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Transfer Path Analysis of Output Noise Using Multi-dimensional Spectral Analysis Method For Vacuum Cleaner

Jae-Eun Jeong (1), In-Hyung Yang (1), Goon-Dong Park (1), You-Yub Lee (2) and Jae-Eung Oh† (3)

(1) Dep. of Mechanical Engineering, Hanyang Univ., Seoul , Korea

(2) School of Mechanical and Automotive Engineering, Howon Univ., Gunsan, Korea

(3) School of Mechanical Engineering, Hanyang Univ., Seoul, Korea

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ABSTRACT

Noise reduction of vacuum cleaner is important, according as estimating quality of product. To reduce noise of vacuum cleaner, we need analysis of correct noise source and contribution grasping about Identified noise sources' output noise. Because noise sources' correlation exists in vacuum cleaner that is small and complicated system, and analysis is not easy. In this case, we need to apply Multi-dimensional spectral analysis (MDSA) method that can remove correlation among noise sources and grasp pure contribution degree of noise sources. In this study, we analyze transfer path analysis between output noise and input noise that measured in inside/outside of vacuum cleaner.

1. INTRODUCTIONS

Recently, as quality of life has improved, customer complaints about the noise level of products have increased. The level of noise has become one of the key factors that are considered, in addition to performance, when purchasing an appliance. In particular, this is the case for the household vacuum cleaner, in which consumers complain about the noise that is generated while using the dust inhalation condition. The designer of the product must determine the source of the noise in order to eliminate the source. In order to efficiently reduce the noise, systematic methods were used to determine quantitatively the main influence of each of the components including the inhalation nozzle, cyclone exist, dust inflow pipe, and exhaust pipe. This was difficult because there are many noise sources in a vacuum cleaner that correlate with each other. A frequency response function method (FRF) was used to analyze the Multi-Input Single Output (MISO) system. However, the FRF method is usable only in the case that input sources do not influence each other. Therefore, MDSA (Multi-Dimension Spectral Analysis) was applied, which can diminish the influence among the input sources and determine how each input factor contributes to output noise. The MDSA consists of the Partial Coherence Function (PCF), the Multiple Coherence Function (MCF), the Residual spectrum, and the Partial Coherent output spectrum. In this study, according to domestic regulation (KS 9101), which is the provision to measure the noise level of a vacuum cleaner, the noise level of a vacuum cleaner was measured and the characteristics of the noise that the vacuum cleaner generated during the inhalation condition were analyzed. Two models were constructed that consisted of 3 inputs(outside noise)/1 output and 3 inputs(inside noise)/1 output, in order to apply the MDSA.

2. MDSA(MULTI-DIMENSIONAL SPECTRAL ANALYSIS)

Cause of interactions between transfer paths, when a number of inputs show as outputs, we apply that to a multi-inputs/single-output model such as the Fig. 1.5 When bringing a output spectrum kind of this system, it's the following

$$S_{yy}(f)=\sum_{i=1}^{q}\sum_{j=1}^{q}H_{iy}^{*}(f)H_{jy}(f)S_{ij}(f)+S_{nn}(f) \tag{1}$$

Also, if the (1) expression is supposed to have the relationship between inputs, we can display the output spectrum like the following

$$S_{yy}(f)=\sum_{i=1}^{q}\left|H_{i}(f)\right|^{2}S_{ii}(f)+S_{nn}(f) \tag{2}$$

In a same group with the Fig. 1, it shows higher than a term of the original spectrum. Because the term related to inputs is overlapped when calculating with the FRF (Frequency Response Function), it is hard to figure out a source input which affects the output, with only the coherent output spectrum between the income and output.

Therefore, it is considered as a multi-inputs/single -output group, and modeled as a multi-inputs/single-output group having same terms with the Fig. 2, that the related ingredient between inputs are eliminated. To know a pure quantitative coherency by eliminating the related ingredient between inputs in the actual machine system, we need to use the MDSA. So the spectrum, that the related ingredients between inputs are eliminated, is called the Residual spectrum, shows like the following (3) term.

$$S_{ij\cdot r!}(f) = S_{ij\cdot(r-1)!}(f) - L_{rj}(f)\cdot S_{ir\cdot(r-1)!}(f)$$
$$(i, j = 2,3,\cdots, y \quad i, j > r) \tag{3}$$

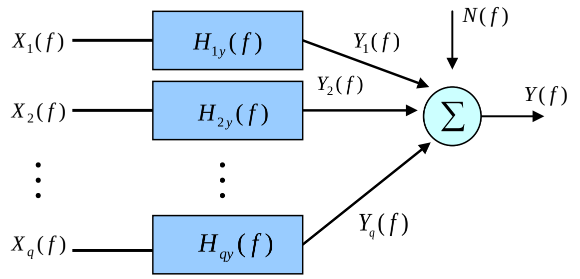

Figure 1: Correlated multi-inputs/single-output model

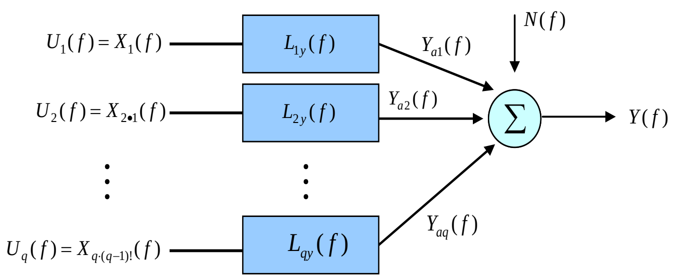

Figure 2: Conditioned multi-inputs/single-output model

At this, the $L_{rj}(f)$ is a conditioned transfer function of the case, that the related ingredients among inputs and between inputs and output. It shows like the following

$$L_{rj}(f) = \frac{S_{rj\cdot(r-1)!}(f)}{S_{rr\cdot(r-1)!}(f)} \qquad (i = 2,3,\cdots, y \quad i > j) \tag{4}$$

In the multi-inputs/single-output, when modeling the multi-inputs/single-output group using the conditioned transfer function as related ingredients among inputs, a coherence of the i th input to the output is the PCF(Partial Coherence Function). It shows like the following

$$\gamma^2_{iy\cdot r!} = \frac{\left|S_{iy\cdot r!}(f)\right|^2}{S_{ii\cdot r!}(f) S_{yy\cdot r!}(f)} \tag{5}$$

This function is regard as a ordinary coherence function which can calculate after analytically eliminating the relationship among inputs. The MCF(Multiple Coherence Function) is a direct extension of the concept of ordinary coherence, which provides a measure of the linear dependence between a collection of q inputs and an output. It shows like the following

$$\gamma^2_{y:q!} = 1-(1-\gamma^2_{1y})(1-\gamma^2_{2y\cdot 1})\cdots(1-\gamma^2_{qy\cdot(q-1)!}) \tag{6}$$

It is a function showing the used inputs are considered appropriately. When the value is larger than 0.9, we can judge it is appropriate

Actually, when detecting a vibration source, it needs to calculate a pure coherence quantity about the output of input source. So the Coherent output spectrum between a output spectrum and a coherent function is used. Like the (7) term, the Partial Coherence Output Spectrum that shows pure coherence quantity of the specific input is used.

$$S_{y:i\cdot(n-1)!}(f) = \gamma^2_{iy\cdot(n-1)!}(f) S_{yy\cdot(n-1)!}(f) \tag{7}$$

In the (7) term, to grasp a coherent relationship of the each vibration source in all over the frequency domain, a integrated level of the coherent output spectrum shows on the next term.

$$\phi_i = (0 \sim f) = \int_0^f \gamma^2_{iy\cdot(n-1)!}(f) S_{yy\cdot(n-1)!}(f)df \tag{8}$$

Algebraic sum of the accumulated level from the (8) term becomes an overall level

3. Experiment

I used vacuum cleaner that inhalation power is 500W and consumption electric power is 1100W in this experiment. The output noise set on the ground at top side 1m of vacuum cleaner according to standard of KSC 9101. Also, noise measurement of input part divides to indoor and outside of vacuum cleaner. Experiment schematic diagram is displayed to fig.3 and fig.4

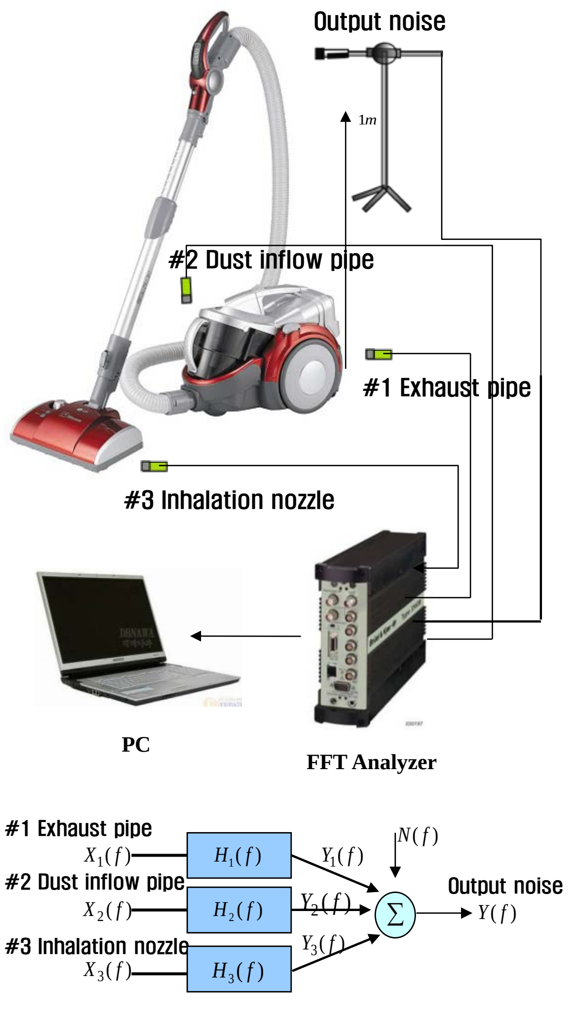

Fig.3 The experiment set up for transfer path analysis (outside noise)

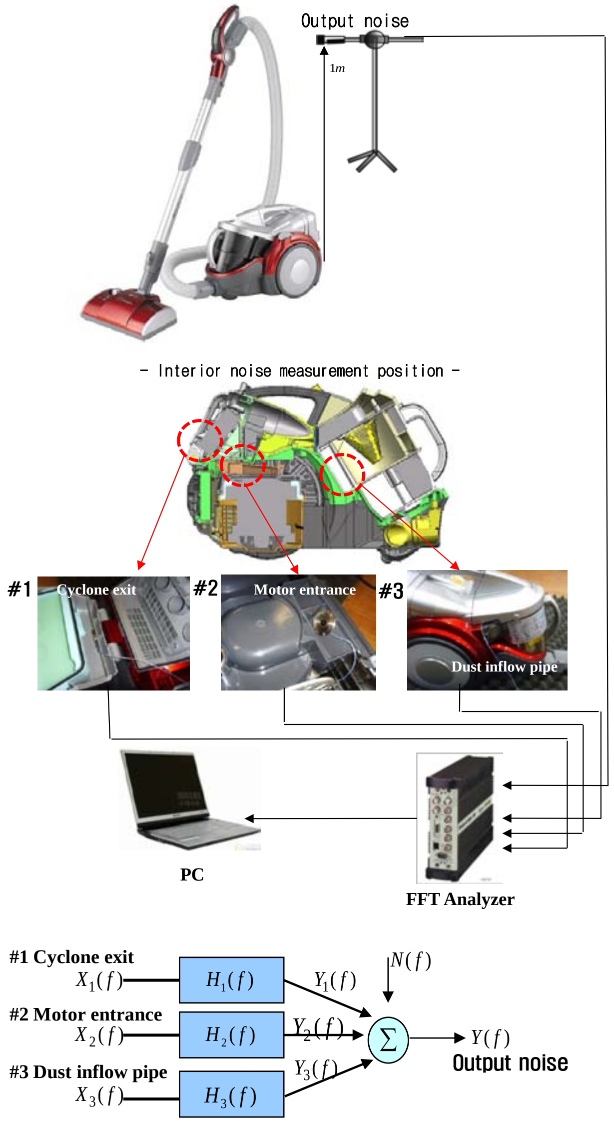

Fig.4 The experiment set up for trasfer path analysis (interior noise)

I measured vacuum cleaner interior and outside noise using experiment equipment B&K 1/2" microphone, B&K surface microphone and B&K Pulse FFT analyzer.

I chose input source by exhaust pipe, dust inflow pipe, inhalation nozzle of vacuum cleaner for external noise transfer path analysis. And I chose input source by cyclone exit, motor entrance, and dust inflow pipe of vacuum cleaner for interior noise transfer path analysis.

4. Experiment result and consideration

4.1 Selection of target frequency and ordinary coherenc function

I displayed spectrum of vacuum cleaner upper direction 1m noise by KS measurement standard.

Table.1 The ordinary coherence function among the 3 inputs (outside noise)

Frequency	γ^2_{12}	γ^2_{13}	γ^2_{23}
operating Freq.	0.7899	0.7263	0.7441
1st BPF	0.8534	0.7954	0.7705

Table.2 The ordinary coherence function among the 3 inputs (inside noise)

Frequency	γ^2_{12}	γ^2_{13}	γ^2_{23}
operating Freq.	0.7987	0.742	0.6652
1st BPF	0.9355	0.8904	0.7631

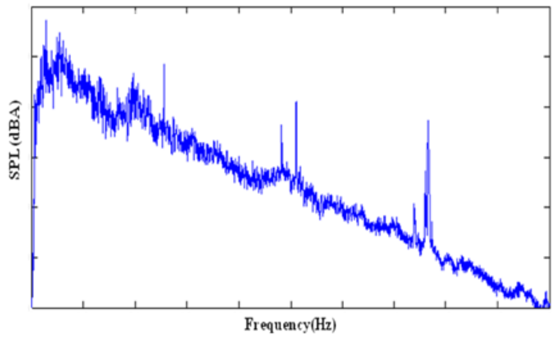

Fig.5 A-weighted sound pressure level of output noise (Up 1m)

And, I analyze this spectrum, and then appeared correlation among inputs of outside noise to Table.1 and correlation among inputs of interior noise to Table.2.

Also, I appeared correlation among input and output of outside noise to Table.3 and correlation among input and output of interior noise to Table.4.

Table.3 The ordinary coherence function among the inputs and output signal (outside noise)

Frequency	γ^2_{1y}	γ^2_{2y}	γ^2_{3y}
operating Freq.	0.6784	0.9379	0.8151
1st BPF	0.9616	0.3515	0.7127

Table.4 The ordinary coherence function among the inputs and output signal (outside noise)

Frequency	γ^2_{1y}	γ^2_{2y}	γ^2_{3y}
operating Freq.	0.7796	0.6026	0.6474
1st BPF	0.8975	0.7919	0.8531

We need to analyze correlation among inputs and correlation among input/output to predict inputs whether have independence each other or whether correlation exists in theoretical assumption of multi dimensional spectral analysis (MDSA). This can be confirmed through ordinary coherence function.

I chose operating(driving motor) frequency and 1st BPF(Blade Passing Frequency) through spectrum of output noise by target frequency.

Correlation among inputs of outside noise/ interior noise is expressed high contribution value more that 0.5 as shown Table.1 and Table.2. Also, Correlation among inputs of outside noise/interior noise and output noise is expressed high contribution value more that 0.5 as shown Table.3 and Table.4.

Like this, we can know that application of MDSA about output noise and interior noise is possible because correlation among inputs and correlation among input and output exist.

4.2 Contribution relation of each noise sources and output noise

I appeared partial coherence function value about each input source (noise source) to Table.5 and Table.6.

Table.5 The partial coherence function among input and output signals (outside noise)

Frequency	$\gamma^2_{1y\_23}$	$\gamma^2_{2y\_13}$	$\gamma^2_{3y\_12}$
operating Freq.	0.4677	0.6486	0.3006
1st BPF	0.3577	0.63	0.1616

Table.6 The partial coherence function among input and output signals (inside noise)

Frequency	$\gamma^2_{1y\_23}$	$\gamma^2_{2y\_13}$	$\gamma^2_{3y\_12}$
operating Freq.	0.4297	0.7201	0.4099
1st BPF	0.3268	0.3515	0.7127

In case of transfer path analysis about output noise, we can grasp contribution order of each noise that influence at whole output noise as shown Table.5. Contribution order was appeared by dust inflow pipe > exhaust pipe > inhalation nozzle at operating frequency and 1st BPF equally.

And, we must confirm multiple coherence function (MCF) value to judge about validity of modeling through degree that is expressed in output of considered input sources.

Table.7 The multiple coherence function at the target frequencies (outside noise)

Frequency	$\gamma^2_{y:x}$
operating Freq.	0.8991
1st BPF	0.9373

Table.8 The multiple coherence function at the target frequencies (inside noise)

Frequency	$\gamma^2_{y:x}$
operating Freq.	0.9088
1st BPF	0.8251

In case of transfer path analysis about output noise, we can know that modeling is valididy because it was expressed high value more than 0.5 as shown Table.6.

In case of transfer path analysis about interior noise, contribution order was appeared by motor inlet > cyclone exist > dust inflow pipe at operating frequency and by dust inflow pipe > motor inlet > cyclone exist at 1st BPF as shown Table.6. We can know that modeling is validity because MCF value was expressed high value more than 0.5.

4.3 Determination of contribution order by coherence output spectrum

The result that integrate coherent output spectrum that express the pure contribution amount about output of input source over whole frequency band was appeared to Fig.6 and Fig.7.

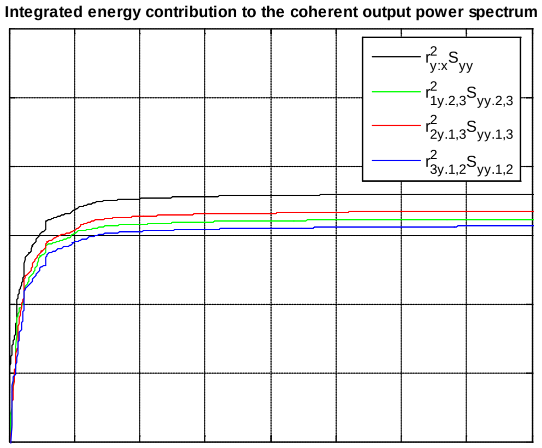

Fig.6 Coherent output spectrum (outside noise)

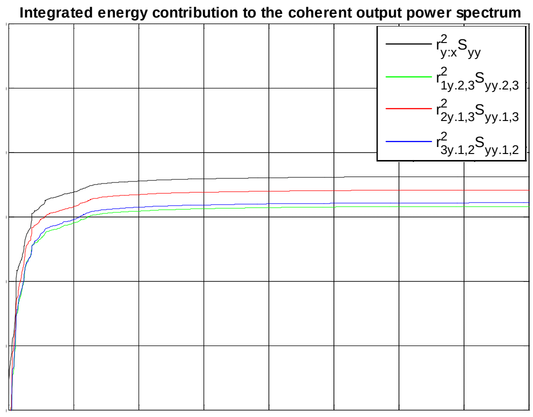

Fig.7 Coherent output spectrum (inside noise)

Also, I appeared all level that calculated logarithmic summation about this result to Table.9 and Table.10.

Table.9 Overall level contributions estimated by coherence functions (outside noise)

Overall level		Output (dB)
Measured level		74.5
Coherence Function	Total level	72.9
	$\int \gamma^2_{1y\cdot 2,3} S_{yy\cdot 2,3}\, df$	65.5
	$\int \gamma^2_{2y\cdot 1,3} S_{yy\cdot 1,3}\, df$	67.8
	$\int \gamma^2_{3y\cdot 1,2} S_{yy\cdot 1,2}\, df$	63.4

In case of output noise, contribution order was appeared by dust inflow pipe > exhaust > inhalation nozzle at whole frequency band. In case of interior noise, contribution order was

appeared by motor inlet > dust inflow pipe > cyclone exist at whole frequency band.
Through this, we can know that need countermeasure establishment for motor inlet and dust inflow pipe.

Table.10 Overall level contributions estimated by coherence functions (inside noise)

Overall level		Output (dB)
Measured level		74.5
Coherence Function	Total level	72.2
	$\int \gamma^2_{1y\cdot 2,3} S_{yy\cdot 2,3}\, df$	64.3
	$\int \gamma^2_{2y\cdot 1,3} S_{yy\cdot 1,3}\, df$	69.4
	$\int \gamma^2_{3y\cdot 1,2} S_{yy\cdot 1,2}\, df$	65.4

And, we can know that have existence possibility of other input source besides input source that consider through difference measured value and output spectrum that calculate by MDSA.
Additionally, I investigate about 'shield effect'. The results can be shown at fig.8 and table.11.

Table.11 FRF comparison using shield effect (inside noise)

	Overall level	Output (dB)
Frequency Response Function	Total overall	82.81
	$\int A(H_1=0)df$	78.8
	$\int B(H_2=0)df$	65.2
	$\int C(H_3=0)df$	75.81
$A=\lvert H_2\rvert^2 S_{22}+\lvert H_3\rvert^2 S_{33}+H_2^* H_3 S_{23}+H_2 H_3^* S_{32}$ * B,C analyze same method		

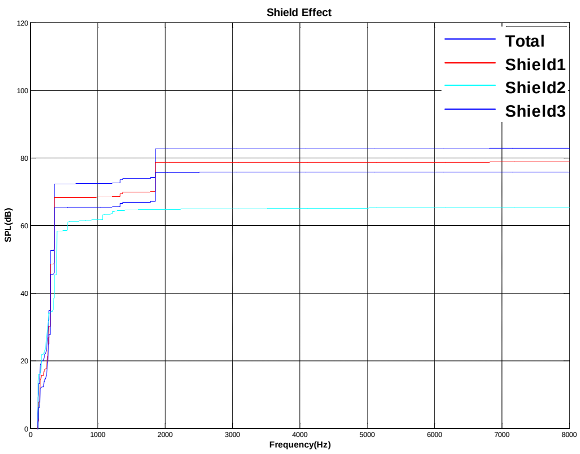

Fig.8 FRF comparison using shield effect (inside noise)

I can know that elimination of H_2(motor entrance) has good results about reduction of noise. Also, total overall level is larger than original output noise(73.2dB), because it consider not correlation among inputs.

5. CONCLUSIONS

In this research, I constituted vacuum cleaner by 3 inputs/1 output model and then defined correlation among outside noise/input of interior noise and transmission characteristic. Also, I got conclusion that analyze correlation among input source and output using MDSA such as,

(1) I verified that MDSA is valid to define contribution degree about output of input source, when correlation among inputs exists at multiple input/single output system.

(2) I knew that in case of output noise, contribution order was appeared by dust inflow pipe > exhaust > inhalation nozzle and in case of interior noise, contribution order was appeared by motor inlet > dust inflow pipe > cyclone exist about output noise that is happened in operation state of vacuum cleaner that is used in this experiment.

(3) I knew that considered input sources reflected enough in output.

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