Lab Report: Analysis of 3-axis Piezo stage

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Ansys File Model name: 651709_FEM_Final_Project

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1. Introduction

1.1. Objective of the analysis:

The purpose of this report is to determine the evaluation on the design of an XY-stage of Piezo Actuators. The tasks which are to be accomplished are given below.

Task 1: Determine the stage stiffness in x- and y-direction regarding the output load point. Give your results in [N/mm].

Task 2: Determine the workspace of the output load point if the actuators accept a voltage range of -200V ... +200V

Task 3: Mesh convergence study based on the required results to prove correct mesh sizing and provide a hand calculation of the expected X and Y displacement for the output load point.

1.2. Brief overview of the tool(s):

The model assembly is designed using the software Ansys Workbench 2023 R2. The Ansys program use computer-based methods to find solutions and resolve challenging issues. The geometry and design are produced using the static structural design modeler feature. Engineering data like Young's modulus, Poisson's ratio, kind of material, and environmental circumstances are entered using the isotropic elasticity in the linear elastic design feature. To manually calculate the solution and insert the graphs for the mesh convergence, we used Microsoft Word for report preparation and MS Excel for the graph.

1.3. Material Parameters and Ambient Conditions applied to the analysis:

Material: Steel

Young's Modulus				Actuator's coefficient
Actuator	Lever	Hinges	Frame	
E/MPa	E/MPa	E/MPa	E/MPa	d/ 1/V
90000	16000	48000	240000	1,2E-04

Table 1: Material Characteristics

Ambient Conditions: 20°C, 1bar atmospheric pressure, no harsh environment

2. Description of the FEA model:

The FEA Model consists of 3 Piezo Actuators connected with hinges to a Lever and Frame. These materials have their Isometric Elastic properties as mentioned in Table 1. The materials are connected to the frame and lever as shown in Figure 1. The results of the required analysis are carried out at Output Load point as shown in Figure 2.

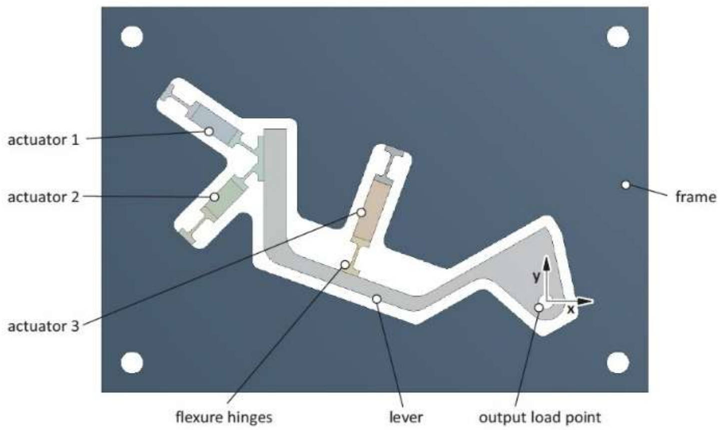


Figure 1: The design of 3- Axis Piezo stage.

Key dimensions and Boundary conditions are shown in Figure 2 with assigned dimensions for the Analysis. The dimensions mentioned in Figure 2 are as per the below table.

A15 (°C)	A5 (°C)	L1 (mm)	L10 (mm)	L2 (mm)	L22 (mm)	L26 (mm)	V8 (mm)
113	40	3	15	6	4	15	13

Table 2: Geometric Dimensions of FEA Model in XY Plane

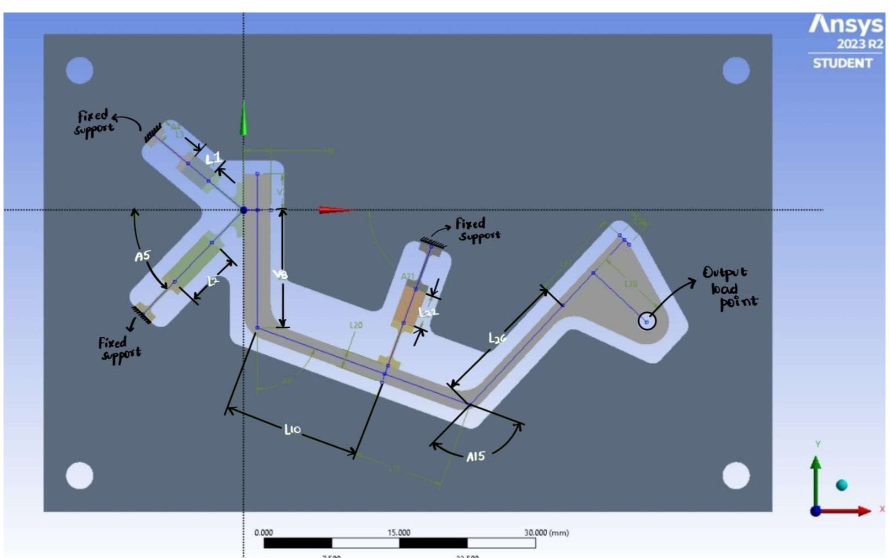


Figure 2: Detailed FEA Model of 3-Axis Piezo Stage

3. Details of Mesh Convergence Study:

A mesh convergence study in ANSYS is like finding the right level of detail for a picture. We want to make sure our results are accurate, so we check how changing the mesh affects them. We keep refining the mesh, making it more detailed, and see if the result changes a lot. We look at things like how much something moves or how stressful it gets to see if the results are stable as we refine the mesh. In short, a mesh convergence study helps us make sure our computer model gives us reliable answers by checking how various levels of detail affect our results.

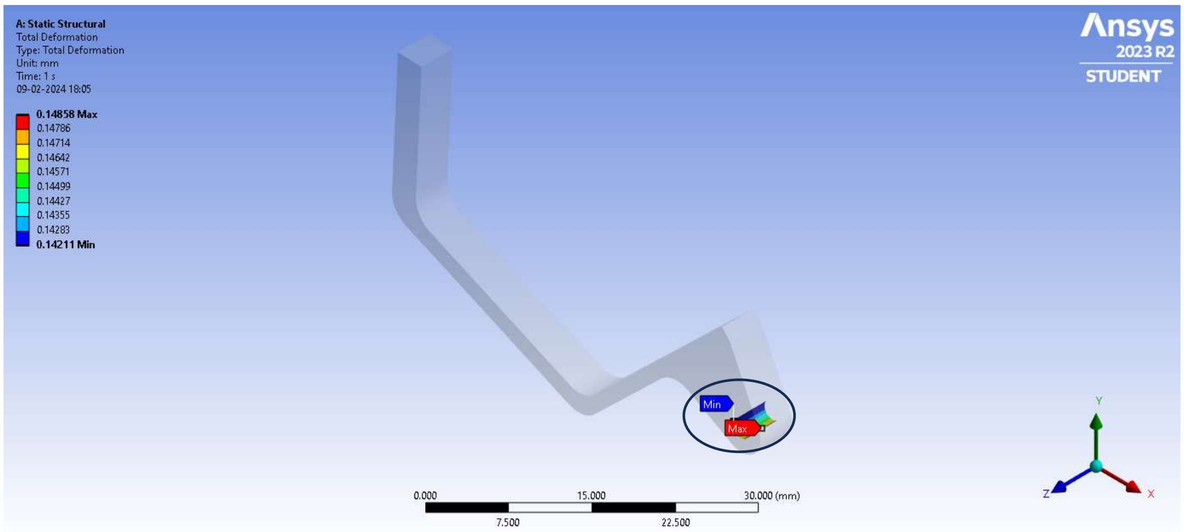


Figure 3: Total Deformation at Output load point.

Figure 3 shows the Total deformation at the output load point with maximum and minimum deformations. The Total deformation at the load point is found at different element sizes and are tabulated in Table 3. The mesh is converged at the element size 0.6 mm. Figure 4 shows the graph plotted in between Mesh nodes and Total deformation at Output Load Point.

Mesh Element Size	Mesh Nodes	Mesh Elements	Total Deformation Maximum
mm			mm
1	11387	1792	0.146995199
0.9	13502	2140	0.14714566
0.7	24932	4344	0.148288997
0.6	35023	6370	0.148579009
0.5	53451	10208	0.148466503
0.45	73655	14559	0.148549119

Table 3: Mesh Convergence Study at Output Load Point

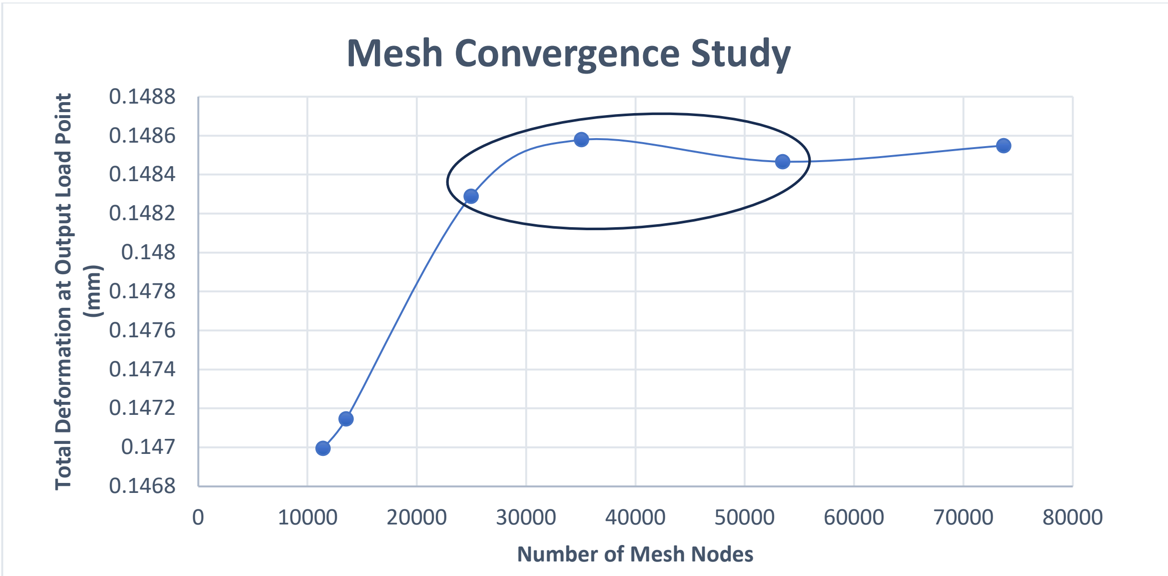


Figure 4: Plot of Mesh Convergence

4. Figure of Final Mesh

The below figure shows the Detailed figure of refined mesh with Element size 0.6 mm which consists of 41300 Nodes and 19463 Elements.

Element Size	0.6 mm
Nodes	41300
Elements	19463

Table 4: Nodes & Elements

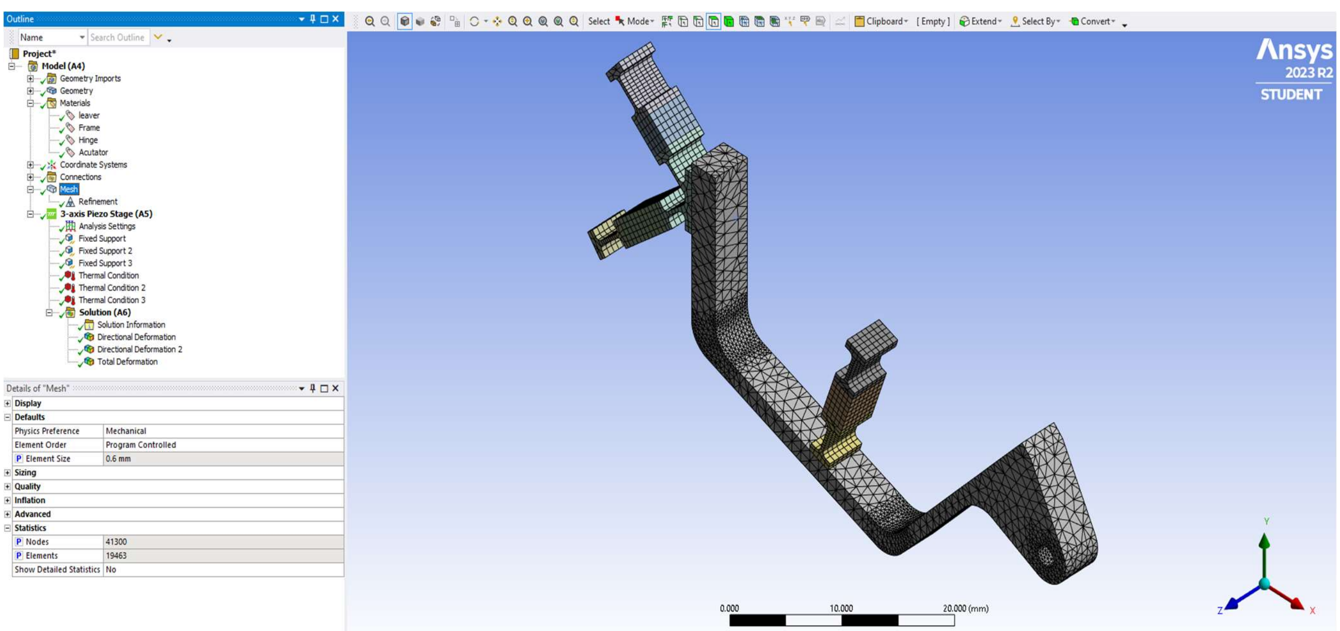


Figure 5: Detailed Refined Mesh

5. Results

5.1. Stage Stiffness in X and Y Directions

Material stiffness refers to how resistant it is to bend or stretching under force, measured by Young's Modulus, with higher values indicating less deformation. It is calculated by the formula as shown below.

$$Stage\ Stiffness(k) = \frac{\text{Force Applied (F)}}{\text{Displacement }(\Delta \text{u})}$$

For the given material the Stiffness is calculated in both X and Y directions by applying various values of force at the output load point.

5.1.1. Stiffness at Load point when Force Applied in X-Direction

The Directional deformation towards X direction is calculated by applying various forces in X direction as shown in Table 4 and the plot for this is show in Figure 5.

Force X Component (N)	Maximum Directional Deformation (mm)
100	9.387073517
90	8.448366165
80	7.509658813
70	6.570951462
60	5.63224411
50	4.693536758
40	3.754829407
30	2.816122055
20	1.877414703
10	0.938707352

Table 5: Directional Deformation towards X-direction for different Forces Applied

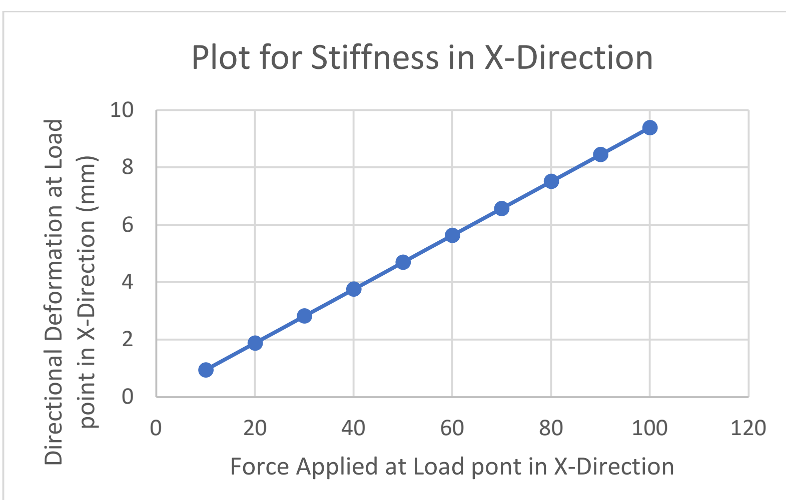


Figure 6: Stiffness Plot in X-Direction

5.1.2. Stiffness at Load point when Force Applied in Y-Direction

The Directional deformation towards Y direction is calculated by applying various forces in Y direction as shown in Table 5 and the plot for this is show in Figure 7.

Force Y Component (N)	Maximum Directional Deformation (mm)
100	40.6464653
90	36.58181763
80	32.51717377
70	28.45252609
60	24.38787842
50	20.32323265
40	16.25858688
30	12.19393921
20	8.129293442
10	4.064646721

Table 6: Directional Deformation towards Y-Direction for different Forces Applied

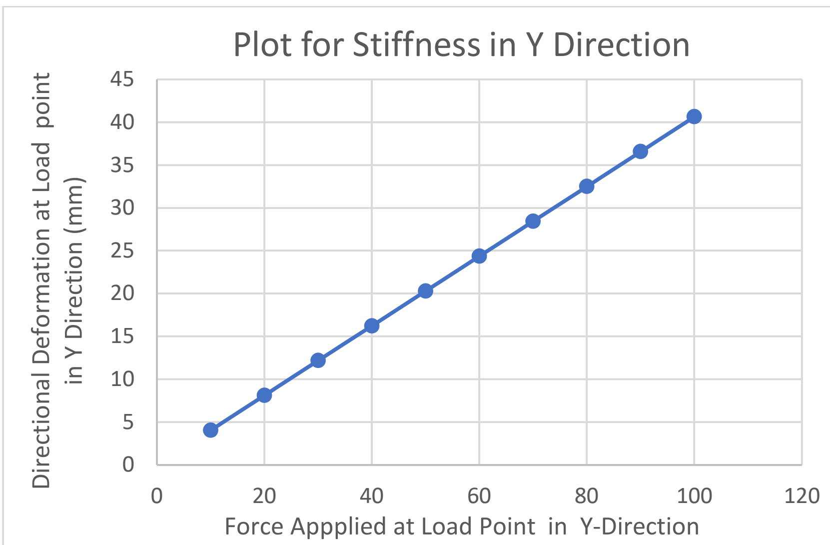


Figure 7: Stiffness Plot in Y-Direction

The Stiffness can be calculated from the plots by calculating the Slopes. These Slope values are provided in below Table 6.

Direction	**Stiffness**
X-axis	0.09387073
Y-axis	0.40646465

Table 7: Stiffness in X and Y directions

5.2. Workspace of Output Load Point

The workspace of the output load point depends on the voltages that actuators use, which goes from -200V to +200V. This voltage range decides how far the actuators can push the load point. By using this voltage range, the actuators can make the load point move in different directions, letting it go to different spots within its limits.

For Actuators varying in thermal conditions i.e., Temperature will increase the Resistance which increases Voltage. So here in this analysis we vary temperature in Actuators for varying Voltage. Table 7 shows the values of Deformation in both X and Y directions by providing different temperatures to three actuators.

Thermal Condition Actuator 1 (C)	Thermal Condition Actuator 2 (C)	Thermal Condition Actuator 3 (C)	Directional Deformation Maximum X-Axis (mm)	Directional Deformation Maximum Y-Axis (mm)
200	200	200	0.024658507	-0.311635464
200	200	-200	0.113832586	0.090890728
200	-200	200	-0.00520959	0.091991469
200	-200	-200	0.101000778	0.511553943
-200	200	200	-0.075770088	-0.403194398
-200	200	-200	0.011641347	-0.002430869
-200	-200	200	-0.115716733	-0.009646027
-200	-200	-200	-0.009506362	0.409916431

Table 8: Deformations at Load Point in X & Y Directions for the given Temperature range

The below graph represents the workspace of the Output Load point when Temperature in Actuators are Varied.

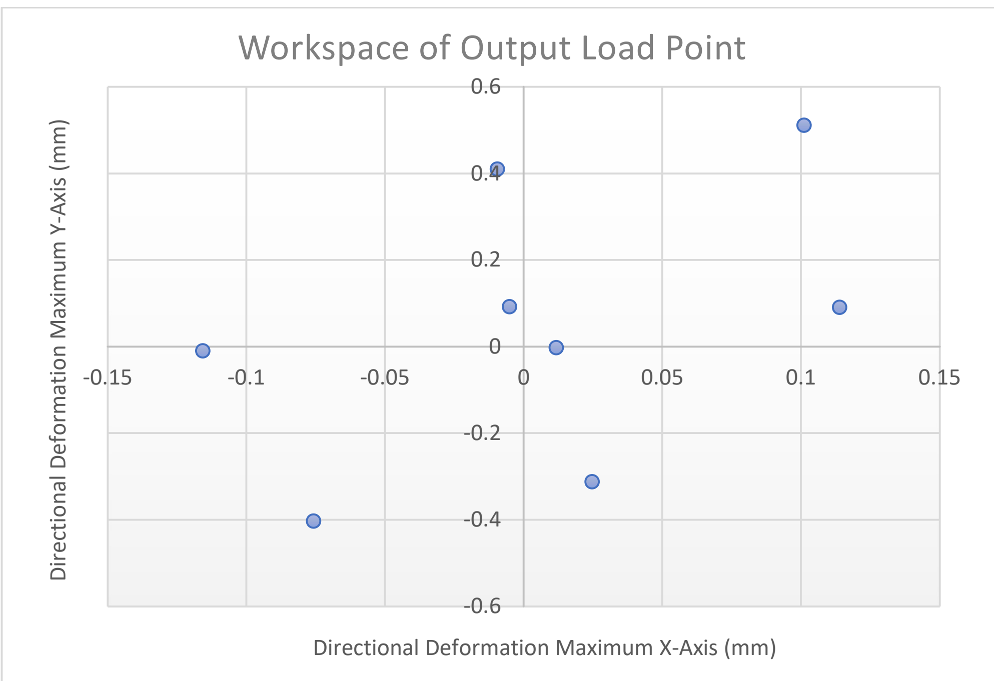


Figure 8: Workspace of the Output Load Point

6. Verification by Hand Calculation

In our manual calculations we consider the Actuator 1 and Actuator 2 are Fixed and there is no temperature effect on it. As Actuator 3 deforms due to change in Temperature. It causes the entire lever shift in response. Consequently, we can simplify the problem by focusing on how various segments of the lever displace as it rotates around point O.

As the lever undergoes a specific angle of rotation, it creates two similar triangles, as illustrated in Figure below.

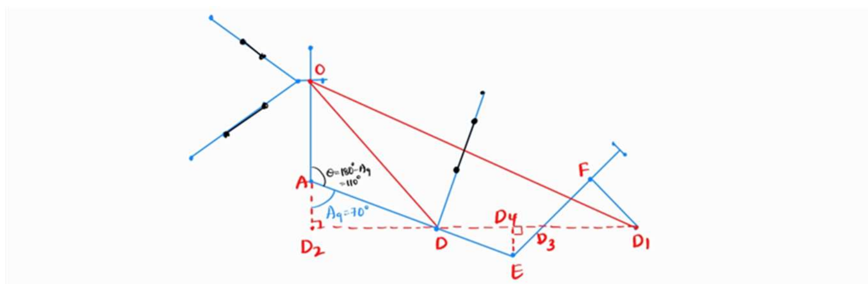
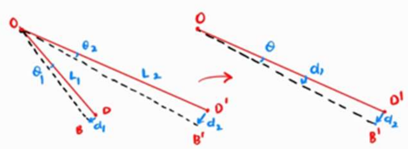


fig: Simplified structure of the provided model



here, $\theta_1 = \theta_2$, $OD = OB$, $OD' = OB'$ $\rightarrow$ $\triangle OBD \sim \triangle OB'D'$

from the above figure, d_2 can be determined by formula

$$\boxed{d_2 = \frac{OD'}{OD} d_1}$$

where $d_1 \rightarrow$ displacement generated by Actuator 3. which can be Obtained from

$$d_1 = L_{22} \times \Delta\varepsilon = 4\,mm \times 1.2 \times 10^{-4} \frac{1}{V} \times 200\,V$$

$$\boxed{d_1 = 0.096\,mm}$$

The length OD is calculated from triangle OAD from Simplified figure.

$$\angle OAD = 180^\circ - A_9 = 180 - 70 = 110^\circ$$

from $\triangle OAD$

$$\cos\angle OAD = \frac{AO^2 + AD^2 - OD^2}{2 \cdot AO \cdot AD}$$

from the data we have

$$OD \Rightarrow \sqrt{AO^2 + AD^2 - 2 \cdot AO \cdot AD \cos\angle OAD}$$

$$\Rightarrow \sqrt{V_8^2 + L_{10}^2 - 2 \cdot V_8 \cdot L_{10} \cos 110^\circ}$$

$$\Rightarrow \sqrt{13^2 + 15^2 - 2 \cdot 13 \cdot 15 \cdot \cos 110^\circ}$$

$$\boxed{OD \Rightarrow 22.9649\,mm}$$

The length of OD_1 can be calculated from $\triangle OD_1D_2$

$$\boxed{OD_1 = \sqrt{D_2O^2 + D_2D_1^2}}$$

but here

$$D_2D_1 = D_2D + DD_4 + D_4D_3 + D_3D_1$$

finding

① D_2D from $\triangle ADD_2$

$$\hookrightarrow D_2D = AD \cos\angle D_2DA = 15 \times \cos(20^\circ)$$

$$\boxed{D_2D \Rightarrow 14.0954\ mm}$$

$$A_9 + 90^\circ + \angle D_2DA = 180^\circ$$

$$\angle D_2DA = 180 - 90 - 70^\circ \quad (\because A_9 = 70^\circ)$$

$$\Rightarrow 20^\circ$$

② DD_4 from $\triangle EDD_4$

$$\angle EDD_4 = \angle D_2DA \quad (\because \text{Angle at point of intersection of straight lines})$$

$$= 20^\circ$$

$$\therefore DD_4 = DE \cdot \cos\angle EDD_4$$

$$\Rightarrow L_{11}\cos 20^\circ \Rightarrow 10mm \cdot \cos 20^\circ$$

$$\boxed{DD_4 = 9.3969\ mm}$$

③ D_3D_4 from $\triangle ED_3D_4$

$$D_4D_3 = D_3E \cdot \cos\angle ED_3D_4 \qquad \angle ED_3D_4 = 45^\circ$$

here

$$D_3E = EF - FD_1 \Rightarrow \left(L_{26} + \frac{L_{27}}{2}\right) - L_{28}$$

$$\Rightarrow 15 + \frac{10}{2} - 8 = 12mm$$

$$\therefore D_4D_3 = 12 \cdot \cos 45^\circ$$

$$\boxed{D_4D_3 = 8.4853mm}$$

④ D_1D_3 from $\triangle FD_1D_3$

$$D_1D_3 = \frac{FD_1}{\cos\angle FD_1D_3} = \frac{L_{28}}{\cos 45} = \frac{8}{\cos 45^\circ}$$

$$\boxed{D_1D_3 = 11.3137\ mm}$$

$\therefore$ from ①, ②, ③ & ④

$$D_2D_1 = D_2D + DD_4 + D_4D_3 + D_3D_1$$

$$= 14.0954 + 9.3969 + 8.4853 + 11.3137$$

$$\boxed{D_2D_1 = 43.2913\ mm}$$

$$D_2O = OA + AD_2 \qquad AD_2 = AD \sin\angle ADD_2$$

$$\Rightarrow V_8 + L_{10}\sin 20^\circ \qquad \Rightarrow L_{10}\sin 20^\circ$$

$$\Rightarrow 13 + 15\sin 20^\circ \qquad \left(\because \angle ADD_2 + \angle DAD_2 = 90^\circ\right), \ \angle DAD_2 = 70^\circ$$

$$\boxed{D_2O = 18.1303\ mm}$$

$$\therefore OD_1 = \sqrt{D_2O^2 + D_1D_2^2}$$

$$OD_1 = \sqrt{(18.1303)^2 + (43.2913)^2}$$

$$\boxed{OD_1 = 46.9345\ mm}$$

So, displacement at load point

$$d_2 = \frac{OD_1}{OD} d_1 = \frac{46.9345}{22.9649} \times 0.096 = 0.1962$$

$$\boxed{d_2 = 0.1962 \text{ mm}}$$

Verification by finding Percentage Deviation:

→ ANSYS simulation result

$$d_{simulation} = 0.1486 \text{ mm}$$

→ Hand calculation result

$$d_{calculated} = 0.1962 \text{ mm}$$

$$\therefore \text{Percentage deviation} = \frac{d_{calculated} - d_{simulation}}{d_{calculated}} \times 100\%$$

$$\Rightarrow \frac{0.1962 - 0.1486}{0.1962} \times 100\%$$

$$\boxed{\text{Deviation} \Rightarrow 24.26\%}$$

Declaration of Independence

We declare on our honour that the work presented in this dissertation, entitled “Lab Report: Analysis of 3-axis piezo stage,” is original and was carried out by Sreekanth Reddy Suda (651709), Krishna Vamsi Chalamalasetti (651815), Chakra Shree Harsha Aravilli Venkata (651503), and Nishkala Kambham (651422) under the supervision of Prof. Dr.-Ing. Frank Dienerowitz (Frank.Dienerowitz@eah-jena.de).

Date od Submission: 09th February 2024.

Signed,

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