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Yamaguchi, Zenzo
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Sakagami, Kimihiro
Morimoto, Masayuki

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Numerical Study on Reduction of the Elevated Structure Noise by Surface Absorption on Plate Girders

Kazutoshi Michishita*, **Zenzo Yamaguchi****[+], **Noboru Nakajima****[++], **Kimihiro Sakagami**** **and Masayuki Morimoto****

*Kyoto Research & Development Centre, Kinden Corporation, 3-1-1 Saganakadai, Kizugawa, Kyoto 619-0223, Japan, and Graduate School of Science & Technology, Kobe University, Rokko, Nada, Kobe 657-8501, Japan.

**Environmental Acoustics Laboratory, Graduate School of Engineering, Kobe University, Rokko, Nada, Kobe 657-8501, Japan.

[+]Present address: Kobe Steel, Ltd., Kobe, Japan

[++]Present address: Kajima Corporation, Tokyo, Japan

Corresponding author:	Kazutoshi Michishita
Corresponding address:	Kyoto Research & Development Centre, Kinden Corporation, 3-1-1 Saganakadai, Kizugawa, Kyoto 619-0223, Japan
Tel:	+81 774 73 0730
Fax:	+81 774 73 0735
e-mail:	michishita_kazutoshi@kinden.co.jp

ABSTRACT

With the aim to propose a reasonable and effective countermeasure for the elevated structure noise, the sound field radiated by a steel plate girder, which is the main source of the elevated structure noise, have been theoretically analysed. In the present study, steel plate girders are modelled as infinitely long elastic plate strips placed in parallel and numerical examples on the sound field radiated by the steel plate girders are shown. In the analysis of the radiated sound field, the equivalent source method is employed. Effect of the surface absorption on the sound field radiated by the girders is discussed through numerical examples. The results show that the surface absorption is effective for reduction of the radiated sound field, especially in the area that increase of sound pressure due to reflection by adjacent plate girders is observed. Furthermore, to design for reasonable countermeasure, variation of the noise reduction effect due to changing the pattern of surface absorption area on plate girders is classified.

Keywords: elevated structure noise, steel plate girder, sound absorption, the equivalent source method

1 Introduction

Recently, the elevated structure noise has become one of the main sources of road traffic noise around elevated motorways. Some studies in attempt to establish a prediction model of the elevated structure noise have been performed, and *in situ* measurement data have been published [1-4], however, few studies to discuss a countermeasure have been reported. An undercover enclosing the girders is known as the only effective countermeasure against the elevated structure noise [5]. However, it is originally aimed to reduce the reflection of the noise from an underpass by under surface of the elevated motorways and it can be excessive in some situations in which only the elevated structure noise is concerned. Considering countermeasures, it is necessary not only to be acoustically efficient, but also to be reasonable. Therefore, to establish a countermeasure, a physical insight into the phenomenon of the problem is required. To gain the physical insight, a theoretical study is useful.

In the previous studies, the authors have analysed the sound field radiated by an infinitely long elastic plate strip, which is a simple model of a web plate of a steel plate girder [6, 7]. In those studies, it is confirmed that the steel plate girder can be the main source of the elevated structure noise around the motorway with a concrete slab. The radiated sound field by a steel plate girder changes in a complex manner due to the presence of the various elements of the elevated structure, e.g., concrete slab, adjacent steel plate girders and braces in actual condition of an elevated motorway. The elevated structure noise is affected by a reflection and diffraction due to the presence of these elements. This means that it is possible to reduce the elevated structure noise by controlling not only the sound radiation from the plate girders, but also the reflection and diffraction due to the other surrounding elements. Therefore, to establish an appropriate countermeasure for elevated structure noise, it is necessary to clarify the effect of acoustical phenomena due to the motorway elements on the sound field radiated by each steel plate girder, and considering the some elements of the elevated structure as one sound source system is more advantageous than dealing with each element individually.

A concrete slab and adjacent steel plate girders are likely to affect the most the sound field radiated by each steel plate girder due to those location and dimensions. For this reason, the effect of a concrete slab on the sound field radiated by a steel plate girder has been analysed in the previous study [8]. In the same study, a steel plate girder in contact with a concrete slab is modelled as an infinitely long elastic plate strip in contact at its edge with an infinite reflecting surface. The results obtained indicate that the effects of a slab appear mainly at lower frequencies than the frequency range (500-1000 Hz) where the main component of the elevated structure noise is observed. This results imply the sound absorption on the under surface of a slab cannot be effective for reduction of the elevated structure noise.

The effects of adjacent steel plate girders on the sound field radiated by each steel plate girder has been analysed in the previous study [9]. In that study, steel plate girders are modelled as infinitely long elastic plate strips placed in parallel and in contact at their edges with an infinite reflecting surface. The results obtained indicate that the elevated structure noise level at certain locations around motorways, which in many cases corresponds to residential area, should be larger than the simple sum of the direct sound pressures radiated from each steel plate girder due to the reflections between the girders. According to these results, the control or suppression of the reflections is suggested to be one of the countermeasures for the elevated structure noise.

The surface absorption of the plate girders is simple as a countermeasure to suppress the reflections and it seems to be practical method. The aim of this study is to reveal the effect of the surface absorption on the elevated structure noise level. Furthermore, to design for reasonable countermeasure, variation of the effect due to changing the pattern of surface absorption area on plate girders is clarified.

In the analysis of the radiated sound field, the equivalent source method is employed. The method is based on the idea that a real source can be replaced by free-field radiating sources which fulfil the given boundary conditions. This basic idea is used in different way focussing mainly on the acoustic radiation problem [10-13].

2 Analysis procedure

Figure 1 shows the two-dimensional calculation model of steel plate girders with a concrete slab. The variations of the effects of adjacent plate girders on the radiated sound field due to the varying number of the girders are demonstrated in the previous study [9]. In the same study, the results imply that the effect of the adjacent girders is hardly changed even if the number increases more than four. Considering the actual motorways and the result of the previous study, the effect of sound absorption on the surface of plate girders on the sound field with five girders is analysed in this study. The steel plate girders are modelled by infinitely long elastic plate strips in contact at their edges with the concrete slab. Although a concrete slab has finite width, it is modelled as a rigid infinite reflecting surface, and its effect on the sound field is taken into account by introducing the image sources of the girders to simplify the model. This model of a concrete slab should be reasonable according to the result of the previous study [8], because the acoustical effect of the slab appear mainly at frequencies lower than the main component of the elevated structure noise. The infinitely long plate strips of thickness h have the width L_x, and the distance between the girders is d as shown in Fig. 1.

Following the equivalent source method, the boundary conditions for both the real and image sources have to be fulfilled by equivalent sources. Because the boundary condition on girders is fulfilled by equivalent sources, the sources do not have to be mirrored by the adjacent plate girders. Line sources are used as the equivalent sources in the present study. The boundary condition for the sound field and the transfer function of the equivalent sources are needed for the analysis. The surface absorption of the girders is considered by introducing acoustic admittance ratio to the surface of the girders.

The particle velocity on the plate surfaces is identical to the vibration velocity of the plates in the case that the plate surfaces have no sound absorptivity. In the case that the plate surfaces have sound absorptivity and that the plate surfaces does not vibrate, the particle velocity on the plate surface is p/Z. Here, p is the sound pressure and Z is the specific acoustic impedance on the plate surface. Therefore, the particle velocity on the left-hand side surface of the plate v'_{left} which vibrate with vibration velocity v in Fig. 1 is expressed as $v'_{left} = v + p/Z$. On the right-hand side surface in Fig. 1, the particle velocity v'_{right} is expressed as $v'_{right} = v - p/Z$. Therefore, the boundary condition for the sound field is expressed using the vibration velocity of the elastic plate.

Because a plate girder has I-shaped section, the downward ~~side~~ edge of the plate girder as shown in Fig. 1 is stiffened for z-direction motion by the flange plate and it could be rotated with twist of the flange plate [14]. On the other ~~side~~ edge of the plate girder, i.e., the ~~side~~ edge that the flange plate contacts to a concrete slab, the connection between the web plate and the flange plate should behave like a simple support rather than a clamped support because the stiffness of the web plate is ~~weaker~~ smaller than that of the flange plate. Thus, although the edges of the web plate are not ~~simple~~ simply supported strictly, the edges of each web plate ~~are~~ can be assumed to be simply supported to the first approximation in this study to derive an analytical expression of the vibration pattern of a web plate as boundary conditions. Girders are usually connected to a slab, and the vibration of the slab is supposed to excite the girders. Therefore, although the actual excitation conditions of the girders have not been clarified due to the structure's complexity, each steel plate girder is assumed to be excited by a line moment at its edge. The line moment excitation can cause all possible vibration modes [6]. The vibration pattern of a web plate strip generated by the line moment excitation is calculated from an analytical expression in which the acoustic loading to the strip is assumed to be negligible. This assumption is reasonable as long as the strip is much more massive enough compared to the surrounding medium [15].

When the plate strip is excited by a harmonic line force of amplitude F_0 at $x = l$ and vibrates with the displacement $w(x)$, the equation of motion of the plate strip is:

$$D\nabla^4 w(x) - \rho_p h\omega^2 w(x) = -F_0\delta(x-l)\,. \qquad (1)$$

Here, $D = Eh^3(1-i\eta)/12(1-\nu^2)$ is the flexural rigidity of the plate, where E is Young's modulus, h is the thickness, η is the loss factor, and ν is the Poisson's ratio of the plate. In the above equation, ρ_p is the plate's density, ω is the angular frequency, and δ denotes the Dirac delta function. The time factor $\exp(-i\omega t)$ is suppressed throughout. The x-dependent function $w(x)$ can be expanded into a series of the eigenfunctions satisfying the boundary condition for the plate vibration. The solution for a moment excitation can be derived in a similar procedure to Refs. [16, 17]. By adding the displacement due to a line force of equal magnitude with the opposite sign at $x = l - \Delta x$, and taking the limit of $\Delta x \to 0$ with $F_0 = M_0 / \Delta x$, the displacement due to a line moment acting at $x = l$ is obtained. Substituting $l = 0$, the displacement by a moment excitation on the strip edge is obtained. Finally, the vibration velocity by a moment excitation on the strip edge is derived as:

$$v_{real}(x) = \sum_n \frac{2i\omega M_0 k_n}{DL_x(k_n{}^4 - \mu^4)} \sin k_n x; \quad k_n = n\pi / L_x\,, \quad n = 1, 2, 3, \cdots, \quad 0 \le x \le L_x \qquad (2)$$

where $\mu^4 = \rho_p h\omega^2 / D$. Equation (2) is used as the boundary condition for the real source. The boundary condition for the image source is also obtained from Eq. (2) as:

$$v_{image}(x) = -\sum_n \frac{2i\omega M_0 k_n}{DL_x(k_n{}^4 - \mu^4)} \sin k_n x \ , \qquad -L_x \le x \le 0 \tag{3}$$

The velocity potential $\phi_m(\mathbf{r},\mathbf{r}_0)$ at an arbitrary point in a two-dimensional free field $\mathbf{r} = (x, z)$, produced by a monopole line source at $\mathbf{r}_0 = (x_0, z_0)$ with the volume velocity U per unit length, is given by [18]:

$$\phi_m(\mathbf{r},\mathbf{r}_0) = U\frac{i}{4}H_0^{(1)}(k_0 \,|\, \mathbf{r}-\mathbf{r}_0 \,|), \tag{4}$$

where $H_0^{(1)}$ is the first kind Hankel function of order zero, $k_0 = \omega / c_0$ is the acoustic wavenumber, where c_0 is the sound speed in the air. The particle velocity in z-direction on the plate surface at $\mathbf{r} = (x, z)$, which is produced by the j-th line source located at $\mathbf{r}_j = (x_j, z_j)$, is obtained from Eq. (4) as:

$$v_j(\mathbf{r}) = -\frac{\partial \phi_m}{\partial z} = U_j \frac{ik_0(z - z_j)}{4\,|\, \mathbf{r}-\mathbf{r}_j \,|} H_1^{(1)}(k_0 \,|\, \mathbf{r}-\mathbf{r}_j \,|) \ , \tag{5}$$

where U_j is an unknown volume velocity to be determined later to fulfil the boundary conditions given by Eqs. (2) and (3). The sound pressure on the plate surface at $\mathbf{r} = (x, z)$, which is produced by the j-th line source located at $\mathbf{r}_j = (x_j, z_j)$, is obtained from Eq. (4) as:

$$p_j(\mathbf{r}) = \rho_0 \frac{\partial \phi_m}{\partial t} = U_j \frac{\rho_0 \omega}{4} H_0^{(1)}(k_0 \,|\, \mathbf{r}-\mathbf{r}_j \,|), \tag{6}$$

where ρ_0 is the air density.

The particle velocity of the right-hand side surface of each plate girders and its image sources in Fig.1 by equivalent sources is expressed as:

$$v(x) = \sum\nolimits_{j=1}^{n} (v_j + \frac{p_j}{Z_j}) = \sum\nolimits_{j=1}^{n} (v_j + \frac{p_j A}{\rho_0 c_0}), \tag{7}$$

where n is the number of the line sources, A is acoustic admittance ratio and c_0 is sound velocity. On the left-hand side surface of each plate girders and its image sources in

Fig.1 by equivalent sources is expressed as:

$$v(x) = \sum_{j=1}^{n} (v_j - \frac{p_j}{Z_j}) = \sum_{j=1}^{n} (v_j - \frac{p_j A}{\rho_0 c_0}) \tag{8}$$

If the set of unknown volume velocity U_j is determined by Eqs. (7) and (8), the sound pressure p is calculated as the sum of the sound pressure contributed by all the monopole line sources, i.e., the equivalent sources:

$$p(\mathbf{r}) = \sum_{j=1}^{n} p_j = \sum_{j=1}^{n} U_j \frac{\rho_0 \omega}{4} H_0^{(1)}(k_0 |\mathbf{r} - \mathbf{r}_j|) \tag{9}$$

The number of equivalent sources needs to be large enough to make possible the sound field calculation, up to the highest frequency of interest [12]: in the present study, the number of equivalent sources per wavelength is at least eight in the x-direction in Fig. 1. The plate surfaces as the boundary condition have width, while the particle velocity calculated by Eq. (5) is on the point $\mathbf{r}$. To make more accurate value, an element is divided to sub-element and the average of Eq. (5) from a line source to the surface of sub-elements is calculated [7].

Numerical calculations have been performed assuming the following plate's properties: $E = 10^{11}$ Nm^{-2}, $\eta = 10^{-3}$, $\rho_p = 8000$ kgm^{-3}, $\nu = 0.3$, $h = 0.02$ m, $L_x = 2.0$ m, $d = 3.5$ m, unless otherwise noted. These are common values for actual steel plate girders of elevated motorways.

3 Numerical results and discussion

3.1 The effects of absorption on the all surfaces of plate girders

The effect of the surface absorption of the plate girders when all the girders are excited and radiate the sound is calculated. The vibration of the slab is assumed to be in 'diffuse' condition at high frequency range. Therefore, the excitation force and the vibration of the girders are incoherent to each other, and the sound pressures radiated from each steel plate girder are treated as incoherent in this study. Namely, the sound field radiated by five girders as the sum of sound pressure radiated by each plate girder in the presence of the other four girders that are assumed to be immobile is calculated. In the previous study [5], the results imply that the effect of the surface absorption is hardly changed even if the number increases more than four.

Figure 2 shows the effect of the surface absorption in the A-weighted 2-octave band sound pressure in the case that the specific acoustic admittance of absorption surfaces is 0.172. This value corresponds to the normal absorption coefficient of 0.5, and it has reality in the scope of countermeasures for the elevated structure noise. The 2-octave band sound pressure is calculated by integration of the values at each 1/9-octave included in the two 1/1-octave band centred at 500 Hz and 1000 Hz. The value in Fig.2 indicates the level difference between with and without surface absorption at the dot point, i.e., larger number indicate the larger noise reduction effect. The result shows that the surface absorption can be effective for the elevated structure noise, especially in the area of more than 10 metre apart from the centre of the elevated motorway which is usually the residential area; the average value is 3.7 dB. This is sufficient value in the scope of traffic noise reduction.

3.2 Thorough investigation on the acoustical phenomena

For thorough discussion on the effect of the surface absorption on the radiated sound field, the sound field radiated by two steel plate girders are analysed, and the effects of the adjacent steel plate girder on the radiated sound field and the noise reduction effect of surface absorption are discussed in numerical examples.

To clarify the effect of reflection and diffraction due to the adjacent girder, only the girder 1 is assumed to vibrate and radiate sound, and the girder 2 is assumed to be immobile. Girders 3, 4 and 5 are absent. The sound pressure level difference (*LD*) between the cases with and without the girder 2 is calculated for 1/3-octave band centred at 1000 Hz. These are the frequencies where the main component of the elevated structure noise is observed. The *LD* is obtained by integrating the *LD*s for every 1/27-octave within the 1/3-octave band. The calculation is performed at every 0.5 m grid points in the calculation area described in the caption to Fig. 1. Positive or negative *LD* indicates the increase or decrease of the sound pressure level due to the presence of the girder 2, respectively.

Figure 3 shows the calculated *LD* in the case that the plate surfaces have no sound absorptivity. The *LD* distribution is complicated because of the interference, however, there are tendencies. In the region $90° \leq \theta \leq 180°$, the positive *LD* is observed at many receiving points. These increases in sound pressure are caused by reflections due to the presence of the girder 2. In this region, the *LD* is small in $170° \leq \theta \leq 180°$ but especially large in $140° \leq \theta \leq 165°$. For the former, the reason is that the girder 1 works as a sound barrier on the reflected sound from the girder 2. For the latter, the reason will be discussed later. Turning now to the region $0° \leq \theta \leq 90°$, the negative *LD* is observed in $0° \le \theta \le 40°$ because the girder 2 works as a sound barrier on the radiated sound from the girder 1. However, the large positive *LD* observed at around $\theta = 20°$. This increase in sound pressure is caused by the reflected sound from the girder 1, i.e., multiple reflections. It is noted that these receiving points and the region $140° \le \theta \le 165°$ mentioned above locate symmetrically to each other. Therefore, the large increase in the sound pressure observed in $140° \le \theta \le 165°$ can contain the effect of the multiple reflections. These results suggest that the elevated structure noise level at residential area around motorways should be larger than the simple sum of the sound pressures radiated from each steel plate girders. Therefore, the noise level can be supposed to be reduced when the surfaces have absorptivity, because the reflections between the plate girders are suppressed.

Figure 4 indicates the effect of surface absorption on the sound field radiated by girder 1 and girder 2 for 1/3-octave band centred at 1000 Hz. Fig. 4 is drawn in the region $1.75\,\mathrm{m} \le z \le 31.75\,\mathrm{m}$ because the radiated sound field becomes symmetrical in this case. In comparison with Fig. 3, it is confirmed that the sound pressure at around $\theta = 20°$ which is the area that the sound reflections affect significantly decreases. The surface absorption can reduce the radiated power from the girders itself, however, this result indicates that the surface absorption can suppress the reflection between the girders and the suppression of the reflection can reduce the noise level in the residential area around elevated motorway.

3.3 Design guide on surface absorption patterns

Considering the practical applications, an economical countermeasure is preferred. On the method of surface absorption, if possible, it is better to obtain the good acoustical effect with smaller absorption area. Thus, the variation of the acoustical effect according to the absorption pattern is calculated and the results are classified according to noise reduction effect. The results are shown in Table 1. The effect is calculated as the average of the discrete points in the region of 10 metre apart from the centre of the elevated motorway which is the same as in Fig. 2.

Generally speaking, the number of sound absorption surface becomes larger, the noise reduction effect becomes large. However, despite of the number of absorption surface of pattern (f) is larger than pattern (g), the noise reduction effect of the pattern (f) is smaller than that of the pattern (g). This result indicates that the effect cannot be determined by the number of absorption surface.

In the case that the number of absorption surface is 8, the pattern (b), (c) and (d) have the absorption area on the outside surface on two outer girders as shown in Table 1. On the other hand, the pattern (e) and (f) have the absorption area on the outside surface of only one of the two outer girders. Table 1 shows that the noise reduction effect of pattern (b), (c) and (d) are greater than that of the pattern (e) and (f). As mentioned above, the effect of pattern (g) which also has the absorption area on the outside surface of two outer girders is greater than that of the pattern (f), though the number of absorption surface is smaller than that of the pattern (f). These results indicate that the absorption on the outside surfaces of two outer girders is effective in the scope of noise reduction.

Furthermore, Table 1 shows that the noise reduction effect of the pattern that the number of the absorption surface is 5 can be equal to the effect of the pattern that the number of the absorption surface is 8 for one side on the elevated motorway.

4 Summary

The sound field radiated by infinitely long elastic plate strips in parallel has been numerically analysed. This is a simple model for the sound field radiated by steel plate girders in contact with a concrete slab.

Numerical examples indicate that the surface absorption can reduce the elevated structure noise level according not only to the reduction of radiated power from the girders, but also to the suppression of the sound reflection between girders. The noise reduction effect by the making the absorptive of the surface 50 % can be expected about more than 3 dB. This effect may be sufficient in the scope of traffic noise countermeasure

Furthermore, the variation of the acoustical effect according to the absorption pattern is calculated and classified according to noise reduction effect. It is important that the outside surface on two outer girders should be absorptive.

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Captions of Figures

Figure 1: The model of steel plate girders with a concrete slab for analysis by the equivalent source method: ● the equivalent sources (line sources).

Figure 2: Effect of the surface absorption in the A-weighted 2-octave band (the sum of 1/1-octave bands centred at 500 Hz and 1000 Hz) sound pressure. The specific acoustic admittance of absorption surfaces is 0.172.

Figure 3: Sound pressure level difference (*LD*) between the cases with and without the girder 2 on the sound pressure radiated by the girders 1 and 2 for 1/3 octave bands of centre frequencies at 1000 Hz. Grey scale indicates 1 dB level difference. White zone indicates decrease of the sound pressure and black zone indicates more than 6 dB increases due to presence of the girder 2. The calculated area is $0\,\mathrm{m} \le x \le 15\,\mathrm{m}$ and $-28.25\,\mathrm{m} \le z \le 31.75\,\mathrm{m}$ in Fig. 1.

Figure 4: Effect of surface absorption on the sound field radiated by the girders1 and 2 for a 1/3 octave band of centre frequency at 1000 Hz. The specific acoustic admittance of absorption surfaces is 0.172. Other parameters for calculation are the same as in Fig. 3. White zone indicates more than 6 dB decrease of the sound pressure and black zone indicates increases in pressure due to surface absorption of the girders. The calculated area is $0\,\mathrm{m} \le x \le 15\,\mathrm{m}$ and $1.75\,\mathrm{m} \le z \le 31.75\,\mathrm{m}$ in Fig. 1.

Table 1: Classification of surface absorption patterns according to noise reduction effects. Effect in the table indicates average reduction level in the area $0\,\mathrm{m} \le x \le 15\,\mathrm{m}$ and $17\,\mathrm{m} \le z \le 42\,\mathrm{m}$ in Fig. 1.

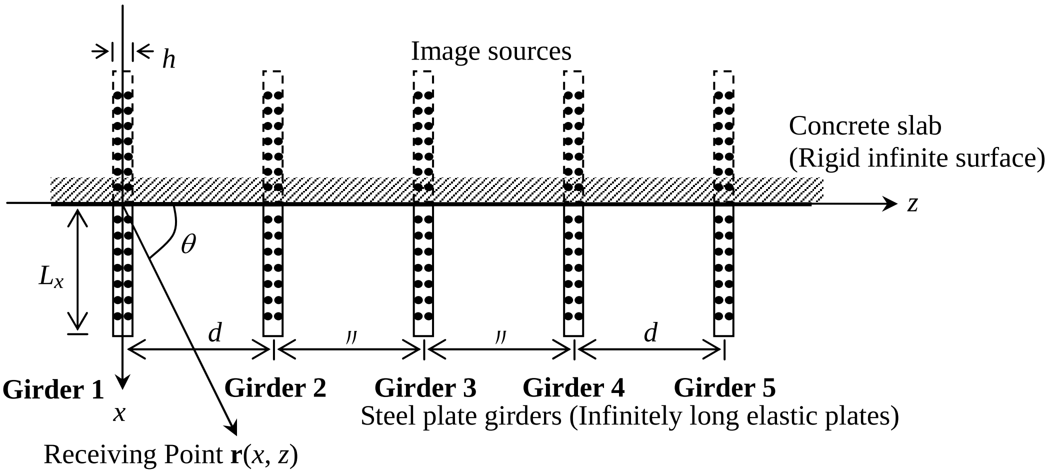


Figure 1

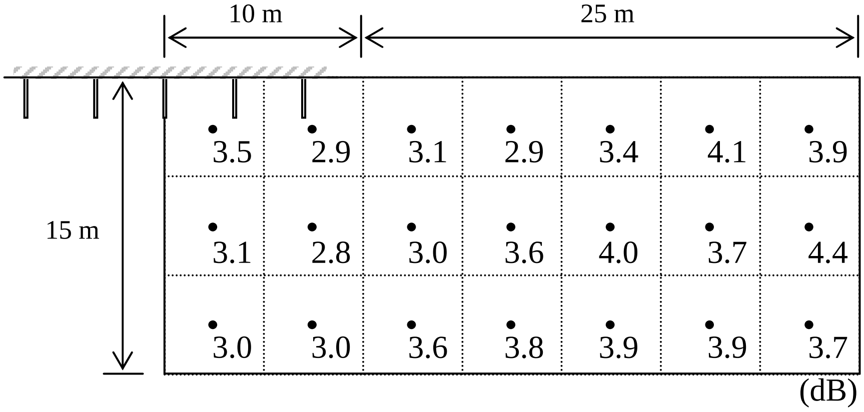


Figure 2

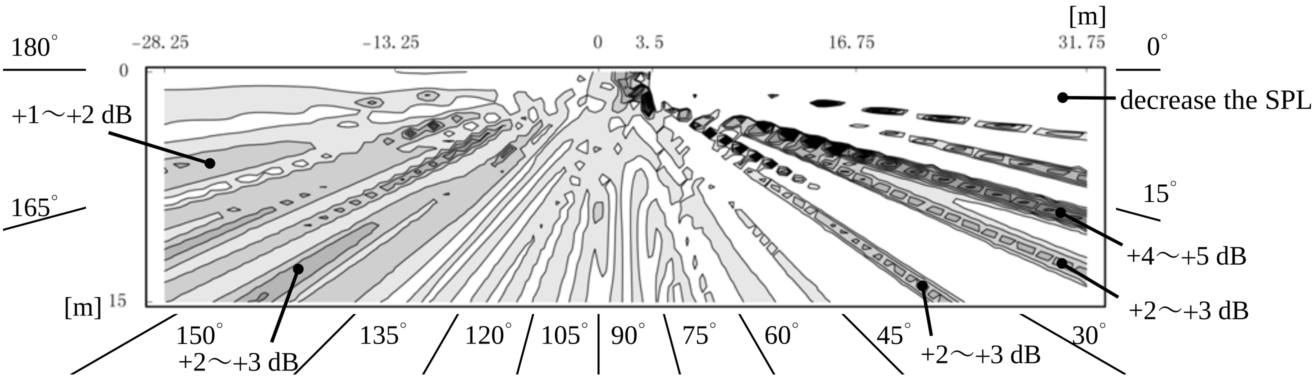


Figure 3

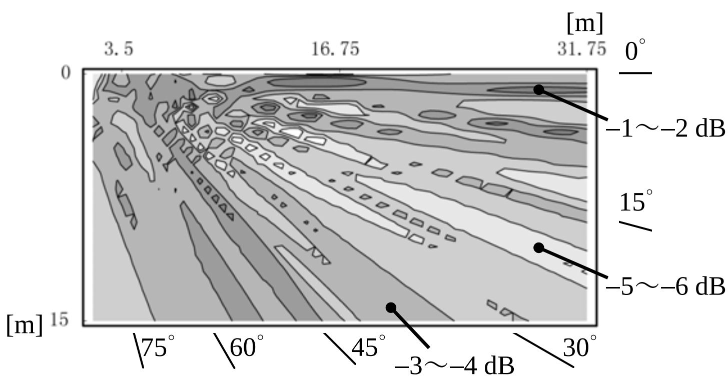
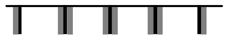
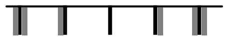
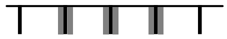
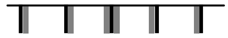


Figure 4

Table 1

Rank	Effect	Absorption pattern with the number of absorption surfaces (: absorption surface)			
A	3.9dB ≀ 3.5dB	(a) 10 (all) 			
A’	3.4dB ≀ 3.0dB	(b) 8 	(c) 8 	(d) 8 	(q) 5 (for right-side) 
B	2.9dB ≀ 2.5dB	(e) 8 	(g) 6 		(r) 5 (for right-side) 
B’	2.4dB ≀ 2.0dB	(f) 8 	(h) 6 	(i) 6 	(s) 4 (for right-side) 
		(j) 6 	(k) 6 	(l) 6 	
C	1.9dB ≀ 1.5dB	(m) 6 	(n) 6 	(o) 6 	(p) 6