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Design of an Overload Protection Device for Six-axis Force/torque Sensors

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***Abstract*— Six-axis force/torque sensor is widely used in various industries. The existing products have high precision and delicate structure, but they are easy to be damaged due to the use of the super range. Guarantee the safe use of six axis force/torque sensor can effectively reduce the cost. In this paper, an overload protection device for six-axis force/torque sensor has been proposed, which is realized by designing a mounting flange with protection pins and clearance hole structure to limit the movement of the six-axis force/torque sensor. Meanwhile, an application program has been designed to calculate the key dimensions of the device. The successful application to an end effector validated the function and performance of the overload protection device.**

***Index Terms*— Six-axis force/torque sensor, overload protection, robotic application**

I. INTRODUCTION

Due to its function of sensing full force/torque information in 3D space at the same time, six-axis force/torque sensor is widely used in intelligent robot, automatic control, aerospace, and many other research areas. It plays an important role in science and technology development, industrial production and national defense construction. Although the existing six-axis force/torque sensor products possess the advantages of high precision accuracy and compact structure, they have the fatal flaw of outrange vulnerability and beyond repair, which will lead to the increased cost of research. Traditional protection method of six-axis force/torque sensor is often through software design, which sets emergency stop control based on force/torque range of the sensor, but lack of effective protection on the structure design of the hardware. Due to programming errors, in the process of actual debugging or some sudden touch by mistake from the outside, it is also easy to damage the six-axis force/torque sensor.

Six-axis force/torque sensor is through the detection of the inner elastomer deformation to get the space force/torque information. The typical elastomers within six-axis force/torque sensor are shown in Fig. 1. The reason for damage of six-axis force/torque sensor is the inner elastomers rupture while using beyond the range. So, for six-axis force/torque sensor overload protection, the main point is to restrict the inner elastomer in the range of elastic deformation. However, most of the existing six-axis force/torque sensor products are lack of overload protection function, and only a few references propose to add additional overload protection structure in the inner elastomer. [1-4] describe different elastomer structures for six-axis force/torque sensor, but not involving the overload protection function. [5] describes a cross beam six-axis force/torque sensor with overload protection function, which is through adding protection pin structure into the inner elastomer to limit the movement, so as to achieve the overload protection. Institute of Intelligent machine of Chinese Academy of Science, combined with Southeast University and Harbin Institute of Technology have developed SAFMS series of six-axis force/torque sensor, using screw in the inner elastomer to realize overload protection. This kind of design with overload protection structure in the inner elastomer of the six-axis force/torque sensor can play a certain amount of overload protection function. However, the threshold value of the overload protection is limited by the inner elastomer stiffness and six-axis force/torque sensor structure size itself, which cannot increase the size of the overload protection structure to improve the overload protection threshold value according to the actual demand.

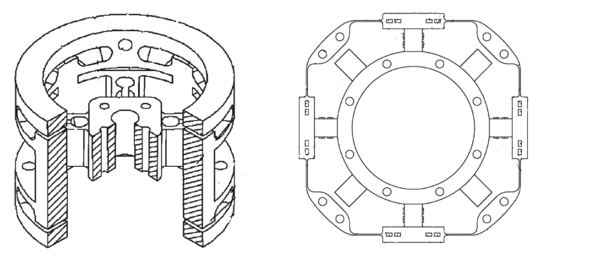

Fig. 1. Typical elastomers within six-axis force/torque sensor. Left: elastomer without overload protection. Right: elastomer with overload protection.

In view of the problem of the existing six-axis force/torque

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sensor without overload protection function or with small overload protection threshold value, we propose an overload protection device for six-axis force/torque sensor, which is realized by designing a mounting flange with protection pins and clearance hole structure to limit the movement of the six-axis force/torque sensor. Different from adding additional overload protection structure in the inner elastomer of the sensor, the design proposed in this paper is through the external structure to limit the amount of rotation and displacement of the sensor, which can provide greater protection threshold for the sensor.

The rest of the paper is organized as follows. Section II introduces the design principle of the overload protection device. Section III provides the calculation method of critical dimensions, and designs a calculation application program based on VC++6.0. Section IV gives the example application to confirm the feasibility of the device. Section V summarizes our study.

II. STRUCTURE DESIGN

The overload protection device for six-axis force/torque sensor is mainly to realize the limitation of the amount of rotation and displacement of the sensor in permitted range. In this paper, the device we proposed is shown in Fig. 2. The device mainly include three parts: the fixed end connecting flange, the movable end connecting flange, and the protecting pin. The fixed end connecting flange and the movable end connecting flange are mounted with six axis force/torque sensor. And combined with the protection pin, the clearance holes, which are designed on the movable end connecting flange, can limit the amount of rotation and displacement of the sensor from the external structure, so as to protect the sensor being used in an allowable range. The details of the design of the device are follows: (1) Four interference holes are set uniformly on the sensors fixed end connecting flange, while four clearance through-holes are made on the corresponding position of the sensors movable end connecting flange. (2) Protecting pins are set into the interference holes across the clearance through-holes. (3) By adjusting the clearance of protecting pin and the clearance through-hole, the amount of rotation and displacement of the sensor is limited, thus the sensor is under protect.

Different from the method of designing the overload protection structure on the inner elastomer directly, this paper proposes a way to design an additional device to assembly on the outside of the sensor, which can be more free to adjust the overload protection threshold value by change the size of the device, or select different hardness materials for the structure according to the practical application requirements.

III. CALCULATION OF THE KEY DIMENSIONS

The overload protection device proposed in this paper is through adjusting the clearance of protecting pin and the clearance through-hole to control the amount of rotation and displacement of the sensor. Protecting pin is generally standard parts, so the clearance size is determined by the clearance through-hole size. As shown in Fig. 3, the key

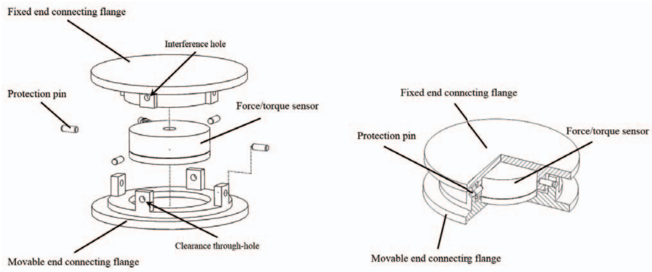

Fig. 2. An overload protection device. Left: exploded view. Right: assembly diagram.

dimensions of the clearance through-hole are its width L and height H. According to the result of calculation, the shape of the hole can be set to circular, oval or rectangular.

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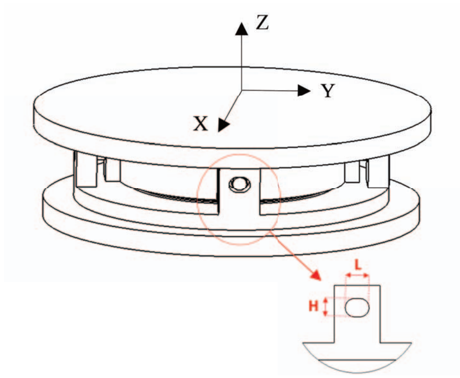

Fig. 3. The key dimensions of the clearance through-hole.

Calculation method is as follows.

According to the force/torque range, stiffness of the six-axis force/torque sensor, and the distribution radius of the protection pin in the overload protection device, the rotation value R_i and the displacement value P_i of the sensor can be calculated.

$$R_i = 2 \times r \times T_i / K_{ti} \tag{1}$$

$$P_i = 2 \times F_i / K_i \tag{2}$$

where $i = \{x, y, z\}$. T_i, F_i, K_{ti} and K_i correspond to all directions force range value, torque rang value, rotation stiffness, displacement stiffness of the sensor. r is the distribution radius of the protection pin in the overload protection device.

1) The value of width mainly determines the rotation range of the Z direction and the displacement range on the XY

plane. Choosing R_z, P_x or P_y as the limited value along L direction depends on the actual working condition. The minimum value of the clearance through-holes width L is equal to the sum of the diameter of the protection pin and the limited value. And the maximum value of L is equal to the sum of the diameter of the protection pin and x times of the limited value. x is the multiple of the allowable overload value of the sensor. The equation of L is as below.

$$L_{min} = D_0 + l \tag{3}$$

$$L_{max} = D_0 + x \times l \tag{4}$$

$$l = \begin{cases} R_z & \text{while } R_z \text{ is the main condition} \\ P_x & \text{while } P_x \text{ is the main condition} \\ P_y & \text{while } P_y \text{ is the main condition} \end{cases}$$

where D_0 is the diameter of the protection pin. l is the limited value along L direction based on the range of the sensor.

2) The value of height H mainly determines the displacement range on the Z direction and the rotation range of the X and Y direction. Choosing P_z, R_x or R_y as the limited value along H direction depends on the actual working condition. The minimum value of clearance through-holes height H is equal to the sum of the diameter of the protection pin and the limited value. And the maximum value of H is equal to the sum of the diameter of the protection pin and x times of the limited value. The equation of is as below.

$$H_{min} = D_0 + h \tag{5}$$

$$H_{max} = D_0 + x \times h \tag{6}$$

$$h = \begin{cases} P_z & \text{while } P_z \text{ is the main condition} \\ R_x & \text{while } R_x \text{ is the main condition} \\ R_y & \text{while } R_y \text{ is the main condition} \end{cases}$$

where h is the limited value along H direction based on the range of the sensor.

According to the calculation method above, we design an application program based on VC++6.0. As shown in Fig. 4, the application program includes three modules, which are basic parameters, working condition, and calculation results. In the basic parameters module, the value of senor ranges, stiffness, the minimum multiple of the allowable overload value, and the distribution radius of the protection pin should be fill. Then choose the main working condition of l and h, or choose the minimum value of them directly. The calculation results will appear in the final module after the calculate button is pressed.

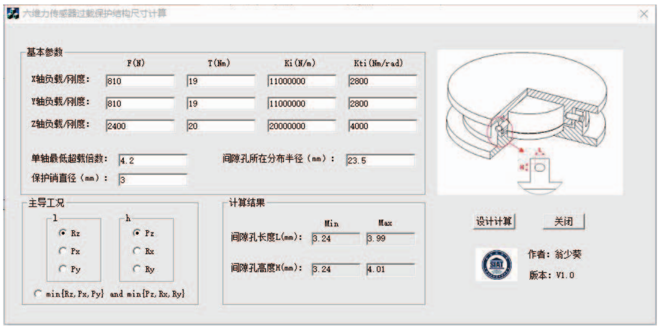

Fig. 4. Application program for calculation of the key dimensions.

IV. APPLICATION

The six-axis force/torque sensor Mini 40, which is produced by ATI Company, is assembled with the overload protection device proposed in this paper as an application sample. Its whole size is $\Phi 40 \times 12.25$ mm, and its basic parameters,like the allowable overload value, stiffness and multiple of the allowable overload value are as follows: $F_x, F_y = 810N, F_z = 2400N, T_x, T_y = 19Nm, T_z = 20NmK_x, K_y = 1.1 \times 10^7 N/m, K_z = 2.0 \times 10^7 N/m, K_{tx}, K_{ty} = 2.8 \times 10^3 Nm/rad, K_{tz} = 4.0 \times 10^3 Nm/rad, x = 4.2$ 18.9. Through the calculation application program, the calculation results are $L_{min} = 3.24mm$ and $H_{min} = 3.24mm$. And set these values as the size of the clearance through-hole. The parameter settings are shown in Fig. 3, in which R_z and P_z are chosen as the main working condition. According to the results, the cross section shape of the clearance through-hole is designed as a circle.

The six-axis force/torque sensor Mini 40 assembled with the overload protection device has been used to an end effector (shown in Fig. 5), which is used for archwire bending [6]. For some minor outrange wrong operation, the device can play an effective overload protection function for the sensor. The threshold value of the overload protection device is analyzed as follows.

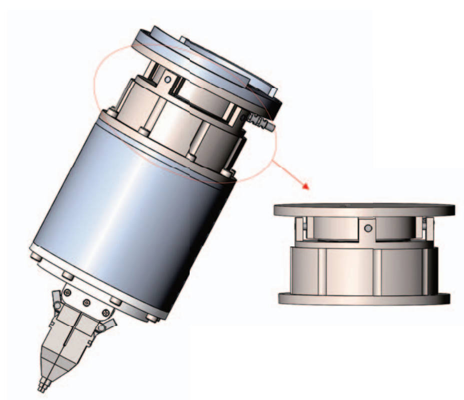

Fig. 5. Application example.

According to the working condition of the effector, the force and torque on the Z axis is much greater than those on the other two axis. So it is necessary to analyze the protection threshold value of the overload protection device on the Z axis. The minimum multiple of the allowable overload value of the sensor is 4.2. And the values of L_{max} and H_{max} were calculated based on the minimum multiple (as shown in Fig. 3). According to the values of L_{max} and H_{max}, the maximum displacement and rotation value on the Z axis of the movable end connecting flange can been calculated, which is $0.50mm$ and 1.2 degrees respectively. Based on the ANSYS (a finite element software)[7], the threshold value of the overload protection device is analyzed.

The models of the overload protection device were imported into finite element software ANSYS Workbench16.1 (Ansys Corp, Canonsburg, PA). In the software, the material of the overload protection device was set to be stainless steel. The contacts among parts were frictionless. And the model was meshed with 10-node tetrahedral element (solid 187). On the constraint relation, the lower face of the movable end connecting flange was fixed. Then, a mandatory displacement on the value of $0.5mm$ was put on the upper face of the fixed end connecting flange. When the fixed end connecting flange had moved $0.12mm$, the device begins to occur deformation. After doing the solution, the total deformation was presented (as showed in Fig. 6). The result data showed that the value of the force along Z axis was $109146.6N$.

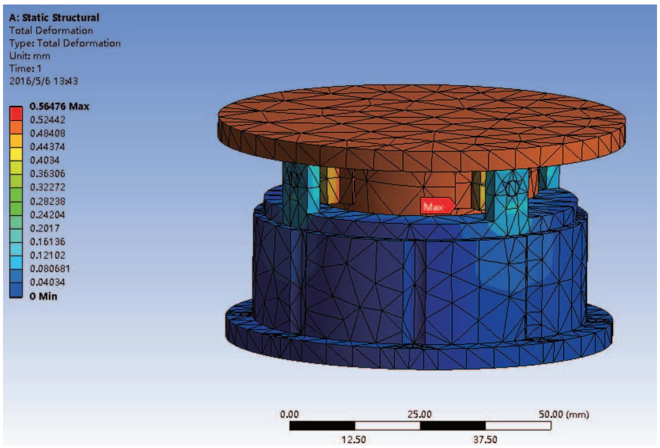

Fig. 6. Total deformation under $0.5mm$ displacement.

For the analysis of the torque threshold value of the device, the pretreatment process was the same. A mandatory rotation on the value of 1.2 degrees was put on the fixed end connecting flange. When the fixed end connecting flange had rotated 0.29 degrees, the device began to occur deformation. After doing the solution, the total deformation was presented (as showed in Fig. 7). The result data showed that the value of the torque around Z axis was $341.66Nm$.

The results showed that the overload protection device can improve the threshold value of the overload protection of $109146.6N$ along the Z axis and $341.66Nm$ around Z axis.Compared to the owner maximum allowable load values of the sensor Mini40 , whose maximum allowable load value along the Z axis $F_{zmax} = 2400 \times 4.2 = 10080N$, maximum allowable load value around the Z axis $T_{zmax} = 20 \times 4.2 = 84Nm$, the overload protection device can improve the overload protection threshold of more than 10 times on F_{zmax} and more than 4 times on T_{zmax} in this case.

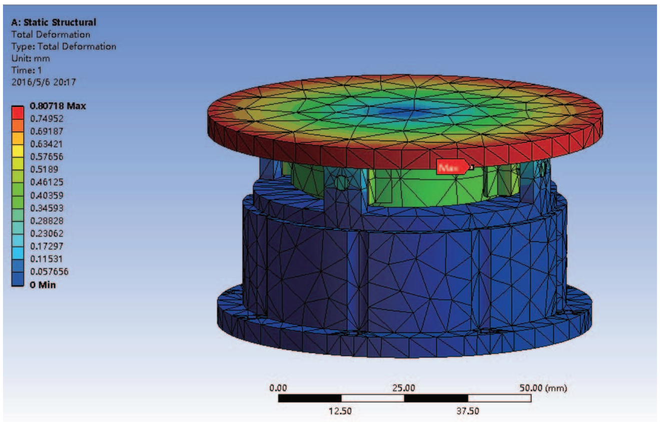

Fig. 7. Total deformation under 1.2 degrees rotation.

V. CONCLUSION AND FUTURE WORKS

In this paper, an overload protection device for six-axis force/torque sensor and its design method has been proposed. For calculating the key dimensions of the device, an application program based on VC++6.0 has been designed. The successful application to an end effector validated the function and performance of the overload protection device. On the whole, compared to the exited overload protection method for six-axis force/torque sensor, the device proposed in this paper has the following advantages. First, it is simple be realized and has strong ability of overload protection. Second, the applicability is good, so it can be directly applied to the existing six-axis force/torque sensor products. Third, device damage risk can be reduced so as to cut down the development costs.

However, this overload protection device need high requirements on the processing and assembling accuracy. In the future, we will focus on how to manage the modular design of key parts in the structure to form a design standard, thus improving the structure and reducing assembly difficulty.

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