

## Research on error sources analysis of six-axis force sensor

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Piezoelectric six-axis force sensor is a dynamic force measurement form by using piezoelectric quartz. Piezoelectric effect theory and application fundamental research have been the core issue of the piezoelectric disciplinary research. Piezoelectric six-axis force sensors generally require multiple sets of quartz group to detect six-axis force. Rational arrangement of quartz group is the key for sensor design. Whereas, how to overcome interference of sensor in each load is an effective way to improve the measurement accuracy of the piezoelectric sensor. This paper presents analysis of the error sources in the process of six-axis piezoelectric force sensor's assemble. It can provide theoretical basis and implementation methods to improve the measurement accuracy of the piezoelectric multi-axis force sensor.

*Keywords:* Six-axis force sensor; Quartz group; Error source.

### 1. Introduction

Generalized six-axis force sensor is a way to check the space force system in three-axis normal force ( $F_x$ ,  $F_y$ ,  $F_z$ ) and three-axis orthogonal moments ( $M_x$ ,  $M_y$ ,  $M_z$ ) multi-function sensor [1-4]. The robot with a six-axis force sensor has become a hot topic of research scholars since the 1970s. A variety of six-axis force sensor is invented [5, 6].

The structural design of the sensing element is the core key issues in robotic force sensor research [7, 8]. To a certain extent, the sensor performance is determined by structure. Parallel structure symmetry and compact structure makes it particularly suitable as a multi-axis force sensor force-sensitive structural element [9, 10]. In the six-axis force sensor simulation and experimental study, theoretical lateral force  $F_x$  and  $F_y$  are the same, the bending moment  $M_x$  and  $M_y$  are also the same. However, the experimental data can be drawn,  $F_x$  and  $F_y$  output values are not the same and there is a certain gap, the output value of  $M_x$  and  $M_y$  are not the same [11-13]. In this paper, the six-axis force sensor test performance, the possibility of analysis of the sources of error is

obtained, and the impact axis parallel piezoelectric six-axis force sensor measurement accuracy error sources are the following.

## 2. Quartz Group Factor

The quartz group major impact including: wafer saw cutting angle orientation error, the crystal axis discrimination and mark on the error, the crystal axes relative to the unit crystal group and the combination of crystal group constituting error, Combination of crystal group structured may bring geometry errors. These errors would make the theoretical calculation of the elastic coefficient and the piezoelectric strain coefficient changes, and make theoretical formula  $d$  not comply with the current value. Leading measured the direction of the applied load and the maximum sensitivity direction of the group of the crystal is not aligned, so the conversion efficiency is not high, the interference increases.

It is the main reason for the interference caused to the horizontal that cutting angle of the crystal are not allowed for multi-axis force sensor. Both for the one-axis or multi-axis force sensor, the conversion efficiency are reduced by the cutaway error. Cutaway error chip usually can not be corrected, which often result in a large number of chips wasted.

If the top and bottom of the quartz group is not parallel as shown in Fig.1, regardless of the superstructure deflection or not, there will be tangential load and will also generate interference to affect sensor accuracy.

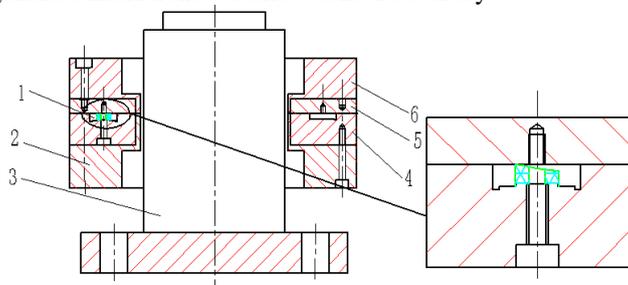


Figure 1. Influence of piezoelectric quartz crystal with unparallel plane. 1-piezoelectric quartz crystals, 2-lower clamp, 3-shaft, 4-lower cover, 5-upper cover, 6-lower clamp

## 3. Quartz Group Affected by the Installation

The quartz group is affected by the impact of the sensor shell design and sensor error during the installation process.

#### 4. The Impact of the Sensor Shell Design

Sensor shell design, manufacturing unreasonable, will result in a decline in accuracy linear and produced crosstalk. Sensor lower cover has two elastic links, the outer wall A and the inner wall B. Influence of uneven deformation on elastic body is shown in Fig. 2.

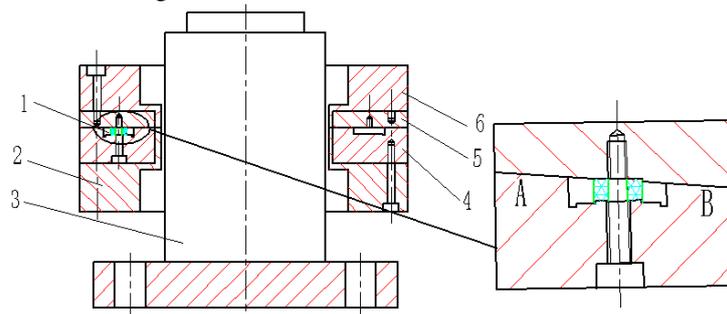


Figure 2. Influence of uneven deformation on elastic body

If shell deformation of the flexible link is inconsistent, it will lead to a combination of grain group not parallel to the top and bottom. If the requirements to the flatness are not enough between the sensor upper and lower cover and the contact surface with the quartz group, it also will lead to a combination of grain group not parallel to the top and bottom. Quartz group which can not be rigidly connected will result in a decline in accuracy linear and produced crosstalk. In the parameter selection and allocation of the elastic ring, it should be equivalent to the stiffness of both. In order to not interfere with each other, it makes deformation to uniform under loads. It requires equal width over its entire circumference on each elastically deformable membrane (either the outer or the inner wall) and a uniform thickness. Both surfaces of the upper and lower cover of the contact with the quartz group need to ensure that sufficient flatness and surface roughness.

#### 5. Sensor Error during the Installation Process

Affects of Quartz group installation on the parallel piezoelectric six-axis force sensor mainly include orientation error when the quartz assemble, and the inconsistencies error which is caused between combination of crystal group the maximum sensitivity of the cell transistor group-axis direction and corresponding reference sensor shell. As shown in Fig. 3,  $x'Oy'$  stands for the unit crystal axes of the group,  $Oy'$  stands for direction tangential to the axis of maximum sensitivity of the load  $F_y$ .  $xOy$  stands for the sensor housing corresponding reference coordinate system.  $\gamma$  stands for the reference deviation angle. It can be seen from Figure 3, when measuring the tangential load  $F_y$ , due to the inconsistent coordinate system, not only the transmission efficiency of the tangential load  $F_y$

is reduced, but also interference will occurred in the maximum sensitivity axis direction of tangential load  $F_x$ . The interference is  $F_x = F_y \sin(\gamma)$ . The bigger  $\gamma$  is, the greater interference is.

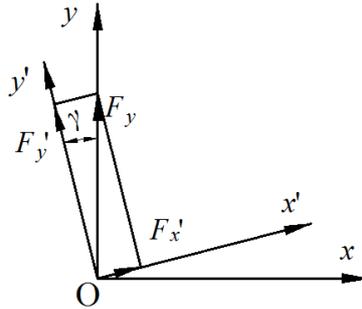


Figure 3. Error caused by uneven benchmark

The quartz group installed shape error of the measurement performance of the axis parallel piezoelectric six-axis force sensor has a great influence. It should try to choose the four sensor crystal group with almost the same performance in the selection of quartz group. Four groups quartz group in the circle of radius  $R$  is square layout. However, absolute square installation is difficult to accomplish and will inevitably lead to the size of the error in the sensor mounting as shown in Fig.4.

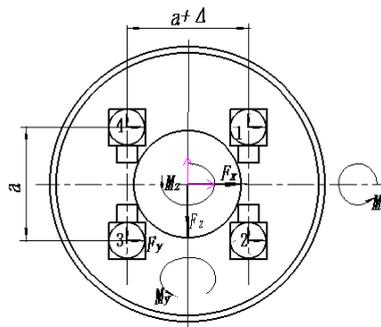


Figure 4. Shape error caused by installation of piezoelectric crystals

Let the error is  $\Delta$ , then square decoupling calculated is shown as following.

$$\begin{cases}
 F_x = F_{x1} + F_{x2} + F_{x3} + F_{x4} \\
 F_y = F_{y1} + F_{y2} + F_{y3} + F_{y4} \\
 F_z = F_{z1} + F_{z2} + F_{z3} + F_{z4} \\
 M_x = k_{Mx} \{-aF_{z1} + (a + \Delta)F_{z2} + (a + \Delta)F_{z3} - aF_{z4}\} / 2 \\
 M_y = k_{My} \{-(a + \Delta)F_{z1} - aF_{z2} + aF_{z3} + (a + \Delta)F_{z4}\} / 2 \\
 M_z = k_{Mz} \{(a + \Delta)F_{y1} + (a + \Delta)F_{y2} - (a + \Delta)F_{y3} - (a + \Delta)F_{y4} + (aF_{x1} - aF_{x2} - aF_{x3} + aF_{x4})\} / 2
 \end{cases} \quad (1)$$

It can be obtained by comparison with the formula. The error  $\Delta$  has no effect on the force measurement. However, it has an impact on the measurement of torque. Changing amount is shown in Eq.(2) above, the greater the error, the greater the amount of the torque variation.

$$\begin{cases} \Delta_{M_x} = k_{M_x}(\Delta F_{Z2} + \Delta F_{Z3}) / 2 \\ \Delta_{M_y} = k_{M_y}(-\Delta F_{Z1} + \Delta F_{Z4}) / 2 \\ \Delta_{M_z} = k_{M_z}(\Delta F_{Y1} + \Delta F_{Y2} - \Delta F_{Y3} - \Delta F_{Y4}) / 2 \end{cases} \quad (2)$$

### 6. The Influence of the Force

Affects of force on parallel piezoelectric six-axis force sensor mainly include whether the force pass through the axis or parallel to the coordinate system. It is easy to gradually in-depth discussions in order to simplify the problem, two assumptions are firstly made. Cutaway precision of quartz crystal fully meets the design requirements. Both coordinate system to be measured and the sensor of the external force given reference coordinate system are consistent.

When it is not perpendicular between the axial component  $F_z$  of the measured force and normal plane with the combination of crystal group  $y00$  unit grain group, normal plane of the tangential component  $F_z'$  is effected as shown in Fig.5. Its size availability is represented by the following formula.

$$F_x' = F_z \sin \alpha \quad (3)$$

Where,  $\alpha$  stand for the angle between the normal axis of  $y00$  crystal group and line of action  $F_z$ .

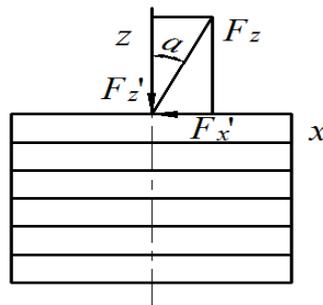


Figure 5. Influence of horizontal load caused by axial load

Thus, either  $F_z$  or  $\alpha$  increasing, the increase in  $F_x'$  will be caused. Tangential force  $F_x'$  for the grain group  $y00$  is an interference component. If the direction of force  $F_x'$  does not coincide with zero sensitivity axis of  $y00$  crystal group, the

lateral interference is produced from  $F_z$  to  $F_x$ . When  $F_x'$  and  $y_00$  crystal group sensitive axis are in the same direction, the lateral interference is also the largest.

When they are not perpendicular between the direction of measured tangential force and normal plane of crystal  $x_00$  unit crystal group. The normal component  $F_z'$  will be occurred. Its value can be represented by the following formula.

$$F_z' = F_x \sin \beta \quad (4)$$

Where,  $\beta$  stands for the angle between the tangential plane of the grain group and the tangential force.

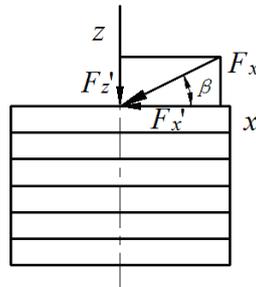


Figure 6. Influence of axial load caused by horizontal load

The greater the  $F_x$  or  $\beta$ , the larger the  $F_z'$ . It is a normal the interference component that we do not want to. The lateral interference is produced from  $F_z$  to  $F_x$ . If the unit  $y_00$  in the  $y$ -axis of the crystal group and  $F_x$  is not vertical, due to the vertical component of the presence of the same, the conversion efficiency is reduced.

The above discussions are consistent between the system of the measured external force sensor and design or installation reference system. If there are errors between the two systems, the interference will also be produced. If two conditions co-exist, then the lateral interference sometimes may be greater which could make the corresponding conversion efficiency lower.

## 7. Error Caused by the Numerical Observation

In the detection of the sensor, there will inevitably be many observation errors caused by random factors affecting observations. Some errors are caused by a measuring instrument, such as a charge amplifier drift. Some error is caused due to human factors, such as loading error and the shielding effect change. These errors can be changed under the influence of temperature, humidity and

atmospheric pressure or other factors. Each of these factors can make a measured value to produce a small amount of error. So a total error is obtained due to the combined effect of all these errors of measurement results. The total error can be seen as a random variable, which is the sum of much small value of independent random variables. Normal distribution occupies a special position in many possible distribution of the random variable. The random variable and its limit distribution of the normal distribution of the results are demonstrated by the central limit theorem in probability theory. If the study of random variables can be expressed as a large number of independent random variables, each individual random variable for integrated only play a minor role, that this random variable is actually a normal distribution.

Other reasons, such as the unreasonable use of the sensor, it will have an impact on the axis parallel piezoelectric six-axis force sensor accuracy.

## **8. Conclusions**

In this paper, the possibility of the error sources in the assemble process of six-axis piezoelectric force sensor is analyzed and obtained. we found the main reasons which affecting axis parallel piezoelectric six-axis force sensor measurement accuracy include the quartz group major impact, wafer saw cutting angle orientation error, the crystal axis discrimination and mark on the error, the crystal axes relative to the unit crystal group and the combination of crystal group constituting error, combination of crystal group structured may bring geometry errors. The quartz group is affected by the impact of the sensor shell design, sensor error during the installation process, and implications of force direction. The unreasonable use of numerical observations and sensor and other reasons will also affect the measurement accuracy of the piezoelectric six axis force sensor.

## **9. Expectations**

The next step is necessary to carry out the research work on the reliability and uncertainty of the sensor. The author and the research team members have carried out some research work in the field of uncertainty caused by the loading force.

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