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DESIGN AND OPTIMIZATION OF SIX-AXIS FORCE/MOMENT SENSOR USING FEA

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Abstract - *Over the next decade, the number and variety of robots in the workplace will be soar, taking over many jobs that are too dirty, too dull or too dangerous for people to do. In order to develop such intelligent robot, we need to give them a strong sense so that it can interact with its environment. In this paper, design of six-axis Force/Moment (F/T) sensor in three perpendicular directions with the stepped beam is developed. The design is checked using FEA method and found to be safe. Preliminary design is developed using FEM and then Design of Experiments (DoE) is carried out in order to get optimum design variables using FEA. Central Composite Design Type Design of experiments is carried out and Genetic aggression type response surface is generated. For optimization by screening method, objective functions and constraints are decided.*

Keywords*-Force/Moment Sensor, Strain Gauge, FEA, DOE, Optimization.*

I. INTRODUCTION

With the ever-increasing demand for the quality product, it is necessary to increase the productivity, qualityand accuracy in manufacturing or any assembly operation. If the machine is an intelligent enough to interact with their working environment, then these goals can be achieved. Robot-like humanoid also required the better joint control in order to walk on uneven tertiary. When an intelligent robot grasps an object of unknown weight into Cartesian space, it should accurately measure all the three forces (F_x, F_y,F_z) and three moments (M_x, M_y,M_z).

Gab Soon-Kim [1]developed six-axis Force/Moment sensor using rectangular taper beams whose rated output is not same for all the three forces and three moments. Also, maximum interference error is 3.65 %. Gab Soon-Kim et al.[2]derived the equation of strain at a particular point on the beam which is used to predict the strain value analytically. Authors have also compared the strain value obtained by theory with the value obtained using FEA software and found that maximum error is less than 5.7% and maximum interference error is less than 2% but a rated moment in all three axes are not same. Yingjian Wang et al.[3]suggest that in order to find out the stress and strain distribution along the elastic beam, Finite Element Analysis simulation tool is very effective and quick. Authors have derived the analytical equation of strain using Timoshenko beam theory to derive a mathematical relationship between strain and size of the sensor plate. Their comparison shows that analytic and numerical solution obtained using FEA shows good agreement but its generalized rated loads are not same for all the three axes. Chao Yuan et al. [4]developed a systematic method of deriving a mathematical model of F/T sensor which can be used to compare analytic solution with software. The compliance matrix which shows the relationship between strains with generalized force is derived. F. Beyeler et al.[5] have designed capacitive type multi-axis F/T sensor which has a capacity of monitoring forces in sub-milli-newton and moments of sub micronewton-meter which are used for the microrobotic application. Yongjun Sun et al. design a sensor with largest coupling error is 6.5 % and lowest sensitivity in F_z direction. It provides the method to reduces the error in measurements of strain. Gab-Soon Kim et al.[6] developed a sensor for humanoid robot's foot to walk on uneven terrain safely with different rated load and moment with parallel plate beams with the same rated output. R. Ranganath et al. [7] concluded that near-singular configurations, small applied force-torque in certain directions can give rise to the large forces in the links. Yuichiro Hayashi et al. [8] designed four axis F/T sensor used to measure twisting moment on finger cushion of the robotic hand and optimized the structure using Finite Element method to get optimum design variables.KenalTandel et al. [9]derived the equation for the normal strain for rectangular beam type configuration for six-axis F/T sensor and compared the theoretically strain value with experimental strain.

There are so many multi-axis F/T sensors available which are not customized. So it is necessary to develop F/T sensor which has optimum design variable to give the maximum output. So that cost of the prototype making, product cycle time and cost of the sensor reduces. This paper describes the method to do optimization using Finite Element Tool.

II. Design of Sensor

Table 1: Basic Dimensions of Six-Axis F/T Sensor

Basic Dimensions	Variable dimensions								
	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)	b (mm)	h1 (mm)	h2 (mm)	t1 (mm)	t2 (mm)
Sensor	85	70	38	20	8	6.43	8	12	4.4

The basic dimensions of the sensor are derived from analytic equations by using boundary condition and load applied which are 250 N forces for the three axes (F_x, F_y,F_z)and 50 N-m moments for all three moments (M_x, M_y,M_z). In order to increase the sensitivity, a new six-axis F/T sensor with new dimensions are introduced as shown in Table 1.

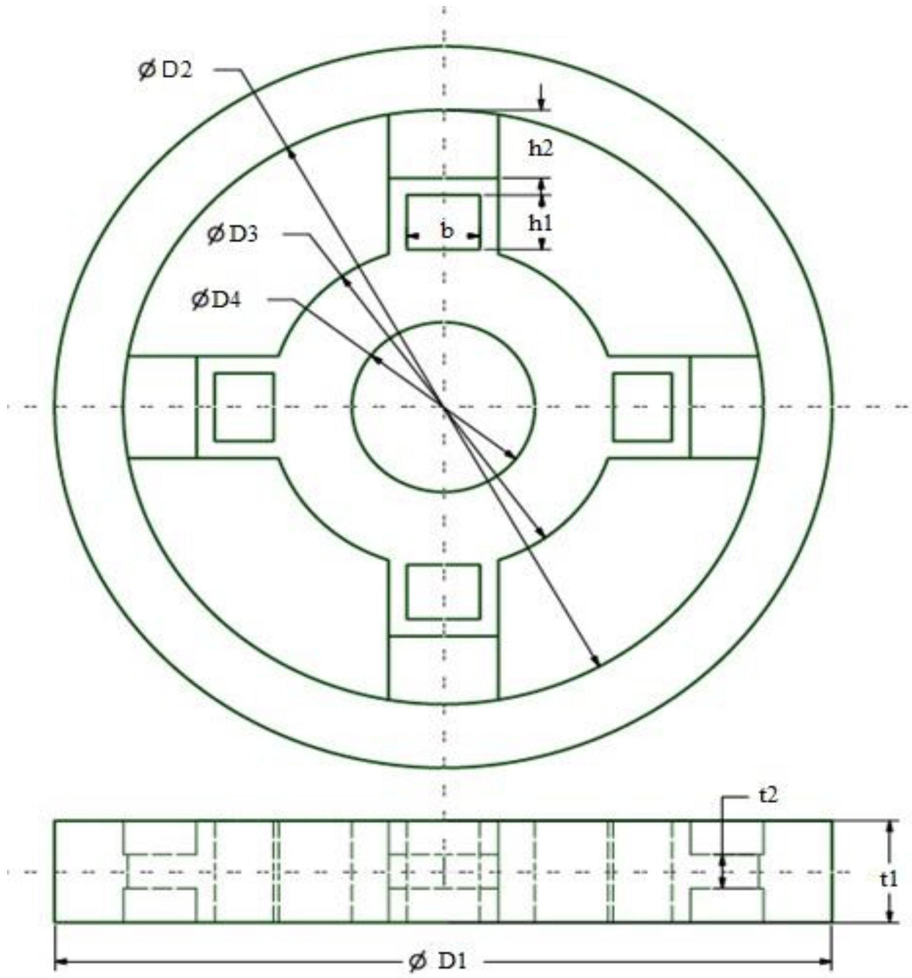

Figure 1:Six-axis F/T sensor

A basic drawing of the Six-axis F/T sensor is shown in Figure 1. The material selected for this analysis is Aluminum alloy having Modulus of Elasticity of 71 Gpa and Yield strength in tensile is 280 Mpa. This design is checked by the FEA software ANSYS Workbench and found to be safe.

Strain gauges are used as sensing element in order to measure forces and moments. Strain Gauge is ultra-thin heat treated metallic conductive coil whose resistance is changed according to the applied load. The output of the strain gauge is a very small voltage which can be accurately measured with the help of Wheatstone bridge. When the load is applied the Wheatstone bridge becomes unbalanced. This change in resistance can be accurately measured and hence the forces and moments are measured.

III. FEA Analysis

Finite Element Analysis is a very strong tool for analysis of complex problems. Once the design of F/T sensor is done, strain value using FEA software is found out. Problems can be solved even there is no prototype available, by using FEA, problems can be solved in the conceptual phase from CAD model itself. Optimization can also be done using FEA software. It will drastically reduce the product cycle and cost of the product by minimizing the prototype making.

The dimensions of the beam 50×10×5 mm, consider for the software validation. The strain is calculated at 10 mm from the fixed end.By theoretically, we can calculate the strain at the point 10 mm from the fixed end as below:

$$\sigma = \frac{M \times y}{I} = E\varepsilon$$

Where σ = Bending Stress
y = Distance from centerline to extreme fiber
M = Moment due to Load
I = Moment of Inertia

$$\varepsilon = \frac{M \times y}{E \times I} = 6.76056 \times 10^{-4}\ mm/mm$$

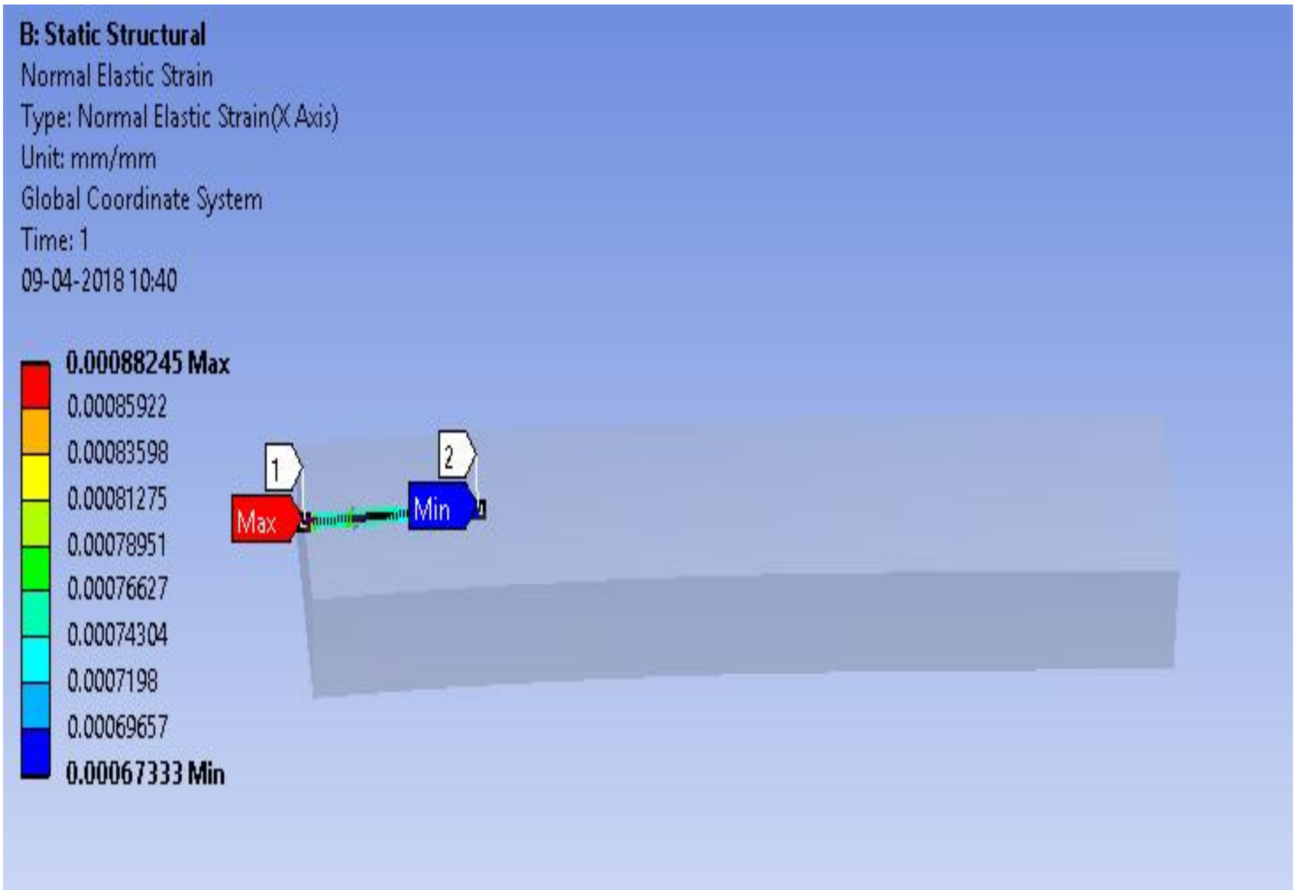

Figure 2: Software Validation for Cantilever Beam

By using software, strain obtained is 6.7333×10^{-4} mm/mm. So both valuesarenearer to same. So software can be used in order to find out strain distribution in the beam.

A parametric 3D model of six-axis F/T sensor is made using SpaceClaim software and geometry is used for the further analysis in ANSYS Workbench. The outer ring of the sensor plate will be fixed and the load is applied to the inner ring of the sensor as shown in Figure. 3.

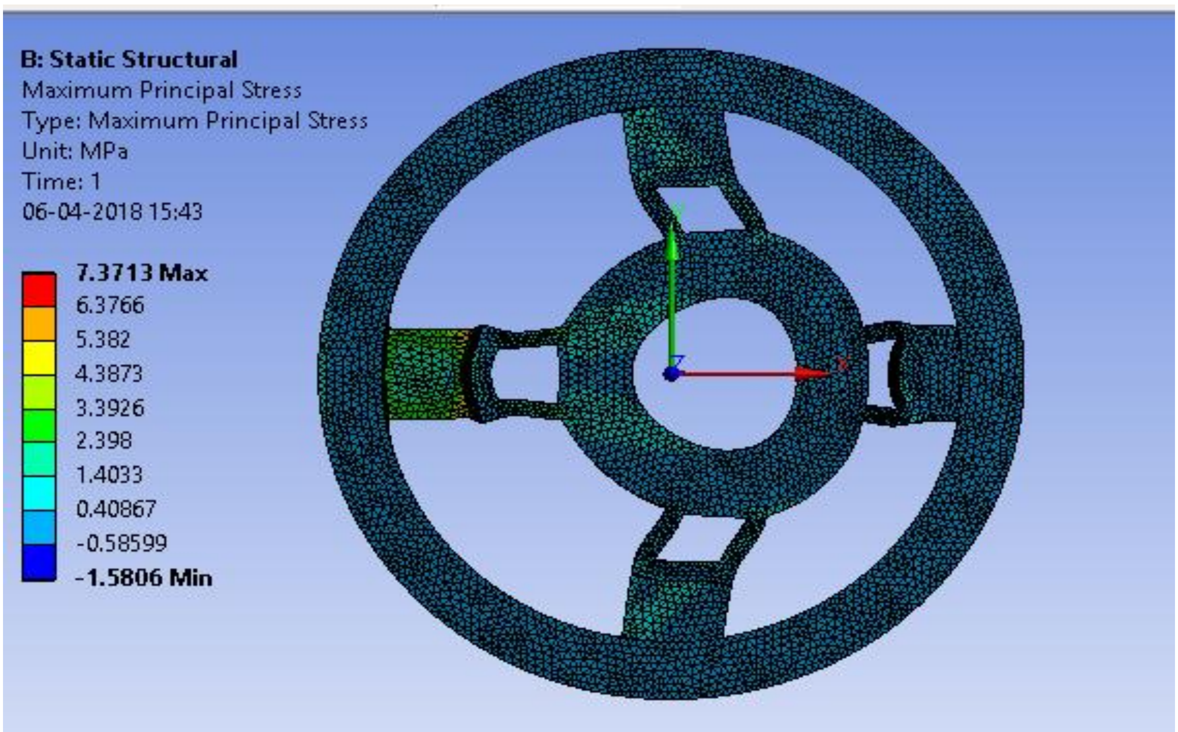

Figure 3: FEA model

The list of maximum Principle stress and Von-misses stress for load acting in F_x, F_y&F_z and $M_{x,}$ M_y &$M_z$are tabulated in Table 2.

Table 2. Maximum Principle stress and Von-misses stress

Direction of Load Application	Maximum Principal Stress (Mpa)	Von-misses Stress (Mpa)
F_x	7.37	6.64
F_y	7.21	6.38
F_z	15.96	12.46
M_x	175.5	155.73
M_y	172.21	146.77
M_z	136.34	98.04

The material which is going to use should have higher yield strength compared to max principle stress. So our design is safe.

A. Design of Experiments using FEA Software

Design of experiments (DOE) is a systematic method to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output. Here in this case output of our sensor is strain value. So dimensions of the beam and slot should be varied and find the effect of that variable on the output strain value. This way we can get the optimum design and minimize the cost and time of making prototype.
The three factors and two-level design of experiments using Central Composite Design (CCD) is used as shown in Table 3.

Table 3: Three-Factor Two level DOE

Input Parameter	Basic Dimensions	Lower Bound	Upper Bound
Slot Height	6.73	5.787	7.073
Slot width	4	3.6	4.4
Beam thickness	2	1.8	2.2

In this paper, three-factortwo-level design with Central Composite Design (CCD) is used. The CCD design mainly consists of one center point, 2×n axis points located at –a and +a positions (where a= (no. of the factorial run)$^{1/4}$[10]) on each axis of selected input parameters and 2^n design points. So, total fifteen points are found out by using CCD as shown in Table 4.

Table 4: CCD type DOE

Slot height	Width	Thickness
6.43	**4**	**2**
5.787	4	2
7.073	4	2
6.43	3.6	2
6.43	4.4	2
6.43	4	1.8
6.43	4	2.2
5.907219	3.67479	1.837393
6.952781	3.67479	1.837393
5.907219	4.32521	1.837393
6.952781	4.32521	1.837393
5.907219	3.67479	2.162607
6.952781	3.67479	2.162607
5.907219	4.32521	2.162607
6.952781	4.32521	2.162607

B. Response Surface

Response surfaces are an efficient way to get the variation of a given performance with respect to input parameters. From the DOE results, a Genetic Aggregation Type Response surface is computed for each output variables. This Response surface is further used for optimizations. There are five response surface types available in ANSYS Workbench which are Standard Response Surface (2nd order polynomial), Kriging, Non-parametric Regression, Neural Network and Sparse Grid.

C. Multiple Objective Type Optimization

To get the optimum design dimensions, the Screening method of optimization is used. It will collect 1000 sample points from the response surface and gives the three best candidates points. The Objective function and constraints for this analysis are given in Table 5.

Table 5: Objective function and Constraints

Input Parameter	Objective Function	Constrains
Slot Height	Maximize (P1)	
Slot Width	Maximize (P2)	
Beam Thickness	Minimize (P3)	
Output Parameters		
Normal Elastic strain for F_x and F_y sensor	Maximize (P4)	1e-07 < P4 <1e-03
Von-Misses Stress for F_x and F_y sensor	Minimize (P5)	P5 < 280 Mpa
Normal Elastic strain for F_z	Maximize (P6)	1e-07 < P6 <1e-03
Von-Misses Stress for $F_z$sensor	Minimize (P7)	P7 < 280 Mpa
Normal Elastic strain for M_x and M_y sensor	Maximize (P8)	1e-07 < P8 <1e-03
Von-Misses Stress for M_x and M_y sensor	Minimize (P9)	P9 < 280 Mpa
Normal Elastic strain for M_z	Maximize (P11)	1e-07 < P11 <1e-03
Von-Misses Stress for M_z	Minimize (P12)	P12 < 280 Mpa

So, the software gives the best three candidate points which will satisfy our objective function and constraints. This Way, optimum design dimensions without actually making prototypes could be found out. The three candidate points are shown in Figure 4.

Candidate Points	Candidate Point 1	Candidate Point 2	Candidate Point 3
P1 - Slot_height	5.787	7.073	7.073
P2 - width	3.6	3.6	4.4
P3 - thickness	2.2	2.2	2.2
P4 - Normal Elastic Strain 2 Maximum (mm mm^-1)	5.5051E-05	5.8143E-05	6.4382E-05
P5 - Equivalent Stress Maximum (MPa)	10.349	11.053	13.627
P6 - Normal Elastic Strain 2 Maximum (mm mm^-1)	0.00033677	0.00043111	0.00051615
P7 - Equivalent Stress Maximum (MPa)	126.07	130.55	179.86
P8 - Equivalent Stress Maximum (MPa)	65.928	95.098	156.63
P9 - Normal Elastic Strain Minimum (mm mm^-1)	2.8786E-05	0.0002568	0.00029898
P10 - Normal Elastic Strain 4 Minimum (mm mm^-1)	3.1266E-05	0.00025683	0.00029954
P11 - Equivalent Stress Maximum (MPa)	4.7564	6.5955	8.7646
P12 - Normal Elastic Strain 3 Maximum (mm mm^-1)	6.8319E-06	2.5523E-07	4.7419E-06

Figure 4: Best Suited Candidate points

IV. Conclusion

In this paper, the six-axis F/T sensor is designed by using FEA. The design is checked by software and found to be safe. The Optimum Design variable is found out using FEA. To find out optimum design variables, CCD type Design of Experiments is carried out with three factor and two level. With the help of DOE, the best suited genetic aggression type response surface is generated. From the generated response surface, screening type of optimization is carried out. The objective functions and constraints are decided based on the design parameters. From the given details, the software would give us optimum design variables that satisfied our objective function and constraints. So, the cost of prototype making and product cycle would be reduced.

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