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A Fundamental Study of Multi-Dimensional Force/Moment Analysis Dynamometer

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Abstract: *The exactness in the measurement estimation of three-dimensional power/second is important for the assembling procedure, for satellite, and in military hardware. The motivation behind this examination is to plan a multi-dimensional multi-point power/second (F/M) estimation MP-M dynamometer model dependent on three-pivot piezoelectric sensors establishment. The FEM reproduction is performed utilizing ANSYS programming and scientific examinations are completed utilizing determined conditions. The deliberate FEA results are predictable with the applied standard power/minutes. The blunder distinction of FEM investigation is under 1%. The FEM reproductions results are roughly 99-100% of the applied hub power, vertical power and pitch second individually. The planned MP-M dynamometer model is able to gauge spatial power/second precisely and reenactment tests are examined.*

Key Word:*Three-axis piezoelectric sensor, multi-dimensional measurement, SolidWorks design, and FEM simulation.*

I. Introduction And Literature Review

This article outlines „Theoretical investigation of multi-dimensional force/moment measurement dynamometer‟ is designed at the school of mechanical engineering experimental lab at Dalian university of technology DUT, China. The model is designed and analyzed using FEM analysis [1] and constructed designs have been sent to the manufacturing company. The MP-M dynamometer model can measure both the magnitude and direction of the applied force and the moment vectors in three-coordinates [2]. However, in this model, an axial force and normal force are applied maximum up to 15 kN and a pitch moment is applied maximum up to 11.97 kNm. The dynamometer model mainly consists of a long balance plate dynamometer with eight three-axis piezoelectric sensors uniformly mounted between the clamped plates, a base bed to support the entire model, two hydraulic loaders to apply the force/moment in horizontal and in the vertical directions.

The demand for accuracy in the measurement of multi-dimensional force is increasing with the time in global competition as it has wide applications in experimental work [3] and in real life such as humanoid robots [4], automotive industry [5]-[6] and aerospace industry[7]. The designed multi-point measurement model is capable of measuring the three coordinates of force/torque [8]-[9]-[10]-[11]. The model has been designed by providing an upper and lower plate support type assembly to piezoelectric sensors to reduce assembly error[12] and to provide easiness in the installation of load sensors in the model. Thus, it is essential for force-measuring devices to precisely measure forces with multi-points locations. The studied research is based on designing a rectangle pattern allocation of tri-axial piezoelectric sensors on a long plate dynamometer which can measure six-components force/torque measurement[13]-[14]. The piezoelectric technology has been used in this research is based on converting the mechanical energy into an electric voltage or signal. Moreover, when a quartz wafer[15] is packaged as a mono-axial piezoelectric sensor or tri-axial load sensor[16]-as shown in Figure 2. The measuring range of six-axis force/torque sensors is very wide and sensors survive high overload is more than 100 percent of full-scale output. Therefore piezoelectric force sensors are suitable for measurements in experimental laboratories, industrial measurements, and mechanical robotics [18].

This article is based on installing a rectangle pattern of eight tri-axial piezoelectric sensors on a long dynamometer model. In the experimental system test, a total of eight points are allocated on specific positions to apply the pull and push force/moment (F/M). However, in this paper, the FEM analysis[19]-[4] has been carried only for the selected three points as the MP-M dynamometer model is under the fabricating process. The proposed FEM model describes the static calibration in terms of total deformation, stress and force reactant analyses of the located points using FEA. Further research will be studied after the manufacturing and assembly of the dynamometer model to perform the experimental calibration.

II. Design Review

The designed model selects the piezoelectric sensors as the sensing element is mainly based on the positive effect, load sensors can produce induced charges caused by force. The main design of the MP-M dynamometer model includes a base bed for supporting the whole model, a vertical hydraulic loader, a horizontal hydraulic loader, a standard force measurement device, a bottom long late, a cover long plate and tri-axle piezoelectric sensors mounted in between the base and cover plates. SolidWorks 2018 software is used to design all components of the MP-M dynamometer model and after the successful designing of all the parts, they were assembled together to construct the multi-dimensional multi-point force/moment measurement dynamometer model.

2.1. The Tri-Axial Piezoelectric Sensor Assembly Unit

The tri-axial piezoelectric sensors assembly is designed by providing two supporting assembly parts to the tri-axial piezoelectric sensor to reduce the installation error of sensors (Figure 2(b)). Figure 2 shows the 3D design of the tri-axial piezoelectric sensor using Solid Works software. The piezoelectric sensor assembly contains a total of four parts as, an upper supporting, a lower supporting part, a long-connected bolt, and a pre-tightening nut. The main coordinates of the sensor are shown in Figure 2(a) and the mesh with coordinates is shown in Figure 1.

Figure 1. Mesh analysis and coordinates of the tri-axial sensor

Three-axis sensor (b) Components of the assembled unit (c)The tri-axial sensor assembly unit
Figure 2. 3D design of tri-axial piezoelectric sensor assembled unit

2.2. MP-M Dynamometer Model Design

The MP-M dynamometer model is designed in the form of a long balance plate dynamometer model, in which a total of eight three-axis piezoelectric sensors are installed. The main dynamometer model consists of a cover plate and a base plate and sensors mounted in between theclamped plates. The total length of the multi-points measurement MP-M dynamometer model is = 3600 mm, breadth „ ‟ is 900 mm and the height ‟ is 760 mm (Figure 4). The developed model consists of two hydraulic load stations to apply the load (force/moment) on allocated points. The six-components of force/moment of the dynamometer model are shown in Figure 3.

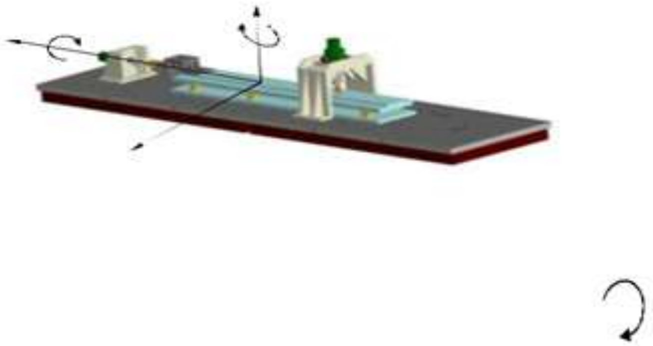


Figure 3. 6 DOFs of the MP-M model (rotation axes definition)

2.2.1. SolidWorks Modeling

SolidWorks 2018 is used for designing all main parts of the model and all components are then assembled together to form the entire model. The final assembly of the dynamometer model consists of a subassembly of clamped plates with the installation of tri-axial sensors, a horizontal and a vertical hydraulic load station equipped with a standard force measurement device and a connecting rod to apply the point load and the main base which is fixed on the floor to support the entire model. The all mentioned components of the MP-M dynamometer model are highlighted in Figure 4 and the features are also listed in Table 1. The bellow Figure 4 illustrates the SolidWorks design of the entire model with a description of all main parts of the designed model like (1) horizontal hydraulic loader (2) force measurement standard device (3) small axial plate (4) three-axis assembly unit (5) vertical hydraulic loader (6) Connected rod (7) top cover plate (8) bottom plate (9) main base bed.

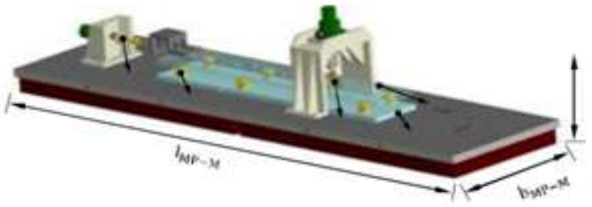
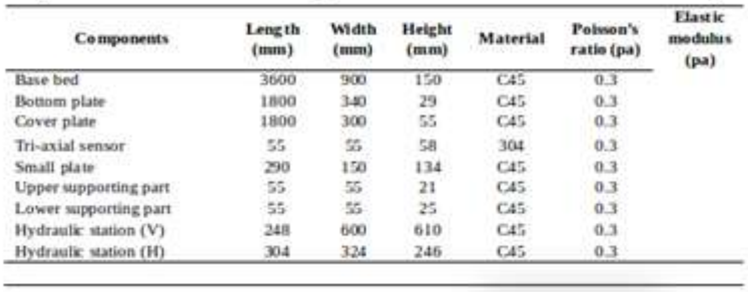


Figure 4. 3D design of MP-M dynamometer model with transparent cover plate for the clear view ofinstalled sensors

Table 1. Structural parameters of the components assembled in MP-M dynamometer model



Components	Length (mm)	Width (mm)	Height (mm)	Material	Poisson's ratio (pa)	Elastic modulus (pa)
Base bed	3600	900	150	C45	0.3	
Bottom plate	1800	340	29	C45	0.3	
Cover plate	1800	300	55	C45	0.3	
Tri-axial sensor	55	55	58	304	0.3	
Small plate	290	150	134	C45	0.3	
Upper supporting part	55	55	21	C45	0.3	
Lower supporting part	55	55	25	C45	0.3	
Hydraulic station (V)	248	600	610	C45	0.3	
Hydraulic station (H)	304	324	246	C45	0.3	

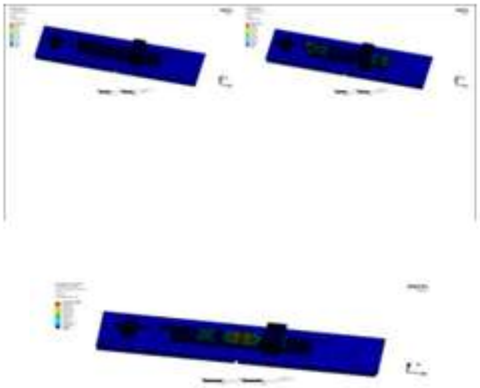
2.2.2. Meshing

The ANSYS 18.1 software is used to mesh the design model and generated mesh is shown in Figure 5. The model is meshed into 591023 nodes and 334342 elements. Mesh sizing function is adaptive with a coarse relevance center and coarse span angle center. The mesh smoothing quality has been selected medium and minimum edge length is 0.2 mm.

Figure 5. The generated mesh of the MP-M dynamometer model with coordinates

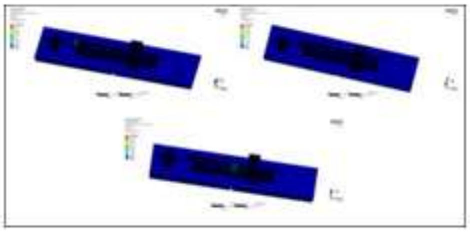
2.2.3. Stress and Deformation Analyses

The total deformation and stress analysis of the MP-M dynamometer model is carried out using ANSYS Workbench. A total of three individual points are allocated to apply the axial, vertical and moment force. The following Figure 6 and Figure 7 illustrate the total deformation analysis and equivalent stress analysis respectively when a maximum force =15 kN is applied on the allocated points P1 and P2 and maximum moment = 11.97 kNm is applied to P3 in defined direction



(a) axial force =15 kN (b) Pitch moment=11.97 kN-m

Figure 6. Total deformation analysis of MP-M dynamometer model



(a) axial force=15 kN on P1 (b)Pitch moment = 11.97 kN-m on P3

(c) vertical force =15 kN on P2

Figure 7. Stress analysis of MP-M dynamometer model

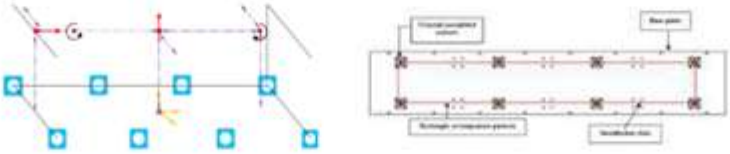
The maximum deformation value of vertical force at the center and pitch moment is approximately the same and is = 0.027-0.032 mm and of axial force is =0.60 mm as shown in Figure 6 respectively. The maximum stress is = 114 MPa, 53.62 MPa, and 34.78 MPa in the axial, center and bending moment direction respectively (can be seen in Figure 7). The values of total deformation and the stress in the axial, normal and moment direction are acceptable and provide satisfactory results to perform the experimental calibration.

III. Measurement Principle

The measurement principle of the designed model is based on a long dynamometer model which includes the established rectangle pattern combination of three-axis piezoelectric sensors mounted in between two clamped plates. Tri-axial sensors are used together in rectangular pattern combinations to design and construct a six-component force/torque measurement dynamometer. Tri-axial piezoelectric sensor response outputs are , and are the drag, side and lift forces. The dynamometer response output is three components of force and three components of the moment as, and are rolling, pitching and yawing moments.

3.1. Measurement Structure

The measuring structure and developed directional view of the dynamometer model is shown in Figure 8(a). The model structure is based on the designing of the dynamometer model using the rectangular patterned installation of the assembled units as shown in Figure 8(b).

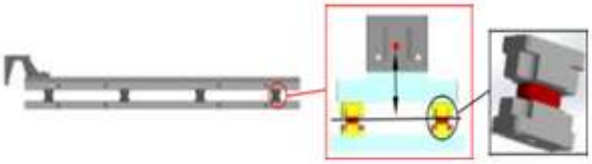


(a)Schematic diagram of axial force (P1), the normal force (P2) and pitch moment (P3)

The layout of the rectangular arrangement pattern of installed sensors

Figure 8. Structural measurement diagram of MP-M dynamometer model

In above Figure 8(a), three allocated points are highlighted as and to apply the designed range of force/moment and S1-S8 are the corresponding piezoelectric sensors. The arrangement is total length of the rectangle combination = 1488 mm and breadth is = 224 mm as shown in Figure 8(b). ,are the distances of the allocated point P1‟ in the horizontal direction in the x-axis, perpendicular distance to the x-axis and vertical distance in z-axis respectively (Figure 8(a)). The same way and are distance for normal central force „P2‟ and moment force respectively. The measured distances of all located points in along the Y and Z-directions are the same that is 112 mm and = 55 mm respectively except the = 105 mm. The assembly unit of the three-axis piezoelectric sensor is designed with two supporting lower and upperparts and the sensor is mounted in between them as shown in Figure 2(b). The total length „‟ of the balance plate dynamometer model is 1800 mm, breadth „‟ is 390 mm and height „‟ is 192 mm.



(a) Dynamometer model (b) Assembly unit fixation (c) sensor unit

The rectangular arrangement mode is established to drive the mathematical equation to measure the total force and moments of the six-dimensional force/moment measurement model. The horizontal distance between the installed sensors is symbolled by „‟ and „‟ and their perpendicular distance to the x-axis is symbolled by „‟(Figure 10). The exerted standard force/moment can be calculated by using the derived mathematical equations.

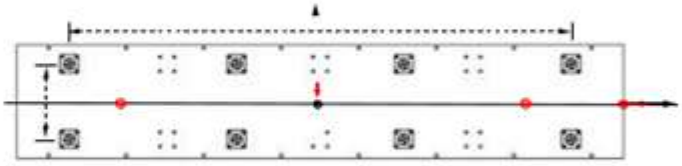
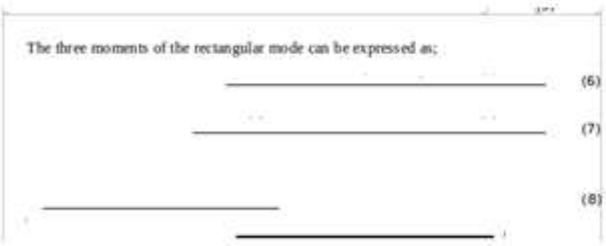


Figure 10. Rectangular arrangement mode for mathematical equations

The force and moment can easily be calculated by using the general formula;
The three forces of the rectangular mode can be expressed as;
$\sum$
$\sum$
$\sum$
The three moments of the rectangular mode can be expressed as;

Where , (i=1...n) as shown in equation (3, 4, 5) are the drag, side and lift forces
as shown in equation (6, 7, 8) are rolling, pitching and yawing mome
and, and



The three moments of the rectangular mode can be expressed as;

(6)

(7)

(8)

IV. Numerical Model (Finite Element Model: Fem)

The structure of the designed MP-M dynamometer model is symmetrical in all three coordinates. ANSYS 18.1 software has been used to carry on the finite element analysis and to determine the safety of the dynamometer model for the various designed load application. The bottom part (base plate) of the model is fixed and the force sensors are mounted in between the clamped plates. Therefore, the connection of the sensors with the upper and lower plates can be regarded as a rigid connection. In this way a total of three static analyses have been conducted using FEM simulation and are listed as follows:

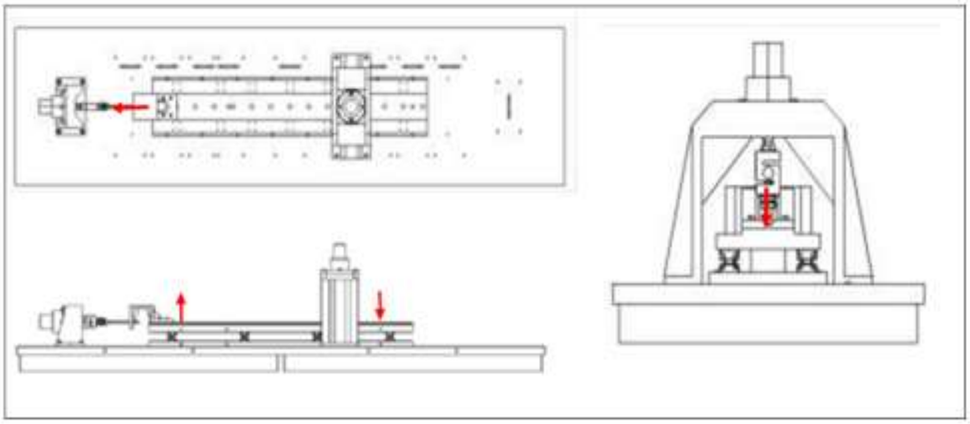


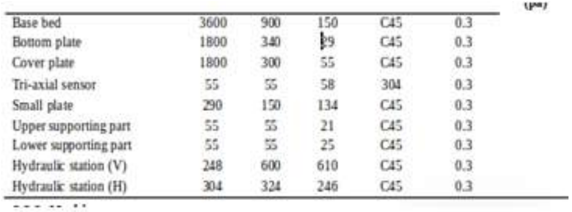
Figure 11.

Schematic diagram of applied of MP-M dynamometer model with the designed load onallocated positions

4.1. Static Analysis of Axial Force

The x-axis is parallel to the dynamometer and perpendicular to the vertical hydraulic loader in this MP-M dynamometer model as shown in Figure 11(a). The vertical and perpendicular distance of the located axial point „" is shown in Figure 8(a). The applied axial force also contributes some pitch moment along the y-axis because the axial force is applied on a height approximately 105 mm above the axial center Figure 9(b). The three co-ordinates force reactant (finite element analysis: FEM) output of the axial force point is listed in Table 2

Table 2. Static FEA (simulation) of the axial point (   )

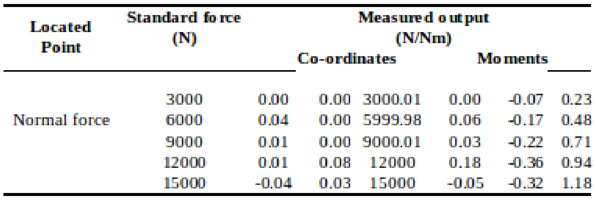


Base bed	3600	900	150	C45	0.3
Bottom plate	1800	340	29	C45	0.3
Cover plate	1800	300	55	C45	0.3
Tri-axial sensor	55	55	58	304	0.3
Small plate	290	150	134	C45	0.3
Upper supporting part	55	55	21	C45	0.3
Lower supporting part	55	55	25	C45	0.3
Hydraulic station (V)	248	600	610	C45	0.3
Hydraulic station (H)	304	324	246	C45	0.3

4.2. Static Analysis of Normal (Center) Force

The z-axis is in the vertical direction and perpendicular to the dynamometer plate in this model as shown in Figure 11(c). The distance , , and for the designed normal force point „‟ are shown in Figure 8(c). The normal applied force does not contribute any roll, yaw or pitch moment.

Table 3 Static FEA (simulation) of the normal force point ()

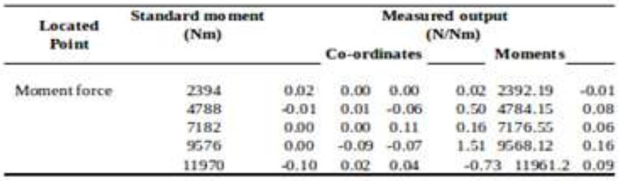


Located Point	Standard force (N)	Measured output (N/Nm)					
		Co-ordinates			Moments		
Normal force	3000	0.00	0.00	3000.01	0.00	-0.07	0.23
	6000	0.04	0.00	5999.98	0.06	-0.17	0.48
	9000	0.01	0.00	9000.01	0.03	-0.22	0.71
	12000	0.01	0.08	12000	0.18	-0.36	0.94
	15000	-0.04	0.03	15000	-0.05	-0.32	1.18

4.3. Static Analysis of the Pitch Moment

The pitch moment corresponds to the motion of the dynamometer head up (positive) or down (negative) as shown in Figure 11(b). The moment in the designed ranges are applied along y-axis on the pitch moment „‟ point and the position of the point „‟ is highlighted in Figure 8(c). The FEM calibration analysis of the six-component force/moment of P3 is discussed in Table 4.

Table 4 Static FEA (simulation) of the moment force point (   )



Located Point	Standard moment (Nm)	Measured output (N/Nm)					
		Co-ordinates			Moments		
Moment force	2394	0.02	0.00	0.00	0.02	2392.19	-0.01
	4788	-0.01	0.01	-0.06	0.50	4784.15	0.08
	7182	0.00	0.00	0.11	0.16	7176.55	0.06
	9576	0.00	-0.09	-0.07	1.51	9568.12	0.16
	11970	-0.10	0.02	0.04	-0.73	11961.2	0.09

V. Discussion

A structural model, mathematical model, and FEM model have been designed to analyze the MP-M dynamometer model. At first, a structural model has been constructed to highlight the allocated points to apply the load and the corresponding coordinate of the designed model as shown in Figure 8(c). The FEM force reactant analysis of allocated points is shown in Table2,

Table 3and Table 4. The FEM analysis results of the dynamometer model are approximately 99-100%. Hence, the analysis results of FEM simulation experiments are in agreement with the standard force/moment. Therefore, the designed MP-M dynamometer model is suitable for further tests for experimental calibration measurements as the FEM simulation results are in agreement and provide satisfactory results. The experimental calibration will be performedafter the manufacturing and assembly of the model. The scheduled period for the experiment system of the MP-M dynamometerproject is March 2020 in winterat the factory of the school of mechanical engineering at Dalian University of technology.

VI. Conclusion

This article is the basis to design the main components of the MP-M project model and to perform FEM simulation experiments for satisfactory investigations. The structural model of the multi-dimensional dynamometer is built and then analyzed using FEM simulation. The FEM analysis results of axial force, normal central force, and the pitch moment proved regularity with the applied range of standard force/moment. The investigated results of the FEM model are closer to the input values and the measured percent error is under 1%.

VII. Declaration Of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to research, authorship, and/or publication of this article.

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