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Prediction by Numerical Simulation of Conventional Railway Noise Including Structure Noise




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Taking countermeasures against sound for steel railway bridges along conventional lines where structure noise stands out is an important issue for JR East. However, a method of quantitatively predicting noise along the track including structure noise generated from steel railway bridges has not yet been put in place.

We thus surveyed structure noise and vibration on conventional line railway bridges in the Kanto area, and measured vibration at main vibration locations on steel railway bridges and relation to structure noise radiating with that vibration. Then, based on the measurement results, we put together a procedure for predicting structure noise using the vibration of steel railway bridges and finally established a method for predicting conventional line noise including structure noise by the finite-difference time-domain (FDTD) method.

As a result, we were able to predict at accuracy of around 3 dB or less. Furthermore, we confirmed that noise could be predicted at the same accuracy level in verification measurement conducted at measurement points of the same structural form.

●Keywords: Numerical simulation, Structure noise, Conventional railway noise, FDTD method

1 Introduction

Along conventional lines, we receive many complaints regarding steel railway bridges where structure noise stands out, so countermeasures against structure noise at steel bridges is an important issue. Development of construction methods that can control structure noise has been carried out in the past or is underway. However, a method of quantitatively predicting and evaluating noise along the track including structure noise generated from steel railway bridges, which is needed to propose an effective noise control construction method, has not yet been put in place.

We thus surveyed and measured structure noise and vibration at an I-shaped steel deck girder ("I-girder 1": Fig. 1) and steel deck box girder ("box girder 1": Fig. 2) of a steel bridge and at flat ground (Fig. 3) along a conventional line in the Kanto area[1]. Based on the measurement results, we investigated vibration on main vibrating locations on steel railway bridges and relation to the structure noise radiating with that. Then, we put together a procedure for predicting structure noise using the vibration of steel railway bridges and finally established a method for predicting conventional line noise including structure noise by the FDTD method.

This article will report on a comparison of actual and predicted values at an I-shaped steel deck girder ("I-girder 2) and a steel deck box girder ("box girder 2") having the same structural form and the results gained from verification tests. The comparison and verification were conducted to confirm the appropriateness of the developed prediction method.

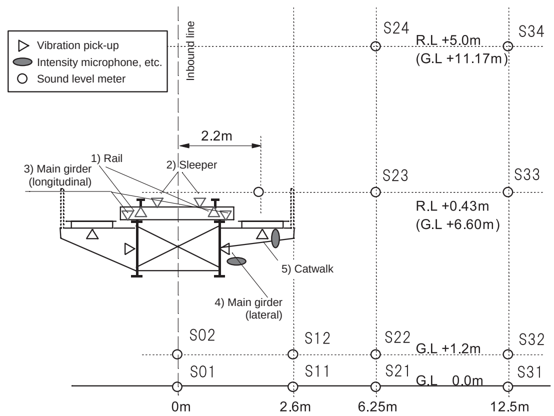

Fig. 1 Measurement Points on I-girder 1

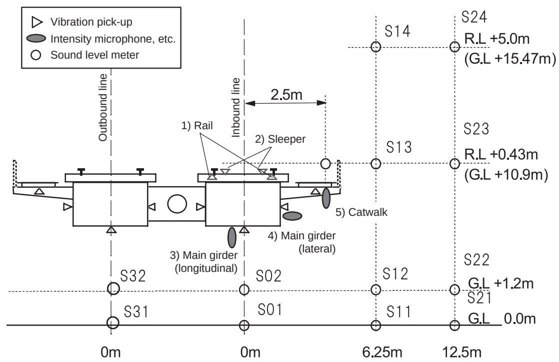

Fig. 2 Measurement Points on Box girder 1

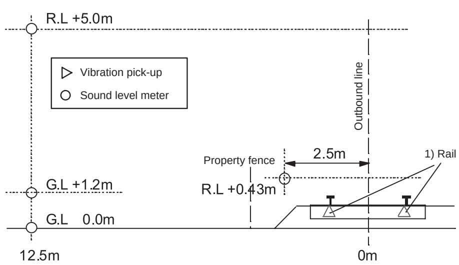

Fig. 3 Measurement Points on Level Ground

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2 Survey of Structure Noise and Measurement of Vibration

2.1 Survey Overview

An overview of the survey carried out on a conventional line in the Kanto area is as follows.

I-girder 1, box girder 1 and flat ground along a conventional line in the Kanto area were selected as survey points with little noise from rail joints, as shown in Fig. 1–3.

In the survey, we measured noise in two cases: where an actual train ran and where an artificial vibrator was used. For those cases, we presumed radiating power of the noise radiated along with the vibration of the structure.

2.2 Survey Method

2.2.1 Rail Vibrating Test

As shown in Fig. 4, we vibrated rails by hammering and measured noise, vibration and sound intensity at the measurement points. To prevent the effect of the radiated sound from the hammered point of the rail, we tried to reduce that radiated sound by enclosing the hammering point with a sound insulating box. In this way, we identified the structure noise by rail vibration and estimated the relation between the vibration of the main structure and the radiated sound.

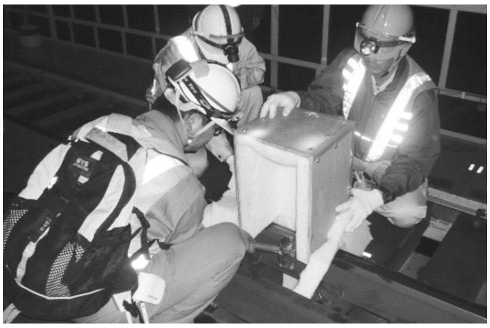

Fig. 4 Rail Vibrating Test

2.2.2 Survey of Noise and Vibration Caused by a Running Train

At the measurement points, we measured noise, vibration and sound intensity when a train ran. To eliminate the influence of train mechanical noise and the wheel/rail noise, we later measured rolling stock noise (train mechanical noise and wheel/rail noise) of the same train in the flat section and subtracted that from the noise at the steel bridge in terms of energy. In this way, we were able to estimate structure noise.

Track conditions differ between the steel bridge section without ballast and the flat section with ballast. Thus, as shown in Fig. 5, we set a speaker that radiated test sound of the same power on the track of each survey section to consider the difference of transmission characteristics of rolling stock noise and wheel/rail noise according to the track structure. To compare vibration of the structure and radiated sound, vibration caused by a running train was evaluated as vibration speed. The standard vibration speed level was set as 5×10^{-8} m/s.

Fig. 5 Speaker Test

2.3 Relation between Vibration of Major Parts of the Steel Bridge and Radiated Sound

When a train passes on a steel bridge, vibration transmitted from the rails to the parts of the bridge that vibrate causes radiated sound (structure noise). The source of the structure noise caused by the vibration by a passing train is considered to be of the same length as that of the train on the bridge. Therefore, radiation power of the whole source of the structure noise can be calculated from the area of the virtual boundary surfaces that enclose each vibrating member as shown in Fig. 6 and the sound intensity passing the point involved.

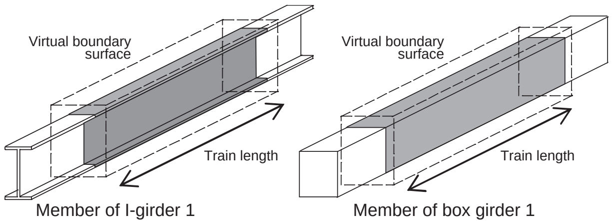

Fig. 6 Virtual Boundary Surfaces Enclosing Vibrating Members

As the procedure of calculating the radiation power of the whole source of the structure noise caused by vibration by a passing train, we first looked into the relation between vibration speed and radiated sound based on the measurement results of vibration speed level at major vibrating members of the bridge and the sound intensity level at nearby points when the rails were vibrated (Fig. 7, 8). Next, from the results shown in Fig. 7 and 8, we estimated the intensity of radiated sound from each part according to the vibration speed at the train passing (Fig. 9, 10).

As we thought that radiated sound from the upper and lower surfaces of I-girder 1 and the upper surface of box girder 1 did not make a large contribution due to factors such as shielding by sleepers, we did not take into account the radiated sound from those members.

The prediction results of I-girder 1 in Fig. 9 shows that the left and right main girders V02 and V03 (I-girder 1) as well as left and right catwalks V01 and V04 have almost equal sound power, and their frequency characteristics were largely equal to each other. Comparing the sound power of the main girder and the catwalk, the sound power of the main girder was slightly larger than that of the catwalk.

The estimation results of box girder 1 in Fig. 10 show that the sound power of catwalk V01 and box girders (side) V02 and V04 was almost the same and that the smallest sound power

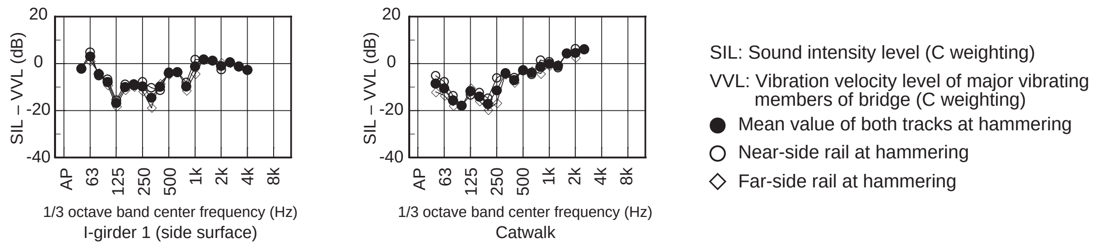

Fig. 7 Relation between Vibration Velocity and Radiated Sound of I-girder 1 and Catwalk (analysis results of the rail vibrating tests)

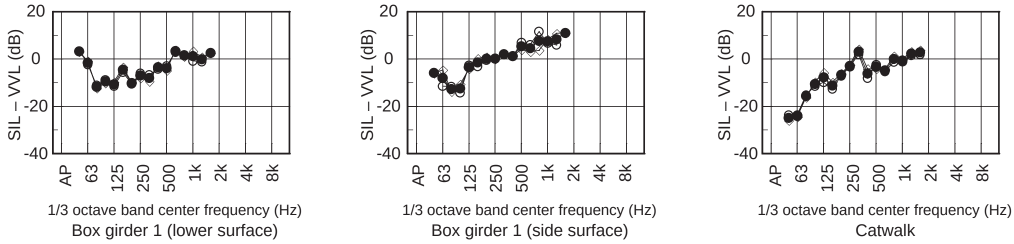

Fig. 8 Relation between Vibration Velocity and Radiated Sound of Box Girder 1 (lower and side surfaces) and Catwalk (analysis results of the rail vibrating tests)

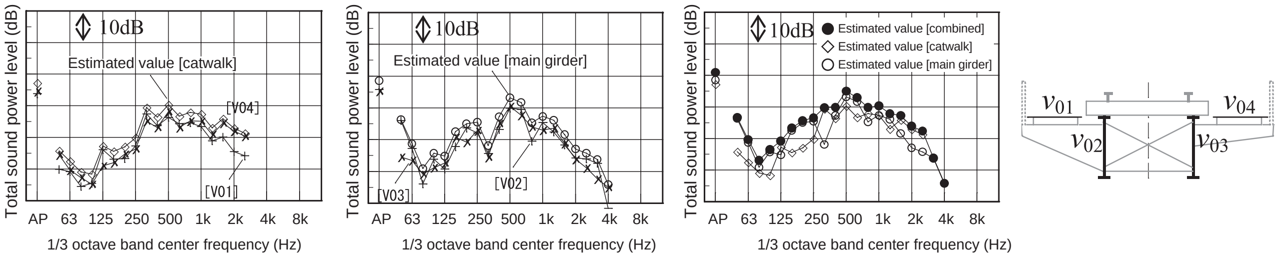

Fig. 9 Total Sound Power Level of Structure Noise at I-girder 1

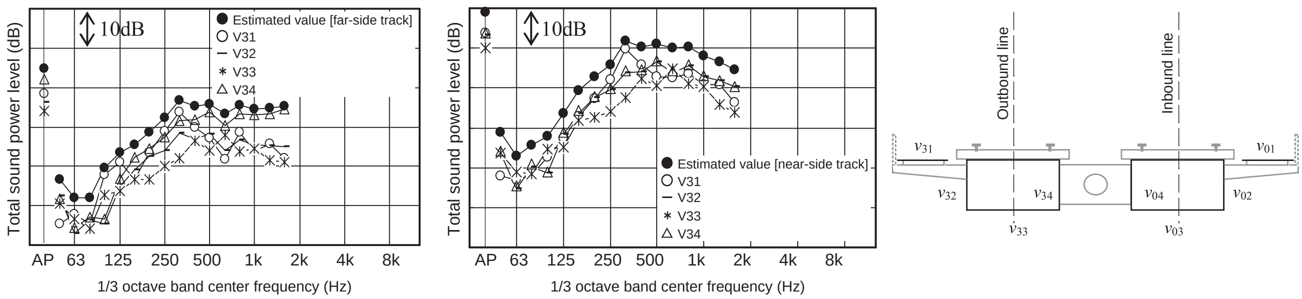

Fig. 10 Total Sound Power Level of Structure Noise at Box Girder 1

was that of box girder (lower surface) V03. The sound power level of the far-side track was less than 10 dB different from that of the near-side track (train running side). As it had little contribution to noise along the steel bridge, we decided to predict noise level without taking structure noise from the far-side track into account (see 3.3).

3 Overview of Establishment of a Method for Predicting Conventional Line Noise

3.1 Noise Prediction by the FDTD Method

Based on the structure noise survey and vibration measurement results introduced in section 2, we estimated noise level by the FDTD method. In the prediction, we handled the analysis area as a 2D sound field and divided the area into square meshes. Then, by alternately calculating sound pressure *q (x, y, t)* in the sound field and particle velocity in the *x, y* directions *u (x, t)* and *v (y, t)* according to the equation of motion (Formula 1) and the equation of continuity (Formula 2), we gained the time waveform of sound pressure *q (x, y, t)* at the measurement points.

$$-\frac{\partial q(x,y,t)}{\partial x} = \rho \frac{\partial u(x,t)}{\partial t}$$
$$-\frac{\partial q(x,y,t)}{\partial y} = \rho \frac{\partial v(y,t)}{\partial t} \qquad \cdots (1)$$

$$-\frac{\partial q(x,y,t)}{\partial t} = \kappa \left(\frac{\partial u(x,t)}{\partial x} + \frac{\partial v(y,t)}{\partial y} \right) \qquad \cdots (2)$$

(ρ : Air density, κ : bulk modulus of elasticity)

3.2 Study on Initial Conditions

We studied on the initial conditions for simulation by the FDTD method to predict noise at the measurement points along the steel bridge shown in Fig. 1 and 2. The noise was calculated by combining the train running noise and structure noise which were separately estimated due to the difference of the natures of the sources.

Train running noise, with the initial value of particle velocity at zero, was given the Gaussian distribution of sound pressure at the time t = 0. To structure noise accompanying vibration, we decided to give a vibration speed waveform of certain duration time. Thus, with the initial sound pressure at zero, the Gaussian pulse time waveform U(t) (Formula 3) was applied as the particle velocity.

$$U(t) = A \cdot e^{-\{(\Delta t \times n - T)/(0.29 \times T)\}^2} \quad \cdots (3)$$

Here, Δt is the time resolution of the FDTD method (= $1/f_s$, f_s = 64 kHz), n is the number for the discrete data with the standard of $t = 0$. $t = \Delta t \times n$ and n = 0, 1, 2 and so forth. T is the value gained by Formula 4.

$$T = 0.646/f_0 \quad \cdots (4)$$

Here, f_0 (Hz) is the cutoff frequency at which the power spectrum of the Gaussian pulse represented by Formula 3 is lowered by 3 dB. In this report, we applied the Gaussian pulse time waveform *U (t)* at f_0 = 1 kHz. Fig. 11 and 12 show the time waveform of *U (t)* and the fast Fourier transform (FFT) analysis results.

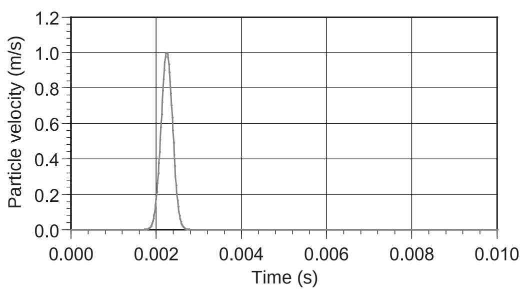

Fig. 11 Time Waveform of Gaussian pulse *U(t)*

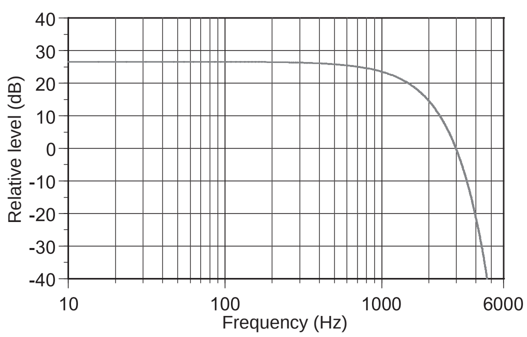

Fig. 12 FFT Analysis Results of Gaussian pulse *U(t)*

3.3 Creation of Model of Source of Sound Radiated from Steel Bridge

In this report, we created the following model of the source of sound radiated from a steel bridge. The source of rolling stock noise was a 2D non-directional point sound source and the source of structure noise was 2D plane sound sources of major vibrating members of the bridge. We assumed that, with I-girder 1 shown in Fig. 1, the major vibrating members for the structure noise would be the web of the main girder and the catwalk and that the upper and lower flanges of I-girder 1 that had only small member area would be non-vibrating members. On a panel-type vibrating surface such as the web of the main girder or the catwalk, it was expected that both sides of the panel would vibrate and front-back antiphase radiation would occur. Thus, we created a plane sound source model that causes antiphase radiation on both surfaces. With box girder 1 shown in Fig. 2, we assumed that both side surfaces and the lower surface of the box girder (without its upper surface facing sleepers) and the catwalk would be the major vibrating members. Considering that transmission of radiated sound by the vibration of the side and lower surfaces from inside to outside the box girder was negligibly small, we made the plane sound source model be for radiation to the outside only.

3.4 Study on Radiating Characteristics of Plane Sound Source

We assumed directional characteristics for the 2D plane sound source modeling of vibrating members to make the measurement results of noise from I-girder 1 and box girder 1 along the track match the prediction results of the 2D sound field.

As shown in Fig. 13, the surface where structure noise occurs was assumed to be a 2D plane sound source of the width *L* (m). Dividing this surface into four equal parts, the two middle parts and the two end parts would vibrate in opposite phase to each other. The complex amplitude (*A* in Formula 3) of the middle two was Å = +1.0 and that of the end two was Å = -0.6. Fig. 14 shows the amplitude distribution of vibration velocity. By setting like this, virtual directional characteristics could be given to the 2D plane sound source.

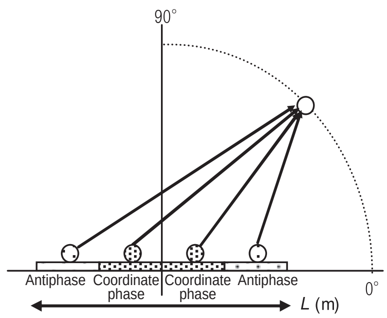

Fig. 13 Model of Sound Radiated from Structure Noise Source

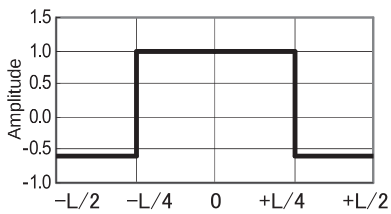

Fig. 14 Distribution of Vibration Amplitude Applied to Plane Sound Source

4 Comparison of Measured and Predicted Values

Through the procedure explained in sections 3.1 to 3.4, we predicted the noise by the FDTD method of fourth order difference approximation. The analyzed area was a 2D semi-free sound field that had reflective ground surface (width 22 m × depth 13 m for I-girder 1 and width 24 m × depth 17 m for box girder 1 with 5 m-wide boundary absorbing layer given to left and right side surfaces and upper surfaces of each fields). Simulation was performed with 1.6 × 10^{-2} m spatial resolution, 15.625μs (1/(64 kHz)) time resolution and 2.048 s simulation duration (65,536 sequential simulations). The upper limit bandwidth of the analysis frequency was 2.5 kHz (1/3 octave band center frequency).

In prediction of rolling stock noise, we applied FFT analysis to the time waveform of the sound pressure $q\ (x, y, t)$ obtained by the FDTD method at the measurement points on the level ground to find the band sound level L_n (dB). Next, we calculated the difference ΔL_n between the band sound level L_n^{ref} (dB) to find the sound waveform $q_{ref}\ (x, y, t)$ by the FDTD method using a point nearby the rails as the reference points and the band sound level measured at the same measurement points $L_n^{ref,meas}$ (dB) by applying Formula 5. By adding that level difference as the correction amount to the band sound level L_n (dB) at each measurement point, we made the simulation value agree with the actual rolling stock noise at the point nearby the rails, thereby evaluating the simulation results as rolling stock noise.

$$\Delta L_n = L_n^{ref,meas} - L_n^{ref} = 20 \times \lg(p_n^{ref,meas} / q_n^{ref}) \qquad \cdots(5)$$

In the prediction of structure noise, we calculated the difference ΔL_n^V between the band vibration velocity level $L_n^{U,ref}$ (dB) obtained from the vibration velocity (particle velocity) used in numerical simulation $U_{ref}\ (x, t)$ and the band vibration velocity level of the vibration velocity actually measured at the same measurement points $L_n^{Vref,meas}$ (dB) by applying Formula 6. Then, we added as the correction amount the band sound pressure level L_n (dB) obtained from the sound pressure at each measurement point $q\ (x, y, t)$ by the FDTD method with ΔL_n^V.

$$\Delta L_n^V = \Delta L_n^{V,ref,meas} - L_n^{u,ref} = 20 \times \lg(V_n^{ref,meas} / U_n^{ref}) \qquad \cdots(6)$$

In calculating the vibration velocity level, the standard value for 0 dB was $u_0 = 5.0 \times 10^{-8}$ (m/s).

In the above-mentioned procedure, we calculated the structure noise of each vibrating member such as the main girder, catwalks and side and lower surfaces of the box girder. By combining those with rolling stock noise, we predicted the total noise along the steel bridge.

Table 1 lists the comparison of the predicted and actual values with I-girder 1 and box girder 1. Here, the actual value is the arithmetic mean value of the sound exposure level when a typical train passed on the steel bridge at approx. 90 km/h. The predicted value is the combined value of structure noise using the average vibration velocity level with major members when the same train passed and the rolling stock noise using the average noise at the point nearby the rails on level ground[1] when a train of the same series passed at the same speed. The arithmetic mean values of the predicted and actual values were an average of -0.6 dB (root mean square (RMS) 1.3 dB) with I-girder 1 and -2.0 dB (RMS 2.6 dB) with box girder, showing that noise along the steel bridge was calculated for largely with error of 3 dB or less except for noise at some measurement points. Moreover, the frequency characteristics of the predicted and actual values shown in Fig. 15 and 16 clarify that the frequency characteristics of the predicted values relatively well agree with the measured values. However, there are some peaks and dips by the interference typical to a 2D sound field. The tendency for level of contribution of structure noise and rolling stock noise to total noise along the steel bridge to reverse with the border at around the 1 kHz frequency bandwidth also agrees well with the analysis result in the past report[1].

Table 1 Comparison of Predicted and Measured Values

I-girder 1: Measurement point	I-girder 1: * Prediction accuracy (dB)	Box girder 1: Measurement point	Box girder 1: * Prediction accuracy (dB)
S01	-0.2	S31	-1.9
S02	2.0	S32	0.1
S11	-1.4	S01	-1.3
S12	-0.8	S02	1.4
S21	0.6	S11	-3.3
S22	0.3	S12	-1.9
S23	-1.7	S13	-4.8
S24	-0.7	S14	-3.0
S31	-0.3	S21	-2.8
S32	-0.9	S22	-1.5
S33	-1.9	S23	-2.6
S34	-2.0	S24	-2.8
Arithmetic mean value	-0.6	Arithmetic mean value	-2.0
RMS	1.3	RMS	2.6

* Prediction accuracy: Difference between predicted and measured values

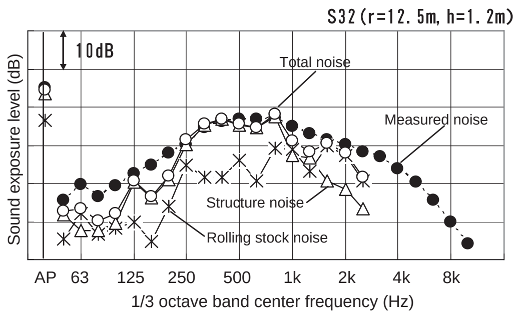

Fig. 15 Example of Comparison of Prediction and Measurement Results (I-girder 1)

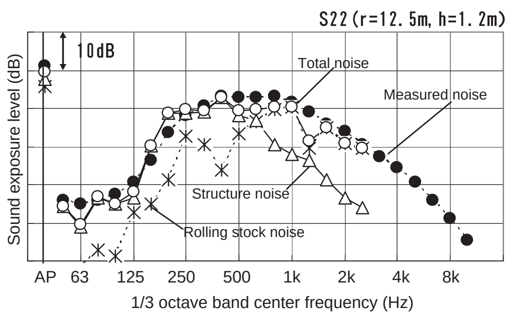

Fig. 16 Example of Comparison of Prediction and Measurement Results (Box Girder 1)

5 Measurement to Verify the Conventional Line Noise Prediction Method

In order to verify the appropriateness of this prediction method, we carried out verification measurement with I-girder 2 and box girder 2 of the same structure of the steel bridge in Fig. 1 (see Fig. 17). Those measurement points are also located along the conventional line in the Kanto area. The major vibrating members to be used in the prediction were the web and the catwalk of main girder of I-girder 2 and the side and lower surfaces of box girder 2, the same as those of I-girder 1 and box girder 1.

Fig. 18 and Fig. 19 show comparisons of predicted and measured frequency characteristics of I-girder 2 and box girder 2 at the point 12.5 m from the bridge. Those figures also show that the frequency characteristics of the predicted values by the FDTD method agreed relatively well with those of the measured values, while there were some peaks and dips, suggesting that generally accurate prediction was made in the frequency bandwidth. We further clarified that the predicted and measured values agreed well in the overall values of wayside noise for each steel bridge. Accuracy of the prediction simulation using the FDTD method was found to be good since the difference between the prediction and measurements was largely less than 3 dB at the points directly under the steel bridge and at 6.25 m and 12.5 m from the bridge. The prediction results per sound source further suggest that structure noise is predominant in the frequency area roughly less than 1 kHz.

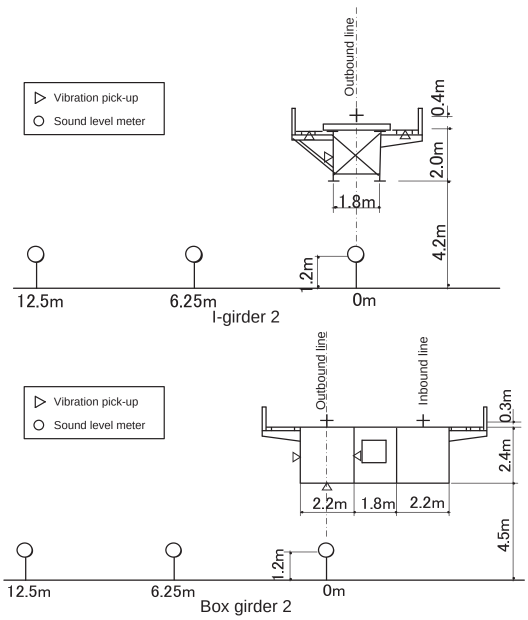

Fig. 17 Measurement Points for I-girder 2 and Box Girder 2

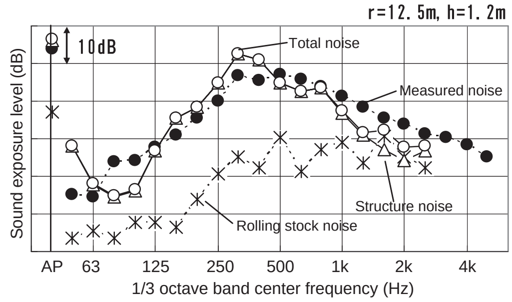

Fig. 18 Comparison of Prediction and Measurement Results (I-girder 2)

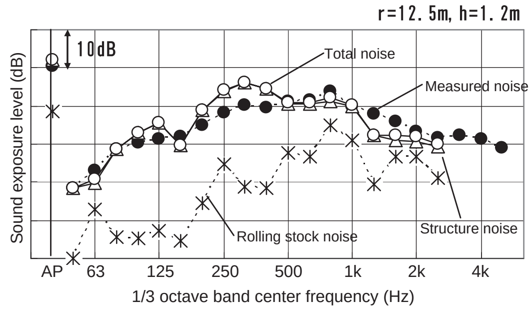

Fig. 19 Comparison of Prediction and Measurement Results (Box Girder 2)

6 Conclusion

Based on the structure survey and the vibration measurements in steel bridge sections on a conventional line in the Kanto area, we revealed the relation between vibration of the major vibrating members of a steel bridge and structure noise radiated with such vibration. Then, we developed a procedure to predict structure noise from vibration of the steel bridge based on the measurement results. The prediction results of noise along the steel bridge using two simulation models (for an I-shaped girder and a box girder) confirmed that largely accurate prediction could be done.

The verification measurement in the sections of two steel bridges of the same structure also confirmed that relatively accurate prediction could be done.

We plan to further conduct studies on predicting noise from steel bridges to which noise control measures are applied to reduce structure noise from the bridge. An example of that is applying vibration control material to vibrating members of the bridge.

Reference:

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