

Identification of Sound Source Model Using Inverse-Numerical Acoustic Analysis: Validation of Effectiveness and Applicability

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ABSTRACT

This paper describes an identification of a sound source model for a diesel engine installed on an agricultural machine by Inverse-Numerical Acoustic analysis (INA), and the applicability of the identified sound source model. INA is a method to identify surface vibrations from surrounding sound pressures. This method is applicable for a complicated-shaped sound source like an engine. In order to confirm the accuracy of the identified sound source model, the surface vibrations of the engine are compared with the measured results. Moreover, in the condition of the simulated engine room, the surrounding sound pressure levels of the engine are predicted using the sound source model and the boundary element method (BEM). For the verification of the prediction accuracy, the surrounding sound pressures of the engine are measured using the testing device which simulated actual engine room, namely an enclosure. As a result, the sound source model of the diesel engine is identified accurately using the INA. In addition, the surrounding sound pressure levels of engine enclosure are predicted accurately using the sound source model. These results mean that a suitable engine room design for noise is possible, using sound source model obtained by INA.

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INTRODUCTION

In recent years, a demand for low noise of agricultural machines is increasing. An engine installed on a machine is one of a major sound source. Air-borne noise radiated from an engine surfaces affect the noise of a machine surrounding and an operator position. For a reduction of noise radiated from the engine, engine enclosures and sound absorbing materials into the engine room are adopted. However, the installation of sound absorbing materials causes the increase in product costs. The structural improvement of the engine room also causes the increase in the development period of products. In order to reduce the noise level effectively at evaluation points, it is necessary to grasp the characteristics of the sound source, and predict the improvement effect in advance. Inverse-Numerical Acoustic analysis (INA) is used to identify a sound source model. INA is a method to identify surface vibrations from surrounding sound pressures. Regarding INA, many studies have been conducted. Martinus et al. studied the relation between the error of identified sound source model and the measurement points of sound pressure [1]. For the diesel engine which is a complicated shape, the sound source model was constructed using INA, and the improvement of identified accuracy and efficiency was discussed [2,3,4,5]. In the

application example except the engine, Uehara et al. used this method for the enclosure of cogeneration system [6]. Ando et al. used the method for high frequency gear whine noise up to 4.1 kHz [7]. Herrin et al. used the method for a generator set, and predicted the sound pressure of far field which is the point at 7 meter from source, using the sound source model obtained from INA [8,9]. Tao et al. predicted the far field sound pressure, using INA which was defined as a virtual plane between sound source and measurement points [10]. These past studies are the studies on improvement of the identified accuracy and the applications in the free sound field or hemi-free sound field.

In this study, the sound source model is constructed using INA, and the applicability of the sound source model is validated in the sound field that is considered reflections and diffractions. The surface vibration of the engine is identified using the surrounding sound pressure of the engine and the acoustic transfer functions obtained from the boundary element method (BEM). To confirm the accuracy of the identified sound source model, the surface vibrations of the engine are compared with the measured results. Moreover, in the condition of the simulated engine room, the surrounding sound pressure levels

of the engine are predicted using the identified sound source model and the BEM. For the verification of the prediction accuracy, the surrounding sound pressures of the engine are measured using the testing device which simulated actual engine room, namely an enclosure. The prediction results are compared with the measured results to confirm the applicability of the sound source model in the sound field that is considered reflections and diffractions.

THEORY OF INVERSE-NUMERICAL ACOUSTIC ANALYSIS

The relation between sound pressures and surface vibrations can be written as the following equation:

$$\{p\} = [H]\{v\} \quad (1)$$

where $\{p\}$ is the vector of sound pressure at m field points, $\{v\}$ is the vector of normal velocity at n surface points of the sound source, and $[H]$ is the $m \times n$ transfer function matrix set up by BEM.

INA is the inverse problem of solving [equation \(1\)](#) for the unknown $\{v\}$ given the vector of the measured sound pressure $\{p\}$. Surface vibration velocity $\{v\}$ can be obtained by the matrix inversion method. However, the inverse matrix of the matrix $[H]$ cannot always be obtained because $[H]$ is not usually a regular matrix. Instead of the inverse matrix, the pseudo inverse matrix is widely used in an identification of sound source, as in the following equation:

$$\{v\} = [H]^{-1}\{p\} \quad (2)$$

, where $[H]^{-1}$ is a pseudo-inverse matrix of $[H]$.

In calculation of a pseudo inverse matrix, singular value decomposition is useful. By using a singular matrix, the transfer function matrix can be written as the following equation:

$$[H] = [V][\Sigma][U]^T \quad (3)$$

, where $[V]$ and $[U]$ are a $m \times m$ unitary matrix and a $n \times n$ unitary matrix satisfying, $[V]^T[V] = [U]^T[U] = [I]$ and $[\Sigma]$ is a diagonal matrix containing the singular values of $[H]$ in non-increasing order. The total number of singular values is, $\min(m, n)$. Here superscript $[T]$ means the complex conjugate transposition.

From [equation \(3\)](#), the pseudo-inverse matrix of $[H]$ can be obtained as follows:

$$[H]^{-1} = [U][\Sigma]^{-1}[V]^T \quad (4)$$

In this calculation, the pseudo-inverse matrix is sensitive to $[\Sigma]^{-1}$. In general, $[H]$ is ill conditioned, so that $[\Sigma]$ contains small values. This results $[\Sigma]^{-1}$ in containing huge values and $[H]^{-1}$ becoming unreliable. To avoid this problem, huge terms of $[\Sigma]^{-1}$ are set to zero. A criterion for dropping small singular value is called Tolerance. Tolerance is defined as follows:

$$Tolerance = \sigma_i / \sigma_1 \quad (5)$$

, where σ_1 is the maximum singular value in the singular matrix $[\Sigma]$, and σ_i is the minimum singular value in the singular matrix $[\Sigma]$. It is important to select the appropriate tolerance for the identification of sound source. Because, a small tolerance causes large errors because of huge inverse matrix values and a large tolerance causes large errors because of information loss. In this study, tolerance is determined from the L-curve method, which is based on a plot of the result norm versus the corresponding residual norm in a log-log scale [2].

In this paper, the surface normal velocity $\{v\}$ is given as follows:

$$\{v\} = [U] \begin{bmatrix} 1/\sigma_1 & & & 0 \\ & \ddots & & \vdots \\ & & 1/\sigma_i & \\ & & 0 & \ddots \\ 0 & & & & 0 & 0 \end{bmatrix} [V]^T \{p\} \quad (6)$$

The error of $\{v\}$ are suppressed using the approximate pseudo-inverse matrix [11].

EXPERIMENT AND SIMULATION

Experimental Material

[Figure 1](#) shows the experimental material, inline 3-cylinder water-cooled diesel engine installed on the combine harvester. [Table 1](#) shows the specifications of the diesel engine. The dimensions of the engine are: length (in the direction of the crankshaft) 587 mm, width 527 mm, and height 716 mm. In the experimental condition, engine speed was 2800 rpm which is rated engine speed. The target frequency range to evaluate the sound pressure is from 200 to 2000 Hz.

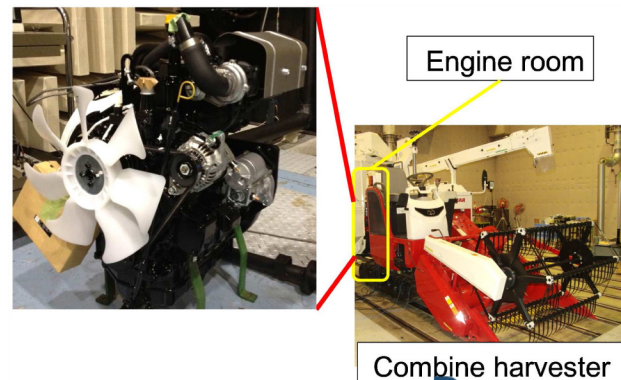


Figure 1. Experimental material, inline 3-cylinder water-cooled diesel engine

Table 1. Specification of diesel engine

Rated output	kW	29.7
Rated engine speed	rpm	2800
Combustion	-	Direct injection
Number of cylinders	-	3
Bore*Stoke	mm	84*90
Displacement	liter	1.496
Aspiration	-	Turbocharged

Flow of Validation and Simulation Model

This section describes the validation flow and the simulation model of BEM. In this study, *NX by Siemens PLM Software* is used for the preprocessor, and *LMS Virtual. Lab* is used for the simulation of BEM. Figure 2 shows the validation flow of the sound source model identification and applicability. The flows are as follows.

1. Construction of BEM model and measurement of sound pressures: The BEM model of engine surface is constructed, and the sound pressures at the engine surrounding which are input data of INA are measured.
2. Identification of surface vibration: The surface vibration of the engine is identified by INA, and the identified results are compared with the measurement results.
3. Prediction of sound pressure at the engine surrounding: The sound pressures at the engine surrounding are predicted, using the identified surface vibration and BEM. These prediction results are compared with the measurement results.
4. Prediction of sound pressure using engine enclosure: Similarly, the sound pressures at the engine surrounding are predicted in the condition of the engine enclosure, using the identified surface vibration and BEM. These prediction results are compared with the measurement results.

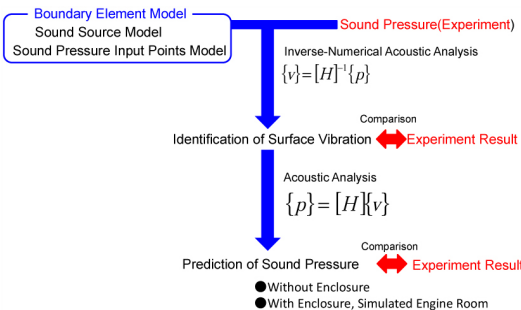


Figure 2. Flow of validation

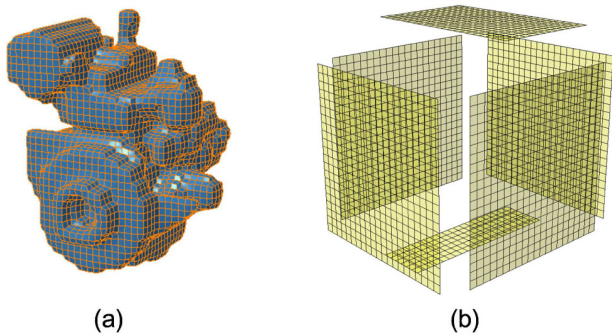


Figure 3. BEM model used for identification of sound source model (a) Engine surface model (b) Input model for INA

Figure 3 shows BEM model used for the identification of sound source model. Figure 3a shows the engine surface model, and Figure 3b shows the model that inputs sound pressure measured with the operating engine. The element length of the engine surface defined as 20 mm to consider the target upper frequency. This element length is satisfied the classical criterion that more than 6 elements are required for the wavelength of the target upper frequency, 2000 Hz. The number of nodes and elements are 5806 and 5800, respectively. Furthermore, the number of the sound pressure input point was defines as 2398. Figure 4 shows BEM model used for the prediction of the sound pressure. Figure 4a shows the predictive model without the engine enclosure. Prediction points were set at a 1000 mm from the surface of the engine in four directions. The detailed prediction points are gear case side, exhaust side, intake side, and the top side of the engine. Figure 4b shows the predictive model with the engine enclosure. Prediction points were the same as the enclosureless model. The surface of the engine enclosure was defined as a complete reflection in BEM model.

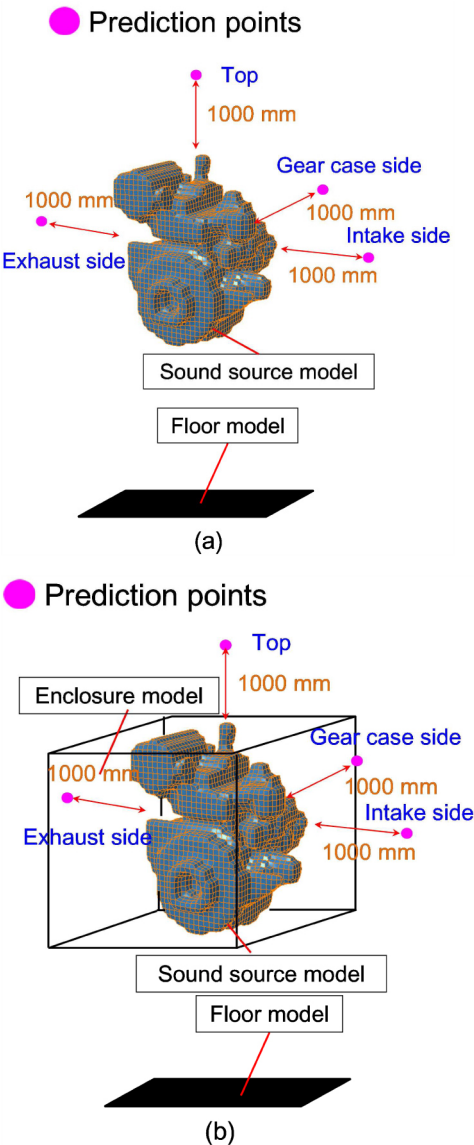


Figure 4. BEM model for prediction of sound pressure (a) Without enclosure, (b) With enclosure