

Research on Technique for Identification of Sound Source of Pass-by Noise Using Matrix Inversion Method

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ABSTRACT

Identification of the contribution of individual sound sources is an essential step in attempting to reduce vehicle pass-by noise. This paper discusses a technique of source identification which utilizes the matrix inversion method. In this technique, multiple observation points are established around a sound source, and the source is identified using the observed sound pressures and a matrix of the acoustic transfer functions. The stability of the inverse matrix of the acoustic transfer function has a significant effect on the accuracy of sound source identification. An index expressing the stability of the inverse matrix of the transfer was therefore devised. The use of this index has made it possible to determine optimum observation points. The capability of this method to predict far-field sound pressures with a high degree of accuracy has been confirmed by actual vehicle tests.

1. Introduction

Sound sources of vehicle pass-by noise include engine noise, noise from the air intake system and exhaust system, and tire noise. Many components are responsible for this noise. For this reason, it is important to perform a factor analysis in order to know the contribution of each individual noise path.

One method conventionally used to identify a sound source is contribution analysis by masking⁽¹⁾. However, this method necessitates much preparation time and also is unsuitable for pinpointing detailed parts. Other sound source location methods include acoustic intensity⁽²⁾, acoustic holography, and the beam forming method⁽³⁾. These methods are superior in that they enable the condition of the acoustic field to be represented visually. However, they are unsuitable for cases in which the sound source is covered by the body

such as the engine mounted in an actual vehicle. Research is being carried out for these methods with a view to realizing a more detailed analysis of the contribution of the sound source to by-pass noise^{(4), (5)}. However, there are not many cases in which these methods are used for the actual analysis.

In this research, attention was focused on a method of calculating the intensity of a sound source by the acoustic transfer function matrix inversion method. To this end, empirical analysis methods that could be applied to source identification of vehicle pass-by noise, were studied.

2. Identifying a Sound Source Using Matrix Inversion Method

2.1. Outline

In the analysis of pass-by noise, it is important to obtain a grasp not only of the intensity of the sound source itself, but

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also of the acoustic transfer characteristics from the vehicle. As shown in Fig. 1, it is possible to express the acoustic pressure P_F at a far field evaluation point 7.5 m from the vehicle, as the product of the volume velocity, Q_i at the source location and H_i , the acoustic transfer function from the source to the far acoustic field evaluation point, using Eq. (1).

$$P_F = \sum_i H_i Q_i \quad (1)$$

Where,

H_i : Acoustic transfer function [Pa/(m³/s)]

Q_i : Volume velocity [m³/s]

i : Number of sound sources

Examples of volume velocity (Q_i) identification methods include calculating volume velocity from the vibration acceleration of the radiation surface⁽⁶⁾ and calculating the volume velocity using an acoustic tube⁽⁷⁾. In this research, however, the volume velocity was identified by the matrix inversion method using transfer functions obtained by empirical measurements using the reciprocity principle⁽⁸⁾.

Here, a description is given of the principle of sound source identification using the matrix inversion method. It is assumed that there are M non-directional point sound sources, and that the sound sources are identified using N proximity observation points (Fig. 2). Here, if it is assumed that the volume velocity of the sound sources is Q_{Sm} ($m=1, \dots, M$), the acoustic pressure at the observation points is P_{Rn} ($n=1, \dots, N$), and the transfer function from point sound source m to observation point n is H_{SmRn} ($m=1, \dots, M$, $n=1, \dots, N$), these relational expressions can be expressed as Eq. (2).

$$\left. \begin{aligned} P_{R1} &= H_{S1R1} Q_{S1} + \dots + H_{SMR1} Q_{SM} \\ P_{R2} &= H_{S1R2} Q_{S1} + \dots + H_{SMR2} Q_{SM} \\ &\vdots \\ P_{RN} &= H_{S1RN} Q_{S1} + \dots + H_{SMRN} Q_{SM} \end{aligned} \right\} \quad (2)$$

It is also possible to express these relationships as a matrix, as shown in Eq. (3).

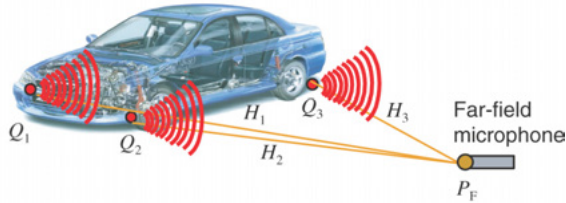


Fig. 1 Far-field sound pressure

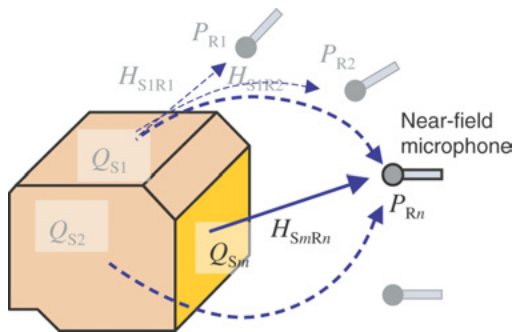


Fig. 2 Inverse matrix method

$$\mathbf{P} = \mathbf{H}\mathbf{Q} \quad (3)$$

Consequently, it can be seen that the volume velocity of each of M sound sources can be identified by obtaining the acoustic pressure at the N observation points and also the inverse matrix of the $M \times N$ transfer function matrix. This is expressed in the form of Eq. (4).

$$\mathbf{Q} = \mathbf{H}^+ \mathbf{P} = \mathbf{G}\mathbf{P} \quad (4)$$

Where,

$$\mathbf{G} = \begin{pmatrix} G_{R1S1} & G_{R2S1} & \dots & G_{RNS1} \\ G_{R1S2} & G_{R2S2} & \dots & G_{RNS2} \\ \vdots & \vdots & \dots & \vdots \\ G_{RNS1} & G_{RNS2} & \dots & G_{RNSM} \end{pmatrix} \quad (5)$$

The + sign in this equation indicates that the matrix is a Moore-Penrose general inverse matrix. The actual matrix takes the form of Eq. (5). A general inverse matrix is an expanded matrix of an ordinary inverse matrix, and can also be applied to matrixes other than regular matrixes of the form $M = N$. In this paper, this general inverse matrix is hereafter referred to simply as an inverse matrix.

2.2. Features and Issues

As mentioned in sub-section 2.1, the volume velocity of each sound source can be determined by obtaining the inversion of the transfer function matrix. Consequently, the stability of an inverse matrix significantly affects the accuracy of the sound source volume velocity identification. In order to perform highly accurate sound source identification, the following conditions must be satisfied.

- (1) $M \leq N$. In other words, the number of observation points N must be greater than the number of sound sources M .
- (2) The transfer function vectors must intersect each other orthogonally.
- (3) A highly accurate transfer function must be measured.

(1) means that if $M > N$, it will not be possible to obtain a solution to the inverse matrix of the transfer function.

(2) means that the location of the observation points has a large effect on the sound source identification accuracy. For example, even if many observation points are set in order to satisfy condition (1), if the observation points are very close to each other, the transfer function vectors from each of the sound sources will be similar. As a result, they will fail by a long way to intersect each other orthogonally, bringing about the possibility of divergence of the matrix. Also, even if the matrix does not diverge, this may result in increased errors during sound source identification.

A description of this is given using the two sound sources and two observation points shown in Fig. 3.

Here, each transfer function is shown below.

$$\begin{aligned} H_{S1R1} &= a, & H_{S2R1} &= b \\ H_{S1R2} &= c, & H_{S2R2} &= d \end{aligned} \quad (6)$$

The transfer function inverse matrix in this case is shown in Fig. 4.

$$D = ad - bc \quad (7)$$

$$\begin{aligned} H_{R1S1} &= d/D, & H_{R2S1} &= -b/D \\ H_{R1S2} &= -c/D, & H_{R2S2} &= a/D \end{aligned} \quad (8)$$

D is the determinant of the transfer function matrix, and is a coefficient that is equivalent to the denominator of the transfer function inverse matrix. Consequently, in the case where D is near 0, the measured acoustic pressure increases. If there is no error, the reason for the volume velocity identification value under-estimating the source is that the direct paths, a and d are cancelled by the indirect paths b and c . In other words, if the transfer coefficient of the cross path is over estimated, the coefficient of those paths will also increase and thereby cancel the volume velocity components of the direct paths.

Next, a theoretical explanation is given concerning the fact that if an error is included in the observation point acoustic pressure, the error will increase. Assuming that error E is added to the observed acoustic pressure vector P , resulting in P' , and the volume velocity is identified in this state, the identification value Q' of the volume velocity in the state that includes the error will be as follows.

$$\begin{aligned} Q' &= H^{-1}P' \\ &= H^{-1}(P+E) \\ &= H^{-1}P + H^{-1}E \\ &= Q + H^{-1}E \end{aligned} \quad (9)$$

The resulting error in the volume velocity identification value is the error E when the acoustic pressure is measured multiplied by the inverse matrix. This means that the magnitude of the inverse transfer function determines the increase in the error. In the case of a 2×2 matrix, the nature of the increase in the coefficient of the inverse transfer function is determined by matrix D , and becomes greater the closer the magnitude of the cross path approaches the magnitude of the direct path. Thus, in the case of a 2×2 matrix, it is possible to analyze the amplification ratio of an error relatively easily. However, if there are many points (including a non-square matrix), the coefficient of the inverse matrix will be represented by a complex equation, the number of terms of which is proportional to the exponential of the size of the matrix. This makes it difficult to perform an evaluation using an equation that includes the original coefficient.

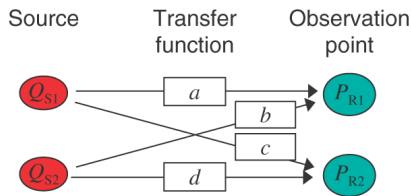


Fig. 3 Transfer function

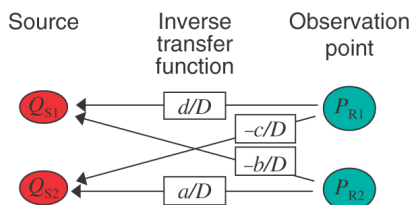


Fig. 4 Inverse transfer function

(3) means that the error included during measurement of the transfer function or the acoustic pressure at the observation point is a factor that produces an error in the sound source identification value. This particularly effects the transfer function measurement, since the reciprocity principle is applied, which means that the measurement is performed using microphones located near the sound sources and speakers located near the observation points. Which, in other words, is in the opposite location to that of actual sound propagation during operation. Consequently, an error occurs in the measured transfer function due to the location of the speakers and the difference in directionality. This is also one of the factors that degrade the sound source identification accuracy. Therefore, a transfer function identification method that is relatively unaffected by measurement errors is necessary.

Accordingly, in order to satisfy (2) and (3), the following were studied.

- Use of an energy transfer rate based on a 1/3 octave band conversion
- Application of an index for evaluating whether or not the transfer function is stable.

2.3. Reduction of Measuring Errors by Using 1/3 Octave Band Conversion

A measurement error due to a misalignment in the measurement position mentioned in (3) of sub-section 2.2 is likely to occur as a general phase error. In order to carry out robust sound source identification that is relatively unaffected by phase errors, the 1/3 octave band-converted energy transfer rate was used. In contrast to Eq. (4), the calculation equation is as shown in Eq. (10).

$$\begin{pmatrix} Q_{S1}^2 \\ Q_{S2}^2 \\ \vdots \\ Q_{SM}^2 \end{pmatrix} = \begin{pmatrix} \bar{H}_{S1R1}^2 & \bar{H}_{S2R1}^2 & \dots & \bar{H}_{SNR1}^2 \\ \bar{H}_{S1R2}^2 & \bar{H}_{S2R2}^2 & \dots & \bar{H}_{SNR2}^2 \\ \vdots & \vdots & \dots & \vdots \\ \bar{H}_{S1RM}^2 & \bar{H}_{S2RM}^2 & \dots & \bar{H}_{SNRM}^2 \end{pmatrix}^+ \begin{pmatrix} P_{R1}^2 \\ P_{R2}^2 \\ \vdots \\ P_{RN}^2 \end{pmatrix} \quad (10)$$

Here, $\bar{H}_{SnRm}^2$ is the value of the energy transfer rate $|H_{SnRm}|^2$ averaged over a 1/3 octave band. Consequently, the error resulting from fluctuations and differences in measuring conditions of both the transfer function and acoustic pressure is reduced. However, there is a possibility of a new error occurring as a result of failure of the interference effect due to phase to be taken into account. It is considered, however, that this error can be reduced by increasing the number of measurement points, for example, and also that the effect of interference due to phase on pass-by noise is small. Consequently, it is important to improve the stability of the inverse matrix by using 1/3 octave band conversion.

2.4. Use of an Index of Stability of a Transfer Function Matrix

In order to obtain a stable transfer function matrix, it is necessary to ensure that the location of the sound source points and observation points is appropriate. Taking the engine as an example, an appropriate location of sound source points is equivalent to dividing of the engine, which is a plane sound source, into “appropriate” sound source elements. Regarding the observation points, this is equivalent to the laying out of microphones around the engine. However, an “appropriate” location depends greatly on the sound source and the sound profile in the vicinity. Generally, the observation points should be arranged at equal intervals from each other and equidistant from the sound sources and

surrounding them. However, it is sometimes difficult in practice to arrange the observation points at equal intervals in the case of an actual engine mounted in the engine compartment. Consequently, it is necessary to judge whether or not the microphone positions as observation point are appropriate. As an index for obtaining this appropriateness, instability I was defined as shown in Eq. (11), and studied.

$$I = \text{Max}\{|\mathbf{g}_n| \cdot \text{Max}\{\mathbf{h}_n\}\} \quad (11)$$

Here, $\mathbf{g}_n$ is the vector of the n th row of the inverse transfer function matrix, $\mathbf{h}_n$ is the vector of the n th column of the transfer function matrix and $\text{Max}\{\}$ is the maximum value inside $\{\}$. The instability is expressed as the degree to which the error increases when identification of volume velocity using multiple points is compared to the case where there is one sound source and one observation point.

First, consider the identification of volume velocity Q_n by conventional 1-point estimation, using transfer functions recorded at multiple points. In the conventional 1-point estimation, there is a degree of freedom regarding what observation points to use as the basis for identification. When performing identification based on acoustic pressure P_m at observation point m , the identification value is as follows.

$$Q_n = P_m / H_{SnRm} \quad (12)$$

Here, like in the case of 2-point estimation mentioned above, the error contained in the acoustic pressure P_m is multiplied by $1/H_{SnRm}$. If the magnitude of the measurement error in all channels is assumed to be the same, the error will be minimum in the case where the volume velocity is estimated based on the observation point at which the transfer rate from Q_n will be largest, that is, on the measurement point m where H_{SnRm} is greatest. The amplification ratio R_1 of the error in this case can be expressed as follows.

$$\begin{aligned} R_1 &= 1 / \text{Max}\{H_{S1R1}, H_{S1R2}, \dots, H_{S1RN}\} \\ &= 1 / \text{Max}\{\mathbf{h}_n\} \end{aligned} \quad (13)$$

On the other hand, when volume velocity is identified using inverse transfer functions at multiple points, the identification equation will be as follows.

$$Q_n = G_{R1Sn}P_1 + G_{R2Sn}P_2 + \dots + G_{RMSn}P_M \quad (14)$$

Here, if the errors contained in the measured acoustic pressure P_1 to P_M are defined as E_1 to E_M , the estimated error in the volume velocity E_q can be expressed according to the following equation.

$$E_q = G_{R1Sn}E_1 + G_{R2Sn}E_2 + \dots + G_{RMSn}E_M \quad (15)$$

From this equation, it can be seen that the amplification ratio of the error differs depending upon the channel, and its value is assigned by G_{RmSn} . Here, if it is assumed that the magnitude of each error from E_1 to E_M is the same, and there is no correlation between the errors, the expected value $|E_q|^2$ of the square of the estimated error will be as follows.

$$\begin{aligned} |E_q|^2 &= |G_{R1Sn}E_1 + G_{R2Sn}E_2 + \dots + G_{RMSn}E_M|^2 \\ &= |G_{R1Sn}E_1|^2 + |G_{R2Sn}E_2|^2 + \dots + |G_{RMSn}E_M|^2 \\ &= (G_{R1Sn}^2 + G_{R2Sn}^2 + \dots + G_{RMSn}^2) \cdot |E_1|^2 \end{aligned} \quad (16)$$

Consequently, the amplification ratio R_2 of the magnitude of the estimated error when an inverse matrix is calculated from the expected value is as follows.

$$R_2 = \sqrt{G_{R1Sn}^2 + G_{R2Sn}^2 + \dots + G_{RMSn}^2} = |\mathbf{g}_n| \quad (17)$$

The ratio I_n of the amplification ratios of the two errors obtained using Eqs. (12) and (16) is shown in Eq. (18).

$$I_n = R_2 / R_1 = |\mathbf{g}_n| \cdot \text{Max}\{\mathbf{h}_n\} \quad (18)$$

This I_n indicates the degree to which the error is increased when the matrix inversion method is used to calculate the volume velocity Q_n compared to a single point based estimation. It can be used as an index that expresses the instability during inversion. The value of the instability I that corresponds to the most unstable calculation is used as a representative value, when all of the volume velocity values of Q_1 to Q_N have been identified. In other words, it is defined as follows.

$$I = \text{Max}\{I_1, I_2, \dots, I_N\} = \text{Max}\{|\mathbf{g}_n| \cdot \text{Max}\{\mathbf{h}_n\}\} \quad (19)$$

As an index of the stability of a matrix, the condition number is generally used. However, this poses issues, namely that it is difficult to obtain coherence with physical meaning and also when the dimensions of the matrix are different it is not possible to make a direct comparison. The instability is used to overcome this issue. This index enables the effectiveness of increasing the number of observation points in reducing the error, for example, to be judged.

3. Basic Verification Using a Speaker Sound Source

3.1. Speaker Experiment

An engine-like unit consisting of six speakers (Fig. 5) was used as a sound source, and the effectiveness of the index of the instability was confirmed. Mutually independent noise (white noise) was emitted simultaneously from the six (top, bottom, left, right, front, rear) speakers. Twenty four observation points were set in the vicinity of this unit, and the acoustic pressure at each point was measured. Also, $6 \times 24 = 144$ transfer functions between the sound source and the observation points were measured using the reciprocity principle. The matrix inversion method was used to identify the volume velocity of each speaker by means of the observation point acoustic pressure and the transfer function. Also, in order to confirm the relationship between the instability due to the layout and the sound source identification accuracy, an experiment using two layouts in which the observation positions were changed was carried out (Fig. 6).

Figure 7 shows the instability of each location. The solid line in the figure applies for the case where the distance between the sound source and the observation point is 20 cm

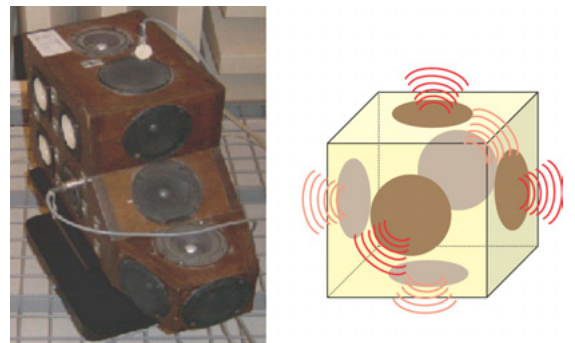


Fig. 5 Dummy noise source with loud speakers

(layout 2), and the broken line is for the case where this distance is 1 m (layout 1). When the frequency is higher than 500 Hz, the instability values for both distances were roughly equal. However, for 500 Hz or below, a distance of 20 cm resulted in lower instability. Figure 8 shows one of the volume velocities for the six identified sound sources. Here, only one sound source was driven, and the volume velocity that was identified using one sound source and one observation point was defined to be the true value. The observation point used here was located 20 cm in front of the sound source. Regarding the types of lines in the figure, the broken line was the true value, the long and short dash line was the identification value for layout 1, and the solid line was the identification value for layout 2. At a frequency of more than 500 Hz, both identification values agreed roughly with the true value. However, at 500 Hz or below, the sound source was not correctly identified in the case of layout 1, whereas the sound source could be identified with an error of about 3 dB in the case of layout 2. This agrees roughly with the trend indicated by the instability. As a result, it was possible to quantitatively judge the appropriateness of the observation point location for obtaining high sound source identification accuracy.

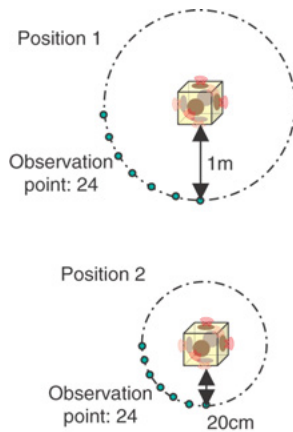


Fig. 6 Measurement conditions

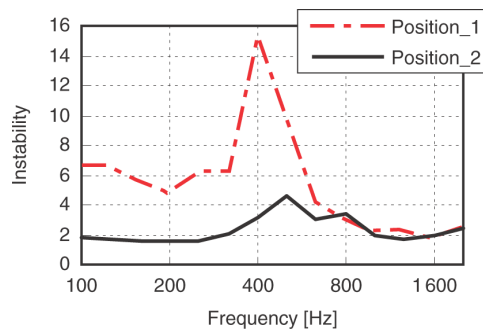


Fig. 7 Instability

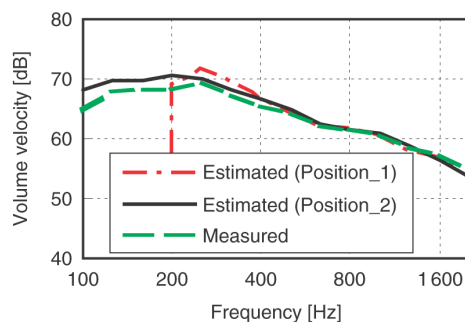


Fig. 8 Volume velocity

4. Example of Application to Actual Vehicle

4.1. Outline of Measurement

Shown below is an example of the application of the sound source identification method of this research to an actual vehicle. The vehicle used contained a 2.4L in-line 4-cylinder engine and a manual transmission.

As shown Fig. 9, the vehicle was placed on a chassis dynamometer in a semi-anechoic room, and the dynamometer was rotated by running resistance control operation that simulated actual running of the vehicle.

The acoustic pressure on the observation points in the vicinity of the sound source and also the far acoustic field acoustic pressure were measured in 3rd gear when the engine was running at 3 000 rpm. The far acoustic field was set at a point 7.5 m in the lateral direction from the front edge of the vehicle, and 5 m to the rear of it.

The sound sources were broadly divided into four areas, engine radiation noise, intake orifice noise, exhaust radiation noise, and exhaust orifice noise. The number of each type of sound source was, engine radiation noise: 6 points, intake orifice noise: 1 point, exhaust radiation noise: 5 points, and exhaust orifice noise: 2 points. Regarding the tires, slick tires were used to ensure that the contribution of the tires to the far acoustic field was as small as possible.

The number observation points for each area was, engine radiation noise: 42 points, intake orifice noise: 6 points, exhaust radiation noise: 30 points, and exhaust orifice noise: 12 points.

Table 1 shows the number of sound sources, observation points and transfer function in each area. A transfer function matrix was formed for each area, and the instability was calculated. The result is shown in Fig. 10. From this, it was confirmed that a stable transfer function matrix was obtained.

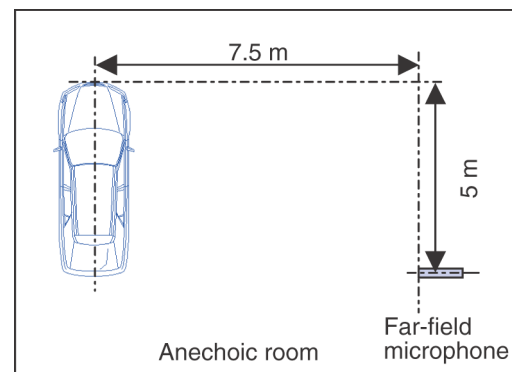


Fig. 9 Measurement conditions

Table 1 Measurement point readings

Area	Source	Observation point	Transfer function
Engine noise	6	42	252
Intake orifice noise	1	6	6
Exhaust radiation noise	5	30	150
Exhaust orifice noise	2	12	24
Total	14	90	432

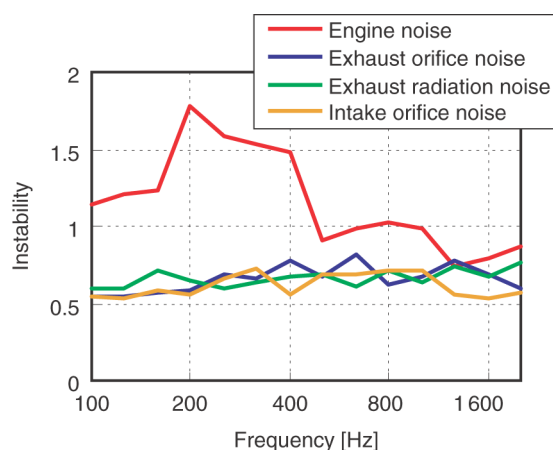


Fig. 10 Result of instability

4.2. Far Acoustic Field Prediction Results

The far acoustic field acoustic pressure was predicted by means of the volume velocity of each identified sound source and the transfer function to the far acoustic field. The results are shown in Fig. 11.

From this, it was confirmed possible to predict the far acoustic field acoustic pressure level to an accuracy of within ± 3 dB.

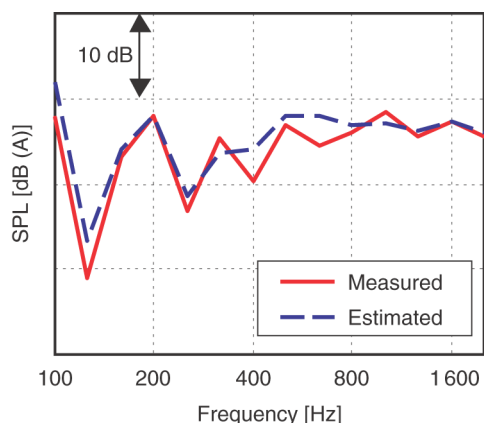


Fig. 11 Result of far-field SPL

5. Conclusion

A matrix inversion method was used to identify a sound source for use in contribution analysis of pass-by noise.

Here, an index of stability of a transfer function matrix that affects the sound source identification accuracy (instability) was used and studied. As a result, it was possible to quantitatively indicate the appropriateness of the locations of the observation points that affect the accuracy of sound source identification by means of instability.

Also, in verification using an actual vehicle, the far acoustic field acoustic pressure could be predicted to an accuracy of within $\pm 3\%$ of the measured value.

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