Research on Multi-points Measurement of a Novel Alternate arrangement dynamometer Model

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Abstract. The basis of this research is to design and fabricate a new type of alternating arrangement of three-axis piezoelectric sensors dynamometer for measuring six-component force/torque measurement. The system consists of a long dynamometer with eight tri-axial piezoelectric sensors alternatively distributed. The design theory of the piezoelectric six-axis force dynamometer is established, including a finite element model (FEM: ANSYS analysis) and experimental model (static and dynamic calibrations). Structural design is constructed for analyzing the operating principle and performing the experimental measurements. The multi-points measurement (MP-M) model is fabricated based on the established alternate arrangement pattern and force application of multi-points allocation to apply the force/torque. Therefore, this work describes linearity error, repeatability error and cross-talk error of the constructed model. However, the designed model is not limited only to an alternate arrangement pattern of tri-axial sensors. But in the future, other types of arrangements will be researched and will be experimentally performed.

1. Introduction

The multi-points measurement model (MP-M) concept can be implemented in the manufacturing process, robot design, Rocket thrust measurement and space station. The model is designed for measuring the external forces and collecting the spatial force information. The model has been designed, constructed and tested based on using tri-axial piezoelectric sensors technology. Therefore, this study requires a detailed review of the literature and an overall design approach based on the static characteristics of the fabricated model.

There are various ways to measure spatial force/moments by arranging sensors in different locations and using a different types of arrangements. A lot of research has been done on the selection of sensors and their arrangement geometry which supports the measurement of six components force/moments[1]. Literature can be found on a different combination of sensors arrangement as Zhenyuan Jia et al, investigated a multi-point and a square arrangement with 3 and 4 sensors mounted respectively and their maximum error is up to 5.3%[2]. Moreover, Hexagonal and octahedral arrangements with six and eight tri-axial piezoelectric sensors installed respectively and their cross-talk error is within 4.5%[3]-[4].

A six-component force sensor may be a base, a table dynamometer, or a wrist type according to its location of application, although the force-sensing principles are basically the same[5]. However, table dynamometers offer precise and effective force measurement, usually typical dynamometer consists of force sensors that are mounted in between two plates[6]. The different types of combinations of the tri-axial sensors allow for six degrees of measurement as Brimhall Z.N. used a combination of tri-axial sensors on the forward structure and in the back to measure six degrees of freedom of rocket motor test.
stand[7]. Alexander Winkler and Jozef Suchy used a 12DOF sensor for dynamic force/torque measurement[8]. Another researcher discussed strain-gauge balances as high-precision instruments that are capable of measuring up to six degrees of freedom of aerodynamic loads[9].

A Multi-point piezoelectric balance enabling the measurements of 6DOFs is designed and is developed for the experimental calibration. The Tri-axial piezoelectric load cells are developed to be used in this designed arrangement pattern as they offer an increased stiffness and fast response. At the first stage, all the sensors are statically calibrated one by one and their sensitivity and errors have been recorded. Secondly, the design arrangement has been implemented in the MP-M model during the experimental setup system. And in the last static and dynamic calibrations have been performed by applying designed load for developed model.

2. Model structure and measurement principle

According to the structural characteristics of the tri-axial piezoelectric force, sensors can measure the three components of force in X, Y and Z directions. But for measuring the moments such as pitching, yawing and rolling the single sensor is not enough, therefore, a combination of piezoelectric sensors by a specific arrangement has been designed and implemented for measuring force/torque measurements. The model structure is based on the designed distance between the alternate allocated sensors and assigned multi-directions force output to the sensors.

2.1. Model structure

The analysis of the structure is defined as the following assumptions are made; the rigidity of all the tri-axial sensors regarding the quartz crystals are identical, with almost equal sensitivities and symmetric output ratios. The base plate and cover plate for sensors installation of the long dynamometer are rigid bodies.

Fig 1. Multi-points measurement model structure

In Fig 1, ‘l’ is the total length of arrangement pattern in which the eight sensors are installed in an alternate method. The same way, breadth ‘b’ is considered as the horizontal distance between installed sensors in the Y direction and height ‘h’ is measured as the vertical height of sensors in the Z direction. However, eight mode supports of piezoelectric sensors offer high rigidity and a wide measuring range. Because of the flexibility in the model, the pattern can be changed during the experimental work or in future research.

2.2. Measurement principle

The measurement principle of the MP-M model mainly includes a base plate, a cover plate, and eight triaxial piezoelectric sensors alternate installation as a long dynamometer. The main measuring principle is using piezoelectric technology for measuring the external forces. Piezoelectric quartz crystal chips are used as an active element inside the tri-axial piezoelectric sensors and tri-axial sensors are used together to design and construct a dynamometer as shown in below Fig 3. And the alternate arrangement shape pattern of the designed model is shown in Fig 2 with eight tri-axial sensors alternatively mounted.
3. Numerical model
ANSYS software is used to evaluate the static characteristics of a multi-points dynamometer model in which total deformation and stress analyses have been performed. A designed modeling approach and static load methods application are used in FEM analysis to verify the effectiveness of the designed model.

3.1. Modeling and Meshing
The design of all components of the main model is built with SolidWorks and all parts are assembled according to the operating and measurement principle to construct the MP-M model. Then the designed geometry model is imported into ANSYS software and a mesh is generated. The dimensions of the main parts of the designed model and the material are stated in above Table 1. The ANSYS Workbench is used for meshing the MP-M model, the model has meshed into 564894 elements and 851447 nodes as shown on the right side of Fig 4.

Table 1. Main structural parameters of Multi-points measurements model

| Component’s name | Length (mm) | Width (mm) | Height (mm) | Material | Poisson’s ratio (pa) | Elastic modulus (pa) | Density (Kg/m$^3$) |
|------------------|-------------|------------|-------------|----------|---------------------|---------------------|-------------------|
| Base plate       | 1800        | 340        | 29          | C45      | 0.3                 | 2$^{11}$             | 7850              |
| Cover plate      | 1800        | 300        | 55          | C45      | 0.3                 | 2$^{11}$             | 7850              |
| Tri-axial sensor | 30          | 30         | 12          | 304      | 0.3                 | 2$^{11}$             | 7850              |
| Small plate      | 150         | 150        | 100         | C45      | 0.3                 | 2$^{11}$             | 7850              |
| Preload bolts    | 75          | M10        | -           | 304      | 0.3                 | 2$^{11}$             | 7850              |
The 3D modeling of the MP-M model highlight all components which are assembled together to construct the main model. The cover plate is shown transparent to easily distinguish the position of tri-axial sensors as shown in above Fig 4. The total length of the balance plate model is 180cm, breadth is 39cm and height is 9.6cm. The vertical distance and horizontal distance between mounted sensors are 19cm and 40.25cm respectively.

3.2. Total deformation and force reactant output
The following Fig 5, illustrates the deformation when a maximum force 12kN is applied on the allocated point and the area with maximum deformation can be assessed nearer the force applied point. The load applied in the Z direction is push force and is taken as positive and load in X-direction can be considered as pulling force. The force reactant output of applied load in X- and Z-direction are discussed in below Table 5.

4. CALIBRATION EXPERIMENT AND DISCUSSION
The calibration of the multi-points measurement model is very important in designing and constructing the six-axis force/torque measurement model since the use of the model is directed to calibration results. Two types of experimental calibrations are designed for MP-M model one is static calibration and the second one is dynamic calibration.

4.1. Static calibration
The static calibration model mainly focuses on such indexes as linearity, repeatability and cross-talk error of the MP-M model. The fabricated model as shown in Fig 6 is calibrated for a single force up to 12kN applied on each assigned point individually, and the data output in all three directions recorded for every 3kN. This step is repeated three times to get the average values and to calculate the linearity and repeatability errors for the allocated points.
Fig 6. Diagram of experimental work (b) horizontal force load method $F_x$ in X-direction (c) vertical force load method $F_z$ in Z-direction.

4.1.1. Static calibration in Z- and Y-directions

The multi-load range force is applied in Z-direction on the marked point on the top of the cover plate of the designed model. The same way load is applied on one selected point on side of the cover plate in X-direction. $\sum x_i, \sum y_i$, and $\sum z_i$ where $i=1,2,3,\ldots,8$, is the summation of the output of eight sensors in the respective directions respectively. The calibration analysis of both points is discussed in below Table 2 and Table 3.

Table 2. Calibration experiment analysis in Z-direction

| Located Point | Standard force (N) | Measured voltage (V) | Nonlinear Error (%) | Repeatability Error (%) | Sensitivity (pC/N) | Cross-talk error (%) |
|---------------|--------------------|----------------------|---------------------|------------------------|-------------------|----------------------|
| $F_z$ Push force in Z-direction | $F_z$ | $\sum x_i$ | $\sum y_i$ | $\sum z_i$ | | | |
| 0 | 0.00 | 0.00 | 0.00 | | | | |
| 3000 | 0.01 | 0.04 | 3.13 | | | | |
| 6000 | 0.01 | 0.08 | 6.26 | 4.32 | 0.75 | 4.4 | 1.18 |
| 9000 | 0.01 | 0.11 | 9.41 | | | | |
| 12000 | 0.01 | 0.15 | 12.61 | | | | |
Table 3. Calibration experiment analysis in X-direction

| Located Point | Standard force (N) | Measured voltage (V) | Nonlinearity Error (%) | Repeatability Error (%) | Sensitivity (pC/N) | Cross-talk error (%) |
|---------------|---------------------|-----------------------|-------------------------|-------------------------|-------------------|----------------------|
| Fx            | Fx                  | Co-ordinates         |                         |                         |                   |                      |
| Pull force in X-direction | 3000 | 2.84 | 0.01 | 0.01 | 8.8 | 0.97 |
| 6000          | 6.11               | 0.04                  | 0.02                    | 2.65                    | 0.51              |                      |
| 9000          | 9.43               | 0.08                  | 0.02                    |                         |                   |                      |
| 12000         | 12.7               | 0.10                  | 0.12                    |                         |                   |                      |

In above Table 2 and Table 3, in their first column, the located point has been mentioned and the direction of force is highlighted whether the force is pulling or pushing force. The second column shows the applied standard forces in every 3kN and maximum up to 12kN. Furthermore, in the static calibration experiment, the linearity, repeatability, sensitivity and cross talk error are calculated for the constructed model.

4.2. Dynamic calibration

The dynamic calibration of the MP-M model as the response characteristics to the input signal that varies as a function of time. To calibrate dynamic characteristics of fabricated model an impact technology is used as shown in Fig7 and an FFT analysis carried out using DEWESoft software to find out the natural frequency (\(\omega_n\)). The dynamic response values for each coordinate are listed in Table 4.

![Fig 7. Schematic diagram of dynamic calibration](image)

Table 4. Natural frequencies in each direction

| Natural frequency | Fx   | Fy   | Fz   |
|-------------------|------|------|------|
| \(\omega_n\) (Hz) | >1000| >400 | >350 |

The model has a good response characteristic, frequency curve and can gratify measurement requirement as the three-dimensional natural frequency is 1000Hz, 400Hz, and 350Hz in X, Y and Z directions respectively.

4.3. Comparison of load output (%)

According to analysis discussed in above Table 2 and Table 3, the load-out ratios of FEM and Experimental analyses are obtained of multi-points are shown in the below Table 5.

Table 5. Comparison of Load output percent values of FEM and Experimental analysis

| Multi-load points | Load output (%) |
|-------------------|-----------------|
|                   | FEM analysis    | Experimental analysis |
| Fz                | 99.9            | 105.1                  |
| Fx                | 99.9            | 105.9                  |
Load output percent values of the MP-M model are in a range from 99.9 to 100 percent in FEM analysis and approximately 105.1 to 105.9 percent in experimental analysis. It can be observed, the percent output difference of FEM analysis is lower than the experimental analysis, because of the symmetry in structure and rigid body analysis in FEM. The load output percent differences between the FEM and Experimental analyses of \( F_z \) is 5%, in Z-direction and on point \( F_x \) is 6% in X-direction respectively.

The experimental results can be compared to the known rigid body FEM analysis result, an agreement is within approximately 1-6% error. The multi-points load output percent values of FEM and experimental analyses are close which proves the rationality of the theoretical model and supports the calibration experiment results of the novel designed alternate arrangement model.

5. CONCLUSION

The proposed research is based on the theoretical and experimental calibration of an established novel alternate arrangement shape dynamometer. A structure model is constructed to highlight the proposed arrangement of tri-axial sensors and to confirm the designed coordinates for sensors. The measurement principle of the established model is discussed and a mathematical model is derived. The developed model is verified by theoretical and experimental analyses. The experimental analysis of the fabricated model is in agreement with the theoretical analysis results of the designed model. The experimental results are compared to the known rigid body FEM analysis result and the consistency is in the range of about 1-6%. The static calibration verifies that the cross-talk error of the studied model is under 4 percent. However, the developed model needs more research for experimental calibration to minimize the occurred errors.

6. DECLARATION OF CONFLICTING INTERESTS

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

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