FE analysis with Experimental Investigation of flexure mechanism in 'X' plane

Prasad V. Suryawanshi[1], Suhas P. Deshmukh[2]
[1]*Assistant professor, Trinity Academy of Engineering, kondhwa bk, pune.*
[2]*Associate professor, Sinhgad Academy of Engineering, kondhwa bk, pune.*

***Abstract* — In mechanical engineering flexible mechanisms that transfer an input force or displacement to another point through elastic body deformation. These may be monolithic (single-piece) or joint-less structures. In this research work, motion stage of flexure mechanism set-up will move by using spiral arm coil with 720^0 of spiral angle. The arrangement is such that two spiral coils are attached to the frame. Central part of coil is attached by the bar of motion stage. Motion stage will move in X direction as we require. One of spiral coil is connected to the voice coil motor. Voice coil motor gets current from controller. With the help of Dspace microcontroller we can calibrate the readings of setup. Given readings are executed in MATLAB software and find out various graphs and curves. After simulation in ANSYS software compare the expt. And numerical results and validate it.**

***Index Terms*—flexure mechanism, spiral coil of beryllium copper, PRO-E model, Drafting of setup in CATIA V5 R20, MATLAB, control desk developer, FEA analysis in ANSYS.**

I. INTRODUCTION

Flexures are compliant structures that rely on material elasticity for their functionality. Motion is generated due to deformation at the molecular level, which results in two primary characteristics of flexures – smooth motion and small range of motion. From the perspective of precision machine design, one may think of flexures as being means for providing constraints. It is this capability of providing constraints that make flexures a specific subset of springs.

In fact, all the applications listed above may be resolved in terms of constraint design. Flexure mechanism in applications such as Nano metric positioning, the high quality motion attribute of flexures so strongly outweighs any limitations that most existing Nano-positioners are essentially based on flexures. A further advantage of using flexures is that the trouble of assembly can be minimized by making the mechanism monolithic. This makes flexures indispensable for micro fabrication, where assembly is generally difficult or even impossible. Thus despite small range of motion and a fundamental performance trade-off between the DOF and DOC, flexures remain important machine elements. To achieve the motion of motion stage by using spiral flexure mechanism setup. As per industrial requirement we have to take precision motion of motion stage. By using drawing of flexure mechanism setup analysis shall do. Using control system and actuators move the motion stage. After experimental setup compare the experimental results and FEA results.

Here we have to achieve some objectives such that:

a) To achieve precise motion of motion stage by using spiral flexure setup.
b) Compare other flexure mechanism setup with spiral flexure mechanism setup.
c) Check the efficiency, properties of spiral flexure mechanism with others.
d) Validate the Experimental as well as numerical results.

II. METHODOLOGY

A. Literature review

1) Design and analysis of totally decoupled flexures based on XY parallel manipulators.
2) Development of high performance moving coil linear compressors for space sterling-type pulse tube cry coolers.
3) A Novel Piezo-actuated XY Stage With Parallel, Decoupled, and Stacked Flexure Structure for Micro /Nano-positioning.

B. Experimental model

1) Manufacturing of spiral flexure mechanism with appropriate material and design.

C. CAD model generation

1) Model is generated in PRO-E.

2) As per requirement and correction from manufacturers further design modification done in CATIA V5R20.

D. Determination of loads

1) At the center of spiral flexure with the help of VCM get a force from 4.52N to 101.7N plus and minus direction.

E. Numerical modeling

1) Linear static analysis is done by using ANSYS software.

F. Simulation

1) Simulation has been done in ANSYS software with single and double spiral flexures.

G. Validation

1) Results are validated with minimum deviation.

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III. EXPERIMENTAL METHOD

We have to move the motion stage in 'X' direction with very precise movement. For that experimental setup has been made. Some parts are made up of polycarbonate (white nylon). Other parts are of mild steel. Flexure is made up of beryllium copper material. With the help of voice coil motor (VCM); At the Centre of VCM there is a tap of M3 (mm) into which threaded rod is fitted and move with to and fro motion with maximum displacement up to 25mm.

This threaded rod is connected to the two flexures with M3 nut of four pieces and there is washer in between spiral flexures and nut. 90*90*10 mm of motion stage is slotted and drilled in such a way to pass guided bar and threaded rod. In between threaded rod and guided bar of motion stage; motion stage is mount and it fix to the threaded rod with the help of M3 grap screw. Motion stage will move along the axis of guided bar and threaded rod as these are parallel to each other. On the top surface of motion stage optical scale is attached by tecso-tape in such a way that center of that motion stage is given and also center of that optical scale is given. After that this scale is properly attached on the top of tape which sticks on surface of motion stage. For the testing purposes optical sensor has to mount with the help of fixture which sense the defection occurs in the motion stage. This all setup is mounted on the breed board on which there are holes with M6 tapping. The C.D. (center distance) between consequent two holes is of 25mm. 70mm diameter of flexure is thickness of 1mm and there are 8 holes for constraint. For testing and experimental purpose spiral angle are Choose are of 7200. VCM is connected to the Dspace microcontroller which is connected to linear current amplifier (LCAM) circuit. We have to do input to the LCAM circuit as voltage by voltmeter. In MATLAB software with the help of block diagram algebra connections are created. This program is contacted into 'control desk developer' version software. In that software we get all possible results as force deflection, natural frequency, etc.

Manufacturing and assembly following issues are to be ensured before experimentations

1) Appropriate alignment of each component
2) Parasitic error checking
3) Orthogonal axis alignment
4) Actuator alignment
5) Sensor alignment

These alignments are to be checked and ensured they are within acceptable tolerances. Simple workshop techniques are to be used for measuring the alignments using surface plate, slide gauges and dial gauges (indicators). Manufactured mechanism is to be further integrated with PC via micro-controller and desired electronics.

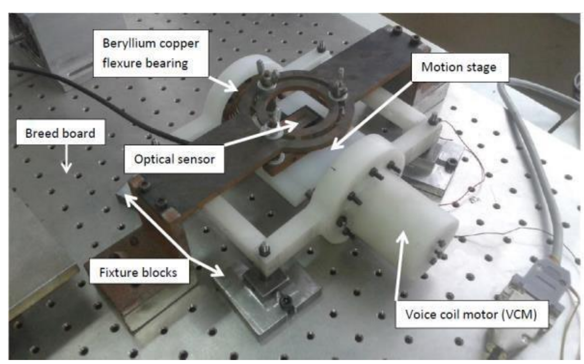


Fig 1 Expt. Setup of flexure mechanism

IV. EXPERIMENTAL SETUP COMPONENTS

Fig 2 Spiral flexure bearing

Fig 3 motion stage

Fig 4 Guided bars

Fig 5 voice coil motor (VCM)

Fig 6 Fixture blocks

Fig 7 Optical sensor

Fig 8 stand bars

Fig 9 optical scale

Fig 10 Dspace microcontroller

Above are the simply components that are used in spiral flexure mechanism project. While considering the 'controldeskdeveloper' and MATLB software following parameters are to be considered.

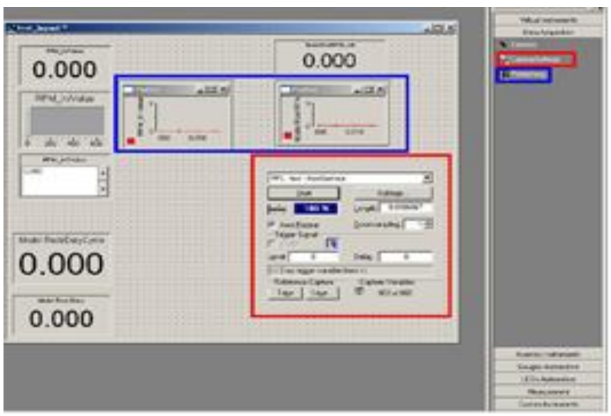


Fig 11 capture setting instrument

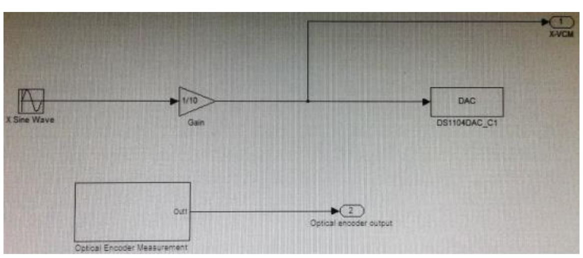


Fig 12 Simulink model

V. MATERIAL SELECTION

A. BERYLLIUM COPPER

For precise motion of motion stage we use a material which is of high tensile and fatigue strength. For that beryllium copper material is perfectly suited for these properties.

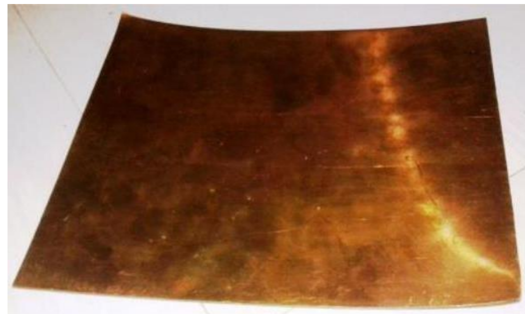


Fig 13 Beryllium copper sheet metal

Fig 14 spiral flexure from Be-Cu sheet metal part

While manufacturing point of view we need two circular discs; diameter of 70 mm. so that we purchase 72*144*1 mm of metal sheet. After that wire EDM cutting takes place on that sheet metal part which is spiral flexure angle of 720^0.

Following are the specifications of beryllium copper material as we require in numerical analysis:

Table No. 1
Properties of beryllium copper

Sr No.	Properties	Metric
1	Density	8.25 gm/cm^3
2	Tensile strength, ultimate	1280-1480 MPa
3	Tensile strength, yield	965-1205 MPa
4	Modulus of elasticity	125-130 GPa
5	Poisons ratio	0.3
6	Shear modulus	50 GPa

B. POLYCARBONATE (WHITE NYLON 66)

All wide amount of material for this setup is of polycarbonate. Polycarbonate material is very chip in cost and also light in weight. Following are specifications of polycarbonate as we require in numerical analysis:

Fig 15 polycarbonate (white nylon 66)

Table No. 2
Properties of polycarbonate (white nylon 66)

Sr No.	Properties	Metric
1	Density	1.27-1.38 Mg/M^3
2	Bulk modulus	14.2-20.49 GPa
3	Tensile strength, yield	965-1205 MPa
4	Modulus of elasticity	13.5-21.4 GPa
5	Poisson's ratio	0.3182-0.3487
6	Shear modulus	5.03-8.078 GPa
7	Tensile strength	124-165 MPa

C. MILD STEEL

Mild steel is very chip in cost, easily available and its tensile strength is very high. Following are the specifications of mild steel as we require in numerical analysis:

Fig 16 mild steel

Table No. 3
Properties of mild steel

Sr No.	Properties	metric
1	Density	7.87 g/cc
2	Tensile strength, ultimate	440 MPa
3	Tensile strength, yield	370 MPa
4	Modulus of elasticity	205 GPa
5	Poisson's ratio	0.29
6	Shear modulus	80 GPa

VI. EXPERIMENTAL WORK

As shown in above setup of spiral flexure mechanism; testing is performed with various amplitudes and various frequencies. The linear current amplifier is connected to both voice coil motor and voltmeter. Now in MATLAB software make a Simulink model for motion of motion stage in X direction only.

By creating Simulink in MATLAB make a program. Now execute this Simulink in that program and open the controldeskdeveloper software for the further execution of testing. By opening the python layout file in that software we have to do input as an amplitude and frequency.

By putting various inputs we get .mat files. As these files we save as 'amp_25_f001'. In that 25 means we give amplitude as .025 mm and 001 as frequency we give as 1 HZ.

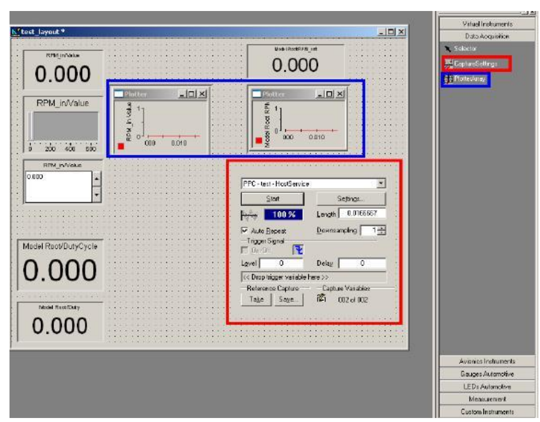


Fig 17 Capture Settings instrument (red boxes) added to a layout with associated Plotter Arrays (blue boxes). A Numeric Input instrument is also included in this layout below the slider.

VII. NUMERICAL WORK

Analysis of that spiral flexure is done in ANSYS software as static linear. In given setup there are two spiral flexures. The results are given on both single and double flexures. While considering the single spiral flexure the boundary conditions are such that;

Force at the centre of 1N to 15N at the centre of that spiral flexure. There are 8 holes at the corner of the spiral flexure. The constraint is given as all holes and at the centre of that hole takes a force in X direction.

- Analysis for single spiral flexure

While considering the applied force on the flexure by VCM; we give input as amplitude. The voltage from voltmeter factor is constant as 2. Frequency of that parameter given as 1 Hz. Following are applied forces on spiral flexure. With the help of formula we can measure the force applied by VCM to the flexure.

'Amp * L-CAM factor * VCM gain = force N'

Table No. 4 By using above formula find out the forces

Sr No	**Amplitude**	**L-CAM factor**	**VCM gain**	**Force**	**U**
1	0.25	2	22.6	11.3	N
2	0.50	2	22.6	22.6	N
3	0.75	2	22.6	33.9	N
4	1.00	2	22.6	45.2	N
5	1.25	2	22.6	56.5	N
6	1.50	2	22.6	67.8	N
7	1.75	2	22.6	79.1	N
8	2.00	2	22.6	90.4	N
9	2.25	2	22.6	101.7	N
10	2.50	2	22.6	113	N
11	3.00	2	22.6	135.6	N
12	4.00	2	22.6	180.8	N
13	5.00	2	22.6	226	N

By taking force as we calculated and mentioned in above table; here are some numerical results.

Material properties –

Spiral flexure of material is beryllium copper. By solving these following parameters has to be given.

- ✓ Young‘s modulus – 1.3 * 105 MPa
- ✓ Poisson‘s ratio – 0.3
- ✓ Bulk modulus – 1.833 * 105 MPa
- ✓ Shear modulus – 50000 MPa

Put these values in ANSYS workbench and further meshing is done.

Fig 18 ANSYS (put the physical properties of beryllium copper material)

Meshing -

After importing the .stp file in workbench meshing has to be done. There are following parameters are found.

- ✓ Nodes for geometry - 34385
- ✓ Elements for geometry – 5056
- ✓ Element size - 2 mm.
- ✓ Minimum edge length - 0.50 mm.

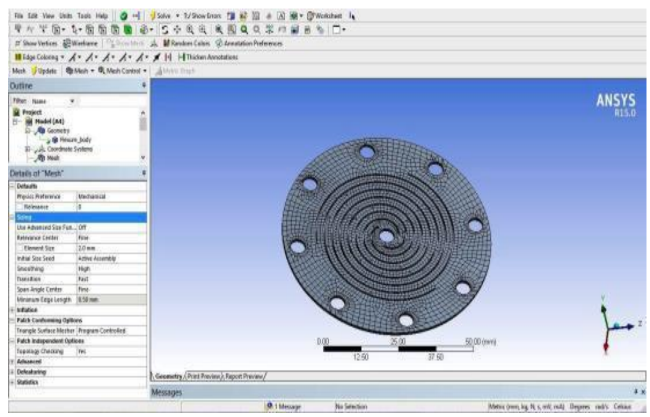


Fig 19 Meshed model

Boundary conditions –

On the spiral flexures bearing there are following boundary conditions.

✓ Single point constraint – constraints are given at the eight corner holes of flexure with zero degree of freedom. At the center of flexure there is a hole of diameter 5mm. In that motion stage bar is fixed and it‘s motion is only *to and fro*. So that among six degree of freedom; four degree of freedom are active. So that material will not displace or deform in another direction.

Forces – at the center of that flexure apply the force with particular parameter. Because of forces in expt.

Setup; same these forces applied in FEA as 4.52 N, 11.3 N, 22.6 N, 33.9 N, 45.2 N, 56.5 N, 67.8 N, 79.1 N, 90.4 N and 101.7 N.

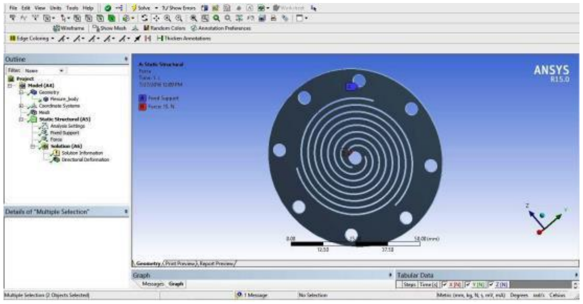


Fig 20 Boundary conditions on flexure Analysis

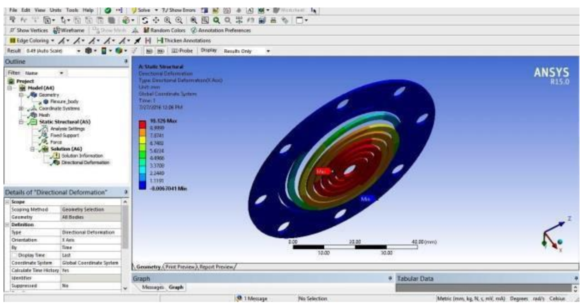


Fig 21 Numerical results for single spiral flexure

•Analysis for double spiral flexure

In case of double spiral flexure forces are added with high amplitude range.

Material properties –

All the material properties of beryllium copper are same for double spiral flexure. The design is made such that two flexures are separated by 150mm. these flexures are attached by cylindrical bar of mild steel

Meshing -

After importing the .stp file in workbench meshing has to be done. There is three main components; two flexure and mild steel bar. By meshing of this geometry we are going to apply force at the center of that bar axially.

Boundary conditions –
Single point constraint – at the two flexures of holes are to be constraint.

Force – force is given at the center of that mild steel bar axially. Magnitude of that bar is mentioned in above table.

Analysis –

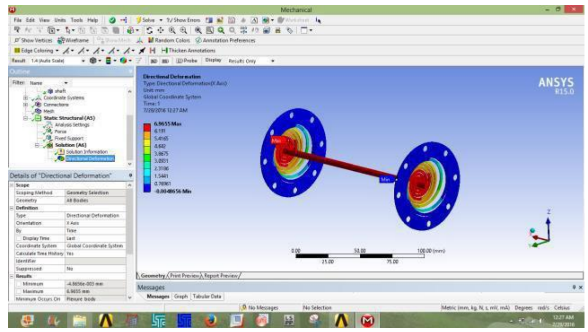
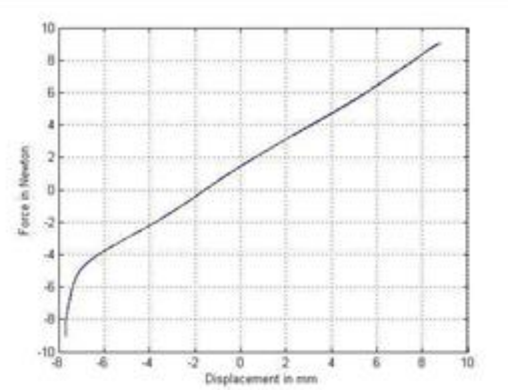


Fig 22 Numerical results for double spiral flexure

VIII. RESULTS AND DISCUSSION

For Single Spiral flexure:

From the experimental investigation of spiral flexure bearing mechanism we can say that as force of VCM goes on increases then deflection goes on increases.



Graph 1 Expt. Investigation of force Vs deflection

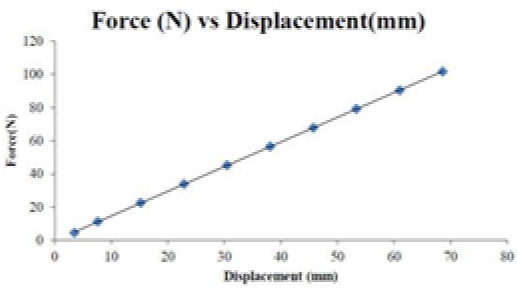
Also from numerical investigation following results are obtained. As we give the force from VCM to motion stage it gives displacement in mm with the help of optical encoder.

Following is the table which contains force and it's consequent deflection in single flexure.

Table No. 5 Force and displacement for single spiral flexure

FORCE (N)	DISPLACEMENT (mm)
4.52	3.512
11.3	7.638
22.6	15.25
33.9	22.88
45.2	30.512
56.5	38.14
67.8	45.78
79.1	53.39
90.4	61.02
101.7	68.652

From above table we have graph of force verses displacement. As from graph it shows straight line; so as increases in force increases the displacement.



Graph 2 force and displacement

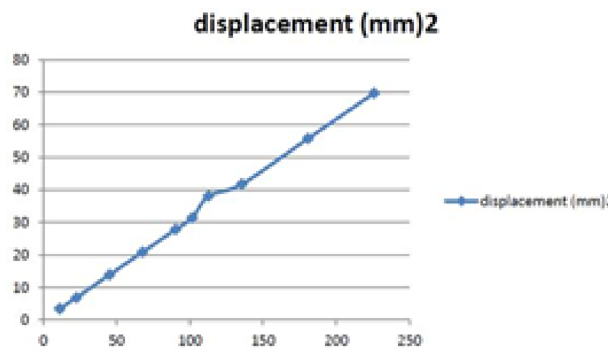
- For double spiral flexure –

From the experimental investigation for double spiral flexure same graph has been made as single spiral flexure. This forces and displacement are constant but surprisingly increasing. While considering the double spiral flexures high amplitude to be considered. So that high amount of force acts on motion stage. Following is the table which contains the force and it's consequent displacement.

Table No. 6
Force and displacement for double spiral flexure

FORCE (N)	DISPLACEMENT (mm)
11.3	3.4827
22.6	6.92
33.9	13.931
67.8	20.896
90.4	27.86
101.7	31.45
113	38.128
135.6	41.8
180.8	55.81
226	68.652

From above table we have graph of force verses displacement. As from graph it shows straight line; so as increases in force increases the displacement.



Graph 3 force Vs displacement for double flexure

IX. DISCUSSIONS

We know that the formula stiffness = force / deflection = F / d.

In following table we calculate stiffness value for each force and it's deflection. Also we get the stiffness value in double flexure setup.

Table No. 7 Force, displacement and stiffness for single spiral flexure

FORCE (N)	DISPLACEMENT (mm)	STIFFNESS (k)
4.52	3.512	1.2870
11.3	7.638	1.4794
22.6	15.25	1.4819
33.9	22.88	1.4816
45.2	30.512	1.4813
56.5	38.14	1.4813
67.8	45.78	1.4809
79.1	53.39	1.4815
90.4	61.02	1.4814
101.7	68.652	1.4813

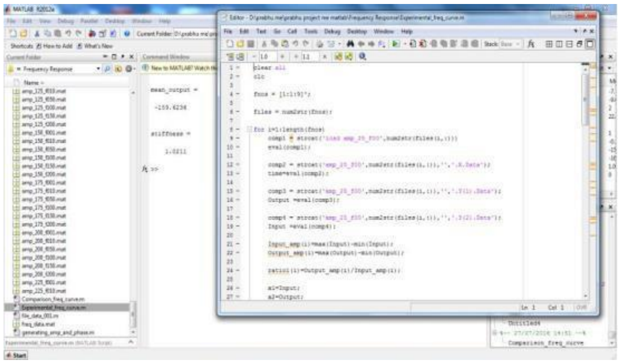


Fig 23 Stiffness value output for single flexure

In above table we give the stiffness for various forces. By calculating mean stiffness from above table is **1.4617** and we have stiffness from experimental analysis is **1.0211**. So that with very small value we have the stiffness for single spiral flexures.

Table No. 8 Force and displacement for double spiral flexure

FORCE (N)	DISPLACEMENT (mm)	STIFFNESS (k)
11.3	3.4827	1.2870
22.6	6.92	1.4794
67.8	20.896	1.4816
90.4	27.86	1.4813
101.7	31.45	1.4813
113	38.128	1.4809
135.6	41.8	1.4815
180.8	55.81	1.4814
226	68.652	1.4813

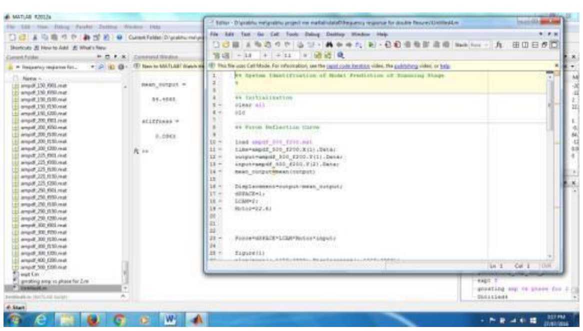


Fig 24 Stiffness value output for double flexure

In above table we give the stiffness for various forces. By calculating mean stiffness from above table is **3.2217** and we have stiffness from experimental analysis is **3.0963**. So that with very small value we have the stiffness for double spiral flexures.

X. CONCLUSION

In spiral flexure bearing mechanism setup the motion of motion stage successfully move in X direction with precise motion. As from experimental and numerical results we conclude that as the force of VCM acts on spiral flexure increases with increase in deflection of that flexure. Stiffness value of single spiral flexure is validated by experimental as well as numerical work and it becomes approx. same. It‘s for single flexure of 1 N/mm and for double flexure is 3 N/mm. To displace the motion stage in ‘X’ plane very precisely.

To make the design setup in such a way that it should be light weight and rigid we use polycarbonate material for making parts of setup. Fixture is made by mild steel blocks. Use high tensile strength and high fatigue strength material for spiral flexure bearing; so that beryllium copper is used.

Simulation of spiral flexure with various angles in ANSYS software. To use MATLAB for experimental setup. Proper fixture is to be made for fixing of setup; for that use breadboard, fixture and M6 bolts. We tested setup and find the various graphs as amplitude Vs frequency, force Vs Deflection and phase angle Vs frequency for both flexures.

FUTURE SCOPE

- This spiral flexure bearing setup is only in X direction. We can move the motion stage in XY direction. So that extra arrangement needed.
- Spiral flexures are used in this setup are of 720^0. We can increase the spiral angle of that flexure; as its stiffness going to decreases and force magnitude decreases.
- Also by changing the thickness of flexures it affects on stiffness and overall power loss.
- The readings in this setup are 1Hz to 200Hz. If we take the all possible readings with maximum amplitude and maximum frequency then results we will get accurate.
- For XY stage of mounting we need large fixtures for both; for XY setup and optical sensor.

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