Analysis of the Influence of Temperature Gradient on the Measurement Accuracy of Axial Force in Balance

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Abstract. As a measuring element in wind tunnel test, it is important to ensure the measurement accuracy of strain balance.However, in the continuous wind tunnel, due to the long running time of the wind tunnel and the continuous transformation of Mach number, the temperature distribution of the balance body will be uneven, resulting in temperature gradient.This temperature gradient has an obvious influence on the measurement accuracy of the axial force of the balance.In order to explore the influence of temperature gradient on the axial force and strain output of the balance in the continuous wind tunnel, three temperature loading conditions were summarized according to the actual working conditions, and the thermal-solid coupling analysis of the 80A balance was carried out by ANSYS Workbench.The results show that the higher the temperature of the base point of the temperature gradient is, the faster the temperature input is, the more uneven the temperature distribution of the balance is, and the larger the temperature gradient is, the larger the axial force and strain output is. Considering the heat conduction of the back support rod, the temperature distribution of the balance body is relatively uniform, the temperature gradient is small, and the output of axial force and strain is small.

Keywords: Continuous wind tunnel; Temperature gradient; Strain balance; Finite element analy.

1. Introduction

As the key core equipment of wind tunnel test, strain balance is mainly composed of balance element (elastic element), strain gauge and measurement circuit [1].During the wind tunnel force measurement test, the strain balance directly senses the multi-dimensional aerodynamic load of the measured model, so the force measuring element and the pasted strain gauge produce elastic deformation together, resulting in the change of the resistance value of the strain gauge, which breaks the balance of the original Wheatstone bridge. The generated resistance change is converted into the change of the bridge voltage through the Wheatstone bridge. Finally, after the A/D conversion, Wind tunnel test data were obtained [2, 3]. However, in continuous wind tunnels with long running time and continuous Mach number change, the temperature of the balance increases due to heat conduction between the model and the support rod, resulting in uneven temperature distribution of the balance body. This situation has a particularly obvious impact on the output of axial force measurement. This problem has seriously hindered the development of wind tunnel tests today.

Since 1978, the performance test of low-temperature balance was carried out in the Netherlands, and it was concluded that temperature gradient was the key factor affecting the force measurement test of low-temperature balance [4]. James Hereford and Peter A. Parker et al. carried out A study on the influence of temperature gradient on low-temperature balances, and found that the temperature gradient span of the balance body was very large, and this temperature gradient had the most significant influence on the force measurement of axial force elements, and proposed to use genetic algorithm to compensate the temperature [5]. In order to find an effective means to compensate the temperature gradient, the Langley Research Center in the United States launched the project named TIGER [6]. Masataka Kohzai et al. in Japan designed and manufactured a six-component balance with a matching strain gauge based on materials with low expansion coefficient, so as to reduce the influence of temperature gradient on the force measurement output of the balance [7]. In addition, in order to reduce the thermal zero drift of strain balance output during force measurement, the team proposed a preheating method to preheat, so as to reduce the correction error of thermal zero drift [8]. In order to reduce the influence of temperature gradient on wind tunnel force measurement test data, Klaus Hufnagel et al. in Germany mainly optimized the structural design of the balance [9]. In order to solve the zero-point temperature effect of the balance, Li Chun et al. selected a variety of materials to carry out the temperature compensation test and the final results reached the expectation [10]. Yang Hongsheng et al. carried out a large number of simulation calculations for low-temperature wind tunnel balances. The task temperature gradient of the team was mainly caused by heat convection and heat conduction, and finite element calculation was carried out on support beams and resistance elements of different structures [11]. Wang Yanyang et al. analyzed the causes of temperature effect in continuous wind tunnels and proposed a method to solve the zero-point temperature effect of balance, and the final results reached the relevant technical indexes [12]. Considering the influence of temperature on the strain balance force measurement, Miao Lei et al. established the thermodynamic coupling loading system of strain balance, and the test results showed that the comprehensive loading error of each component of the balance was better than 0.3% [13].

To sum up, western countries have carried out a lot of research on wind tunnel balances, and proposed that temperature gradient is the main factor affecting the wind tunnel force measurement test results, and achieved a wealth of research results, but there are few related studies in China. In addition, continuous wind tunnel is different from other wind tunnels in its operation mode. There is no domestic or foreign research on the influence of temperature gradient on axial force elements in continuous wind tunnels. Therefore, this paper will use ANSYS workbench to carry out temperature field-statics analysis and calculation for 80A balance, so as to prevent and predict the influence of temperature gradient on the force measurement of axial force elements.

2. Thermal stress analysis and modeling

2.1. Thermal stress analysis of strain balance

When the temperature of the strain balance body changes, due to the mutual constraints of the internal parts, the flat body is heated, and each measuring beam of the balance cannot expand or contract freely, resulting in thermal stress.

Heat mainly includes three methods: heat conduction, heat convection and heat radiation. These three heat exchange modes all exist objectively in the balance body. According to literature [12], heat transfer from the model and rear support is the main factor to generate temperature gradient, so only the influence of heat transfer on the axial force element is considered.

Heat transfer mainly occurs between different temperature carriers, heat is always transferred from the high temperature carrier to the low temperature carrier. It follows Fourier's law:

$$q^n=-k*dT/dx \tag{1}$$

Where, q^n is heat flux, unit W/m^2; k is the thermal conductivity, and the unit is W/m·°C, where the minus sign represents the heat flow to the side with lower temperature [14].

According to the temperature data obtained from the test as the basis of finite element analysis, the thermal stress of the axial force element of the balance was calculated using the heat-solid coupling module of ANSYS workbench. The finite element analysis process is shown in Figure 1. The balance material is 00Ni18Co8No5TiAl high-strength martensitic aged steel, and martensitic steel with yield strength of 250 is generally selected [11]. The material properties are shown in Table 1.

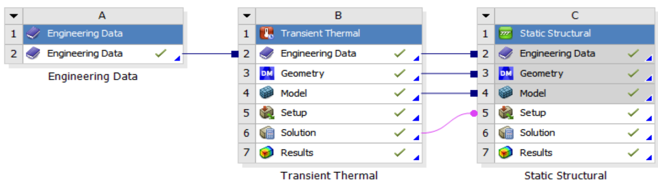


Fig 1. Finite element analysis process.

Table 1. Material property table.

Thermal conductivity W/m*°C	Specific heat capacity J/kg*°C	Density g/m3	Coefficient of linear expansion 10-6/°C	Modulus of elasticityGPa
17.9	423	8	10.7	180

2.2. Modeling and meshing of strain balance

CATIA was used to model the 80A wind tunnel balance. In order to reflect the change of strain output when the balance is subjected to temperature load more truly and accurately, the size of the model is exactly equal to that of the real thing in the three-dimensional modeling by using CATIA, and the components of the model and the real thing are also completely consistent. The three-dimensional model of the balance established by using CATIA is shown in Figure 2.

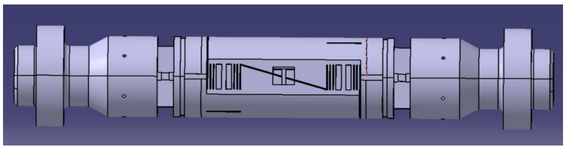


Fig 2. 80A balance model.

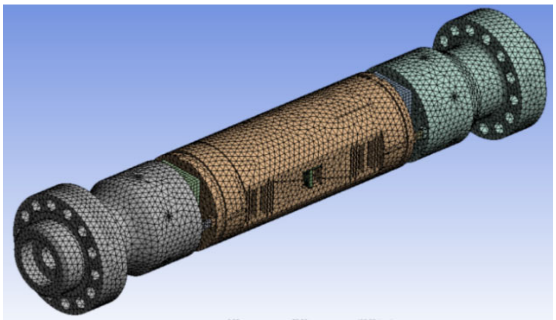


Fig 3. Balance model after meshing.

The 3D model modeled using CATIA was saved in stp format and imported into ANSYS Workbench. Before the balance model is analyzed and calculated, the balance should be meshed. In order to ensure the accuracy of the calculation results, the grid of each load measuring beam of the balance can be encrypted. Hex Dominant module was used to divide the grid for each force measuring beam, and the unit size was 3mm. Other parts use automatic modules to divide the grid, the cell size is 5mm. The result was 152,530 grids and 242,624 nodes. The final meshing effect is shown in Figure 3.

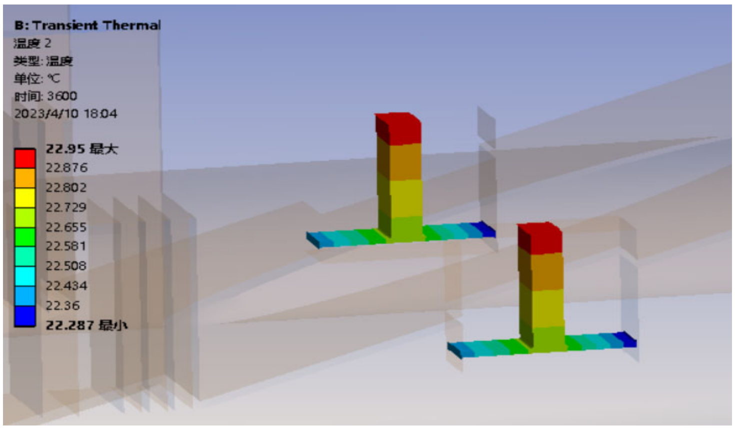
2.3. Temperature load

By default, the front and rear flanges are the base point of temperature gradient, and three different temperature loading simulation calculations are carried out on the balance body. The three loading conditions are: (1) the front flange is the temperature gradient base point, base point temperature is 30°C, 40°C and 50°C; (2) The front flange is the temperature gradient base point, base point temperature 50°C, change the heating time; (3) The front and rear flanges are the same temperature gradient base point, the loading time of the rear flanges is late 1800s and the base point temperature is 30°C.

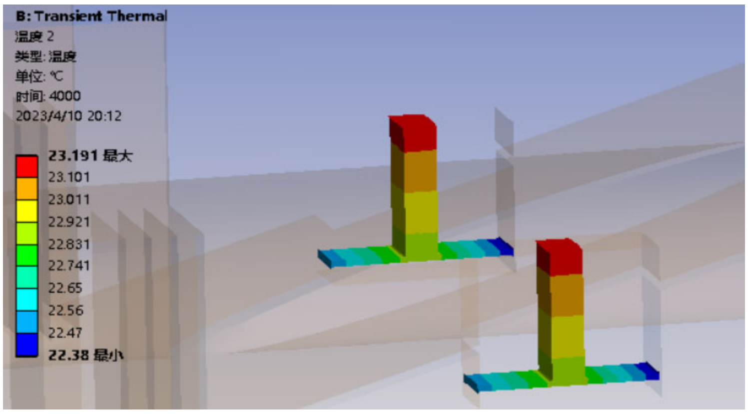
3. Finite element analysis

3.1. Axial mechanothermal strain analysis with different base temperature

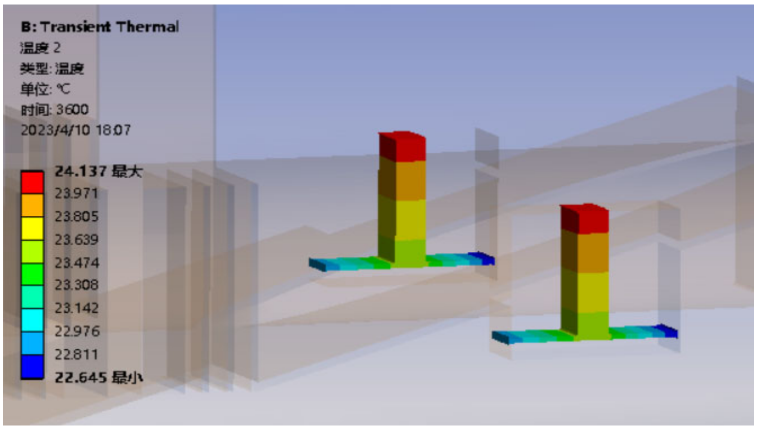
FIG. 4(a) ~ (f) represent temperature cloud diagram of axial force element at 360s and 4000s when the base temperature is 30°C, 40°C and 50°C, respectively. FIG. 5(a) ~ (f) respectively represent the thermal strain of axial force element at 360s and 4000s when the base temperature is 30°C, 40°C and 50°C.



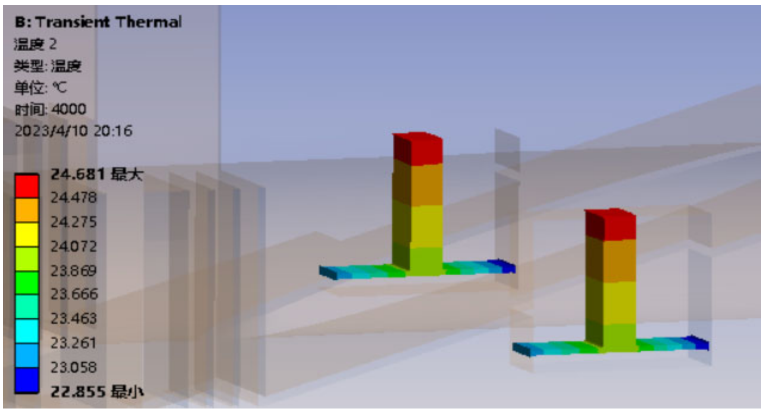
(a) Axial force element temperature distribution (Base temperature 30°C, 3600s).



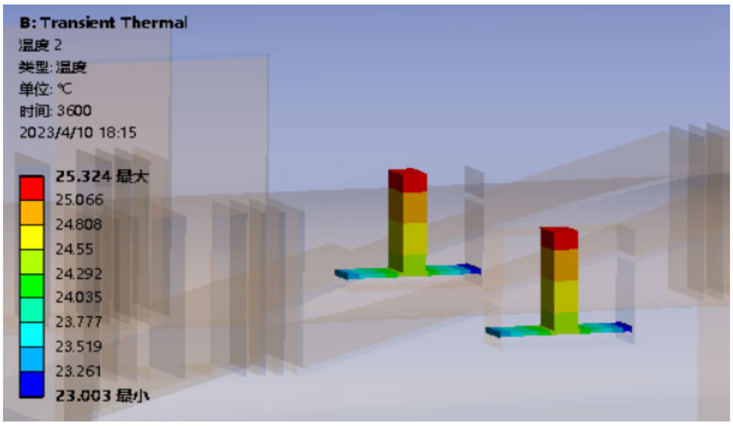
(b) Axial force element temperature distribution (Base temperature 30°C, 4000s).



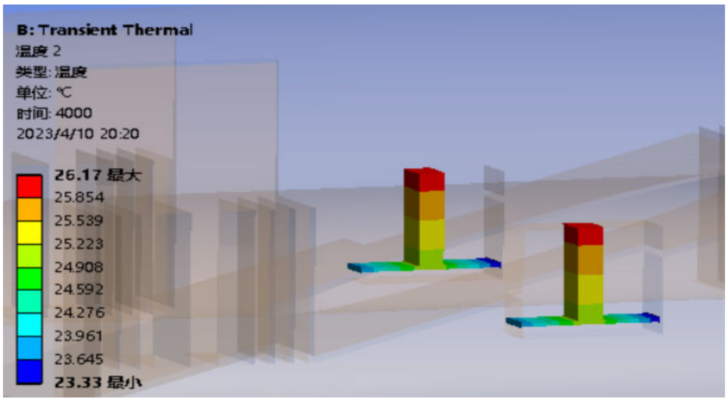
(c) Axial force element temperature distribution (Base temperature 40°C, 3600s).



(d) Axial force element temperature distribution (Base temperature 40°C, 4000s).

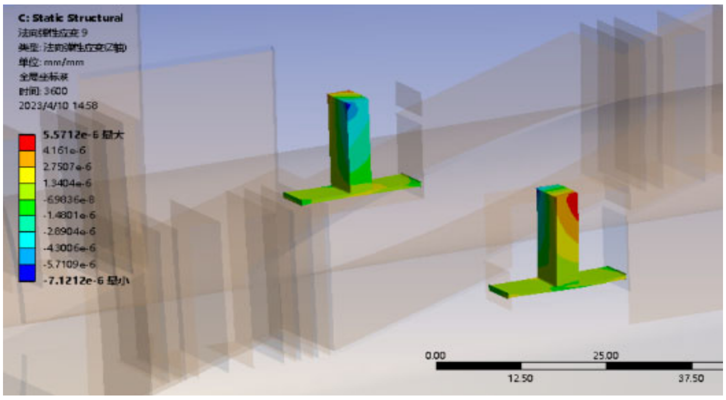


(e) Axial force element temperature distribution (Base temperature 50°C, 3600s).

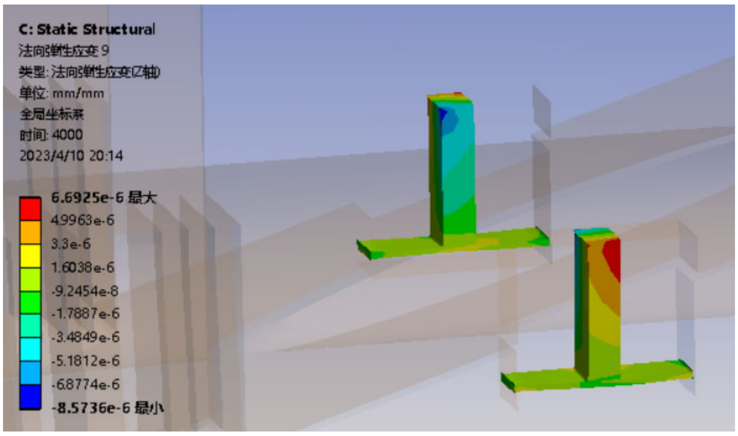


(f) Axial force element temperature distribution (Base temperature 50°C, 4000s).

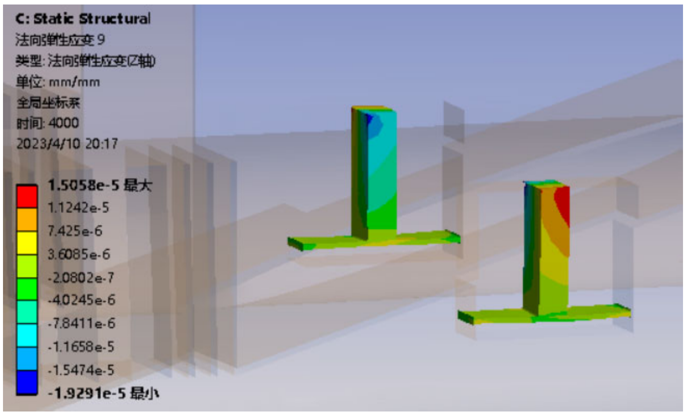
Fig 4 (a, b, c, d, e, f) Axial force element temperature distribution.



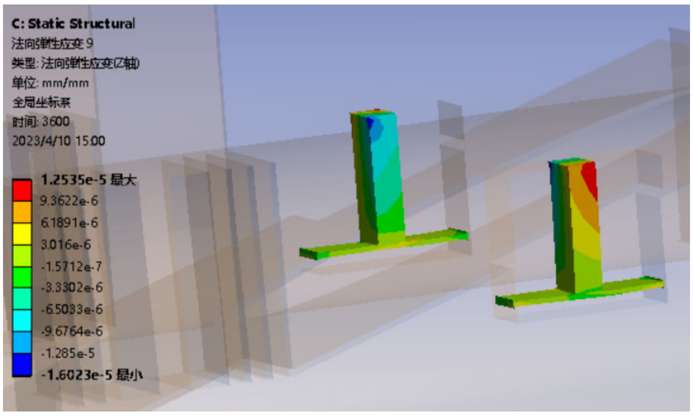
(a) Thermal strain of axial force element (Base temperature30°C, 3600s).



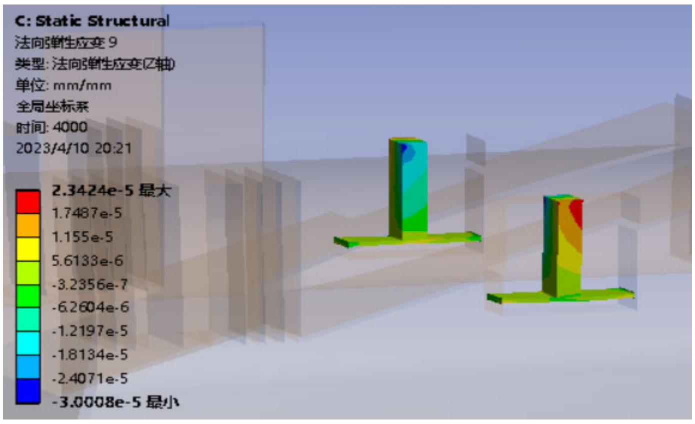
(b) Thermal strain of axial force element (Base temperature30°C, 4000s).



(c) Thermal strain of axial force element (Base temperature40°C, 3600s).



(d) Thermal strain of axial force element (Base temperature50°C, 3600s).



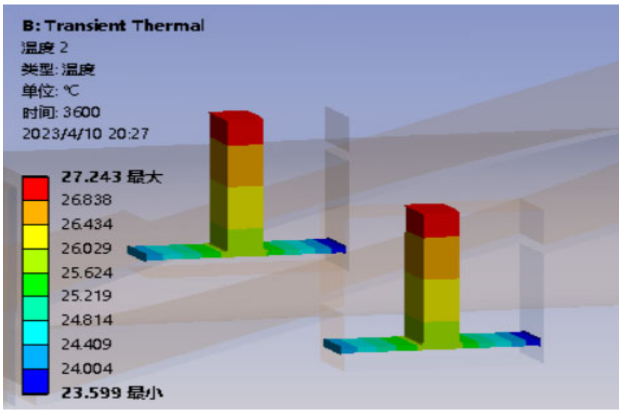
(e) Thermal strain of axial force element (Base temperature50°C, 3600s).

Fig 5 (a, b, c, d, e) Thermal strain of axial force element.

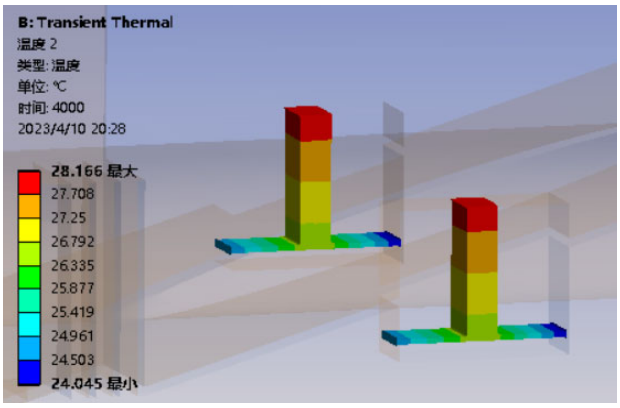
The finite element calculation shows that, as shown in Figure 4, the temperature of the axial force element of the balance has not reached a stable state, and the temperature gradient increases. As can be seen from Figure 5, the thermal strain of the axial force element of the balance shows a trend of gradual increase. Therefore, the axial load-thermal strain output of the balance is positively correlated with the temperature gradient of the balance element.

3.2. Analysis of axial force and thermal strain of base point heating time

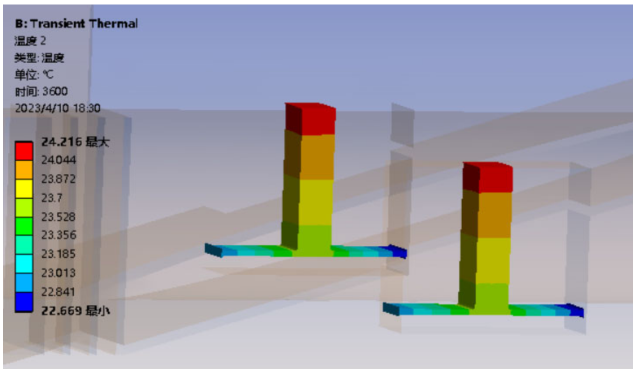
FIG. 6 shows the temperature cloud diagram of axial force elements at 360s and 4000s when the base temperature was 50°C and the heating time was as follows: 1800s and 5400s respectively. Figure 8 shows the axial force-thermal strain at 360s and 4000s when the heating time is as follows: 1800s and 5400s.



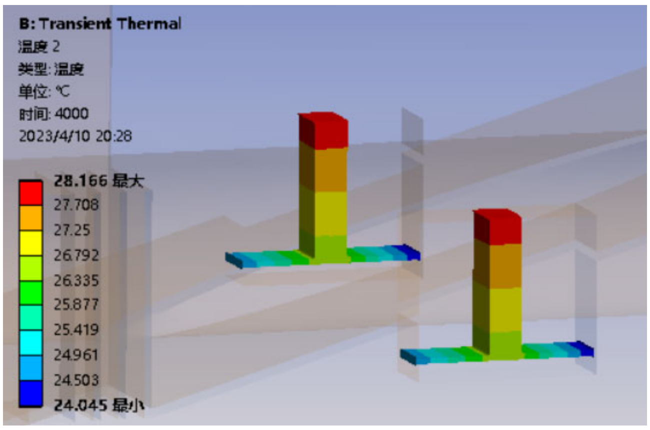
(a) Axial force element temperature distribution (Heating duration1800s, 3600s).



(b) Axial force element temperature distribution (Heating duration1800s, 4000s).

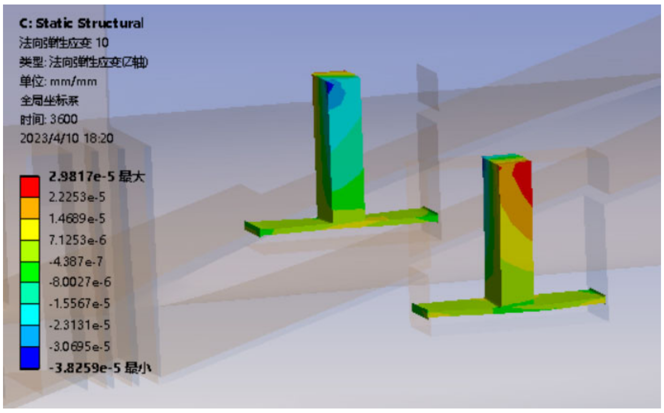


(c) Axial force element temperature distribution (Heating duration5400s, 3600s).

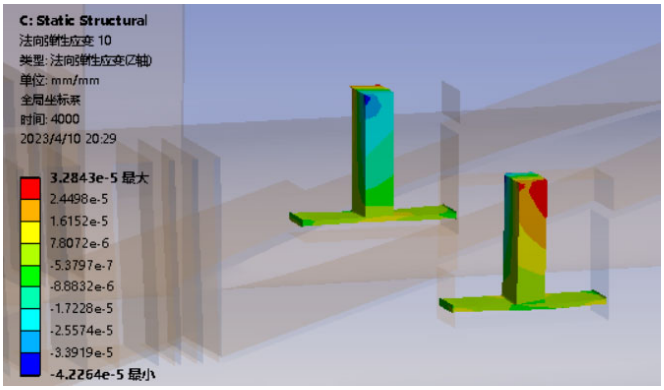


(d) Axial force element temperature distribution (Heating duration5400s, 4000s).

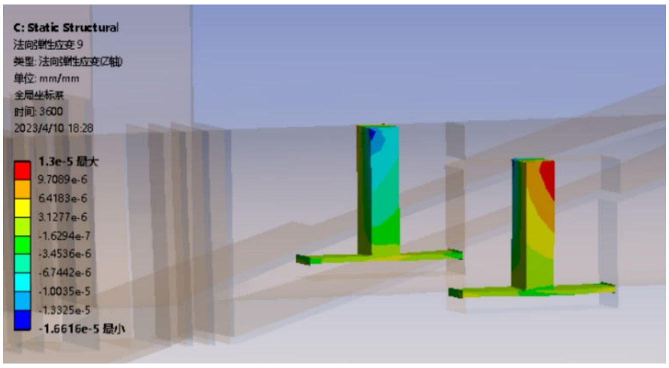
Fig 6 (a, b, c, d) Axial force element temperature distribution.



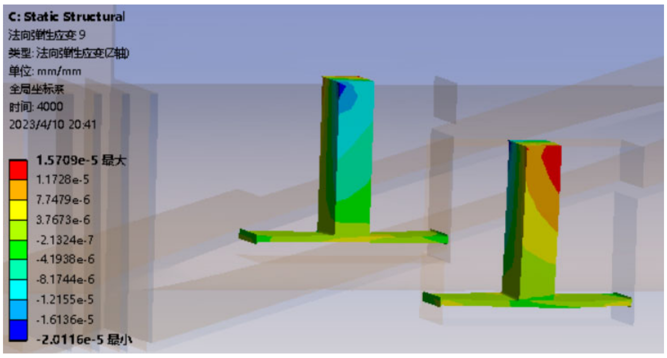
(a) Thermal strain of axial force element (Heating duration1800s, 3600s).



(b) Thermal strain of axial force element (Heating duration1800s, 4000s).



(c) Thermal strain of axial force element (Heating duration5400s, 3600s).



(d) Thermal strain of axial force element (Heating duration5400s, 4000s).

Fig 7 (a, b, c, d) Thermal strain of axial force element.

As can be seen from Figure 6, the shortening of heating time can be regarded as the more intense temperature rise of the balance. Therefore, the more intense temperature rise of the balance, the greater the temperature step difference of the axial force element of the balance. Between 360s and

4000s, the temperature of axial force element of the balance does not reach a steady state, so the temperature step difference increases. As can be seen from Figure 7, the greater the temperature rise of the balance, the greater the axial load-thermal strain output of the balance. The thermal strain output of axial force is positively correlated with the temperature rise time and temperature step difference of the balance.

4. Conclusion

According to the finite element analysis of the 80A balance, it can be concluded that the temperature of the heat source and its heating rate will lead to the uneven distribution of the temperature of the axial force element of the balance, there is a large temperature gradient, and the axial force and strain output will increase, which will eventually affect the wind tunnel force test. In addition, the finite element analysis calculation by workbench can predict the influence of temperature gradient on the strain output of each load measuring element. Finally, the finite element simulation shows that the influence of temperature gradient on the measuring accuracy of axial force can be effectively reduced by using the balance made of ardent steel.

In this paper, the influence of temperature gradient on the output of axial force and strain is obtained by analogical simulation method, but no relevant tests are carried out to verify it, and the corresponding results can only be obtained by finite element simulation. Similar tests can be designed later to verify.

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