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PREDICTION OF ENGINE SOUND AND SOUND QUALITY CONTROL USING WAVELET TRANSFORM

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Abstract

In order to produce the comfortable engine sound, estimation of the engine sound and evaluate its sound quality in the early design stage are essential to conduct the development of the advanced and competitive internal combustion engine. This paper presents a theoretical approach to estimate the time history of engine sound and the evaluation procedure of engine sound quality using wavelet transform technique.

INTRODUCTION

High-speed diesel engines for motor vehicles and construction machineries are required noise reduction and good sound quality along with high performance and clean exhaust gas emission. Sound level and quality control of internal combustion engine in early design stage enjoins the analytical procedure to estimate excitation forces, vibratory behaviour of engine block, sound radiation properties and the time history of engine sound at any measuring point. Theoretical approach has been offered by author to predict the vibratory response of the crankcase coupled with the rotating crankshaft and the frequency spectrum of the engine sound [1][2].

However in order to evaluate the engine sound quality in the design stage, it is needed to develop a system to simulate the time history of the engine sound. In this paper, the prediction method of the time history of the engine sound at any measuring point is discussed by use of the Boundary Element Method (BEM) conjunction with the calculated vibratory response of the engine block surface. On the other hand, to evaluate the estimated engine sound quality, it is important that designers and users of the engine can listen to the estimated sound by themselves. In this proposed system, it enables them to listen to the engine sound which is regenerated on the personal computer. Furthermore, the engine sound can be modified and led to the comfortable sound quality using the Wavelet transform technique.

ESTIMATION OF ENGINE SOUND IN THE TIME DOMAIN

The Calculation Method of Time History of Engine Sound

Boundary Element Method (BEM) is used to calculate the acoustic radiation from the vibration engine block surface. As shown in Figure 1, the surface of engine block was divided into boundary elements, and the acoustic pressure on the surface was determined in the frequency domain. Computational procedures are as follows.

Step 1: Eigenvalue analysis of an engine structure.
Step 2: Calculation of modal response of each vibration mode.
Step 3: Estimation of sound pressure spectrum at arbitrary measuring points using BEM.
Step 4: Prediction of time history of engine sound using Inverse Fourier Transform.

The details of Step 1 and Step 2 are discussed in Reference [1][2]. Therefore Step 3 and Step 4 are mentioned in this paper. The vibration response of an engine structure is expressed by the following equations using modal analysis technique.

$$\mathbf{x}(\omega) = \mathbf{\Phi}\mathbf{a}(\omega) \tag{1}$$

$$\ddot{\mathbf{x}}(\omega) = \mathbf{\Phi}\ddot{\mathbf{a}}(\omega) \tag{2}$$

where $\mathbf{x}(\omega)$ is a displacement response vector, $\mathbf{\Phi}$ is normal mode vector, $\mathbf{a}(\omega)$ is a modal response vector and $(\ddot{\ })$ denotes the time derivative of $(\ )$.
The sound pressure p_l at point l in the 3-dimensional sound field is expressed as following integral equation.

$$p_l = \frac{1}{\Omega_l}\iint_{s_m}\left\{p_m\frac{\partial}{\partial n}\left(\frac{\exp(-jkr_{lm})}{r_{lm}}\right)-\frac{\partial p_m}{\partial n}\frac{\exp(-jkr_{lm})}{r_{lm}}\right\}ds_m \tag{3}$$

where n denotes the normal direction of the boundary surface. The sound pressure on the engine block surface p_m is expressed using discretized form of the equation (3).

$$\mathbf{H}_{BB}(\omega)\mathbf{P}_B(\omega) = \mathbf{G}_{BB}(\omega)\frac{\partial \mathbf{P}_B(\omega)}{\partial n}$$
$$\mathbf{H}_{BB}(\omega) = [h_{lm}] = \begin{cases} -1 & l = m \\ \dfrac{1}{\Omega_l}\iint_{s_m} \dfrac{\partial}{\partial n}\left(\dfrac{\exp(-jkr_{lm})}{r_{lm}}\right) ds_m & l \neq m \end{cases} \tag{4}$$
$$\mathbf{G}_{BB}(\omega) = [g_{lm}] = \frac{1}{\Omega_l}\iint_{s_m} \frac{\exp(-jkr_{lm})}{r_{lm}} ds_m$$

From equation (1) and (4), sound pressure vector of engine surface $\mathbf{P}_B$ can be determined as follows.

$$\mathbf{P}_B = -\rho \mathbf{H}_{BB}{}^{-1}\mathbf{G}_{BB}\ddot{\mathbf{x}}_n \tag{5}$$
where, $\dfrac{\partial \mathbf{P}_B}{\partial n} = -\rho \ddot{\mathbf{x}}_n$

On the other hand, sound pressure vector $\mathbf{p}_0$ at measuring point (o) in free space is re-written from equation (3).

$$\mathbf{p}_0 = \mathbf{H}_{0B}\mathbf{P}_B - \mathbf{G}_{0B}\frac{\partial \mathbf{P}_B}{\partial n} \tag{6}$$

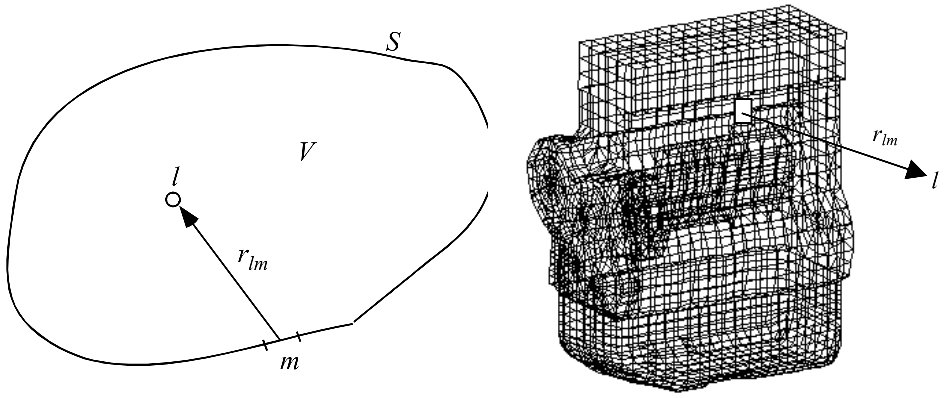
The substitution of equation (5) into equation (6) yields an equation between sound pressure $\mathbf{p}_0$ and engine block vibration $\ddot{\mathbf{x}}(\omega)$.

$$\mathbf{p}_0 = -\rho(\mathbf{H}_{0B}\mathbf{H}_{BB}{}^{-1}\mathbf{G}_{BB} - \mathbf{G}_{0B})\ddot{\mathbf{x}}_n \tag{7}$$

From equation (1), the sound pressure vector $\mathbf{p}_0$ is re-written using normal mode vector $\mathbf{\Phi}$ as follows.

$$\begin{aligned} \mathbf{p}_0(\omega) &= \rho\omega^2(\mathbf{H}_{0B}\mathbf{H}_{BB}{}^{-1}\mathbf{G}_{BB} - \mathbf{G}_{0B})\Phi\mathbf{a} \\ &= \sum \rho\omega^2(\mathbf{H}_{0B}\mathbf{H}_{BB}{}^{-1}\mathbf{G}_{BB} - \mathbf{G}_{0B})\Phi_n a_n(\omega) \end{aligned} \tag{8}$$

Sound pressure at the measuring point (o) is obtained by Inverse Fourier Transform of equation. (8).



(a) Boundary Element Method *(b) Radiated sound from engine surface*
Figure 1 Boundary Element Method

Result of Numerical Simulation

In this paper, the diesel engine sound is predicted in the case of the 4cycle-4cylinder Diesel engine at running speed 2200rpm. The objects of vibration analysis are a crankshaft, a crankcase, cam shafts and an oil pan and frequency range is up to 3 kHz. Simulation models are shown in Figure 2 and 3.

Comparisons of numerical simulation results with experimental ones are shown in Figure 4 and 5. The calculated frequency spectrum and time history of the engine noise fairly agreed with measured ones shown in Figure 4.

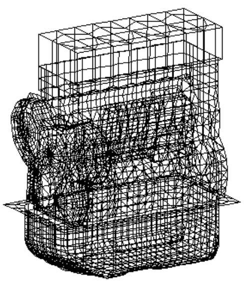
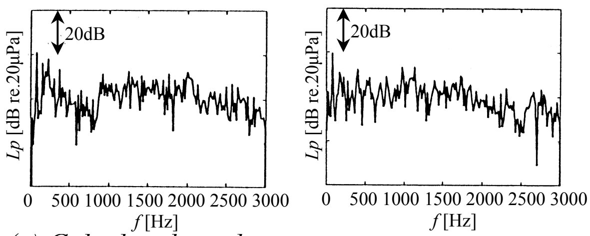


Figure 2 FEM model



(a) Calculated results *(b) Measured results*
Figure 4 Spectra of engine sound

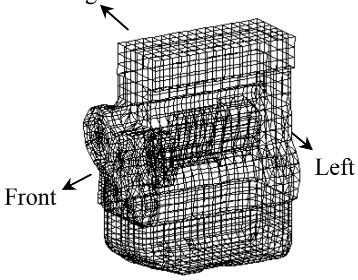
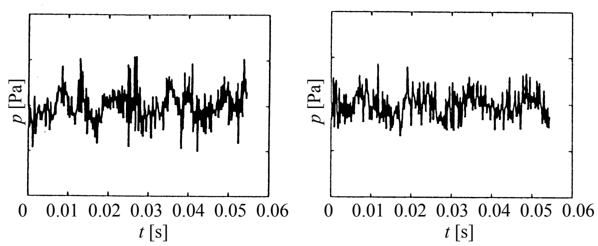


Figure 3 BEM model



(a) Calculated results *(b) Measured results*
Figure 5 Time histories of engine sound

DESIGN OF THE ENGINE SOUND

Modification of The Engine Sound Using Wavelet Transform

In order to improve the engine sound quality, it is important to set the target sound. In this paper, target sound is set by modifying the measured engine sound using Wavelet multi-resolution analysis. The desired engine sound is obtained as following steps,

Step 1: Signal decomposition

Step 2: Change the components at any point in the time domain and the frequency domain

Step 3: Signal reconstruction.

Engine sound signal is assumed by $f_n(t)$.

$$f_n(t) = \sum_k c_k^{(n)} \phi(2^n t - k), \quad k \in \mathbf{Z} \tag{9}$$

$\phi_n(t)$ is decomposed as following equation.

$$\phi(2t - l) = \frac{1}{2} \sum_k \{a_{2k-l}\phi(t-k) + b_{2k-l}\psi(t-k)\}, \quad l \in \mathbf{Z} \tag{10}$$

$f_n(t)$ is expressed as following equations.

$$f_n(t) = f_{n-1}(t) + g_{n-1}(t) \tag{11}$$

$$f_{n-1}(t) = \sum_k c_k^{(n-1)} \phi(2^{n-1} t - k)$$

$$g_{n-1}(t) = \sum_k d_k^{(n-1)} \psi(2^{n-1} t - k) \tag{12}$$

In equation (11), $f_{n-1}(t)$ shows a low frequency component of $f_n(t)$ and $g_{n-1}(t)$ shows high frequency component of $f_n(t)$. And decomposition and reconstruction of $c_k^{(n-1)}$ are expressed as following equations.

・Decomposition

$$c_k^{(n-1)} = \frac{1}{2} \sum_l a_{2k-l} c_l^{(n)}, \quad d_k^{(n-1)} = \frac{1}{2} \sum_l b_{2k-l} c_l^{(n)} \tag{13}$$

・Reconstruction

$$c_k^{(n)} = \sum \{p_{k-2l} c_l^{(n-1)} + q_{k-2l} d_l^{(n-1)}\} \tag{14}$$

where, $a_{2k-l}, b_{2k-l}, p_{k-2l}$ and q_{k-2l} are decided by Wavelet function.
Therefore deciding $c_k^{(n-1)}$ and $d_k^{(n-1)}$ leads to decompose the engine sound signal. And desired sound wave form is obtained by reconstructing the decomposed signal after changing the components in time domain and frequency domain.

Numerical Simulation

The present method is applied to the actual sound wave form of 3-cylinder diesel engine running at 2400 rpm. Engine sound wave form at right hand 1m point from engine surface in shown Figure 6. The mother wavelet function (The 3rd order Cardinal B-Spline function) is shown in Figure 7.

Figure 8 shows decomposition of engine sound. Time period is 2 cycles (2 / (2400/60/2) = 0.1 sec). In figure 8, sound level of g_{-5} is increased once a cycle.

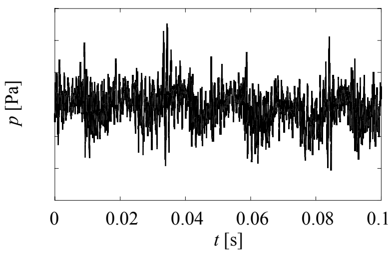
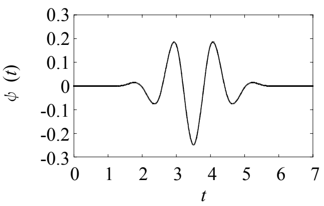
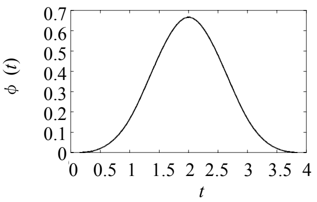


Figure 6 Measured engine sound

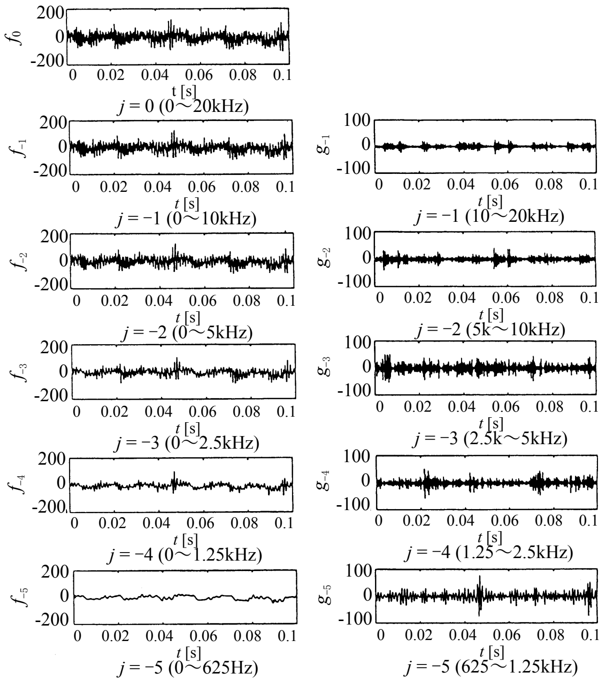


(a) Wavelet function



(b) Scaling function

Figure 7 Cardinal B-splines



(a) f_j (b) g_j

Figure 8 Wavelet decomposition of engine sound

We modified the engine sound changing g_{-5} in figure 8. In order to change g_{-5}, $d_k^{(-5)}$ is modified. The condition of simulation is as follows.

<Case 1> Reduction of peak level of 1kHz band (g_{-5})

- In case of $| d_k^{(-5)} | > 150$, the value of $d_k^{(-5)}$ is quartered.

- In the vicinity of peak level point is also reduced one-third.

<Case 2> Modification of a signal of 2.5~5kHz band (g_{-3}) to cyclic pulse signal

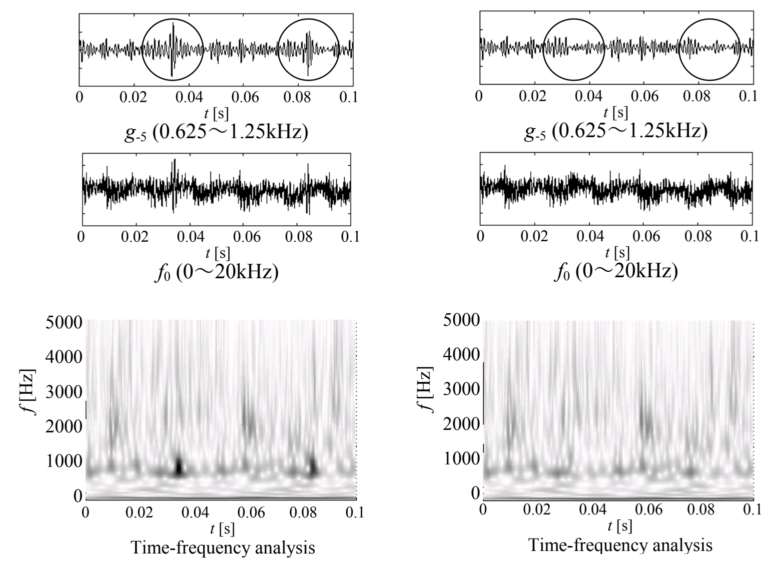
- Set pulses once a cycle in 2.5~5kHz band (g_{-3}).
- The value of $d_k^{(-3)}$ in pulse region is 3 times.

The results of numerical simulation are shown in Figure 9 and 10. The peak level of sound is decreased in Figure 9 and the cyclic pulse in 2.5~5kHz band decreased in Figure 10. However another time and frequency components are not changed.
From the results mentioned above, the availability of this presented method is confirmed for changing the level of any components in time and frequency domain and evaluation of influence on the engine sound quality.

REGENERATION OF ENGINR SOUND AND MODIFICATION

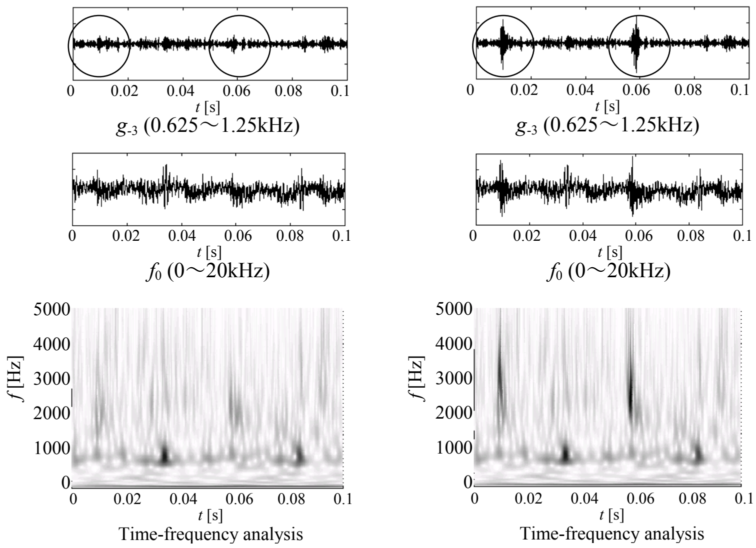
As an estimated sound and a modified sound are calculated in the time domain, it is possible to listen to them through a personal computer. Therefore designers and users are able to listen them and judge it comfortable or not.

Moreover combination of the present method and the conventional sound quality evaluation system enable us to evaluate the sound quality without experimental production and to reduce development period.



(a) Original engine sound *(b) Modified engine sound*

Figure 9 Modified engine sound using Wavelet transform : case1



(a) Original engine sound *(b) modified engine sound*

Figure10 Modified engine sound using Wavelet transform : case2

CONCLUTION

This paper offered the engine sound prediction system and the procedure of sound quality design as follows.

- Using the engine sound prediction system and boundary element method, it is possible to estimate sound pressure in time domain at any measuring point.
- Any components of measured and estimated engine sound in time and frequency domain are modified by Wavelet transform. And it enables us to listen to modified sound and to evaluate the sound quality without experimental production.

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