

Method Using Multiple Regression Analysis to Separate Engine Radiation Noise into the Contributions of Combustion Noise and Mechanical Noise in the Time Domain

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ABSTRACT

A technique was created to separate the contributions of combustion noise and mechanical noise to engine noise in the time domain in order to achieve efficient measures for enhancing the sound quality of combustion noise.

There is an existing technique based on 1/3 octave band analysis that is known as a method for separating the contributions to engine radiation noise, but this technique cannot provide time-domain data.

Therefore, the author has proposed a technique that separates engine radiation noise into combustion noise and mechanical noise in the time domain by finding the combustion noise for each cylinder and calculating its structural response function by considering its real and imaginary components.

Results of analysis of actual engine radiation noise with this technique confirmed that combustion noise, which is characterized by strong pulsation, and irregular mechanical noise can be separated in the time domain with good precision. Moreover, the structural response function, combustion noise, and mechanical noise characteristics showed a valid changing trend in response to changes in cylinder pressure and structural specifications. This demonstrates the effectiveness of the technique.

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INTRODUCTION

Noise emitted from the engine main unit is broadly classified as combustion noise, caused by cylinder pressure, and mechanical noise, caused by the mechanical behavior of the driven valve system or auxiliary equipment, etc. In completed vehicle, the former combustion noise sounds like noises with strong pulsation, such as rumbling, rattling, or rasping. Combustion noise is one factor lowering engine sound quality during acceleration.

On the other hand, reducing combustion noise conflicts with the objectives of enhancing fuel economy and output performance and making the engine lighter, so it is desirable to take steps to keep combustion noise to the necessary minimum. To do this, it is first necessary to determine with good precision the contribution that combustion noise is making to engine radiation noise.

There is an engine radiation noise contribution separation technique based on 1/3 octave band analysis that is known as an effective way of doing this. This technique uses multiple regression analysis, treating engine noise as the objective

variable and cylinder pressure and engine load as explanatory variables, to estimate the contributions of combustion noise, mechanical noise, and load-dependent noise.[1, 2]

Applying this technique to combustion noise countermeasures for gasoline engines, the author and others have confirmed that this is an effective technique for giving direction to such countermeasures. This technique, however, does not provide data in the time domain, and cannot be used for sound quality analysis using, for example, psychoacoustic analysis tools.[3] Therefore it was discovered that the technique is not suited to stricter examinations of countermeasures, such as screening proposed countermeasures to find those that are highly effective for enhancing sound quality.

In order to perform a sound quality evaluation, it is necessary to get time-domain data that can be played back and listened to.

Thus, a technique was devised that separates the contributions of combustion noise and mechanical noise in the time domain by finding the combustion noise for each cylinder and calculating its structural response function of each cylinder

using narrow-band Fourier transform and multiple regression analysis by considering its real and imaginary components. This paper gives an overview of the technique and confirms its validity applied to actual engines.

TECHNIQUE OVERVIEW

Combustion Noise and Mechanical Noise

This section explains this paper's stance on combustion noise and mechanical noise.

The noise emitted from intake and exhaust ports is fully muffled, and considers the case where only radiation noise that occurs from the engine main unit is transformed into a measuring object.

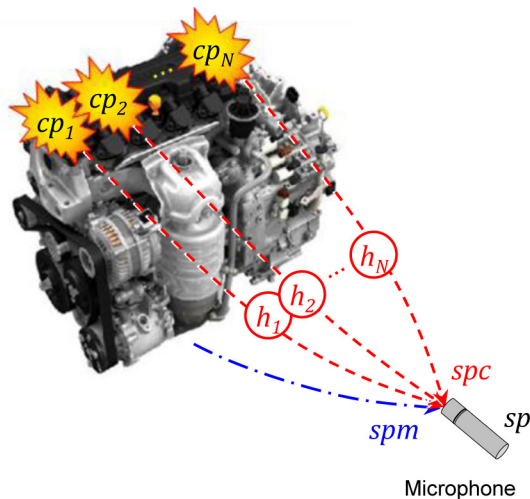


Figure 1. Transfer path of combustion noise

Combustion noise $spc(nT)$ and mechanical noise $spm(nT)$ are assumed to be as shown in Eqs. (1) and (2), respectively, at some evaluation point as in Fig. 1 (* means a convolution operation). In these Equations, $sp(nT)$ represents the measured acoustic pressure at any discretized time nT during sampling cycle T , while $cp_k(nT)$ represents the cylinder pressure of each cylinder.

$$spc(nT) = \sum_{k=1}^N h_k(nT) * cp_k(nT) \quad (1)$$

$$spm(nT) = sp(nT) - spc(nT) \quad (2)$$

Where,

T	Sampling period
N	Number of cylinders
$sp(nT)$	Measured noise at evaluation point
$spc(nT)$	Combustion noise
$spm(nT)$	Mechanical noise

$cp_k(nT)$	Cylinder pressure of each cylinder
$h_k(nT)$	Structural response function from each cylinder

Equation (1) finds that, considering the combustion noise is a linear phenomenon, the convolution sum of the cylinder pressure of each cylinder $cp_k(nT)$ and impulse response functions from the cylinder pressure to the sound pressure of evaluation point $h_k(nT)$ (hereafter referred to as structural response function), and for combustion noise $spc(nT)$ of an engine with N cylinders, this sum is assumed to be the total for N cylinders in the time domain. As a result, this technique doesn't only take into account differences of combustion noise between cylinders, but also takes into account the portion of combustion noise that is cancelled between cylinders. The earlier technique ignored those factors.

Equation (2) means that all noise that is included in measured noise $sp(nT)$ other than combustion noise $spc(nT)$ is considered to be mechanical noise $spm(nT)$. This is in reference to an application example of residual noise with an operational transfer path analysis technique [4] and is based on the assumption that combustion noise $spc(nT)$ and mechanical noise $spm(nT)$ are independent, and the sum of the two in the time domain is the measured noise $c(nT)$.

In this point of view, nonlinear phenomena, such as the mechanical noise or the flow noise caused by combustion is contained in the mechanical noise $spm(nT)$. Although possibly some might feel a sense of incongruity for not including the phenomenon of changing with the changes in the cylinder pressure in the combustion noise, I believe that there is no practical problem for engine noise development. The reason is because this nonlinear combustion noise and the linear combustion noise in Eq. (1) have different characteristics of sound quality and general countermeasures are also different.

Calculating Structural Response Function by Multiple Regression Analysis

As Eqs. (1) and (2) show, the contributions of combustion noise $spc(nT)$ and mechanical noise $spm(nT)$ can be separated in the time domain if one can determine the structural response function $h_k(nT)$ with good precision.

If the relationship between cylinder pressure and combustion noise is a linear time-invariant system, then Eq. (1) also holds true for a Fourier spectrum at any angular frequency ω . Therefore, if the complex Fourier spectra of $spc(nT)$, $h_k(nT)$, and $cp_k(nT)$ at angular frequency ω are written as $SPC(\omega)$, $H_k(\omega)$, and $CP_k(\omega)$, Eq. (3) can be derived.

$$SPC(\omega) = \sum_{k=1}^N H_k(\omega) \cdot CP_k(\omega) \quad (3)$$

Next, the relationship between the combustion noise Fourier spectrum $SPC(\omega)$ of Eq. (3) with measured noise $sp(nT)$'s Fourier spectrum $SP(\omega)$ is considered. The combustion noise component $SPC(\omega)$ is mixed with the mechanical noise component, which has no linear relationship with cylinder pressure. If the latter is represented as $E(\omega)$, Eq. (4) holds true.

$$SP(\omega) = SPC(\omega) + E(\omega)$$

$$= \sum_{k=1}^N H_k(\omega) \cdot CP_k(\omega) + E(\omega) \quad (4)$$

Here, it is supposed that the position of the recording microphone is fixed, that there are m sets of measurement data $SP(\omega)$ found by intentionally varying the cylinder pressure, and that there are $CP_1(\omega) \sim CP_N(\omega)$. If it is assumed that $E(\omega)$ changes without correlation to cylinder pressure, but the unique structural characteristic structural response function $H_1 \sim H_N$ does not change, Eq. (5) can be derived for any angular frequency ω (for simplification, ω is omitted). This Equation substitutes the m sets of measurement data into Eq. (4) and arranges it in matrix form.

$$\begin{bmatrix} SP_1 \\ SP_2 \\ SP_3 \\ SP_4 \\ \vdots \\ SP_m \end{bmatrix} = \begin{bmatrix} CP_{1,1} & CP_{2,1} & \cdots & CP_{N,1} \\ CP_{1,2} & CP_{2,2} & \cdots & CP_{N,2} \\ CP_{1,3} & CP_{2,3} & \cdots & CP_{N,3} \\ CP_{1,4} & CP_{2,4} & \cdots & CP_{N,4} \\ \vdots & \vdots & \ddots & \vdots \\ CP_{1,m} & CP_{2,m} & \cdots & CP_{N,m} \end{bmatrix} \cdot \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_N \end{bmatrix} + \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ \vdots \\ E_m \end{bmatrix}$$

$$\begin{matrix} \downarrow & \downarrow & \downarrow & \downarrow \\ [SP] & = & [CP] & \cdot & [H] & + & [E] \end{matrix} \quad (5)$$

Here, matrices $[SP]$, $[CP]$, $[H]$, and $[E]$ of Eq. (5) are referred to respectively as the recorded noise vector, combustion pressure matrix, structural response function vector, and error vector (all of these are complex matrices).

In Eq. (5), the structural response function vector $[H]$ and error vector $[E]$ are unknown. Thus, multiple regression analysis [5] is introduced into Eq. (5), and, as shown in Eq. (6), the structural response function vector $[H]$ is found that minimizes the square value $[E]^H[E]$ of the size of the error vector with no correlation to cylinder pressure ($[]^H$ refers to a conjugate transpose matrix). This operation means the same thing as maximizing combustion noise, and the idea is to extract from the recorded noise as much of the component as possible that correlates to cylinder pressure.

$$[H] = ([CP]^H[CP])^{-1}[CP]^H[SP] \quad (6)$$

The operation of Eq. (6) is done for all angular frequencies ω , and the frequency response function $H_k(\omega)$ undergoes inverse Fourier transform, the result of which is the impulse response function $h_k(nT)$.

Generating a Time Domain Signal

Finally, this structural response function $h_k(nT)$ is substituted into Eq. (1) and a convolution operation is performed with the measured cylinder pressure $cp_k(nT)$, which makes it possible to find the combustion noise $spc(nT)$ in the time domain. In addition, using Eq. (2) enables determining the mechanical noise $spm(nT)$ in the time domain by the residual from $sp(nT)$.

Application Example

An example is described below of actual analysis of engine radiation noise using the above technique. The power plant used for this analysis was an approximately 2.0L four-cylinder direct-injection turbocharged engine combined with a manual transmission.

Test Conditions

All tests were conducted on a semi-anechoic dynamo test cell. Orifice noise, which inhibits measurement of radiated noise from the engine itself, was muffled with a large muffler. Pressure transducers built into spark plugs were installed at all four cylinders to measure cylinder pressure. To measure sound pressure, 1/2-inch microphones were placed at four points 1 m away from the engine surface, as shown in Fig. 2.

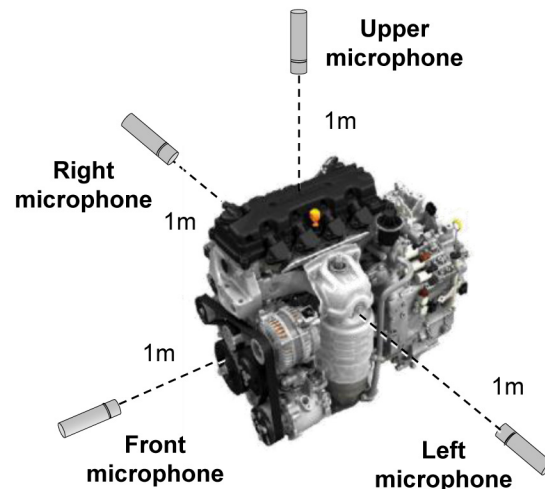


Figure 2. Measurement position of sound pressure

In the tests, time domain signals on a total of eight channels were input to a multi-channel measurement analysis system and measured simultaneously, and Fourier spectra were continuously calculated over time. This time, the sampling frequency was set at 8,192 Hz, taking cylinder pressure measuring accuracy into account.

Operating conditions were set as a full-load run up fixed in third gear. Varying the engine speed is very significant for subsequent statistical processing.

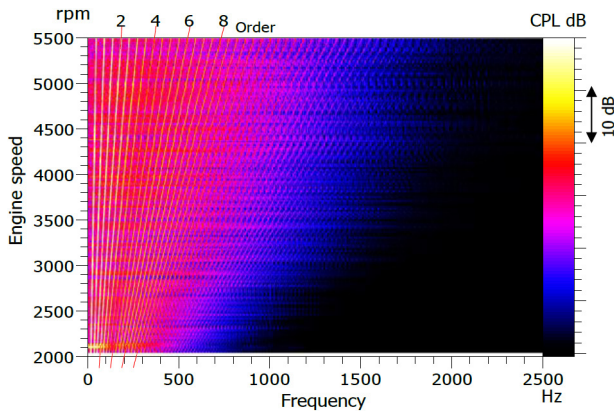


Figure 3. Cylinder pressure level (#1 Cylinder)

Ordinarily, as shown in the color contour plot of Fig. 3, the main component of cylinder pressure is the 0.5 n order component, which corresponds to the combustion cycle and its high-frequency component, and combustion noise resulting from it is similar. Therefore, if the structural response function is calculated using only data from an engine at fixed speed for example, there would be a problem in that calculating precision would fall significantly in frequency bands other than the 0.5 n order, where there is not enough excitation. Using engine speed sweep data avoids this problem because the combustion cycle gradually changes.

Structural Response Function Calculation Results

Figure 4 gives an example of the structural response function calculated by the multiple regression analysis in Eq. (6) by showing it in the form of a Bode diagram (in the graph of the lower berth, the unit is Pa / Pa and the value is RMS / RMS). The example shown here is for the noise measured at 1 m on the left side. For one response point, this technique calculates as many response functions as there are cylinders, so the result for each of the four cylinders is shown in a different color. In addition, the four cylinders' response amplitude power additional values are shown at a +5 dB offset for reference in order to gauge the overall sensitivity trend.

In the example of Fig. 4, peaks occur in the 1.1 kHz, 1.4 kHz, and 1.9 kHz bands, and it can be easily predicted that combustion noise will increase in these bands.

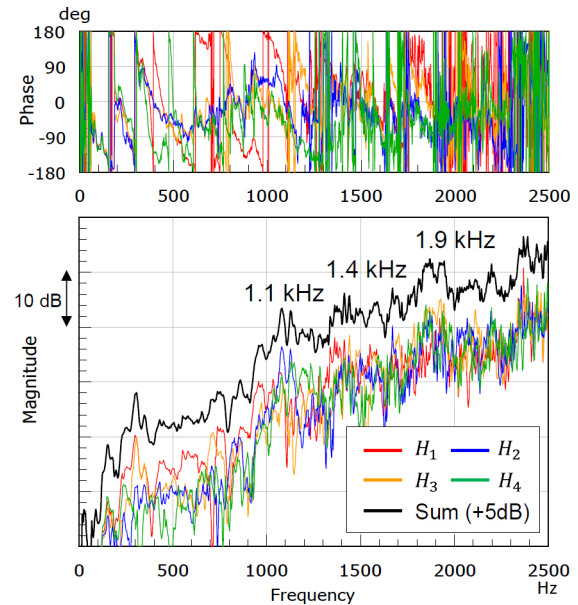


Figure 4. Structural response function (response: left microphone)

Results of Separation of Time-Domain Contribution of Combustion Noise and Mechanical Noise

Figures 5 [Appendix] and 6 [Appendix] show the results of separating the time-domain contribution for the noise at 1 m to the left using the structural response function in Figure 4. Figure 5 [Appendix] is a time-series waveform for engine speed 4,500 rpm, and is expressed together with cylinder pressure. Figure 6 [Appendix] shows A weight sound pressure narrow-band power spectrum in the form of a color contour plot, with frequency on the horizontal axis and engine speed on the vertical axis. Within the figure, (a) represents recorded noise, (b) combustion noise, and (c) mechanical noise.

A turbocharging device is located on the left side of this engine. Therefore, as the power spectrum of Fig. 6 [Appendix] (a) shows, the recorded sound 1 m to the left of the engine is, in addition to combustion noise, a mix of mechanical noises including turbocharger device noise and transmission gear tooth striking noise (especially at low engine speeds).

The combustion noise whose contribution is separated in Fig. 6 [Appendix] (b) contains none of the mechanical noise component that has no direct correlation to cylinder pressure, and in the frequency spectrum the 0.5 n order component, which is the combustion cycle, is dominant. Additionally, the impacts of the 1.1 kHz, 1.4 kHz, and 1.9 kHz peaks in the structural response function are clearly shown, and the rise in