REDUCING ACOUSTIC FEEDBACK FOR ACTIVE NOISE CONTROL IN DUCT

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Abstract

In most practical applications of active noise control, the acoustic feedback is a major problem that often interferes with the operation of the control system and even renders it unstable. The traditional dual-microphone reference sensing technique is discussed and modified in this paper. Further, we propose a frequency-domain method based on transfer function to reduce the influence of acoustic feedback based on plane wave transmission theory of sound in a duct. The original signal of primary noise is obtained from the measured signals of reference microphone and error microphone which are transformed to frequency domain by FFT and operated by the proposed method. Finally, the performance of the proposed method is verified by means of an ANC experiment in a finite-length duct. The results showed that the proposed method can effectively reduce the influence of acoustic feedback. In practical application of active noise control in a duct, the adaptive control or other control method incorporate the proposed method in this paper will improve the stability and performance effectively.

INTRODUCTION

Active noise control (ANC) techniques have been widely applied to suppress low frequency noise [1,2]. The traditional feedforward ANC system uses the reference signal measured by an upstream reference microphone to generate a control signal that drives a secondary source to radiate an anti-noise to cancel the unwanted noise downstream in a duct. Unfortunately, sound from the secondary source will propagate both upstream and downstream, and the use of a reference microphone which measures the primary noise to be canceled introduces the possibility of undesired acoustic wave from the secondary source. The coupling of the acoustic wave from secondary source to the reference microphone is called acoustic feedback.

It is usually an annoying problem to feedforward ANC system that a feedback loop occurs between the secondary source and the reference microphone. Acoustic feedback introduces poles to the ANC system and therefore produces a stability problem if a large loop gain exists. Some solutions to the problem of acoustic feedback have been proposed such as, directional microphones and loudspeakers [3-5], electronic compensating network [6], dual-microphone reference sensing technique [7], filter-u LMS method [8-10], H_∞ synthesis technique [11], and so on. In some situation, acoustic feedback can be avoided in feedforward control if a non-acoustic reference signal such as vibration signal is available. However, only the acoustical noise reference is available in many practical situations, and acoustic feedback usually arises in feedforward ANC system for suppressing broadband noises.

In this paper, we will firstly discuss the problem of dual-microphone reference sensing technique, also known as dual sensing microphone (abbreviating to DSM), and modify it from the stand point of acoustic theories [12]. But in practice, it appears that the lack of symmetry of the acoustic system prevents perfect reduction of acoustic feedback for a DSM system. Therefore, we will propose another method to reduce the influence of acoustic feedback in a duct.

MODIFICATION OF DSM METHOD

A single-channel feedforward ANC system with DSM technique in an infinite duct is illustrated in figure 1. In this system, a primary source produces the primary noise and a reference microphone measure this sound pressure as the reference input signal to the ANC system to outputs a driving signal for a secondary source on a duct wall to generate an anti-noise. An error microphone located where noise should be cancelled picks up the error signal that presents the system performance to the ANC system to update the adaptive filter coefficients. Because the secondary source will radiate acoustic wave propagating both upstream and downstream, the reference signal contains not only the original acoustic disturbance but also the upstream acoustic wave from the secondary source. This acoustic feedback introduces poles in the ANC system and thus brings on potential instability if a large gain of this feedback loop exists. Traditional DSM technique uses the reference signal that is the difference of reference microphone and error microphone, placed on either side of the secondary source at equal distances. But this signal is different from the original primary noise. We will verify and modify it in the following paragraphs.

Figure 1 depicts a dual-microphone reference sensing system in an infinite duct. A reference microphone and an error microphone are placed on either side of the secondary source at equal distances d. A primary source is located upstream at distance L from the secondary source. Regarding the study on the active control of sound in an infinite duct, we concentrate our interest only on the sound propagation in a rectangular duct at a frequency lower than the cut-off frequency, i.e., only the plane wave in the

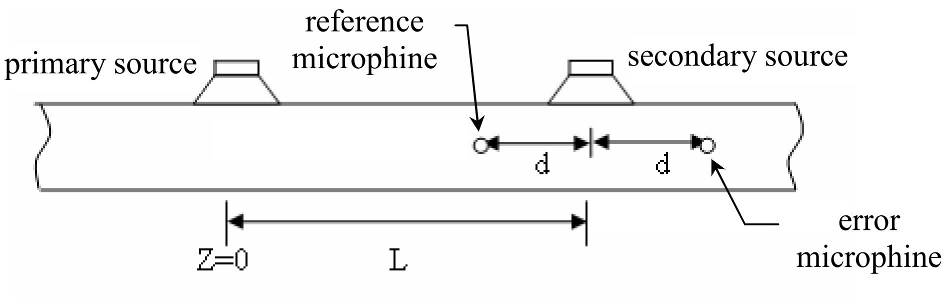

Figure 1 – dual-microphone reference sensing system in an infinite duct

duct is propagating. Therefore, the sound pressure $P_{r,p}$ measured by the reference microphone and radiated from the primary source before ANC is actuated can be expressed as [12]

$$P_{r,p} = Q_p Z_p e^{-jk(L-d)} \tag{1}$$

where $Q_p = \left|Q_p\right| e^{j(\omega t+\phi)}$ is the complex strength of primary source at time *t*, $\left|Q_p\right|$ is the magnitude of Q_p, $j = \sqrt{-1}$ is a purely imaginary number, ω is the circular frequency of the sound wave involved, and ϕ is the initial phase angle($t = 0$). Source strength also known as volume velocity is the product of surface particle velocity and acoustical radiation area of sound source. Z_p is the acoustic impedance of primary source when no other incident sound wave exists. k is the wave number of acoustic wave involved. Further, the sound pressure $P_{e,p}$ measured by the error microphone and radiated from the primary source before active control is actuated can be expressed as

$$P_{e,p} = P_{r,p}\, e^{-jk(2d)} \tag{2}$$

When active control is applied, the sound pressure $P_{r,s}$ measured by reference microphones and radiated from secondary source is equal to the sound pressure $P_{e,s}$ measured by reference microphones and radiated from same source due to symmetrical location. They can be expressed as

$$P_{r,s} = P_{e,s} = Q_s Z_s e^{-jkd} \tag{3}$$

Here Q_s is the complex strength of secondary source, Z_s is the acoustic impedance of secondary source when no other incident sound wave exists. Therefore, the resulting total sound pressure measured by reference microphone and error microphone respectively can be expressed as

$$P_r = P_{r,p} + Q_s Z_s e^{-jkd} \tag{4}$$

and

$$\begin{aligned} P_e &= P_{e,p} + Q_s Z_s e^{-jkd} \\ &= P_{r,p} e^{-jk(2d)} + Q_s Z_s e^{-jkd} \end{aligned} \tag{5}$$

In traditional DSM method, the reference input signal to the controller is the difference $P_r - P_e$ between the outputs of two microphones. But the original acoustic disturbance $P_{r,p}$ as described in Eq. (1) is different from this value. It can be obtained from the difference between Eq. (4) and Eq. (5):

$$P_r - P_e = P_{r,p} - P_{r,p}e^{-jk(2d)}$$

$$P_{r,p} = \frac{(P_r - P_e)}{1 - e^{-jk(2d)}} \tag{6}$$

Eq. (6) is the modified DSM algorithm to get the pure primary noise signal $P_{r,p}$ and reduce the effect of acoustic feedback. In practice, it appears that the lack of symmetry of the acoustic system prevents perfect reduction of acoustic feedback for a DSM system. In the next section, we will propose a further method to reduce acoustic feedback for general disposition of the ANC system in a duct.

FREQUENCY-DOMAIN METHOD BASED ON TRANSFER FUNCTION

Figure 2 depicts the general disposition of two microphones and secondary source in ANC system. Here we discuss the acoustic path transfer function according two different situations. Firstly, when the primary source is switched on and the secondary source is switched off, we can express the sound pressure $P_{r,p}$ measured by the reference microphone and radiated from the primary source as

$$P_{r,p} = Q_p Z_p e^{-jkb} \tag{7}$$

and the sound pressure $P_{e,p}$ measured by the error microphone and radiated from the primary source as

$$P_{e,p} = Q_p Z_p e^{-jk(b+c+d)} \tag{8}$$

Then the acoustic path transfer function from reference microphone to error microphone can be obtained as

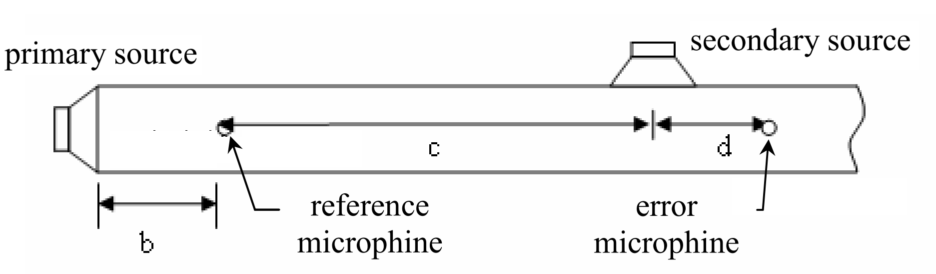

Figure 2 – a general ANC system

$$H_1 = \frac{P_{e,p}}{P_{r,p}} \tag{9}$$

Secondly, when the primary source is switched off and the secondary source is switched on, we can express the sound pressure $P_{r,s}$ measured by the reference microphone and radiated from the secondary source as

$$P_{r,s} = Q_s Z_s e^{-jkc} \tag{10}$$

and the sound pressure $P_{e,s}$ measured by the error microphone and radiated from the secondary source as

$$P_{e,s} = Q_s Z_s e^{-jkd} \tag{11}$$

Then the acoustic path transfer function from reference microphone to error microphone can be obtained as

$$H_2 = \frac{P_{e,s}}{P_{r,s}} \tag{12}$$

Therefore, after ANC is actuated, the resulting total sound pressure measured by reference microphone and error microphone respectively can be expressed as

$$P_r = P_{r,p} + P_{r,s} \tag{13}$$

and

$$P_e = P_{e,p} + P_{e,s} \tag{14}$$

Eq. (13) is multiplied by H_2, and subtracts Eq. (14). We can obtain the following result:

$$P_r H_2 - P_e = P_{r,p} H_2 + P_{e,s} - \left(P_{e,p} + P_{e,s}\right)$$
$$P_r H_2 - P_e = P_{r,p} H_2 - P_{e,p}$$
$$P_r H_2 - P_e = P_{r,p} H_2 - P_{r,p} H_1$$
$$P_{r,p} = \frac{P_r H_2 - P_e}{H_2 - H_1} \tag{15}$$

We can use Eq. (15) to get the pure primary noise signal $P_{r,p}$ and reduce the effect of acoustic feedback if the lack of symmetry of the acoustic system. Figure 3 depicts the processing procedure of this frequency-domain method based on transfer function. Here FFT is the fast Fourier transform, and IFFT is the inverse fast Fourier transform. C is the controller transfer function of ANC system, $H_{r,e}$ is the acoustic path transfer function from reference microphone to error microphone, $H_{s,r}$ is the acoustic path transfer function from secondary source to reference microphone, and $H_{s,e}$ is the acoustic path transfer function from secondary source to error microphone. Note that $H_{s,r}$ is just the acoustic path transfer function of the acoustic feedback.

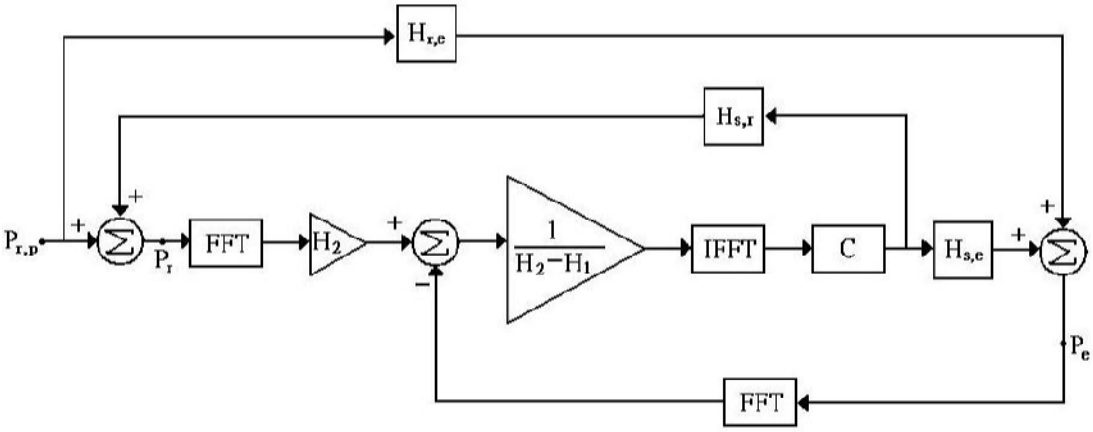

Figure 3 – block diagram of the frequency-domain method based on transfer function

EXPERIMENTAL VERIFICATION

An experiment was conducted to verify the proposed method in a rectangular duct of cross-section 0.2×0.2 m and length 4 m. With these dimensions, the cut-off frequency can be calculated to be approximately f=850 Hz. The primary source was placed at the left end of the duct and the secondary source was 3 m away from the primary source. A reference microphone is placed at a distance 2 m upstream from the secondary source and an error microphone is placed at a distance 0.5 m downstream from the secondary source. The proposed method illustrated by figure 3 is implemented by LabVIEW program at a sampling frequency of 1.28 kHz, and adopt 128 samples to perform FFT.

Firstly, we measure the acoustic path transfer functions H_1 and H_2 respectively in Eq. (9) and in Eq. (12), and substitute them in LabVIEW program. Next, considering the cut-off frequency of the duct and the poor response of speaker at low frequency, we chose dual sine wave at frequency 200 Hz and 400 Hz as the primary noise. Figure 4 depicts the sound pressure $P_{r,p}$ measured by the reference when ANC is switched off. The time index represents a multiple of $\frac{1}{1280}s$. In order to observe the variation of reference input due to the effect of acoustic feedback, we applied adaptive control using a non-acoustic reference signal to achieving the ANC experiment. Figure 5 depicts the sound pressure P_r measured by reference microphone without reduction of acoustic feedback when ANC is switched on. It is clear that this waveform of P_r is much different from that in figure 4. If we use the signal as the reference signal of adaptive control, the reference signal uncorrelated with primary noise will degrade the performance of the ANC system. Finally, we substitute the measuring signal P_r and P_e in Eq. (15) and obtain the convenient reference signal much correlated to primary noise, shown in figure 6.

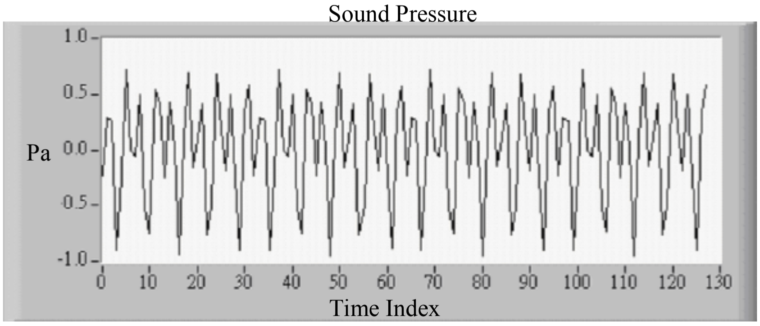

Figure 4 – the sound pressure $P_{r,p}$ measured by the reference microphone when ANC is switched off

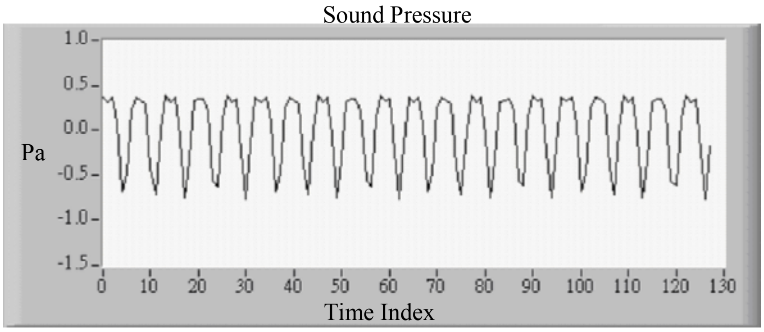

Figure 5 –the sound pressure P_r measured by reference microphone without reduction of acoustic feedback when ANC is switched on

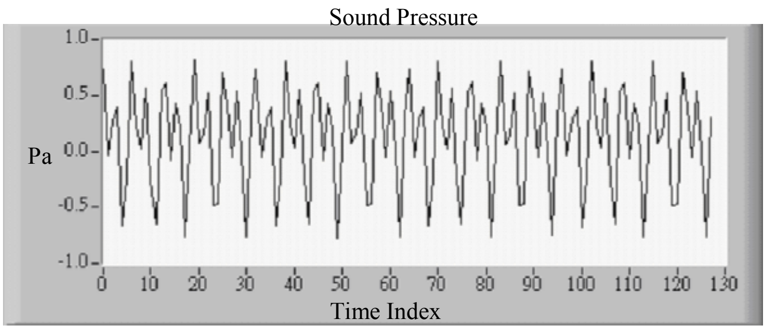

Figure 6 – the reference signal obtained by the proposed method when ANC is switched on

CONCLUSIONS

In this paper, a modified DSM algorithm and a frequency-domain method based on transfer function have been proposed to reduce the influence of acoustic feedback in a duct. Because the lack of symmetry of the acoustic system often appears for a DSM system in practice, we recommend that the later method is adopted for reduction of acoustic feedback. Experimental verifications of the proposed method were conducted by an implementation on a finite-length duct. From the experimental results, it is clear that this method provides an excellent solution for reduction of acoustic feedback in ANC system.

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