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Multi-dimensional spectral analysis of the noise contribution from a drum washer with a dehydrating condition

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Abstract

Recently, there has been a growing consumer interest in the amount of noise produced by household electrical appliances. The designer of the product must determine the source of the noise, in order to eliminate the source. In the case of a household electric appliance such as the washing machine, the consumer's complaint was about the noise that is generated during the dehydrating condition. However, in the case of the washing machine, it is difficult to identify the noise source when the washing machine uses the dehydrating condition. Several noise sources combine making it difficult to determine the key factor that contributes to the noise output. Multi-Dimensional Spectral Analysis (MDSA) is a method that can remove the correlation between different noise sources, and it expresses the key contributing factor as a unique output. This study utilized MDSA to analyze the contribution of each noise source in the output during the dehydrating condition.

Keywords: Multi-dimensional spectrum analysis; Ordinary coherence function; Partial coherence function; Multiple coherence function; Residual spectrum; Partial coherent output spectrum

1. Introduction

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 washing machine, in which consumers complain about the noise that is generated while using the dehydrating 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 drum, motor, tub, and cabinet. This was difficult because there are many noise sources in a washing machine 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 9603), which is the provision to measure the noise level of a washing machine, the noise level of a washing machine was measured and the characteristics of the noise that the washing machine generated during the dehydrating condition were analyzed. A model was

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constructed that consisted of 3 inputs and 1 output, in order to apply the MDSA. The 3 inputs were the drum, tub, and motor, which are the main noise sources of a washing machine during the dehydrating condition. In addition, 4-input and 1-output models were compared, which were added to the cabinet noise of the 3-input and 1-output models, in order to determine which model was more suitable to completely describe the system.

Adaptation of modeling was judged by MCF.

2. Multi-dimensional spectral analysis

Fig. 1 shows the Multi Input Single Output (MISO) modeling result, in which there is no correlation among the inputs. However, there are correlations among the inputs in a real acoustic system. In the case that there are no correlations among inputs, the output spectrum can be derived as,

$$S_{yy} = \sum_{j=1}^{4}\sum_{i=1}^{4} H_{iy}^{*}(f) H_{iy}(f) S_{ij}(f) + S_{nn}(f) \tag{1}$$

where $H_{iy}(f)$ is the mean transfer function contribution to the output. S_{ij} is the cross power spectrum between x_i and x_j. $H_{iy}^{*}(f)$ is the conjugate complex transfer function of $H_{iy}(f)$ and $S_{nn}(f)$ is the auto power spectrum of the noise. In contrast, the output power spectrum is shown in Eq. (2) when there are no correlations among the inputs, as in Eq. (1).

$$S_{yy} = \sum_{i=1}^{4} \left| H_{iy}(f) \right|^2 S_{ii} + S_{nn}(f) \tag{2}$$

Eqs. (1) and (2) are called Frequency Response Functions (FRF). The FRF method would be used in the case that there is no correlation among the inputs. However, there is a correlation among the inputs in a real system. Therefore, the MDSA method must be used, which is able to determine the contribution of an input for an output by eliminating the correlation among the inputs.

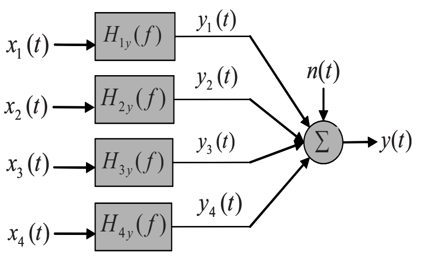


Fig. 1. 4-inputs/1-output model for an arbitrary system.

Eq. (3) represents the residual spectrum after the correlation is removed among the inputs.

$$S_{jj\cdot r!} = S_{jj\cdot(r-1)!} - \left| L_{rj} \right|^2 S_{rr\cdot(r-1)!} \qquad (j > r) \tag{3}$$

$L_{rj}(f)$ is the optimum transfer $L_{rj}(f)$ function after the correlation is removed among the inputs. Fig. 2 shows the Multi Input Single Output (MISO) model that is represented by the optimum frequency function. Fig. 3 is the residual spectrum expressed by the optimum transfer function, where, L_{2y} is the optimum transfer function between x_2 and an output. The Ordinary Coherence Functions (OCF) between each input and the output are as follows,

$$\gamma^2_{ij}(f) = \frac{\left| S_{ij}(f) \right|^2}{S_{ii}(f) S_{jj}(f)} \tag{4}$$

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

$(i = 1,2,3,4; \quad j = 1,2,3,4; \quad i \neq j)$

The Partial Coherence Function (PCF) is as follows,

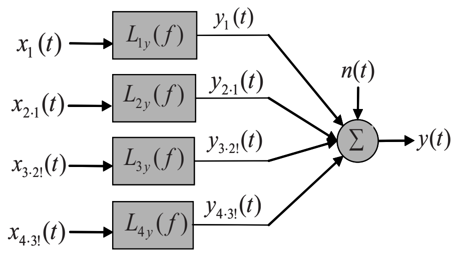


Fig. 2. 4-input/1-output model for conditioned inputs.

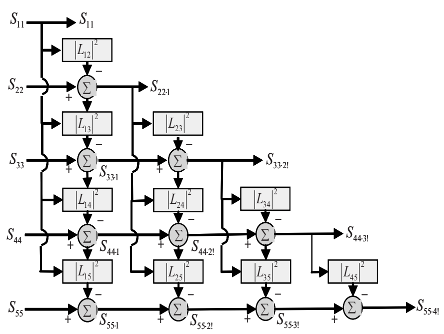


Fig. 3. Diagram showing how ordered conditioned auto-spectra are obtained from the original auto-spectral.

$$\gamma^2_{iy\cdot(i-1)!} = \frac{\left|S_{iy\cdot(i-1)!}\right|^2}{S_{ii\cdot(i-1)!}S_{yy\cdot(i-1)!}} \tag{6}$$

The Multiple Coherence Function (MCF) 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. The MCF is represented as follows,

$$\gamma^2_{y:q!} = 1-(1-\gamma^2_{1y})(1-\gamma^2_{2y\cdot1})\cdots(1-\gamma^2_{qy\cdot(q-1)!}) \tag{7}$$

Eq. (8) is the partial coherent output spectrum that can be expressed as the pure contribution rate of the input for an output.

$$S_{y:j}(f) = \gamma^2_{jy\cdot r}(f)S_{yy\cdot r}(f) \qquad (j > r) \tag{8}$$

3. Experiments and simulation

This test was performed with a front-loading laundry machine, which can handle loads up to 10 kg. Fig. 4 shows how the experiment was setup. The experiment mode was the dehydrating cases of 600 rpm and 1200 rpm. The output noise was set on the ground at 1m from the laundry system. The drum, tub, and motor, as shown in Fig. 5, were examined with the Multiple Coherence Function (MCF), which was obtained through Multi-Dimensional Spectral Analysis (MDSA). MDSA was used to judge whether the MCF was suitable for explaining this system. Then, the MDSA was applied after cabinet noise was added to the existing inputs and compared with the model, which had 3 inputs and 4 inputs. The signal from the microphone was received through an amplifier and an FFT Analyzer (DP440). Finally, time data were saved and the MDSA was applied.

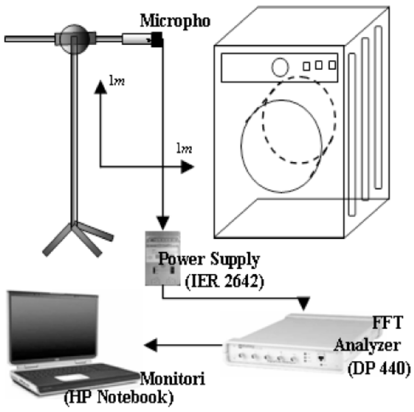


Fig. 4. The experiment setup used to measure the noise characteristic for the washing machine.

4. Evaluation

The auto power spectrum of the output noise during the dehydrating condition is shown in Fig. 6. The

Table 1. Values of the total mean ordinary coherence function.

Function		γ^2_{12}	γ^2_{13}	γ^2_{23}
Mean value	600	0.25	0.20	0.69
	1200	0.11	0.34	0.61
Function		γ^2_{1y}	γ^2_{2y}	γ^2_{3y}
Mean value	600	0.19	0.56	0.62
	1200	0.25	0.67	0.74

Table 2. Values of the partial coherence function.

Function (600 rpm)		γ^2_{1y}	$\gamma^2_{2y.1}$	$\gamma^2_{3y.12}$
1	240.9	0.1201	0.7455	0.6937
2	252.4	0.2013	0.5457	0.5441
3	363.7	0.0737	0.9876	0.9614
4	737.5	0.0644	0.6541	0.5132
5	155.1	0.2065	0.5724	0.6362
6	120.2	0.1542	0.5684	0.9824
Function (1200 rpm)		γ^2_{1y}	$\gamma^2_{2y.1}$	$\gamma^2_{3y.12}$
1	462.2	0.1482	0.6274	0.0993
2	249.9	0.1002	0.0893	0.4960
3	921.8	0.2353	0.2404	0.4270
4	231.2	0.3607	0.8604	0.4199
5	403.1	0.1934	0.8411	0.7260
6	518.8	0.1824	0.3820	0.4442
7	115.6	0.1331	0.9609	0.3527
8	96	0.3675	0.8426	0.6228

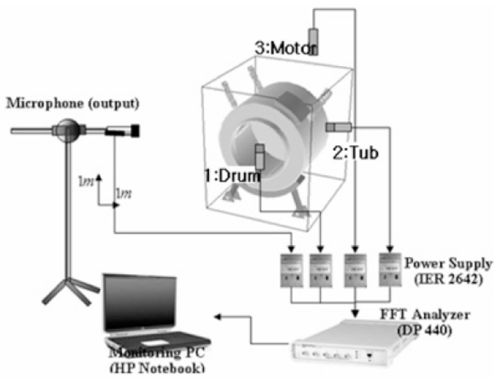


Fig. 5. The experiment setup used to obtain a signal from each component of the washing machine.

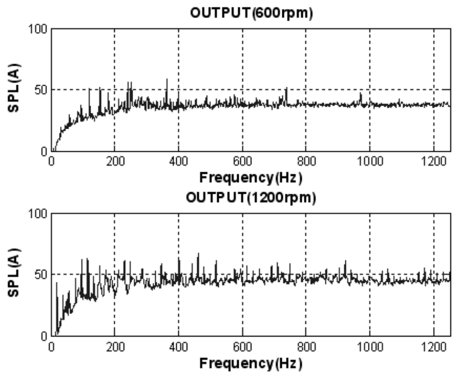
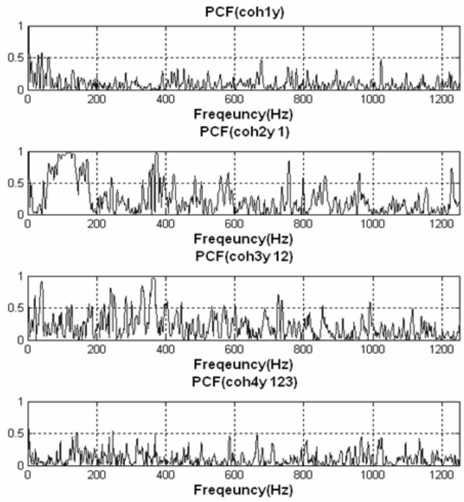
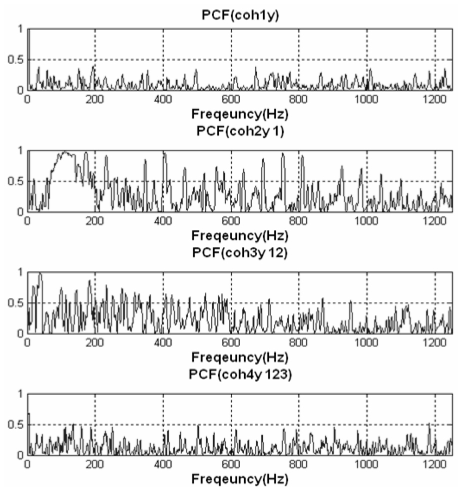


Fig. 6. A weighted sound pressure level of the output noise under 600 rpm and 1200 rpm.



(a) 600 rpm



(b) 1200 rpm

Fig. 7. Partial coherence function at 600 and 1200 rpm.

target frequency, which was chosen according to Fig. 6, is expressed in Table 2. The OCF between inputs is very important because it reveals the correlation among the inputs. The OCF among the inputs is shown in Table 1.

For most of the target frequencies, the OCF value is more than 0.5. This means that the MDSA is needed in order to remove the correlation among the inputs. The PCF is shown in Table 2 and Fig. 7.

The order of interest frequency in Table 2 is the order of magnitude of the auto power spectrum of the output noise that is shown in Fig. 6. It is known that the order of magnitude of the PCF is tub, motor, and then drum. However, the results must be analyzed because the PCF does not indicate the contribution rate of the inputs for an output. The MCF is used to determine the contribution rate of each input about an output noise quantitatively, as shown in Table 3 and Fig. 8.

Table 3. Values of the multiple coherence function.

$\gamma^2_{y:x}$					
600 rpm			1200 rpm		
1	240.9	0.8774	1	462.2	0.6807
2	252.4	0.6375	2	249.9	0.5413
3	363.7	0.9317	3	921.8	0.6185
4	737.5	0.7190	4	231.2	0.9321
5	155.1	0.7428	5	403.1	0.9605
6	120.2	0.9882	6	518.8	0.6572
Mean value		0.5817	7	115.6	0.9756
			8	96	0.9447
			Mean value		0.5972

(a) Multiple coherence function of a system composed of 3-inputs

$\gamma^2_{y:x}$					
600rpm			1200rpm		
1	240.9	0.9125	1	462.2	0.7960
2	252.4	0.7460	2	249.9	0.7284
3	363.7	0.9897	3	921.8	0.7682
4	737.5	0.6945	4	231.2	0.9512
5	155.1	0.7986	5	403.1	0.9660
6	120.2	0.9903	6	518.8	0.7472
Mean value		0.7475	7	115.6	0.9801
			8	96	0.9656
			Mean value		0.7542

(b) Multiple coherence function of system composed of 4-inputs.

Table 4. Overall level contributions estimated by coherence function.

600 rpm		
Overall level		Output(dB)
Measured level		56.8
Coherence function	$\int \gamma_{y:x}^2 \; S_{yy} \; df$	55.4
	$\int \gamma_{1y}^2 \; S_{yy} \; df$	32.1
	$\int \gamma_{2y.1}^2 \; S_{yy.1} \; df$	48.0
	$\int \gamma_{3y.12}^2 \; S_{yy.12} \; df$	45.5
	$\int \gamma_{4y.123}^2 \; S_{yy.123} \; df$	40.7
1200 rpm		
Overall level		Output(dB)
Measured level		62.7
Coherence function	$\int \gamma_{y:x}^2 \; S_{yy} \; df$	60.7
	$\int \gamma_{1y}^2 \; S_{yy} \; df$	35.5
	$\int \gamma_{2y.1}^2 \; S_{yy.1} \; df$	52.1
	$\int \gamma_{3y.12}^2 \; S_{yy.12} \; df$	48.2
	$\int \gamma_{4y.123}^2 \; S_{yy.123} \; df$	43.3

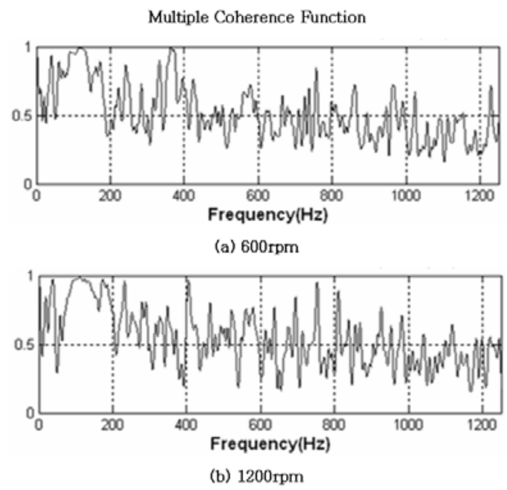


Fig. 8. Multiple-coherence function at 600 and 1200 rpm.

It was found that the MCF value that is composed of 4 inputs is larger than the MCF value that is composed of 3 inputs including 252.2 Hz at 600 rpm, 249.9 Hz, and 921.8 Hz at 1200 rpm, as shown in Table 3. This indicates that modeling that is composed of 4 inputs (#1: drum, #2: tub, #3: motor, #4: cabinet) is suitable to explain the output noise during the dehydrating condition. From these results, it can be concluded that the main noise sources of output noise during the dehydrating condition are the tub,

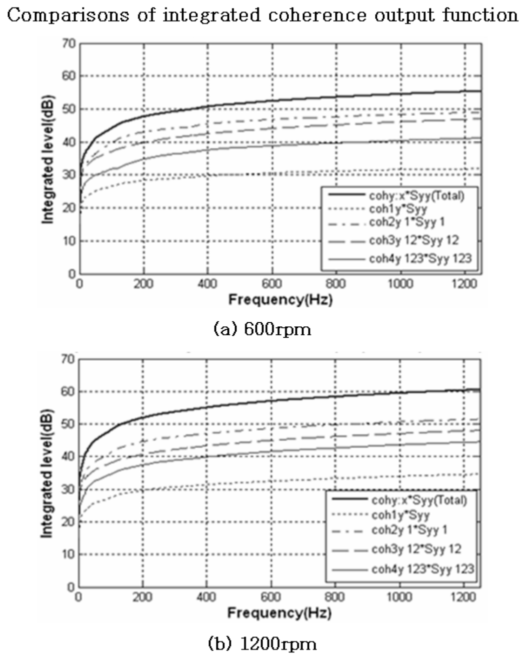


Fig. 9. Comparison of integrated partial coherent output power spectrums.

motor, drum, and cabinet. In the low frequency band, smaller than 200 Hz, as shown in Fig. 7, the PCF value of the tub is the highest when compared with the other inputs. This is due to the structure noise of the tub.

The partially coherent output spectrum, which is integrated into the entire frequency, in order to understand the contribution rate of each input about an output, is shown in Table 4 and Fig. 9. In Table 4 and Fig. 9, the contribution rates of each input for an output are, in descending order, tub(#2), motor(#3), cabinet(#4), and drum(#1).

5. Conclusion

The Transfer Pass Analysis (TPA) of noise sources from appliances, such as the washing machine, is used to reduce the noise during operating conditions. In this study, the following conclusions were found by applying MDSA to the noise that occurred during the dehydrating condition of a washing machine.

(1) In the multi-input single-output (MISO) system, it was verified that the MDSA is valid for characterizing the contribution rate of each input for an output when there are correlations among the inputs.

(2) TPA (Transfer Pass Analysis) was performed to determine the noise produced during the dehydrating condition.
(3) Through the use of the Multiple Coherence Function (MCF), it was confirmed by modeling a washing machine during the dehydrating condition that the main noise inputs were the tub, motor, cabinet, and drum.

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