The technologies for active noise control

Ken'iti Kido

Chiba Institute of Technology
2-17-1, Tsudanuma, Narashino, 275 Japan

This paper reviews the progress in the technology of active noise control (ANC) with some examples and discusses what are the key points in this technology. In the first place, the principle of the ANC is briefly explained and it is shown that the cancellation of noise by the sound wave radiated by the additional sound source can be considered to be equivalent to the control of the internal impedance of additional sound source. And an example of the noise control by the adaptive directivity control is explained. Then, some method to decrease the closed loop gain are shown as the instability is usually fatal in the ANC system. Next, the FIR filter to synthesize the signal to drive the additional source is introduced as an indispensable equipment. It is finally pointed out that the adaptive control of the coefficients of FIR filter is the most important technology in the active noise control because the optimum values of the coefficients vary with the changes in the noise transmission path.

Keywords: Noise control, Active, ANC, Impedance, Directivity

PACS number: 43. 50. Ki

1. INTRODUCTION

The active control of sound and vibration has a long history. The oldest examples of the active vibration control are the control of ship rolling proposed between the 19th century and the 20th century^{1,2)} and they were fit for practical use in 1920's.³⁾ On the contrary, it was in 1930's that the first idea of the active noise control was proposed⁴⁾ and the first trial of the active noise control was carried out in 1940's.⁵⁾ And it was 1960's that the active noise control had become a research object of a number of researchers as a practical technology.⁶⁻⁹⁾ That is, it can be said that the active control of vibration has progressed much earlier than the active control of sound. One of the reasons why the active vibration control of ship shows remarkable progress is its technical feasibility due to the very low frequency and another is the strong demand. Anyway, it is remarkable that the idea of active control of vibration was proposed and developed almost 100 years ago.

This paper describes first the outline of the

principle of active noise control in the view points of impedance control and the directivity control. Next, how to keep the active noise control system stable is discussed because the system tends to oscillate due to the feedback from the additional source through the acoustic path between the additional source and the source microphone. Finally, the importance of the adaptive control in the active noise control system will be described.

2. PRINCIPLE OF THE ACTIVE NOISE CONTROL

When the original sound in an objective field is controlled to a desirable state by some active means, it may be said the active control of sound. It can be to make echoes or reverberation in the architectural acoustics, and to cancel echoes in the telecommunication.

In the active noise control (ANC) the noise should be canceled by the sound radiated by an additional sound source. The sound radiated by the additional source should have the same waveform and the inverse polarity as the noise in the objective space.

To radiate the sound to cancel the primary noise, the additional source is driven by a synthesized signal. How to synthesize the signal and how to arrange the additional sound source are key problem to realize the active noise control system.

The size of the additional sound source should be much smaller than the wavelength and the source should be set at the same position as the primary noise source to make all the space silent. It may be difficult to make such the condition except for the case of very low frequency noise radiated by a small noise source.

By limiting the space to be made quiet, it becomes possible to control noise by the sound radiated by the additional sound source.⁹⁾ But, it is unavoidable that the total sound power in the space increases by the sound radiated by the additional source and the sound pressure increases at the outside of the silent zone.

When the space is one dimensional as in the case of duct noise, the sound pressure level at the duct end can be decreased by the sound radiated by the additional source.¹⁰⁾

When it is desired to decrease the noise in a specific direction from a noise source, the control of the directivity pattern is effective. To control the directivity pattern, some sound sources radiating the same sound as the primary noise source are arranged close to the primary source and the amplitude and the phase of every frequency component are adjusted.

The absorption of sound by a loudspeaker set on a wall can be effective in a duct but it is difficult to decrease the sound pressure level in a broad space by such the loudspeaker. The silent zone will be limited to very narrow range if the sound is absorbed. The effect of the sound absorption by a loudspeaker on a wall may not be observed in the decrease of sound pressure level but in the decrease of reverberation time.

As discussed in the precedings, the methods for the active noise control can be divided into the following two methods: a) the superposition of the sound of the same waveform and the inverse phase to the noise and b) the absorption of sound energy by some controlled loudspeakers. The control of the directivity pattern belongs to a), and it is possible to make unified concept for those methods as described in the next chapter.

3. UNIFIED STUDY BY USE OF THE CONCEPT OF IMPEDANCE

We can find a description on the noise suppression by a monopole system in which the output of a microphone set in front of a loudspeaker is amplified and fed to the driving terminal of the loudspeaker in a well-known paper by H. F. Olson.⁵⁾ The principle of monopole system was transcribed to the active control of the acoustic impedance of the loudspeaker by Okda who carried out an experimental study first place in Japan.⁶⁾ But, the noise suppression by the control of internal impedance of loudspeaker could not be developed due to the difficulty of the compensation of phase rotation around the resonance frequency of loudspeaker or the realization of inverse transfer characteristic of loudspeaker. This difficulty indicates the limitation of analogue control.

After that work, Okda and his colleagues have developed the theory of active control of duct noise using the concept of impedance. And they give the useful information on the active noise control that the cancellation of sound in duct by phase reversed sound is equivalent to make the internal impedance of the control loudspeaker zero.¹¹⁾

As pointed out by Okda, the various methods for the active noise control by use of additional sound sources can be unified by use of the concept of impedance control. Why the radiation of sound by the additional sound source is equivalent to the control of impedance will be briefly explained in the followings using a duct as an example of one dimensional space. That is, the dimension of the duct in the cross section is sufficiently smaller than the wavelength in the following explanation.

A loudspeaker is set on the inner wall of a duct in which noise propagates from the upper stream. The sound radiated by the loudspeaker should have the same wave form as the incident noise and the phase should be inverse to diminish the sound in the down stream direction. The same sound travels to the upper stream direction.

Here, the sound pressure and the particle velocity of the primary sound (noise) and the secondary sound radiated by the control loudspeaker are expressed by p_1 , v_1 , p_2 and v_2 , respectively. The coordinate x is set along with the direction of the duct and the original point $x=0$ is set at the point of the loudspeaker. Then, the components of frequency f of the

sound pressure and the particle velocity of the primary sound can be expressed by $P_1 \exp(-jkx)$ and $V_1 \exp(-jkx) = (P_1/\rho c) \exp(-jkx)$, respectively, where $k = 2\pi f/c$ and ρc is the characteristic impedance of the medium.

The sound pressure of the secondary sound $P_2 \exp(-jkx)$ should have the relation $P_2 = -P_1$ to cancel completely the primary sound in the down stream.

Here, P_2 is assumed to be αP_1 . Then, $V_2 = \alpha V_1$.

In the upper stream, the direction of the sound propagation is opposite to the positive direction of the particle velocity. And the following relations are held.

$$P_2 \exp(jkx) = \alpha P_1 \exp(jkx),$$

$$V_2 \exp(jkx) = P_2 \exp(jkx)/(-\rho c)$$

$$= -\alpha V_1 \exp(jkx).$$

Therefore, the sound pressure and the particle velocity in the upper stream are expressed as follows:

sound pressure: $P_1 \{\exp(-jkx) + \alpha \exp(jkx)\}$

particle velocity: $V_1 \{\exp(-jkx) - \alpha \exp(jkx)\}$

Those equations are the same as those in the case

where the duct is terminated by an impedance $Z = \rho c(1 + \alpha)/(1 - \alpha)$. That is, to radiates secondary sound proportional to the incident sound is equivalent to the termination by an impedance. And the primary sound is completely canceled when $\alpha = -1$.

The above description indicates the possibility of active noise control by the active control of the internal impedance of a loudspeaker.

When a loudspeaker is set in a duct and the impedance of the loudspeaker is made reactive by the active control, the loudspeaker can act as a compliance and the system composes a low pass filter. And the cut off frequency of an acoustic filter type

(a) Geometry of the primary sound source "+" and the additional sound source "-" on an infinite baffle board.

(b) The attenuation of radiated sound power by setting additional source(s) for the arrangements shown in (a) where the volume velocity of the additional sound source is the same as that of the primary source except for the sign.

Fig. 1 Numerical investigation of the decrease in the sound radiation by setting additional source close to the primary sound source.

silencer can be decreased by the active control of the impedance of loudspeaker. That is, the loudspeaker can enlarge the effective volume of the cavity of an expansion type silencer when it is set in the cavity.¹²⁾

But, an effective noise suppression can not be expected by making the internal impedance of loudspeaker small when the loudspeaker is set in a big space. For example, a loudspeaker suspended in a room or a loudspeaker set on a broad wall has a very small radiation impedance at the low frequency range and the sound absorption by such the loudspeaker is trivial.

It is also an effective method of noise control to make the radiation impedance of the noise radiator small. The active control of radiation impedance is realized by setting a secondary sound source close to the noise radiator. Figure 1 shows the change in the radiated power by setting a secondary source close to the primary source. The distance between the primary source and the additional source should be shorter than a quarter wavelength and the radiated power is remarkably attenuated at the lower frequency range when the secondary source is set on the center of the primary source.¹³⁾

4. NOISE REDUCTION BY CONTROL OF DIRECTIVITY PATTERN

It is sometimes a useful method to control directivity of radiated noise as the noise problem is solved if the radiated noise is directed only to a non-res-

idential area. The noise control by use of the control of directivity pattern will be introduced here referring the active control of transformer noise.^{7,14)}

The transformer noise is composed of discrete frequency noise and the random noise. The former noise is caused by the magneto-strictive vibration of iron core and the latter by the cooling fan. The former one is composed of even numbered harmonics of power frequency and stable both in frequency and in amplitude. This type of steady sound can be frequently an object of complaint as it has a special sound quality. The stability of the sound makes the analogue control possible.

Figure 2 shows the outline of the system. The directivity pattern is controlled by use of additional loudspeakers surrounding the power transformer. The loudspeakers are driven by the signals which is synthesized from the waveform of the power line. The amplitude and the phase of each frequency component are controlled so as to make the power sum of the output of monitor microphones set on the field minimum by the analogue adaptive controller. The system is composed of three controllers, three microphones and three loudspeakers. The amplitudes and the phases of the frequency components up to 400 Hz are controlled.

Figure 3 shows the transient characteristics of the system. The system reaches the final state in 20 seconds after switch is turned on. The largest attenuation in sound pressure level is observed in 100 Hz component. Figure 4 shows the spatial

Fig. 2 Schematic diagram of transformer noise control system by use of adaptive directivity controller.

Fig. 3 Changes in the overall noise level, 100 Hz component and the control voltages with time. The controller is turned on at T_1 and off at T_2 .

Fig. 4 Directivity pattern of the transformer noise in horizontal plane obtained experimentally. The thick line stands for uncontrolled and the broken line for controlled. Three microphones and three loudspeakers are used.

distribution of the sound pressure level on a semi circle of 10 meter radius. Using three monitor microphones, the sound pressure level within 30 degrees decreases more than 10 dB. But the sound pressure increases in some direction. More loudspeakers and monitor microphones will be necessary to decrease sound pressure level in a wider angle. The loudspeaker interval should be less than a quarter wavelength. It might give a practical limitation of the use of this system.

The method described above is the control of

noise radiated into open air by the directivity synthesis. The directivity synthesis can be effective also for the reduction of noise in the signal picked up by a microphone system. That is, when the noise comes from one direction, the S/N of the picked up signal may be increased by making a dip in the directivity pattern in the direction of incident noise.

The directivity pattern can be arbitrarily controlled using a number of microphones. A new technology for adaptive control of the directivity pattern is necessary as the direction of incident noise changes usually. The AMNOR system is developed for such the case. In the AMNOR system, the direction of low sensitivity is controlled to make the output noise level minimum.^{15,16)}

5. DECREASE OF CLOSED LOOP GAIN FOR STABLE CONTROL

In the active control of sound in a space, a signal to drive the secondary sound source is synthesized from the signal of the primary sound source and the noise from the primary source is canceled by the sound radiated by the secondary source. The system can be unstable if the sound radiated by the secondary sound source is feedback to the source microphone to pick up the sound signal radiated by the primary sound source. The instability is caused by forming a closed loop through the

acoustic path from the secondary sound source to the source microphone. Various methods are proposed to make the system stable.

In the control of transformer noise described in the previous section, the driving signal of the secondary source is synthesized by the signal in the power line. The sound radiated by the transformer is not used in that case. Therefore there is no closed loop in the system. The stability of the system is thus assured.

In the case of duct noise control, the method setting two microphones at the points symmetrical to the secondary source¹⁷⁾ is an effective example. Some varieties are proposed on the arrangements of the microphone(s) and the secondary source(s).¹¹⁾ The acoustic feedback can be diminished setting the secondary source outside of the duct end.^{18,19)}

When the noise is radiated by the vibration of a stiff body, the formation of the closed loop can be avoided using the vibration signal to synthesize the signal to drive the secondary sound source. Even if the body radiating noise is shaken by the sound radiated by the secondary source, the gain of the closed loop can be made sufficiently small. When the noise is produced by the vibration of motor and/or compressor, the stable control of noise by this method is possible. This principle is effectively used for a home use refrigerator.²⁰⁾

The stable control is easy if the purpose is to reduce noise in the electric signal picked up by a microphone in a noisy environment. The waveform to cancel the noise in the microphone output is synthesized by a signal picked up by another microphone set in the noisy environment. And the cancellation is carried out at the electric terminal. The canceling signal is not radiated and no feedback loop is formed in this case. Therefore, the system is stable. The remaining problem is to reduce the objective signal in the output of the source microphone to pick up the noise.

When the noise is radiated by the vibration of a panel, the objective sound can be clearly picked up without attenuation by the cancellation using the vibration wave form for the synthesis of the signal for cancellation.^{21,22)} In this case, the canceled noise should be the signal coherent to the vibration of the panel.

The experiment was carried out using two kinds of plywood panels for the noise source, one of which the thickness is 5 mm and the other one 20 mm.

Fig. 5 Schematic diagram of the experimental system for the active suppression of noise in microphone output caused by panel vibration.

Fig. 6 Changes of noise spectrum in microphone output.

Figures 5 and 6 shows the outline of the experimental set up and results of the experiments. As seen in the figures, a large attenuation is achieved in the case of thick panel but there are many narrow frequency bands of little attenuation in the case of thin panel. It was made clear by the further investigation that the cancellation is incomplete at the frequencies where the point of vibration pick-up coincides with one of the nodal lines. The cancellation signal must have all frequency components that exist in the noise.²³⁾ When there remain some frequency components which are not canceled, the use of two or more vibration pick-ups is effective. Using some pick-ups, the remaining frequency components can be canceled with the signals synthesized from the signal picked up by the other vibration pick-

up.²²⁾

6. THE USE OF A FINITE IMPULSE RESPONSE FILTER

A finite impulse response filter (FIR filter) with many coefficients is convenient for the synthesis of signal to drive the secondary source, because a filter with complicated characteristics is required for the cancellation and any characteristics can be realized by the FIR filter. Figures 7 and 8 show the schematic diagram of an FIR filter and an active noise control system using FIR filter for the synthesis of signal to drive the loudspeaker to radiate canceling sound. It is necessary for the noise cancellation that the transfer function of control circuit is equal in magnitude and inverse in phase to the transfer function Z_a of the acoustic transmission path from the noise source signal pick-up point to the objective point. The transfer function of the control circuit is the multiplication of the transfer function of the FIR filter Z_f , that of the electric circuit including microphone Z_e and that of the loudspeaker Z_s . Therefore, the transfer function of the FIR filter should be:

$$Z_f = \frac{Z_a}{Z_e \cdot Z_s}$$

As shown in this equation, the inverse transfer function of the loudspeaker and of the electric

Fig. 7 Schematic diagram of an FIR filter.

Fig. 8 Schematic diagram of active noise control system by use of FIR filter for the synthesis of signal to cancel noise.

circuit are necessary.

A number of computation is usually necessary for obtaining the inverse transfer function, as the computation of the inverse matrix is necessary in that process. We proposed a simple experimental method for obtaining the necessary transfer function without complicated computation.¹⁸⁾ The filter coefficients can be determined with experimental procedure only. Using the FIR filter designed by this method, the duct noise is fairly well suppressed. But, there remains a practical problem which can not be ignored.

In the above-described system, the filter coefficients are fixed to those determined in the first place as shown in Fig. 8. But the changes in the environmental condition, such as the changes of temperature and air flow and/or movements of materials, require to change the filter coefficients for minimizing the noise. The system with fixed coefficients can not respond to these changes.

7. THE USE OF ADAPTIVE CONTROL

The problem described in the previous section is solved by the use of adaptive filter to which Widrow's contribution²⁴⁾ is highly appreciated. Figure 9 shows the schematic diagram of active noise control system for duct noise by use of adaptive filter. In compliance with the use of an adaptive filter, it becomes unnecessary to estimate the transfer function of the transmission path of noise for the design of active control system. It is confirmed experimentally that the coefficients of the adaptive FIR filter approach automatically to the optimum values in the passage of time, and the noise level is effectively reduced. It is also necessary in this case to

Fig. 9 Schematic diagram of active noise control system for duct noise by use of adaptive filter.

prevent acoustic feedback from the secondary sound source to the microphone to pick up source signal. This problem is solved by the use of two microphones at the points symmetrical to the secondary source and to use the difference of the outputs of two microphones as the source of synthesizing control signal.¹⁷⁾

The adaptive method for the determination of the coefficients of FIR filter is used for the experiments to reduce radiated noise by many researchers and the usefulness of the method is confirmed.^{25,26)}

The adaptive control algorithm is, of course, very useful for the control of sound in three dimensional space.^{27,28)}

8. CONCLUSION

The concept and the methodology of active control of sound and vibration is discussed with a brief review of old works. The contents are divided into the following six categories: the principle of active control, unified study by use of the concept of impedance, noise reduction by the control of directivity pattern, decrease of closed loop gain for stable control, the use of finite impulse response filter for the synthesis of the signal to drive secondary sound source and the use of adaptive filter.

The active control of sound and vibration is already put to practical use, but there remain many technical problems in the individual applications, especially in the technologies for stable control of wide area. The cost of the system will also be an important problem for applications.

We convince that the technology of the active noise control will show remarkable progress in the near future and will be used in many field in the problems which can not be solved by the conventional passive methods.

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