OPTIMIZATION OF AN ULTRATHIN CENTRIFUGAL FAN BASED ON THE TAGUCHI METHOD WITH FUZZY LOGICS

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ABSTRACT

This paper presents the use of fuzzy-based Taguchi method to optimize the design of the ultrathin centrifugal fan with multiple performance characteristics. An orthogonal array, the signal-to-noise (S/N) ratio, multiresponse performance index, analysis of variance (ANOVA), and computational-fluid-dynamics were used to study the multiple-objectives in the ultrathin centrifugal fan design. The design parameters, outlet dimensions, inlet dimensions, blade angle, and impeller diameter were optimized with considerations of the performance characteristics, including volume flow ratio, static pressure, and noise. The results demonstrate that volume flow rate of the new design fan was almost 29% larger than that of the original design. This study also identified the optimized design parameters that affect the cooling performance of the centrifugal fan.

Keywords: Taguchi method; fuzzy logic; optimization.

OPTIMISATION D'UN VENTILATEUR CENTRIFUGE ULTRA LÉGER UTILISANT LA MÉTHODE TAGUCHI DE LA LOGIQUE FLOUE

RÉSUMÉ

Dans cet article, on présente l'utilisation d'une méthode basée sur la logique floue pour optimiser la conception d'un ventilateur centrifuge ultra mince aux multiples caractéristiques de performance. Un réseau orthogonal, le rapport signal/bruit, l'index de performance multi-réponse ; l'analyse de variance (ANOVA), et la dynamique numérique des fluides furent utilisés pour étudier les multiples objectifs de la conception d'un ventilateur ultra mince. Les paramètres de conception, les dimensions du point de sortie, l'angle de lame et le diamètre de l'agitateur furent optimisés en considérant les caractéristiques de performance, incluant le rapport du flux volumétrique, la pression statique et le bruit. Les résultats démontrent que le rapport du flux volumétrique du nouveau ventilateur est presque de 29% plus grand que celui du design original. Cette recherche a aussi identifié les paramètres optimisés de conception qui affectent la performance réfrigérante du ventilateur centrifuge.

Mots-clés : méthode Taguchi ; logique floue ; optimisation.

NOMENCLATURE

A	inlet area (m^2)
L_S	noise of the fan (dB(A))
L_{SA}	noise ratio (dB(A))
P	pressure (pa)
Q_M	maximize volume flow rate (m^3/s)
V	fluid velocity (m/s)
X_1	outlet dimensions of the fan
X_2	inlet dimensions of the fan
X_3	blade angle of the fan
X_4	impeller diameter of the fan
x_{1-2}	input of the fuzzy logic
z	output of the fuzzy logic
Greek symbols	
ρ	density of the fluid (kg/m^3)
η	S/N ratio
Subscripts	
1	inlet
2	outlet
d	dynamic
s	static
t	total

1. INTRODUCTION

The Taguchi method [1–3] is a functionary and effective design of the experiments method. It provides a simple and systematic approach to optimizing designs for performance by the signal-to-noise (S/N) ratio and analysis of variance (ANOVA). Parameter design of the Taguchi method can optimize the performance characteristic by setting of design parameters, and can reduce the sensitivity of sources variation. However, the Taguchi method can only process a single-objective program, and cannot manage a multi-objective problem. This study used fuzzy logic to perform fuzzy inference of multiple-objectives of the ultrathin centrifugal fan. The multiple-objective optimization [4–7] can transfer into optimization of a single performance index by fuzzy logic [8, 9].

This paper presents the optimization design of the ultrathin centrifugal fan with multiple-objectives by fuzzy based Taguchi method. The cooling fan was developed by computational-fluid-dynamics (CFD) [10] in the 1970s as an approach to simulation, design, optimization, and flow analysis. In the flow field of the fan, parameters must be determined for analyzing a procedure, which is time consuming and costly for the design procedure. Although CFD can achieve a superior flow field, it has difficulty in achieving the optimal design by selecting the appropriate parameters of the fan. Therefore, this study used an alternative approach based on the combination of CFD, the Taguchi method, and fuzzy logic to determine the optimal design parameters of the ultrathin fan.

This paper is organized as follows: Section 2 introduces the Taguchi method; Section 3 provides the experimental details of using the Taguchi method to determine and analyze the optimal design parameters; Section 4 presents the optimal design parameters of the fuzzy-based Taguchi method regarding performance indices, such as volume rate, static pressure, and noise; and lastly, Section 5 offers a conclusion.

2. THE TAGUCHI METHOD WITH MULTIPLE PERFORMANCE CHARACTERISTICS

In the Taguchi method, engineering optimization is performed in three steps, as follows: system design, parameter design, and tolerance design. First, the system design examines the process sequences, production equipment, and tentative process parameter values. The parameter design determines the optimal settings of the process parameter values to modify the performance characteristics. Finally, tolerance design is used to analyze tolerances around the optimal settings recommended by the parameter design. The parameter design proposed by the Taguchi method was used to obtain high cooling performance in the ultrathin centrifugal fan.

The experiments in this study used the Taguchi method, which uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. These experimental results were subsequently transformed into an S/N ratio. Use of the S/N ratio is recommended to measure the quality characteristics deviating from the desired values. Three types of characteristics were presented in the analysis of the S/N ratio, as follows: the lower-the-better (minimize), the higher-the-better (maximize), and the nominal-the-best. The objective was to reduce variability around a specific target by use of the nominal-the-better, the test was optimized when the response was as large as possible using the higher-the-better, and the test was optimized when the response was as small as possible using the lower-the-better. The objective of this study was to produce a maximal volume flow rate (Q_M) and static pressure (P_S), and ensure that the resulting noise does not exceed constraints. Larger Q_M and P_S values represent superior performance. Therefore, this study implemented a higher-the-better quality characteristic. The S/N ratio is typically derived by [1, 11]

$$S/N = -10\log[\mathrm{MSD}], \tag{1}$$

where MSD refers to Mean Square Deviation of objective function.

The S/N ratio for each level of the control factors was computed based on the S/N analysis. Regardless of the type of performance characteristic, a larger S/N ratio corresponds to superior performance. Therefore, the greatest S/N ratio (η) represents the optimal level of the control factors. Furthermore, statistical ANOVA was performed to help to identify the source of potential problems in the production process, and whether the variation in measured output values is caused by the variability among various manufacturing processes or within them. By varying the factors in a predetermined pattern and analyzing the output, statistical techniques can be used to identify the cause of variation in a manufacturing process.

The Taguchi method was designed to manage optimization of a single-objective program, and cannot manage the optimization of multiple-objectives program because the category of each objective may not be same, the engineering unit may be different in each objective, and the importance of the objective may differ. Consequently, the Taguchi method cannot be directly applied in a program with multiple-objectives. This paper presents an attempt to manage the optimization design of the centrifugal fan with multiple-objectives. Several fuzzy rules were obtained based on the performance requirement of the fan. The loss function corresponding to each objective was fuzzified, and a multi-response performance characteristics index (MPCI) was subsequently obtained through fuzzy inference using fuzzy rules. Based on the Taguchi approach, the MPCI can be used for optimization.

3. DESIGN PARAMETERS OF THE TAGUCHI METHOD

The design parameters of the centrifugal fan, such as the outlet dimension, inlet dimension, blade angle, and impeller diameter must be optimized to achieve cooling performance of a centrifugal fan and meet the cooling requirements of the system. The optimal design fan must have maximal volume flow rate, static pressure, and noise less than 25.5 dB(A).

Table 1. Design parameters and their levels.

Control factors and levels				
	Design parameter	Level 1	Level 2	Level 3
X_1	Outlet dimensions (mm)	16*	19	22
X_2	Inlet dimensions (mm)	19*	21	23
X_3	Blade angle (°)	0	33	66*
X_4	Impeller diameter (mm)	22	22.8	23.5*

*Original design parameter.

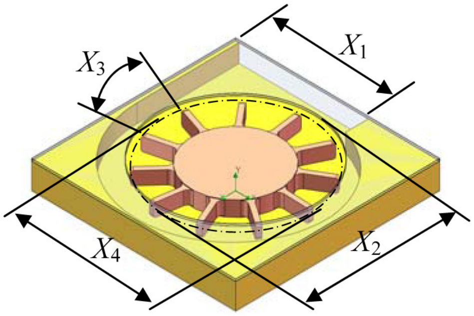


Fig. 1. The centrifugal fan design parameters.

The centrifugal fan, shown in Fig. 1, included the following: outlet dimensions, $X_1 = 16$ mm; inlet dimensions, $X_2 = 19$ mm; blade angle, $X_3 = 66°$; and impeller diameter, $X_4 = 23.5$ mm. The feasible space for the design parameters was defined by varying the outlet dimensions in the range of 16–22 mm, the inlet dimensions in the range of 19–23 mm, the blade angle in the range of 0–66°, and the impeller diameter in the range of 22.0–23.5 mm. Table 1 shows the three levels of the design parameters.

The cooling performance of the ultrathin fan can be mathematically expressed as follows:

$$\text{maximize volume flow rate: } Q_M = VA, \tag{2}$$

$$\text{maximize static pressure: } P_S = (P_{t2} - P_{t1}) - P_{d2}, \tag{3}$$

subject to the following constraint:

$$\text{minimum noise of the centrifugal fan: } L_S = L_{SA} + 10\log_{10} Q_M P_{T2} \leq 25.5, \tag{4}$$

where Q_M is the volume flow rate, V is the fluid velocity, A is the inlet area, P_S is the static pressure of fan, $P_d = (\rho/2)V^2$, $P_T = P_{t2} - P_{t1}$, and P_d is the dynamic pressure of fan. ρ is the fluid density, P_T is the total pressure of the fan, P_{t1} is the total pressure of the inlet, and P_{t2} is the total pressure of the outlet. P_{d1} is the dynamic pressure of the inlet, P_{d2} is the dynamic pressure of the outlet, P_{S1} is the static pressure of the inlet, P_{S2} is the static pressure of the outlet, L_S is the noise of the fan, and L_{SA} is the noise ratio, which is equal to 65 dB(A).

This study had eight degrees of freedom; the $L_9(3^4)$ orthogonal array has nine degrees of freedom, which is greater than that of the design parameters, and can manage three-level design parameters. The Taguchi method has three type of quality characteristics, as follows: the lower-the-better, the higher-the-better, and the nominal-the-best. The higher-the-better performance characteristic was used for volume flow rate, static pressure, and the noise of the fan. Table 2 shows the experimental results for volume flow rate, static pressure, and noise of the fan; the volume flow rate and static pressure by executing Eqs. (2) and (3); the noise of the fan by use of Eq. (4); and the S/N ratio by implementation using Eq. (1).

Table 2. Experimental set-up and S/N ratio.

Ex. no.	X_1	X_2	X_3	X_4	Q_M (l/min)	S/N 1	P_S (Pa)	S/N 2	L_S (dBA)	S/N 3
1	16	19	0	22.0	1.7681	4.9502	11.6713	21.3424	25.22	28.0344
2	16	21	33	22.8	2.1594	6.6867	9.8493	19.8681	25.83	28.2439
3	16	23	66	23.5	2.5824	8.2405	7.6518	17.6753	25.59	28.1604
4	19	19	33	23.5	1.7718	4.9684	9.4230	19.4838	24.51	27.7884
5	19	21	66	22.0	2.1558	6.6722	8.6277	18.7179	24.46	27.7676
6	19	23	0	22.8	2.6004	8.3006	8.3599	18.4441	25.21	28.0317
7	22	19	66	22.8	1.7636	4.9282	8.1464	18.2194	23.55	27.4383
8	22	21	0	23.5	2.1610	6.6931	8.3246	18.4072	24.49	27.7781
9	22	23	33	22.0	2.5819	8.2388	7.4576	17.4519	24.42	27.7552

Table 3. Response table of the noise.

	X_1	X_2	X_3	X_4
1	**28.1462**	27.7537	27.9480	27.8524
2	27.8626	27.9298	27.9292	27.9046
3	27.6572	27.9824	27.7888	27.9090
MAX-MIN	0.4890	0.2287	0.0189	0.0523

Table 4. New experimental set-up and S/N ratio.

Ex. no.	X_1	X_2	X_3	X_4	Q_M (l/min)	S/N 1	P_S (Pa)	S/N 2	L_S (dBA)	S/N 3
1	19.0	19	0	22.0	1.7693	4.9560	10.6539	20.5502	24.47	27.7736
2	19.0	21	33	22.8	2.1605	6.6912	8.7926	18.8824	24.81	27.8938
3	19.0	23	66	23.5	2.5835	8.2440	7.1195	17.0490	24.43	27.7585
4	20.5	19	33	23.5	1.7730	4.9741	9.3045	19.3739	24.48	27.7768
5	20.5	21	66	22.0	2.1557	6.6717	8.3046	18.3864	24.24	27.6918
6	20.5	23	0	22.8	2.6003	8.3003	7.9811	18.0413	25.06	27.9788
7	22.0	19	66	22.8	1.7636	4.9282	8.1464	18.2194	23.55	27.4383
8	22.0	21	0	23.5	2.1610	6.6931	8.3246	18.4072	24.49	27.7781
9	22.0	23	33	22.0	2.5819	8.2388	7.4576	17.4519	24.42	27.7552

Table 3 shows the response table of the noise. The mean effects corresponding to level 1 of A exceeds the transformed constraint limit provided by $10\log(25.5^2) = 28.13$; therefore, this level is excluded. After decreasing the design space, the new levels for the design factors are identified as follows:

$$19 \le X_1 \le 22, \quad 19 \le X_2 \le 23, \quad 0 \le X_3 \le 66, \quad 22 \le X_4 \le 23.5. \tag{5}$$

According to the decrease in the design space, Table 4 shows the new experimental set-up and S/N ratio. As shown in Table 4, the engineering units are different in all objectives. To consider the two different objectives in the Taguchi method, the S/N ratios corresponding to the deposition rate and dilution were processed by the fuzzy logic system.

4. FUZZY LOGIC SYSTEM

The basic architecture of fuzzy system includes the following [8, 9]: a fuzzifier, membership functions, a fuzzy rule base, an inference engine, and a defuzzifier. The fuzzifier uses membership functions to fuzzify the S/N ratios, the inference engine performs fuzzy inference on fuzzy rules to generate a fuzzy value, and

Table 5. Fuzzy rule table.

MPCI	S/N of Q_M			
		S	*M*	*L*
S/N of P_S	*S*	*VS*	*S*	*M*
	M	*S*	*M*	*L*
	L	*M*	*L*	*VL*

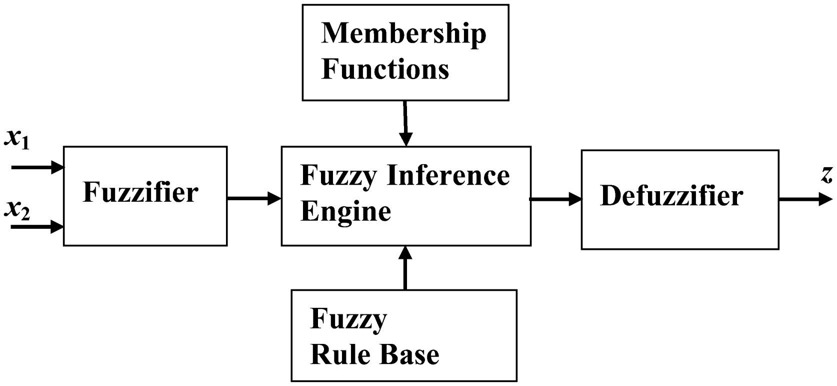


Fig. 2. The fuzzy logic system.

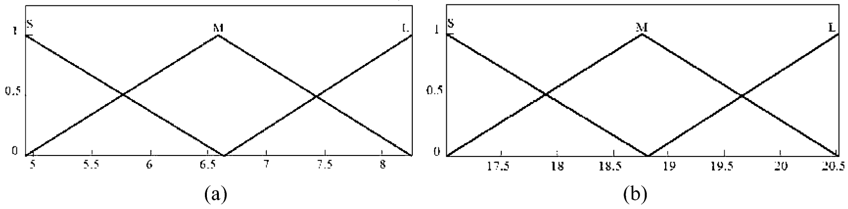


Fig. 3. Membership functions of S/N ratio: (a) S/N ratio of Q_M; (b) S/N ratio of P_S.

the defuzzifier converts the fuzzy value into a multiresponse. This study used the two-input-one-output fuzzy logic system, as shown in Fig. 2. A brief description of two-input-one-output fuzzy logic system is presented. The fuzzy rule base consists of a group of if–then control rules with the two inputs, x_1 (S/N 1) and x_2 (S/N 2), and one output, z (MPCI), that is:

Rule 1: if x_1 is S and x_2 is S then z is VS else
Rule 2: if x_1 is S and x_2 is M then z is S else
$\vdots$
Rule 9: if x_1 is L and x_2 is L then z is VL.

Use S/N 1 and S/N 2 as the input of fuzzy inference, and subsequently determine the solution of MPCI. By using triangle membership functions to fuzzify the input, the level of Q_M and *PS* are defined as large (*L*), medium (*M*), and small (*S*). Figure 3a shows membership functions of S/N ratio of Q_M. Figure 3b shows membership functions of S/N ratio of P_S. Fuzzy rule table shows in Table 5. By using triangle membership functions for the output, the level are defined as very large (*VL*), large (*L*), medium (*M*), small (*S*), and very small (*VS*), as shown in Fig. 4. The fuzzy inference engine is Mamdani, and uses center of gravity defuzzifier. Table 6 shows results of fuzzy inference for MPCI.

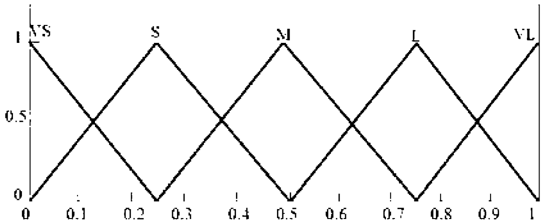


Fig. 4. MPCI.

Table 6. Results for MPCI.

No.	1	2	3	4	5	6	7	8	9
MPCI	0.506	0.518	0.488	0.351	0.443	0.638	0.235	0.450	0.554

Table 7. S/N ratio and ANOVA for MPCI.

	MPCI								
	Mean effects								
	Level 1	Level 2	Level 3	SS	DOF	MS	SS’	F	% Cont.
X_1	**0.5040**	0.4773	0.4130	0.01313	2	0.0066	0.0055	1.72	5.02
X_2	0.3640	0.4703	**0.5600**	0.05780	2	0.0289	0.0501	7.56	45.79
X_3	**0.5313**	0.4743	0.3887	0.03094	2	0.0155	0.0233	4.05	21.29
X_4	**0.5010**	0.4637	0.4297	0.00764	2				
Error				0.00764	2	0.0038	0.0306		27.91
Total				0.10950	8		0.1095		100.00

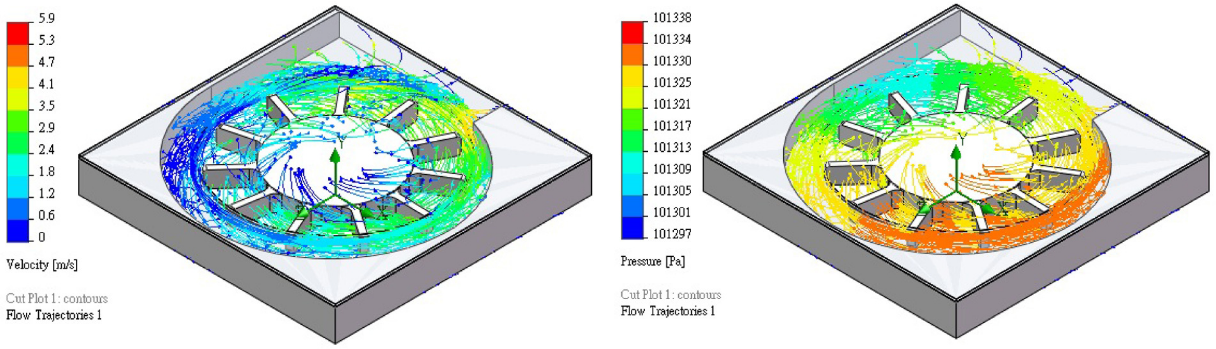
Table 8. Comparison performance of the fan.

	Performance characteristics	
	$Q_M(l/min)$	$P_S(Pa)$
Original design	4.41	13.50
Fuzzy inference design ($X_{11}X_{23}X_{31}X_{41}$)	5.70	13.50

Table 9. Comparison design parameters of the fan.

	Design parameter	Original design	Optimum design
X_1	Outlet dimensions	16.0 mm	19.0 mm
X_2	Inlet dimensions	19.0 mm	23.0 mm
X_3	Blade angle	66°	0°
X_4	Impeller diameter	23.5 mm	22.0 mm

The S/N ratios and ANOVA for MPCI listed in Table 7 demonstrates that factors X_1, X_2, and X_3 have a considerable effect on the MPCI. The results of S/N ratio to obtain the optimal level are $X_{11}X_{23}X_{31}X_{41}$. The results of ANOVA to obtain factors X_2 and X_3 its percentage contribution are 45.79 and 21.29%, and for factor X_1, its percentage contribution is 5.86%. Factor X_4 does not have a considerable effect on MPCI. Table 8 shows the performance comparison of the fan, in which the Q_M of fuzzy inference is higher than that of the original fan. Table 9 shows a comparison of the original and fuzzy inference optimized fan design parameters.



(a) (b)

Fig. 5. Predicted velocity fields and total pressure for the centrifugal fan of the optimum design: (a) velocity field; (b) total pressure field.

5. CONFIRMATION EXPERIMENTS

Confirmation experiments were performed to test the fuzzy-based Taguchi method design of the centrifugal fan, which used CFD software, Solidworks Flow Simulation. In the fuzzy-based Taguchi method optimal design, a maximal volume flow rate and static pressure were chosen to obtain the corresponding volume flow rate and static pressure. The performance (P-Q) curves of the fan obtained from the corresponding volume flow rate and static pressure were subsequently drawn to compare the difference between the original and optimized design parameters.

Figure 5 shows the predicted velocity fields and total pressure for the optimally designed fan, with the fluid velocity of inlet at 0.1 m/s. In addition, the noise value of less than 25.5 dB(A) of the optimized fan can fit the standard of a heat dissipation system, and is considerably quiet.

6. CONCLUSIONS

This study optimized the design of an ultrathin centrifugal fan with specific constrained conditions by using the fuzzy-based Taguchi method. According to the results of the experimental analysis, the fuzzy-based Taguchi method obtains an optimal solution. The optimized design of the centrifugal fan increases cooling capability and reduces the noise considerably (25.5 dB(A)). The Q_M of the new design fan was almost 29% larger than that of the original design. Decreasing the sensitivity of the design parameter variation further established the design capability. This study combined the Taguchi method and fuzzy inference to obtain an optimal solution, which can serve as a reference for engineers.

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