Structure Design for the Elastic Body of a Six-axis Wrist Force Sensor

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Abstract

Calculating model on static and dynamic characteristics of the elastic body of a wrist force sensor used in space robot is built with finite element method. The stress distribution pattern for various load cases, natural frequencies and vibration shapes of the elastic body are analyzed. The influence of main structure parameters on static and dynamic characteristics is investigated comprehensively by using orthogonal test design. The regression equations between the structure parameters and performances of the sensor are obtained by using step regression analysis based on numerical results. And the optimization design of elastic body for the wrist force sensor is put into implementation.

Keywords: Wrist force sensor, finite element analysis, orthogonal test design, optimization design

1 Introduction

A six-axis wrist force sensor can detect all force information in three-dimensional space simultaneously, and it is one of the most important sensors for force control and force/displacement control in robot [1], [6]. As piezoelectric component can't measure static loading and is not applicable to robot, the wrist force sensors generally used presently still adopt strain gauges [1]. Therefore, the design of the elastic body of multi-axis wrist force sensor is its key technology. During the past several ten years, many patents about the six-axis wrist force were mostly based on the various kinds of designs of elastic body [2], [7]. In order to improve the performance of sensor further, the designers urgently want to know the mechanical behavior of elastic element of sensor deeply and comprehensively [6].

With the development of robot in the direction of high speed and high accuracy, the problems on dynamic force measure is more and more glove [8]. Multi-axis wrist force sensor not only require high sensitivity in various axial directions, little cross-coupling, but also require adequate work bandwidth to meet the need of dynamic force measurement. Numerical analyses had been carried out on the mechanics behavior (mostly is static behavior) of elastic element of sensor in recent years [3-5], but many questions are worth discussing, in several aspects such as structure simplification, models building and results obtained etc.. In this paper, numerical analysis has been used to the static and dynamic characteristics of elastic body of a six-axis wrist force sensor which is used in space robots, and on this base, the optimization design of elastic body has been carried out, which offers references for designing this kind of sensor.

2 Static analysis

This kind of sensor is a cross-beam structure with various section or is a cellular design six-component force sensor [1]. It is made up of central platform, main beam and floating beam etc. as shown in **Fig. 1**. There, the inside of central platform is scooped into blind hole (placing circuit board inside to reduce weight and volume); strain gauges are adhered in the surface around the main beam; the thickness of floating beam is very thin, which is like a sheet and its two ends connect with the husk.

2.1 Calculation model

The direction of main beam in elastic body is chosen as the directions of x-axis and y-axis in the integral coordinate system, and the z-axis cross through the center of central platform. Three-dimension finite element analysis has been carried out on the whole structure. According to the structure parameters (as shown in letter), the shape and the calculation accuracy, the mesh was generated for the finite –element model using an eight-mode hyperelastic brick-type element. The structure is divided into 240 discrete three-dimension brick-type elements and has 466 nodes totally. As all external loadings act on the upper surfaces of central platform, and they are general forces in arbitrary direction, they can be simplified as force or moment which cross through the center of upper surface of central platform by mechanical principle as shown in **Fig. 1**.

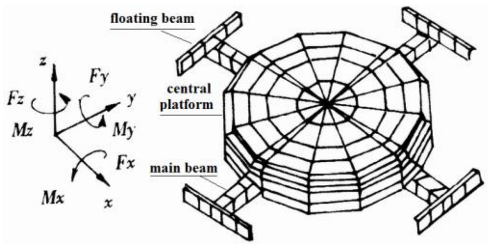

Fig. 1 The structure of elastic body and FE mesh

When elastic body is working, the material is in the state of a bit deformation, thus, the external forces of any form applied on the elastic body in any direction can be represented by the above six kinds of different load cases respectively, or by the linear combination of the six ones .Allowing for the symmetry of structure and boundary restriction, according to the scale of the sensor, four kinds of load cases can be defined as follows: load case 1, the concentrate force along z-axis F_Z=50N, which acts on the center of upper surface of the central platform; load case 2, the moment around z-axis which acts on the center of upper surface of central platform M_Z=2.5NM; load case 3, the concentrate force along y-axis F_y=50N, which acts on the center of upper surface of the central platform; load case 4, the moment around y-axis which acts on the center of upper surface of central platform M_y=2.5 NM.

In the elastic body, only the two ends of floating beam are connected with husk, which is fixed, therefore the degrees of freedom in two ends of the floating beam are all restricted. The restrictions processing in calculation model are same under four typical load cases.

The material of the elastic body is aluminous alloy LY12, its material properties are as follows: Young's modulus $E=0.72\times10^{11}$ N/m^2; Poisson's ratio μ=0.33; Density$\rho=2.7787\times10^3$kg/m^3. The width, height and length of main beam are 5mm, 7mm, 22mm respectively; The width, height and length of floating beam are 1.5mm, 7mm, 36mm respectively; The outer diameter,, inner diameter and depth of central platform are 86mm,50mm, and 15mm, respectively.

2.2 Calculative results

Based on the above model, the displacement and the stress under these four kinds of load cases can be obtained. The normal stresses in every direction, the shear stresses, maximal and minimal main stresses, the equivalent stresses, or linear combinations of various stresses under various load cases can be outputted respectively. The maximal value of various stresses in the main beam corresponding to various load cases are shown in **Table 1**, there into σ_x, σ_y, σ_z represent the normal stress along x-axis y-axis and z-axis in the integral coordinate system respectively, τ_{xy}, τ_{yz}, τ_{zx} represent the shear stress on x-y plane y-z plane and z-x plane respectively.

Table 1 The maximal values of various stresses in main beam under various load cases (Unit:MPa)

	σ_x	σ_y	σ_z	τ_{xy}	τ_{yz}	τ_{zx}
Load case 1	5.72	1.31	0.51	0.22	0.19	0.36
Load case 2	5.53	0.39	1.67	0.29	0.29	0.18
Load case 3 (X-beam)	8.20	0.58	2.46	0.58	0.43	0.34
Load case 3(Y-beam)	2.88	2.17	0.26	0.08	0.11	0.07
Load case 4(X-beam)	8.82	2.24	0.85	0.36	0.31	0.54
Load case 4(Y-beam)	0.14	0.31	0.16	0.58	0.58	0.05

3 Dynamic analysis

3.1 Calculation results

The FEM model for dynamic analysis is same as in static analysis. The Sub-Space Iteration Method is used to calculate the natural frequency and natural vibration shape of elastic body. The results obtained are complete, which were checked by the Sturm Sequence method .The natural frequencies and the characteristics of vibration shapes of first six orders are shown in **Table 2**.

3.2 Discussion

As the symmetry of structure and restriction the first-order and the second-order vibration mades of structure had the same natural frequency and similar vibration shape, and the same did the fifth-order and the sixth-order .The wrist force sensor is low-pass type of sensor, its working bandwidth can be generally estimated as 1/3 of the first-order natural frequency. Therefore, the working bandwidth of this sensor is about 0-275 Hz by estimating.

Table 2 The first six orders natural frequencies and the characteristics of vibration shapes

order	1	2	3	4	5	6
frequency（Hz）	823.5	823.5	999.9	1698.6	1878.8	1878.8
Characteristics of vibration shapes	Translation along X-axis	Translation along Y-axis	Translation along Z-axis	Rotation with Z-axis	Rotation with X-axis	Rotation with Y-axis

4 Analysis based on orthogonal test design

The elastic body's structure of multi-axis wrist force sensor is very complex, with a lot design parameters and intricate loading conditions, if we supposed some conditions, simplified the elastic body as cantilever beam for analysis [3], or as two -dimension plane stress problem to calculate in only one kind of loading condition [3], the reference value of the result obtained was quite limit. However if we carry out numerical analysis on the arbitrary combinations of different structure parameters and different loading conditions, the work of calculation is too large, and the calculation results still can't offer enough information [10]. Therefore we use the orthogonal test design in order to reduce the work of calculation to a great extent, to analyze the influence of main structure design parameters on the static and dynamic characteristics of sensor, and to summarize design principle for improving the performance of this kind of sensor.

4.1 Orthogonal test design [10]

Choosing the first order natural frequency of elastic component structure and the maximal normal strain in the main beam as indexes, and choosing structure parameters which have the most great influence on these two indexes as factors, such as the structure parameters of the main beam (length, width, height) and the floating beam (length, width, height). Because central platform is rigid in general, whose upper surface is subjected to external forces/torques and the calculative circuit is placed inside, we suppose the structure parameters of the central platform are unchanging. Choosing the original design parameters of elastic body of sensor as basic parameters and each factors fluctuate up or down based on these parameters, the breadths of fluctuation are mostly some and equate 10% of basic parameters. According to the demand of real structure design, for example, we choose the level number of each factors is 5 for a sensor and obtain **Table 3**.

Table 3 The levels of each factor for orthogonal test design (mm)

	x_1	x_2	x_3	x_4	x_5	x_6
Level 1	4.0	5.0	18.0	1.20	5.0	33.0
Level 2	4.5	6.0	20.0	1.35	6.0	36.0
Level 3	5.0	7.0	22.0	1.50	7.0	39.0
Level 4	5.5	8.0	24.0	1.65	8.0	42.0
Level 5	6.0	9.0	26.0	1.80	9.0	46.0

Table 3 shows it is a $L_{25}(5)^6$ orthogonal table with 6 factors and 5 levels as shown in **Table 3**. In Table 3, x_1 ,x_2, and x_3 represent the width, height and length of main beam respectively, x_4, x_5, and x_6 represent the width ,height and length of floating beam respectively.

The number of 1 2 3 4 and 5 represents the level corresponding to each test respectively, and each row represents one test .It is easy to see that, in all 25 tests the time that different level of each factor emerge is same (5 times), and all combinations of different levels of arbitrary factors are emerged, which means that levels are equipollent, and combinations are equipollent too. These 25 tests can represent those 15625(5^6) tests, and reflect comprehensively the influence of each level in each factor on those indexes

4.2 Results

According to the orthogonal test design, we have built the 3-dimension finite element analysis model of elastic body with different structure parameters, and given the boundary restrictive conditions and the load cases of different loading, then used the static analysis program and the dynamic analysis program to analyze these models. The five results calculated of 25 tests are listed in **Table 4** due to limited space.

In the **Table 4**, frequency (Hz) represents the first-order natural frequency of elastic body; normal strain σ_1 represents the maximal normal strain of main beam in the first kind of load case, and normal strain σ_2 represents the maximal normal strain of main beam in the second kind of load case.

Table 4 The orthogonal test design and the calculation results

Test Number	x_1	x_2	x_3	x_4	x_5	x_6	Frequency (*Hz*)	Normal Stress σ_1 (*MPa*)	Normal Stress σ_2 (*MPa*)
№1	1	1	1	1	1	1	620	11.984	11.393
№7	2	2	3	4	5	1	861	8.16	7.30
№13	3	3	5	2	4	1	721	6.83	6.46
№19	4	4	2	5	3	1	1152	4.18	4.10
№25	5	5	4	3	2	1	930	3.52	3.75

4.3 Range analysis [11]

In orthogonal test design, range analysis method (i.e. “R” method for short) is applied to decide the quality level of factor and the major or minor influence of factor on indexes. Applying the range analysis method to the above calculative results and we can obtain the results listed in **Table 5**. In this Table, (+) represents positive influence, (-) represents negative influence and (0) represents little influence.

From the **Table 5**, we can see that the influence of each factor on indexes is different under different load cases, and the result drawn from the analysis of some kind of load case is not applicable to the others, at the same time, we can see that the improvement of dynamic performance indexes will lead to the reduction of static performance ones, vice verse. So in the structure design of elastic body for multi-axis wrist force sensor, it is necessary to consider dynamic and static performance indexes simultaneously.

5 Optimization design

5.1 Step regression analysis on orthogonal test design

Beginning with a batch of data, regression analysis studies and judges whether connected relationship exits in several special variables, if does, then manages to obtain the constant relationship formula among these variables .The best regression equations so called mean these regression equations include all variables with obvious influence on indexes Y and without those with little influence. The general method to obtain the best regression equations is step regression analysis [9], [10]. According to the results calculated, we adopt the following regression model after analyzing:

$$y = b_0 + \sum b_i x_i + \sum a_i x_i^2$$

where, a_i and b_i are undefinited coefficients. Applying the calculation results of orthogonal test design using finite element method, we can obtain 25 observational points, then carry out the test of significance of regression to those factors [9]. By applying the step regression analysis, the best regression equations can be obtained as follows:

(1) Regression equation of frequency:

Table 5 Range analysis of calculation results

	Frequency						Normal Stress σ_1						Normal Stress σ_2					
	x_1	x_2	x_3	x_4	x_5	x_6	x_1	x_2	x_3	x_4	x_5	x_6	x_1	x_2	x_3	x_4	x_5	x_6
I	3224	3180	4577	3440	3630	4287	39.8	55.6	30.0	35.5	36.5	34.7	44.8	41.9	30.4	35.4	34.8	33.0
Ⅱ	3599	3788	4212	3631	3690	3853	37.1	40.9	32.8	34.7	35.2	34.6	37.5	35.9	32.2	33.3	34.0	32.4
Ⅲ	3838	3957	3813	3871	3780	3823	34.1	31.4	34.4	35.2	34.6	33.6	31.4	31.7	32.3	33.1	32.3	32.6
Ⅳ	4190	4177	3517	3944	4026	3660	33.0	24.6	36.9	33.3	33.4	34.7	24.2	28.4	34.1	30.8	31.9	32.2
V	4387	4136	3119	4352	4112	3615	28.1	19.7	38.1	33.4	32.3	34.6	22.5	25.4	34.3	30.7	30.3	33.0
R	1163	997	1458	912	482	672	11.7	35.9	8.1	2.2	4.2	1.1	22.3	16.5	3.9	4.7	4.5	0.8
major or minor influence of factor on indexes	2nd (+)	3rd (+)	1st (-)	4th (+)	6th (+)	5th (-)	2nd (-)	1st (-)	3rd (+)	5th (-)	4th (-)	6th (0)	1st (-)	2nd (-)	5th (+)	3rd (-)	4th (-)	6th (0)

$$Y_1=116.680x_1+295.42x_2-36.11x_3-85.146x_6-7.814x_2^2+95.238x_4^2+1.865x_5^2+0.958x_6^2+1353.227$$

where Y_1 represents the first-order natural frequency of elastic body.

(2) Regression equation of tensile stress in main beam surface under the action of Fz:

$$Y_2=-6.192x_2+0.202x_3-0.192x_5-0.110x_1^2+0.316x_2^2-0.255x_4^2+34.390$$

where Y_2 represents the tensile stress in main beam surface under the action of Fz.

(3) Regression equation of tensile stress in main beam surface under the action of Mz:

$$Y_3=-6.259x_1-2.173x_2+0.097x_3-1.576x_4-0.221x_5+0.406x_1^2+0.097x_2^2+39.502$$

where Y_3 represents the tensile stress in main beam surface under the action of Mz.

Table 6 The results obtained before and after optimization

	Before Optim.	After Optim.
Width (main beam)	6.0mm	5.3820mm
Height (main beam)	8.0mm	6.8114mm
Length (main beam)	22.0mm	18.00mm
Width (floating beam)	1.35mm	1.8mm
Height (floating beam)	5.0mm	9.0mm
Length (floating beam)	46.0mm	33.0mm
Y2	4.14 *MPa*	4.14 *MPa*
Y3	4.18 *MPa*	4.18 *MPa*
Y_1	803*Hz*	1210 *Hz*

5.2 Optimization design

Based on the above regression equations, the optimization design of elastic body of sensor can be carried out using general optimization methods [9]. The example of optimization designs on the elastic body using complex search method [9] is as follows:

Example: The elastic body is expected to have the maximal first order natural frequency in the circumstances of constant sensitivity. The results obtained before and after optimization are shown in **Table 6**.

From **Table 6,** we can see the frequency after optimization is 50% higher than that before optimization.

6 Conclusions

With the example for designing the six-axis wrist force sensors of a space robot, the paper presents the whole process of optimization design of this kind of sensor: the FEM model building; the numerical analysis on static and dynamic characteristics; the orthogonal test design and the range analysis; the step regression analysis of results calculated and the optimization design of elastic body of sensor.

Firstly, the stress distribution pattern for various load cases, natural frequencies and vibration shapes of the elastic body are analyzed.

Secondly, the orthogonal test design is applied to reduce work of calculation greatly, and the influence of main structure parameters on static and dynamic characteristics is investigated comprehensively. It is shown that the sensor design has to trade –off between the better static performance and the better dynamic one.

Finally, the regression equations between the structure parameters and performances of the sensor are obtained by using step regression analysis on numerical results. And the optimization design of elastic body for the wrist force sensor is put into implementation. Some examples are given to show the efficiency of the methods in the paper. The results obtained in the paper offer important reference for the design of this kind of sensors, and have been applied in the elastic body structure design of six-axis wrist force sensors in the space robot.

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