ACTIVE CONTROL OF ELEVATOR NOISE FROM VENTILATOR

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ABSTRACT

Noise emitted from an elevator ventilation duct into a car is reduced by using active noise control. This paper describes the problems inherent in duct design for active noise control, and the relationship between flow velocity, sound coherence in space, and the effect of noise reduction. By adopting the proposed technology, noise was reduced by 10 dB (35-500Hz) at the evaluation microphone point. The results obtained constitute a major advance toward the commercialization of elevators using active noise control.

1. INTRODUCTION

Elevators must run at ever-increasing speeds as the height of high-rise buildings increase. However, noise increases with speed, and this must be minimized to maintain passenger comfort. Ventilation ducts are one source of noise inside elevator cars. One of the authors has previously adopted active noise control with respect to compressor noise of a refrigerator[1][2]. As a result, he and his project members commercialized quiet refrigerators. The authors of this papers applied the same technology to reduce noise emitted into an elevator car through a ventilation duct[3]. This noise was generated by elevator operation and a ventilation fan.

The high-frequency components of sound from the duct are absorbed by sound absorbing materials inside the duct, but the low-frequency components are absorbed to a limited slight extent only by these materials. In contrast, active control reduces comparatively low-frequency noise.

Former noise reduction methods were passive, using only sound-absorbing and sound-insulation materials. On the other hand, active noise control emits sound which is anti-phase to that of the noise sources, and cancels the noise by interference. This idea has been proposed since old times, but the comparatively advanced technologies necessary for its practical application were not available. However, with the recent progress in wave signal processing and digital signal processing, it is now possible. Using active noise control to achieve noise reduction in elevators was difficult for various reasons. This paper describes the problems inherent in duct design for active noise control, and the relationship between flow velocity, sound coherence in space and the effect of noise reduction.

First, the theoretical background to active noise control is explained. Second, the practical use of active noise control in noise reduction and its application to an elevator are shown.

2. HISTORICAL BACKGROUND

Lueg acquired a US patent for active noise control technology in 1936[4]. A lot of research into noise reduction was conducted in the 1960's, focusing on various applications including transformers, periodic sound, etc. Thus, active noise control does not seem like a new technology. However, achieving the desired effects in actual applications was difficult with only this fundamental knowledge. This is because noise is not a simple frequency component. Rigid adjustment of amplitude and phase are also necessary. Furthermore, the adjustment must be changed according to the conditions. Thus, comparatively advanced control technologies are necessary. In recent years, research from a new view point has proceeded briskly with the development of high speed computation devices, especially DSP (Digital Signal Processor), and with progress in wave processing and digital signal processing. Recently, there have been several attempts to commercialize this technology [5], and active noise control has been realized in some applications.

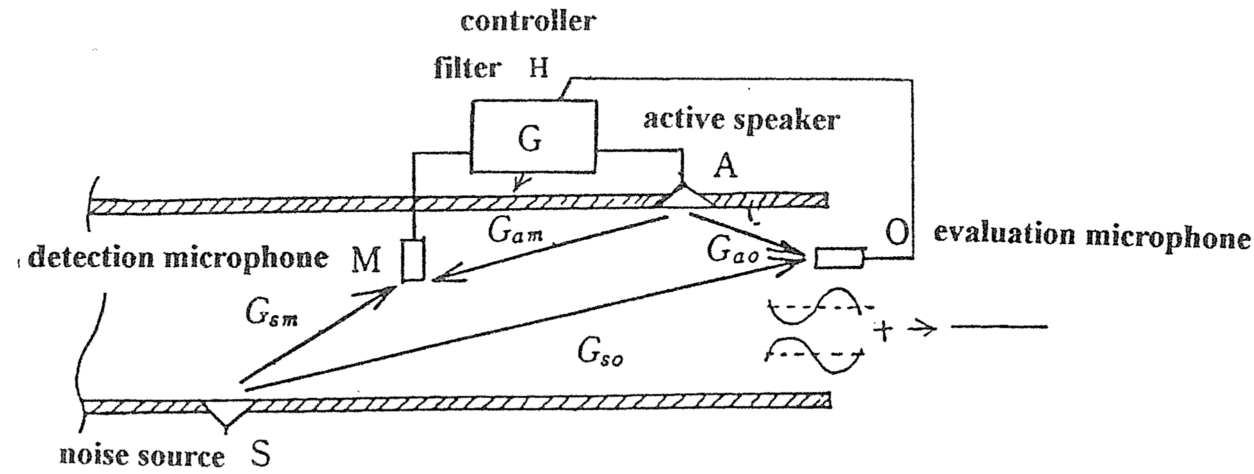

Fig. 1 Schematic drawing of the configuration of active noise control using adaptive control

3. BASIC PRINCIPLES AND TECHNICAL PROBLEMS

3.1 Basic principles

Sound is a kind of waves. Therefore, it disappears if a secondary sound that is anti-phase and of the same amplitude is superimposed so as to interfere with it. A conceptual configuration of an active noise control system is shown in figure 1. Signals from a detection microphone M convolute with filter coefficients H and are output from a control speaker A so that the output sound becomes anti-phase with the sound from the original source at the object point. A sound from the source S and a sound from the control speaker A interfere and the sounds disappear at the control object point. The cancellation quantity is monitored by the evaluation microphone O installed at the object point. Adaptive control changes the coefficients G of the filter H to minimize the noise.

3.2 Energy supplies and losses

How is the sound level is reduced by adding energy from a secondary sound source? Needless to say, this does not contradict the law of energy conservation. There are several cases depending on the conditions:

(1) The outside sound level from an opening decreases but the inside sound pressure increases.

In this case, either the sound is altered to heat energy by the sound absorption of the inside parts or it is emitted from the opposite side opening. This happens when the distance

between the two sound sources is longer than the wavelength, for example, when the original sound source is located at the other end of the opening of a long duct and the secondary sound source is located midway along the duct.
(2) The radiation impedance of the sound source decreases and the sound emission quantity changes.

This happens when the distance between the original sound source and the secondary sound source is shorter than the wavelength of the sound. At this time, the sound radiation efficiency of the source itself changes and the sound power decreases.

3.3 Application problems

An advantage of active noise control is that it is effective at comparatively low frequencies, at which noise reduction by using sound absorption and sound insulation material is difficult. However, there are other problems:
(1) Compensation of control coefficient
(2) Acquisition of one dimension
(3) Acquisition of real time
(4) Prevention of hawling
(5) Correspondence to characteristic changes of the system
(6) Acquisition of spatial coherence of sound at a high level

Solutions to these problems are explained below.
(1) Compensation of control coefficient

It was expressed anti-phase for easiness in the preceding sections, but it is not sufficient to simply reverse the signal and output. This is because the additional sound source is not ideally located at the control object point. Because of a lag of position and an influence of reflection, fairly precise compensation corresponding to the transfer function is necessary. The authors call these compensation values "control coefficients".

The setting of the control coefficients is explained by using the system of figure 1. The components are a sound source S, a control speaker A, a detection microphone M, an evaluation microphone O and transfer functions between the devices like Gsm, Gso, Gam and Gao, in which attached characters correspond to the symbol of the devices. In this case, it is sufficient for the signal of the evaluation microphone to be set to zero for noise cancellation. Therefore, the transfer function G, by which the signal from the detection microphone should be multiplied, is given by the equation:

$$G = \frac{G_{so}}{G_{sm}G_{so} - G_{sm}G_{ao}} \qquad (1)$$

(2) Acquisition of one dimension

A sound spreads in three dimensions. Therefore, if the total sound is made smaller at a certain point because of the two sounds are in anti-phase, it may become bigger at another point because the two sounds are in the same phase. However, this phenomenon does not occur if the sound path is made longer and the diameter of the open section is shorter than the wavelength of the sound, which is accomplished in many air conditioning ducts. The ducts are one dimensional from the acoustical point of view. When a sound wave spreads in one dimension, the sound is uniformly small downstream from the sound control point. Thus, noise cancellation by active control is realized. Active noise control in a duct was comparatively ease to realize in this case. The application to a duct was firstly considered.

(3) Acquisition of real time

In the previous section, the compensation of the control coefficients is explained as a transfer function in the frequency domain. However, actual control is performed in the time domain as follows. A digital filter is used to output sound from a secondary source in real time. As the convolution is calculated in the digital filter, the processing is expressed as a discrete system by the equation:

$$y(n) = \sum_{k=0}^{n-1} x(n-k) \cdot h(k) \qquad (2)$$

The processing is discontinued after a limited number of n points in this equation. Therefore, it is called a finite impulse response (FIR) filter. The impulse response function, h(k) is almost equivalent to the inverse Fourier transform of G.

What is meant by "almost" is explained as follows. In same cases, the coefficients of the inverse Fourier transform of G appear in the negative time range. The system is physically impossible to compose. The result appears after the cause in a physically possible system, i.e. the result does not precede the cause. This is called the law of causality. The following matters are necessary to fill the law of causality.

To simplify the control, the signal must be processed and the secondary sound must be output while the original sound passes from a sensing microphone to an active speaker (Figure 2). The distance from the sensing microphone to the active speaker must be sufficiently long.

Understandably from equation (2), the digital filter is performs only product-sum operations and delays. Real-time control is linked to the computation speed. The DSP is optimal for this computation.

To summarize, the use of high-speed DSP and a sufficiently long duct are needed to secure real-time control.

(4) Prevention of hawling

Hawling is an oscillating phenomenon that is sometimes observed when a microphone and a speaker put close together. As shown in figure 3, a control sound source and a sensing

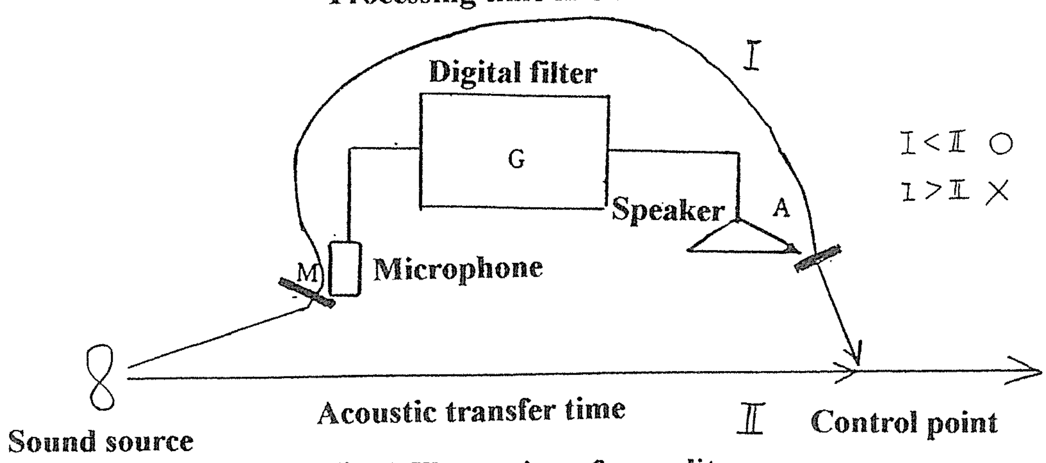

Fig. 2 Illustration of causality

microphone make a closed loop in a normal active noise control system, thus causing oscillation. The system oscillates when the loop transfer function of this closed loop exceeds 1. Oscillation must be avoided.

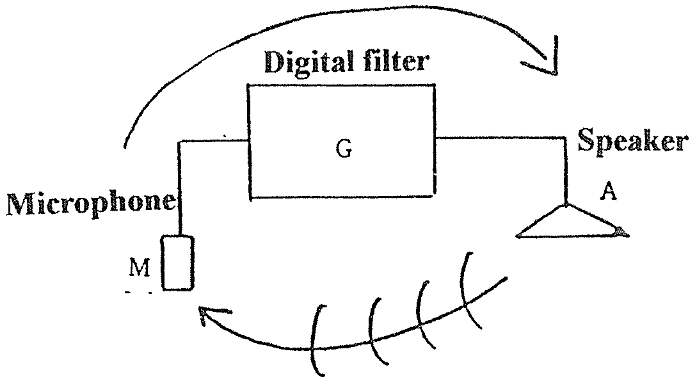

Fig. 3 Hawling phenomenon

(5) Correspondence to characteristic changes of the system

The coefficients multiplied by the signal have already been mentioned in the proceeding chapter. However, coefficients are not always constant. For example, they vary according to the temperature inside the duct, the flow velocity and the other factors. A noise cancellation effect is not achieved in many cases. The coefficients must be varied corresponding to the temporal changes of the transfer functions. Adaptive control is used for corresponding to the characteristic changes of the system. An evaluation microphone is put at a control object point. The coefficients are changed to optimize the control effect. The Least Mean Square (LMS) method is often used as the algorithm. The algorithm updates the coefficients by using the following equation so that the error approaches zero. The new filter coefficients are expressed in this equation by using the filter coefficients of the previous time[6].

$$h_{new} = h_{old} - \mu e s \qquad (3)$$

Where,

μ : Step size parameter

s: Vector of input signal

e: Monitoring signal of evaluation microphone

It is considered that correct values are not obtained while the coefficients are big and the system changes them quickly, but it is considered that the coefficients approach the correct values when the error becomes small and the system reduces their changing rate.

(6) Acquisition of spatial coherence of sound at a high level

Noise reduction is not attained if the system is controlled by using a sound that is unrelated to the control object point. In other words, the system can not control if the coherence between the sound at the sound detection point and that of at the control object point is not high. Whether the spatial coherence of the sound is high or not is in active control. However, flow is disturbed at bends in duct, thus reducing the coherence. Spatial coherence of a sound is also reduced if the flow velocity is high. This is because local pressure fluctuations are produced at each point and a microphone picks them up as sounds. Turbulence of flow at the bend must be decreased and the flow velocity must be made slow.

4. APPLICATION TO ELEVATOR VENTILATION DUCTS

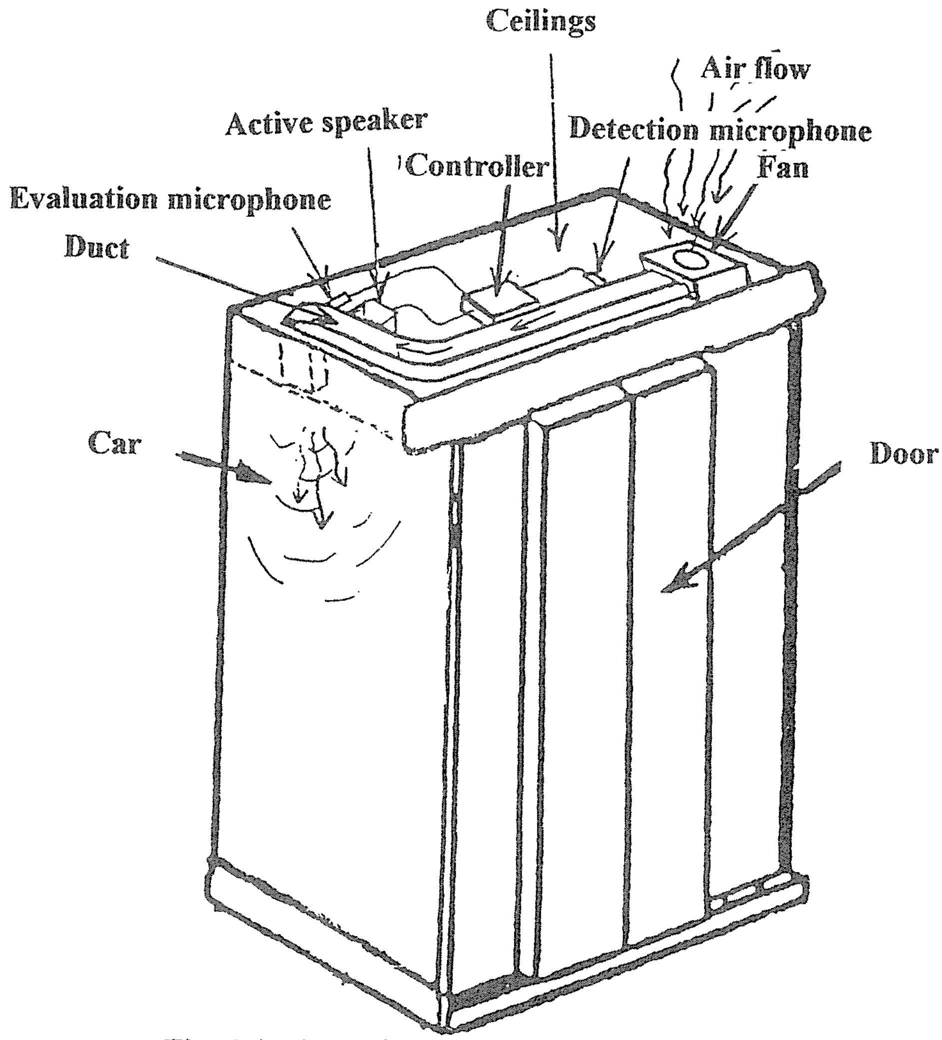

Fig. 4 Active noise control system for elevator

There are several problems in the realization of active noise control, as it explained in the chapter of basic principles and technical problems. Solutions to these problems are given in this chapter.

4.1 Design of a duct

Figure 4 is a schematic drawing of a ventilation duct designed for active noise control. This paper explains the critical importance of duct length and flow straining plates to the design.

4.1.1 Duct length

From the viewpoint of causality, the duct should be sufficiently long. More simplify, to execute control, within the time it takes for sound to travel the distance from a sensing microphone to an active speaker, the signal has to be processed and sound output from the speaker. The effect on control of changing the distance from the speaker to the microphone is shown in Figure 5. The duct needs to be sufficiently long in consideration of the time required for signal processing by a low pass filter, delay of the speaker, and so on. The delay of a low pass filter and a speaker is longer than the computation time of DSP. In this case, Figure 5 shows that a duct length of more than 1300 mm is necessary. This value can be estimated from the delay of the processing system. For example, if signal processing time is 3.5ms, the distance from the sensing microphone to the active speaker needs to be more than 1.2m [= 340m/s (speed of sound) x 0.0035s].

4.1.2 Strainers

On the other hand, noise control cannot be executed without high-level sound coherence between the sensing point and the control object point. For active control, it is important whether sound spatial coherence is high or not. As the flow is confused at the bends of the duct, coherence is at a low level. Strainers are installed in the bend (Figure 6). Implementation of strainers is desirable since they help to secure flow amounts by reducing flow resistance.

4.2 Relation between fluid flow velocity and coherence

Flow velocity effects sound coherence in space. To achieve high coherence, flow velocity in the duct is reduced to a relatively low level, and the duct should be short in order for the sensing point to be near the control object point (Figure 7).

From the viewpoint of causality, the duct should be sufficiently long. Thus, determining the optimum duct length involves a trade-off.

Experimental results clearly indicate that spatial coherence of sound is at a low level if flow velocity is high. Coherence changes greatly in accordance with flow velocity. If the flow velocity is under 6m/s, coherence is sufficiently high for active control, as shown in Figure 8. The reason is that a local sound caused by turbulence is emitted if flow velocity is high. If the duct size is widened to 130mm x 130 mm, flow velocity becomes 6m/s and high coherence is realized.

It is better for the flow velocity to be slow, the distance between the microphones to be short and the number of bends to be few in order to achieve high-level coherence.

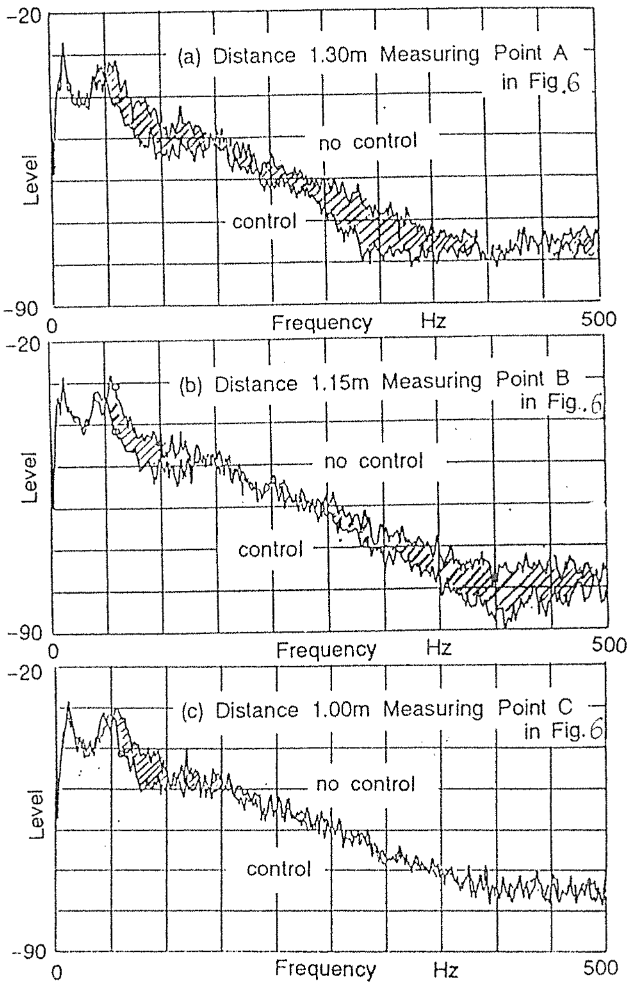

Fig.5 Relationship between the ANC effect and *the distance from sensing microphone to active speaker*

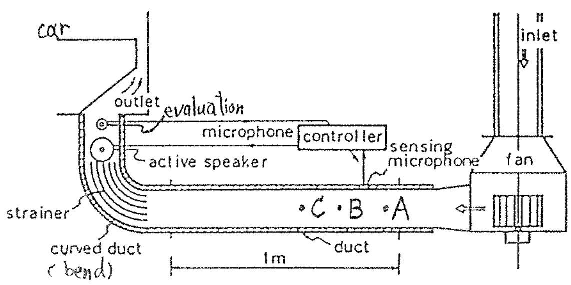

Fig.6 Control system and duct

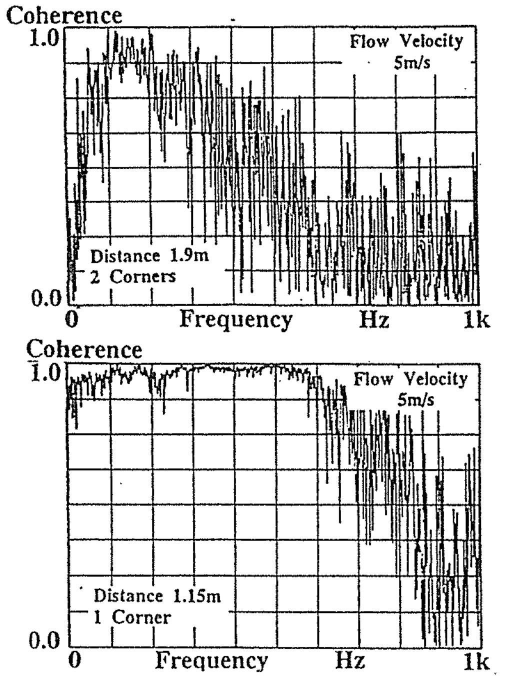

Fig.7 Relationship between coherence and the distance from sensing microphone to evaluation microphone

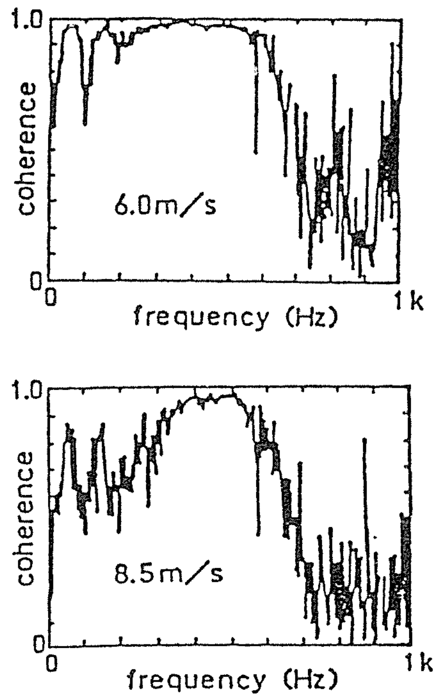

Fig.8 Difference of coherence in relation to flow velocity

4.3 Configuration of the controller and the system

The controller is composed of an FIR filter using adaptive control by an LMS algorithm. The method is as explained in the chapter on basic principles and technical problems. An echo canceling method is used to prevent hawling.

4.4 Active noise control and stuffy sound

There are plural numbers of natural frequencies in the space of an elevator car. Therefore, if there is a sound source with the frequencies close to these natural frequencies, it resonates and the sound becomes a rasping, stuffy noise. Therefore, canceling sounds of these frequencies by active noise control is effective on auditory. In the 125 Hz band, noise inside the car is at a high level, so reduction of the low frequency range is important. A speaker that emits sound at under 130 Hz, that is, at a sufficiently low frequency, was used.

4.5 Noise reduction effects

The measuring result at the position of the evaluation microphone is as shown in Figure 9. A 10dB reduction effect was obtained at 35～500Hz. Thus, the effect of active control was confirmed.

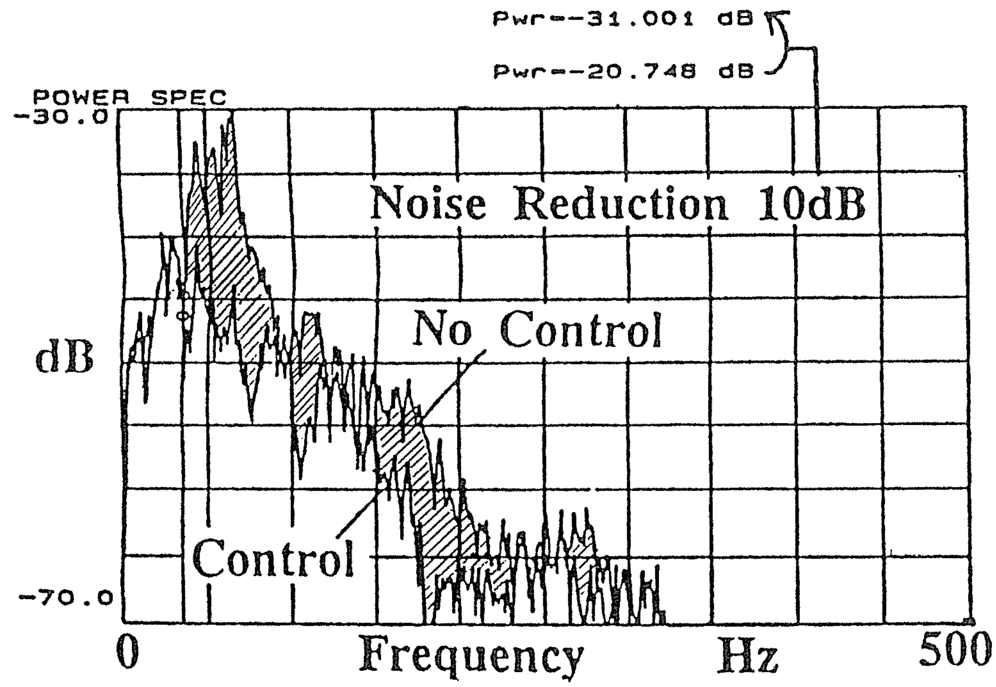

Fig.9. Effect of ANC at evaluation microphone

5. FUTURE DEVELOPMENTS

Basic principles of active noise control, technical problems in applying active noise control to the noise reduction of an elevator ventilation duct are described. The sound transfers in one dimension. However, the control of in a three-dimensional sound field must be considered for extending applications. Noise control by multi-dimensional signal processing using many sensors and active speakers became a new theme. The development of this technology will proceed for indoor (dwellings / automobile / airplane) noise control.

6. CONCLUSIONS

Active noise control techniques were adopted to minimize elevator noise emitted from the ventilation duct into the car. Through an investigation of several problems related to design, noise was reduced by 10dB at the evaluation microphone point. The authors commercialize elevators using active noise control.

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BIOGRAPHY

Katsuyoshi Nagayasu was born in Tokyo, Japan in 1953. He received the B. E. degree in mechanical engineering from Tokyo University in 1977 and joined Toshiba Corp. in the same year. He is now senior research scientist at the Research and Development Center, Toshiba Corporation. His research interests include application of signal processing, acoustic and vibration analysis, and control system design.

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