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A Method on Measurement of Six-DOF Force for Heavy Load Equipment

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Abstract. Aiming at solving the problem of the six axis force measurement and improving measurement precision for heavy load equipment in manufacturing, this study presents a new six axis force measurement method based on the heavy load division principle which is made with piezoelectric quartz as the force sensitive element. This study proposes a type of four point support structure and deducts the spatial mechanics model for the sensor. Finally, the static calibration experiment is carried out in this study. Experimental results show that, the six axis force can be measured with this method for heavy load equipment. The basic performance of the sensor shows that it can meet the engineering requirements well.

Introduction

The giant heavy manufacturing equipment is the basic equipment in manufacturing industry chain and it is the embodiment of extreme manufacturing capability. Heavy load manipulator equipment has the characteristics of large load, large inertia, multi degree of freedom, the multidimensional force position control ability, and the need to adapt to the load, walking, operation, coordination of complex work. Heavy load operating equipment and heavy load processing equipment can greatly improve the manufacturing capacity, precision manufacturing, production efficiency and material utilization and can also reduce energy consumption. In order to avoid load increase caused by the conflict of constraints or clamping failure, the terminal actuator for operating equipment is required in compliance with force with displacement caused by the deformation of the workpiece in the manufacturing process. Therefore, the study of six axis force measurement and force feedback has important significance, namely dynamic measurement of six axis heavy load conditions is the key technology in design of heavy load operating equipment in control system. Six axis force sensor can detect the force and moment in three dimensional space, which is important to improve the level of intelligent components.

SIR company in America designed the modular structure for sensor in 1973. Because its design, processing and assembling precision has great influence on it, the accumulated error is large [1]. A three vertical rib structure six axis force sensor was designed by P.C Watson in 1975 [2]. Brussel and Kroll of Israel also developed a four vertical rib structure of six axis force sensor [3-4]. Yoshikawa and Uchiyam and Bayo analyzed leMaltese structure type of six axis force sensor, [5-7]. Hatamura developed a ring structure of six axis force sensor [8]. Little studied for a small cylindrical force sensor [9]. Kaneko proposed a kind of double heads type six axis force sensor [10]. Hirose studied six axis force sensor using the photosensitive element[11-12]. Kerr, Nguyen [13],

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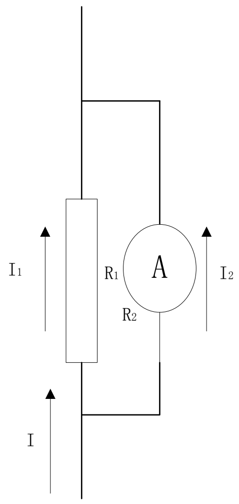
Ferraresi[14], Dwarakanath[15], Youlun Xiong in Huazhong University of Science and Technology and Chen Bin in Peking University carried out six axis force sensor design problem on the Stewart platform. At present, the measurement of these six axis force sensors are mostly confined to a small range. A six dimensional detection method to measure the load of 20KN or above has not been proposed. In this study, by using the quartz crystal sensor as sensitive element, a new method for the measurement of the force / torque of large equipment in heavy load conditions based on parallel load distribution principle is put forward.

Parallel Force Division Principle and Model for the Sensor

In the present study, in order to implement the dynamic measurement of the large space load on operating shaft, it is not feasible to load directly in the piezoelectric quartz group for the reason that the maximum bearing capacity of piezoelectric quartz is about 130N/mm^2, even if the large size of piezoelectric quartz is used, which can bear the load limit of about 12.5t, it is hard to meet the requirements of the operating load of hundreds of tons from the giant machines. That is to say the direct load type is not advisable. The sensor should use the load division mechanism, to make it acceptable in the range of a direct effect on the force sensing element.

The measuring principle of parallel force division is similar to the principle of DC high current shunt measurement, as is shown in Fig 1(a), The elastic model of heavy load division is shown in Fig 1(b).



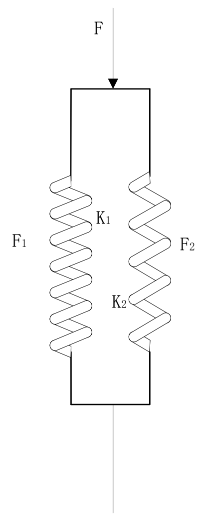


Figure 1(a) Model of current division **Figure 1(b) Model of heavy load division**

It is not feasible to use galvanometer directly to measure large DC current. The current division principle is used to slove the problem, Which shows that the algebraic sum of currents in a network of conductors meeting at a point is zero. According to this principle, When $R_1 << R_2$,we have:

$$I \approx \frac{R_2}{R_1} I_2 = C_r I_2 \tag{1}$$

Similarly, parallel force division principle for heavy load measurement is realized due to the stiffness force distribution principles of parallel mechanism. It is described as following:

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$$F = \left(\frac{k_1}{k_2} + 1 \right) F_2 = \frac{1}{C_r} F_2 \tag{2}$$

$$C_r = \frac{F_2}{F} = \frac{1}{\frac{k_1}{k_2} + 1} = \frac{k_2}{k_1 + k_2} \tag{3}$$

where k_1 represents the stiffness of parallel mechanism and k_2 represents the stiffness of force-sensitive element. C_r is defined as the load division ratio of the load measurement mechanism, that is, the ratio of load on force sensitive element in total load.

Piezoelectric quartz force sensor is mainly based on the piezoelectric effect, various cutting types of piezoelectric quartz that is sensitive to different directions of load can be designed according to the piezoelectric quartz matrix. X0°types which are sensitive to longitudinal load and Y0°types which are sensitive to shear loading are most commonly used. In order to improve the sensitivity of piezoelectric sensors and simplifies the structure, it is generally designed with two chips of same cutting type to form a crystal group, then a certain structure of a sensor is decided by assembling several crystal groups mentioned above.

Spital Structure and Mathematical Model

According to the measuring principle, the six axis force can be measured under the condition that the points of spital structure of piezoelectric quartz is not less than three. The external force is noted as F and can be decomposed into tri-direction normal force noted as F_x, F_y, F_z which can be lineal accumulated after measurement, and the same for the torque M_x, M_x, M_z. The value of torque is relied on the distance between piezoelectric quartz and the action point of external force. The mathematical model for six axis force sensor with n groups of piezoelectric quartz in spital structure can be presented as following:

$$\begin{cases} F_X = \sum_{i=1}^{n} f_{xi} \\ F_Y = \sum_{i=1}^{n} f_{yi} \\ F_Z = \sum_{i=1}^{n} f_{zi} \\ M_X = \sum_{i=1}^{n} f_{zi} x_i \\ M_Y = \sum_{i=1}^{n} f_{zi} y_i \\ M_Z = \sum_{i=1}^{n} f_{xi} x_i + \sum_{i=1}^{n} f_{yi} y_i \end{cases} \tag{4}$$

where i is noted as the point of piezoelectric quartz, x_i is projection distance between attachment point of force sensitive element and x-axis and y_i to y-axis.

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It can be learned from the model that when the amount of distribution point is odd, there must be a point in the coordinate axis of the sensor which may lead asymmetry of layout spatial structure. It may not only increase the amount of calculation, but also more error in the measurement results. With the increase of support points, quartz crystal groups also increased in number which will increase the cost. To determine the support point, it depends on the measurement requirements, Appropriate spatial layout structure points should be chosen according to the measurement requirements.

The four point support type is selected in this study for the reason of avoiding affection on the measurement results when the large change occurs on the action point of external force. It can also reduce the the cross interaction to sensors. By changing the installation location of force sensing element, it can get two kinds of layout for four point supporting type in structure: the rhombus layout,shown in Fig.2, and the square layout, shown in Fig.3.

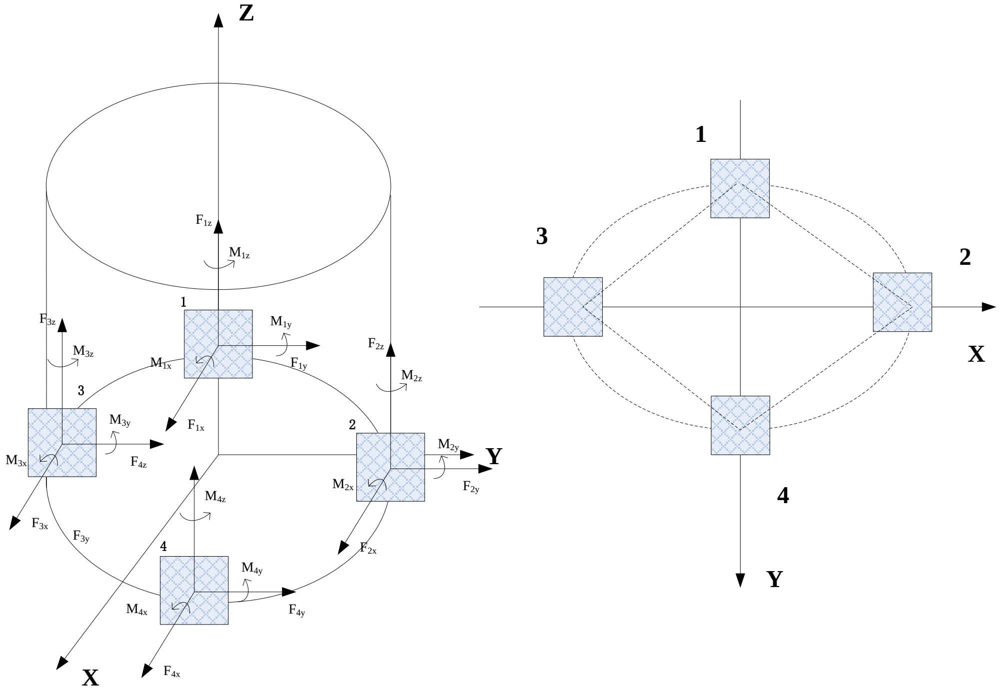

Figure 2 Model of the rhombus layout

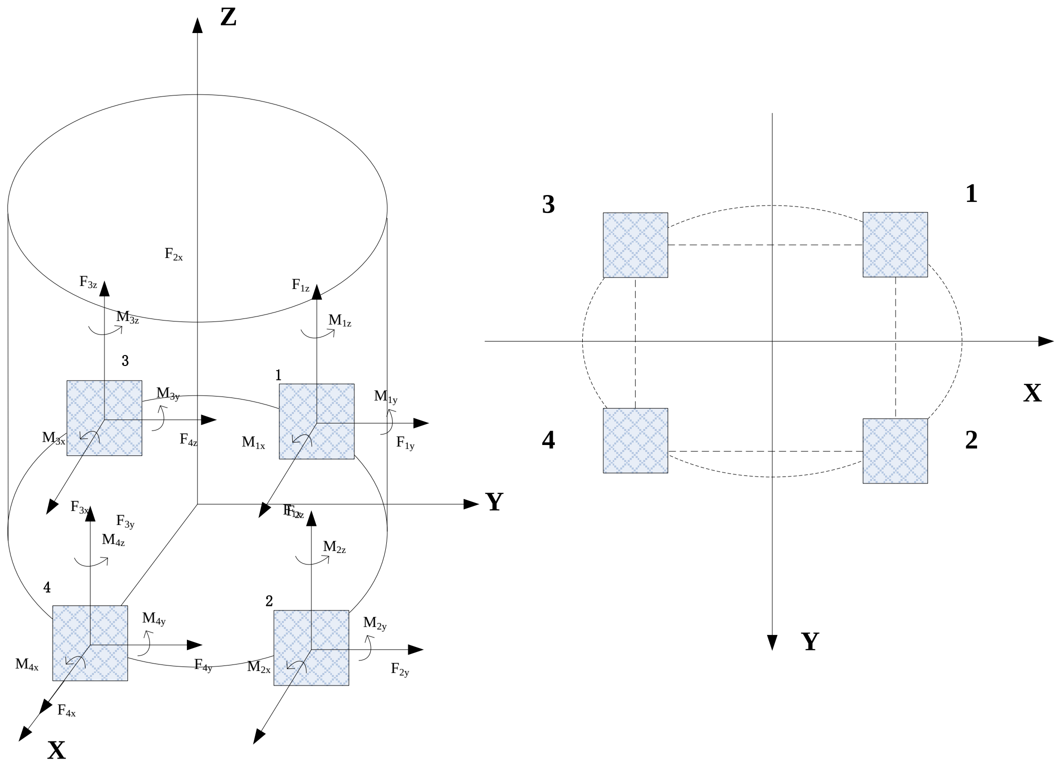

Figure 3 Model of the square layout

The six axis force of rhombus layout can be expressed as following:

$$
\begin{cases}
F_X = F_{1x} + F_{2x} + F_{3x} + F_{4x} \\
F_Y = F_{1y} + F_{2y} + F_{3y} + F_{4y} \\
F_Z = F_{1z} + F_{2z} + F_{3z} + F_{4z} \\
M_X = a(F_{2z} - F_{4z}) \\
M_Y = a(F_{3z} - F_{1z}) \\
M_Z = a(F_{1y} - F_{3y} + F_{4x} - F_{2x})
\end{cases} \tag{5}
$$

The six axis force of square layout can be expressed in Eq.(5):

$$
\begin{cases}
F_X = F_{1x} + F_{2x} + F_{3x} + F_{4x} \\
F_Y = F_{1y} + F_{2y} + F_{3y} + F_{4y} \\
F_Z = F_{1z} + F_{2z} + F_{3z} + F_{4z} \\
M_X = \dfrac{\sqrt{2}}{2} a(-F_{1z} + F_{2z} + F_{3z} - F_{4z}) \\
M_Y = \dfrac{\sqrt{2}}{2} a(-F_{1z} - F_{2z} + F_{3z} + F_{4z}) \\
M_Z = \dfrac{\sqrt{2}}{2} a(F_{1y} + F_{2y} - F_{3y} - F_{4y} + F_{1x} - F_{2x} - F_{3x} + F_{4x})
\end{cases} \tag{6}
$$

According to the analysis above, the rhombus is chosen in this study for easy calculation.

Static Calibration Experiment

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Comprehensive performance appraisal should be carried out according to the design index after the sensor assembly is completed. To determine the relation between the sensor input and output through the experiment and get the calibration curve, the data obtained according to the measured results of the sensor's performance should be analyzed with its' sensitivity, linearity and repeatability.

The relationship between input and output can be described with decoupling matrix in Eq.(7):

$$\begin{bmatrix} F_x & 0 & 0 & 0 & 0 & 0 \\ 0 & F_y & 0 & 0 & 0 & 0 \\ 0 & 0 & F_z & 0 & 0 & 0 \\ 0 & 0 & 0 & M_x & 0 & 0 \\ 0 & 0 & 0 & 0 & M_y & 0 \\ 0 & 0 & 0 & 0 & 0 & M_z \end{bmatrix} = G \begin{bmatrix} U_{11} & U_{12} & U_{13} & U_{14} & U_{15} & U_{16} \\ U_{21} & U_{22} & U_{23} & U_{24} & U_{25} & U_{26} \\ U_{31} & U_{32} & U_{33} & U_{34} & U_{35} & U_{36} \\ U_{41} & U_{42} & U_{43} & U_{44} & U_{45} & U_{46} \\ U_{51} & U_{52} & U_{53} & U_{54} & U_{55} & U_{56} \\ U_{61} & U_{62} & U_{63} & U_{64} & U_{65} & U_{66} \end{bmatrix} \tag{7}$$

The date obtained from static calibration is processed below:

$$F = G \bullet V + E \tag{8}$$

where E is the error matrix. Transposing the row i of calibration force matrix, the calibration force vector F_i is expressed as following:

$$F_i = \begin{bmatrix} F_{i1} & F_{i2} & F_{i3} & F_{i4} & \cdots & F_{in} \end{bmatrix}^T \tag{9}$$

Transposing the row i of calibration matrix, the calibration vector G_i is expressed as following:

$$G_i = \begin{bmatrix} G_{i1} & G_{i2} & G_{i3} & G_{i4} & \cdots & G_{in} \end{bmatrix}^T \tag{10}$$

Transposing the row i of error matrix, the error vector E_i is expressed as following:

$$E_i = \begin{bmatrix} E_{i1} & E_{i2} & E_{i3} & E_{i4} & \cdots & E_{in} \end{bmatrix}^T \tag{11}$$

It is expressed as:

$$F_i = V^T \bullet G^i + E^i \tag{12}$$

According to the least square method, the index $J_i = \sum_{J=1}^{n} E_{iJ}^2 = E_i^T \bullet E_i$ to be minimized as following:

$$\frac{\partial J_i}{\partial G_i} = \frac{\partial \left(F_i - V^T \bullet G^i \right)^T \left(F_i - V^T \bullet G^i \right)}{\partial G_i} = 0 \tag{13}$$

When the matrix ($V \bullet V^T$) is full rank, the inverse of it exist. The calibration vector can be described as following:

$$\overrightarrow{G_i} = \left(V \bullet V^T \right)^{-1} \bullet V \bullet F_i, \qquad i = 1,2,3,4,5,6 \tag{14}$$

The calibration matrix can be redefined as:

$$G = \begin{bmatrix} \overrightarrow{G_1} & \overrightarrow{G_2} & \overrightarrow{G_3} & \overrightarrow{G_4} & \overrightarrow{G_5} & \overrightarrow{G_6} \end{bmatrix} = F \bullet V \bullet \left(V \bullet V^T \right)^{-1} \tag{15}$$

The result of calibration experiment is shown in Fig. 4:

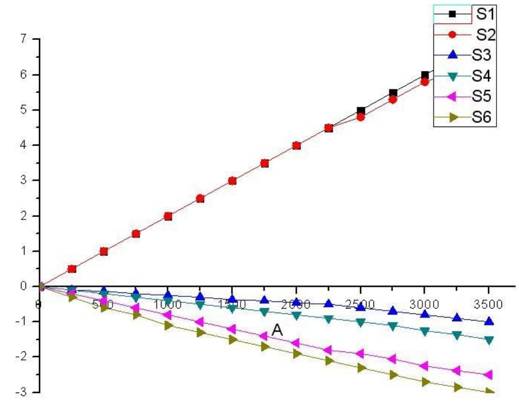

Figure 4(a) The calibration curve of F_x

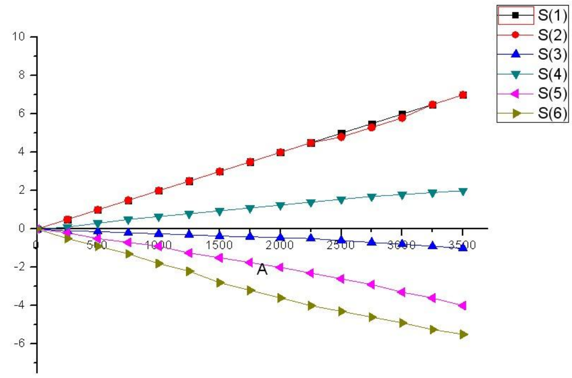

Figure 4(b) The calibration curve of F_y

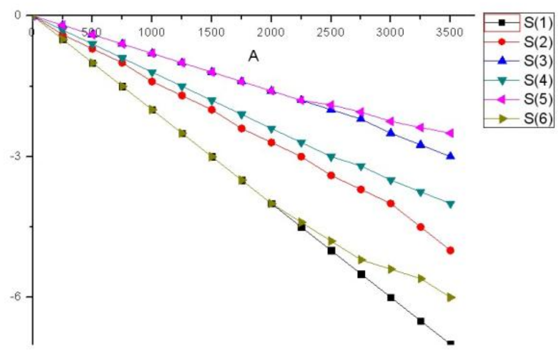

Figure 4(c) The calibration curve of F_z

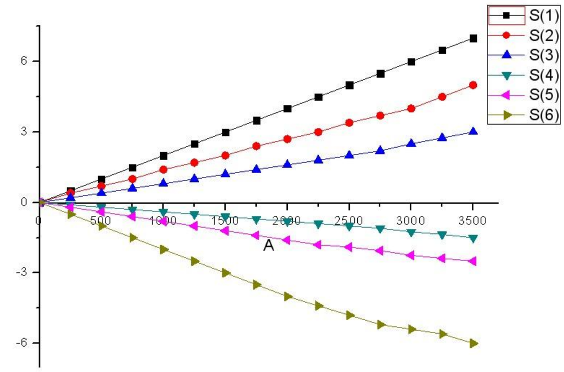

Figure 4(d) The calibration curve of M_x

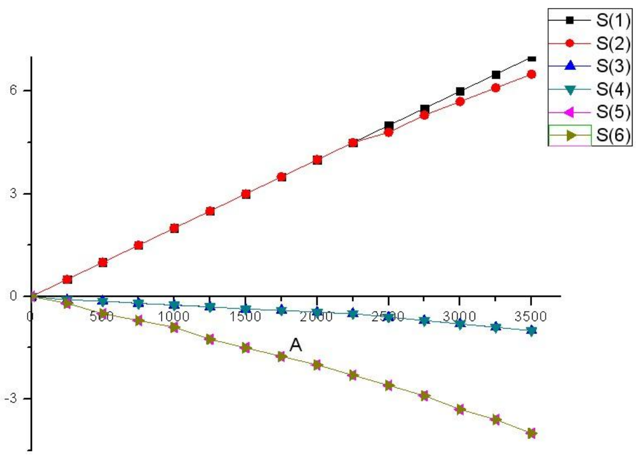

Figure 4(e) The calibration curve of M_y

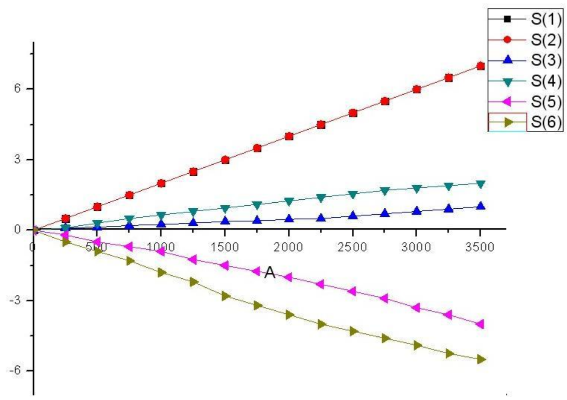

Figure 4(f) The calibration curve of M_z

Conclusions

Aiming at solving the problem of measurement of six dimensional force for heavy load operating equipment based on static first order coefficient matrix, vigorously parallel load distribution principle and piezoelectric force measuring principle, this study put forward a kind of force sensor based on the quartz crystal. Structure optimal design, manufacture, assembly and debugging of the six dimensional force sensor is researched in this study. At the end, the static calibration experiment is carried out. The conclusion of the study are as follows:

(1) The spatial structure of six dimensional force sensor is determined based on the measuring principle. The mechanical model and mathematical model of the sensor is also given out.

(2) The static calibration experiments is done in the specific calibration device and the calibration curve of good linearity is obtained. The decoupling matrix of sensor si also obtained on the basis of the experimental data.

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