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Development and Optimization of a Compliant Clamp for Grasping Robotics

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ABSTRACT: The study aims to investigate the development and the optimization of a compliant clamp in accuracy high required robotic mechanisms. In this research, a compliant clamp is developed based on flexure hinges to offer the flexibility of movement. Firstly, Solidwork software is used to create a compliant clamp model. Next, a finite element analysis (FEA) is performed using ANSYS software to explore the deformation behavior and stress distribution. The stress and the displacement of the mechanism are two important objective functions considering simultaneously to find the best optimal dimension of flexure hinges. Finally, to improve the strength and increase movement capacity (i.e. how to minimize the stress and maximize the displacement of this mechanism simultaneously), the fuzzy logic reasoning combined with Taguchi method that is proposed in this paper for multiple quality optimization problem. The results reveal that the proposed clamp has the mechanical advantages and the optimal dimension of proposed flexure hinge is the length of 15 mm, the width of 6 mm, and the thickness of 1mm. Therefore, the strength of suggested compliant clamp was improved. It is expected to used in robotic industry and other fields.

KEYWORDS: Compliant clamp, FEA, Fuzzy logic reasoning, Taguchi method, Multi-objective optimization.

BACKGROUND

Flexure based mechanisms, compliant mechanisms, are mechanisms that reply on elastic deform of components to transfer force, moment, translation, rotation, etc. They have been commonly used in high precision actuators, manipulators, robotics, and chemical environment to other industrial areas because they are a monolithic mechanism, lowest cost for manufacturing. From these view of points, a novel compliant clamp is proposed in this paper with regard to multiple quality characteristics optimization problem via using the Taguchi method based fuzzy logic reasoning.

1 INTRODUCTION

A clamp is considered as a device/an end-of-arm tooling or robotic hand for grasping, holding, and picking up the various size objects. Fig. 1a shows the traditional clamp consisting of a lot of sub-components, which connected at kinematic joints, but it must require the lubricant due to the friction, maintenance, and high cost. To overcome the limitation of the conventional clamp, a novel clamp was developed based on the flexure joints as in Fig. 1b, it is only monolithic mechanism and offers a lot of advantages such as no joint, high accuracy, no friction, no clearance, backlash, no lubricant, and no maintenance. However, the flexure joints have some defects as the limited fatigue life and the stress concentration. Thus, as the design and manufacture the compliant clamp, it should take into account to minimize the stress and maximize the displacement of whole mechanism. A numerous previous researchers designed and controlled tradition clamp for grasping. Yocshikawa [1] controlled a robotic hand for grasping and manipulator. Kroemer et al. [2] studied on active learning and active control for grasping. Faraz et al. [3] designed a grasper for surgeon for increasing grasping force. To optimize simultaneously the stress and the displacement, there are a lot of approaches as genetic algorithm, neural network, and fuzzy logic combined genetic algorithm/Taguchi method. Of these, the fuzzy logic combined Taguchi method (FLTM) has been also easier common tool. Hsiang et al. [4] used the fuzzy logic combined Taguchi method to optimize extrusion of magnesium alloy bicycle carriers. Another study by Hsiang et al. [5] found the optimal process parameters based on FLTM for the hot extrusion of AZ31 and AZ61 magnesium-alloy bicycle carriers. Luo et al. [6] optimized the multi-objective topology of CM-continuum structures using a density interpolation scheme, the rational approximation of material properties method and a globally convergent version of the method of moving asymptotes. Huang et al. [7] designed and fabricated a micro-gripper with an optimal topology compliant mechanism. Frecker et al. [8] presented a topology of CMs with multiple outputs.

In this paper, a novel clamp mechanism are proposed via using flexure hinges and optimized by using fuzzy logic-Taguchi method.

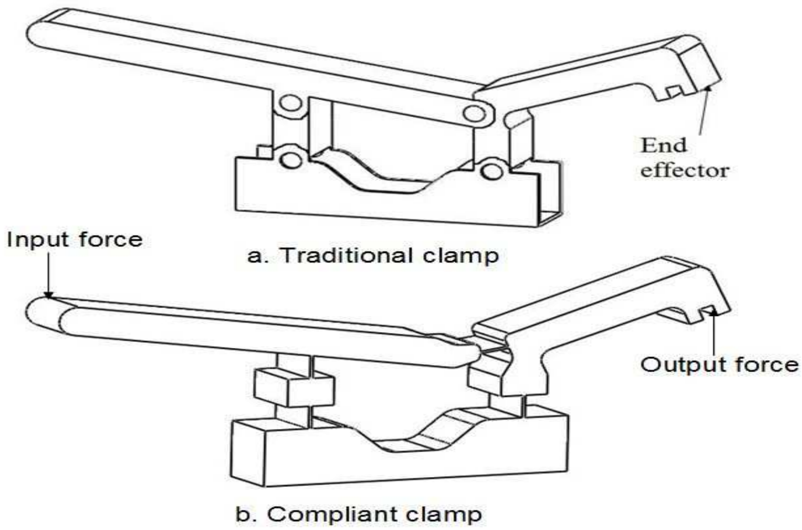

Fig. 1. Model of traditional and complaint clamp

2 Significant and Contribution of Proposed Approach

A clamping robotic hand were developed and based on flexible hinges for the purposes of grasping, holding, and pick up various sized objects. The advantages of compliant clamp for robotic mechanism include monolithic, high accurate, no joint, no friction, no clearance on backlash, no lubricant, and no maintenance. It is expected to use in robotic mechanisms and high precision mechanisms. Also, the proposed methodology for optimization is used to optimize multiple quality characteristics in many engineering areas; in particular, this method is utilized in this paper.

3 Finite Element Analysis (FEA)

The finite element analysis carried out on ANSYS software to investigate the deformation behavior and stress distribution of the proposed clamp, made of polyethylene, such as the stress distribution and the displacement. A meshing method used hex dominant and a meshing type was quadrant; an applied constant force is 2 N. The stress distribution described in as Fig. 2, and the total deformation showed in as Fig. 3. From that, it reveals that the stress concentration and the displacement of flexure hinges are the most significant two aspects result in the flexibility of movement for clamping.

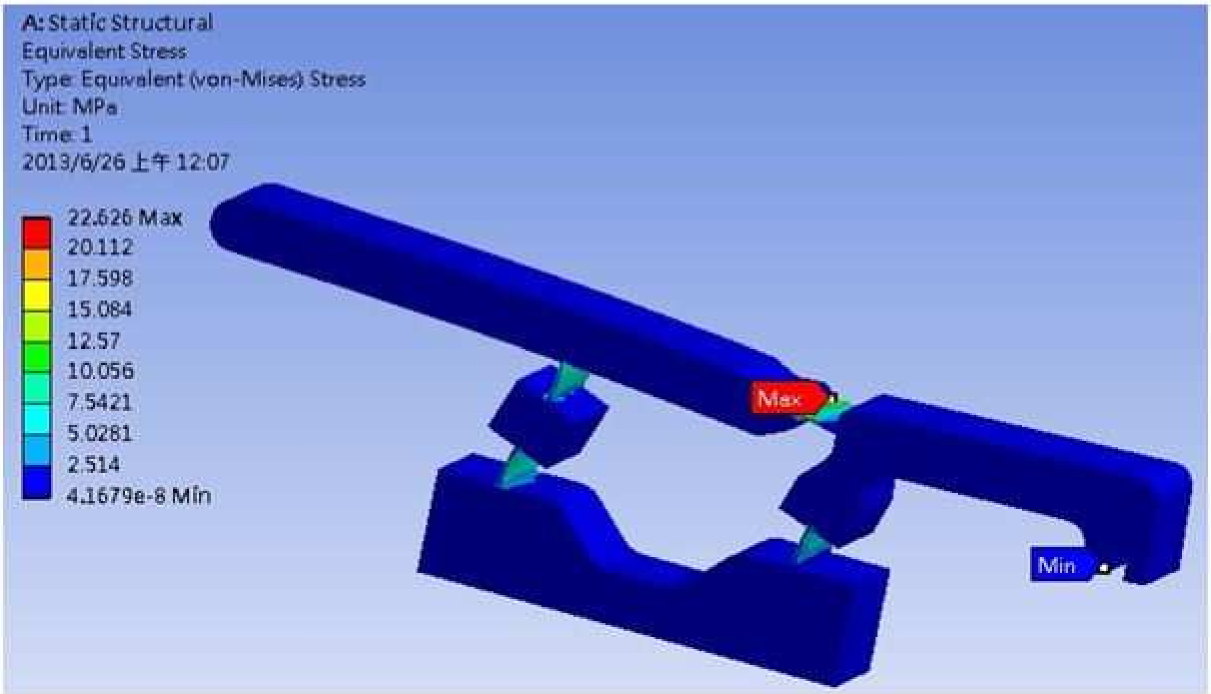

Fig. 2. Stress distribution of clamp compliant

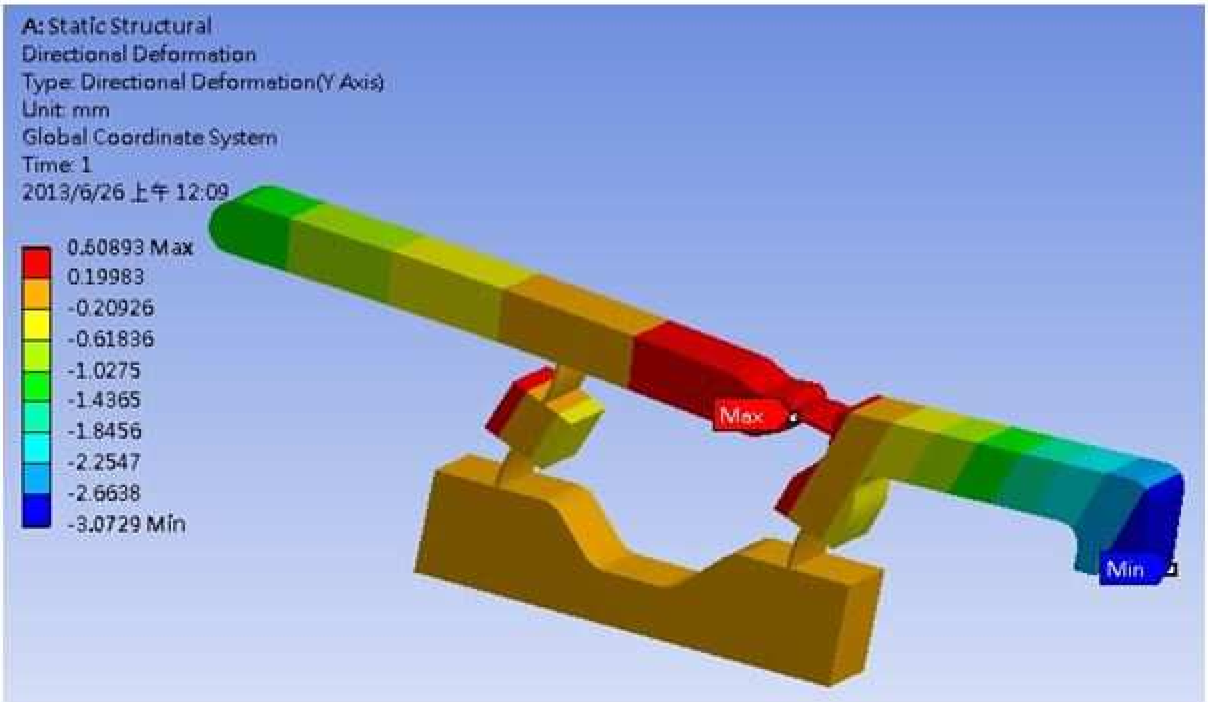

Fig. 3. Total deformation of compliant clamp

4 OPTIMIZATION OF COMPLIANT CLAMP

Because flexure based mechanisms are moved in elastic area, as a result the proposed compliant clamp must also deformed in the limit of material; if this movement is over the limit of material, in plastic area, the mechanism will be failure. Therefore, the resulting stress of the mechanism must be lower than the yield strength of material. Besides, the displacement is also the other aspect that should be considered in any compliant mechanisms because it is often limited in movement.

To obtain the desired motion of the proposed compliant clamp, the optimal design must determine the optimal size of flexural hinges. The first objective function is the maximizing the displacement of a proposed the mechanism. The second one is the minimizing the stress at the flexure hinges. These two objective functions are always in conflict with each other. To handle this conflicting issue of multi-criteria optimization, a fuzzy logic control based on the Taguchi method is discussed in this section.

4.1 FORMULATION OF THE MULTI-OBJECTIVE OPTIMIZATION PROBLEM

The aim of the design of a rectangular flexure hinges is to provide an alternative to a conventional rotary bearing with the same rotational motion function. However, a proposed flexure has drawbacks, such as limited displacement, and the high stress occurring at the flexural pivot. To solve existing issues and to determine the optimal design, the displacement must be maximized, and the stress must simultaneously be minimized. The optimal design problem for the suggested compliant clamp is formulated as follows:

Minimize the stress f_1 (l, w, h)

Maximize the displacement f_2 (l, w, h)

S.T. $f_1 \le \sigma_y$ (1)

where l is the length, w is the width, and h is the thickness of flexure hinges, f_1 is considered as a function of stress that depends on l, w, h. f_2 is a function of displacement that depends on l, w, h. σ_y is yield strength of proposed material (25 MPa)

4.2 OPTIMAL PROCEDURE

In order to find optimal process parameter values based on a single quality characteristic, the Taguchi method is one of the most significant tools because it is an efficient experimental method, and only requires a small number of experiments to measure the quality and analysis of the optimal process. However, optimal results obtained using different quality characteristics always contradict each other. As a result, in an attempt to improve this contradictory problem, fuzzy logic combined with the Taguchi method (FLTM) was utilized in this paper to find the combination of process parameters that optimize the multi-response performance index (MRPI).

4.3 TAGUCHI METHOD

Taguchi method applications are concerned with the optimization of a single performance characteristic. The Taguchi method uses a special design of orthogonal arrays to study an entire parameter space with only a small number of experiments. The experimental results are then transformed into a signal-to-noise (S/N) ratio. The S/N ratio can be used to measure performance characteristics deviating from the desired values. Usually, there are three categories of the performance characteristics in the analysis of the S/N ratio: the lower-the-better, the higher-the-better and the nominal-the-better. In this study, an L_9 orthogonal array experiment was used because there are three parameters and three levels. To obtain optimal motion performance, the displacement of the proposed mechanism and the minimum stress at the flexible pivots are desired. Therefore, the higher-the-better displacement and the lower-the-better stress should be selected. After determining the orthogonal array experiment and the number of parameter levels, this research performs the calculation for the S/N of the displacement and the stress of the flexible hinges, as the following equations briefly describe:

The higher-the-better displacement is:

$$S/N_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{2}$$

The lower-the-better stress is:

$$S / N_S = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{3}$$

where y is the observed data.

To consider the two different performance characteristics in the Taguchi method, the S/N ratios corresponding to the displacement and stress at the fixed end of the flexure hinges are two inputs processed by the fuzzy logic control in order to find the optimal parameter values.

4.4 FUZZY LOGIC BASED ON TAGUCHI METHOD

Using fuzzy logic control, the optimization of multiple performance characteristics can be transformed into the optimization of a single performance index. Thus, the proposed method is the integration of fuzzy logic control with the Taguchi method; they are used to simultaneously achieve the optimization of multiple performance characteristics.

A fuzzy logic unit comprises a fuzzifier, membership functions, a fuzzy rule base, an inference engine and a defuzzifier. First, the fuzzifier uses member functions to fuzzify the signal-to-noise ratios. Next, the inference engine performs fuzzy reasoning on fuzzy rules to generate a fuzzy value. Finally, the defuzzifier converts the fuzzy value into a multi-response performance index. The structure of the two-input-one-output fuzzy logic is shown in Fig. 4. In the following, the concept of fuzzy reasoning is briefly described, based on the two-input-one-output fuzzy logic unit. The fuzzy rule base consists of a group of if-then control rules, with two inputs, x_1 and x_2, and one output, y.

In this paper, fuzzy logic reasoning combined with the Taguchi method is used to optimize multiple performance characteristics for the compliant clamp. An orthogonal array, the S/N ratio and MRPI are used to study the performance characteristics of this mechanism. Matlab 7.1 software is used to solve the roots of nonlinear equations and support for fuzzy logic reasoning. Regardless of the category of the performance characteristic, a larger S/N ratio corresponds to a better performance characteristic. As a result, the optimal level of the process parameters is the level with the highest S/N ratio. The loss function corresponding to each performance characteristic is fuzzified; then an MRPI is achieved through fuzzy reasoning using fuzzy rules.

The flow chart structure of the fuzzy logic controller coupled with the Taguchi method used in the study is shown in Fig. 5. Based on this figure, the optimization problem in this study is easily solved. It shows the procedure of the combined optimal method. At the beginning of the procedure, the given design variables as the thickness h, the width w, and the length l of a flexure hinge are assigned for an optimal process. Then, the allowed range of these parameters will be divided into three levels. Application of Taguchi method, this study selected an orthogonal array L_9 for arranging the experimental matrix. Next, continued work is the formulation of two objective functions; and calculating the S/N for these functions. Two S/Ns are inputs of fuzzy logic system. Based on fuzzy logic reasoning, MRPI or output of fuzzy logic system determined. After that, the mean of MRPI of each level is calculated.

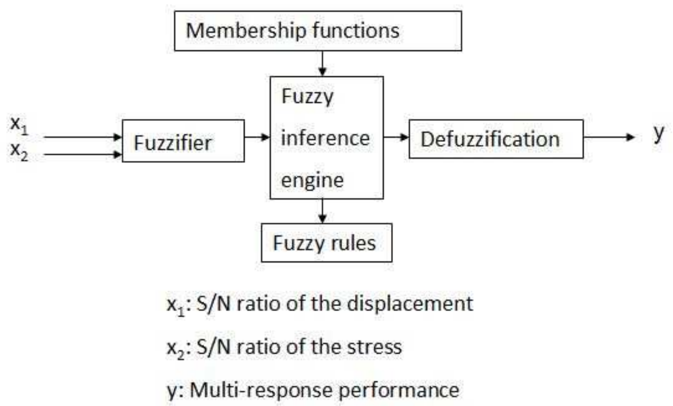

Fig. 4. Structure of the two-input-one-output fuzzy logic control

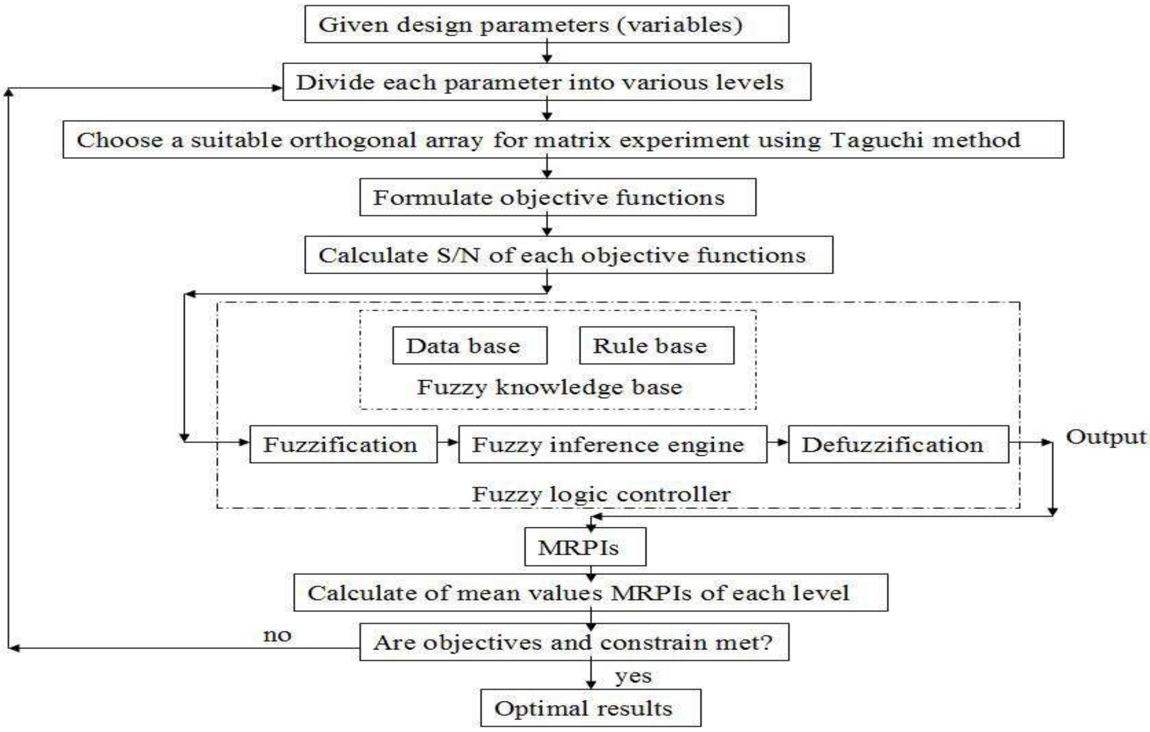

Fig. 5. Flow chart of an FLTM optimization procedure

5 RESULTS AND DISCUSSION

According to the flow chart in Fig. 5, an optimization process for the proposed mechanism is performed using FLTM. This research formulated nine fuzzy rules that are directly based on the fact that the larger the S/N ratio is, the better the performance characteristic in the fuzzy logic controller will be, as presented in Table 1.

The value of each of the process parameters was divided into three levels, as shown in Table 2. Based on the Taguchi method, the L_9 orthogonal array with nine experiments and detailed values of each level is given in Table 3. The higher-the-better displacement of a proposed hinge and the lower-the-better stress should be selected in this study. The results of the S/N ratio of the displacement, the S/N ratio for the stress, and the MRPI are calculated in Table 4. Next, the mean of the MRPI of the input parameters at each of their levels is calculated in Table 5, and shown in Fig. 6. Based on Fig. 6, optimal dimensions are the length level 2 of 15 mm, the width at level 2 of 6 mm, and the thickness at level 3 of 1 mm. The optimal stress is much less than the yield strength value of 25 MPa, which was satisfied constrain in Eq. (1).

Table 1. Fuzzy rules

MRPI		S/N ratio of stress, $f_1(l,w,h)$		
		Small	Medium	Large
S/N ratio of displacement $f_2(l,w,h)$	Small	Very small	Small	Medium
	Medium	Small	Medium	Large
	Large	Medium	Large	Very large

Table 2. The values of process parameters and their levels

Symbol	Parameter	Range	Unit	Level 1	Level 2	Level 3
M	**Length, *l***	10-20	mm	10	15	20
N	**Width, *w***	4-8	mm	4	6	8
P	**Thickness, *h***	0.4-1	mm	0.4	0.7	1

Table 3. Nine trials with detailed values

Motion parameters			
Experiment No.	**M, Length (*mm*)**	**N, Width (*mm*)**	**P, Thickness (*mm*)**
1	10	4	0.4
2	10	6	0.7
3	10	8	1
4	15	4	0.7
5	15	6	1
6	15	8	0.4
7	20	4	1
8	20	6	0.4
9	20	8	0.7

Table 4. Results for S/N ratio and the MRPI

Experiment No.	Displacement along the y-axis, $f_1(l,w,h)$ (*mm*)	S/N ratio (dB) of $f_1(l,w,h)$	Stress, $f_2(l,w,h)$ (*MPa*)	S/N ratio (dB) of $f_2(l,w,h)$	Output of fuzzy logic controller
1	0.60893	-4.3087	22.626	-27.0922	0.394
2	0.3376	-9.4320	10.429	-20.3649	0.439
3	0.26745	-11.4551	7.5235	-17.5284	0.5
4	0.0918	-20.7431	4.3546	-12.7790	0.447
5	0.0857	-21.3404	3.0205	-9.6016	0.532
6	1.472	3.3582	21.221	-26.5353	0.5
7	0.0296	-30.5742	1.721	-4.7156	0.5
8	0.739	-2.6271	17.264	-24.7428	0.438
9	0.30696	-10.2584	5.6238	-15.0006	0.5

Table 5. MRPI for input parameters

Symbol	Input parameters	MRPI			
		Level 1	**Level 2**	**Level 3**	**Max-Min**
M	**Length**	0.4	0.493	0.479	0.093
N	**Width**	0.447	0.470	0.5	0.053
P	**Thickness**	0.465	0.462	0.511	0.046
		Total of MRPI = 0.469			

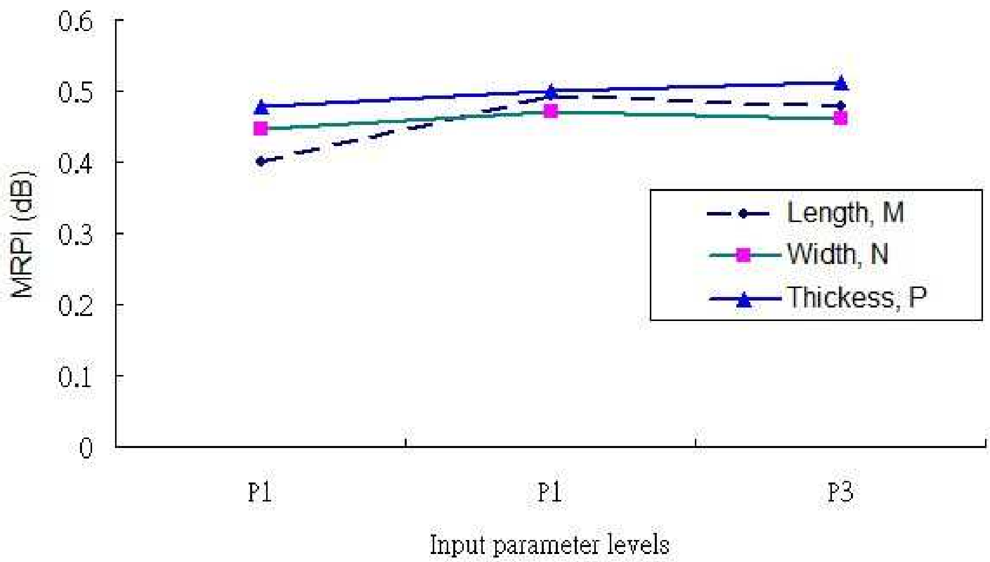

Fig. 6. Schematic diagram of the optimal parameters

6 CONCLUSION

This research presents the development and optimization of a novel flexible clamp mechanism. In this paper, a novel flexible clamp was designed via the use of the concept of compliant mechanism. And then multiple objective optimization problem of the mechanism was performed by using fuzzy logic reasoning combined with the Taguchi method. A FEA conducted on ANSYS software to explore the deformation state and stress distribution. It showed that the compliant clamp has the mechanical advantages better than the traditional clamp. As a result, the strength and mechanical advantage of proposed clamp was improved through the optimization of displacement and stress. Future work will conclude investigation into the thermal effects on the flexibility capacity of compliant clamp.

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