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Noise Reduction of Muffler by Optimal Design

Jae-Eung Oh*
School of Mechanical Engineering, Hanyang University
Kyung-Joon Cha
Department of Mathematics, Lab. of Statistical Data Analysis, Hanyang University

This paper proposes an optimal design scheme to improve the muffler's capacity of noise reduction of the exhaust system by combining the Taguchi method and a fractional factorial design. As a measuring tool for the performance of a muffler, the performance prediction software which is developed by Oh, Lee and Lee (1996) is used. In the first stage of a design, the length and radius of each component of the current muffler system are selected as control factors. Then, the L_{18} table of orthogonal arrays is adopted to extract the effective main factors. In the second stage, the fractional factorial design is adopted to take interactions into consideration, which the L_{18} table of orthogonal arrays can not consider. For an optimal design, the L_{27} table of orthogonal arrays with main and interaction effects is proposed and the noise factors such as temperature, background noise and humidity are analyzed for more efficient design simultaneously.

Key Words : Muffler, Taguchi Method, Fractional Factorial Design, Larger-the-better Characteristic, Table of Orthogonal Arrays

1. Introduction

As the standard of living has been improving, people are more concerned about the noise in their surroundings, especially noise from vehicles such as passenger cars and tractors, for example. In particular, noise from the exhaust systems of vehicles are regarded as the main cause of the environmental noise and they raise the fatigue level of people. That is, this noise negatively affects the working conditions and reduction of the noise from exhaust systems of vehicles becomes one of the main subjects of study.

However, manufacturing companies producing exhaust-inhalent machines are trying to reduce the noise by simple repeated experiments rather than by systematic and theoretical analyses. In the literature, many design techniques using theoretical analyses are applied and these analyses are mostly based on the transfer matrix method of an undulation equation such as Sahasrabudhe et al. (1991). The acoustic theory using the finite element method and boundary element method was adapted by Craggs (1976) and Munjal (1987). In fact, these methods were used to predict transmission loss in mufflers by Young and Crocker (1975). These theories are reliable for the analysis, but are not effective in the first stage of development because they require lots of time and money to perform. Moreover, modeling and analysis need to be reperformed when the design is changed. Hence, efficient design methods which require less effort and cost are needed for systematic muffler noise reduction.

Recently, the Taguchi method has been widely used in the industry and many cases of the research are presented such as Bendell et al. (1989), Mishima et al. (1998), Park (1994), Wang et al. (1999), and Kim (1999). It is known

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* Corresponding Author,
E-mail : jeoh@email.hanyang.ac.kr
TEL : +82-2-2290-0905 ; **FAX** : +82-2-2281-0019
School of Mechanical Engineering, Hanyang University, Seoul 133-791, Korea. (Manuscript **Received** October 7, 1999; **Revised** June 15, 2000)

that the Taguchi method (1991a, 1991b, 1991c), which performs well for real problems, has merit in that it reduces the number of experiments to find the optimal condition using orthogonal arrays (Hwang et al., 1999 and Lee et al., 1995). However, the Taguchi method has problems such as that the interactions of all combinations between each control factor are not allocated.

Thus, in order to perform better analysis, we first adopt the Taguchi method, as a preliminary experiment, to find the significant main factors. Then, we check the interactions of all combinations of factors using the fractional factorial design which is a traditional design for such experiments (See Cochran and Cox (1957) and Mason, Gunst and Hess (1989) for details). That is, the fractional factorial design is performed with the main factors which are obtained by the preliminary experiment. Finally, the Taguchi method is applied with the main factors and interactions by treating these as control factors, and the noise factors are taken into consideration at the same time.

In detail, 8 control factors that affect the noise from the muffler are chosen, then through simulation an L_{18} design is performed to detect the main effects. Because the interaction effects may possibly affect the noise characteristics of a muffler, the fractional factorial design is adopted to find interaction effects using main factors which are obtained by the L_{18} design. At the last stage, the L_{27} design is performed with temperature, background noise and humidity chosen as noise factors and verified by an experiment.

The muffler performance prediction software that is developed by Oh, Lee and Lee (1995) is used for measuring the muffler noise. The software has been verified through some cases such as Oh, Han and Lee (1996), and Oh, Han and Son (1997). This paper suggests a systemetic and efficient design method of the muffler with reduced noise characteristics.

In Sec. 2 and 3, the designs of experiments and the Taguchi method are explained briefly to help the understanding of the whole design process.

2. Designs of Experiments and the Taguchi Method

We call the response value characteristic value and causes, which affect response in the experiment, factors. In the design of experiments, we try to find the optimal condition and significant factors through the analysis of variance. The analysis of variance is a method to find the significant factors using the sum of squares. In other words, the total dispersion of a characteristic value is represented by the sum of squares, and this dispersion is divided into the sums of squares of each factor and the error. Then, the mean square of each factor, that is the value of the sum of the square of each factor divided by the corresponding degree of freedom, can be obtained. Thus, the ratio of the mean square of a factor and the mean square of error leads to the decision whether a factor is significant using the F-test.

The factorial design and multi-way factorial design can be used. However, these designs require excessive numbers of experiments in the case of complex structures such as a muffler. Therefore, it takes more time and causes some difficulties in keeping the same conditions throughout the experiments.

The fractional factorial design and the confounding method can generally be used in this case, since it takes less time than factorial or multi-way factorial designs. These designs are not concerned about interactions with more than three factors, which are not significant, in general.

In this paper, we adopt the fractional factorial design before performing the Taguchi method with the noise factors. Thus, it makes the analysis more systematic and accurate.

The Taguchi method has its own characteristics and is different from traditional designs of experiments. In the Taguchi method, the quality is defined by the total loss from variability of the characteristic values and harmful side effects after the products are shipped.

Then, the S/N-ratio (Signal-to-Noise ratio) is induced by using a loss function. In the Taguchi method, a quality characteristic value is character-

Table 1 Classification of quality characteristics

	Loss function	S/N ratio
nominal the best characteristics	$L(y)=c(y-m)^2$	$10\log\left[\dfrac{(\bar{y})^2-\dfrac{V}{n}}{V}\right]$
larger the better characteristics	$L(y)=c\left(\dfrac{1}{y^2}\right)$	$-10\log\left[\dfrac{1}{n}\sum_{i=1}^{n}\dfrac{1}{y_i^2}\right]$
smaller the better characteristics	$L(y)=cy^2$	$-10\log\left[\dfrac{1}{n}\sum_{i=1}^{n}y_i^2\right]$

ized by three parts and is shown in Table 1, where c is a constant, y is a characteristic value, and m is the target value.

The following represents the characteristics of the Taguchi method.

- Choose the proper quality characteristics
- Use the S/N-ratio
- Use a loss function
- Do not allocate the interaction between possible control factors
- Use a table of orthogonal arrays
- Perform another experiment to confirm

3. Backgrounds of Simulator and Experiments

3.1 Analysis of simulator

As a method of modeling the transfer characteristic of acoustics, the transfer matrix method which introduces the concept of impedance is used. It is widely used for acoustic systems for its computational simplicity. This method makes a design easy since modeling by each factor makes up the whole system.

Adopting acoustic pressure p and mass velocity v as the two state variables in the transfer matrix method, we could find the four-pole parameters from the conditions of both sides which can be written as Eq. (1), where $\{p_r \ v_r\}^T$ is called the state vector at the upstream point r and $\{p_{r-1} \ v_{r-1}\}^T$ is called the state vector at the downstream point $r-1$.

$$\begin{Bmatrix} p_r \\ v_r \end{Bmatrix} = \begin{bmatrix} Transfer\ matrix \\ 2\times 2 \end{bmatrix} \begin{Bmatrix} p_{r-1} \\ v_{r-1} \end{Bmatrix} \tag{1}$$

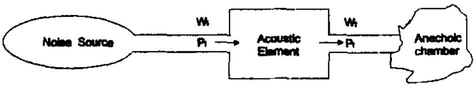


Fig. 1 Schematics of transmission loss measurement

The transmission loss is an energy loss of acoustic elements, so the ratio of sound pressure between the inlet and outlet of acoustic elements can be expressed in dB scale. Equation (2) shows a ratio between incident and reflective pressure through acoustic elements. Also, a two-microphone method is used at the end of the acoustic element to remove the influence of reflected waves.

$$TL(dB)=10\log_{10}\left|\frac{w_i}{w_t}\right|=20\log_{10}\left|\frac{p_1^+}{p_2^-}\right| \tag{2}$$

where w_i is the energy of inlet, w_t is the energy of outlet, p_1^+ is an inlet sound pressure, and p_2^- is an outlet sound pressure. Here, p_1^+ and p_2^- are derived from Eq. (1). Figure 1 shows schematics of transmission loss measurement. Transmission loss obtained from Eq. (2) is used to interpret a muffler system.

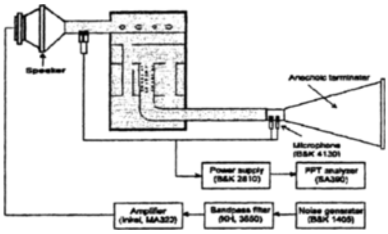
3.2 Analysis of experimental results

The two-microphone method separates the incident wave and the reflected wave in the pipe. The transmission loss can be written as Eqs. (3) and (4) using two-microphones.

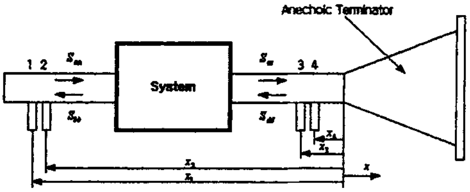
$$TL(dB)=10\log_{10}\frac{S_{aa}}{S_{cc}} \tag{3}$$

$$\begin{aligned}
S_{aa}(f) &= [S_{11}(f)+S_{22}(f)-2C_{12}(f)\cos k(x_1-x_2) \\
&\quad +2Q_{12}\sin k(x_1-x_2)]/4\sin^2 k(x_1-x_2) \\
S_{bb}(f) &= [S_{11}(f)+S_{22}(f)-2C_{12}(f)\cos k(x_1-x_2) \\
&\quad -2Q_{12}\sin k(x_1-x_2)]/4\sin^2 k(x_1-x_2) \\
S_{cc}(f) &= [S_{33}(f)+S_{44}(f)-2C_{34}(f)\cos k(x_3-x_4) \\
&\quad +2Q_{34}\sin k(x_3-x_4)]/4\sin^2 k(x_3-x_4) \\
S_{dd}(f) &= [S_{33}(f)+S_{44}(f)-2C_{34}(f)\cos k(x_3-x_4) \\
&\quad -2Q_{34}\sin k(x_3-x_4)]/4\sin^2 k(x_3-x_4)
\end{aligned} \tag{4}$$

where S_{aa} is an incident spectrum for inlet, S_{bb} is a reflected spectrum for inlet, S_{cc} is an incident spectrum for outlet, and S_{dd} is a reflected spectrum for outlet. Also, c_{12} is a real part of the cross spectrum for inlet, Q_{12} is an imaginary part of cross spectrum for inlet, and k is wave number.



(a) Block diagram of the experimental set-up



(b) Transmission loss measurement using the two-microphone method

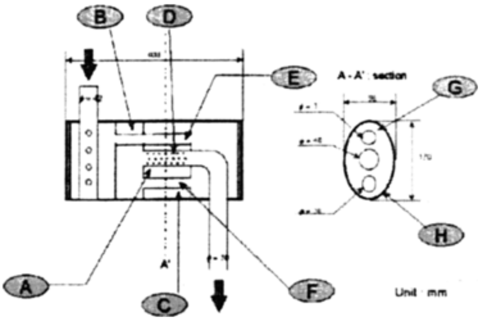
Fig. 2 Experimental setup

Figure 2(a) is a block diagram of the experimental setup and Fig. 2(b) shows the experimental setup of a transmission loss measurement using Eqs. (2) and (3) in detail. We install a non-reflected part (Anechoic terminator) in the outlet for complete separation of the reflected wave in Fig. 2(b). Because Eq. (3) is constructed excluding the information on reflected spectrum, the experiment is performed to get S_{aa} and S_{cc} as shown in Fig. 2. This experimental value is used to evaluate the performance of a muffler system.

4. Statistical Analysis of a Design Process

As a preliminary experiment, we first use the Taguchi method to choose significant main factors. The L_{18} table of orthogonal arrays is used to arrange the control factors most efficiently with the least number of experiments.

Figure 3 shows 8 factors that are chosen as the control factors to apply to the preliminary experiment, and the bold faced numbers are values of the current level. These control factors, which are expected to contribute to the characteristic value, are chosen by experience so that the experiment can be easily modified and the total size of experiments can be kept to a minimum in the design process as well.



	Factors	value of level		
A:	Segment number of perforated pipe	6	7	
B:	length of straight pipe	150	**170**	190
C:	length of straight pipe	80	**100**	120
D:	Radius of perforated pipe	15	**20**	25
E:	Radius of straight pipe	10	**15**	20
F:	Radius of straight pipe	10	**15**	20
G:	Offset length of inlet pipe	50	**55**	60
H:	Offset length of inlet pipe	50	**55**	60

Fig. 3 Control factors of L_{18}

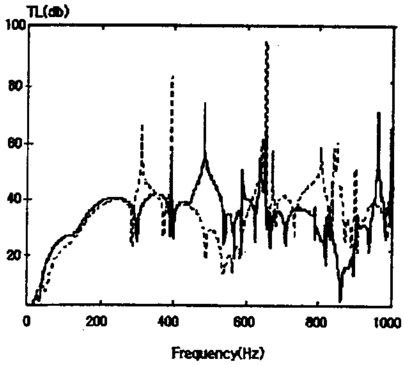


Fig. 4 Comparison between simulation and experimental results

——— simulation result

- - - - - experimental result

The eight control factors are arranged on an L_{18} table of orthogonal arrays which is given in Table 2. For a muffler performance analysis, the muffler performance prediction software that is developed by one of the authors and his associates is used. Figure 4 shows the comparison between the simulation and the experimental results. In general, we would use 0Hz-300Hz for frequency range of interest. Note that the booming noise, overwhelms the muffler noise, hardly

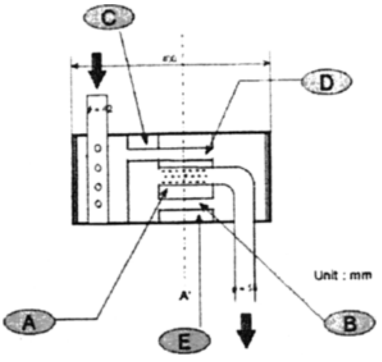
Table 2 Orthogonal arrays of control factors

Exp.	A	B	C	D	E	F	G	H	SN
1	1	1	1	1	1	1	1	1	37.78
2	1	1	2	2	2	2	2	2	37.76
3	1	1	3	3	3	3	3	3	37.57
4	1	2	1	1	2	2	3	3	37.20
5	1	2	2	2	3	3	1	1	36.59
6	1	2	3	3	1	1	2	2	36.85
7	1	3	1	2	1	3	2	3	93.00
8	1	3	2	3	2	1	3	1	38.30
9	1	3	3	1	3	2	1	2	39.01
10	2	1	1	3	3	2	2	1	39.14
11	2	1	2	1	1	3	3	2	39.94
12	2	1	3	2	2	1	1	3	38.79
13	2	2	1	2	3	1	3	2	39.36
14	2	2	2	3	1	2	1	3	39.17
15	2	2	3	1	2	3	2	1	39.83
16	2	3	1	3	2	3	1	2	38.61
17	2	3	2	1	3	1	2	3	38.86
18	2	3	3	2	1	2	3	1	38.50

occurs in the range over 200Hz. Even though a muffler has a frequency characteristic over 1000Hz, it can be neglected by the absorbing characteristics of the car interior. We can see that there is no significant difference between the simulation and the experimental results in the interesting region(0Hz~300Hz). Hence, we would say that the performance prediction software can be used to convert simulation results into the transmission loss of a system.

The overall value, which is the average value of TL in the frequency region of interest, is used as the characteristics value and the larger- the-better characteristic is also applied because the larger value implies better performance.

The S/N-ratio as a characteristic value is analyzed by the analysis of variance method for each experiment and it is noticed that there is no significant factor with the level of significance of 10%. It may show that we should check the interaction effects. Also, the value of R2 which represents the ratio explaining the variation of 8 factors in total variation of characteristic value is 65%. That is, there is 65% of the proportional reduction in the variability of the characteristic value attained by the 8 factors. After finding the optimal condition, a point estimation is done and the value is turn out to be 101.5(dB), but the results of a verification experiment is 92.5 (dB). We can conclude that the main effects do not greatly affect the characteristic value. Thus, it would not be the real optimal condition and leads us to check two factor interactions. Based on the above results from preliminary experiments, the interesting factors which could be considered as interactive with each other are selected and the degree of freedom of each factor is found to analyze all combinations of the two factor interactions. That is, the control factors are adjusted to use the fractional factorial design.



A. number of segments of perforated pipe
B. Radius of straight pipe
C. Length of straight pipe
D. Radius of straight pipe
E. Length of straight pipe

Fig. 5 Modified control factors

Since it is not known which two factor interactions are significant, we have performed a number of experiments which are enough to find significant two factor interactions (at least 81 times). Figure 5 shows the factors allocated for analysis using the fractional factorial design. The modified control factors should contain all the significant factors of the straight pipe since the straight pipe has an important role in this muffler system.

In the case of 5 factors with 3 levels, we need to perform $3^5=243$ experiments using a multi-way factorial design. However, the optimal level is chosen through 81 experiments using 1/3 fractional factorial design. We could test the 5 control factors and 10 two factor interactions as well by analyzing TL values from the prediction soft-

Table 3 ANOVA table

Factors	Mean Square	F Value	Pr > F
A	46.11	3.41	0.0389
B	15.95	1.18	0.3135
C	287.69	21.30	0.0001
D	23.74	1.76	0.1805
E	70.30	5.20	0.0080
D＊E	1469.72	108.79	0.0001

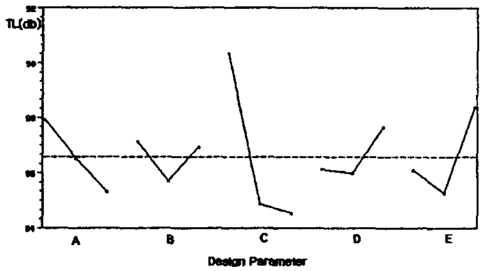


Fig. 6 Mean levels of control factors

ware.

We first choose the models which contain 10 two factors interactions as well as control factors. Thus, the maximum 40 factors which contain all control factors and two factor interactions could be arranged on an L_{81} table of orthogonal arrays. When the model contains all of the two factor interactions, the value of R^2 is 97%. Also, when we use the second model that contains only one significant two factor interaction, interaction between D and E and the main effects, the value of R2 is 88% according to the analysis of variance method shown in Table 3. It can be seen that a strong interaction between D and E exists.

Figure 6 shows the means of the factors of corresponding levels and the dotted line represents the total mean.

From Fig. 6, the greatest overall value can be obtained from $A_1B_1C_1D_3E_3$ and the point estimated value is

$$\begin{aligned}&\hat{\mu}(A_iB_jC_kD_lE_m)\\&=\mu+a_i+b_j+c_k+d_l+e_m+(de)_{lm}\\&=(\mu+a_i)+(\mu+b_j)+(\mu+c_k)\\&\quad\underline{+\{\mu+d_l+e_m+(de)_{lm}\}-3\mu}\\&=x_{i\cdots}+x_{.j\cdots}+x_{..k\cdots}+x_{\cdots lm}-3\bar{x}.\end{aligned} \tag{5}$$

Table 4 Orthogonal arrays of L_{27}

Exp. No	control factors	noise factors				SN ratio
		1	1	2	2	
	1 2 3 4 5 6 7 8 9 10 11 12 13	1	2	1	2	
		1	2	2	1	
1	1 1 1 1 1 1 1 1 1 1 1 1 1	y1,1	y1,2	y1,3	y1,4	37.10
2	1 1 1 1 2 2 2 2 2 2 2 2 2	y2,1	y2,2	y2,3	y2,4	37.56
3	1 1 1 1 3 3 3 3 3 3 3 3 3	y3,1	y3,2	y3,3	y3,4	37.91
4	1 2 2 2 1 1 1 2 2 2 3 3 3	y4,1	y4,2	y4,3	y4,4	37.66
5	1 2 2 2 2 2 2 3 3 3 1 1 1	y5,1	y5,2	y5,3	y5,4	37.04
6	1 2 2 2 3 3 3 1 1 1 2 2 2	y6,1	y6,2	y6,3	y6,4	37.78
7	1 3 3 3 1 1 1 3 3 3 2 2 2	y7,1	y7,2	y7,3	y7,4	38.10
8	1 3 3 3 2 2 2 1 1 1 3 3 3	y8,1	y8,2	y8,3	y8,4	37.79
9	1 3 3 3 3 3 3 2 2 2 1 1 1	y9,1	y9,2	y9,3	y9,4	36.29
10	2 1 2 3 1 2 3 1 2 3 1 2 3	y10,1	y10,2	y10,3	y10,4	36.88
11	2 1 2 3 2 3 1 2 3 1 2 3 1	y11,1	y11,2	y11,3	y11,4	37.48
12	2 1 2 3 3 1 2 3 1 2 3 1 2	y12,1	y12,2	y12,3	y12,4	37.81
13	2 2 3 1 1 2 3 2 3 1 3 1 2	y13,1	y13,2	y13,3	y13,4	37.60
14	2 2 3 1 2 3 1 3 1 2 1 2 3	y14,1	y14,2	y14,3	y14,4	36.82
15	2 2 3 1 3 1 2 1 2 3 2 3 1	y15,1	y15,2	y15,3	y15,4	38.15
16	2 3 1 2 1 2 3 3 1 2 2 3 1	y16,1	y16,2	y16,3	y16,4	37.96
17	2 3 1 2 2 3 1 1 2 3 3 1 2	y17,1	y17,2	y17,3	y17,4	37.97
18	2 3 1 2 3 1 2 2 3 1 1 2 3	y18,1	y18,2	y18,3	y18,4	36.51
19	3 1 3 2 1 3 2 1 3 2 1 3 2	y19,1	y19,2	y19,3	y19,4	36.74
20	3 1 3 2 2 1 3 2 1 3 2 1 3	y20,1	y20,2	y20,3	y20,4	37.66
21	3 1 3 2 3 2 1 3 2 1 3 2 1	y21,1	y21,2	y21,3	y21,4	37.64
22	3 2 1 3 1 3 2 2 1 3 3 2 1	y22,1	y22,2	y22,3	y22,4	37.66
23	3 2 1 3 2 1 3 3 2 1 1 3 2	y23,1	y23,2	y23,3	y23,4	36.55
24	3 2 1 3 3 2 1 1 3 2 2 1 3	y24,1	y24,2	y24,3	y24,4	37.22
25	3 3 2 1 1 3 2 3 2 1 2 1 3	y25,1	y25,2	y25,3	y25,4	37.85
26	3 3 2 1 2 1 3 1 3 2 3 2 1	y26,1	y26,2	y26,3	y26,4	37.28
27	3 3 2 1 3 2 1 2 1 3 1 3 2	y27,1	y27,2	y27,3	y27,4	36.92
	AD E D＊E B C					

We can get the point estimated value of 101.68 (dB) from Eq. (5) and the confidence interval of (99.85 103.50) with a 95% confidence level. We find that the result of a real verification experiment gives 101.1 (dB) which is very close to the estimated value and has a 1.6% error. The noise reduction capability of the muffler is increased by 36% compared with 73.5 (dB) which is the overall value of the current design. Based on these results, we can conclude that the Taguchi method can be used to reduce the dispersion of the quality as well as to increase characteristic value.

Surely, it is important to keep the quality of the product the best, but another object is to reduce the dispersion of the product of quality. One of the distinct characteristics of the Taguchi method is to reduce the dispersion of the product of quality. We use a robust design approach based on Tagnchi method so that the capability of a muffler is not affected by various external noise factors such as temperature, background noise and humidity.

5 control factors with 3 levels and their interactions are arranged using the L_{27} orthogonal array in Table 4. Also, the noise factors with 2 levels are arranged using the L_4 orthogonal array. In order to see the effectiveness of noise factors, we fix the temperature(U) at 18℃ and −10℃, background noise(V) at 20db～30db and 30db～40db, and humidity(W) at 40～60% and 70～100%. The levels of each noise factor are selected according to an approximate average temperature of warm and cold, average noise of day and night, and the levels of humidity of non-rainy and rainy seasons, respectively. Then, the S/N-ratio is found using the larger-the-better characteristic in Table 4.

The value of R^2 becomes 96% when the analysis of variance is performed using the S/N-ratio as a characteristic value.

It is found that every factor is significant except factors D and E with a significance level of 10%. Figure 7 represents the comparison of mean squares for main-factors and error. Note that there exists a strong interaction between the radius of straight pipe and the length of straight pipe. In fact, the same result was found when the overall value was used as a characteristic value. Table 5 shows the results of the analysis of variance and Fig. 8 represents the factor effect for each factor. Here the dummy level is adapted for factor A. Figure 9 represents the effect for the noise factors. We can see that there is no significant effect of noise factors.

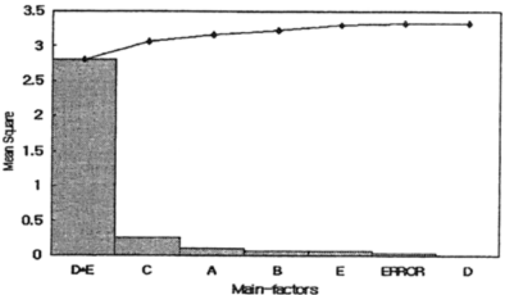


Fig. 7 Pareto diagram of mean square of main-factors and error

From the results of the analysis, the combination which gives the optimal S/N-ratio is $A_1B_1C_1D_3E_1$. We could see that the level of factor E is changed compared with the results from the fractional factorial design. The S/N-ratio of the current design is 36.65(dB) and the point estimated value using Eq. (5) is 38.31(dB) with the optimal condition. From the results of the confir-

Table 5 ANOVA table

control factors	Mean Square	F Value	Pr > F
A	0.104	4.05	0.0454
B	0.074	2.88	0.0949
C	0.254	9.88	0.0029
D	0.003	0.10	0.9076
E	0.069	2.72	0.1064
D * E	5.909	57.53	0.0001

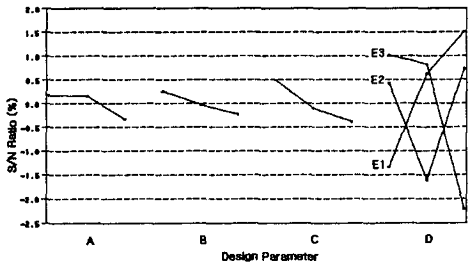


Fig. 8 Plot of factor effect

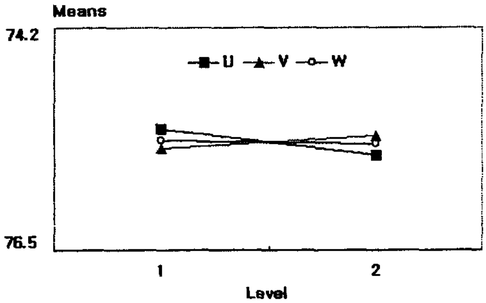


Fig. 9 Overall mean for levels of noise factor
U : temperature, V : background noise, W : humidity

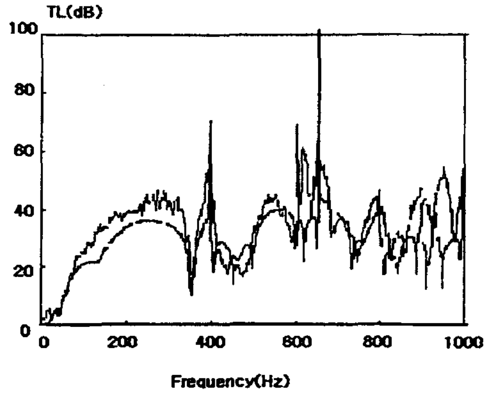


Fig. 10 Simulation results of transmission loss
———— Before modfication
- - - - - After modification

mation experiment, we find that the S/N-ratio is 37.80(dB) using the equation in Table 1. The S/N-ratio, which can be obtained by the fractional factorial design with the optimal condition $A_1B_1C_1D_3E_3$, was 38.04(dB). Thus, it is decided to choose $A_1B_1C_1D_3E_1$ as a final design because it gives the largest overall value as well as ease of reconstruction of the experiment. Note that there are increments of overall value and S/N-ratio up to 26.9(dB) and 1.39(dB), respectively. Figure 10 represents the comparisons between the before and after modification cases. From the results of the comparison, we find that the overall value is increased after modification in the frequeney range of interest(0 Hz~300 Hz).

In Fig. 10, it can be seen that optimal design approach based on the Taguchi method gives noise reduction of more than 3 dB in some narrow bands.

5. Conclusions

The Taguchi method can be easily applied to find significant main effects. Thus, for the preliminary experiment, the L_{18} design is first performed for the 8 control factors. The L_{18} design could not take interactions of all combinations into consideration, and it is possible to miss significant interactions to the optimal condition. The fractional factorial design is used to find significant interactions. The Taguchi method for a robust design is applied to take noise factors into account as well as interactions that are chosen from the results of the fractional factorial design.

In other words, we remove the relatively unimportant factors from the control factors, the radius of the inlet hose and through flow, by estimating the effects of the factor using the Taguchi method as the preliminary experiment. Then, the fractional factorial design is adapted using interactions of all combinations and we find that the radius of straight pipe and the length of straight pipe have a significant interaction. Finally, the Taguchi method with L_{27} design is performed considering temperature, background noise and humidity as noise factors as well as the interaction.

In a verification experiment, we find that the overall value and S/N-ration increase up to 26.9 (dB) and 1.39(dB), respectively, compared with the current design.

As results show, the Taguchi method gives higher values of transmission loss, thus we can obtain reduction of noise by more than 3 dB.

Further research may be carried out based on the optimal level which we have shown. By using different levels which are based upon the optimal level we have chosen, it is possible to get an improved optimal condition.

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