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NOISE PREDICTION SIMULATION AND NOISE REDUCTION TECHNOLOGY AT LOW-FREQUENCIES

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ABSTRACT

Equipment related to city gas includes engines, fans, pumps, and burners. Depending on the installation environment and the hours of use, the noise emitted from such equipment may have undesirable effects on its surroundings. Therefore, when a system including such equipment starts up, we must be mindful of the environmental noise caused by the system. The noise may even be increased due to reflections by many obstacles surrounding the system, such as walls and buildings. Particularly, the low-frequency noise may be increased by wave interference and make people uncomfortable. For this reason, to establish pre- and post-operational measures against such noise problems, noise prediction simulation by the computer and a noise reduction technology using ANC (Active Noise Control), which is effective for reducing low-frequency noise, have been developed.

Simulation methods for noise prediction are classified into the wave acoustic method and the geometrical acoustic method. The geometrical acoustic method is mainly used for noise prediction of gas equipment, because its computational load is lower than that of the wave acoustic method and it can be used for various sizes of equipment. However, the geometrical acoustic method is less accurate than the wave acoustic method. The wave acoustic method can predict wave phenomena by solving wave equations, but the computational load is high. Especially, it is hard to calculate the noise in wide space at high frequencies where the space should be divided into many elements. In this study, for calculating noise emitted from gas equipment, the applicable range of the two methods was confirmed. As a result of the model experiment, the geometrical acoustic method can calculate at high frequencies where the wave character is weak, but cannot calculate the noise in the areas where the effect of interference is dominant. In contrast, the wave acoustic method can calculate the interference accurately. The interference mainly occurs near a wall and in enclosed space at low frequencies. The wave acoustic method can be used in the situation where the interference is dominant, because the space is not required to be divided into many elements at low frequencies. Thus, the noise impact of gas equipment can be predicted by using the two methods as the situation demands.

As post-operation measures, sound absorption and sound insulation are commonly practiced to reduce noise. These passive measures are effective against high-frequency noise but are not effective against low-frequency noise. Therefore, we focused on an ANC which cancels out noise by generating a controlled sound whose amplitude is the same as that of the noise but the phase is opposite. It is often used in one-dimensional space such as the exhaust duct of an engine. In this study, it was applied to three-dimensional space for gas equipment, and the effect was evaluated by experiment. Although, the effective frequency range is restricted to low frequencies with long wavelength, it was confirmed that ANC reduced the noise emitted from gas equipment by about 15 dB.

The noise prediction simulation and a noise reduction technology which can be used for low-frequency noise were developed. As a result of developing pre- and post-operational measures, it became possible to suppress the undesirable effect of the noises from the system exerts on its surroundings.

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2. INTRODUCTION

Equipment related to city gas includes engines, fans, pumps, and burners. Depending on the installation environment and the hours of use, the noise emitted from such equipment may have undesirable effects on its surroundings. Therefore, when a system including such equipment starts up, we must be mindful of the environmental noise caused by the system. The noise may even be increased due to reflections by many obstacles surrounding the system, such as walls and buildings. Particularly, the low-frequency noise may be increased by wave interference and make people uncomfortable. For this reason, to establish pre- and post-operational measures against such noise problems, noise prediction simulation by the computer and a noise reduction technology, which is effective for reducing low-frequency noise, have been developed.

3. NOISE PREDICTION SIMULATION

As a pre-operational measure, the noise impact on the surroundings should be predicted. If the noise emitted from the equipment exerts an undesirable effect, the noise has to be reduced by sound barriers, acoustic absorbents, and silencers. Noise reduction measures are also designed based on noise prediction, because it should be optimized by considering the restrictions by law, cost, feasibility, appearance, etc. Noise prediction is carried out by calculating the propagation of the sound energy emitted from gas-related equipment. If there are not many sound sources or obstacles, the impact of the noise can be calculated by a simple formula. However, there are often many sound sources and obstacles where the equipment is installed. Thus, a complicated calculation involving reflections and diffractions is needed. For calculating such phenomena, many calculation methods which use computer simulation have been suggested.

3.1. Simulation method

Simulation methods for noise prediction are classified into the wave acoustic method and the geometrical acoustic method. The wave acoustic method can predict wave phenomena by solving wave equations, but the computational load is high. In contrast, the geometrical acoustic method calculates the geometrical paths between the noise sources and the measuring points with simple physical models. Naturally, its computational load is lower than that of the wave acoustic method. The geometrical acoustic method is less accurate than the wave acoustic method, but it can be used for various sizes of equipment.

However, the geometrical acoustic method may cause large errors at low-frequencies where wave nature is dominant, because it cannot predict wave phenomena accurately. For this reason, its accuracy at low-frequencies had to be verified by experiments in this study.

3.1.1. Wave acoustic method [1].

The wave acoustic method can predict wave phenomena such as interference and diffraction by solving the wave equation. It is solved by the numerical analysis, because it is difficult to solve the equation with the exception of the simple shapes like a rectangular space. The finite element method and the boundary element method are commonly used for solving the wave equation. The computational load becomes high at high frequencies with short wavelengths, because it is necessary to divide the space or the boundary into 1/6 or less of the wavelength. The low- and high-frequency noises are emitted from the gas equipment. The wave acoustic method can calculate low-frequency noise, but cannot calculate high-frequency noise. The wave acoustic method is not suitable for calculating the noise in a broad frequency range.

3.1.2. Geometrical acoustic method.

In the geometrical acoustic method, the spherical divergence, the reflection, the absorption, and the diffraction of the geometrical path from the sound source to the receiver point are calculated by the physical model. The noise value at the receiver point is obtained as a sum of the noises of all paths. The accuracy of the geometrical acoustic method depends on the physical model used. The wave phenomena can be calculated by the physical model based on a theoretical formula. However, when a theoretical formula is used, the computational load increases, and the advantage of the geometrical acoustic method is lost. Various physical models which consider the balances between the load and accuracy and adapted to different objects, such as roads, railroads, air traffic, industrial plants, and wind turbine generators, have been proposed. Applicable ranges of these physical models are different.

3.2. Verification

A number of physical models for the geometrical acoustic method have been proposed according to the purposes. As for the gas equipment which is installed outdoors, the feature of noise is the same as that of the noise from industry plants, so that a physical model for industrial plants is generally used. The impact of the industrial plant noise is often calculated by the physical model "Nord2000"[2] which includes theoretical formulae. However, the validity of calculation of the reflection of low-frequency noise is not yet confirmed. An experiment using a model was carried out for verifying the accuracy of the physical model. Additionally, the accuracy of the geometrical acoustic method and the wave acoustic method were compared.

3.2.1. Verification method

Ground reflection occurs only once but wall reflection occurs several times depending on the environment. The physical models for ground reflection and wall reflection are therefore different. Calculation of ground reflection and wall reflection had to be verified. For calculation by the geometrical acoustic method, commercially available software, SoundPLAN, was used. As for the wave acoustic method, a self-developed program was used.

The experiment was carried out with a 1:10 wooden model in a hemi-anechoic room. A speaker (FOSTEX, D1400) was used as the sound source. As shown in Fig. 1, the pipe of 8 mm in inside diameter and 500 mm in length was set to reduce the directivity of the speaker. Figure 2 shows the difference in sound pressure level from the front receiver point, which indicates the directivity of this sound source. At 1250 Hz or less, the difference in sound pressure level from the front is small, and so the sound source can be considered to be a point source. White noise was used for the signal sound. Frequencies of 630 Hz and 1250 Hz, corresponding to 63 Hz and 125 Hz in the actual size, were examined as major targets.

The Boundary Element Method (BEM) was used as a numerical analysis method for the wave acoustic method. BEM is a method for solving the integral equation on the boundary. BEM is suitable for noise prediction, because it can calculate the infinite space of outdoors.

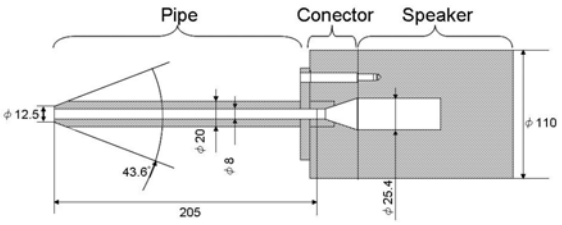

Fig. 1 Composition of sound source.

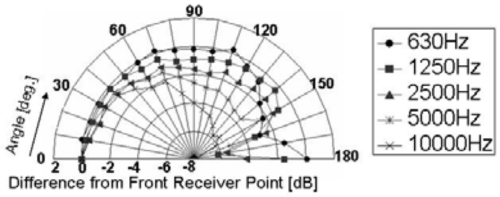

Fig. 2 Directivity of sound source.

3.2.2. Ground reflection

In the model experiment as shown in Fig.3, the sound source was placed toward the same direction of the y-axis, and the sound was measured at the 12 receiver points. The boundary for the calculation was assumed to be rigid, because the wooden board almost completely reflects the sound at 630 Hz or more. Figure 4 shows the difference between the calculated values and the measured values at 630 Hz and 1250 Hz. The permissible error of calculated values is commonly 3 dB, which means half or twice as much sound energy. The calculated values by both methods were within the permissible range.

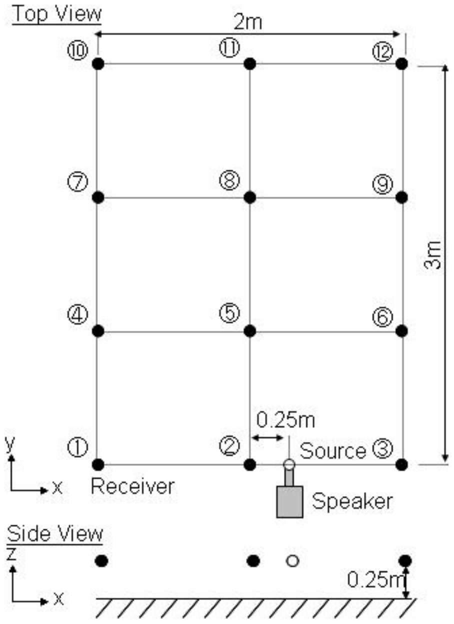

Fig. 3 Layout for ground reflection experiment.

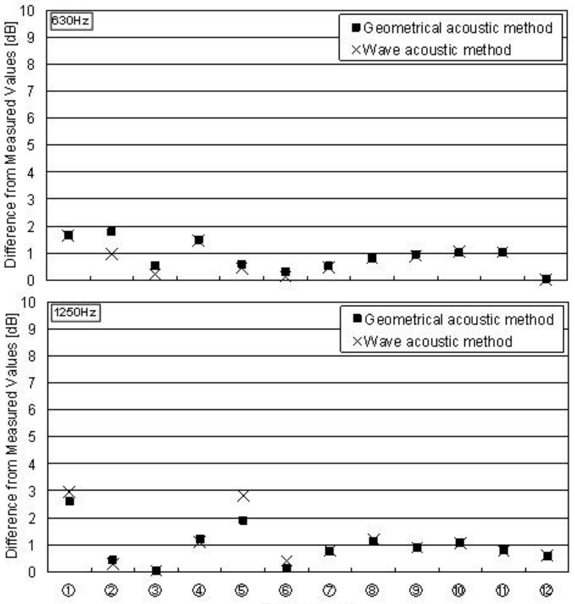

Fig. 4 Difference between measured values and calculated values about ground reflection.

In the geometrical acoustic method, the ground reflection is calculated by Eq. (1), where W means the sound energy emitted from the source. The first term means the spherical divergence, and the second term means a correction factor for the ground reflection L_g.

$$L_p = 10\log_{10}\left(\frac{W}{4\pi R_1^{2}}\right) + L_g \qquad (1)$$

The phase of the direct sound and that of the reflected sound were considered. In Eq. (2), L_g was calculated according to the length of the direct path R_1 and that of the reflected path R_2.

$$L_g = 20\log_{10}\left|1+\frac{R_1}{R_2}Qe^{jk(R_2-R_1)}\right| \qquad (2)$$

As shown in Fig. 5, R_1 and R_2 were different. The difference (R_2-R_1) caused the phase difference at the receiver point. The interference between the direct and the reflected sounds was calculated based on the phase difference. Q means a reflection coefficient of the ground, and the value for the hard ground is 1. By calculating the synthetic value of direct sound and reflected sound in consideration of interference, the propagation of noise can be accurately calculated by the geometrical acoustic method.

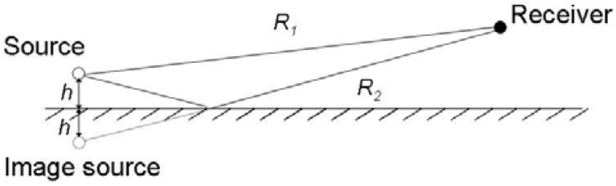

Fig. 5 Physical model of the geometrical acoustic method for ground reflection.

3.2.3. Wall reflection

As shown in Fig. 6, for verifying the accuracy of wall reflection, a wall made of plywood 2 m in length, 0.5 m in width, and 20 mm in thickness was used. The sound source and the receiver points were located in the same way as in the ground reflection experiment. Figure 7 shows the difference between the calculated values and the measured values at 630 Hz and 1250 Hz. The difference in the calculated values by the geometrical acoustic method from the measured values was greater than that by the wave acoustic method.

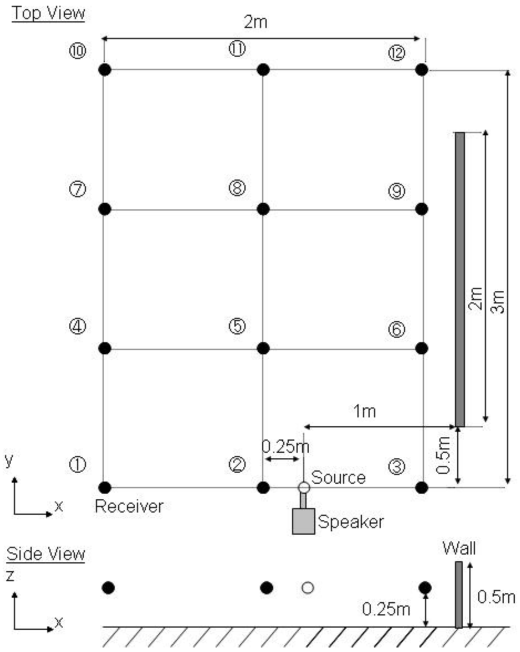

Fig. 6 Layout for wall reflection experiment.

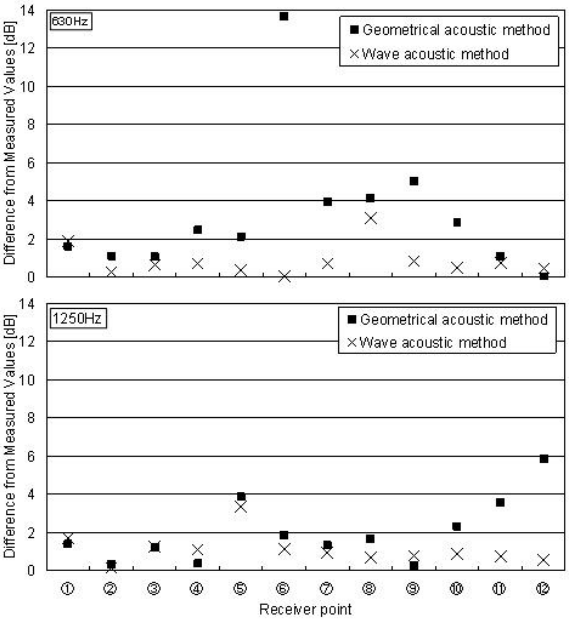

Fig. 7 Difference between experimental value and calculated value about wall reflection.

When the wavelength of the sound wave is short enough compared with the size of the reflecting surface, the sound is reflected almost completely by the surface. However, the reflecting surface is often smaller than the wavelength of the sound wave. In such a case, the reflected sound becomes small. For calculating the sound reflection by the wall which is smaller than the wavelength, the concept of the Fresnel zones is used in the physical model. The concept is widely used within the comprehensive propagation model. When the Fresnel zone is used for the noise propagation, the imaginary sound source and the receiver point become the foci of ellipsoidal body as shown in Fig. 8.

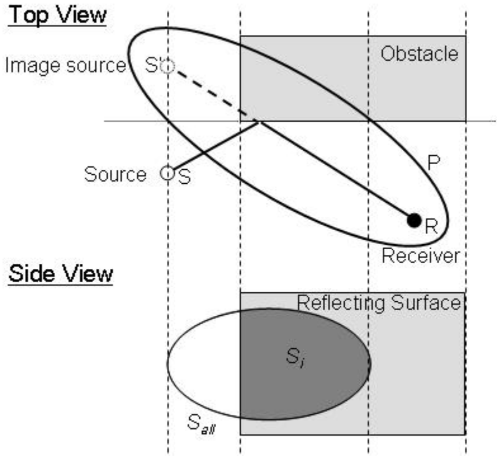

Fig. 8 Conceptual diagram of Physical model for wall reflection.

Then, the strength of the reflected sound is calculated by Eq. (3).

$$L_{p,ref} = 10\log\left(\frac{W}{4\pi|S'R|^2}\frac{S_i}{S_{all}}\right) \tag{3}$$

Where S_{all} is the cross-sectional areas of the ellipsoidal body and S_i is the overlapping part of S_{all} and the reflecting area. The size of the ellipsoidal body was determined from wavelength as shown in the Eq. (4), where F_λ means Fraction of the wavelength and λ means wavelength.

$$|S'P| + |RP| - |S'R| = F_\lambda \lambda \tag{4}$$

Even if the reflecting surface is narrow, the high-frequency noises whose wavelengths are shorter than reflecting surface are reflected almost completely, because the cross-sectional area of the ellipsoidal body is smaller than reflection surface. On the other hand, at low frequencies with long wavelengths, the reflected sound weakens because the cross-sectional area of the ellipsoidal body widens, and S_i becomes small. Moreover, the physical model does not consider the phase of the direct sound and the reflected sound. This is the reason that the difference from the measured values was greater than by the wave acoustic method. At 1250 Hz, the difference was smaller than at 630 Hz. This is because interference was less at high frequencies.

For examining the effect of the reflected sound in detail, the sound reflected by a wall of finite area was calculated. Figure 9 shows the distribution of sound pressure level which excluded the direct sound. In the physical model, the reflection is large at the center of the wall and becomes small around the edges of the wall. It changes gradually. Figure 10 shows the difference between the measured values and the values calculated by the geometrical acoustic method at 2500 Hz, 5000 Hz, 10000 Hz, and 20000 Hz. The directivity of each frequency was corrected by the data shown in fig. 2. The difference was about 3 dB or less at the receiver points. The physical model of the geometrical acoustic method cannot predict nodes and anti-nodes. However, the accuracy at high frequencies was better than at low frequencies, because the effect of interference become weakens at high frequencies.

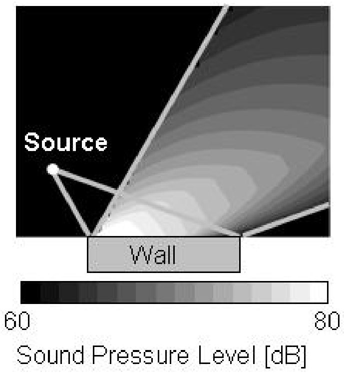

Fig. 9 Distribution of Sound Pressure level of Reflected sound calculated by geometrical acoustic method.

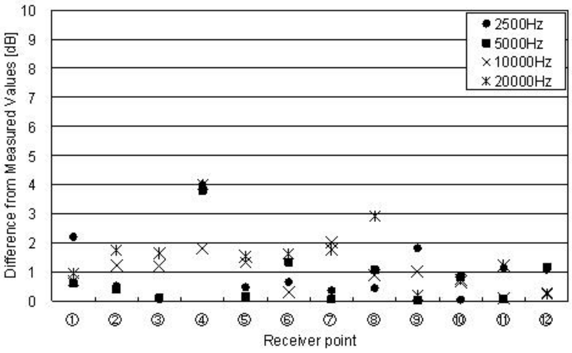

Fig. 10 Difference between Measured values and values calculated by geometrical acoustic method about wall reflection.

However, in the areas where the effect of interference is dominant, there is less accuracy. The distribution of sound under the layout of fig.6 was calculated by both the wave acoustic method and the geometrical acoustic method. The results of the calculation are shown in Fig.11. The interference by the direct sound and the ground-reflected sound is calculated, and the calculated value is almost same at the place where the wall reflection did not affect the calculation. However, there was difference where the interference was dominant.

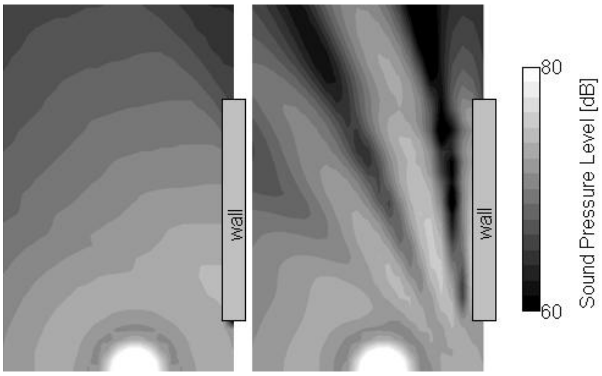

Fig. 11 Distribution of calculated Sound Pressure Level at 630Hz
(Left: Geometrical acoustic method, Right: Wave acoustic method)

It was thus confirmed that the geometrical acoustic method can calculate at high frequencies where the wave character is weak, but cannot calculate the noise in the areas where the effect of interference is dominant. In contrast, the wave acoustic method can calculate the interference accurately. The interference mainly occurs near a wall and in enclosed space at low frequencies. The wave acoustic method can be used in the situation where the interference is dominant, because the space is not required to be divided into many elements at low frequencies. Thus, the noise impact of gas equipment can be predicted by using the two methods as the situation demands.

4. NOISE REDUCTION TECHNOLOGY

Some measures which are specialized for low frequencies were developed. Sound absorption and sound insulation are commonly practiced to reduce noise. However, these passive measures are not effective against the low-frequency noise. In the following, ANC(Active Noise Control) [3], which is an appropriate method for reducing the low-frequency noise, is focused on.

4.1. Principle of ANC

ANC is a technology which cancels out noise by generating a sound whose amplitude is the same as that of the noise but the phase is opposite. Figure 12 shows a schematic diagram of the ANC for one-dimensional space. First, a reference microphone located upstream detects the noise. Next, a wave signal whose phase is opposite to that of the noise is generated by the controller. The secondary source emits controlled sound which is adjusted in the controller. An error microphone located downstream detects the synthesized noise and the controlled sound. The controller then adjusts the controlled sound to minimize the synthesized noise at the error microphone. ANC is often used for headphones, ducts, and automobiles[4-6], but it is rarely used in three-dimensional space. In this study, an ANC system which reduces low-frequency noise in three-dimensional space was developed.

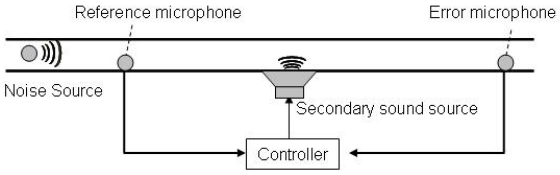

Fig. 12 Schematic diagram of the ANC for one-dimensional space.

4.2. Performance evaluation

In three-dimensional space, ANC can easily reduce noise near the error microphone, but it may increase noise in other areas. However, if the following three requirements are met, it is possible to decrease noise in a wide area. First, the second sound source should be set next to the noise source. Second, the noise is restricted to low-frequencies. Third, the noise is stable such as the noise of a rotary machine in steady state. The performance of ANC was examined, assuming a steadily rotating engine. A reference microphone was set inside the engine room. An error microphone was set in front of the engine. A speaker as a secondary source was set next to the engine. Filtered-X LMS was used as the control algorithm.

The performance of ANC was evaluated in an anechoic room. The noise source and the secondary source were located as shown in Fig. 13. The noise was measured with ANC in operation. Figure 14 shows the sound pressure level near the error microphone. As shown in the figure, ANC reduced the sound pressure level by about 15 dB at the peak frequencies. Figure 15 shows a contour map of variation by ANC at peak frequencies of 32.50 Hz, 48.75 Hz, 65.00 Hz, and 81.25 Hz on the measuring plane of Fig. 13. It was confirmed that the noise in front of the noise source was reduced by ANC.

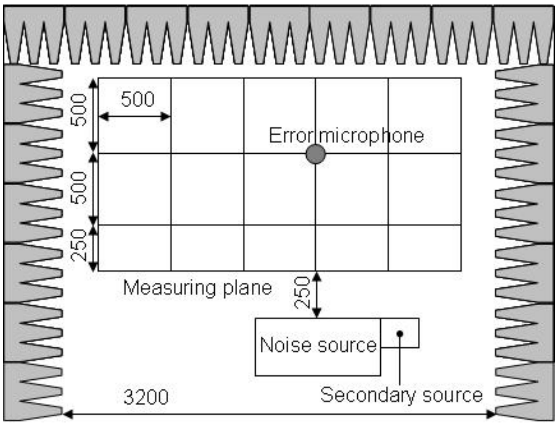

Fig. 13 Layout for experiment in anechoic room.

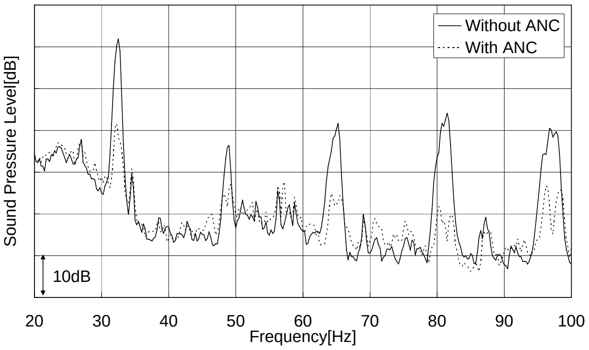

Fig. 14 Variation in sound pressure level by ANC presence in anechoic room.

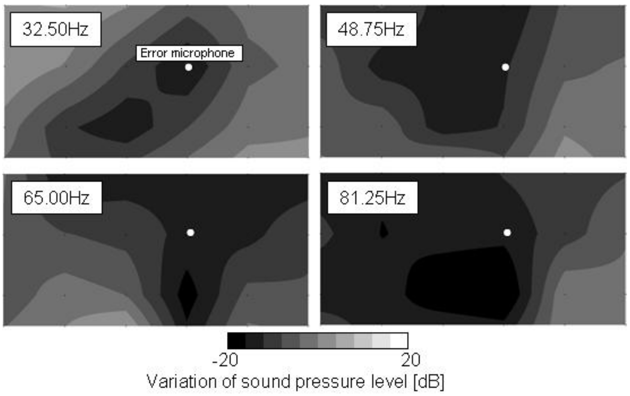

Fig. 15 Contour map of variation by ANC presence on measuring plane in anechoic room.

5. CONCLUSIONS

A noise prediction simulation and a noise-reduction technology which can be used for low-frequency noise whose propagation is difficult to predict and to reduce were developed.

For developing a method of noise prediction simulation, the validity of the geometrical acoustic method and the wave acoustic method was evaluated and confirmed. The phase of the direct sound and the reflected sound should be considered for calculating the propagation of noise. As for the ground reflection, the reflected sounds and the direct sound were synthesized, considering their phases. As for finite wall reflection, it was possible to calculate high-frequency noise by the geometrical acoustic method, but the reliability near the wall at low-frequencies was low. The geometrical acoustic method does not consider the phase of wall reflection. Therefore, the geometrical acoustic method is not appropriate for the sites where there is strong interference. In contrast, the wave acoustic method can calculate the interference accurately. The interference mainly occurs near a wall and in enclosed space at low frequencies. The wave acoustic method can be used in the situation where the interference is dominant. It was confirmed that the environmental noise impact of gas equipment can be predicted by using the geometrical acoustic method and the wave acoustic method as the situation demands.

Additionally, for reducing the low-frequency noise in three-dimensional space, an ANC system whose second sound source was set next to the noise source was developed. Although its noise-reduction effect was restricted to the frequencies in the range of 20 Hz to 100 Hz, the noise at the peak frequency depending on the rotating speed of the machine was reduced by about 15 dB.

As a result of developing pre- and post-operational measures, it became possible to suppress successfully the undesirable effect of the noises from the system exerts on its surroundings.

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Figure 11 Distribution of calculated Sound Pressure Level at 630Hz
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