Sound Radiation From a Housing Containing an Acoustic Source*

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To study acoustic transmission path from the inside to the outside of rectangular enclosures, a simple gear box model made of 1.1mm, 2.3mm and 9.0mm steel plates, has been examined by means of acoustical holography.

The behavior of sound radiation depends on the relation between the bending wave length in plate (λ_{pl}) and the sound wave length in air (λ_{air}). The high frequency sound ($\lambda_{pl}/\lambda_{air} > 1.5$) is radiated from all over the plate according to its resonant mode. However, the sound in the lower frequency range ($\lambda_{pl}/\lambda_{air} < 1.5$) is apparently radiated only from the edges with less power than that of the former condition. This is attributed to the radiation in the tangential directions of side plates.

The result would be applicable to designing a gear system for noise attenuation.

1. Introduction

There are some practical methods to reduce noise generated by a gear system. One method of reducing the noise is to design a pair of gears with low vibration and noise, because they are the primary cause of the noise radiation from the gear system. Another method is to isolate the noise sources by enclosing them in a housing which is designed to have smaller acoustic transmittance. An analysis of the radiation mechanism of the housing is required in order to achieve the effective noise reduction. In a mechanical system, especially a gear transmission system, the housing is one of machine elements, and it finally radiates the sound to outside. However, the mechanism and the location of sound radiation from the housing, whose shape is rectangular or cylindrical as a simple model of gear box, have not been discussed sufficiently yet.

In the case of a rectangular box, since the room inside the box is enclosed by rectangular plates, it is important to analyze the behavior of sound radiation from a plate. Smith[1] has analyzed the transfer function of sound radiation from a plate resonated by an acoustic source. On the sound radiation of ribbed plate, Maidanik[2] introduced "critical frequency" when the wavelength of the elastic wave in the plate is equal to the wavelength of the sound in air. He showed

that the behavior of sound radiation depends on frequency, by computing the radiation resistance of a plate theoretically, and verified it experimentally. After that, Smith[3] has shown that the sound radiation decreases below the critical frequency. Wallace[4] has calculated the radiation efficiency of a rectangular plate in each vibration mode. Saito, et al.[5] have measured the radiation efficiency of various shaped plates by using a reverberation chamber. The literatures introduced above are studies on the behavior of sound radiation from one plate. Since a rectangular box, as a model of gear box, has four more additional side plates with it, it is necessary to consider the influences of the sound radiated from the side plates on the acoustic field. A few papers have touched upon the sound radiation of rectangular box. Lyon[6] has computed the noise reduction by a small rigid rectangular enclosure with one flexible wall.

Regarding a box as an anti-noise element, a cylindrical shaped package for a small size engine was studied by Fukuda [7][8][9]. On the sound radiated by an arbitrarily shaped vibrating body, Hori[10] has calculated the sound fields using the measured directivity of a point source. And a few reports concerning the cylindrical shells are evident[11][12]. However, it is difficult to find a paper which reports on the sound radiation from a rectangular enclosure containing a sound source taking account of the sound radiation from all the surfaces.

In this paper in order to make clear the mechanisms of sound propagation of the sound transmitted from inside to outside of gear box, some experiments have been carried out by the following means: searching for the location of sound

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sources using "Acoustical holography"[13] [14] which can show the location of the sound sources; measuring the sound pressure and the phase angle close to the surface by the use of a microphone scanner; measuring the sound pressure level using a sound level meter(S.L.M.). From these experiments, we have revealed that the behavior of sound radiation from the housing depends on the frequency, and differs from the behavior of sound radiation from one plate.

2. Method of experiments

Figure 1 shows the dimensions of the tested housing. The names of each housing plate and direction from each hologram plane (top and front) to the housing are also indicated. The dimensions of the housing were determined considering the requirements that it should be intermediate size as a gear box, much larger than the speaker and easy to handle. For housings of 1.1mm and 2.3mm thickness, the four edges of front plate were formed by bending and the other edges were welded. On the other hand, a housing of 9.0mm thickness was made by welding all edges. Then there was no leakage of air in all housings.

Each Hologram (Top plane(a), Front plane(b)) was measured from each indicated direction
Material ; steel
Thickness; 1.1, 2.3, 9.0 mm

Fig.1 Dimensions of the test enclosure

Fig.2 Measuring of sound pressure and phase

One of the most effective apparatus in this paper is an acoustical holography system, which has been developed to visualize the sound sources of the object to be measured. Using this system, we can obtain two images of sound sources of the housing: one is a top view of the sound radiation and the other is a front view. And these two views from the top plane and the front plane, respectively, are obtained simultaneously. Measured images are shown in Figs.5 and 6, in which the solid line shows contour of the housing and the blank region shows the locations of the sound sources.

The other measuring apparatus is shown in Fig.2, that is used to know the acoustic field in the vicinity of housing. The measuring microphone (omnidirectional, 12mm in diameter) is set up on the microphone scanner, which is driven by pulse-motors for the acoustical holography. By the use of this system, the sound pressure and its phase difference from the reference signal are measured. The reference signal is used to drive a speaker inside the housing as a sound generator. In this measurement, a microphone moves parallel to the front plate. A speaker (100 mm in diameter), which is fixed on a wooden box having the dimensions of 250mm height, 200mm width, 165mm depth and 21mm thickness, is placed inside the housing 65mm distant from the front plate.

The following experiments were carried out with the input power to the speaker kept at 10W.

3. The result of experiments

3.1 Sound pressure response and phase near the housing

Firstly, as shown in Fig.3, for each housing, the sound pressure responses to the frequency at 3mm off the front plate are measured at every 10mm interval between upper and bottom edges. Figure 4 shows the measured results on 1.1mm thickness housing, where measuring points are located in 0mm, 270mm and 400mm (on the principal axis of the speaker) distant from the top edge. The result indicates that the sound pressure level for 6045Hz takes a peak value and it varies periodically in the vertical direction over the front plate. Thus we notice the response at this frequency (6045Hz).

Fig.3 Measuring the sound near the surface

Sound pressure level and its phase in the lateral direction are shown in Fig.5. Two measuring lines shown indicate where the maximum sound pressure occurs next to each other in the vertical scanning. The sound pressure distributions on both lines are quite similar to each other. The phase shifts on the lines AA' and BB' by 180° , where the sound pressure level takes a minimum value. Furthermore, the phase difference between the two measured lines (205mm and 235mm) is 180° . This feature is observed in the whole region on the measured lines. As the result, the nodal lines are at right angles to each other, then it is considered that the state of vibration of the front plate is resonant at the frequency of 6045Hz with a lattice shaped mode. Similar results are obtained at other resonant states and in other housings.

3.2 Result of acoustical holography

At the frequency of 6045Hz, a reconstructed image measured by the acoustical holography is shown in Fig.6.a. The images of the sound sources on the plate are located on a speaker axis and along the edges of rectangular housing. This result does not coincide with the sound pressure distribution described in the former section. Then, when the exciting

Fig.4 Sound pressure responses of the housing, 1.1mm thickness

Fig.5 Nature of the vibration over the surface, 6045 Hz

frequency and the thickness of housing vary, we examine how the reconstructed images change. The results on the housings of 1.1mm, 2.3mm and 9.0mm thickness are shown in Figs.6, 7 and 8, respectively. Measured frequencies are the resonant frequencies except for 7986Hz in 1.1mm thickness as in Fig.6.b where the image appears clearly on the principal axis of the speaker center.

In every frequency for 1.1mm thickness (Fig.6) and in range below 8600Hz for 2.3mm (Fig.7), the sources are located along the edges. On the other hand, at 12142Hz for 2.3mm thickness (Fig.7.d) and in every frequency for 9mm thickness (Fig.8), the sound is radiated from all over the surface. Especially, the results for 9.0mm thickness coincide with the measured sound pressure distribution by microphone scanning. Though the plate vibrates with the lattice mode at resonance in all measurements, as in Fig.5, the images are classified into two different types depending upon the relation between the thickness and the frequency.

Fig.6 Reconstructed images of the housing, 1.1mm thickness.

3.3 The relation between the thickness and the frequency on the reconstructed image.

As indicated by the sound pressure distribution, it is considered that the sound radiation at resonance is attributed to the bending vibration of the plate. The wavelength in an infinite plate λ_{pl} is determined by the following equation

$$\lambda_{pl} = \frac{c_{pl}}{f} = \frac{\sqrt[4]{\omega^2 B / \rho_s}}{f} \quad \text{----- (1)}$$

where,

c_{pl} ; velocity of bending wave in the plate (m/s)

f ; frequency (Hz)

ω ; circular frequency (rad/s)

B ; rigidity in bending

$$\cong Et^3 / 12(1 - \nu^2) \quad (\text{Kgf.m})$$

E ; Young's modulus (kgf/m²)

t ; thickness of plate (m)

ν ; Poisson's ratio

ρ_s ; density of plate in unit area (kg/m²)

And the wavelength of the sound in air λ_{air} is determined by

$$\lambda_{air} = \frac{c_{air}}{f} \quad \text{----- (2)}$$

where

c_{air} ; sonic velocity (m/s)

f ; frequency (Hz)

For the measured results shown in Figs. 6, 7 and 8, each wavelength is calculated from Eqs. (1) and (2), respectively, then the ratio of wavelength of the bending wave to that of the sound, $R = \lambda_{pl} / \lambda_{air}$, is obtained for each measurement. As the result, the relation between the reconstructed image and the value of R is shown in Fig. 9. It is clear that $R = 1.5$ gives a critical value; in the range below 1.5 for R , the sound source images are concentrated on the edge part, and in the range above 1.5 for R the images are distributed all over the surface of the plate.

Fig. 7 Reconstructed images of the housing, 2.3mm thickness.

Fig. 8 Reconstructed images of the housing, 9.0mm thickness.

Fig.9 Dependence of the radiation on the ratio $\lambda_{pl}/\lambda_{air}$

4. Discussions

Concerning the sound radiation from a rectangular plate, either "quadrupole cancellation" or "dipole cancellation" are known[2]. In the former case, the sound is radiated only from four corners (corner mode), in the latter case, it is radiated only from a pair of opposing edges (edge mode). But this theory cannot explain the sound radiation from all four edges of the housing.

4.1 The mechanism of sound generation in the case of $R < 1.5$ at resonance — influence of side plates.

For the elucidation of the phenomenon that the sound image appears only along the edge part of the housing, the following two ideas can possibly be available.

1) The sound is radiated actually from the edges.

2) Since the sound from the side plate has a strong directivity along the side plate, the sound image is observed on the edges of front plate.

To verify these ideas, the housing of 1.1mm thickness was excited at resonant frequency of 9500Hz where the sound image appeared on the edge remarkably under this condition. And the following examinations were performed.

1. When the sound radiation along the right side plate towards the front hologram plane is intercepted by glass wool as shown in Fig.10, the sound image on the right edge has disappeared. However, when the glass wool is moved backward 80mm from the front plate of housing, the sound image appears on the right edge again but the radiation power is still weak.

2. The sound pressure level was measured by the use of sound level meter (S.L.M) when the sound radiated from all

four side plates was intercepted by the glass wool as shown in Fig.11. In order to avoid the influence of the directivity of the radiated sound on the measurement, as shown in Fig. 12, the sound pressure level was measured at 284 points (4 lines, 71 points a line) at three distances which are 300mm, 600mm and 900mm from the front plate of housing. The results at each distance were averaged for the 284 points as given in Table 1. The sound pressure level has decreased by about 5dB as the result of interception of the sound from all side plates with glass wool.

Fig.10 Effect of glass wool treatment on the radiation, 1.1mm thick, 9500 Hz

Fig.11 Glass wool treatment on the four edges

3. In order to examine the vibration of the side plate, the sound pressure distribution on the left side plate was measured as shown in Fig.13, by the method shown in Fig.2. It is clear that the side plate is also at resonance.

4. In the reconstructed image under the condition shown in Fig.11, the sound image is observed on the edge, as shown in Fig.14, denoted by "with glass wool". However, the sound image on the speaker position is clearly observed unlike the reconstructed image without glass wool, denoted by "regular". This is caused by the fact that the power of sound image on the edge with glass wool is smaller than that without glass wool*. The ratio of radiation power calculated from the reconstructed image with glass wool to that without glass wool is about 1/4 (-6 dB). The reasons why the sound image on the edges weakly remains, are that the glass wool is not a sufficient sound absorber, and that the edges are also vibrating.

Therefore, in the range of $R < 1.5$ at resonance, the appearance of the sound image along the edge is attributed to the directivity of the sound radiated from the

side plate along its surface. In addition, since the edge does not satisfy an ideal boundary condition of simply supported or built in edge, it is considered, the edge is vibrating and radiating the sound weakly. Therefore, the corner mode, which should occur in the resonant plate with simply supported edge, is not observed.

4.2 The mechanism of sound generation in the case of $R > 1.5$ at resonance.

When the ratio "R" is greater than 1.5, as shown in Fig.8, for the housing with 9mm thickness, each reconstructed image shows a typical resonant state. The sound image does not exist outside the contour of the housing. Therefore, this image indicates the surface mode in which the sound is radiated from all over the surface.

In the case of housing of 9mm thickness at 6155Hz ($R=2.10$), the mode of vibration is clearly observed in the reconstructed image. The treatment with glass wool as shown in Fig.11, for the suppression of the effect from the side plate, does not affect the sound pressure level as shown in Table 2. Furthermore, the obtained holograms and the reconstructed images under both conditions have no difference as shown in Fig.15.a and b, respectively. Thus in this case, there is

Table 1 Mean sound pressure level at resonance; 1.1mm thickness, 9500 Hz, $R=0.91$

Distance (mm)	Without glass wool (dB)	With glass wool (dB)
300	63	60
600	62	57
900	61	55

Fig.12 Measurement of sound pressure level

* The reconstructed image by means of acoustical holography indicates the relative sound intensity distribution referred to the maximum intensity which is obtained from the calculation of each experiment. Therefore, when the glass wool is placed, the sound image located on the speaker, which is not observed without glass wool, becomes strong, and the sound image appears in the reconstructed image.

Table 2 Mean sound pressure level at resonance; 9.0mm thickness, 6155 Hz, $R=2.10$

Distance (mm)	Without glass wool (dB)	With glass wool (dB)
300	69	69
600	68	67
900	64	64

Fig.13 Sound pressure distribution over the left side plate, 9500 Hz

Fig.14 Effect of the glass wool on the four edges, 9500 Hz

no influence of the sound radiation from the side plates on the measurement, and the measured result shown in Table 2 is attributed to the sound radiation only from all over the surface of the front plate.

As a model of sound radiation from the lattice mode of vibration shown in Fig.15.a, a point source is placed on each antinode of vibration and the phase difference of adjacent point sources is set at 180° . The hologram and the reconstructed image are obtained by simulation with the help of computer and shown in Fig.15.c. The simulation result agrees with the measured one shown in Fig.15.a and b. Therefore, the surface mode in which the sound is radiated from all over the surface of the front plate is confirmed.

4.3 Effect of noise reduction

Comparing Table 1 and Table 2, input powers to the speaker are the same, but the housing of 9mm thickness is more noisy by about 5dB than the one of 1.1mm thickness. Transmission loss** of the plate is 44dB in the case of the housing of 1.1mm thickness at 9500Hz ($R=0.91$) and 58dB in the case of the housing of 9mm thickness at 6155Hz ($R=2.1$). Taking these values into consideration, the housing with 1.1mm thickness is much more effective by about 20dB to reduce the noise. This effect is attributed to the differ-

ence of radiation mechanism from a resonant plate in either range of "R" bounded on the value of $R=1.5$. The radiation ratio which gives the efficiency of sound radiation for the plate is applied to sound radiation for the housing.

Thus, in the range of $R < 1.5$, the housing radiates small amount of radiation power to the acoustic field. Considering the housing which is used in the experiment, the frequency corresponding to $R=1.5$ is about 25kHz in the case of housing with 1.1mm thickness and about 3kHz in the case of housing with 9mm thickness respectively. It is one of the effective methods for the design of low noise gear system to arrange such that the meshing frequency of gear and natural frequencies of gear blank and shaft do not coincide with resonant frequency of housing. And it is more important that the main frequency component of noise source be made in the region of $R < 1.5$, for example, in the case of 9mm thickness the frequency of noise be below 3kHz.

4.4 Sound radiation in the case of housing at anti-resonant state

In the case of housing excited at anti resonance, as shown in Fig.6.b, 1.1mm thickness at 7986Hz, the sound image appears on the location of speaker and the edges. It is considered that the sound image on the location of speaker is caused by the sound pressure acting as a vibration force on the plate. In order to understand the image on the edge, the following experiments have been carried out.

1. As shown in Fig.16, in order to intercept the sound radiation from the right side plate, glass wool was placed just as in the experiment at resonant state. When the glass wool was placed close to the edge, the sound image on the edge became weak. However, when the glass wool was placed backward a little far from the edge, the image became similar to the one without glass wool.

2. The glass wool was placed to intercept the sound radiation from the side plates as shown in Fig.11. The measured result on the sound pressure level as shown in Fig.12, is indicated in Table 3. The level does not differ from the level without glass wool in Table 3. And it is clear that the level without glass wool in Table 3 is about 20dB lower than the level in Table 1.

As mentioned above, the sound image observed on the edge is produced by the

Fig.15 Sound radiation under the condition of $R > 1.5$ and the simulated result

** Transmission loss "TL" is expressed as

$$TL = 10 \log \left\{ 1 + \left(\frac{\rho_s \omega}{2 \rho_{air} c_{air}} \right)^2 \right\} - 10 \log \left[2.31 \log \left\{ 1 + \left(\frac{\rho_s \omega}{2 \rho_{air} c_{air}} \right)^2 \right\} \right] \text{ dB}$$

where ρ_s ; density of plate (kg/m^2)
 ω ; circular frequency (rad/s)
 ρ_{air} ; density of air (kg/m^3)

Fig.16 Effect of glass wool on the side plate, 1.1mm thickness, 7986 Hz, (anti resonance)

actual vibration of the edges. Therefore, on the sound radiation at anti resonant state, the plate located near the speaker in the housing is excited by the sound pressure inside the housing, then the excitation produces a bending wave in the plate, and the bending wave propagates in the plate to the edge, and the wave is influenced by the wave propagating in the side plate at the edge, finally the edge vibrates and radiates the sound strongly. However, the acoustic power flow at anti resonant state is no larger than the one at resonant state.

5. Conclusions

In this paper, we have investigated the mechanism of sound radiation from a rectangular housing as a model of gear box containing a speaker. The results of this study by the use of acoustical holography system are summarized as follows:

1. Sound radiation from the housing containing a speaker is different depending on whether the plate is resonant or anti resonant.

2. At resonant state; when the ratio R of the wavelength of the bending wave propagating in the plate to that of the sound radiated from the housing ($\lambda_{pl}/\lambda_{air}$), is greater than 1.5, the sound is radiated from all over the surface of the plate. On the contrary, when $R < 1.5$, the sound images appear only on the edges. It is

Table 3 Mean sound pressure level at anti resonance; 1.1mm thickness, 7986 Hz

Distance (mm)	Without glass wool (dB)	With glass wool (dB)
300	44	44
600	43	42
900	43	42

revealed that the sound is emitted mainly from the side plates along their surfaces, and additionally from the edges themselves. Further, the radiation power is smaller than that in range $R > 1.5$.

3. At anti resonant state; the sound is radiated from both the edges and the region where internal acoustic excitation is strong. But the radiation power is smaller than that in the resonant state.

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