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ANALYSIS OF SENSITIVITY OF A COMPLIANT MICRO-GRIPPER

PHÂN TÍCH ĐỘ NHẠY CỦA TAY GẮP MỀM

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ABSTRACT

This paper aims to analyze effects of design parameters on the sensitivity of compliant micro-gripper. The micro-gripper is constructed based on a four-bar mechanism and a concept of compliant mechanism with circular hinges. The three basic parameters to be considered such as the width of the circular hinge, the thickness of gripper and the material properties. The analysis process is done through ANSYS software and Matlab software. Firstly, the displacement is analyzed to determine the maximum displacement of jaws. Subsequently, the natural frequency characteristics of the gripper are considered. Finally, through the natural frequency characteristics, the effects of each parameter on the sensitivity are analyzed. The results showed that the design parameters of gripper and the sensitivity have a close relationship with each other. Therefore, they should be considered in the design process of the compliant micro-gripper.

Keywords: *Circularhinge; Compliant mechanism; Sensitivity; Four bar mechanism, FEA.*

TÓM TẮT

Bài báo hướng đến phân tích ảnh hưởng của các tham số thiết kế đến độ nhạy của tay gắp mềm. Tay gắp mềm được thiết kế dựa trên cơ sở cơ cấu bốn thanh, nguyên lý cơ cấu mềm và nguyên lý khớp quay dạng bán nguyệt (Circular hinge). Ba tham số cơ bản được xem xét trong nghiên cứu này gồm chiều rộng của Circular hinge, chiều dày của Micro-gripper và thuộc tính của vật liệu. Quá trình phân tích được thực hiện thông qua phần mềm phân tích phần tữ hữu hạn (FEA) Ansys và phần mềm Matlab. Đầu tiên, bài báo tiến hành phân tích chuyển vị của mô hình nhằm xác định giới hạn chuyển vị lớn nhất. Kế tiếp, bài báo khảo sát tần số dao động tự do của mô hình. Sau cùng, thông qua giá trị tần số dao động tự do, sự ảnh hưởng của mỗi tham số thiết kế đến độ nhạy của tay gắp được phân tích. Kết quả phân tích thu được cho thấy rằng, mỗi tham số thiết kế như: chiều rộng của Circular hinge, chiều dày của tay gắp và thuộc tính của vật liệu đều có ảnh hưởng nhất định đến độ nhạy của tay gắp. Do đó những yếu tố này cần được xem xét trong quá trình tính toán thiết kế của một hệ tay gắp chính xác.

Từ khóa: *Khớp mềm bán nguyệt; Cơ cấu mềm; Cơ cấu bốn thanh; Độ nhạy; Phần tử hữu hạn.*

1. INTRODUCTION

With the advantages such as small size, monolithic, low cost, and high precision, compliant micro-gripper is now widely used in the industry. Especially, the industry of biomedical engineering, micro assembling engineering, manipulation of micro-objects [1]–[4].

In recent years, the compliant mechanisms have received considerable attention from researchers such as Huang and Dao [5], Hao [6], Petkovic [7]. Other researchers designed the different structures for compliant micro-grippers. For example, Mianowski et al.[8] developed a new gripper with elastic fingers. Yang et al.[9] proposed the micro-gripper with double-rocker mechanism and the parallelogram mechanism. Ai et al.[10] designed a compliant gripper using an optimal Scott-Russell mechanism. Liu and Xu [11] devised the design of a compliant constant force output gripper mechanism based on the buckled fixed-guided beam.

When designingmicro-gripper, to ensure effective design, the stress, displacement, vibration, buckling, failure and Optimizing design parameters are often considered simultaneously [10], [12-15]. However, the sensitivity analysis of the compliant micro-gripper has been less interested. For this reason, this paper aims to focus on the sensitivity analysis for the micro-gripper.

The purposes of this study are to design and analyze the sensitivity of a compliant micro-gripper. The gripper is constructed based on the four bar mechanism and the concept of compliant mechanism with the circular hinge. Based on the model has been designed, the analysis process is performed on the three parameters as the width of the circular hinge, the thickness of gripper and the material properties. First, the displacement is analyzed to determine the maximum displacement of jaws. Subsequently, the natural frequency characteristics of the gripper are considered. Finally, through the natural frequency characteristics, the effect of each parameter on the sensitivity is analyzed. The analysis process is conducted through the FEA and Malab software.

2. STRUCTURE DESIGN OF THE MICRO-GRIPPER

In this study, the micro-gripper was developed base on the four-bar mechanism, as shown in Figure 1.

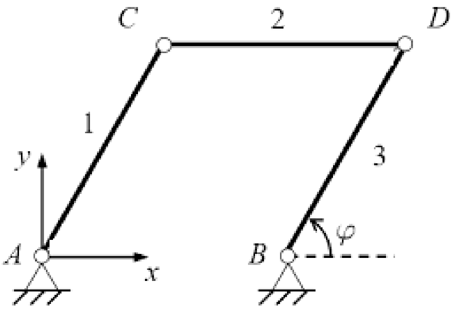


Figure 1. *Four bar mechanisms*

To ensure firmness of the structure, at the position of bar 3 and bar 4 were reinforced by a similar bar, as depicted in Figure 2.

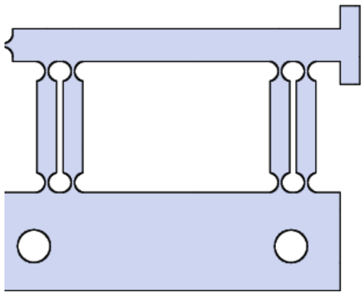


Figure 2. *Four bar mechanims*

Also, the flexure hinges be able to select based on their performance during operation according to the following factors: Precision of rotation, stress levels under fatigue conditions, sensitivity to parasitic loading and capacity of rotation. In this paper, the gripper was designed to the application in two dimensions. With this type of gripper, the circular hinge and rectangular hinge were selected because of their advantages in the limited rotation application. However, the rotation center of the circular hinge was almost unchanged throughout the operation, therefore the operating errors was minimized [5]. Therefore, in this study the circular hinge was chosen for constructed a micro-gripper. According to previous research [16], the spring rate of the circular hinge was given by the equation as follows:

$$k_\theta = \frac{2Ebt^{2.5}}{9\pi R^{0.5}} \qquad (1)$$

where k_θ is the angular stiffness of the circular hinge, b is the width of the circular hinge, h is the height of circular flexure hinge and E is Young's modulus of the material.

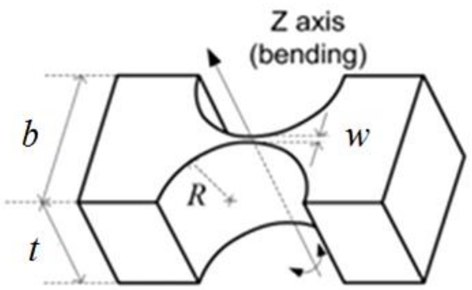


Figure 3. *Circular hinge model*

The operating principle of compliant micro gripper is based on the elastic deformability of the material. There are many types of materials suitable for complaint micro-grippersuch as aluminum alloy, titanium alloy, structure steel, etc. However, to have the micro-gripper with small size, light weight, polyethylene was chosen as a material, which has following properties: Yield strength of 25.10^{-3}GPa, Density $\rho$of 950 kg/m³ and Young's modulus of 1.1GPa.

The compliant micro-gripper was suggested, as in Figure 4. It consisted of elements as follows: (i) Seven fixed holes were utilized to locate the gripper on an un-vibration table so as test it characteristics, (ii) a piezoelectric actuator (PZT) (red color) was used to exert the force to the gripper though a linear mechanism connected with a four bar mechanism, (iii) micro-sized objects would be grasped by a fixed jaw and movable jaw. Thetotal dimension of the model wasabout 75mm×113mm×5mm. The parameters of the micro-gripper were given in Table 1. The proposed gripper was designed to handle micro-sized objects of 500µm.

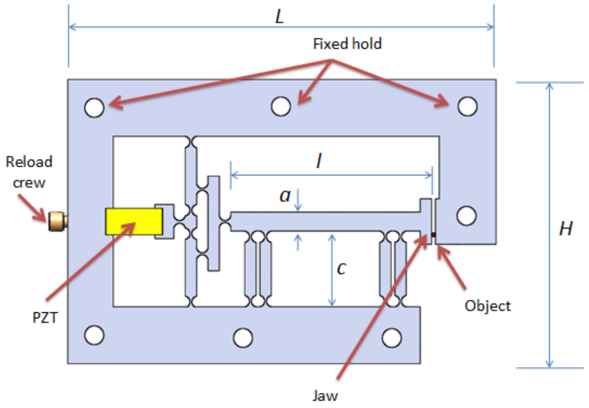


Figure 4. *Schematic of micro-gripper and PZT*

3. FINITE ELEMENT ANALYSIS (FEA)

The finite element method (FEM) - based computation analysis has been widely employed for design testing. In this section, The model of micro-gripper was designed in Solidworks 2015 and later imported into the finite element analysis software ANSYS 16. ANSYS software was used to predict the output displacement, stress distribution, frequency characteristics and sensitivity behaviors of the gripper. The model used for this analysis was similar to Section 2. To perform this analysis, the automatically meshing method was applied in coarsearea, and then each circular hinge was refined to achieve analysis accuracy, as given in Figure 5. Also, the boundary conditions were proposed as follows: the gripper was fixed at the holes and for output displacement analysis the force's PZT was changed from

1N to 7N. For frequency analysis and sensitivity analysis, the force of 2N would be applied to the PZT.

Table 1: *Initial size of the compliant micro-gripper*

Symbol	**Description**	**Value (mm)**
L	Length of model	7.5
H	Height of model	2.2
w	Width of circular hinge	0.5
l	Length of bar	28.5
t	Thickness of model	5
R	Radius of circular hinge	1.53
a	Width of bar	5
b	Width of bar	3
c	Height of four bar mechanism	20
Total: 75 mm x 113mm x 5 mm		

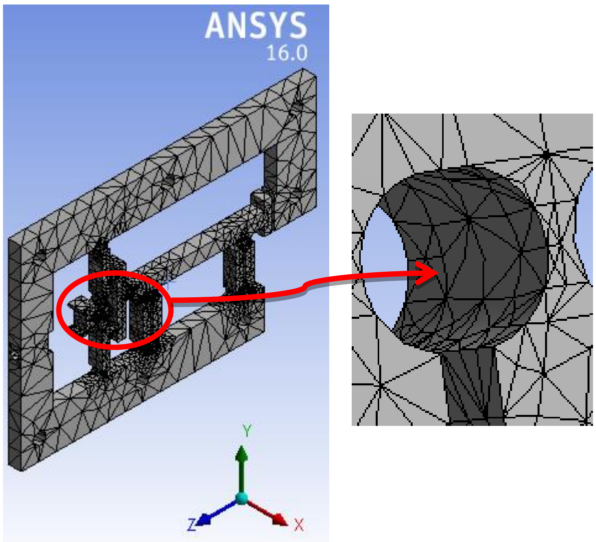


Figure 5. *Mesh generation diagram*

3.1 Displacement of compliant micro-gripper

After the micro-gripper was designed, the output displacement of the model was investigated by increasing the force of PZT from 1N to 7 N, respectively. The achieved results are given by Table 2.

Table 2: *The output displacement*

Fore (N)	**Displacement** d_z (µm)	**Stress** $\times 10^{-3}$ (GPa)
1	90.82	3.79
2	181.64	7.59
3	272.46	11.38
4	363.29	15.18
5	454.11	18.97
6	**544.93**	**22.70**
7	635.75	26.56

According to the results in Table 2, the results indicate that when the force of PZT is 7N then the displacement reaches the position of 635.75 µm. Also, as the resulting stress is 26.56 $\times 10^{-3}$GPa which is greater than the critical stress of the material (25×10^{-3}GPa), the gripper could be a failure. Therefore, the maximum output displacement has been determined as 544.93µm at the force of PZT was 6N and the value of stress was 22.70×10^{-3}GPa .

3.2 Analysis of the frequency characteristics

The natural frequency characteristics are important for dynamic properties. And they affect to the sensitivity of design. Through the frequency analysis result, we can predict the state of the model during operation. In this analysis, we have used a model with design parameters as Table 1. The analysis results are shown in Table 3 and Figure 6 shows the modal shapes at the first six modes.

3.3 Analysis of Sensitivity

The aim of sensitivity analysis is to investigate the effect of the design parameters on the natural frequency of micro-gripper. Based on the results of sensitivity analysis, it could make reasonable adjustments to the design parameters so as to fulfill the goal of designing.

***Table 3:** The Natural Frequency Investigation*

Mode	**Frequency** *f*(Hz)
1	359.13
2	472.51
3	680.57
4	809.23
5	996.7
6	1652.8

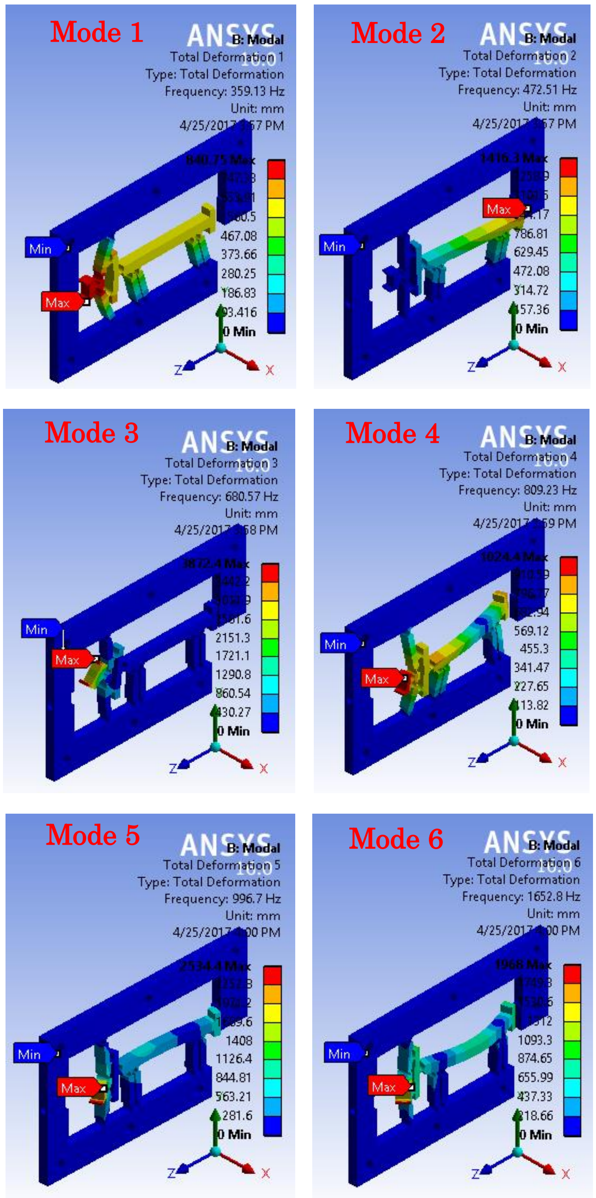


***Figure 6.** Mode shapes of the compliant gripper*

Many methods can be applied for calculating the sensitivity, such as Nelson method, Modal method, matrix perturbation method, differential method [17], Response surface methodology (RSM) [18]. Based on the idea of previous research [17], the direct differential method is used for analyzing the sensitivity of the micro-gripper. And the sensitivity of vibration mode S_x can be written as [17]:

$$S_f = \frac{\partial f_i}{\partial x} \qquad (2)$$

where, f_i , x are the natural frequency and the design parameter, respectively.

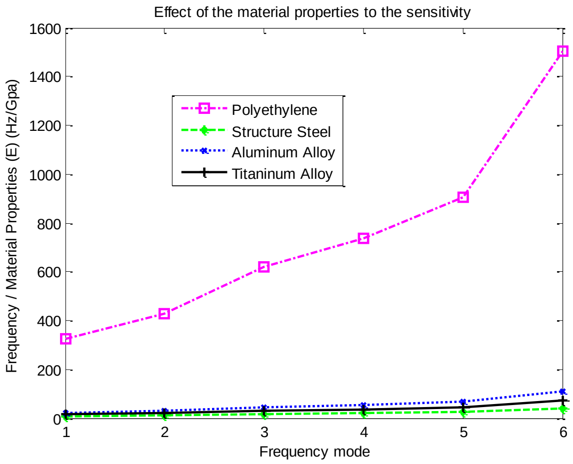
3.3.1 Effect of the material properties on the sensitivity

In this analysis, all of the design parameters of the micro-gripper were selected as Table 1, while material properties such as the density (ρ) and the elastic modulus (E) were chosen as design variables. In more detail, the materials were chosen to compare such as Polyethylene (ρ= 950 kg/m³, E=1.1GPa), Structural steel (ρ=7850 kg/m³, 200GPa), Aluminum alloy (ρ=2770 kg/m³, 71GPa) and Titanium alloy (ρ=4620 kg/m³, 96GPa). Through ANSYS software, the natural frequency of gripper was analyzed, and on that basis, the relationship between the sensitivity and design variable was analyzed by Eq.(2). Table 4 shows the sensitivity values of the first 6 modes.

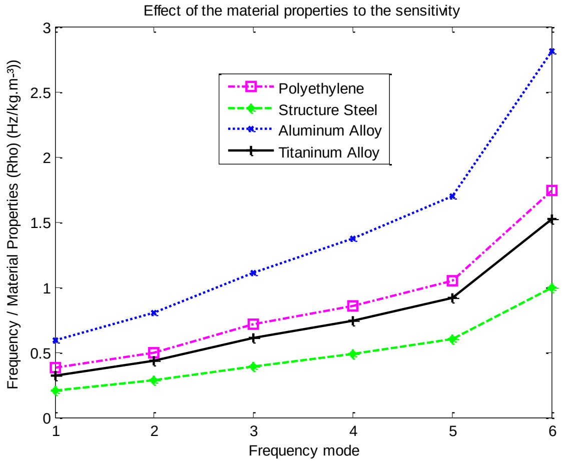
As described in Figure 7, the effect of density (ρ) and elastic modulus (E) to the sensitivity were not the same. It could be seen that, to increase the sensitivity of the gripper, the higher the elastic modulus (E) was selected. In addition, the results showed that the relationship between the sensitivity and density (ρ) did not follow any rules.

3.3.2 Effect of the width on the sensitivity

In this analysis, all of the design parameters of the gripper are selected as Table 1. However, the width of the circular hinge was changed as: 0.4 mm, 0.5mm, 0.6mm, respectively. The Polyethylene was adopted, which has following properties: Yield strength of 25×10^{-3}GPa, density of ρ = 950 kg/m³ and Young's modulus of 1.1Gpa. The analysis results were shown in Table 5.



(a) Effect of elastic modulus (E) on the sensitivity



(b) Effect of density (ρ) on the sensitivity

Figure 7. *Effect of the material properties on the sensitivity*

Through the analysis results, it was found that the sensitivity of the gripper increased when the width of circular hinge decreased and vice versa. In details, for the first order mode when w=0.4 mm, the S_w was 785.35 Hz/mm, when w=0.5 mm, the S_w was 718.26 Hz/mm and when w=0.6 mm, the S_w was 662.95 Hz/mm. It was similar for other modes. Figure 8 illustrates the relationship between the sensitivity of the gripper and the width of circular hinge. Therefore, when designing a gripper, the increase of the width of the circular hinge should be considered.

3.3.3 Effect of the thickness on the sensitivity

In this analysis, all of the design parameters of micro-gripper and material were selected as Section 3.3.1. However, the thickness of the micro-gripper was changed as: 4mm, 5mm, 6mm, respectively. The analysis results were shown in Table 6.

As shown in Table 6 and Figure 9, when t = 4 mm, the sensitivity (S_t=89.17 Hz/mm) was greater than when t = 5mm (S_t=71.83 Hz/mm) or t = 6mm (S_t=59.76 Hz/mm). It means that, when the thickness of the micro-gripper was small, the sensitivity was better and vice versa. In other words, the thickness of gripper had effect on the sensitivity. Therefore, when designing a micro gripper, the decrease of the thickness of the micro-gripper should be considered.

4. CONCLUSION

This paper has presented a prediction of the effect of the design parameters on the sensitivity of the compliant micro-gripper. The compliant micro-gripper was designed based on four bar mechanism and circular hinge. The analysis process was done through ANSYS software and Matlab software with the results obtained as follows: The thickness of the micro-gripper had affected to the sensitivity value. The width of circular hinge was also related to sensitivity. The material properties were related to sensitivity. So it should be considered when designing. In the future work, a prototype should be fabricated to test its behaviors to verify the FEA results.

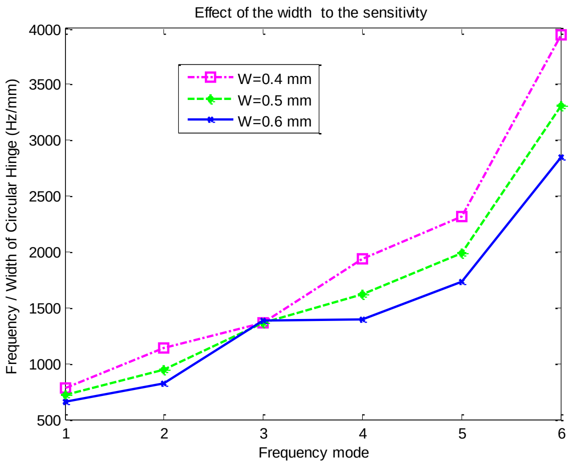


Figure 8. *Effect of the width to the sensitivity*

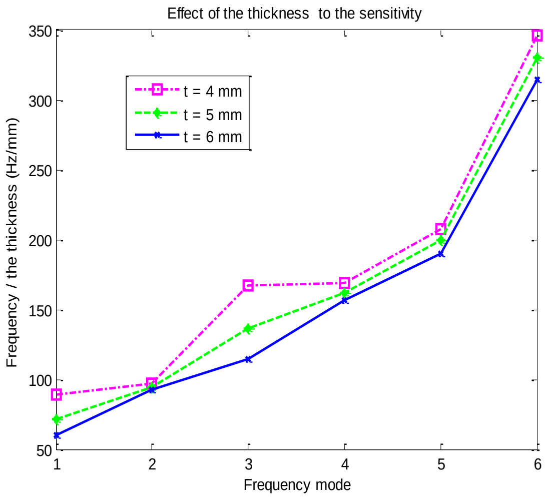


Figure 9. *Effect of the thickness on the sensitivity*

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Table 4: *Effect Of The Material Properties To The Sensitivity*

Mode	**Material**											
	Polyethylene			**Structural steel**			**Aluminum alloy**			**Titanium alloy**		
	Freq. f(Hz)	$S_E=f/E$ (Hz/GPa)	$S_\rho=f/\rho$ (Hz/kg.m^{-3})	Freq. f(Hz)	$S_E=f/E$ (Hz/GPa)	$S_\rho=f/\rho$ (Hz/kg.m^{-3})	Freq. f(Hz)	$S_E=f/E$ (Hz/GPa)	$S_\rho=f/\rho$ (Hz/kg.m^{-3})	Freq. f(Hz)	$S_E=f/E$ (Hz/GPa)	$S_\rho=f/\rho$ (Hz/kg.m^{-3})
1	359.13	326.48	0.378	1629.7	8.15	0.208	1644.6	23.16	0.594	1491.6	15.54	0.323
2	472.51	429.55	0.497	2209.8	11.05	0.282	2216.8	31.22	0.800	1996.8	20.80	0.432
3	680.57	618.70	0.716	3047.3	15.24	0.388	3083.7	43.43	1.113	2805.4	29.22	0.607
4	809.23	735.66	0.852	3808.4	19.04	0.485	3814.1	53.72	1.377	3430.2	35.73	0.742
5	996.7	906.09	1.049	4693.4	23.47	0.598	4700	66.20	1.697	4226.2	44.02	0.915
6	1652.8	1502.55	1.740	7786.3	38.93	0.992	7797.5	109.82	2.815	7011.5	73.04	1.518

Table 5: *Effect Of The Width On The Sensitivity*

Mode	w (mm)					
	0.4		0.5		0.6	
	Frequency (Hz)	$S_w=f/w$ (Hz/mm)	Frequency (Hz)	$S_w=f/w$ (Hz/mm)	Frequency (Hz)	$S_w=f/w$ (Hz/mm)
1	314.14	785.35	359.13	718.26	397.77	662.95
2	455.7	1139.25	472.51	945.02	494	823.33
3	544.14	1360.35	680.57	1361.14	829.07	1381.78
4	774.65	1936.63	809.23	1618.46	837.75	1396.25
5	928.51	2321.28	996.7	1993.40	1038	1730
6	1578.8	3947.00	1652.8	3305.60	1707.7	2846.17

Table 6: *Effect Of The Thickness On The Sensitivity*

Mode	t (mm)					
	4		5		6	
	Frequency f (Hz)	$S_t=f/t$(Hz/mm)	Frequency f (Hz)	$S_t=f/t$ (Hz/mm)	Frequency f (Hz)	$S_t=f/t$ (Hz/mm)
1	356.68	89.17	359.13	71.83	358.56	59.76
2	386.08	96.52	472.51	94.50	555.89	92.65
3	668.37	167.09	680.57	136.11	686.57	114.43
4	676.18	169.05	809.23	161.85	939.16	156.53
5	829.79	207.45	996.7	199.34	1137.9	189.65
6	1382.6	345.65	1652.8	330.56	1886.5	314.42

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