공학석사학위논문

다구치 방법론을 이용한 6절 링크 핑거 클램핑 유닛의 최적 설계

Optimal Design for the Six Bar Linkage Finger Clamping Unit Based on Taguchi Methods

2018 년 8 월

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Tolerance analysis is very important for mass production of a mechanism parts to guarantee satisfactory performance with low production cost. Tolerance analysis of a linkage mechanism is important since linkage mechanism are very sensitive to the tolerance due to many shaft-hole connections. Typically, the tolerances are given by intuition and experiences, but it can be a cause of low performance or high production cost. Especially, the tolerance of a linkage has significant effect near-singularity since little dimension difference can change the performance dramatically. In this paper, we present an experimental tolerance design of a 6-bar toggle linkage mechanism for clamping application. The tolerance design is very important to the 6-bar toggle linkage mechanism since the clamping operation is done near-singularity. Based on design of experiment, the tolerances are determined by optimal criteria with performance and cost deviations. As a result, we determine the position with high tolerance and low tolerance.

Keyword : tolerance design, toggle linkage mechanism, 6-bar mechanism, design of experiment

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Chapter 1. Introduction

1.1. Research background and motivation

Robots have grown rapidly since the inception of robots. Functions of robots are extensive; however, the most important functions are both accuracy and repeatability. Since robots are guaranteed to precisely move to destination points (accuracy), and move back to the same position repeatedly (repeatability), robots are widely used in automobile chassis assembly process. One of the robots successfully utilized in automobile chassis assembly process is Finger Clamping Unit (FCU).

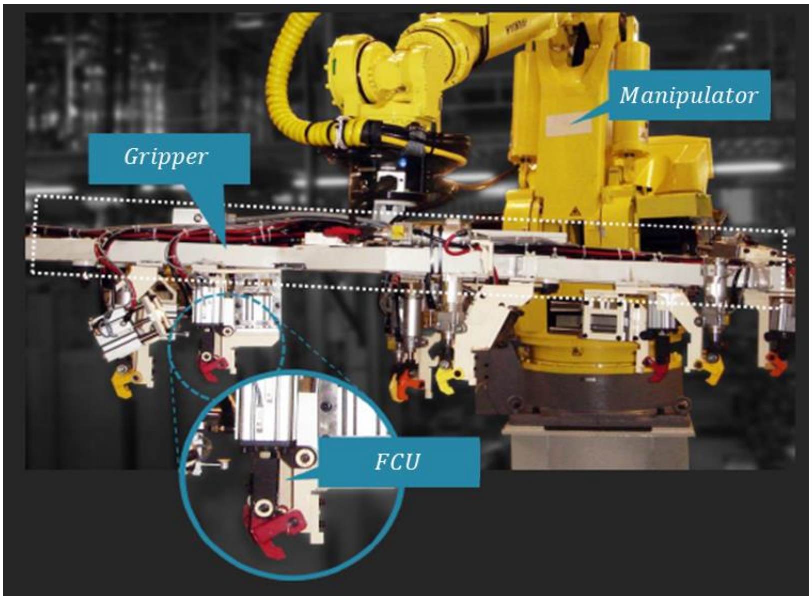

Fig. 1. FCU mounted on the end of a manipulator

FCU in the Fig.1 is the clamping device mounted on the end of a six-degree-of-freedom manipulator, and its main task is to hold and move panels of chassis components to the desired destination points by using a toggle-linkage mechanism. Generally, near-singularity characteristic is used to obtain a high clamping force from a small input force [1].

1.2. Investigation of related research

Tolerance of a FCU is very important to achieve the high clamping performance as analysis. Since the FCU is operated near singularity, the clamping performance is very sensitive to the dimension difference. Several linkage mechanisms have been researched for tolerance design. Koskowicz et al. [2] proposed a kinematic tolerance space to generalize the configuration space representation of nominal kinematic function. The same group extended the idea to statistical method by using the geometric representation [3]. Wang and Masory [4] analyzed the effect of manufacturing tolerance on the accuracy of a Stewart platform. They assumed the tolerance error as a simple deviation in the reference dimension. Recently, Zhan et al. [5] presented tolerance modeling for a planar parallel manipulator. The tolerance in journal-bearing connections are modeled as interval variables by considering the other variables as random variable, and the authors perform Monte-Carlo simulation to get results. Mostly, the tolerance analysis is to find the effect of tolerance to the performance mathematically, and give some guidelines to design the linkage parts.

There are researches on tolerance design optimization for robust design using Taguchi method. The Taguchi method [6-8] is an experimental design technique which helps to design an efficient and cost effective experiment. Rout et al. [9] identified kinematic and dynamic parameter tolerance combinations and selection of optimum tolerance specifications illustrated by using the Taguchi method.

Paredes et al. [10] found the design that offers the maximum allowable tolerance on design variables for a given minimum performance level. Liou et al. [11] proposed a new application of Taguchi's parameter design technique where the inner and outer orthogonal arrays contain tolerance ranges [17] and deviations from nominal respectively. There are many examples in theoretical analyses and simulation, however there is few citable references to get the empirical data on the tolerance design.

1.3. Thesis statement of the study

In this paper, experimenting the performance of FCU incorporating noise effects has been discussed for hole and shaft's tolerance from linkages, and optimum tolerance value has been illustrated using Taguchi method. To illustrate the proposed methodology, a six-bar linkage FCU [12] is used. In order to apply this methodology, objective functions are achieved; it will help to distinguish significant tolerance parameters and evaluate the performance as a function of manufacturing costs and tolerance ranges. In order to be solidified into firm logic, tolerance sensitivity graphs are plotted to supplement the investigations. One of the advantages for above investigations is not only providing guidance of appropriate hole and shaft's tolerance on each linkage but also reducing the manufacturing cost. This study will assist both designers and manufacturer to take decisions of select an appropriate tolerance of each linkage.

Chapter 2. Six bar toggle linkage mechanism

2.1. Six bar linkage mechanism operated in near-singularity configuration

Fig. 1 shows not only the six bar toggle linkage mechanism used for FCU but also the linkage mechanism with mechanical parts developed in the research. The 6−bar is composed of four links with one slider. Four links are denoted by L_i $(i = 1-4)$. Note the L_2 and D_1 is the same rigid link.

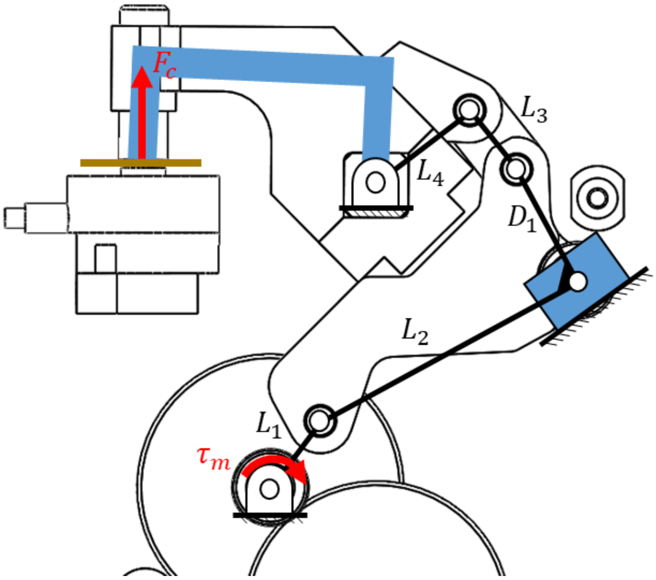

Fig. 2. Six bar toggle linkage mechanism for clamping application operated in near−singularity configurations

One slider joint is located in between L_2 and D_1 to make the single degrees−of−freedom (DOF). As the input motor torque τ_m applied to the linkage mechanism, the clamping force F_c is generated. By this toggle linkage mechanism, the FCU can handle metal plates as denoted by yellow region in the figure.

To generate high clamping force, the 6−bar mechanism is operated in near−singularity configuration. As you can see in the Fig. 1, the operating point is near−singular to make the L_3 and D_1 are almost in the same line. In the previous research [12], we analyzed the near−singularity configuration can generate high clamping force with large workspace by simulation and experiment. However, the near−singularity configuration has problem in mass production since the dimension errors are very sensitive to the performance to make the linkage mechanism do not get satisfactory force or make it be failed. There are two main sources of dimension errors in this mechanism: length error and tolerance error. By pre−research, the length error is less sensitive to the performance than the tolerance error. Also, we think that the length error can be controlled comparatively easier by precision manufacturing than the tolerance error.

2.2. Six bar linkage mechanism with shaft-hole connections

The six bar has six shaft−hole connection denoted by SH_i $(i = 1 - 6)$ in the Fig .3.

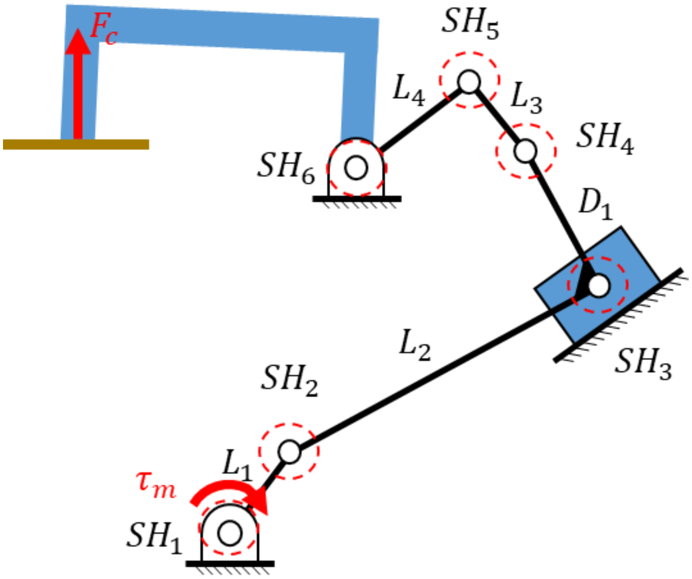

Fig. 3. Linkage mechanisms with shaft/hole connections

In this research, we design the tolerance of the SH_i by the experimental design method. To determine the tolerance, it is important to balance the manufacturing cost and precision manufacturing. Also, the sensitivity analysis on the design parameters are very important to reduce the design cost. Based on the detailed design, we are going to reduce number of design parameters and perform the experiments.

It is important to note that the special feature of L_3 link. To modulate the effect of near−singularity configuration: high clamping force with large workspace, the L_3 link is designed compliantly [13, 14]. By using the compliant link, the clamping force and workspace can be increased dramatically. Also, the mechanism can be operated near−singularity to generated locking−like performance. The effect of compliance is summarized in the [15] in detail.

Chapter 3. Tolerance Design

Taguchi method is well−known as a robust design methodology. To determine the robust design parameters under various disturbances, the Taguchi method is very useful. Even though there are some simulation results are given, the experimental design is very important to guarantee the reliability of the result. In this research, we performed the experimental tolerance design based on Taguchi method considering the objective and disturbances.

3.1. Objective function

The tolerance design has two objectives. First, to guarantee high performance, the tolerance should be precise. If the tolerance is too low, the expected performance in simulation does not guaranteed. Second, to get reasonable cost, the high tolerance should be avoided. High tolerance makes the manufacturing cost and time to be high. The two objectives have conflict and the objective function should be determined to consider them carefully.

The objective function defined in this research is as follows:

$$f(x) = w_1 DEV_{CR} + w_2 Cost \tag{1}$$

where DEV_{CR} denotes the deviation in clamping range to guarantee certain clamping force, $Cost$ is the manufacturing cost according to the tolerance grade, and w_i is the weights, respectively.

The DEV_{CR} is defined by the clamping range deviation. As explained in the [12], advantage of the 6−bar toggle linkage is large workspace with high clamping force. Between the workspace and clamping force, we determined that the workspace is more important than clamping force. If the clamping force is higher than certain value, the performance is satisfactory; while the workspace is considered by larger−the−better value. We set up the required clamping force as 1,500 N for the car assembly application. The DEV_{CR} is calculated from

$$DEV_{CR} = \left|CR - CR_{ref}\right| \tag{2}$$

where CR and CR_{ref} are the clamping range for the case and reference with perfect manufacturing for the assembly.

It is important to define $Cost$ to get reliable results. As the tolerance grade is getting high, the cost is increased. However, $Cost$ is not easy to be defined. The procedure to define $Cost$ is as follows. First, we get estimation of the manufacturing cost by expert, which is composed of the basic manufacturing cost and the reference cost for the tolerance parts that we are interested. Based on the reference cost for tolerance, we used the relation as follows [16]:

$$Cost = Reference\ cost \frac{Reference\ Tolerance^2}{Tolerance^2} \tag{3}$$

The equation simply means that the manufacturing cost is increased as the tolerance in getting precise. The basic cost is not related to the tolerance, and it is also excluded in this paper. Based on this equation, we can assume the expected cost based on the given tolerance.

For the weights and parameters, we used batch normalization for each DEV_{CR} and $Cost$ parameters to consider the effect with the same weights. The weights are 0.5 for the experiment.

3.2. Design parameter

Fig. 4 and Fig.5 show comparison of the linkage mechanism and detailed design for manufacturing.

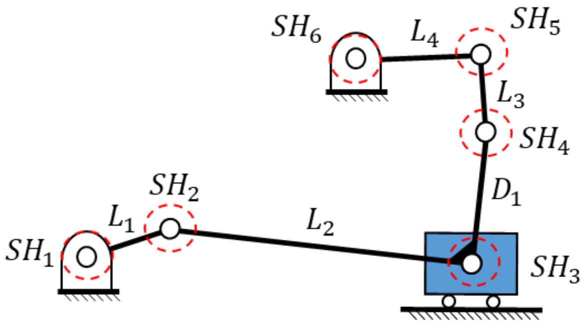

Fig. 4. The mechanism configuration with six shaft-hole connections

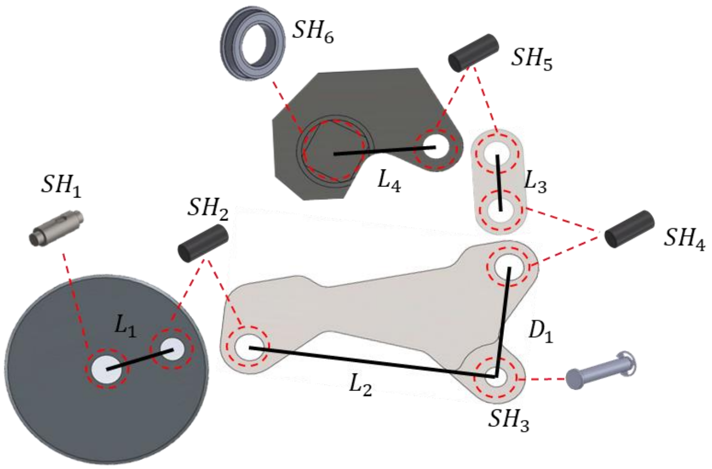

Fig. 5. Mechanical design of the six bar toggle linkage mechanism

As noted in the Section 2, there are six shaft−hole connections. Experiments for all the shaft−hole parameters increase number of test, so we determine reduced number of the design parameters based on the detailed design.

The design parameters for tolerance design in this research are determined by $SH_2, SH_4, \text{and } SH_5$. As you can see in the Fig. 4 and Fig.5, the three design parameters are pin−hole joint that the tolerance has very important role to determine the output performance directly. We do not consider SH_1 because it is input−shaft from motor, where the link is connected to the motor rigidly. Not only that, but SH_3 and SH_6 are also not considered as a tolerance design parameters due to it is the position where rolling bearing are equipped. Important parts for tolerance determination are $SH_2, SH_4, \text{and } SH_5$, where the tolerance should be determined optimally.

Fig. 6 and Fig.7 represent the graphical interpretation of error induced from the tolerance. When there is zero clearance between hole and shaft, two different links will be connected without space between two holes and one pin as shown in the Fig.6.

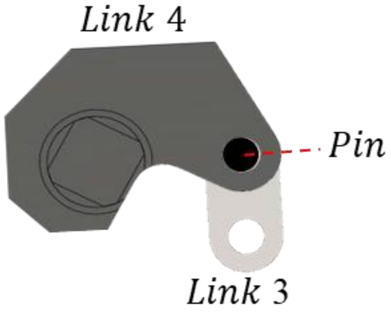

Fig. 6. Zero clearance between hole and shaft

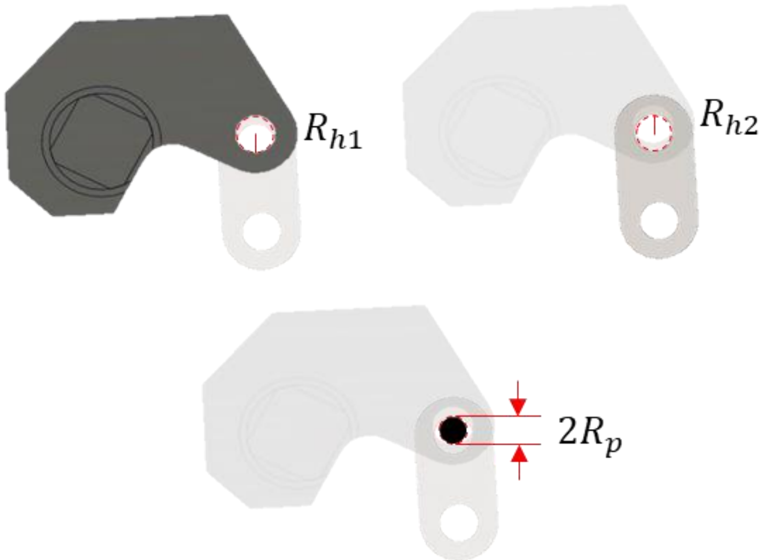

Fig. 7. Maximum error occurs due to loose clearance between hole and shaft

In $SH_2, SH_4, \text{and}\, SH_5$, the pin−hole connection is composed of two holes and one pin. Due to the manufacturing error, the maximum tolerance error in the connection is $R_{h1} + R_{h2} - 2R_p$ as shown in the Fig. 7. Unlike the three shaft−hole connection with motor and rolling bearing, these three tolerances should be clearly defined to make the linkage be high performing and being robust.

3.3. Noise factors

Noise factor in Taguchi method is the factor that influences to the performance which the user cannot control such as disturbance or external condition change. To guarantee the robust performance of optimal design, selecting noise factors are very important.

In this design, we think the repeatability of the clamping operation is very important. As you imagine, the clamping performance is changed over repeated operation. Therefore, we selected the repeat time as a noise factor. In detail, we are going to measure the DEV_{CR} for the first try and DEV_{CR} after 10,000 times repeat. By using the two DEV_{CR} values, the robust design parameters can be determined.

3.4. Problem definition and orthogonal array

The final optimization problem is defined as follows:

$$\min_{SR_i\,(i=2,4,5)} SNR = -\log_{10}\frac{f_1(x)^2 + f_{10,000}(x)^2}{2} \tag{4}$$

where SNR is the smaller−the−better signal to noise ratio. The $f_i(x)$ is going to be determined experimentally, and get some discussion on the results in the next section. Since there are three design parameters, we can design the experiments based on the $L_9(3^4)$ orthogonal array as Table 1.

Table 1. $L_9(3^4)$ orthogonal array

Combination number (C#)	Design parameters			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Chapter 4. Experimental result and discussion

4.1. Experimental set-up

Fig. 8 shows experimental set−up to measure the data to obtain the optimal design parameter. FCU's power source is the step motor (EzM−42s) of which it is connected to the motor driver (EZD−PD−42s). This motor driver is connected to RS−485 device in order to control the motor in the computer. The program we used to control the motor is the LabVIEW.

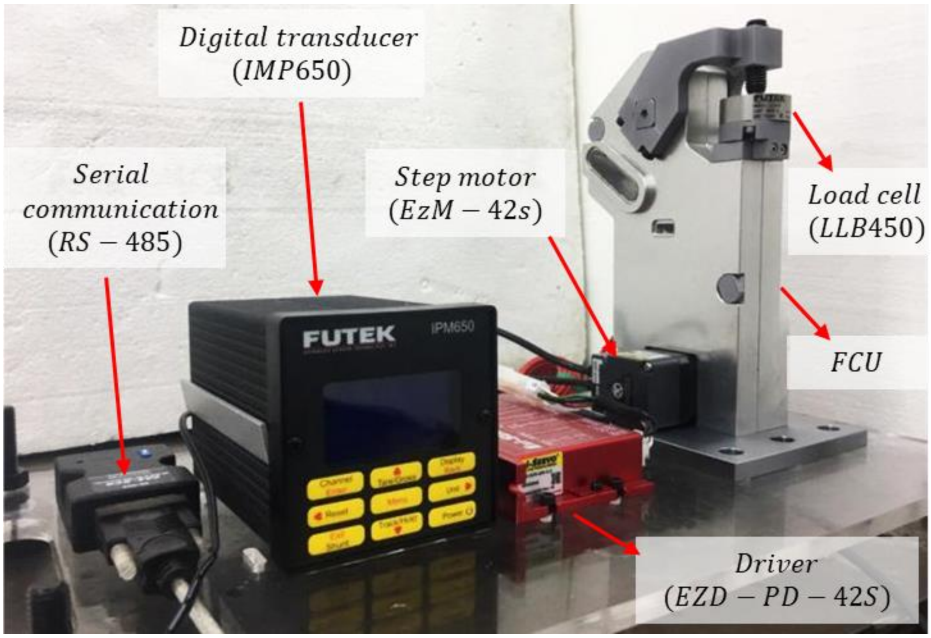

Fig. 8. Experimental set−up

To measure the force, we used the load cell (Futek, llb450) of which its capacity is 22,240 N. The force measured by load cell is displayed on the digital transducer (IMP650).

In Fig. 9, the manufactured parts for the $L_9(3^4)$ array experiments are shown.

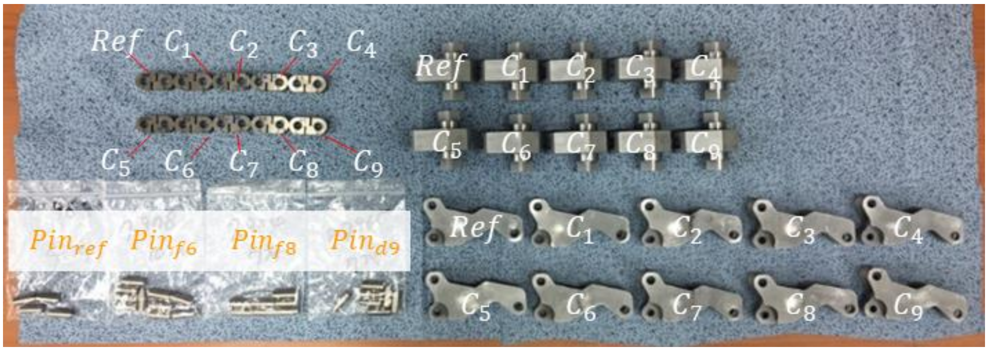

Fig. 9. Manufactured parts for the optimal design

Diameter of hole from all the parts are 8 mm. If those of holes are specified to IT grade of H6, then the tolerance range is from 0 mm to +0.009 mm. We decided to manufacture a part specified to IT grade of H6 with Least Material Condition. LMC is the largest hole size and the smallest shaft size. If a part is manufactured in a condition of LMC, then it would have the largest clearance between a hole and a shaft (a pin). A reason why we decided to manufacture all the parts in a condition of LMC is because it considered to be the worst case from tolerance range. In order to experiment all the parts in a condition of LMC, we should manufacture precisely as much as we could. Therefore, we decided to manufacture within a range from +0.0005 mm to −0.0005 mm in order to experiment in a condition of worst case. For example, diameter of a hole from a part specified to H6 is 8.009 mm if it is manufactured in a condition of the worst case. Experimenting in a condition of worst case will be worthwhile in order to investigate the FCU's performance. Table 2, Table 3 and Table 4 show the worst case of H6 (f6), H8 (f8) and H10 (d9).

Overall, there are ten manufactured parts that one is for the perfect−dimensioned part of which it is manufactured by International Tolerance (IT) grade of 1. This perfect−dimensioned part has an approximately zero clearance between hole and shaft. Not only that but this perfect−dimensioned part is also considered to be an optimal value in order to have the best FCU's performance.

Table 2. The worst case of both H6 and f6 (LMC)

	Diameter [mm]	Tolerance (IT grade)	Tolerance range [mm]	LMC [mm]
Hole	8.0	H6	$\varnothing 8^{+0.009}_{0}$	8.009
Pin	8.0	f6	$\varnothing 8^{-0.013}_{-0.022}$	7.978

Table 3. The worst case of both H8 and f8 (LMC)

	Diameter [mm]	Tolerance (IT grade)	Tolerance range [mm]	LMC [mm]
Hole	8.0	H8	$\varnothing 8^{+0.022}_{0}$	8.022
Pin	8.0	f8	$\varnothing 8^{-0.013}_{-0.035}$	7.965

Table 4. The worst case of both H10 and d9 (LMC)

	Diameter [mm]	Tolerance (IT grade)	Tolerance range [mm]	LMC [mm]
Hole	8.0	H10	$\varnothing 8^{+0.058}_{0}$	8.058
Pin	8.0	d9	$\varnothing 8^{-0.040}_{-0.076}$	7.924

As a result, we selected the three levels to varying the design parameters based on International Tolerance (IT) grades by varying IT6, IT8, and IT10 for each shaft and hole, where IT6 is manufactured precisely than IT10, which causes high manufacturing cost. The compliance in link 3 (Fig. 6) is designed to be k = 126,000 N/mm.

Fig. 10 shows the clamping range data based on the load cell measurement.

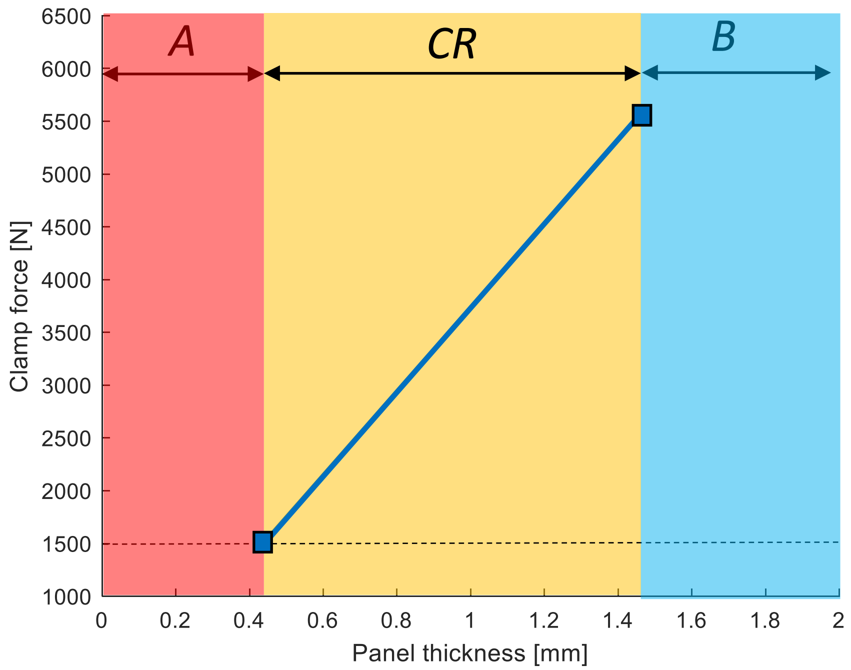

Fig. 10 Clamping force measurement results

We measured the clamping force by changing the thickness of steel plates. As you can see in the Fig.10, the clamping force is monotonically increased as the thickness is increased. The starting point is determined by the minimum thickness when the clamping force is over 1,500 N. The end point is determined by the kinematic structure that the linkage cannot make the near−singularity configuration, which cannot maintain the clamping force. The A and B denotes the regions that the clamping force is less than 1,500 N and that the linkage structure does not make near−singularity characteristics. Based on this data, we can determine the DEV_{CR} to calculate the SNR for optimal design.

4.2. Result and discussion

Table 5 shows the experimental results on measuring DEV_{CR}. We measured the data based on $L_9(3^4)$ orthogonal array for each combination of IT6, IT8, and IT10, as shown in the left side of Table 5. The Cost values are determined by previous results [16], and Table 6 shows the cost and tolerance values to calculate the costs. As shown in the right side of the Table 5, the DEV_{CR} and $Cost$ values are normalized for the same weights. To make all the values to be positive the values has offset with three times of standard deviation. Since the characteristic of this experiment is smaller−the−better characteristic, the final SNR is calculated by [6].

Table 5. Experimental results based on the $L_9(3^4)$ orthogonal array

Comb.	Parameters			Objective Function			Normalized with 3σ offset			SNR (dB)
	A	B	C	$DEV_{CR,1}$	$DEV_{CR,10000}$	$Cost$($)	$DEV_{CR,1}$	$DEV_{CR,10000}$	$Cost$	
1	IT6	IT6	IT6	0.17	0.02	29.85	4.37	2.18	5.03	-12.44
2	IT6	IT8	IT8	0.08	0.04	20.94	1.90	2.59	3.77	-9.58
3	IT6	IT10	IT10	0.08	0.04	12.36	1.90	2.59	2.56	-7.63
4	IT8	IT6	IT8	0.15	0.04	20.94	3.82	2.59	3.77	-10.88
5	IT8	IT8	IT10	0.08	0.06	12.14	1.90	3.00	2.53	-7.97
6	IT8	IT10	IT6	0.1	0	12.25	2.45	1.77	2.54	-7.35
7	IT10	IT6	IT10	0.16	0.11	12.36	4.10	4.03	2.56	-10.40
8	IT10	IT8	IT6	0.14	0.07	12.21	.55	3.21	2.54	-9.42
9	IT10	IT10	IT8	0.12	0.16	6.42	3.00	5.05	1.72	-9.30

Table 6. The cost and tolerance values to calculate the costs

Links	Dimension [mm]	Reference cost ($)	Reference tolerance	IT6	IT8	IT10	Number of manufacturing
L_2	8.0	3.0	IT8	0.009	0.022	0.058	2 (SH_2, SH_4)
L_3	8.0	3.0	IT8	0.009	0.022	0.058	2 (SH_4, SH_5)
L_4	8.0	3.0	IT8	0.009	0.022	0.058	1 (SH_5)

The sensitivity analysis results are shown in Fig. 11. As shown in the figure, the performance is more sensitive to the tolerance between the second and third links, which is the most important pin−hole connection to make the near−singularity configuration. Interestingly, the third level of B and C gives the best results to guarantee high SNR. The high tolerance is not always good due to the cost effect. As a result, the optimal design parameter is determined by IT8, IT10, and IT10 for $SH_2, SH_3, \text{and } SH_5$, respectively.

By analyzing the tolerance regardless the cost, in some case, low tolerance in $SH_4 \text{ and } SH_5$ generates higher clamping range than high tolerance. We thought this is due to the complicated effect in the linkage structure near−singularity. Actually, this phenomenon is not easy to find in theoretical analysis, and the result proves the effectiveness of experimental studies.

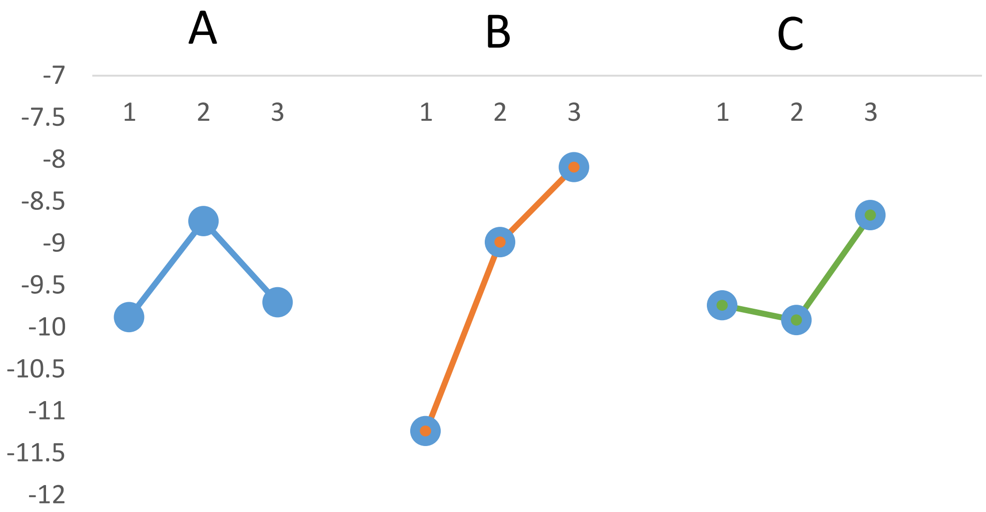

Fig. 11 Sensitivity analysis on the design parameters

Not always the theoretical results give the best results since there is unexpected factors in the real applications. One possible reason we thought is that, as shown in Fig. 12, the large clearance between shaft−hole connections make the locking to be easier in the near−singularity position. There should be more work to prove this phenomenon theoretically.

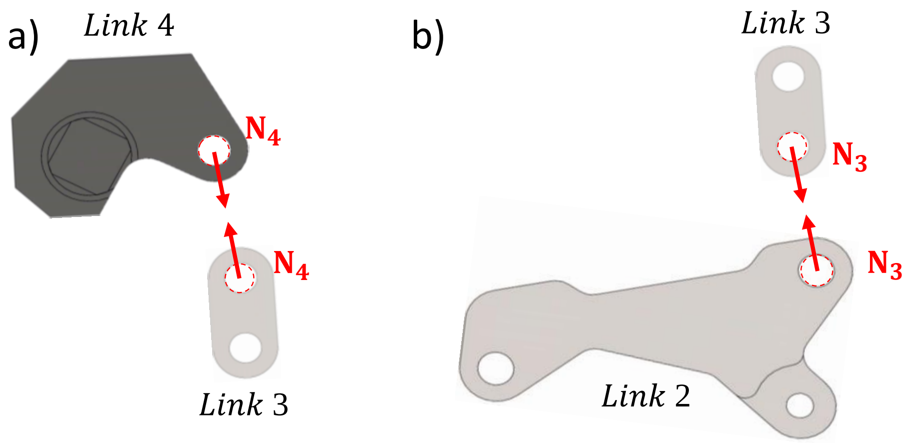

Fig. 12 Geometrical interpretation to see the effect of clearance to the performance

Chapter 5. Conclusion

This paper presented a tolerance design of a 6−bar toggle linkage mechanism for FCU application. Comparing to other simulation−based tolerance design papers, this paper tried to present the procedure and results on the experimental design of the linkage. Especially, the linkage has special characteristics that the operation is done near−singularity, where the tolerance has high effect to the output performance. Three shaft−hole were selected to design parameters for tolerance design, while the objective function is defined by the combination of the clamping range with over 1,500 N clamping force and the manufacturing cost. Repeat time is selected to be a noise factor to test the robustness that clamping range of the fist and 10,000 times after tries were measured. As a result, the tolerance in shaft−hole to make the near−singularity configuration is the most sensitive to the output, and optimal tolerance to guarantee the performance with lost cost is suggested. In the result, we also found that the high tolerance does not guarantee large clamping range empirically. We believe the procedure and results can be referred to other researchers for tolerance design in practice.

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국문초록

공차 분석은 낮은 생산 비용으로 만족스러운 성능을 보장하는 분석과 동시에 대량 생산에서 매우 중요한 분석 도구이다. 특히나 링크 구조로 구성 되어있는 여러 파트들은 핀과 구멍으로 연결이 되어있고 각각의 구멍 및 핀들은 특정 공차를 부여한다. 일반적으로 디자이너의 경험과 직관에 의해 공차를 부여하지만 이후 낮은 성능이나 높은 생산 비용의 원인이 될 수 있다. 특히나 핑거 클램핑 유닛의 링크 구멍 및 핀 공차는 싱귤러리티 근처에서 가장 큰 영향을 받는다. 그 이유는 링크 길이가 적게 변해도 성능에 큰 영향을 미치기 때문이다. 본 논문에서는 6 절 링크와 토글 메커니즘으로 구성 되어있는 핑거 클램핑 유닛의 실험을 통한 공차 분석과 공차 설계를 제시한다. 실험을 통해서 각 구멍 및 핀의 공차는 핑거 클램핑 유닛의 성능 및 가공 비용 편차를 비교하여 최적 값을 선정했다.

주요어 : 공차 분석, 토글 메커니즘, 6절 링크, 구멍 및 핀 공차

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