

Vibration Analysis for GDI Components Using Partial Coherence Function

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ABSTRACT

The contributions of vibration sources in a gasoline direct-injection (GDI) engine are identified by simulating a two input-one output model. A partial coherence function between two inputs and one output was calculated to identify the contributions of the two inputs to the output. In order to evaluate the proposed method, a principle test was performed using a laboratory test rig. The results show that the model can be used to identify the contribution of each input to the output. Finally, this model is applied to the identification of the vibration source in a GDI engine.

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INTRODUCTION

Due to advances in the automobile industry in recent years, today's vehicles are becoming increasingly luxurious and offer enhanced performance. Accordingly, consumers are shifting their interest from output and fuel efficiency to vibration, noise, and ride quality. While numerous studies have been conducted on gasoline engines [1, 2], gasoline direct-injection (GDI) engines require further research. Vibration and noise from a pump due to high pressure occurring in a GDI engine can be felt inside the vehicle, leading to complaints from customers. Therefore, an analysis technology to determine the contributions of vibrations coming from GDI engine parts must be developed. A GDI engine includes a high pressure pump, a fuel rail, an injector, and a pressure sensor. The noise and vibration caused by these parts are perceived inside the vehicle as a mixture of the parts' respective vibration, necessitating analysis of the parts' respective vibration paths and levels of contribution. Noise and vibration from GDI engine parts do not seem to be generated independently. Rather, they mostly exist in a combined form, which makes it difficult to analyze each part's vibration level when examining the effect of a specific source of vibration. In the case of an independent system, spectral frequency analysis is possible by applying the existing frequency response function method. However, the noise and vibration analysis of GDI engine parts has limitations due to correlations among the parts. For such a case, it is easier to use a partial coherence function that considers correlations between each source of input and output, and analyzes their respective effects [3]. We propose

a new model to quantify the contributions of GDI engine parts to the high pressure pump vibration that is a major vibration source among GDI engine parts. A model was developed based on partial coherence theory. A validation test for the proposed model was performed, and the model was applied to the analysis.

SPECTRAL ANALYSIS FOR TWO INPUTS -ONE OUTPUT SYSTEM

An ordinary coherence function is used when there is no correlation between input sources and when the sources are independent from one another. However, the main parts of the GDI engine for this study are a high pressure pump, an injector, a fuel rail, and a pressure sensor, which have correlations among them [5].

Therefore, these engine parts should be modeled to have multiple inputs and a single output, as shown in Fig. 1, rather than a single input. In addition, they need to be analyzed using the multi-dimensional spectral method.

In this study, the parts were modeled with a two-input/single-output system [6], as shown in Fig. 2, based on the multi-input/single-output system.

Through a partial coherence function (one of the multi-dimensional spectral analytical methods), the contribution of each multiple input was analyzed [7]. If outputs are shown as results of mutual interference between the vibration paths of the GDI engine parts, as shown in Fig. 3, their respective actual levels of contribution can be identified by removing correlations between parts.

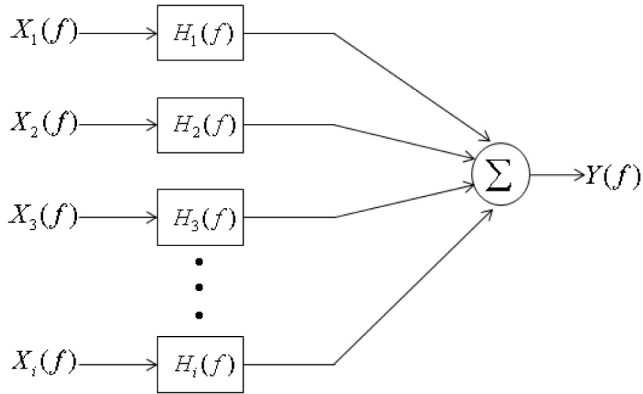


Fig. 1. Multi-input/single-output model of dynamic system for vibration path analysis

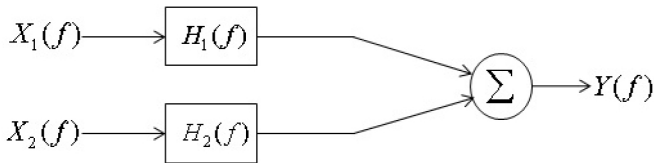


Fig. 2. Two-input/single-output model of a dynamic system with two independent inputs

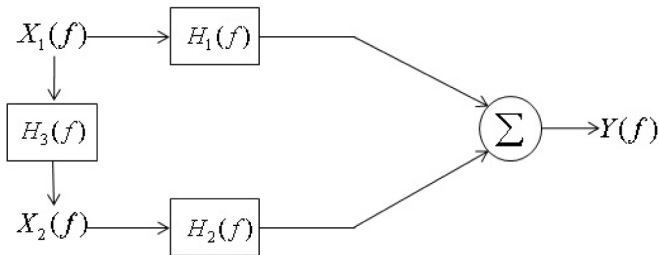


Fig. 3. Two-input/single-output model of a dynamic system with partially correlated inputs.

Ordinary Coherence Function

The portion taken up by each input for the entire output can be expressed as an ordinary coherence function ($\gamma_{iy}^2(f)$), as shown in Eq. (1), by using the auto-spectrum and cross-spectrum [6-7] as follows:

$$\gamma_{iy}^2(f) = \frac{|G_{iy}(f)|^2}{G_{ii}(f)G_{yy}(f)} \quad i = 1, 2, \dots, q \quad (1)$$

In Fig. 2, inputs $X_1(f)$ and $X_2(f)$ against output $Y(f)$ are modeled, where $H_1(f)$ and $H_2(f)$ are frequency response functions. Here, $X_1(f)$ and $X_2(f)$ are the values resulting from the Fourier transformation of $X_1(t)$ and $X_2(t)$, respectively. The ordinary correlation between the input value $X_i(f)$ and the

output value $Y(f)$ can be expressed by Eq. (1). In this study, i is 1 and 2 since two inputs are used. However, if outputs are shown as results of mutual interference between the vibration paths of the GDI engine parts, as shown in Fig. 3, it is difficult to know the actual level of contribution by the input of interest.

In the system as shown in Fig. 3, the correlation of the input $X_1(f)$ does not consider the mutual link of the other input $X_2(f)$. Hence, a partial coherence function from which correlation properties are eliminated was used in a multi-input system.

Partial Coherence Function

The output power spectrum (G_{yy}) of the multi-input/single-output system as shown in Fig. 1, which is a multi-input system, can be calculated as

$$G_{yy}(f) = \sum_{i=1}^q \sum_{j=1}^q H_i^*(f) H_j(f) G_{ij}(f) + G_m(f) \quad (2)$$

where $H_i(f)$ is a frequency response function that contributes to the i -th system, $H_i^*(f)$ is a complex conjugate number of the $H_i(f)$ function, and $G_m(f)$ is the noise power spectrum. In this case, the contribution by any input against its output can be calculated using the frequency response function method. In the case of the system as shown in Fig. 3, it is difficult to determine the extent to which each input value contributes to output values. Therefore, the output spectrum can be expressed as a residual spectrum from which the linear effects of inputs on outputs are eliminated:

$$G_{ij,r!} = G_{ij,(r-1)!}(f) - L_{rj}(f) G_{ir,(r-1)!}(f) \quad (3a)$$

$$L_{rj}(f) = \frac{G_{rj,(r-1)!}(f)}{G_{rr,(r-1)!}(f)} \quad (3b)$$

where, $L_{rj}(f)$ is the optimal transfer function between the r -th input and j -th outputs when the correlation properties between the r -th input and j -th outputs is eliminated. The residual spectrum between the input $X_2(f)$ and the output $Y(f)$, from which the effect of $X_1(f)$ is eliminated from the two input/single-output model, is expressed as follows [6]:

$$G_{2y,1}(f) = E[X_2^*(f)Y(f)] = G_{2y}(f) - \left(\frac{G_{1y}(f)}{G_{11}(f)} \right) G_{12}^*(f) \quad (4)$$

The auto spectrum for input $X_2(f)$, from which the effect of $X_1(f)$ is eliminated, is given by

$$\begin{aligned}
 G_{22 \cdot 1}(f) &= E[X_{2 \cdot 1}^*(f)X_{2 \cdot 1}(f)] \\
 &= G_{22}(f) - \frac{G_{12}(f)G_{12}^*(f)}{G_{11}(f)} \\
 &= G_{22}(f)(1 - \gamma_{12}^2(f))
 \end{aligned}
 \quad (5)$$

The auto spectrum for output $Y(f)$ from which the effect of $X_1(f)$ is eliminated is given by

$$G_{yy \cdot 1}(f) = G_{yy}(f)(1 - \gamma_{1y}^2(f)) \quad (6)$$

The partial coherence function of $X_2(f)$, from which the relation $X_1(f)$ is eliminated, can be expressed as [7]

$$\gamma_{2y \cdot 1}^2(f) = \frac{|G_{2y \cdot 1}(f)|^2}{G_{22 \cdot 1}(f)G_{yy \cdot 1}(f)} \quad (7)$$

Figure 3 shows a model of the contribution of $X_1(f)$ and $X_2(f)$ to output y . Unlike Fig. 2, the model in Fig. 3 was made by considering correlations between each input value. In other words, the input of the excitation forces of $X_1(f)$ and $X_2(f)$ indicates the output vibration of $Y(f)$, whereas the input of $X_1(f)$ goes into y through $X_2(f)$. In this case, the actual level of contribution by $X_1(f)$ should be calculated with a spectrum without the relation $X_2(f)$ and by using a partial coherence function. To actually detect a vibration source, a coherence output spectrum that calculates the pure level of contribution of the input source to the output must be obtained. A coherence output spectrum is used to identify the amount of power at the output generated by a pure input value that is free of linear effects related to the input value. To obtain a partial coherence output spectrum of the two-input/single-output model, Eq. (8) can be used as follows:

$$G_{y:1 \cdot 2}(f) = \gamma_{1y \cdot 2}^2(f)G_{yy \cdot 2}(f) \quad (8a)$$

$$G_{y:2 \cdot 1}(f) = \gamma_{2y \cdot 1}^2(f)G_{yy \cdot 1}(f) \quad (8b)$$

Here, $G_{y:1 \cdot 2}(f)$ is the pure coherence output spectrum of $X_1(f)$ from which the input $X_1(f)$ contributes to the output $Y(f)$, and the correlation of the input $X_2(f)$ is eliminated in this case.

Also, $\gamma_{1y \cdot 2}^2(f)$ is the partial coherence function of the input $X_1(f)$, or pure correlation free of the correlation $X_2(f)$, and $G_{yy \cdot 2}$ is the output power from which the correlation of $X_2(f)$ for the $Y(f)$ output power is eliminated. The coherence output spectrum of $X_1(f)$ can be obtained by multiplication of

the partial coherence function of $X_1(f)$ with $G_{yy \cdot 2}(f)$, which is the output power.

EXPERIMENTAL VALIDATION OF TWO INPUTS AND ONE OUTPUT SYSTEM MODEL

Validation Test

In order to validate the proposed model in our application to engine vibration path identification, a rig test was performed using a prototype pump model and the cylinder head of a practical engine. Two shakers were used to excite the test system. One is a larger power shaker exciting the cylinder head, and the other is a small power shaker exciting the pumper model as shown in Fig. 4.

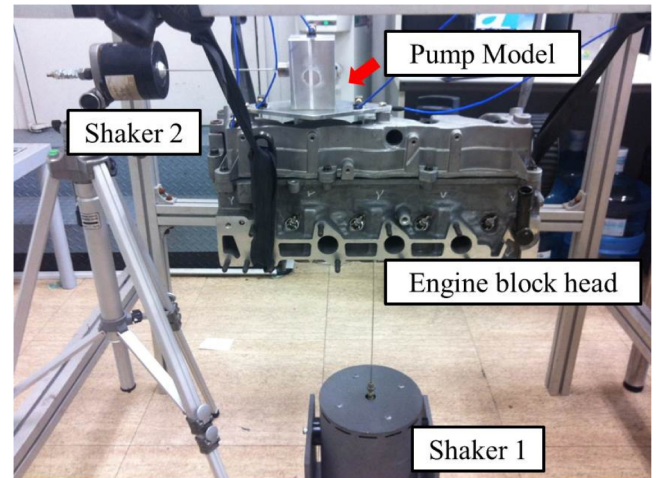


Fig. 4. Experiment set-up for identification of partial coherence.

Figure 5 shows the experimental equipment used for this test.

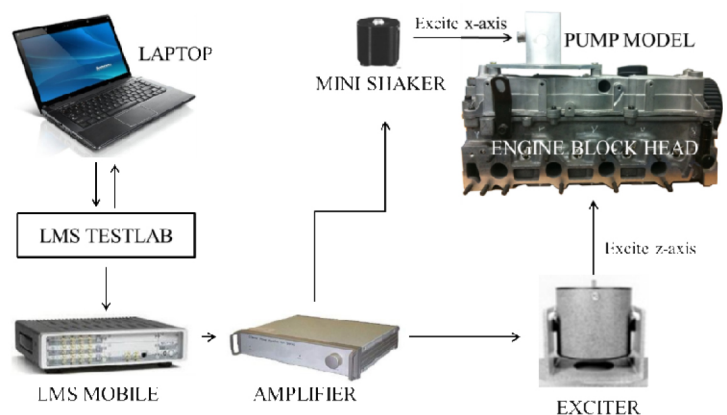


Fig. 5. Set up for the equipment used for the validation test.

The signals of the two input forces were generated by an output channel of LMS Mobile system (LMS Mobile 32 channel, LMS Corporation Belgium) and were enhanced by