Vol. XII & Issue No. 8 August - 2019
INDUSTRIAL ENGINEERING JOURNAL

BEHAVIOURAL STUDY OF SPIRAL FLEXURE DISC BY DESIGN OF EXPERIMENTS AND CONTOUR PLOTS

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Abstract:

Spiral disc flexural mechanism is basically "XY" plane stress carrying elastic flexural members. These members have the capability to stretch below the elastic limit and regain its shape and original position after the forces are balanced from all sides. In short it may be depicted that this memberare also called as shock absorbers. The intensity of the shock absorbed depends upon the physical parameters of the flexural disc. The parameters under study for deflection are: Diameter of the disc, thickness of the disc, number of spiral arms, spiral swept angle, material of the disc. The main aim and scope of the paper is to study the various contours generated across the various parameters responsible for deflection.

KEYWORDS:Contour Plots, Design of Experiments, Flexural Bearing, Flexural disc.

1.INTRODUCTION

The function of the flexural disc in the flexural bearing is to provide relative motion between two assembly members. The relative motion is obtained by stretching of the arms between two fixed known diameters inscribed in the flexural disc. The shaft which is floating on the flexural arm is made by serrations of constant width which is flows in a curvilinear path between the known inscribed diameters.Application of any force at the centre of the shaft displaces the shaft from the mean position and generates a to and fro motion of the shaft. The basic applications where the flexural discs used are Spacecrafts, Measuring instruments, Linear motor compressors, Stirling Cryocoolers.

The origin of the flexural bearing came into existence as they were used in the Cryocoolers [1], [2], "[3], [4], [5], [6], [7], [8]. These flexural bearings" are none other than linear motor compressors[5],[6],[7],[8]. These flexural bearings are used for supporting the shaft and absorb the dynamic forces acting on the shaft[9],[10],[11],[12],[13].

The parameters which are responsible for deflecting its neutral position are:

- *The diameters of the disc "D."*
- *Thickness of the disc "t."*
- *Number of the arms "n."*
- *Slot width of the spiral "w."*
- *Spiral angle "spa."*
- *Total number of discs used in the flexural stack "sta".*[14],[15],[16],[17],[18],[19],[20]

Refer Figure 1 for the nomenclatures and the construction details of the disc. The analysis of the disc in the research paper is done on the above said parameters. The various dimensions that are related to the flexural disc are as follows: Diameter of the disc: 85mm, Thickness of the disc between 0.5-1mm, Slot width between 0.3- 0.5 mm, Spiral Angle between 270° - 300°, Number of arms 4-8. The force applied for the experiment is 20 N at the central axis of the disc. The results of the deflections are calculated from ANSYS, whereas the MINITAB is used for plotting the "*Contour plots*."

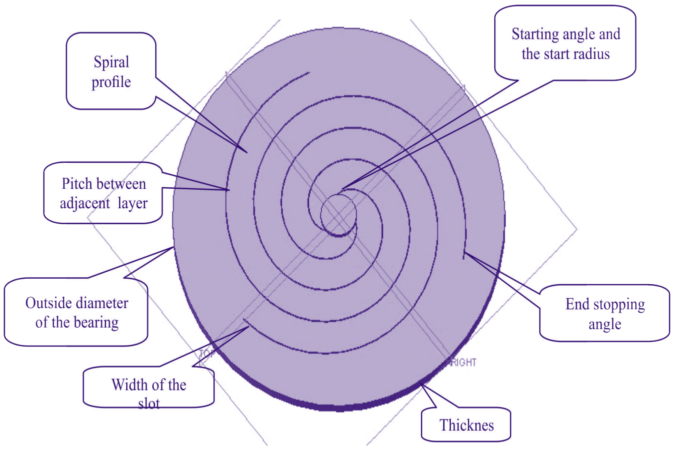

Fig. 1: 3D Model of Flexural Disc.

2. LEVEL AND PARAMETERS USED IN DESIGN OF EXPERIMENTS (DOE):

Table 1. shows the various parameters with its levels used for the study whereas Table 2 shows the standard Orthogonal Array. This coded table is input for the MINITAB for plotting the various results and plots. It can be observed in Table 1 shows that there arefive parameters each having two values (levels). Hence the total number of combinations that will be generated in Design of Experiments will Level Parameters i.e. 2 5 = 32 combinations. If the complete analysis of the experiments is to be done at a glance the various combinations that are possible are shown in Table 2 arecalled as the full factorial design.

The application of DoE in the above research study helps to understand the various possible combination that can be generated in the complete experiment. In order to achieve the best optimized deflection in the minimum possible experiments,the Taguchi method integrated with the DoE gives either the full factorial or the partial experiments in which the optimized deflection can be obtained.

Table 1:Various Parameters with its Levels.

Sr. No	Name of the Parameter	Level 1	Level 2
1	No of spiral arms	3	4
2	Thickness of spiral disc	0.5	1
3	Slot width of the spiral	0.3	0.5
4	Spiral angle	270	300
5	Total number of flexural disc in stack	4	8

Table 2:Full Factorial Design with Standard L32 Orthogonal Array.

Exp. No	Factor "A"	Factor "B"	Factor "C"	Factor "D"	Factor "E"
1	1	1	1	1	1
2	1	1	1	1	2
3	1	1	1	2	1
4	1	1	1	2	2
5	1	1	2	1	1
6	1	1	2	1	2
7	1	1	2	2	1
8	1	1	2	2	2
9	1	2	1	1	1
10	1	2	1	1	2
11	1	2	1	2	1
12	1	2	1	2	2
13	1	2	2	1	1
14	1	2	2	1	2
15	1	2	2	2	1
16	1	2	2	2	2
17	2	1	1	1	1
18	2	1	1	1	2
19	2	1	1	2	1
20	2	1	1	2	2
21	2	1	2	1	1
22	2	1	2	1	2
23	2	1	2	2	1
24	2	1	2	2	2
25	2	2	1	1	1
26	2	2	1	1	2
27	2	2	1	2	1
28	2	2	1	2	2
29	2	2	2	1	1
30	2	2	2	1	2
31	2	2	2	2	1
32	2	2	2	2	2

3. TAGUCHI METHOD:

The experimental results which are drawn through MINITAB uses the Taguchi method for building the results. The "loss function" which is defined by Taguchi is used to obtain the deviation between the experimental and the desired values. The loss function is further converted in Signal to Noise (S/N) η. The experimenter can basically use three options such as:

a) Larger is better

b) Nominal is the best

c) Smaller is better.

The goal of the study is to obtain have lowest deflection of the stack. Hence lower is better is as the quality characteristic for obtaining the result.

Lower is better (Minimize):

$$\eta = \frac{S}{N_S} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right) \quad (1)$$

where y_i is the observed data of i^{th} experiment and n is the number of experiments.

4. ANALYSIS OF MEANS

The interpretation of the Mean graphs plotted in MINITAB is shown in Figure 2. The reading of the deflection generated (response) which is an input to the MINITAB is assessed closely for each factor for level 1 and level 2 respectively. The response table generated in MINITAB is tabulated in Table 3. This table shares the information about the mean of level 1 and level for each factor respectively. For example, the mean of level 1 for a factor *"No of Spiral Arm"* is 0.9312 similarly for its level 2 is

1.3020. Similarly remaining all values means showed in Table 3. The difference between the level 1 and level 2 for all the factor mentioned in Table 3 are tabulated in the "Delta" row. Rank is assigned to all the factors in the decreasing order of the "Delta" values.

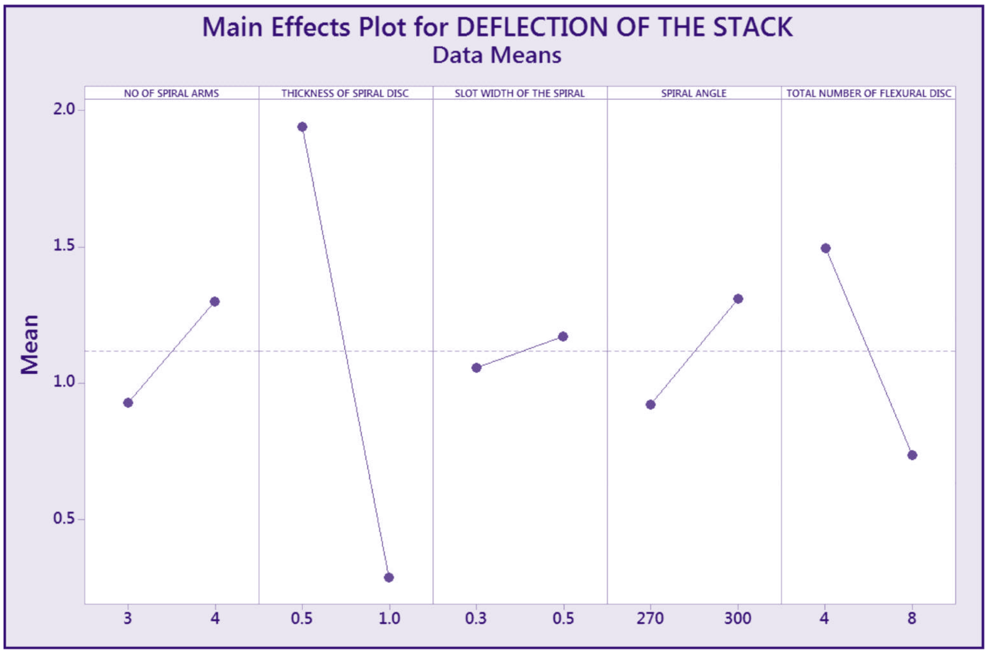

Fig. 2: Main Effects Plot for Deflection of the Stack.

The information obtained from the Rank row shows that factor, Thickness of the spiral disc is assigned with 1 followed by Total number of discs in the stack, Spiral Angle, No of Armsand Slot width of the spiral. Rank 1 indicated factor predicts that the line which is drawn between the level 1 and level 2 points have high slope with respect to the "X" axis. The Grand Mean of all the reading of the response is the average of the 32 experiments. The calculated Grand Mean is 1.117 shown at the centre of the graph.

Table 3:Response Table for Means from MINITAB.

Level. ↓	No of Spiral Arms.	Thickness of The Spiral Disc.	Slot Width of the Spiral.	Spiral Angle.	Total Number of Flexural Disc in Stack.
1	0.9312	1.9432	1.0596	0.9227	1.4951
2	1.3020	0.2901	1.1736	1.3105	0.7382
Delta	0.3708	1.6531	0.1140	0.3878	0.7569
Rank	4	1	5	3	2

5. ANALYSIS OF THE CONTOUR PLOTS IN MINITAB.

Contour plot is a powerful graphical tool which represents the 3D surface by plotting the constant "Z" slices on 2D format (XY plane) called as the "Contour Plots". The various possible contours of the all the five parameters against the response, deflection is explained as below. It helps to investigate about the behaviour of the response on any two parameters at given point of time. Eight color band pointer scale is used to evaluate the response i.e. the deflection scale in the graphs is divided in to 8 zones for analysisthe shape and color of the band indicates the intensity at the respective point. The various plots which are plotted among the group are as below.

5.1 Contour Plot for Deflection Vs Number of Spiral Arms and Thickness of The Spiral Disc.

Figure 3 shows the "Contour Plot for Deflection VS Number of Spiral Arms and Thickness of the Spiral Disc". From the graph it can be depicted that for lower values of both the thickness of the spiral disc i.e. t = 0.5 mm and the number of spiral arms i.e. n = 3, the deflection obtained is indicated by the light blue patch assigned with a value between 1.5 - 2 mm. Whereas for low value of the spiral thickness and high value of number of arms i.e. n = 4, the deflection obtained is indicated by the pale green patch assigned with a value between a value of 2-2.5 mm respectively. There are in all 5-color band indicating high deflection range of the stack. Similarly, for higher value of the thickness of the disc i.e. t = 1 mm and low value of the number of arms. The deflection is indicated by dark blue patch assigned with a value of deflection lower than 0.5 mm. Similarly, for both the higher values of the parameters the deflection is again indicated by blue patch with values of deflection which is lower than 0.5 mm. If observation isfocused on the last dark blue color band the area under the band is not fixed it is varying from top to bottom. The area is less at the top and more at the bottom, this means the stress is more at the top and less at the bottom. As stress is a function of area and area is directly proportional to the deflection this means that the deflection is more 4 number of arms as compared to 3 numbers of arms.

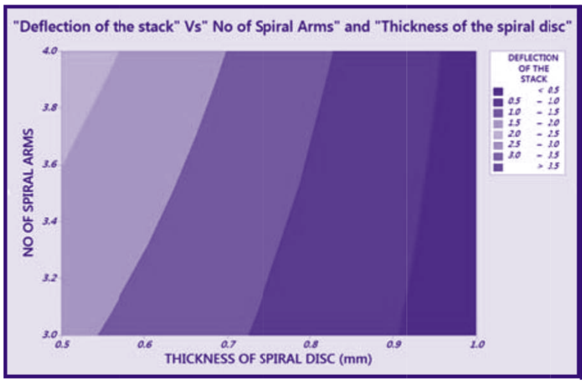

Fig. 3:Contour Plot for Deflection VS Number of Spiral Arms and Thickness of the Spiral Disc.

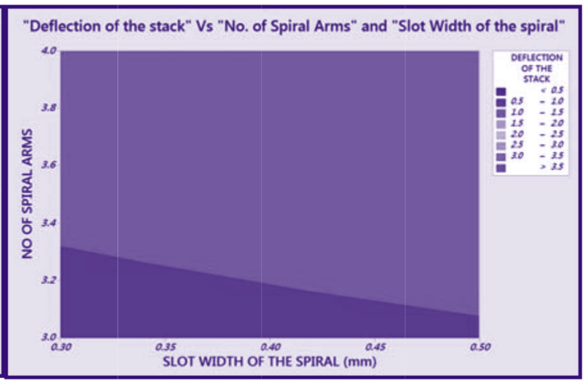

Fig. 4:Contour Plot for Deflection VS Number of Spiral Arms and Slot Width of the Spiral.

From the Figures 3 and 4 it can be depicted that for lower values of both the thickness of the spiral disc i.e. t = 0.5 mm and the slot width of spiral i.e. w = 0.3 the deflection obtained is indicated by the dark blue patch assigned with a value of deflection lower 0.5 mm. Whereas for low value of the slot width and high value of number of arms i.e. n = 4, the deflection obtained is indicated by the light blue patch assigned with a value between a value of 1-1.5 mm respectively. Majority of the area covered in the plot is covered by light blue color.

Similarly, for higher value of the slot width of the spiral i.e. w= 0.5 mm and low value of the number of arms. The deflection is indicated by dark blue patch assigned with a value of deflection lower than 0.5 mm. Similarly, for both the higher values of the parameters the deflection is again indicated by blue patch with a value of deflection which is in between 1-1.5 mm. One most prominent feature is that the area is not constant and band is not parallel to any of the axis indicating that deflection for 3 arms and 0.3 mm slot width is less as compared to 3 arms and 0.5 mm thickness.

5.2 Contour Plot for Deflection VS Number of Spiral Arms and Spiral Angle.

Figure 5 shows the "Contour Plot for Deflection VS Number of Spiral Arms and the Spiral Angle". From the graph it can be depicted that for lower values of both the spiral angle i.e. spa = 270° and the number of arms n = 3, the deflection obtained is indicated by the dark blue patch assigned with a value of deflection lower 0.5 mm. Whereas for low value of the spiral angle and high value of number of arms i.e. n = 4, the deflection obtained is indicated by the light blue patch assigned with a value between a value of 1-1.5 mm respectively.

Similarly, for higher value of the spiral angle spa = 300° and low value of the number of arms. The deflection is indicated by light blue patch assigned with a value of deflection between 1 - 1.5 mm. Similarly, for both the higher values of the parameters the deflection is again indicated by blue patch with a value of deflection which is in between 1.5 - 2 mm. One most prominent feature is that the area is not constant and not parallel to any of the axis indicating that deflection for spiral angle of 270° and number of arms n = 3 is less than that of the spiral disc having spiral angle of 300° and number of arms n = 4.

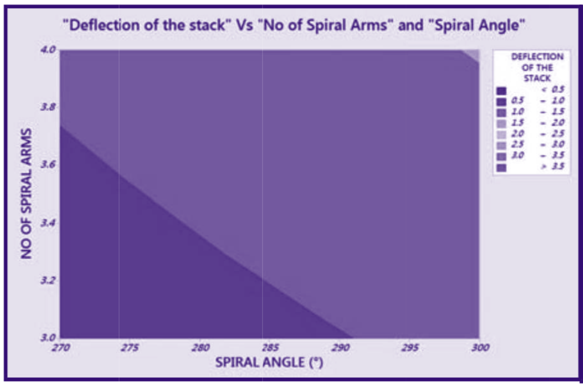

Fig. 5:Contour Plot for Deflection VS Number of Spiral Arms and Spiral Angle.

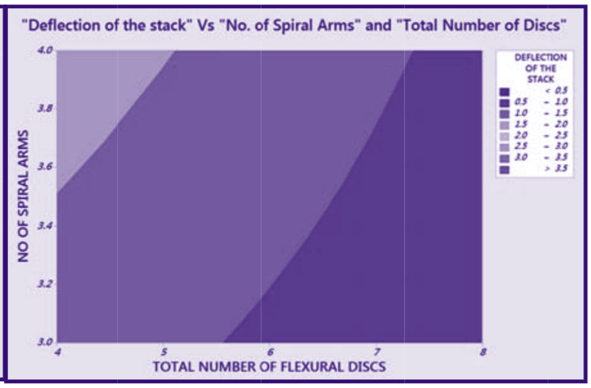

Fig. 6:Contour Plot for Deflection VS Number of Spiral Arms and Total Number of Discs.

5.3 Contour Plot for Deflection VS Number of Spiral Arms and Total Number of Discs.

Figure 6 shows the "Contour Plot for Deflection VS Number of Spiral Arms and Total Number of Discs". From the graph it can be depicted that for lower values of both the total number of discs i.e. st = 4 and the number of arms i.e. n = 3, the deflection obtained is indicated by the light blue patch assigned with a value of deflection between 1 - 1.5 mm, whereas for low value of the total number of discs and high value of number of arms i.e. n = 4 the deflection obtained is indicated by the pale blue patch assigned with a value between a value of 1.5 - 2 mm respectively. The two-colour bands (dark and light blue) are equally balanced in area, are at 45° with respect to the horizontal.

Similarly, for higher value of the total number of discs i.e. sta = 8 and low value of the number of arms. The deflection is indicated by light blue patch assigned with a value of deflection between 0.5 - 1 mm. Similarly, for both the higher values of the parameters the deflection is again indicated by blue patch with a value of deflection which is in between 0.5 -1 mm.

5.4 Contour Plot for Deflection VS Thickness of the Spiral Disc and Slot Width of the Spiral.

Figure 7 shows the "Contour Plot for Deflection VS Thickness of Spiral disc and Slot Width of the Spiral". From the graph it can be depicted that for lower values of both the slot width of the spiral and the thickness of the spiral, deflection obtained is indicated by the pale blue patch assigned with a value of deflection between 1.5 - 2 mm. Whereas for low value of slot width and high value of thickness of the spiral disc, the deflection obtained is indicated by the dark blue patch assigned with a value between a value of 0.5 - 1 mm respectively. All colour bands (dark and light blue) are equally are almost equal in area. The upper band of the graph are parallel to the X axis whereas the low band in the graph are have increase in taper indicating the increase in deflection.

Similarly, for higher value of the slot width i.e. w = 0.5 and low value of the number of thickness of the disc, the deflection is indicated by pale green patch assigned with a value of deflection between2 - 2.5 mm. Similarly, for both the higher values of the parameters the deflection is again indicated by dark blue patch with values of deflection which is in between 0.5 - 1 mm.

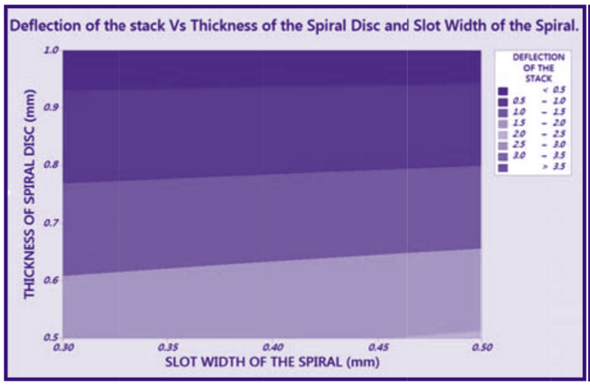

Fig. 7:Contour Plot for Deflection VS Thickness of Spiral Disc and Slot Width of the Spiral.

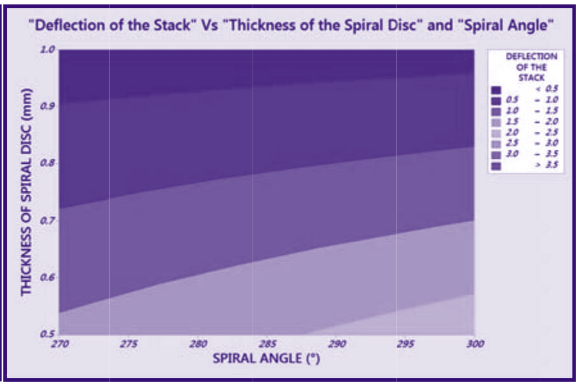

Fig. 8:Contour Plot for Deflection VS Thickness of Spiral Disc and Spiral Angle.

5.5 Contour Plot for Deflection VS Thickness of the Spiral Disc and Slot Width of the Spiral.

Figure 8 shows the "Contour Plot for Deflection VS Thickness of Spiral disc and Spiral Angle". The contour plot has all the 5 different colour bands indicating high level of deflection in the operating range of the parameters.

From the graph(Figure 8) it can be depicted that for lower values of both thickness of the disc and spiral angle, deflection obtained is indicated by the pale blue patch assigned with a value of deflection between 1.5 - 2 mm. Whereas for low value of spiral angle and high value of the thickness of disc, the deflection obtained is indicated by the dark blue patch assigned with a value between a value of 0.5 - 1 mm respectively.

Similarly, for higher value of the spiral angle i.e. spa = 300° and low value of the number of thickness of the disc, the deflection is indicated by pale green patch assigned with a value of deflection between 2 - 2.5 mm. Similarly, for both the higher values of the parameters the deflection is again indicated by dark blue patch with a value of deflection which is in between 0.5 - 1 mm. The area of the dark blue band is almost parallel indicating that the deflection is constant. It can also be depicted that the spiral angle has a low effect on the deflection of the stack.

6. RESULTS AND DISCUSSION:

The various plots generated in the software gives the operating range of the deflection of the stack. Greater the number of color bands greater is the deflection incorporated in the disc. Majority of the plots have dark blue and light blue colors marked on the plots indicating the operating range of the deflection between 0.5 to 1.5 mm respectively. The various outcomes obtained from the plots are enlisted for two level and five parameters are as below:

- Higher the thickness of the disc lesser is the deflection.
- Higher the number of arms more is the deflection.
- Higher the slot width higher is the deflection.
- Higher inscribed spiral angle higher is the deflection.
- Lesser the number of discs in the stack higher is the deflection.

The deflection of the flexural disc which is the function of the resting area or the stiffness of the flexural disc acting against the applied load. On keen observation it can be depicted that thickness of the disc is the prime factor against increasing the resting area hence the deflection is less for higher thickness and vice versa. Similarly, the more the number of arms this makes the flexural disc more flexible. Hence the more number of arms higher is the deflection and vice versa. The slot width of the flexural arm is also responsible for making the flexural disc more flexible; hence it can be depicted that higher slot width, produces more deflection of the flexural disc. The total swept spiral angle of the flexural arm inscribed between the two fixed diameters are also responsible making the flexural disc more flexible. Hence greater the spiral angle more will be the deflection and vice versa. Lastly it can be depicted that greater number of flexural discs resisting to the applied force lesser will be the deflection.

The recommended parameters for designing the flexural disc for low deflection are as follows:

- The thickness of the disc.
- The total number of discs in the stack.
- The number of arms.
- The spiral swept angle.
- The slot width of the arm.

7. CONCLUSIONS:

The thickness of the disc plays an important role in defining the induced deflection. It is the most critical parameter followed by the total number of discs in the stack. The third critical parameter of the disc is the number of arms. The spiral angle swept is the fourth critical parameter. The last critical parameter is the width of the slot.

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