Effect of Quartz Crystal Form on the Measurement Performance of Multi-dimensional Force Sensor

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Abstract. Quartz wafer is an important part of the force sensor of piezoelectric multi-dimensional force sensor. Its structural form affects the overall measurement performance of force-sensitive components and sensors. In this paper, the shape of the quartz crystal group was first analyzed, and then two different types of quartz crystal group models were established using finite element software, and their simulation analysis was performed. The corresponding relationship between the deformation of the two different shapes of quartz crystal set under the same external load and the limitation of external space size was studied. The same axial load and tangential load were applied to two different types of quartz crystals respectively, and the corresponding maximum equivalent stress and stress distribution regions were obtained. This paper provides an important reference for the fabrication of quartz crystal arrays and the selection of quartz wafer shape for piezoelectric multi-dimensional force sensors.

1. Introduction

The multi-dimensional force sensor can sense all the information of the six-dimensional external forces and moments in space. Through the monitoring of the direction and the size of the changing force/torque in the work, complete the more complex force feedback pattern recognition for the operation object, and then realize the force feedback control [1, 2]. It has been widely used in important fields such as intelligent robots, aerospace and military, and has become increasingly prominent. The multi-dimensional force sensor measurement principle mainly includes strain type, piezoelectric type, capacitive type and grating type [3, 4].

Among them, piezoelectric sensor is a kind of self-generating electricity type sensor, with high natural frequency (200 KHz), especially suitable for dynamic measurement. Compared with other measurement methods, piezoelectric measurement is the only measurement technology that meets the requirement of high natural frequency. It is an important development direction of multi-dimensional force sensors [5]. Piezoelectric multi-dimensional force sensors mostly use a four-point three-way force quartz crystal group for combined measurement. Ren Zongjin [6] studied the force vector measurement model based on piezoelectric sensors and designed a four-branch three-way force piezoelectric sensor parallel balance. Zhang Jun [7] developed a new four-point piezoelectric quartz parallel shaft-type six-axis force sensor capable of accurately measuring the six-dimensional force in the axial space. Jia Zhenyu [8] studied the four-point support type large-range six-dimensional force sensor based on the KISTLER Company’s research thinking, which is large and difficult to realize the miniaturization of the sensor. Li Dong [9] developed a small-scale integrated piezoelectric six-axis
force sensor. Liu Jun [10] proposed a flat plate piezoelectric six-dimensional force sensor program, which achieved multi-dimensional dynamic force measurement in a narrow space.

The current research work is all about the overall performance of six-dimensional force sensors. The piezoelectric six-dimensional force sensor uses a piezoelectric quartz crystal set as the sensor force sensor, the quartz crystal group is the core of the multi-dimensional force sensor, but there are few related researches. The quartz crystal group is composed of quartz crystals. Although the performance of piezoelectric quartz is better than that of other piezoelectric materials, the quartz wafer is limited by the cut type, the shape of the wafer is also limited. The shape will affect the entire sensor assembly process and measurement performance. For this reason, this paper mainly studied the effect of the shape of the quartz wafer on the measurement performance.

2. Quartz crystal shape analysis
According to the piezoelectric effect of the quartz crystal set, the sensitivity of the crystal is related to the unique piezoelectric coefficient and external load of the crystal. Quartz crystal shape analysis is mainly to improve the rigidity and life of the quartz crystal. When the crystal groups of different shapes are subjected to the same load, the crystal group is subjected to a smaller stress and the service life is longer. At present, the shape of the quartz crystal group mainly includes two types of structures: Round with hole and a square with a hole. In order to increase the service life of the quartz crystal set and obtain a suitable crystal shape, the ansys15.0 software was used to model and simulate the analysis. Square wafer size is 18*18mm, thickness 1mm, middle hole diameter $\Phi$12mm; round wafer outer diameter $\Phi$18mm, thickness 1mm, inner diameter $\Phi$12mm. With the same external space installation size constraints, the circular wafer has a smaller bearing area.

2.1. Deformation analysis
Constraints are imposed on the lower surfaces of the two different shapes of the crystal group, and the upper surface is applied with the same magnitude and direction of axial force, and the load sizes are: 400N, 800N, 1200N, 1600N, 2000N. Then, the stress and strain of the crystal group and the transverse shear stress generated when subjected to the axial load are compared. The maximum deformation of the two crystal groups when subjected to the same axial force is shown in Table 1. Figure 1 shows the displacement cloud of two different types of quartz crystals when a 2000N load is applied.

![Simulation of deformation of quartz crystal at axial load of 2000N](image)

(a) The deformation cloud of Circular crystal; (b) The deformation cloud of Square crystal

**Figure 1.** Simulation of deformation of quartz crystal at axial load of 2000N

**Table 1.** Simulation data of crystal deformation($10^{-4}$mm)

| Normal force /N | 0   | 400 | 800 | 1200 | 1600 | 2000 |
|-----------------|-----|-----|-----|------|------|------|
| Square crystal group | 0   | 5.97| 11.9| 17.9 | 23.9 | 29.9 |
| Circular crystal group | 0   | 6.91| 13.8| 20.7 | 27.6 | 34.6 |

From Table 1, it can be seen that as the applied stress increases, the deformation of the two crystal groups gradually increases, and the force and the deformation amount become strictly linear, and the
deformation of the circular crystal group is greater than that of the square crystal group. When the applied load is 2000N, the maximum deformation of the square crystal group is 29.9E-4mm, and that of the round crystal group is 34.6E-4mm. The amount of deformation of the crystal group indicates that the crystal is relatively rigid, and it is verified that the piezoelectric force sensor belongs to a micro-displacement type sensor.

2.2. Stress analysis under axial load
The axial force of the same size and direction is applied to the upper surface of two different shapes of the crystal group. The load sizes are: 400N, 800N, 1200N, 1600N, 2000N. The maximum equivalent stress simulation data for two different shapes of crystal groups can be obtained, as shown in Table 2. Figure 2 shows the equivalent stress cloud and the maximum equivalent stress distribution for the two different shapes of the crystal group when the crystal group is subjected to an axial load of 2000N.

![Figure 2. Simulation of equivalent stress of crystal group under axial load 2000N](image)

(a) Maximum stress distribution in circular crystal groups  
(b) Maximum stress distribution in square crystal groups

**Table 2. Simulation data of equivalent tensile stress in crystal group**

| Axial force /N | 400    | 800    | 1200   | 1600   | 2000   |
|---------------|--------|--------|--------|--------|--------|
| Square crystal group (Pa) | 7.16E+07 | 1.43E+08 | 2.15E+08 | 2.86E+08 | 3.58E+08 |
| Circular crystal group (Pa) | 7.41E+07 | 1.48E+08 | 2.22E+08 | 2.96E+08 | 3.71E+08 |
| Stress difference (Pa) | 2.50E+06 | 5.00E+06 | 7.00E+06 | 1.00E+07 | 1.30E+07 |

From the data in Table 2, it can be seen that under the same load, the stress of the circular crystal group is greater than that of the square crystal group, and the sensitivity of the circular crystal group is greater than that of the square crystal group. From the viewpoint of improving sensitivity, the circular crystal group is suitable. It can be seen from the stress cloud diagram of the crystal in Figure 2 that the maximum stress region of the circular crystal group is distributed widely, while the stress region of the square crystal group is distributed more widely. Compared to the circular crystal group, the square crystal group can withstand greater force.

From the piezoelectric properties of the crystal group, it can be seen that when the normal force is applied, the unit crystal group that measures the tangential force has a corresponding charge output due to the shear force. The presence of shear stress will produce a certain amount of lateral interference to the sensor measurement, affecting the tangential measurement accuracy. In the case of axial forces applied to the crystal stack, the resulting coupled shear stress simulation data is shown in Table 3. Figure 3 shows the coupled shear stress cloud in the $F_x$ direction for an axial load of 2000N. When the crystal group is subjected to axial load, there is a corresponding stress output in the shear direction, and the coupled shear stress generated by the square crystal group is smaller than that of the circular crystal group. According to the characteristics of the unit crystal group, the smaller coupled shear stress generated by the crystal group is, the better the transverse interference ability between the crystal groups can be reduced, and the measurement accuracy of the crystal group can be improved.
Figure 3. Simulation of coupled shear stress of quartz crystal in \( F_x \) direction

Table 3. Maximum Coupling Shear Stress Simulation Data for Crystal Groups

| Axial force /N | 400      | 800      | 1200     | 1600     | 2000     |
|---------------|----------|----------|----------|----------|----------|
| Square crystal group (Pa) | 0.495E+07 | 0.990E+07 | 0.149E+08 | 0.198E+08 | 0.248E+08 |
| Circular crystal group (Pa)  | 0.891E+07 | 0.178E+08 | 0.267E+08 | 0.356E+08 | 0.445E+08 |

2.3. Stress analysis under tangential loading

In the crystallographic model and invariable parameters, the end face of the crystal group is fixed, and the end face only bears the equivalent stress generated under the shear force condition. When 200N, 400N, 600N, 800N, and 1000N tangential forces are applied, the maximum equivalent stress distribution regions and equivalent stress cloud diagrams for the two crystal groups can be obtained. Figure 4 shows the shear stress cloud of the two crystal groups and the maximum stress distribution of the measured crystal groups at a shear load of 1000 N.
Table 4. Simulation data of shear equivalent stress (Pa)

| Shear force /N | 0   | 200 | 400 | 600 | 800 | 1000 |
|----------------|-----|-----|-----|-----|-----|------|
| Square equivalent crystal group (Pa) | 0   | 0.133E+08 | 0.266E+08 | 0.399E+08 | 0.531E+08 | 0.664E+08 |
| Circular equivalent crystal group (Pa) | 0   | 0.162E+08 | 0.324E+08 | 0.486E+08 | 0.648E+08 | 0.810E+08 |
| Square measuring crystal group (Pa) | 0   | 0.561E+07 | 0.112E+08 | 0.168E+08 | 0.225E+08 | 0.281E+08 |
| Circular measuring crystal group (Pa) | 0   | 0.934E+07 | 0.187E+08 | 0.280E+08 | 0.374E+08 | 0.467E+08 |

The maximum stress values are shown in Table 4. Table 4 shows that when the two crystal groups are subjected to a shear force, the resulting equivalent stress values and the applied load are strictly linear, and the equivalent stress of the circular crystal group is much larger than that of the square crystal group. When the shear strength limit of the crystal is reached, the round crystal group crystal first appears crushing phenomenon, and the square crystal group has better bearing capacity than the round crystal group.

When subjected to the shear load, the unit crystal group for measuring the axial force will have corresponding tensile stress. The existence of the tensile and compressive stress will generate the corresponding charge output, which will cause some coupling interference to the sensor measurement and affect the tangential measurement accuracy. In the case of axial forces applied to the crystal stack, the resulting coupled shear stress simulation data is shown in Table 5. Figure 5 shows the $F_z$-direction coupled shear stress cloud when the shear load is 1000N. When the crystal group is subjected to a tangential load, there is a corresponding tensile and compressive stress output in the axial direction. Coupling tensile stress generated by the square crystal group is smaller than that of the circular crystal group. According to the characteristics of the unit crystal group, the smaller the coupled tensile and compressive stress generated by the crystal group, the better. It can reduce the horizontal interference between the crystal groups and improve the measurement accuracy of the crystal group.

Table 5. Maximum Coupling Tensile and Compressive Stress Simulation Data for Crystal Groups

| Shear force /N | 200  | 400  | 600  | 800  | 1000 |
|----------------|------|------|------|------|------|
| Square crystal group (Pa) | 0.164E+08 | 0.328E+08 | 0.492E+08 | 0.656E+08 | 0.820E+08 |
| Circular crystal group (Pa) | 0.205E+08 | 0.408E+08 | 0.612E+08 | 0.816E+08 | 0.102E+08 |

(a) Measurement of the $F_z$ direction of the circular crystal group  (b) Measurement of the $F_z$ direction of the square crystal group

Figure 5. Coupled tensile and compressive stress simulation of quartz crystal in $F_z$ direction
3. Conclusion

In summary, through the simulation analysis of two different crystal groups, it can be concluded that under the same load, the square crystal group deformation is smaller.

When the axial load is applied, the maximum stress region of the circular crystal group is distributed widely, and the circumference of the fixed end of the crystal group is the region where the stress should be maximum, and the stress distribution is more concentrated. However, the maximum equivalent stress of the square crystal group is smaller, and the distribution of the stress region of the square crystal group is more dispersed. When the ultimate compressive strength is reached, the circular crystal group is prone to cracking or crushing, and the crystal group is damaged. When the axial stress is applied, the coupled shear stress generated by the square crystal group is also small, and the transverse interference between the unit crystal groups is reduced during the measurement.

When the tangential load is applied, the equivalent shear stress of the circular crystal group is much larger than that of the square crystal group. Although the larger the stress will increase the sensitivity of the crystal group, the crystal group can not be used normally when the larger force value is measured.

Therefore, choosing a square shape for the crystal group not only reduces the damage of the crystal group, but also effectively improves the service life of the crystal group. It also reduces the lateral interference and improves the measurement accuracy of the crystal group to some extent.

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