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ANC System for an Insertion Machine

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Active noise control (ANC) technology is based on canceling sound waves. Noise is actively reduced by adding a sound wave of the same amplitude but phase shifted by 180 degrees to the original sound wave. Using a digital signal processor (DSP), we developed an ANC system.
This report explains the basic concepts of noise control systems and outlines active signal processing. It also describes the features and the results we obtained with our experimental ANC system for insertion machines.

1. Introduction

Amidst the mounting concern for environmental protection worldwide, a comprehensive package of solutions are being sought for problems such as noise pollution, air pollution, and river pollution.

Since 1968, when noise control regulations came into effect, noise control has progressed significantly in Japan. Initially, administrative bodies tackled environmental noise pollution from factories or construction sites adjoining residential areas and automobiles speeding along adjacent highways. The emphasis has now shifted to creating a higher quality of living.

Since 1983, we have been developing sound image control to control the sound heard by regulating the phase and amplitude of musical signals with a DSP, and exploring ways to sound image control and sound field control to enhance the feeling of presence. We aim to reduce noise by controlling the phase and amplitude of signals in real-time.

This paper describes noise control techniques and an environmental-noise control experiment conducted in 1991 with electronic component insertion machines.

2. Noise reduction

Noise is reduced by passive or active methods.

Passive methods, which has been widely used for noise reduction, includes erecting sound-insulating walls along highways, shielding noise sources with concrete blocks or similar objects, installing sound-proofing windows, and using earplugs.

An example of the simplest passive method is a noise source surrounded by passive sound-proofing materials of a certain mass (Fig. 1). The effectiveness of the passive members is shown by the transmission loss, which is a measure of the external leakage of sound emitted from the noise source. The higher the transmission loss, the more useful the passive members are in reducing noise. The transmission loss is also restricted by the mass law which indicates that sound is reduced efficiently using a large volume of high-density, heavy passive members, and that passive control is more effective at high frequencies since less passive sound-proofing material is needed.

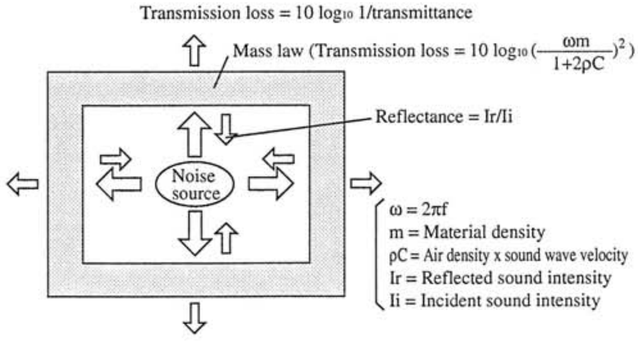


Figure 1. Basic passive method

Active methods involve cancelling noise through sound wave interference by generating a sound opposite in phase to the noise (Fig. 2). In this diagram, the noise signal that has been collected earlier with a microphone is regulated to the phase opposite to the noise at the loudspeaker position through arithmetic processing to interfere with the noise, thereby reducing the subsequent propagation of the noise.

Active methods reduce low-frequency noise, but have a limited effect on high-frequency noise.

Passive and active methods are complementary and cover different frequencies (Fig. 3). Efficient noise reduction requires selective use of these two technologies. A low-cost, compact, and lightweight system must reduce high-frequency noise with a minimum amount of passive

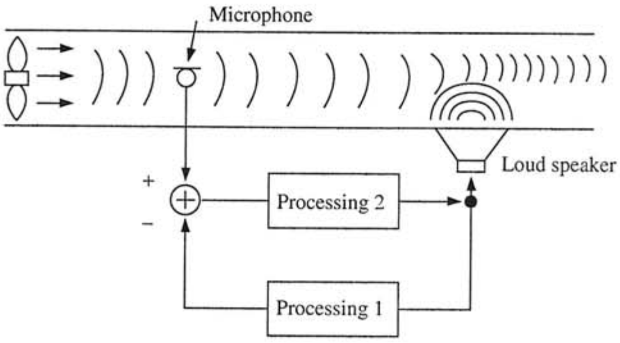


Figure 2. Typical active method

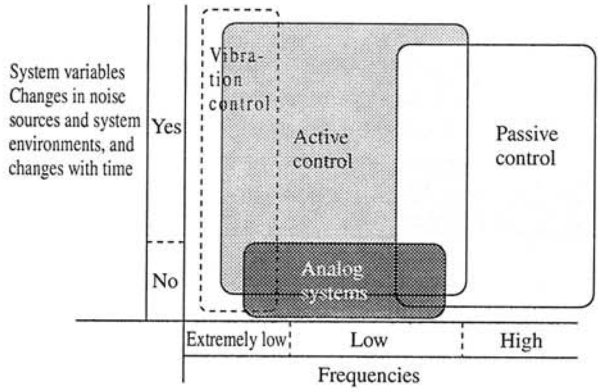
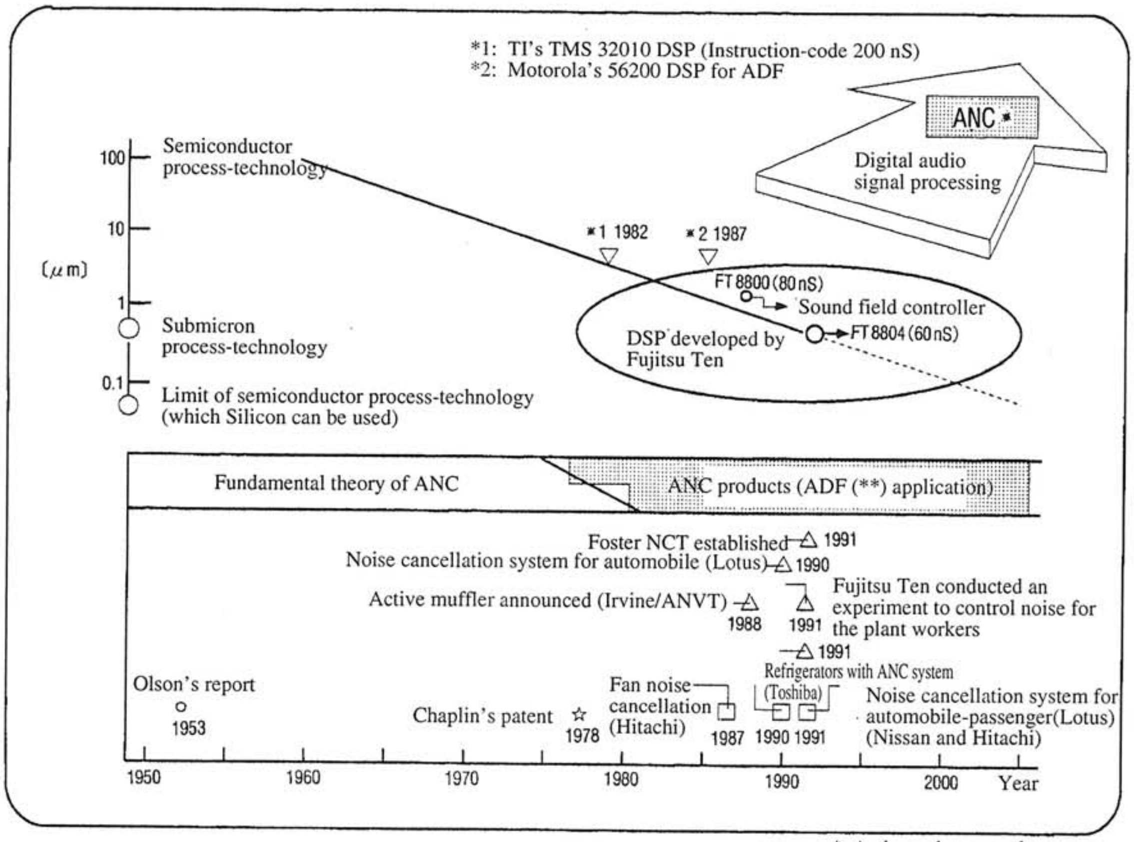


Figure 3. Relationship between active and passive methods



* Active noise control
** Adaptive digital filter

Figure 4. Active noise control technologies activity

sound-proofing materials and use active methods to reduce low-frequency noise, which is difficult to reduce with passive methods. The line of demarcation between active and passive methods is said to be 500 to 700 Hz.

In 1953, a paper (1) describing the fundamental principles of active control was published and, in the 1980s, several basic patents were registered. Active control was not implemented, however, until a few years ago because of the lack of supporting LSI technologies (Fig. 4). Since 1987, some manufacturers have been developing DSP-based products.

3. Noise reduction system

We fabricated an experimental single-microphone single-loudspeaker feedback noise control system to deal with noise at our Nakatsugawa Plant. The system is designed to reduce noise collected at the microphone. A system is installed at each chip component insertion machine to reduce environmental noise.

The configuration, specifications, signal processing functions, and features of the system are described below.

3.1 System configuration

The system contains five units (Table 1).

An operation control panel provides central and concurrent control of multiple systems (Fig. 5).

Table 1. System function

Name of unit	Function
① System power supply	Supplies 12 VDC to ②, ③, and ④.
② Sensor microphone	Collects noise and outputs it to ③.
③ Controller	Uses an input signal from ② to generate a cancellation sound and outputs it to ④.
④ Power amplifier	Amplifies the power of the signal input from ③ and outputs it to ⑤.
⑤ Loudspeaker	Converts the electrical signal from ④ to sound.

The sensor microphone and loudspeaker should be resistant to environmental conditions, such as, temperature, gases, and drafts, since they are installed near the noise source.

Figure 6 shows the controller, and Figure 7 shows the control panel.

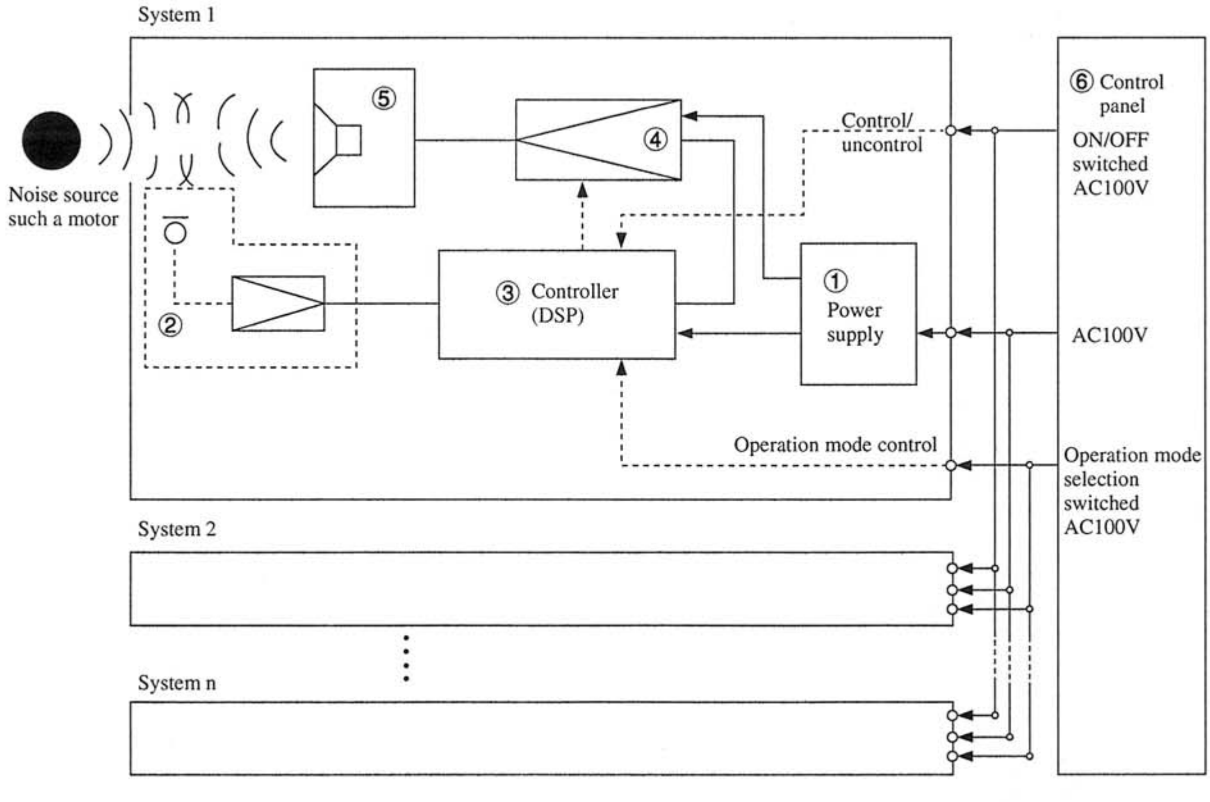


Figure 5. Structure of ANC system

3.2 Specifications

Table 2 summarizes the system specifications.

The high-frequency limit is imposed by physical constraints on space sound cancellation; the shorter the cycle is, the more difficult it becomes to achieve a uniform sound cancellation effect throughout a given space. The limit is equivalent to that of the general noise control equipment.

Since low frequencies come from the loudspeaker's sound-pressure limit, the low-frequency response is improved when the loudspeaker is tailored to low-frequency applications. The sound-pressure limit is imposed by the loudspeaker's reproduction capability. A large loudspeaker is required to reduce noise having a low frequency and a high sound-pressure. The effectiveness of noise cancellation is influenced by the level and kind of the noise concerned. The system will have a greater noise cancellation effect on steady periodic noise.

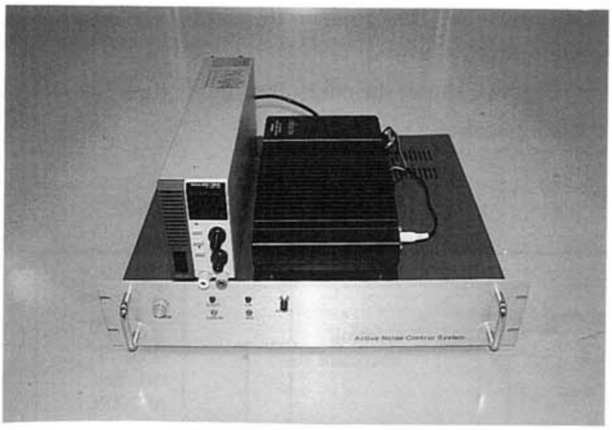


Figure 6. Controller of ANC system

Figure 7. Control panel

Table 2. System specifications

Item	Specification	Remarks
Control frequency	100 HZ-500 HZ	
Control sound-pressure	Up to 105 dB SPL (sound pressure level)	
Standard effect	10 dB-30 dB	Rate of measurement change at the sensor microphone point: 10 Hz/s or less
Control terminal input voltage	AC100 V	
Guaranteed operating environment	Free from corrosive substances	
Operating temperature	–30°C to 85°C	
Operating humidity	85% or less	Relative humidity
Guaranteed operating time	About 5000 h	
Supply voltage	AC100 V	
Power consumption	50 W (100 V)	
Weight	30 kg	
Dimensions	W452 × H417 × D350	Unit: mm
DSP	24-bit floating point calculation	FT8802
ADC/DAC	Fixed 16 bits	
Sampling frequency	1.5 kHz	

3.3 Signal processing functions

The system uses DSP-based adaptive signal processing to generate a precisely controlled cancellation sound (Table 3, Fig. 8)

3.3.1 Signal processing function

The controller that generates the cancellation sound uses an adaptive digital filter to accommodate changes in the noise source condition, such as the noise frequency and amplitude. The learning identification method (LIM), with update constants associated with the noise source level, provides stable control. The transfer function HD1 is used to apply the adaptive filter to noise control so as to correct control delays caused by the cancellation loudspeaker system, such as the analog unit, loudspeaker, space, and microphone. Transfer function HD2 prevents the cancellation sound from wrapping around the sensor microphone and provides a stable reference signal.

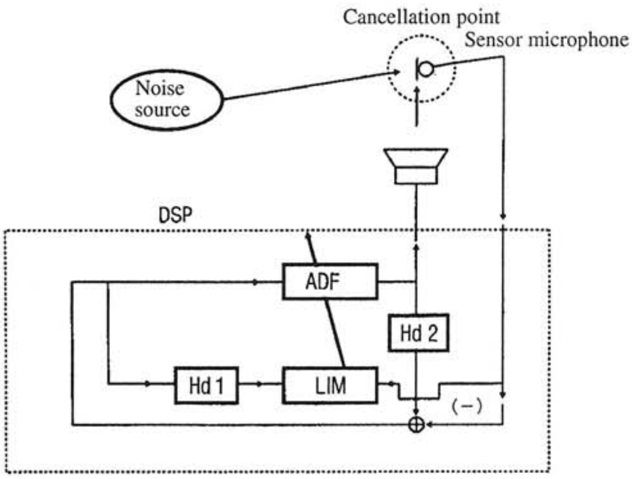


Figure 8. Signal processing

Table 3. Signal processing functions

ADF: Adaptive digital filter	Minimizes the noise at the sensor microphone for each noise source.
LIM: Learning identification method (= NLMS)	An adaptive digital filter coefficient update algorithm alters the update constant according to the noise level. It provides a steady adaptive speed when canceling a varying noise level.
Hd: Noise cancellation loudspeaker transfer function	Transfer function, from the DSP output to the DSP input through the DA converter, amplifier, loudspeaker, space, microphone, and AD converter.
Hd1: (= Hd) Pseudonoise cancellation loudspeaker transfer function	Adaptive filter coefficient update correction system (Adaptive filter application of filtered X)
Hd2: (= Hd) Pseudonoise cancellation loudspeaker transfer function	Feedback ANC system prevents cancelled noise from wrapping around the sensor microphone.

3.3.2 Adaptive filter

Adaptive signal processing allows the characteristics of a system to be altered during signal processing as needed. Such a system is called an adaptive filter, and the scheme of altering system characteristics is called the adaptive algorithm (Fig. 9).

If the response to the input signal $x(n)$ is $y(n)$, processing system parameters are automatically updated by using the difference (error signal) $e(n)$ from the desired response $d(n)$ to constitute an optimal system. The filter provides a transfer function similar to the transfer function Hc to obtain the desired response $d(n)$.

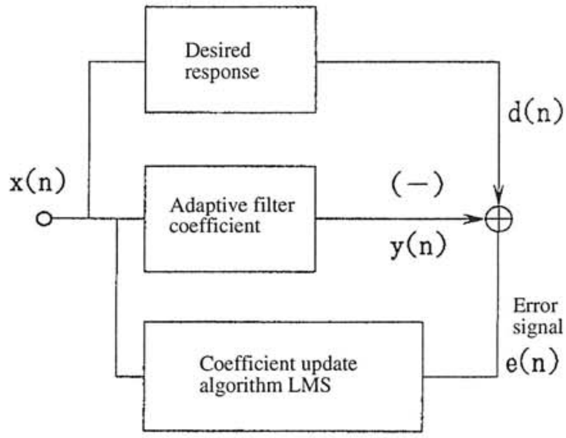


Figure 9. Adaptive signal processing

An adaptive filter serially adjusts the tap weight $\{h(k)\}$ to reduce the error signal.

If an FIR (nonrecursive) adaptive filter is represented as.

$$y(n) = \sum_{k=0}^{M-1} h(k)\, x(n-k) \qquad \cdots (1)$$

The error signal $e(n)$ is

$$e(n) = d(n) - y(n) \qquad \cdots (2)$$

The least mean square (LMS) algorithm, which is commonly used to derive the least error, is

$$h(k+1) = h(k) + 2\mu \bullet e(k)\, x(k) \qquad \cdots (3)$$

This algorithm can be normalized to the normalized LMS (NLMS), or LIM learning identification method (LIM), with the input signal. The NLMS provides a constant response rate even for varying noise signals.

3.3.3 Adaptive filter application

In an active control system a reference signal collected through a noise source microphone is subjected to DSP processing and cancellation sound generated from the loudspeaker to cancel the noise at the sensor microphone point (Fig. 10). A system model is shown in Figure 11.

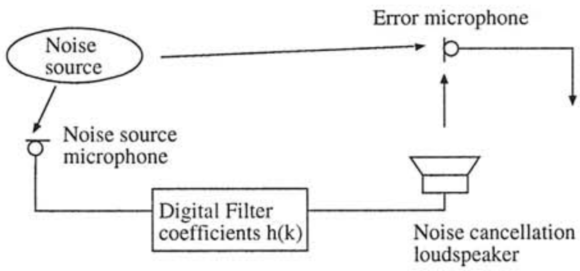


Figure 10. Basic adaptive system

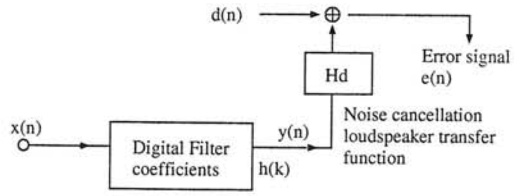


Figure 11. ANC system modeling

The sound pressure at the sensor error microphone is reduced, optimizing the digital filter's coefficients $h(k)$. If $h(k)$ and Hd in Figure 11 are interchanged (Fig. 12), adaptive filtering can be implemented.

When the LMS algorithm is used for the adaptive filter shown in Figure 12, the input signal $v(n)$ to the adaptive filter will provide the output signal of the filter Hd (Fig. 13).

$$v(n) = Hd \bullet x(n) \quad \cdots (4)$$

If Eq. (4) is assigned to the coefficient update formula in Eq. (3), the result is

$$h(k+1) = h(k) + 2\mu \bullet e(k)(Hd \bullet x(k)) \quad \cdots (5)$$

This algorithm is called the "filtered x" algorithm.

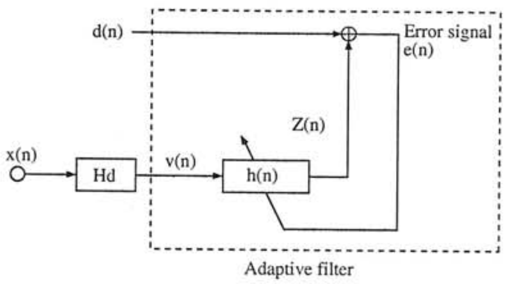


Fig 12. Application of adaptive filter

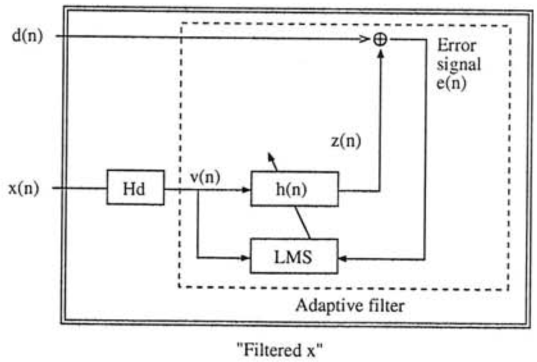


Figure 13. ANC system based on filtered X algorithm

Eq. (5) indicates that to implement an ANC system based on the filtered x algorithm (Fig. 13), a system like that shown in Figure 14 is required.

The loudspeaker transfer function Hd needs to be measured prior to activating the system.

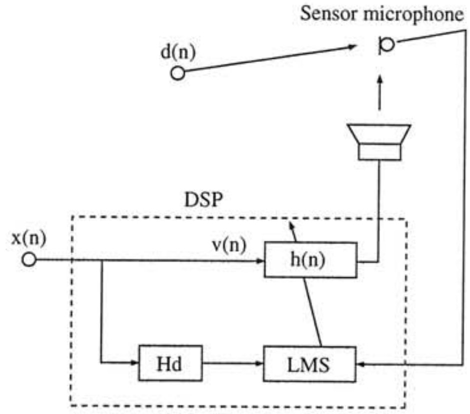


Figure 14. Adaptive filter for ANC system

3.3.4 Measuring the transfer function (Initialization, etc.)

As an impulse response, the loudspeaker transfer function Hd could be measured in various ways. This system uses an adaptive-filter based arrangement like that shown in Figure 15 to measure the loudspeaker transfer function Hd, which is an impulse response.

The DSP generates random noise as a reference signal, which is passed through a loudspeaker and a microphone to make $h(k)$ equivalent to Hd and activate the adaptive filter.

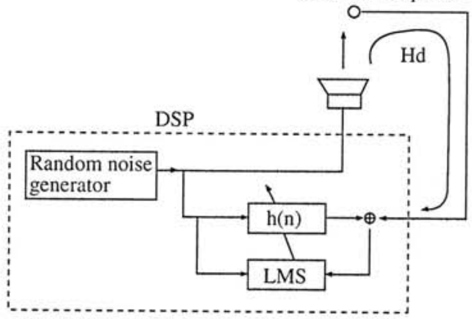


Figure 15. Measuring the transfer function

3.3.5 Application of a feedback system

The system shown in Figure 14 requires noise source and sensor microphones. Using a single microphone for both functions reduces the hardware and makes installation easier.

If the sensor microphone monitors the initial untreated noise, it can be used as a reference signal (Fig. 16). As noise cancellation takes effect, however, the sensor microphone signal decreases, eliminating the reference signal. The cancellation wave amplitude and noise cancellation effect thus decrease. Iterations of this operation cause system instability.

To maintain the cancellation wave, we used another transfer function (Fig. 17) to subtract the cancellation wave from the sensor microphone signal and provide a stable reference signal.

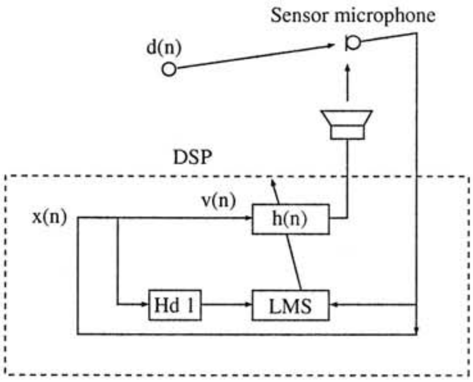


Figure 16. Feedback ANC system

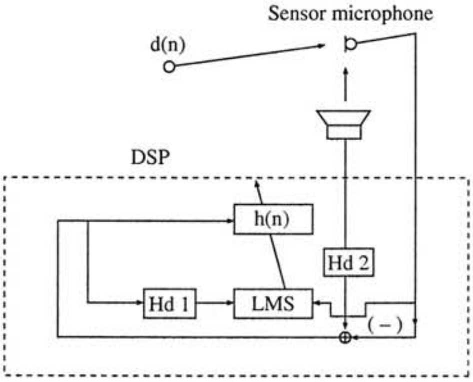


Figure 17. ANC system configuration for mechanical equipment

3.3.6 Features

The system features are summarized below.

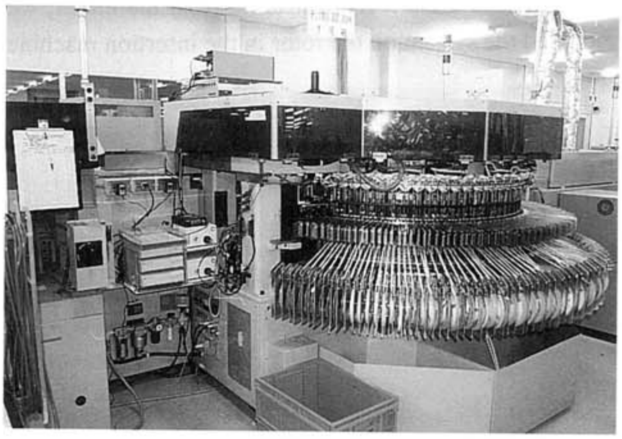
1) A single microphone that functions as both noise source and error sensors reduces the hardware.
2) Eliminating the noise source sensor also eliminates the need for a noise source signal, such as a motor rotation signal. This simplifies the installation.
3) Since noise at the noise cancellation position is used as a reference signal, noise other than that generated during motor rotation, such as harmonics, is also canceled.
4) The system is reprogrammable; it supports a loudspeaker transfer function measurement mode (initial setting) to deal with changes in the noise.
5) Using adaptive filters makes it possible to handle noise frequency and amplitude changes.

4. Sample implementation

We developed the noise control for the insertion machines at Fujitsu Ten's Nakatsugawa Plant.

4.1 Insertion machine noise

Noise generated from insertion machines at Nakatsugawa Plant (Fig. 18) consists of intermittent mechanical noise with relatively high frequencies, and low-frequency noise, such as that from the motor or transformer, which depends on the line frequency. Motor noise has a high sound-pressure at low frequencies (Fig. 19).



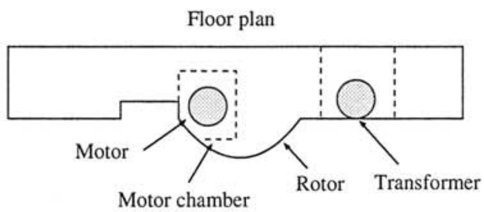


Figure 18. Insertion machine

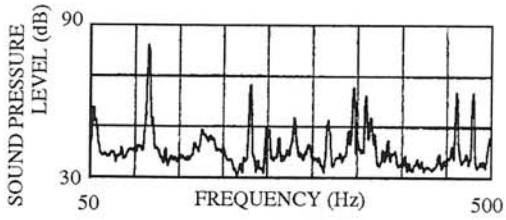


Figure 19. Insertion machine noise

Many of the workers at the plant use earplugs to protect themselves from noise. The earplugs, however, do not protect well against low-frequency noise generated from such motors. Hence, we aimed to reduce the low-frequency noise.

4.2 Noise control examples

Specific actions taken to deal with noise generated from insertion machines are described below.

4.2.1 Noise control system implementation

The motor is installed in the motor chamber at the bottom of the rotor (Figs. 20 and 21). Since heat considerations preclude the possibility of shielding by encapsulation, we used an active noise control system. To avoid the decrease in sound pressure caused by phase shifts, we placed the cancellation loudspeaker and sensor microphone as close as possible to the vacuum-pump motor during system installation.

To avoid the effects of heating from the motor, we mounted the system on the rotor in the insertion machine (Fig. 22).

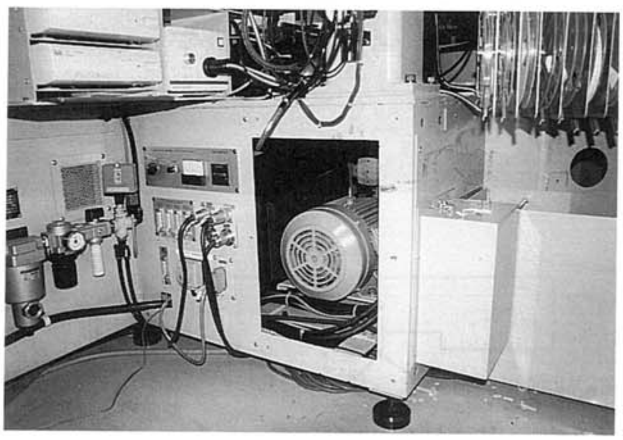


Figure 20. Motor chamber

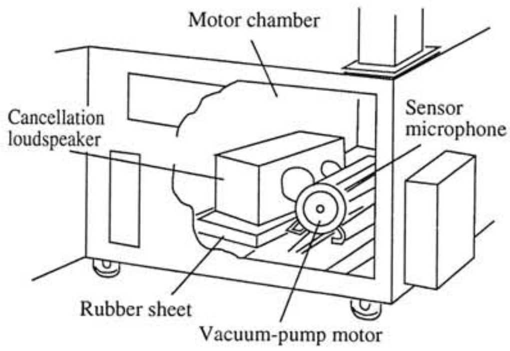


Figure 21. Motor chamber structure

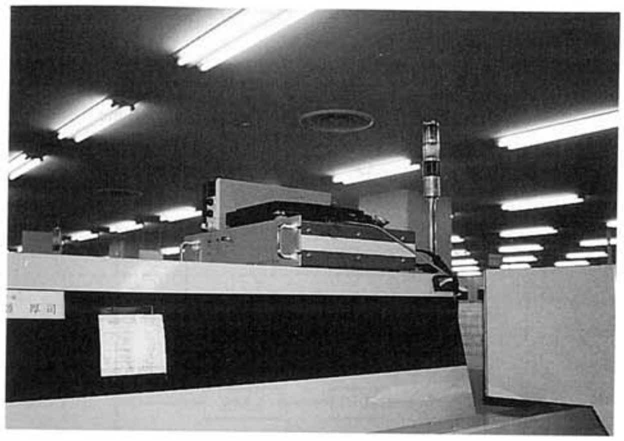


Figure 22. ANC system for mechanical equipment

We ensured that the system was installed in the optimum configuration and installed units for all of the eight insertion machines at the plant.

4.2.2 Passive control

Resonant noise caused by the vibrating metal cover panel of the transformer in the curing unit is difficult to control with this system because it exercises noise control acoustically. Instead, we used passive control.

We covered the panel with a damping material, butyl rubber sheets, which alter the panel's natural frequency and eliminate the resonant noise (Fig. 23).

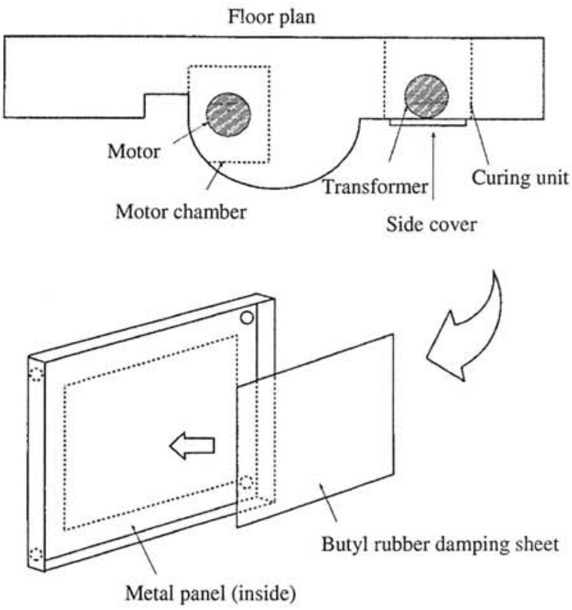


Figure 23. Passive control of noise

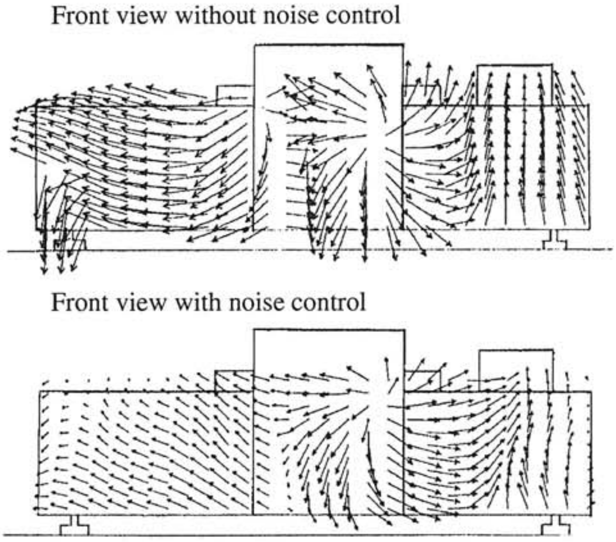


Figure 25. Sound intensity vector maps at 117.5 Hz

4.3 Results

We measured the effects of active and passive noise control.

4.3.1 Effect of active control

We compared the noise spectra measured 1 m away from the motor chamber with the noise control system on and off (Fig. 24).

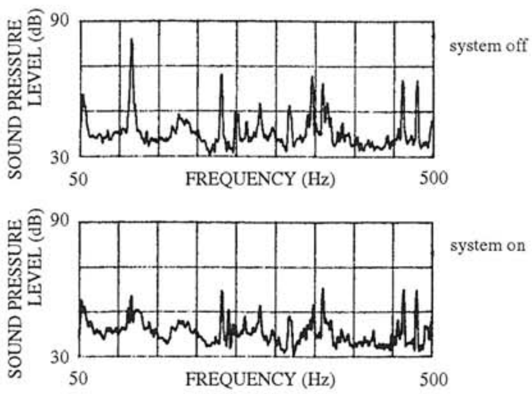


Figure 24. Noise spectra with and without the control system

Noise control reduced the primary and secondary components, 117.5 Hz and 235 Hz, of the low-frequency noise generated by the motors. The insertion machine sound intensity level analysis and vector diagrams show the effect of noise control (Fig. 25) as the length and direction of each vector line varies.

4.3.2 Effect of passive control

The damping material reduced the noise generated from the transformer in the curing unit. In front of the panel 5 cm , the noise was 23.6 dB less with damping at the 120 Hz peak noise level (Fig. 26).

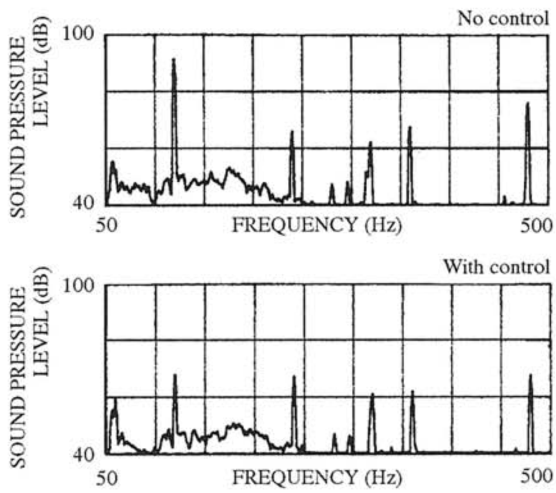


Figure 26. Comparison of noise spectra

4.3.3 Noise reduction effect in plant corridor

We measured the noise spectra with and without noise control in the plant corridor where the centralized control panel has been installed (Fig. 27). Use of both active and passive control reduced the total noise by about 7 dBA.

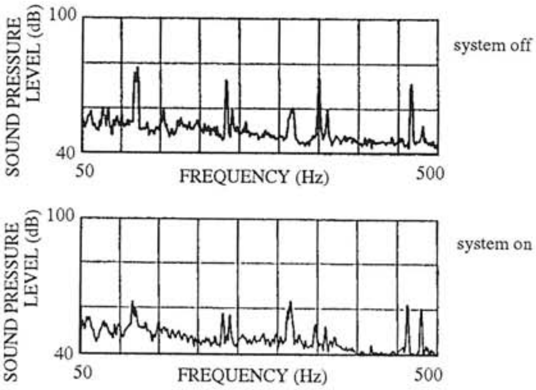


Figure 27. Noise spectra with and without noise control

4.3.4 Sensory evaluation

To compliment the quantitative evaluation, we conducted a survey among the plant workers using a scale of adjectives (Fig. 28).

"Powerful" decreased and "shrill" increased after implementing the noise control system. Since the system reduced low-frequency noise, the influence of higher-frequency noise, such as mechanical sounds, is proportionally higher. "Noisy" and "loud" remained at about the same level as before implementing the noise control. This is probably because the variation in the total noise level was relatively small.

These results agree with our quantitative evaluation of noise control.

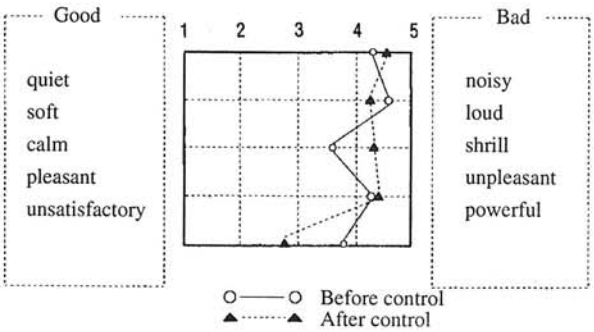


Figure 28. Survey results

5. Evaluation of experimental results

Our experiments have yielded data and technological concepts of vital importance to developing noise control techniques, such as basic noise measurement technologies, feedback active noise control applications, basic passive control technologies using the optimal arrangement of passive members, and the noise sensory evaluation plan.

As the sensory evaluation suggested, however, the advantages of noise control have not yet been fully accepted by the plant workers. This is probably because the evaluation of noise, like that of audio equipment, tends to be subjective and is influenced by background noise.

6. Future study

Future study will aim to define product markets, and to develop products for controlling noise in plants and homes, and supporting devices, such as noise control DSPs, sensors, and actuators, and to establish optimal ways of using them. Noise evaluation technologies must be established, including tone revaluation for setting goals for comfortable sound quality. Passive control technologies must be accumulated and organized, and basic active vibration control technologies to maximize control at the noise source must be developed.

7. Conclusions

Recent studies on active noise control have stimulated interest in noise control applications and manufacturers' expectations.

Further study is needed to optimize noise control products.

We will continue to develop basic technologies for noise control applications to improve the quality of life.

We thank the people at Nakatsugawa Plant for their cooperation.

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