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ABSTRACT

A compressor loop pipe is the most important part in a refrigerator from the view of structural vibration and noise. Vibration energy generated from a compressor's inner body is transmitted to the shell and outside through the loop pipe. So it is very important to design a compressor loop pipe. But, for geometrical complexity and dynamic nonlinearity of the loop pipe, analysis and design of the loop pipe is very difficult. And the statistical and experimental methods have to be used for design of this system. Response surface method (RSM) becomes a popular meta-modeling technique for the complex system as this loop pipe. As starting point of loop pipe's optimization, finite element model and simple experimental model are used instead of the real loop pipe model. After RS model was constructed, using sensitivity-based optimizer performed optimization. And moving least square method (MLSM) is employed to reduce approximation errors.

1. INTRODUCTION

Reducing the noise and vibration of a household refrigerator is important work for good living condition. The main source of the refrigerator's noise and vibration is the valves' motion in its' compressor. Energy generated by this movement is mostly depending on a loop pipe in the compressor. The design of the loop pipe is essential job about development of the compressor in the noise and vibration aspect.

A loop pipe is composed of two parts; a pipe in which compressed gas flows and spring wound on the pipe. The role of the spring is to reduce high frequency noise. But the spring causes the nonlinearity. As shown in Figure 1, there are two appearance of the spring of the loop pipe. First, because of spring's mass effect, resonances move toward low frequency range. Second, peaks are smoothed by spring's damping effect. This phenomenon has nonlinear characteristic and depends on the loop pipe shape. So it is much difficult to expect its dynamic feature using finite element method (FEM). Conventional optimization skill cannot be applied to this system. So in this study, RSM is introduced as new optimization tool of this system because it can be responsible tool for this system as it can handle black box system.

RSM is frequently used for the approximation and optimization of the complicated systems such as the loop pipe [1]. Because of its several advantages, this method has been a popular tool, recently, for designing in many fields such as mechanical, electro-magnetic, chemical, and biological engineering. However, due to its approximation errors, this method may not find accurate solutions.

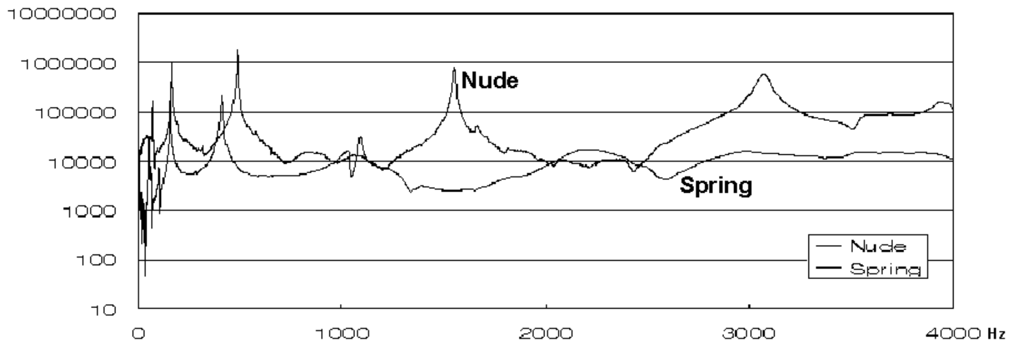

Figure 1. Frequency Response Function of a Simple Loop Pipe (Nude: pipe not including spring)

Conventional RSM is based on the approximation of the scattered function data, so it could be easily obtained using least squares method (LSM). LSM can find only one function that fits the given data through the whole domain. The weighted LSM calculates the least squares function as the weighted sum of the squared errors, and more advanced method, moving least square method (MLSM), is adopted to get more accurate models in this research [2].

The obtained meta-models are used for analysis in the optimization process instead of the original system, so the accurate reconstruction is very important in this methodology.

The developed program has been verified with the loop pipe of the compressor. The part sizes of the loop pipe are optimized to decrease the noise and vibration by using RSM and comparison between LSM and MLSM is carried out.

2. RESPONSE SURFACE METHODOLOGY

2.1 Concept of Moving Least Squares Method

An advanced method for regression is MLSM. This method can be explained as a weighted LSM that has various weights with respect to the position of approximation. Therefore, coefficients of a RS model are functions of the location and they should be calculated for each location. This procedure is interpreted as a local approximation, and Fig. 1 explains the main concept of LSM and MLSM.

In the Figure 2, dotted curve is from the classical LSM. For the scattered data, only one best approximation curve can be obtained from the LSM. In the case of MLSM, there exists one approximation function at one calculation point and there exists a different function at a different calculation point. Therefore, the coefficients of the RS model are not constants but are variables of the calculation position. This locally weighted approximation can be performed from the consideration of effective data near the calculation location, and also the data are weighted according to the distance from the calculation location. Numerical derivation will be shown in the following section.

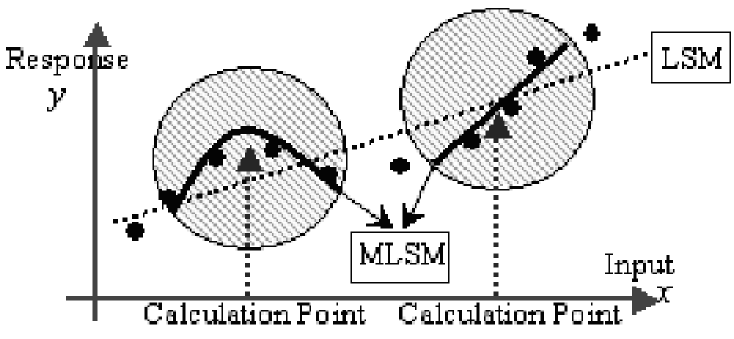

Figure 2. Concept of LSM and MLSM

2.2 Numerical Expression of MLSM

Suppose there are n-response values, y_i, with respect to the changes of x_{ij}, which denote the i^{th} observation of variable x_j. Assume that the error term ε in the model has $E(\varepsilon)=0$, $Var(\varepsilon)=\sigma^2$ and that the $\{\varepsilon_i\}$ are uncorrelated random variables.

The following matrix form can express the relationship between the responses and the variables

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}_y \tag{1}$$

where **y** is an $n\times 1$ vector of the observations, **X** is an $n\times p$ matrix of the level of the independent variables, β is a $p\times 1$ vector of the regression coefficients, and ε_y is an $n\times 1$ vector of random errors.

The least squares function $L_y(\mathbf{x})$ could be defined as in the following equation which is the sum of weighted errors.

$$L_y(\mathbf{x}) = \sum_{i=1}^{n} w_i \varepsilon_i^2 = \boldsymbol{\varepsilon}^T \mathbf{W}(\mathbf{x})\boldsymbol{\varepsilon} = (\mathbf{y} - \mathbf{X}\boldsymbol{\beta})^T \mathbf{W}(\mathbf{x})(\mathbf{y} - \mathbf{X}\boldsymbol{\beta}) \tag{2}$$

Note that the diagonal weighting matrix, **W(x)**, is not a constant matrix in the MLSM. In other words, **W(x)** is a function of location, and it can be obtained by weighting functions. There are several kinds of weighting functions such as linear, quadratic, high order polynomials, and exponential functions. For example, a polynomial-weighting function is defined by

$$w(\mathbf{x}-\mathbf{x}_I) = w(d) = \begin{cases} 1-6\left(\dfrac{d}{R_I}\right)^2 + 8\left(\dfrac{d}{R_I}\right)^3 - 3\left(\dfrac{d}{R_I}\right)^4, & for\ \dfrac{d}{R_I} \le 1 \\ 0 & , for\ \dfrac{d}{R_I} > 1 \end{cases} \tag{3}$$

Where **x** is calculation point, $\mathbf{x}_I$ is I^{th} sampling (or experiment) point, d is the distance between **x** and $\mathbf{x}_I$, and R_I is a size of an approximation region. This function is expressed by a bell-shaped figure. The weighting function has 1 (maximum value) at 0 normalized distance and 0 (minimum value) outside of 1 normalized distance, i.e., w(0)=1, w(d/Ri >1)=0. And the function decreases smoothly from 1 to 0.

Eventually, a weighting matrix, **W(x)**, can be constructed using the weighting function in the diagonal terms.

$$\mathbf{W}(\mathbf{x}) = \begin{bmatrix} w(\mathbf{x}-\mathbf{x}_1) & 0 & \dots & 0 \\ 0 & w(\mathbf{x}-\mathbf{x}_2) & \dots & 0 \\ \vdots & \vdots & \dots & \vdots \\ 0 & 0 & \dots & w(\mathbf{x}-\mathbf{x}_n) \end{bmatrix} \tag{4}$$

And, to minimize $L_y(\mathbf{x})$, the least squares estimators must satisfy

$$\left.\frac{\partial L_y(\mathbf{x})}{\partial \boldsymbol{\beta}}\right|_{\mathbf{b}} = -2\mathbf{X}^T\mathbf{W}(\mathbf{x})\mathbf{y} + 2\mathbf{X}^T\mathbf{W}(\mathbf{x})\mathbf{X}\mathbf{b} = 0 \tag{5}$$

Coefficients of the RS model, **b**(**x**), can be obtained by matrix operation

$$\mathbf{b}(\mathbf{x}) = \left(\mathbf{X}^T\mathbf{W}(\mathbf{x})\mathbf{X}\right)^{-1}\mathbf{X}^T\mathbf{W}(\mathbf{x})\mathbf{y} \tag{6}$$

In this step, readers should know that the coefficient **b(x)** is a function of location or position **x**. Note that a procedure to calculate **b(x)** is a local approximation and "moving" process performs a global approximation through the whole design domain.

3. NUMERICAL EXAMPLES

In the design of the loop pipe, both vibration and noise should be considered. Once each RS model is constructed, we can combine the two RS models and make one object function with weighting coefficients. And it is possible to perform the optimization to satisfy both noise and vibration condition.

A household refrigerator is working at 60Hz if a country provides 60Hz electricity. In this case, vibration energy transmitted to the loop pipe is the largest at 60Hz. It was found from the experiment result that spring contact effect is very small at low frequency like 60Hz. And it can be assumed that the system is linear. So the FE model is applied to make the RS model for reducing vibration because of its advantage to readily create samples.

For reduction of the compressor noise, the high frequency range is interesting as 3~4 kHz. In this range, spring damping effect is bigger than in low frequency range. Since FEM can't perform an analysis, experimental models are applied.

3.1 Optimization of the loop pipe for reducing vibration

Three parts' lengths of the loop pipe are selected as design variables. Constraints are one fixed end of the pipe and the horizontally forced other end. The several responses are defined in Table 1 because engineers can want the different responses.

Table 1. Definition of the Responses

Response	Description
Y1	Acceleration Magnitude in Y coordinate
Y2	Square Mean of XYZ Accelerations
Y3	Three Harmonics Acceleration Magnitude in Y
Y4	Square Mean of Three Harmonics Accelerations in XYZ

The RS models are constructed with 3 design variables and simulated responses by D-Optimal design, one of the designs of experiment (DOE). On optimization, acceleration magnitudes that represent value how to transfer vibration to the outside of the compressor are selected as object functions. Side constraints represent lengths that do not touch shell. In short,

Minimize: Magnitude of acceleration (Y1, Y2, Y3, and Y4)
Side Constraints: $0 \le A \le A\max, 0 \le B \le B\max, 0 \le C \le C\max$.

Procedure of optimization is shown in Figure 3. Once the RS Model is reasonable, optimization can be implemented by using the optimizer such as DOT (Design Optimization Tool).

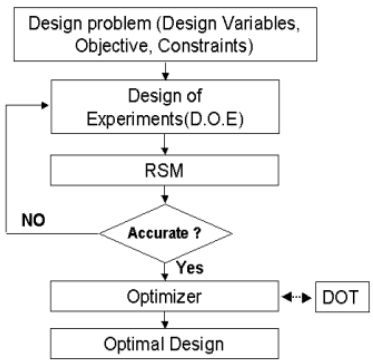

Figure 3. Procedure of Optimization

Optimization results and comparison of the results are shown in Table 2, Table 3.

Table 2. Optimization Results

	Initial	LSM				Moving LSM			
		Y1	Y2	Y3	Y4	Y1	Y2	Y3	Y4
A	0.00	20.00	20.00	9.76	20.00	20.00	20.00	13.69	20.00
B	22.00	34.48	40.00	36.15	31.22	32.60	40.00	37.05	40.00
C	16.40	40.00	0.00	40.00	40.00	40.00	6.07	40.00	40.00

Table 3. Comparison between LSM and MLSM

	Case	Initial Value	Opt. Result	Reanalysis	Error (%)	Improvement (%)
LSM	Y1	18.74	11.47	13.04	12.04	30.42
	Y2	21.65	13.29	13.58	2.14	37.27
	Y3	19.04	14.06	16.52	14.89	13.24
	Y4	22.01	16.55	16.47	-0.49	25.17
Moving LSM	Y1	18.74	11.73	12.94	9.35	30.95
	Y2	21.65	13.55	13.55	0.0	37.41
	Y3	19.04	13.97	15.67	10.85	17.70
	Y4	22.01	16.14	16.00	-0.88	27.31

In comparison table, optimization results and errors have different values with respect to combination between response and design variables. This shows that the selection of the response and design variables is important in the RSM. And the errors of MLSM are smaller than these of the LSM. It is verified that MLSM gives more accurate results.

As the result of optimization, performance improved about 30~37% when only 60Hz is considered, or 13~27% when harmonic components are considered.

3.2 Optimization of the loop pipe for reducing noise

Instead of the real model, simply shaped loop pipe is used for easy generation of samples. After fixing the end of the pipe and hitting at the other end, acceleration data is received as shown in Figure 4.

Object function for reducing noise is considered as integration value of frequency response function (FRF) between interest ranges. If the important frequency range of the compressor is 5~6 kHz, reducing the corresponding integration of FRF is equal to decreasing the noise level. In this study, the specified value to reduce noise is defined as integration divided by the specific frequency range.

Design variables are defined in Figure 4 and samples generated by D-Optimal design are shown in Figure 5. The side constraints of design variables are $50 \le A \le 100$, $80 \le B \le 150$. (Unit: mm)

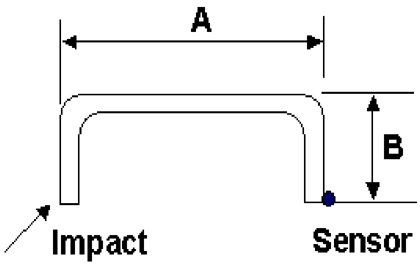

Figure 4. Definition of the Problem

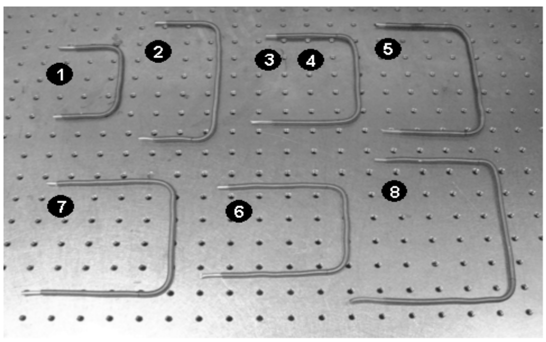

Figure 5. Samples for the RSM

Constructed the RS model is shown in Figure 6 and optimization result is in Table 4.

Table 4 shows the usefulness of RSM. Optimum result of MLSM has small error with re-experiment. (In this case re-experiment is performed only about MLSM because of very small difference.) The effect of optimization is presented as the hatched area between optimum and a sample 2 case as shown in Figure 7. The gain to reduce noise is 20.14% with sample 2 values, 36.98.

Table 4. Optimization Result

Optimum Result	MLSM
X1(A)	73.86
X2(B)	112.76
RSM Result	32.48
Re-experiment	30.78
Error (%)	-5.5

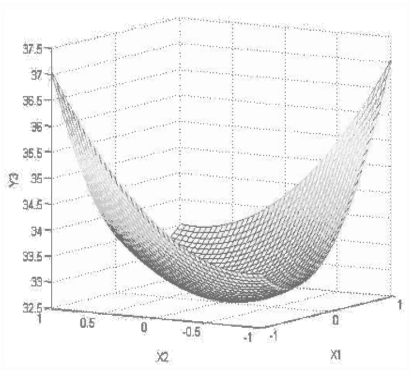

Figure 6. Response Surface Result

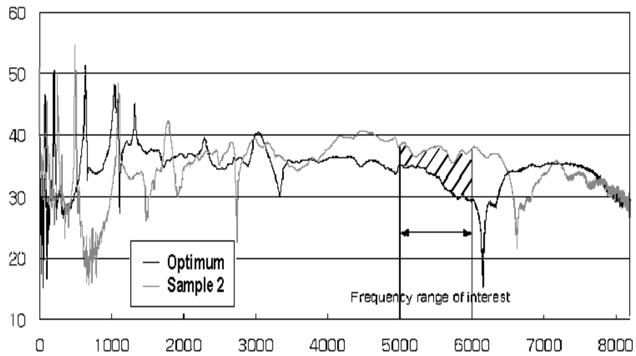

Figure 7. Comparison Diagram between Optimum and Sample2

4. CONCLUSIONS

In this study, optimization of the loop pipe is performed with respect to the part sizes of the pipe using the response surface method. Optimization for reducing vibration is done about 60Hz at which transmitted power is the largest. And high frequency range's integral of FRF is selected as optimization's object function for noise.

RSM has inevitable errors, especially with nonlinear system. But this research reduced the errors with advanced method such as MLSM. RSM using MLSM is a good tool for the loop pipe's optimization for reducing noise and vibration of the compressor with selected object function and design variables.

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ACKNOWLEDGEMENT

This work was supported by Digital Appliance Research Center, LG Electronics Inc and Center of Innovative Design Optimization Technology (iDOT), Korea Science and Engineering Foundation.