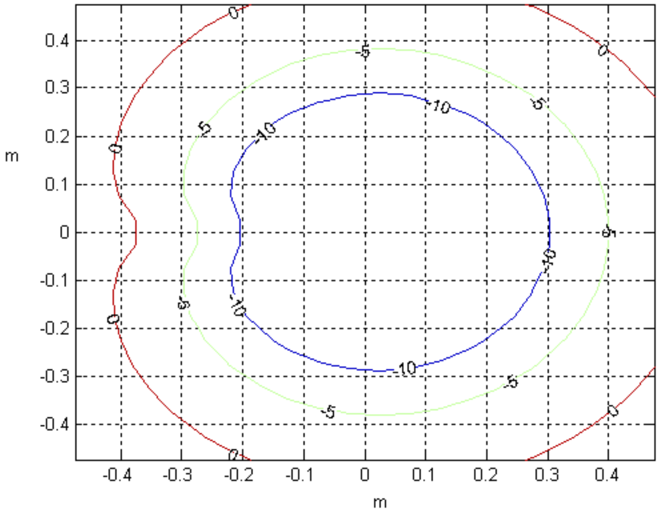

Fig. 5. Attenuation contour (2-D)-one secondary source (ultrasonic transducers)–216 Hz

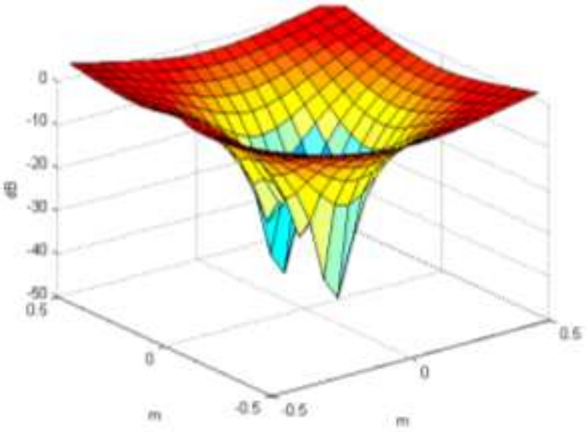

Fig. 6. Attenuation (3-D)-one secondary source (ultrasonic transducers)–216 Hz

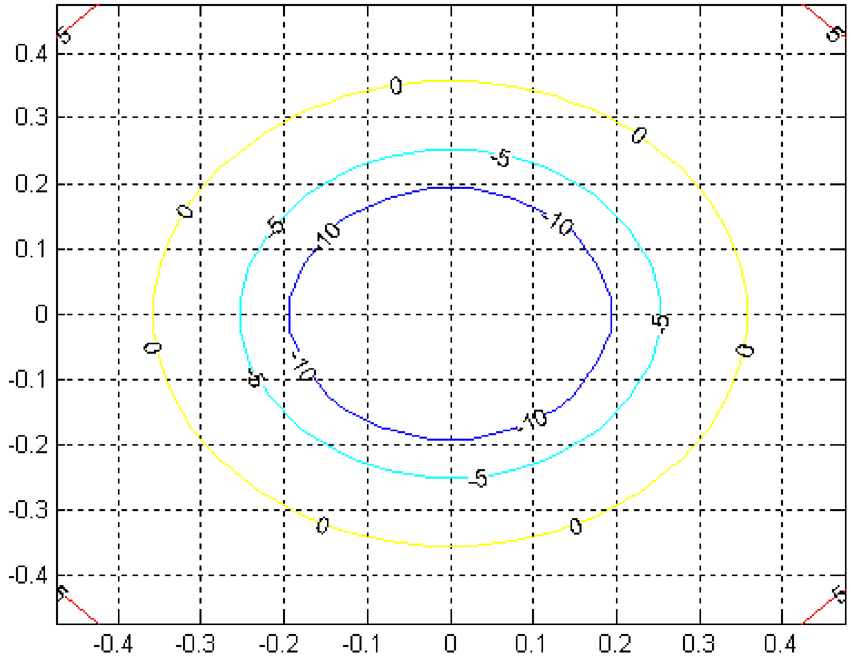

Fig. 7. Attenuation contour (2-D)-one secondary source (loudspeaker)–216 Hz

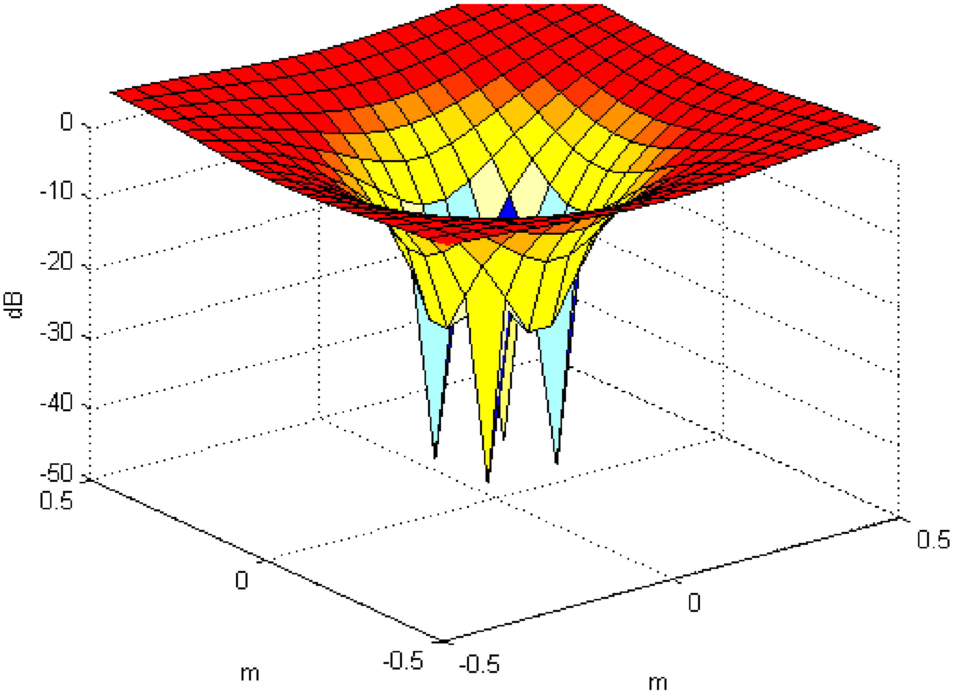

Fig. 8. Attenuation contore (3-D)-one secondary source (loudspeaker)–216 Hz

CONCLUSION AND RECOMMENDATIONS

This paper evaluated the performance of active noise control systems using the ultrasonic transducer and the acoustic holography technique. The quiet zones created using ultrasonic transducers were analyzed and compared to those created using conventional loudspeaker. The results showed that quiet zone created by using the ultrasonic transducer was larger than that created by using the conventional loudspeaker. This is because the sound pressure of the ultrasonic transducer does not decay rapidly with distance. However the sound pressure of the conventional loudspeaker decays rapidly with distance. Therefore the secondary field created by the ultrasonic transducer can fit the

Primary filed well and the larger quiet zone could be obtained. The results also showed that the quiet zone created by using one ultrasonic transducer was still larger than that created by using one conventional loudspeaker when the frequency of the primary field was increased.

Declaration of Conflicting Interests

No competing interests either finacial or non-financial are associated with the current study.

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