



CAD-model-based Optimal Design of Slide-hinge Spring

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ABSTRACT

This research proposes the methodology of using the 3D CAD model of a slide-hinge spring as the basis to analyse the stresses and reaction forces, and implementing Taguchi method to find the optimal parameters of the spring. Firstly, 3D meshes are generated out of the 3D CAD model. In accordance to the mechanism characteristics of the slide hinge, primary data for engineering analysis are determined, including mesh properties, material properties, boundary conditions, contact definitions, and iterative procedure. MARC, a well-known CAE software, is then used to find von Mises stresses and reaction forces of the spring during its movement in a slide hinge. In order to prevent plastic deformation and damage of the spring, the Taguchi method is adopted in this paper to reduce the maximum stress during spring movement. All details of optimizing the dimensional parameters of the spring will be discussed in the paper, including the determination of control factors and their levels, setup of orthogonal arrays, calculation of S/N ratios, completion of variation analysis, and estimation of confidence intervals.

Keywords: CAD, CAE, optimal design.

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1 INTRODUCTION

Slide hinges are a typical device in cell phones which provides a physical keyboard for text and numeral input. As for the design of a slide hinge, the spring inside the hinge affects both the feel of the cell phone and its product life, thus the spring is one of the important components in a sliding mechanism. In early designs, it was difficult for engineers to estimate the smoothness of the sliding mechanism or the spring life from the geometry of the spring. Therefore, this paper uses the 3D CAD model of the sliding mechanism as the basis to analyze the stress of the spring and its distribution when the sliding hinge is in motion. Relevant data, for instance, mesh properties, material properties, boundary conditions, contact definitions, iterative procedure, etc. are investigated to complete the

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settings of pre-processing for FEM analysis. The purpose of this process is to analyze the changes in reaction force during the spring movement, and to provide a general estimation of product performance for the engineers at the early design stage. Then, according to the design parameters, physical spring samples are produced for mechanical experiments and reaction measurements. The experimental results are then compared with the results obtained from the finite element method, in order to achieve a better setting for engineering analysis. In addition, this paper also employs Taguchi method to optimize the design of spring dimensions, which reduces the spring's maximum stress and appropriate reaction forces.

In literature, the finite element method has been widely used in solving various types of engineering problems, for instance, structural analysis, heat transfer, fluid mechanics, and electromagnetism [1~3]. This paper focuses on applying FEM to conduct structural analyses for a continuously deforming spring. There are many case studies of structural analysis and improvement in conjunction with finite element analysis and optimal design. For instance, Ou and Balenrea [4] used FEM to simulate the forging of aerofoil sections to investigate the effect of variations in parting line and friction on material flow, forging force history, and elastic deflections. Hsu *et al.* [5] used ANSYS, a well-known CAE software, to optimize designs for electronic connectors, achieving an optimal insertion force. Another popular approach of design analysis is the Taguchi method. This method is based on statistical principles, and was developed to determine the optimum number of experiments to reduce experimental cost and maximize data reliability [6]. The general procedure of this approach is to apply an orthogonal array to decide experimental contents, then to employ variation analysis and signal/noise ratio to determine and measure characteristics that may affect the final product. By applying the concept of design parameters, product variance will reduce and result in improved product robustness. Since the Taguchi method is a general method, this methodology is widely applicable in various fields. For example, Lin *et al.* [7] were able to determine the optimal combination of electrode-wear and material removal rate during electrical discharge machining. Kunjur and Krishnamurty *et al.* [8] developed a robust multi-criteria optimization approach, which is based on the Taguchi method, and integrated it with statistical variation analysis to estimate relative dominance and significance of design factors and to provide sufficient information for selecting levels of design parameters. Similarly, Tarng *et al.* [9] also combined the Taguchi method with fuzzy theory to develop a multi-criteria algorithm. This method allows users to integrate multiple characteristics into one, and to obtain the optimized result for all control factors. Similar research projects were also studied by several researchers [10~14].

Fig. 1 illustrates the sliding mechanism of a slide hinge. The system includes three major components: spring, moving part (upper case) and fixed part (lower case). Normally, there is a 0.03mm gap between upper and lower cases. The spring are attached to the sliders separately. When a user moves the upper case forwards or backwards, the spring deforms accordingly. Once the moving part travels beyond halfway of the distance, the spring releases its stored energy to push the slider into desirable position, which is the basic sliding mechanism of the system. Although sliding hinge is one of the modern 3C products, apply CAD, FEM and Taguchi method on analysing the spring of a sliding hinge is rarely observed in previous research. In this work, a detailed description of employing FEM to analyse the non-linear stress during elastic deformation of the spring is presented. Furthermore, the use of this analysis as a basic operation and the implementation of the Taguchi method are also included. In brief, this approach aims to obtain the optimal design parameters for the spring, and to minimize the stress generated during the deformation process, so as to extend the operational life of the spring.

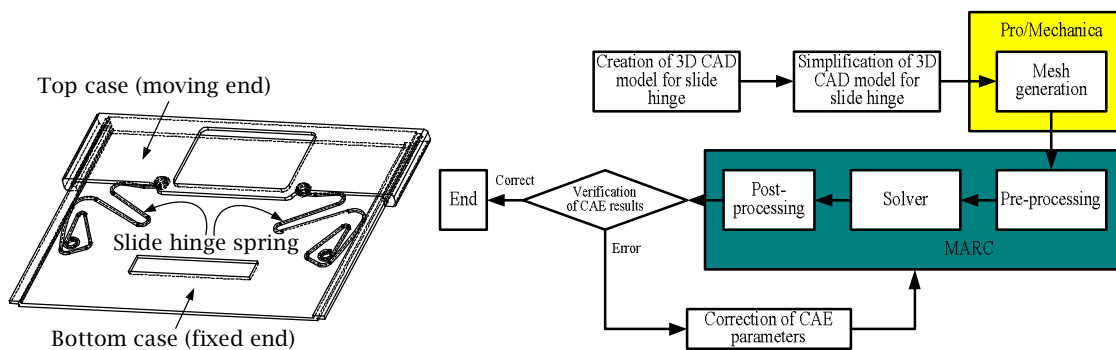


Fig. 1: 3D CAD model of slide hinge.

Fig. 2: Flow chart of mechanic analysis for slide hinge.

Fig. 2 is a flow chart of the engineering analysis for slide-hinge springs. Firstly, Pro/ENGINEER is used to build a 3D CAD model of the sliding mechanism, which is then converted into mesh elements by the Mechanica module in Pro/ENGINEER. Then, MARC is used for the pre-process of FEM, as well as to set the solver and find appropriate parameters. Finally, the engineering analysis is conducted, and the results are discussed. In the following sections, each step is explained in detail.

2 CAD MODEL AND MESH GENERATION OF SLIDE-HINGE SPRING

Fig. 1 is the 3D CAD model of the sliding mechanism created by Pro/ENGINEER. Since both upper and lower cases do not deform during their movements, these two components are omitted in the generation of meshes. Moreover, the entire sliding mechanism is symmetrical, therefore it only needs to conduct finite element analysis on one single spring, and the entire mechanism can be simplified as the geometric model shown in Fig. 3.

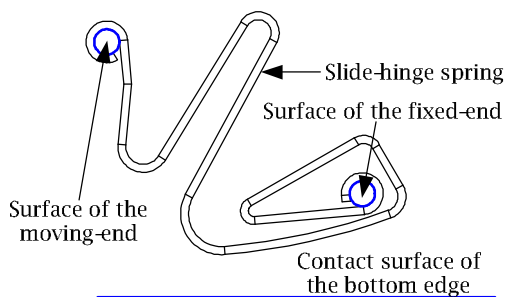


Fig. 3: Simplified 3D CAD model of slide hinge.

During the movement of the spring, both the moving pin and fixed pin are rigid. Thus they are considered as rigid surfaces and expressed in IGES format. Meanwhile, the spring itself is divided into tetrahedral elements by the Mechanica module in Pro/ENGINEER. As Fig. 5 shows, the maximum element size is 0.2mm, in other words, the side length of the mesh elements is less than 0.2mm. In total, there are 27,000 mesh elements, and both linear and curved regions are shown in Fig. 6.

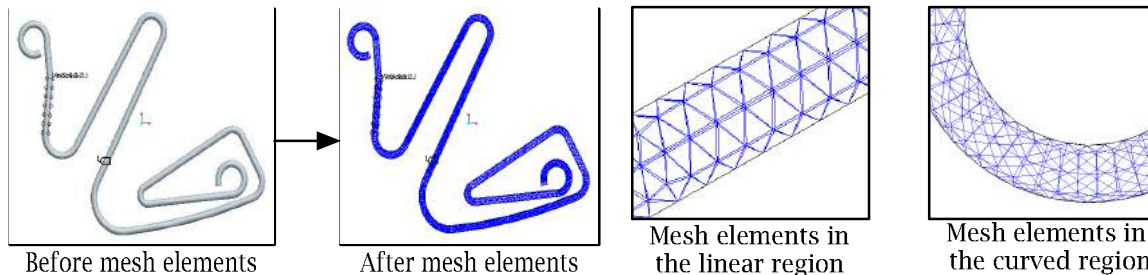


Fig. 5: Generation of mesh elements

Fig. 6: Mesh elements in linear and curved regions.

3 COMPUTER-AIDED ENGINEERING ANALYSIS OF SLIDE-HINGE SPRING

This research uses MARC, a well-known CAE software, to perform engineering analysis of a slide-hinge spring. The moving case moves from one end to the other and the moving distance is 30mm, as shown in Fig. 7. The settings of pre-processing include:

- (1) *Geometric information:* As afore-mentioned, the spring itself is in a mesh format, while the moving end, fixed end and the contact surface are depicted as IGES surfaces, shown in Fig. 8.

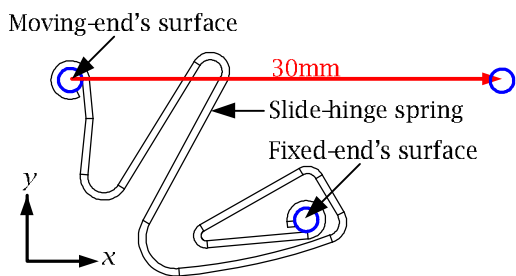


Fig. 7: Moving distance of the moving-end.

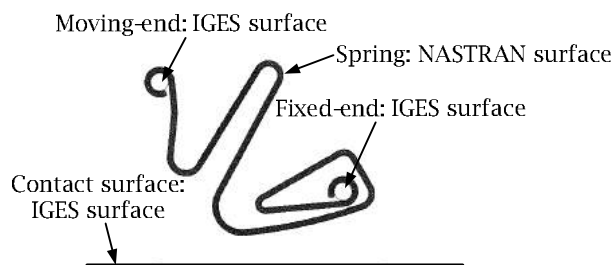


Fig. 8: Various file types for meshes.

- (2) *Material properties:* The material of the spring is assumed as homogeneous and isotropic, and it is in agreement with von-Mises yield criterion. The material used in this case is annealed SUS304 with the following mechanical properties: Poisson's ratio = 0.29, Young's Modulus = 100,000 MPa, and Yield stress = 2,200 MPa. The range of stress-strain is set as elastic-plastic.
- (3) *Contact conditions:* Initially, the spring is assumed as a deformable body; from 0 to 0.5 second, the bottom contact surface moves 3mm along the y direction with a constant speed; from 0.5 to 1.5 second, the moving end travels 30mm towards the x direction with a steady speed, as illustrated in Table 1. Then, the contact conditions between the spring and moving end surface, fixed end surface, and bottom contact surface are set as touching.

Name	Contact Type	Body Control	Parameters
Spring	Deformable		
Moveable side	Rigid	Position	$x=30, y=z=0$

Fixed side	Rigid	Position	$x=y=z=0$
Bottom side	Rigid	Position	$y=3, x=z=0$

Tab. 1: Setting of contact conditions.

- (4) *Boundary conditions*: Since there is no movement along the z direction, the displacement at z axis is locked at 0.
- (5) *Loading*: The type of loading is assumed as static load with 1.5 second loading period at 0.01 second increments.
- (6) *Solution control*: The Full Newton–Raphson method is used as the iterative procedure, where relative residuals convergence is applied.
- (7) *Analysis*: A nonlinear procedure is employed to conduct a static analysis. The deformation of each mesh element is not significant during the spring movement, thus the strain is set as small strain. In contrast, there is a significant rotation of the spring during its movement, thus, a large rotation is selected.

Fig. 9 plots the acting force in the x direction against time. As the figure shows, the acting force changes its direction at 1.04 second. In other words, after being pushed 16.2mm from left to right, the moving component continues sliding forward automatically, until it reaches the fixed point at 30mm. Before the acting force changes its direction, the maximum force is 1.2N (122gf), which means it requires 1.2N to push the spring to a desired position.

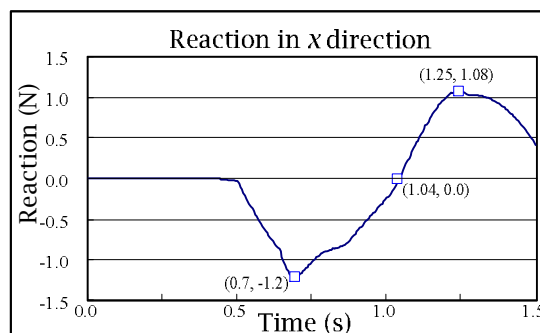
Fig. 9: Reaction force in the x direction.

Fig. 10 shows the spring deformation when the acting force reaches its maximum value. From this figure, it can be seen that three large deformation regions A , B and C all have stress concentration, as well as self-contact of the spring geometry. Fig. 11 illustrates the geometry of the deformed spring at the turning point of the acting force. The figure indicates that the relative distance between the moving case and fixed case is minimal, which indicates that the spring compression is maximal at that moment. The stress is 1,647 MPa, quite close to the maximum stress of the entire body, 1,651 MPa.

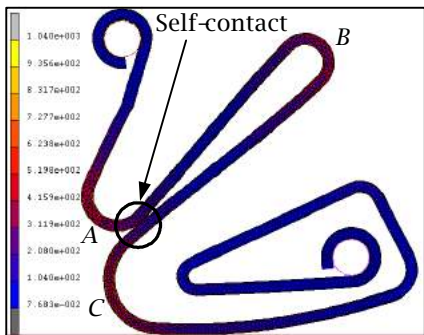


Fig. 10: Spring deformation at maximum reaction.

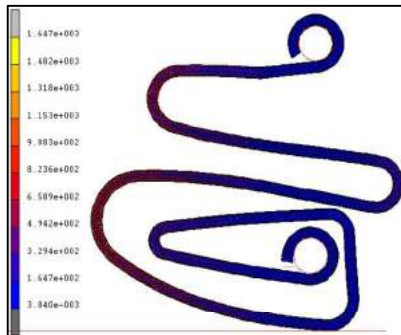


Fig. 11: Spring deformation at force turning point.

In summary, during the spring movement, region A, B and C generates significant stresses and stress concentration occurs. As Fig. 12 shows, the maximum stress is 1,651 MPa, which occurs at the inside curve of region C. Fig. 13 and 14 also suggest that the inside stress is larger than the outside one.

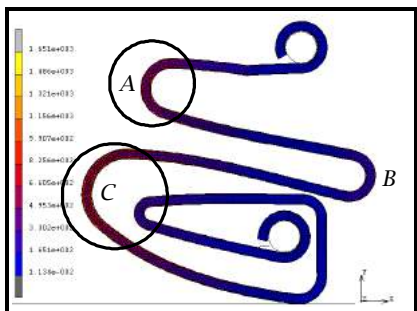


Fig. 12: Places of maximum stress.

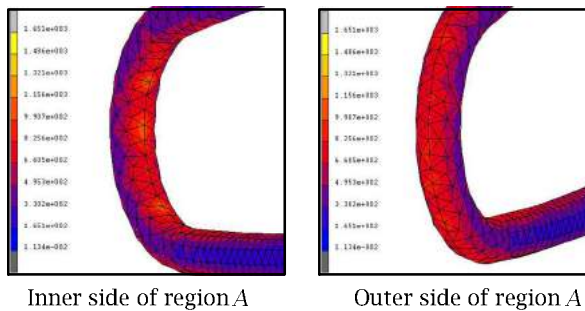


Fig. 13: Stress distribution of region A.

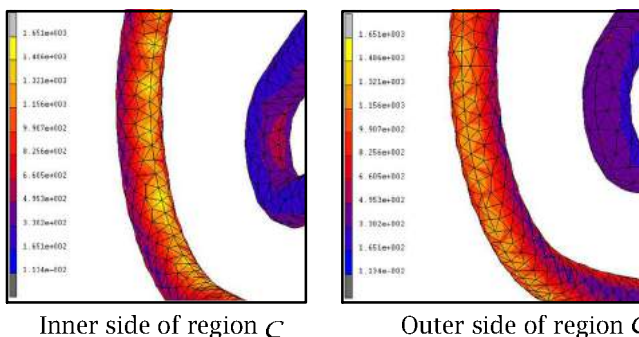


Fig. 14: Stress distribution of region C.

4 PHYSICAL MEASUREMENT OF SLIDE-HINGE SPRING

Aside from computer-aided engineering analysis, this research also makes physical samples of the springs and the entire sliding mechanism. Then the equipment, as displayed in Fig. 15, is utilized to measure the acting force to verify the results from the computer-aided analysis. In using the measuring equipment, a fixture is used to fasten the slide body above an x-y table. The electronic motor at the bottom of the equipment drives the table motion, which results in the movement of the sliders. Simultaneously, the load cell at the right side of the fixture records the acting forces of the spring. The spring forces gained by the load cell are plotted as shown in Fig. 16. Since the measurements are conducted on the whole slide body, the data is the composite force of two springs. As the positions of those springs are symmetrical, half of the measured value, hence, is for one single spring. The comparison between the physically measured results and the computer-aided analysis is summarized in Table 2, which verifies the reliability of the above computer-aided analysis.

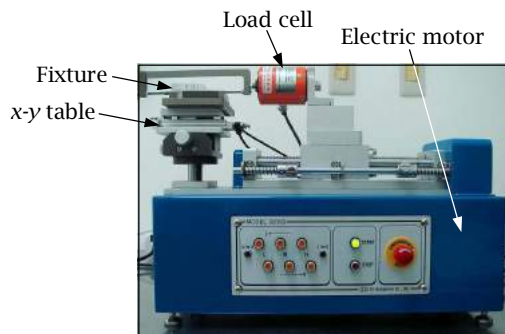


Fig. 15: Slide-hinge measurement machine.

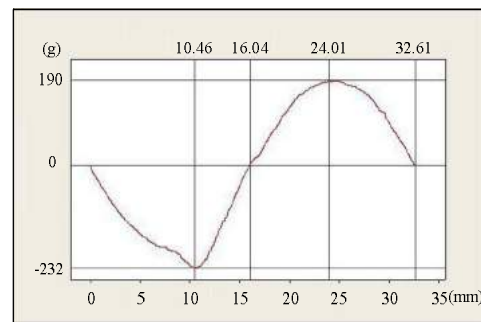


Fig. 16: Measured forces in the x-direction.

	<i>Reaction force</i>	<i>Acting force</i>	<i>Location of force's turning point</i>
CAE results	122gf	110gf	16.2mm
Measurement's results	116gf	95gf	16.04mm
Error	5.17%	15.78%	1%

Tab. 2: Comparison of CAE results and practical measurement's results.

5 OPTIMAL DESIGN OF SLIDE-HINGE SPRING

After confirming the reliability of computer-aided engineering analysis, this research applied the Taguchi method to seek better design parameters for the spring in order to minimize the stress generated during the springs' elastic deformation.

To apply the Taguchi method, firstly, the spring geometries such as length, angle, radius, etc, are set as control factors. The levels of each factor are also defined. Then, an orthogonal array is built, and MARC is utilised to find the maximum stress and stress distribution for each group of data in the orthogonal array. Ultimately, through a variation analysis, the optimal combination of spring parameters can be obtained. Details of each step are explained below.

5.1 Control Factors and Its Levels

The 8 design parameters of the slide-hinge spring are shown in Fig. 17, the parameters of which are defined as control factors. Table 3 lists the levels of each control factor. Since the decrease of angle A1 would result in self-intersection of other portion of the spring, thus, only 2 levels are used for this factor, while the rest consists 3 levels. Therefore, an $L_{18}(2^1 \times 3^7)$ orthogonal array is selected for Taguchi analysis, as shown in Table 4.

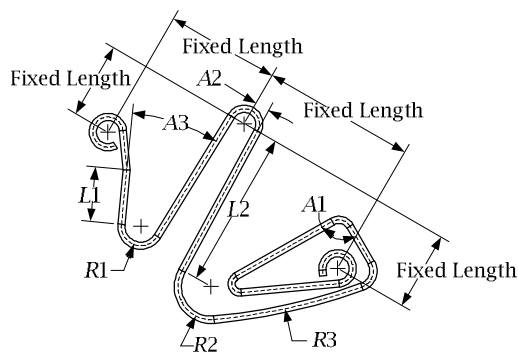


Fig. 17: Geometry of control factors.

	A1	A2	A3	R1	R2	R3	L1	L2
	A	B	C	D	E	F	G	H
1	90	1.0	22	1.2	2.1	30	2.6	10
2	100	1.5	26	1.35	2.3	40	3.8	11
3		2.0	30	1.5	2.5	50	5.0	12

A: angle, R: radius, L: length

Tab. 3: Levels of control factors.

Exp.	A	B	C	D	E	F	G	H
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2

12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

Tab. 4: $L_{18}(2^1 \times 3^7)$ orthogonal array.

5.2 Orthogonal Array

Once the control factors and their levels are determined, and the appropriate orthogonal array is found, the characteristic index “the-smaller-the-better” is selected to conduct the Taguchi-method-based analysis, in order to reduce the maximum stress of the spring. Since each combination of the parameters in the orthogonal array is analysed using MARC, the S/N ratio η , which is used to judge the characteristics index, can be calculated by the following equation:

$$\eta = -10 \log_{10}(\sigma^2) \quad (1)$$

where η is the maximum stress of the slide-hinge spring. Table 5 lists the results of the 18 parameter combinations in the orthogonal array.

<i>Experiment</i>	<i>Max stress σ (MPa)</i>	<i>S/N ratio η (dB)</i>
1	1605	-64.1095
2	1582	-63.9841
3	1468	-63.3345
4	1281	-62.1510
5	1800	-65.1055
6	1742	-64.8210
7	1429	-63.1006
8	1427	-63.0885
9	1697	-64.5936
10	1563	-63.8792
11	1566	-63.8958
12	1395	-62.8915
13	1330	-62.4770
14	1387	-62.8415
15	1487	-63.4462
16	1427	-63.0885
17	1380	-62.7976
18	1738	-64.8010

Tab. 5: Results of S/N ratios of 18 experiments in the orthogonal array.

5.3 Optimal Combination of Design Parameters

From the results of maximum stress σ and S/N ratio η , a response table can be obtained. Take control factor A at level 1, i.e. A1 = 90°, as an example, the response of levels is calculated as follow:

$$\eta_{A1} = \frac{1}{9}(\eta_1 + \eta_2 + \eta_3 + \eta_4 + \eta_5 + \eta_6 + \eta_7 + \eta_8 + \eta_9)$$

$$= \frac{1}{9}(-64.11 - 63.98 - 63.33 - 62.15 - 65.11 - 64.82 - 63.10 - 63.09) = -63.81 \text{ dB}$$

Applying the same procedure to other factors, the responses of S/N ratio of each factor and all the levels are summarized in Table 6. An S/N ratio curve is then plotted as shown in Fig. 18. A higher S/N ratio is preferred, according to the principles of the Taguchi method. Thus, from the S/N ratio curve, the optimal combination of spring's design parameters can be found as A2 B2 C1 D1 E2 F1 G3 H3.

	A	B	C	D	E	F	G	H
Level 1	-63.81	-63.68	-63.13	-63.50	-63.93	-63.36	-63.77	-64.07
Level 2	-63.35	-63.47	-63.62	-63.73	-63.11	-63.71	-63.67	-63.81
Level 3		-63.58	-63.98	-63.51	-63.70	-63.66	-63.29	-62.85
Average	-63.58	-63.58	-63.58	-63.58	-63.58	-63.58	-63.58	-63.58
Effect	0.46	0.21	0.85	0.23	0.82	0.34	0.48	1.22
Rank	5	8	2	7	3	6	4	1

Tab. 6: Response table of various levels of the 8 control factors.

Fig. 19 shows the geometric shape of the optimized spring. In addition, Fig. 18 also indicates that control factor C, E and H have more significant impacts on the results than the other factors.

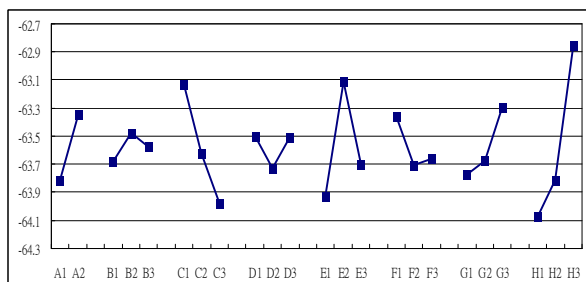


Fig. 18: Response graph of S/N ratios.

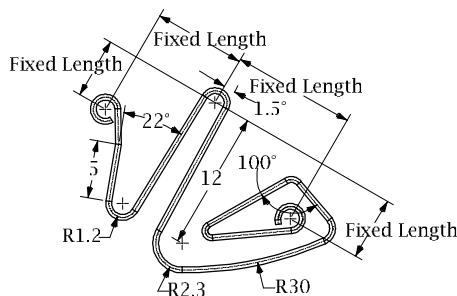


Fig. 19: Dimensions of the optimized spring.

5.4 Variation Analysis

Based on the S/N ratio in Table 5, the variation table can be obtained in Table 7, which shows the confidence levels, C , of control factor B, D, F and G are all below 50%, which also agrees with the S/N ratio curve in Fig. 20. Those four factors have insignificant influence on reducing the maximum stress. Thus, the variation caused by those four factors is considered as single source of error by the process of pooling of errors. Then, the rest of the factors, A, C, E and H are processed for variation analysis again. The results suggest that the confidence levels of these four factors are raised up to 90%, as shown in Table 8. Therefore, the latter four factors are defined as significant factors.

Factor	SS	DOF	MS	F	P(%)	C(%)
A	0.97	1	0.97	2.01	29.2	70.8
B	0.13	2	0.07	0.14	88.0	12.0
C	2.17	2	1.08	2.25	30.7	69.3
D	0.20	2	0.10	0.21	82.9	17.1
E	2.15	2	1.07	2.23	30.9	69.1
F	0.42	2	0.21	0.44	69.7	30.3
G	0.77	2	0.39	0.80	55.5	44.5
H	4.94	2	2.47	5.14	16.3	83.7
Error	0.96	2	0.48			
Total	12.70		17			

Tab. 7: Table of variation analysis.

Factor	SS	DOF	MS	F	P(%)	C(%)
A	0.97	1	0.97	3.90	7.7	92.3
B	Pooled					
C	2.17	2	1.08	4.37	4.3	95.7
D	Pooled					
E	2.15	2	1.07	4.33	4.4	95.6
F	Pooled					
G	Pooled					
H	4.94	2	2.47	9.96	0.4	99.6
Error	2.48	10	0.25			
Total	12.70		17			

Tab. 8: Table of variation analysis after the pooling of errors.

5.5 Prediction of Optimal Characteristic of Slide-hinge Spring

From the above discussion, the optimal combination of spring's design parameters is $A_2 B_2 C_1 D_1 E_2 F_1 G_3 H_3$. Hence the S/N ratio of maximum stress is calculated below:

$$\bar{\eta} = \frac{\sum_{i=1}^n \eta_{EX_i}}{n} = (\eta_{EX_1} + \eta_{EX_2} + \dots + \eta_{EX_17} + \eta_{EX_18})/18 = -63.58 \text{ dB}$$

$$\eta_{opt} = \bar{\eta} + \sum (\eta_{factor} - \bar{\eta}) = \bar{\eta} + (\eta_{A_2} - \bar{\eta}) + (\eta_{C_1} - \bar{\eta}) + (\eta_{E_2} - \bar{\eta}) + (\eta_{H_3} - \bar{\eta}) = -61.02 \text{ dB}$$

where η_{EX_i} is the S/N ratio of i^{th} combination of control factors and n is the number of total experiments. Since factor B , D , F and G are pooled into errors, the prediction of minimization of spring stress only includes the other four factors A , C , E , and H in the above equations. Moreover, the calculated optimal characteristic index η_{Eopt} is -61.02 dB , and the maximum stress can be computed by equation 1, as 1,125 MPa.

5.6 Discussion

The optimized results, summarized in Table 9, indicate that the four major control factors are $A1$, $A3$, $R2$ and $L2$, and the degree of their influence follow the sequence as $L2 > A3 > R2 > A1$, where $L2$ has the most significant impact on the results.

	$A1$	$A2$	$A3$	$R1$	$R2$	$R3$	$L1$	$L2$
Original shape	90	1.5	26	1.35	2.3	40	3.8	11
Optimized shape	100	1.5	22	1.2	2.3	30	5.0	12
Dimension change	↑	—	↓	↓	—	↓	↑	↑
Contribution(%)	05.65	—	13.16	—	12.99	—	—	35.00

Tab. 9: Results of optimal combination of the 8 control factors.

According to the analysis of the original spring, when the moving end is pushed to the 16.2 mm position, the spring generates a maximum stress at 1,606 MPa. At this point, the stress mainly concentrates in region A and C, and the maximum stress appears in region C, as shown in Fig. 20.

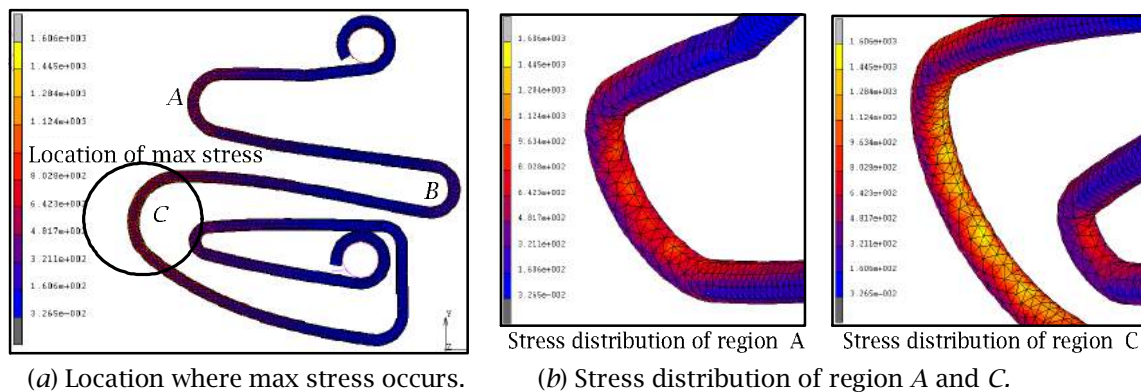


Fig. 20: Stress distribution of the original spring design.

The analysis of the optimal spring shows that when the moving end travels to the same 16.2 mm position, although the stress concentration and maximal stress occur in the same region, the maximum stress decreases significantly to 1,161 MPa, as shown in Fig. 21.

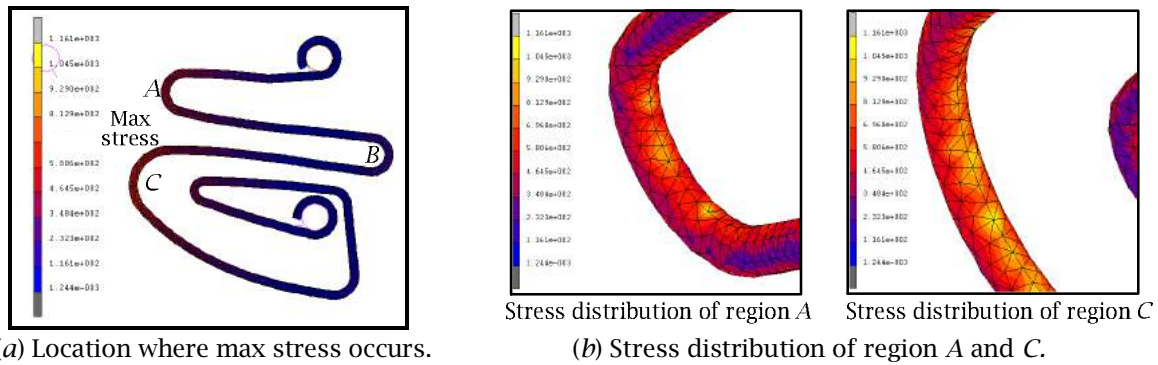


Fig. 21: Stress distribution of the original spring design.

6 CONCLUSIONS

This paper discusses in detail the computer-aided mechanic analysis and optimal parameter design of a slide-hinge spring, which is the key component of the popular cell phone. The computer-aided engineering analysis initiated by generating the polyhedral mesh elements for the spring, followed by setting the pre-process for CAE. Finally, the analysis of the stress and acting force during the spring deformation resulted in a predicted acting force of 122 gf. Experimentally, this research also physically measured the same acting force as 116 gf. Thus, the computer-aided analysis can provide a 95% accuracy of force estimation. Moreover, the simulated force curve perfectly agreed with experimental measurements.

Furthermore, this paper applied the Taguchi method to optimize the design parameters of slide-hinge springs to reduce the stress generated by elastic deformation. After the optimization, the maximum stress decreased by approximately 27%, from 1,606 to 1,161 MPa. In this context, the confidence interval is also utilized to verify the accuracy of the analysis. When the experimental data is within the 90% confidence interval, the accuracy of the maximum stress prediction of the optimized spring can reach 97%. Therefore, the Taguchi method is a sufficient approach to achieve optimal design of slide-hinge springs.

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