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Active Noise Control for Tractor Operator

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Abstract

Active noise control (ANC), which is one of the active control methods applied to reduce noise using the interference of sonic waves, aims at suppressing the noise around the operator of an agricultural tractor. By several simulations of adaptive system using an adapting digital filter (ADF), the possibility of noise reduction by ANC was confirmed Results of simulations showed that the amount of noise reduction for sound pressure level (SPL) would be about 15 dB, which indicates that only one-sixth of the primary sound pressure may remain under ANC. An evaluation system of ANC was developed. 'Filtered-x LMS (least mean square)' algorithm was applied to this system to carry out the noise reduction. Its ability to reduce noise was confirmed by experiments with two tractors. Amount of noise reduction was about 10 dB at control point. Three target systems were developed to reduce the noise around the tractor operator: one based on the same method of feedforward control as that of the evaluation system, the others based on the method of feedback control. The effect on the reduction of noise was also confirmed. Amount of noise reduction was 4-7 dB at operator's ear for SPL, which was equivalent to 1-2 dB (A) for A-weighted SPL because the effective frequency range of ANC was less than 500 Hz.

Discipline: Agricultural machinery
Additional key words: adaptive control, noise reduction, signal processing, sound

Introduction

Mechanization of rice farming in Japan since the 1960s has brought about a remarkable reduction of farmer's working load and time. It also resulted in the development of a consistent mechanized rice farming system, and currently efforts are concentrated on the mechanization of fruit and vegetable cultivation.

The role of farm mechanization is very important as a substitute for farmer's labor. From the viewpoint of occupational health and safety, however, some problems in the working environment, such as dusts, noises, and vibrations caused by agricultural machinery and mechanized farmwork, have not been completely solved.

Under these circumstances, the Ergonomics Laboratory of IAM (BRAIN)** has undertaken various studies to improve the safety and comfort of farmwork by using agricultural machinery and to prevent accidents and physical troubles associated with this practice.

In the present paper, the reduction of the noise transferred from agricultural machines to the operator was analyzed, as noise is one of the important problems in the man-machine system of agricultural machinery. To reduce noise, ANC (active noise control) method was evaluated compared with the conventional passive methods of sound absorption and sound insulation.

Outline of ANC

1) Principle of ANC

Vibrating phenomena, such as sounds, vibrations and waves, are characterized by 'interference'. Fig. 1 shows the principle of ANC[2] for reducing or clearing a sonic wave by the interference phenomenon. If anti-wave P2, which has the same amplitude as

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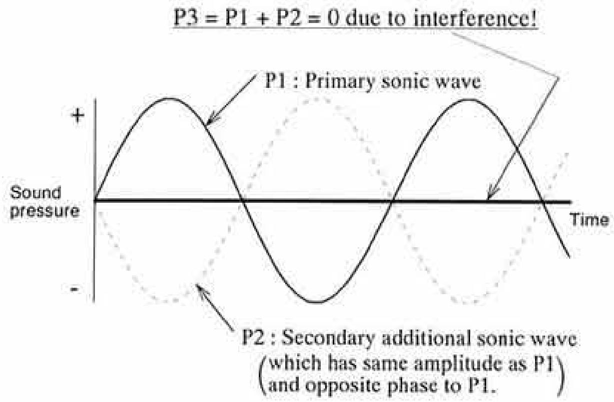

Fig. 1. Principle of ANC (interference of wave)

and opposite phase to the primary wave P1, is applied to P1, the addition of P1 and P2 will result in the absence of sonic waves.

2) *Fundamental concept of ANC*

To generate an anti-wave, ANC generally uses the adaptive control method shown in Fig. 2. Sounds (noises) produced by a sound (noise) source are transferred to any direction with a sonic velocity. If both characteristics, namely the 'transfer function', from the sound source to a certain listening point and current wave form produced by a sound source are determined, arrival of wave form to the listening point can be predicted. This prediction is executed by ADF (adaptive digital filter) shown in Fig. 2. ADF also predicts the transfer function from the sound source to the listening point. Therefore, this system is often referred to as 'system identification model'[4].

3) *Implementation of ANC*

In practice, to implement an ANC system, some microphones are used to measure the noise at the

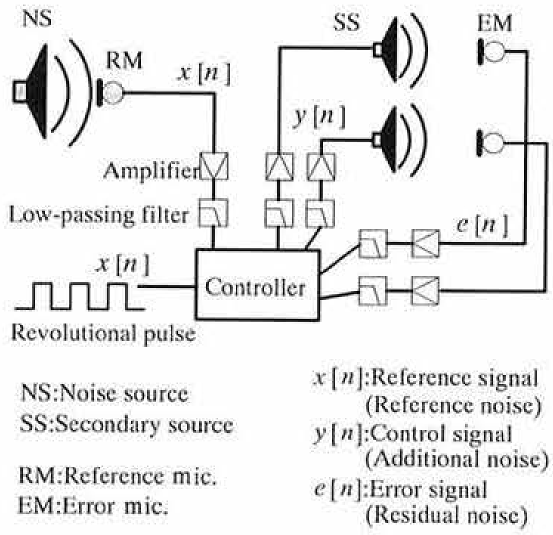

Fig. 3. Typical hardware configuration of ANC

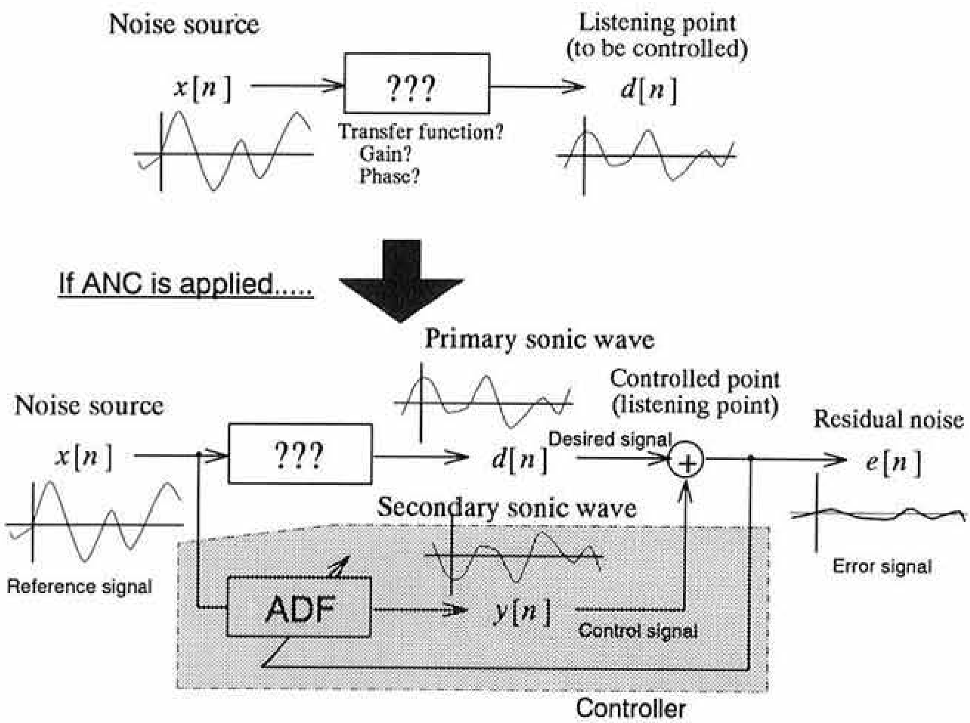

Fig. 2. Concept of ANC

noise source and at the listening point, where the noise can be controlled and reduced by ANC. Some loudspeakers are also used to generate an anti-noise. A computer system with DSP (digital signal processor) for rapid operation, A/D, D/A converter, low-passing filter is used to implement ADF. An example of implementation is illustrated in Fig. 3, where the computer system is designated as 'controller'.

Feasibility study for application of ANC[5]

1) Analysis of noise of tested tractors

Before applying ANC to an agricultural tractor, characteristics of noises produced by two tested tractors (tractors A and B, both made in Japan) were examined. The specifications are listed in Table 1. As they have no safety cab, the condition of sound field is considered to be 'half-free' under outdoor use.

Table 1. Specification of tested tractors

	Tractor A	Tractor B
Year of manufacture	1980	1990
Length (mm)	3,100	3,180
Width (mm)	1,480	1,455
Height (mm)	1,990	1,475
Weight (kg)	1,180	1,210
Engine type	Water-cooled diesel engine with 3 cylinders	
Engine output (kW)	23 (at 2,600 rpm)	24 (at 2,800 rpm)
Displacement (l)	1.498	1.499

As shown in Fig. 4, the characteristics of the noises transferred to the operator were different between tractors A and B, because tractor A was manufactured about 10 years ago without enough consideration for noise reduction, in contrast to tractor B which has been manufactured recently. However, there were still high peaks with almost the same value for SPL (sound pressure level) in the low frequency range of the noise from both tractors A and B. Therefore, these peaks were considered to be the targets for reduction by ANC.

2) Simulation study of adaptive system

A feasibility study of ANC was carried out by simulating the action of the adaptive system with ADF using a personal computer, before applying ANC directly for the suppression of noise around a tractor operator.

The following two aspects were considered: (1) where to place the sensor microphone for reference signal of ANC system, and (2) which adaptive algorithm, such as LMS (least mean square) and its variations, should be selected for ANC system.

Fig. 5 illustrates an example of simulated results. It shows several RMS (root mean square) values of simulated signals in the adaptive system. 'Error sig.' indicates RMS of residual noise, while 'Primary sig.' indicates that of primary noise. Based on these

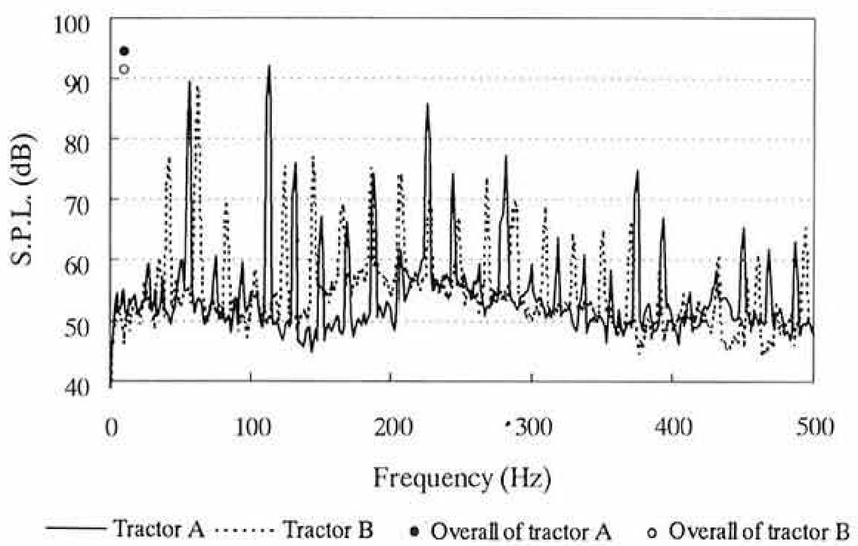

Fig. 4. Noise spectra of tested tractors at the level of the operator
Measuring conditions were as follows:
Tractor A: 2,250 rpm, no load,
Tractor B: 2,500 rpm, no load.

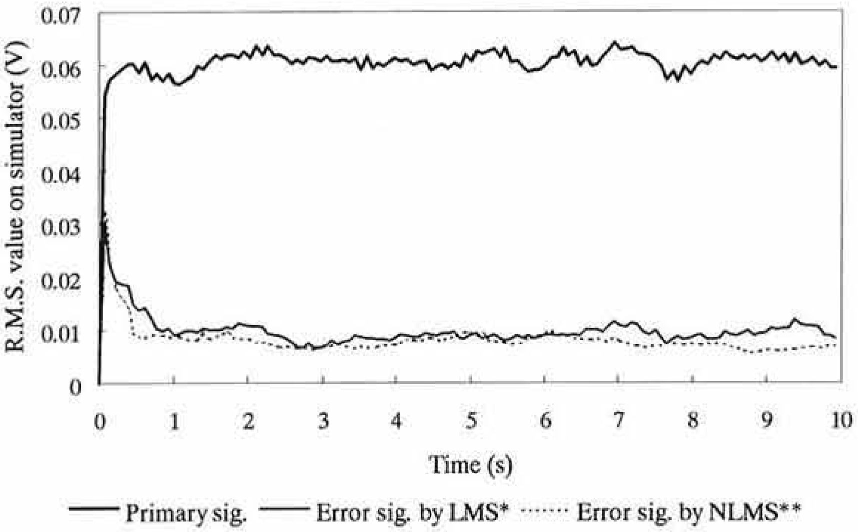

Fig. 5. Adaptive system simulation
* LMS: Least mean square.
** NLMS: Normalized LMS.

results, the possibility of noise reduction by ANC was confirmed. Amount of noise reduction by ANC would be about 15 dB for SPL, suggesting that only one sixth of the primary sound pressure may remain under the control of ANC, if an adequate area near the noise source is selected where the noise shows a good coherence with the noise around the operator.

3) Advanced real-time simulation of adaptive system as a prediction system

In this section, an adaptive system of measurement using ADF for ANC was considered in order to obtain the coherence function between the reference signal (noise at the source) and the desired one (noise at the operator) instantaneously in time domain. By the advanced simulations of the adaptive system with DSP, which enabled to perform the real-time simulation shown in Fig. 6, the ability of the adaptive system was confirmed.

An example of simulated results is shown in Fig. 7. Predicted amount of noise reduction was approximately 12 dB in the frequency range from DC to 500 Hz, indicating that only one-fourth of the primary noise remained. Difference in the amount of noise reduction between 12 dB (1/4) and 15 dB (1/6) in the previous section is considered to be caused by the accumulation of rounding errors of DSP, which is a fixed point type and the limitation of computational word#.

Fig. 8 shows an example of the relationship

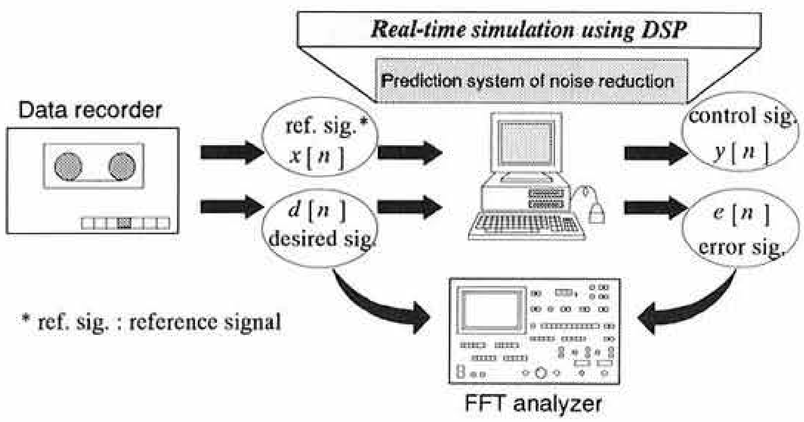

Fig. 6. Schematic diagram of real-time simulation system

Word indicates the number of bits of DSP's register.

between the simulated reduction and the calculated one based on the coherence function, whereby frequencies with a high reduction agreed with each other. This predicting ability of the adaptive system enables to optimize the structure of the ANC system.

Development of evaluation system of ANC and its performance[6)]

Based on the results of several simulations, a practical evaluation system of ANC was developed.

1) Outline of evaluation system of ANC

The evaluation system, whose block diagram is shown in Fig. 9, has one DSP for real-time operation, two analog inputs (A/Ds) and two analog outputs (D/As) for one reference input, two control outputs, and one error input. 'Filtered-x LMS' algorithm[4)], introduced by B. Widrow, was applied to this system to carry out noise reduction after

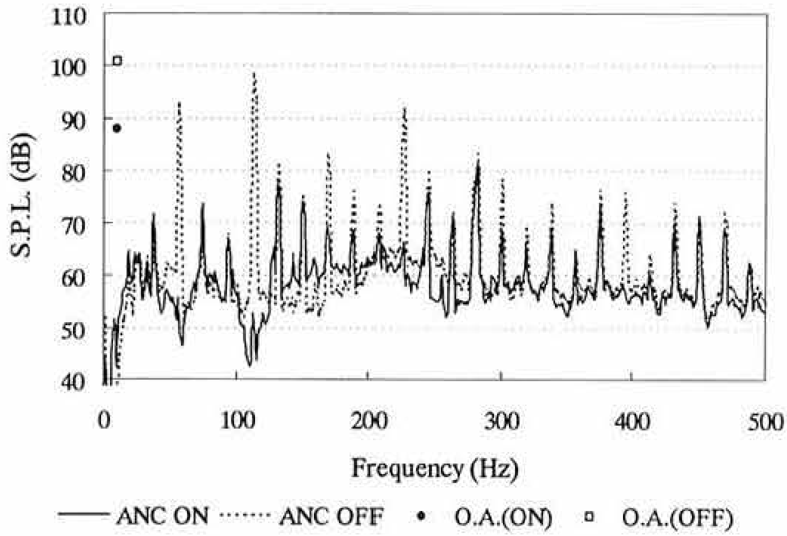

Fig. 7. A result of real-time simulation
ANC ON shows the spectrum of error signal.
ANC OFF shows the spectrum of desired signal.
O.A. means 'Overall'.
Noise of tractor A is simulated.

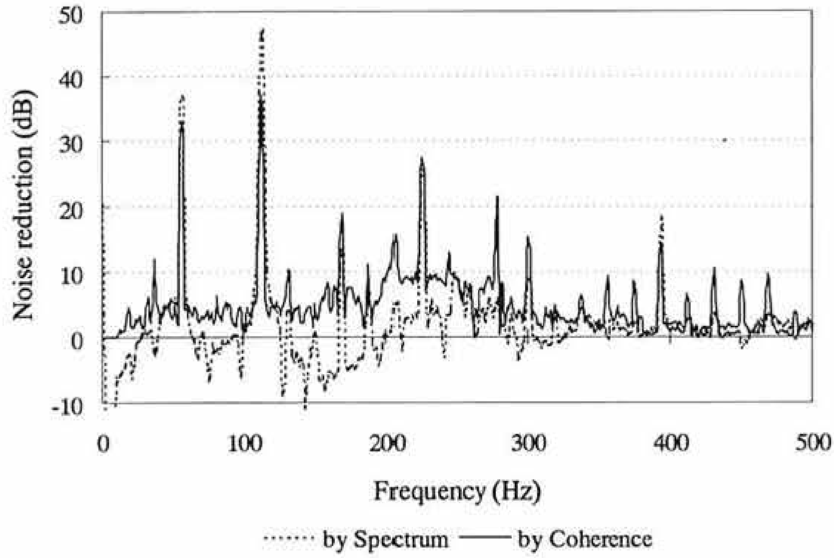

Fig. 8. Comparison of noise reduction by simulation and by calculation based on coherence

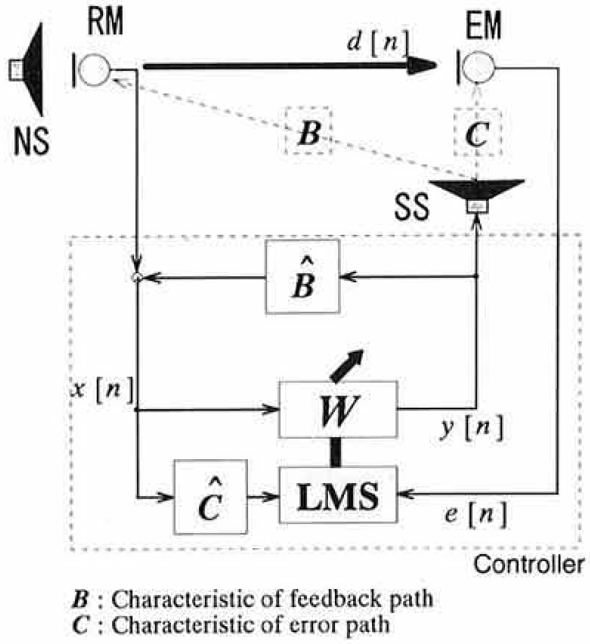

Fig. 9. Schematic diagram of evaluation system

identification of feedback path (from secondary source* to reference microphone) and error path (from secondary source to error microphone).

2) Performance of evaluation system

Suitability of the evaluation system was confirmed by experiments with two tractors. Amount of noise reduction was about 10 dB at the control point (i.e. at the error microphone: EM). The area with more than 6 dB (1/2) reduction around the control point was as large as 25 × 25 cm or larger in the area containing the error microphone and secondary source (SS).

Development of target system of ANC and its performance[7]

Based on the evaluation system, three target systems for tested tractors were developed, which reduced the noise around the seated operator on the tractor. These block diagrams are shown in Fig. 10.

1) Outline of target systems

The first system (Type I) uses the same method of feedforward control as that of the evaluation system. It can be applied to any noise, but a high coherence and sufficient distance are necessary between the reference microphone and the error one.

The second system (Type II) uses another method of feedback control. Although its application is limited to periodic noise, it works with error input and without reference input. As a result, the amount of calculation executed by DSP is reduced. In addition, the coherence function is always assumed to be 1[3].

The last system (Type III) also uses the method of feedback control as Type II, but it refers to an imaginary pulse train synchronized to noise as a reference input[1]. As no convolution operations are executed by DSP, high speed operation and extension of frequency range of noise to be controlled can be achieved.

2) Performance of target systems

These three target systems were tested in the field with two tractors to reduce the noise around the operator, and their suitability was confirmed. Results on the amount and area of noise reduction are shown in Figs. 11 and 12.

Maximum amount of noise reduction by Types I and II was approximately 11 dB in a frequency range of DC–500 Hz at the control point, and 4–7 dB in whole frequency range at the operator's ear for SPL. This reduction is equivalent to 1–2 dB (A) for A-weighted SPL because the effective frequency range of ANC is less than 500 Hz.

The number and arrangement of the error microphones and secondary sources were well adapted to the characteristics of noise to which ANC was applied. In the case of tractor B, a combination of two error microphones and two secondary sources was considered to be most suitable to generate a silent zone around the operator's head (Fig. 12).

Based on these results, basic wave length of noise is considered to be a very important factor for the application of ANC, because it is easier to obtain a certain silent zone for a noise with a longer wave length (lower frequency).

On the other hand, as the performance of Type III has not been evaluated yet, additional studies on the effect of high frequency are necessary.

3) Improvement of stability of control[8]

As in the target systems described above there were no considerations about the stability of their controlling effect, they sometimes ran out of control. In these cases, outputs from secondary sources increased rapidly and the control loop (i.e. signal

* Secondary source indicates loudspeaker used in an ANC system.

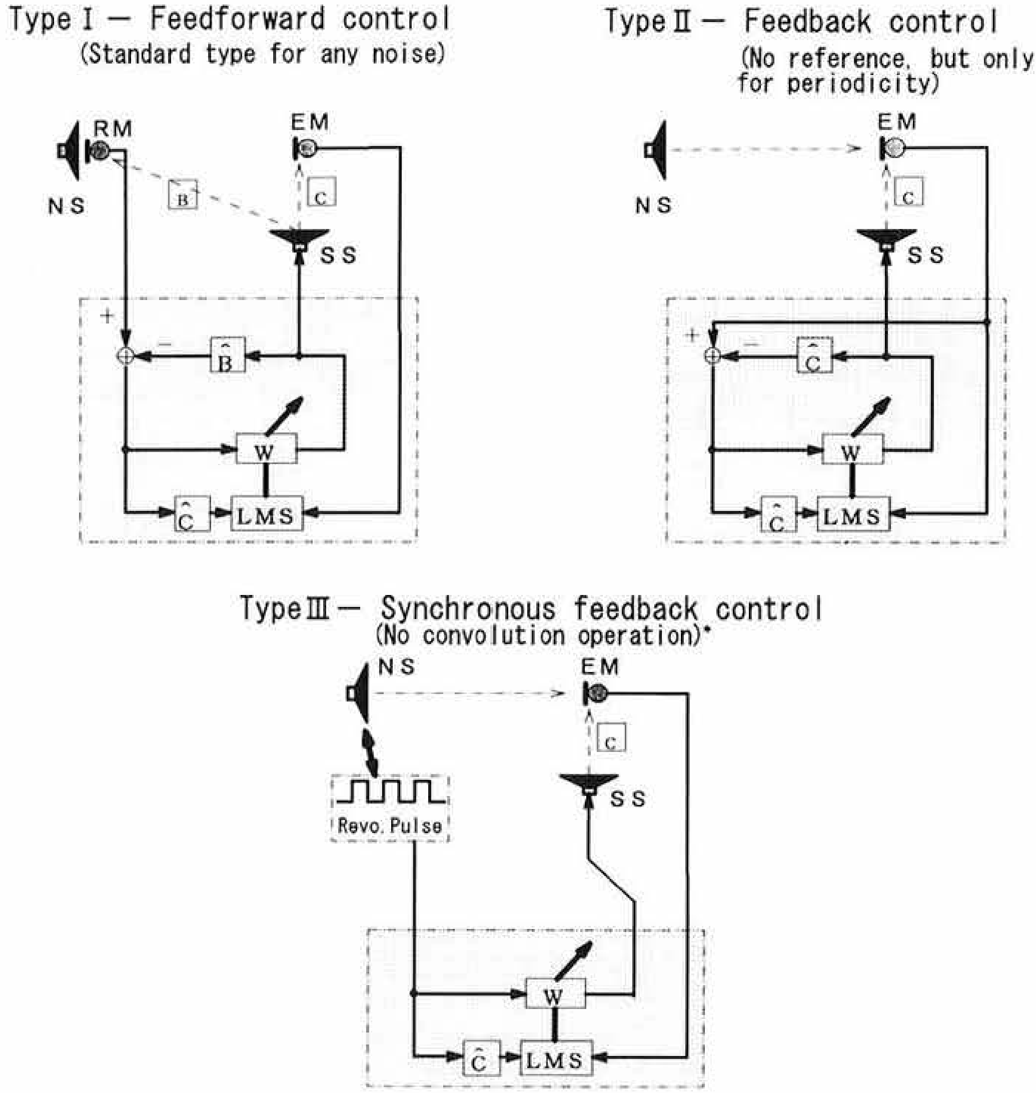

Fig. 10. Block diagrams of three target systems
Type I : Based on reference signal, control signal is generated by W filter, and interferes at EM. According to the result of interference, W filter is upgraded by Filtered-x LMS algorithm.
Type II : Due to the periodicity of noise, primary noise consists of control noise and residual one. Causality is assumed due to periodicity, which enables feedback control. This is F.B. Filtered-x algorithm.
Type III: Based on synchronized pulse with periodicity of noise, control signal is achieved by W filter, which is upgraded by SFX-LMS algorithm. This system also depends on periodicity of noise.
* High speed operation and extention of frequency range of noise can be achieved.

circulation) from secondary sources to error microphones through the system deteriorated. Once such a condition occurred, the system was never able to function normally afterwards. Therefore, some modifications of the stability of the controlling effect were considered to be necessary.

To address this problem, a combined adaptive algorithm of Filtered-x LMS with Leaky LMS[4] was considered and applied to Type II. Equation of this combined algorithm is as follows:

$$W_{n+1} = \gamma W_n - \alpha R_n e_n$$

where W_n: specifies weight vector of ADF at time n, R_n: specifies filtered reference vector[4] at time n, e_n: specifies error signal from error microphone at time n, α: a step-size parameter (convergence

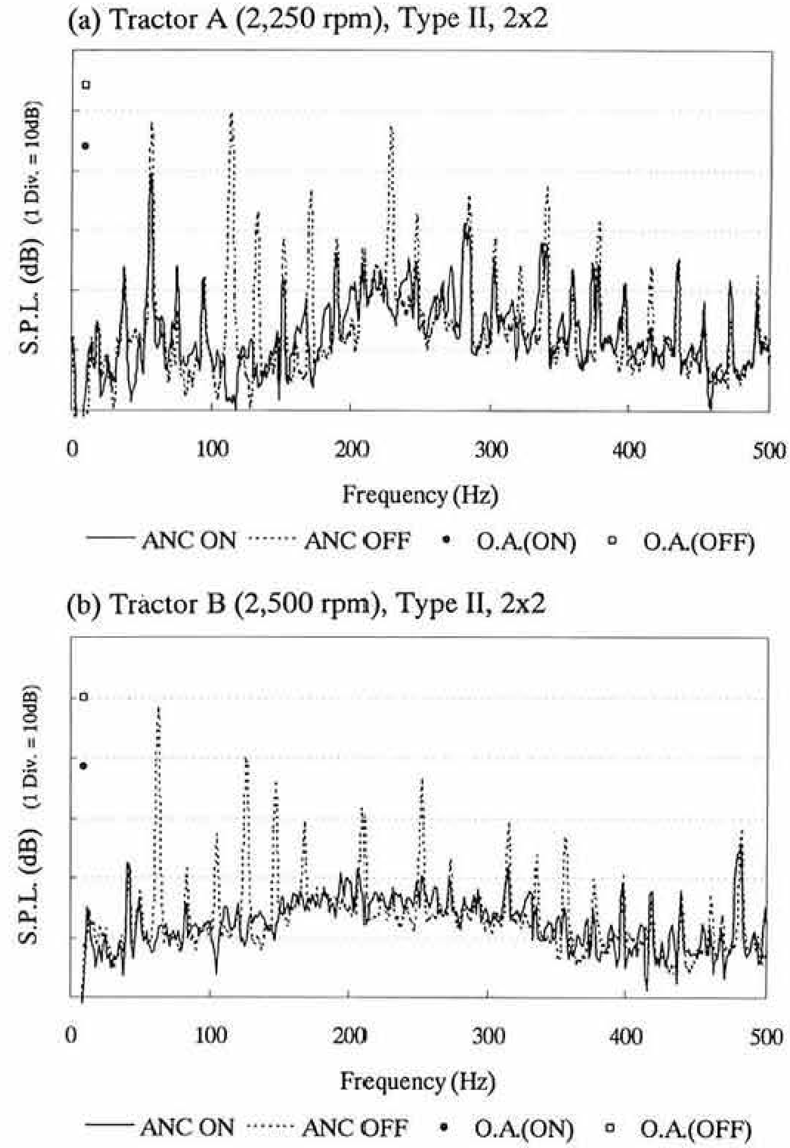

Fig. 11. Examples of noise reduction by target systems at the error microphone
2x2 indicates 2 SSs and 2 EMs, etc.

coefficient), γ: a leak parameter (forgetting factor).

Table 2 shows the results of the stability test after the modification of Type II. The larger the value of α, the faster the system converged and the less stable the effect. The smaller the α value, the slower the system converged and the smaller the amount of noise reduction. However, when γ was set at a value slightly smaller than 1.0, such as 0.99995, the divergence of $\boldsymbol{W}$ was removed and the system remained stable, while the convergence was rapid and the amount of noise reduction large.

4) Performance in rotary tilling

Fig. 13 shows an example of noise reduction by ANC in the case of rotary tilling with a throttle fully opened. In this case, several noises from the engine and other sources, such as the rotary tiller, were transferred to the operator. Under these conditions, the amount of noise reduction was approximately 7 dB for SPL at the error microphone, as shown in Fig. 13.

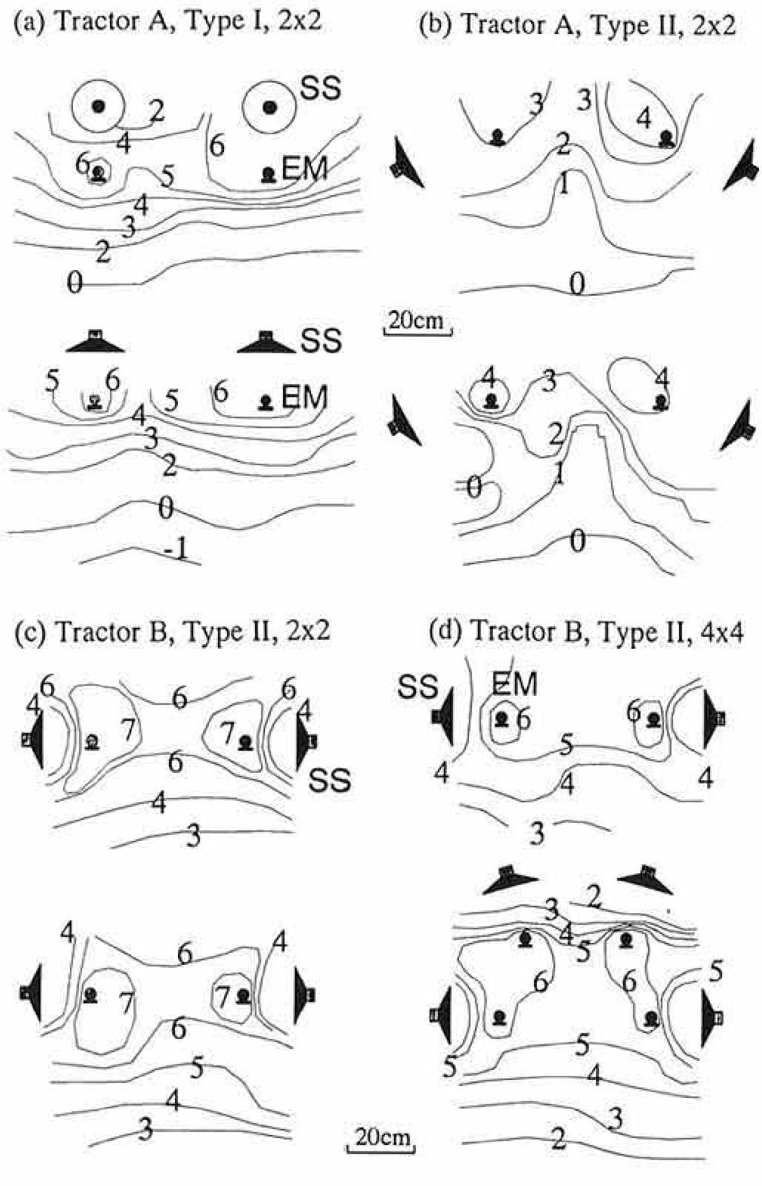

Fig. 12. Contours of noise reduction using target systems
Upper: Vertical plane including EM.
Lower: Horizontal plane including EM.
Each number specifies the amount of reduction in SPL (dB).

Table 2. Noise reduction (dB) and stability at each set of α and γ

α \ γ	1.0	0.99995	0.9999	0.9995	0.999	0.995	0.99
0.05	×	×	×	×	×	×	×
0.02	11.8 (×)	10.7 (×)	11.0 (×)	7.2 (×)	5.7 (×)	4.4 (×)	3.1 (×)
0.01	12.0 (×)	11.7 (○)	11.4 (○)	6.0 (○)	4.9 (○)	2.8 (◎)	2.0 (◎)
0.005	11.2 (○)	10.9 (○)	10.3 (○)	5.2 (◎)	3.4 (◎)	1.2 (◎)	0.7 (◎)
0.002	10.2 (◎)	9.6 (◎)	9.4 (◎)	5.1 (◎)	3.6 (◎)	1.0 (◎)	0.4 (◎)
0.001	8.8 (◎)	7.9 (◎)	8.1 (◎)	5.0 (◎)	3.0 (◎)	0.8 (◎)	0.5 (◎)

1) Amount of noise reduction was measured when the system was stable.
2) Marks in parentheses indicate the results of stability as follows:
◎: Stable, even if noise added, ○: Stable but slightly affected, if noise added,
×: Becomes unstable, if noise added.

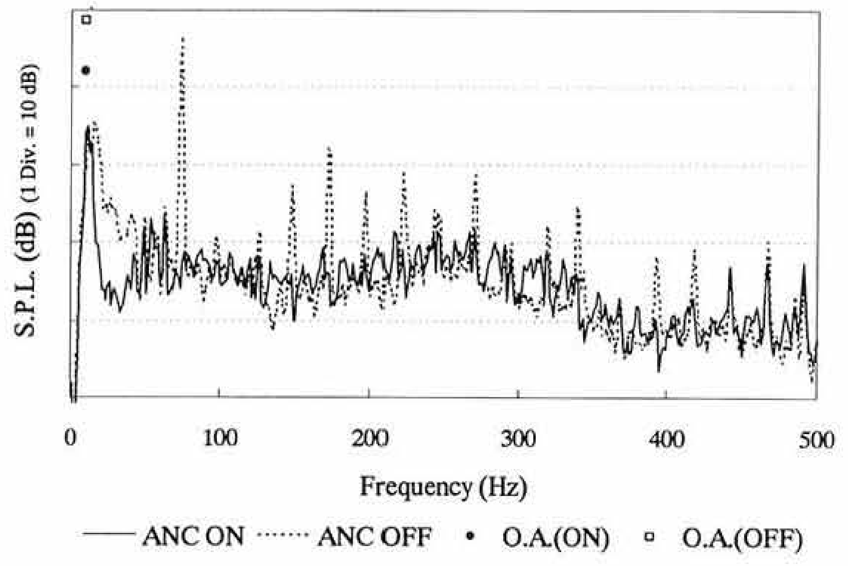

Fig. 13. Example of noise reduction in rotary tilling at the error microphone
Measuring conditions: Tractor B (full throttle), Type II, 2x2.

Conclusion

In order to improve the working environment of the operator, noise reduction by ANC was applied to agricultural tractors. Its performance and several characteristics were evaluated. As a result, the ANC method was found to be very efficient in reducing noise in the low frequency range up to 500 Hz because of the limitation of digital operation speed.

In the near future, increased digital operation speed will enable to control and reduce noise in a higher frequency range. Higher frequency, however, indicates that the wave length is shorter and more microphones and secondary sources will be necessary in order to generate a silent zone, suggesting that the frequency controlled by ANC reaches a limit. Therefore, the combined use of ANC and conventional methods, such as insulation and absorption, is important for noise reduction in whole frequency range in practice.

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