Research on the simulation technology of the combined effects of transient thermal shock and a triaxial 6-DOF

Zemin Yao¹,²,³, Xiaokai Huang¹,², Shouqing Huang¹,² and Shouwen Liu¹,²

¹Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China
²Beijing Key Laboratory of Environment and Reliability Test Technology for Aerospace Mechanical and Electrical Products, Beijing 100094, China
³E-mail: buaayzm@126.com

Abstract. During the reentry of a spacecraft, it will encounter extreme environment of transient thermal shock and a triaxial 6-DOF. Currently, there is a lack of experimental verification means. Taking a second power supply as an example, the finite element simulation model is established, and the model is verified by the heat balance test and random vibration modal test. The thermal response distribution of rapid temperature change, low-temperature holding and high-temperature holding phrases is obtained through the transient thermal shock simulation; Based on the multi-stress simulation of the workbench, the stress-strain response distribution under the triaxial 6-DOF random vibration is obtained. According to the principle of stress coupling, the thermal response distribution matrix and stress-strain response distribution matrix are applied to the finite element model of electronic products at the same time, and then the transient thermal shock and the triaxial 6-DOF coupling simulation is realized, which provides a theoretical guidance for test verification of the extreme environment during the reentry of a spacecraft.

1. Introduction

There are five phases for a spacecraft to return to the ground from the orbit, which are the adjustment phase, the braking phase, the transition phase, the reentry phase and the landing phase. The reentry phase is the most characteristic flight phase during the return, and it is also the worst and most complex phase in the return orbit. It will encounter an extreme environment of transient thermal shock and a triaxial 6-DOF. At present, there is a lack of experimental verification means. Therefore, it is necessary to study the reliability of electronic products in the extreme environment during the reentry.

Some researches on transient thermal shock and a triaxial 6-DOF have been carried out. Xu analyzed the two types of typical turbine rotor structures undergoing transient thermal impact, obtained transient thermal stress on the turbine rotor is greater than the steady state thermal stress [1]. Ren used experiment technique and CFD approach to study the slot film cooling scheme under the transient thermal shock conditions, acquired that the DES approach performed more efficiently in predicting the adiabatic effectiveness [2]. Based on Patron software, Zhang set up the 3D finite element models of double-bump solder joints, analysed the natural frequency, vibration mode and frequency response rule of models, obtained the strain distribution and the response curves of strain power spectrum density [3]. By studying the theory of thermally induced vibration (UTIV), Kong proposed a finite analysis method of uncoupled thermally induced vibration, three thermal shock loads with different frequencies were used to test the feasibility of UTIV analysis method [4]. Yang studied
the transverse vibration characteristics of an axially moving beam subjected to a thermal shock, obtained that equivalent thermal axial force played a dominant role on natural frequencies of the beam, changing of elastic modulus and equivalent thermal moment played a secondary role [5]. Taking a beam and a plate structure in the equipment for example, Liu divided the thermal load into high and low temperature stress and cyclic stress, and according to different temperature fields, the thermal load analysis and thermal stress of the structure are solved [6]. Xu implemented an aerodynamic/thermal/structural multi-fields coupling analysis using the partition algorithm in order to predict the aerodynamic and aerothermal environment accurately, and this coupling method was validated by the experiments [7]. Wang investigated the thermoelastic response of an elastic medium with variable material properties under the transient thermal shock, revealed the effect of the temperature dependency of material properties comparing with those obtained from the case of constant material properties [8]. The research group of Wangs studied the transient crack problem under the generalized thermoelastic theory, and obtained the theoretical solution of the crack tip temperature field and stress intensity factor considering the effect of heat-wave [9-11].

To sum up, the simulation technology of electronic products under the extreme environment of transient thermal shock and a triaxial 6-DOF random vibration is still in its infancy at home and abroad. Therefore, taking the secondary power supply of spacecrafts as an example, the transient thermal simulation and the triaxial 6-DOF random vibration simulation are separated carries out, and then based on the principle of stress coupling, the combined effect simulation of the transient thermal shock and the triaxial 6-DOF are realized, which provides theoretical support for the analysis of extreme environment effect during reentry of spacecrafts.

2. Theory foundation and overall idea

2.1. Theory foundation
In this paper, the simulation is mainly a comprehensive simulation of transient thermal shock and triaxial six degrees of freedom, so its theory foundation is heat transfer and dynamics. The heat distribution of each part of the product can be obtained from the following differential Equation (1) of transient temperature field:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right)$$

In Equation (1), $\rho$ is the material density; $k_x$, $k_y$, $k_z$ is the thermal coefficient along the x, y, z directions in the coordinate system; C is the specific heat capacity. The results calculated above are input to the dynamic Equation (2).

$$M \ddot{u} + C \dot{u} + K u = B_0 f$$

In Equation (2), M is the mass matrix, K is the stiffness matrix, C is the damping matrix and u is the displacement matrix.

The Equation (2) is transformed by Fourier to obtain the acceleration frequency response function matrix of the system, as in Equation (3).

$$H(\omega)_{68} = -\omega^2 \left( -\omega^2 M + j\omega C + K \right)^{-1} B_0$$

Thus, the stress and strain of each part of the model can be obtained.

2.2. Overall idea
The main research idea of the simulation is: through the actual measurement, the transient thermal shock and the triaxial 6-DOF environmental loads experienced by the spacecraft electronic products during reentry are obtained, and then the failure mode analysis and environmental effect is carried out under the corresponding load. Taking the second power supply for aerospace as an example, the finite element model is established, the model is verified by a thermal balance test and a modal test. The transient thermal shock simulation is carried out to obtain the thermal stress response distribution...
matrix of the second power supply under high temperature, low temperature and rapid temperature change. The vibration under a triaxial 6-DOF is simulated to obtain the stress and strain response distribution Matrix of the power. According to the principle of stress coupling these two kinds of stress distribution matrices are applied to the finite element model of the electronic product at the same time, so that the simulation results of the integrated effects of the second power supply can be obtained. The flow chart of the transient thermal shock and the triaxial 6-DOF combined response simulation is shown in Figure 1.

Figure 1. The flow chart of combined effect simulation.

3. Analysis of environment effect

3.1. The effect of transient thermal shock
During the reentry of spacecrafts, the electronic products installed in the bulkhead of spacecraft will encounter the environment of great heat flow from 0 to 5.5Mw/m⁰ in 100s, which will cause the temperature of the products to rise from −35°C to 70°C in 100s, and then affects the output voltage / current accuracy, switches contact jitter and other failure. The transient thermal condition is shown in Figure 2, the applied position is on the mounting surface of the base plate.

1) Temperature: -35°C ~70°C;
2) Temperature change rate: 63°C/min;
3) Cycle times:5 times (Designed to be reused 10 times);
4) Residence time under high/low temperature: 10mins (Each high/low temperature cycle is equivalent to two reentries);

Figure 2. The environmental load of transient thermal shock during reentry.
During the transient thermal shock, the failure modes of spacecraft electronic products include solder joint failure, ceramic capacitor failure, power device transistor failure (IGBT), etc.

The main reason of solder joint failure is that the thermal mismatch between the substrate and the chip makes the solder joint undergo shear stress, and there is stress concentration on the interface between the solder joint and the chip. From the microcosmic point, it can be concluded that the main IMC ((Cu, Ni) and Sn, Ag, Cu) interface are quite different from the material properties such as the elastic modulus and thermal expansion coefficient of the solder matrix, which leads to the thermal mismatch between the solder matrix and IMC during thermal shock. The main failure modes of ceramic capacitor are reflow soldering, wave soldering and soldering iron soldering. The main cause of reflow soldering fails are insufficient preheating or high solder temperature. The capacitors are easily damaged by the thermal shock stress, and cracks generally penetrate the surface of the capacitors. The failure reason of mask wave soldering is that the mask wave soldering is in the critical area of mask opening, and there are two areas of uneven heating in the single plate. The temperature of tin wave contact position is high, PCB is deformed, and the temperature change is small in the area covered by mask fixture; the failure reason of soldering iron soldering is that excessive soldering tin causes unbalanced heating stress and fracture. Power device (IGBT) failure can be divided into packaging failure and chip failure. During reentering of spacecraft, a large amount of heat will be generated by the electronic products, which cannot be released inside the module in time, resulting in the temperature rising inside the module. Because IGBT devices are mainly composed of layers of various materials, there are great differences in thermal expansion coefficient between materials, and the internal temperature of devices increases, so that alternating shear stress between materials causes thermal deformation. On the other hand, the product has the function of power cycle, and the complex external environment accelerates the fatigue crack growth caused by the thermal stress of power cycle.

3.2. The vibration effect of a triaxial 6-DOF

During the reentry of spacecrafts, the measured random vibration of a triaxial 6-DOF at the product installation boundary are as follows: acceleration x = y = z = 9g, angular velocity x = y = z = 18°/ S (i.e. 0.314rad / s), the duration of each reentry is 300s, and the acceleration power spectral density is shown in Table 1.

| Frequency: Hz | PSD: g²/Hz |
|--------------|------------|
| 20           | 0.0105     |
| 20~50        | +6dB/oct   |
| 50~800       | 0.0649     |
| 800~2000     | 0.0105     |
| Loading time | 300s       |
| Total RMS acceleration | 9grms    |
| Loading direction | X, Y, Z, three directions |

The triaxial 6-DOF vibration environment mainly excites the failures, such as component connection failure, welding point fatigue failure and pressure joint fatigue failure. During the reentry of spacecrafts, due to severe vibration and free rotation, PCBA is coupled with its natural frequency, the resonance leads to severe mechanical response, which makes the response of sensitive components on the base plate exceed their anti-vibration ability and failed. Because of the huge aerodynamic noise and overturning effect during the reentry, the local stress level of pins and joints exceeds the yield limit of the material, which makes the solder joint of the pin crack or break, and the large amplitude can cause the pressure connector to break out or fall off. In addition, the stress at the connection between PCBA and its upper device exceeds the limit of the sensitive device, which are the main reasons for the failure of the electronic products under the triaxial 6-DOF.
4. Modeling and simulation analysis

4.1. Finite element modelling and verification

4.1.1. Finite element modelling [14]. Taking the secondary power supply as an example, it is composed of input and output components, power distribution components, DC / DC components, intelligent components and supporting structural parts. In the process of finite element modeling, the "bonded" connection mode is adopted between the components, and the material properties are set reasonably, grid size (Element size) is set to 2.3mm, the free mesh method is adopted, and the transition section is optimized at the same time, so as to obtain the product finite element model with 305208 elements and 1148989 nodes, as shown in Figure 3.

Figure 3. The finite element model of a secondary power supply.

4.1.2. The verification of the thermal balance test. Set the surrounding environment as a vacuum environment with a temperature of 50°C, the convective heat transfer coefficient between the product and the outside is 0W / (M2·°C), and the inside of the product is a low-pressure environment with a pressure of about 10Pa, so the internal convective heat transfer coefficient is 2W / (M2·°C). The thermal control surface of the product is the installation base plate, and the temperature is 50°C. At the same time, set the power consumption parameters of each component as required. On the basis of the above boundary conditions, the steady-state thermal simulation is carried out, and the temperature distribution of the product under the steady-state condition of thermal balance at 50°C is shown in Figure 4.

Figure 4. Thermal balance temperature distribution of the secondary power supply.
At the same time, the thermal balance test of secondary power supply was carried out, the temperature measurement results of key components were compared with the results of simulation analysis, and then the difference between actual temperatures and simulation results was found to be less than 2°C, which verified the effectiveness of the finite element simulation model.

4.1.3. The verification of modal test. The modal test of secondary power supply was carried out, and the comparison between the modal test results and simulation results is shown in Table 2. The relative errors of the first order to the sixth order are less than 5%, which verifies the validity of the dynamic simulation model.

Table 2. Modal verification of the finite element mode.

| modal | Test results | simulation results | Relative error |
|-------|--------------|--------------------|----------------|
| 1     | 550.41       | 568.62             | 3.3%           |
| 2     | 644.40       | 666.93             | 3.5%           |
| 3     | 687.04       | 675.44             | -1.7%          |
| 4     | 701.37       | 698.17             | -0.5%          |
| 5     | 754.82       | 762.69             | 1.0%           |
| 6     | 861.26       | 850.13             | -1.3%          |

4.2. Transient thermal shock simulation analysis [15-18]
The transient thermal shock condition of -35°C ~ 70°C and 63°C / min is applied on the installation base plate of the secondary power supply. The ambient temperature is 23°C, and the convective heat transfer coefficient between the secondary power supply and the air in the cabin is 2W / (m²·°C). The transient thermal simulation is carried out, and the temperature variation law of the key components of

Table 3. Extreme thermal environmental effects-thermal cycling.

| Components | Environmental effect | -35°C ~ 70°C, 63°C / min, Transient thermal shock measured in flight | -35°C ~ 70°C, 5°C / min, Qualification test thermal cycle | -15°C ~ 50°C, 5°C / min, Product design thermal cycle |
|------------|----------------------|-------------------------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------|
| Module power | High temperature °C | 68.7                                                              | 69.967                                                | 50.865                                               |
|             | Low temperature °C  | -25.2                                                             | -31.793                                               | -12.914                                              |
|             | Temperature change rate °C / min | 0.13                                                              | 0.06                                                 | 0.03                                                 |
| Hall power sensor | High temperature °C | 53                                                                | 63.646                                                | 46.576                                               |
|             | Low temperature °C  | -11.4                                                             | -24.923                                               | -8.5784                                              |
|             | Temperature change rate °C / min | 0.083                                                             | 0.018                                                 | 0.012                                                 |
| Relay | High temperature °C | 36.6                                                              | 46.542                                                | 42.741                                               |
|             | Low temperature °C  | 21.9                                                              | -0.51                                                 | -2.7383                                              |
|             | Temperature change rate °C / min | 0.004                                                             | 0.0054                                                | 0.013                                                 |
| Single chip | High temperature °C | 69.9                                                              | 69.97                                                | 49.989                                               |
|             | Low temperature °C  | -10.6                                                             | -24.93                                                | -22.826                                              |
|             | Temperature change rate °C / min | 0.11                                                              | 0.0345                                                | 0.0177                                                |
the secondary power supply, such as Hall current sensor, Power module, Relay and Circuit board under the transient thermal shock is obtained. The thermal effect is shown in Table 3.

It can be seen from Table 3 that the actual temperatures of the key components inside the secondary power in the flight measured transient thermal shock, such as 0.13°C/min, 0.083°C/min, 0.11°C/min, far exceed the rates in flight qualification test and product design thermal cycle test. So, the current test is not enough to assess the environmental effect of temperature change rate. It is necessary to analyse the influence of temperature change rate (0.13°C/min) on the reliability of secondary power supply, Hall current sensor and single chip microcomputer, including the reliability of device itself and the reliability of packaging process.

4.3. Simulation analysis of a triaxial 6-DOF

On the basis of modal analysis, triaxial vibration simulation is carried out. First of all, at the installation location of the secondary power supply mounting ear, the triaxial random vibration excitation is applied as shown in Table 4, the damping coefficient is set to the empirical value of 0.035, and then the random vibration simulation is carried out, the response results of Hall current sensor, Module power, Relay and Circuit board are got under the measured flight triaxial random vibration shown in Table 4.

**Table 4.** The triaxial random vibration response of key components.

| Product          | 36 Stress (Pa) |      |      |      |      |
|------------------|----------------|------|------|------|------|
|                  | maximum        | minimum | average |      |      |
| Module power     | 1.609×10⁷      | 1.3185×10⁵ | 5.321×10⁵ |      |      |
| Hall current sensor | 7.2101×10⁶   | 361.52       | 2.2094×10⁴ |      |      |
| Relay            | 2.3232×10⁷      | 6868.8       | 5.8424×10⁵ |      |      |
| Circuit board    | 1.6134×10⁷      | 52520         | 1.6368×10⁶ |      |      |

Then, the “Equivalent Stress” of the triaxial random vibration simulation is exported in the format of “.txt”, and the “External Data” module is built in the “Project Schematic” of the workbench. The “.txt” file of the triaxial random vibration “Equivalent Stress” results are imported into the “External Data” model, and the corresponding settings are made.

A new “Static Structural” module is built to carry out static stress analysis. The angular velocity of 0.314rad/s is applied to the X, Y and Z axes of the secondary power supply respectively, and the “Equivalent Stress” of the triaxial random vibration is applied to the “Static Structural” of the secondary power supply as the initial constraint condition, the static structure analysis is carried out, and then the simulation results of the triaxial 6-DOF of the secondary power supply are obtained. The maximum deformation is 0.048176mm.

The results are refined, and the stress-strain effects of key components such as Module power, Hall current sensors, Relays, and Circuit boards are shown in Table 5.

| Product          | Stress (Pa) | Strain (m/m) |      |      |      |      |
|------------------|-------------|--------------|------|------|------|------|
|                  | Maximum     | Minimum      | Average | Maximum | Minimum | Average |
| Module power     | 2.6085×10⁷  | 3412.4       | 2.2245×10⁵ | 1.1151×10³ | 3.0002×10⁷ | 4.7951×10⁻⁷ |
| Hall current sensor | 6.5947×10⁶ | 1882.6       | 1.9148×10⁵ | 5.9882×10⁴ | 9.3442×10⁷ | 3.7721×10⁻⁵ |
| Relay            | 1.0048×10⁷  | 15767        | 5.127×10⁵  | 1.1847×10⁴ | 1.0107×10⁶ | 1.4184×10⁻⁵ |
| Circuit board    | 1.7064×10⁷  | 32434        | 1.5247×10⁶ | 4.6925×10⁴ | 8.097×10⁶  | 7.9334×10⁻⁵ |

The results are refined, and the stress-strain effects of key components such as Module power, Hall current sensors, Relays, and Circuit boards are shown in Table 5.
It can be concluded from Table 5 that the maximum stress response of the module power is $2.6085 \times 10^8$ Pa under the triaxial 6-DOF, and the maximum stress response of the qualification test is $1.8442 \times 10^8$ Pa. It shows that the environmental effect of the triaxial 6-DOF is better than that of single vibration in qualitative test.

### 4.4. Simulation analysis of transient thermal shock and a triaxial 6-DOF

First, based on the simulation results of transient thermal shocks measured during flight, we obtained the five-group data of the secondary power heat distribution from $23^\circ C \rightarrow -35^\circ C$, $-35^\circ C \rightarrow 70^\circ C$, $70^\circ C$ for 10 minutes, $-35^\circ C \rightarrow 70^\circ C$, and $70^\circ C \rightarrow 23^\circ C$, and these data are exported in "txt" format.

Then, with the heat distribution at each time as the initial constraint, the "txt" file in the form of "External Data" is applied to the finite element model of the second power.

The simulation results are refined, and the stress-strain response of key components such as Module power, Hall current sensors, Relays, and Circuit boards are shown in Table 6.

**Table 6.** The stress-strain response of extreme thermal and a triaxial 6-DOF.

| Components | Response | Flight measured thermal shock, the triaxial 6-DOF (X=Y=Z=9g, X=Y=Z=0.314rad/s) |
|------------|----------|----------------------------------------------------------------------------------|
| Module power | Stress (Pa) | 23°C → -35°C for 10 minutes | -35°C → 70°C | 70°C for 10 minutes | 70°C → 23°C |
| Max | $1.5451 \times 10^8$ | $1.8862 \times 10^8$ | $2.8086 \times 10^7$ | $4.4062 \times 10^7$ | $3.6197 \times 10^7$ |
| Min | 32315 | 39870 | 5476.7 | 15738 | 11021 |
| Avg | $7.4978 \times 10^6$ | $9.0164 \times 10^6$ | $1.1948 \times 10^6$ | $2.8428 \times 10^6$ | $2.3543 \times 10^6$ |
| Min | $1.0807 \times 10^2$ | $1.2982 \times 10^2$ | $2.3852 \times 10^3$ | $3.1277 \times 10^3$ | $2.6855 \times 10^3$ |
| Avg | $2.1179 \times 10^3$ | $2.7212 \times 10^3$ | $4.2757 \times 10^4$ | $8.2516 \times 10^4$ | $6.1918 \times 10^4$ |
| Min | $2.7339 \times 10^3$ | $3.3101 \times 10^3$ | $4.0511 \times 10^4$ | $1.0451 \times 10^5$ | $8.3931 \times 10^4$ |
| Avg | $8.3731 \times 10^6$ | $5.1095 \times 10^7$ | $2.9578 \times 10^7$ | $2.5759 \times 10^7$ | $3.1996 \times 10^7$ |
| Min | 2938.3 | 11608 | 6407.4 | 5380.7 | 5474 |
| Hall current sensor | Stress (Pa) | 23°C → -35°C for 10 minutes | -35°C → 70°C | 70°C for 10 minutes | 70°C → 23°C |
| Max | $7.4778 \times 10^5$ | $4.9778 \times 10^6$ | $2.8448 \times 10^6$ | $2.6127 \times 10^6$ | $3.2379 \times 10^6$ |
| Min | $1.0348 \times 10^3$ | $5.1371 \times 10^5$ | $2.9995 \times 10^5$ | $2.6714 \times 10^5$ | $3.3015 \times 10^5$ |
| Avg | $2.7868 \times 10^4$ | $2.0965 \times 10^5$ | $1.191 \times 10^5$ | $1.1301 \times 10^5$ | $1.3995 \times 10^5$ |
| Min | $3.3643 \times 10^4$ | $2.4002 \times 10^5$ | $1.3662 \times 10^5$ | $1.2931 \times 10^5$ | $1.5991 \times 10^5$ |
| Avg | $4.2058 \times 10^7$ | $8.8659 \times 10^7$ | $4.0895 \times 10^7$ | $3.1481 \times 10^7$ | $5.4111 \times 10^7$ |
| Min | 18074 | 1.3912×105 | 54771 | 61349 | 75516 |
| Relay | Stress (Pa) | 23°C → -35°C for 10 minutes | -35°C → 70°C | 70°C for 10 minutes | 70°C → 23°C |
| Max | $2.8428 \times 10^6$ | $4.7292 \times 10^6$ | $2.154 \times 10^6$ | $2.1564 \times 10^6$ | $3.876 \times 10^6$ |
| Min | $4.1943 \times 10^4$ | $9.0416 \times 10^4$ | $4.1218 \times 10^4$ | $3.3241 \times 10^4$ | $5.6158 \times 10^4$ |
| Avg | $1.2479 \times 10^6$ | $1.5716 \times 10^6$ | $1.3477 \times 10^6$ | $1.3207 \times 10^6$ | $1.5957 \times 10^6$ |
| Min | $3.5514 \times 10^5$ | $4.9982 \times 10^5$ | $2.6701 \times 10^5$ | $2.7188 \times 10^5$ | $4.5021 \times 10^5$ |
| Circuit board | Stress (Pa) | 23°C → -35°C for 10 minutes | -35°C → 70°C | 70°C for 10 minutes | 70°C → 23°C |
| Max | $1.6898 \times 10^8$ | $1.451 \times 10^8$ | $7.1803 \times 10^7$ | $4.143 \times 10^7$ | $7.1358 \times 10^7$ |
| Min | $1.6387 \times 10^7$ | $55362$ | $1.7608 \times 10^6$ | $1.127 \times 10^6$ | $1.3043 \times 10^6$ |
| Avg | $1.0797 \times 10^7$ | $9.056 \times 10^6$ | $5.6495 \times 10^6$ | $5.6366 \times 10^6$ | $7.6571 \times 10^6$ |
| Min | $2.4999 \times 10^5$ | $2.1965 \times 10^5$ | $1.396 \times 10^5$ | $6.2409 \times 10^4$ | $1.0918 \times 10^5$ |
| Avg | $1.0883 \times 10^5$ | $6.0765 \times 10^6$ | $7.0022 \times 10^6$ | $6.8263 \times 10^6$ | $6.6746 \times 10^6$ |
| Min | $1.9447 \times 10^4$ | $1.7251 \times 10^4$ | $1.1858 \times 10^4$ | $1.2081 \times 10^4$ | $1.4759 \times 10^4$ |

From Table 6, it can be concluded that under the coupling effect of transient thermal shock and a triaxial 6-DOF, the stress-strain response of the Module power, Hall current sensor, and relay is greater than under the triaxial 6-DOF vibration and transient thermal shock alone and the stress-strain response is an order of magnitude higher ($10^8$ Pa VS $10^7$ Pa). This simulation result not only provides a theoretical support for the adequacy design of the qualification test, but also escorts the reliability of spacecraft electronics.
5. Conclusions
This paper presents the combined simulation technology of transient thermal shock and a triaxial 6-DOF random vibration for the spacecraft secondary power, and draws the following conclusions.

1. Under the combined environment of transient thermal shock and a triaxial 6-DOF, the stress and strain of each component in the secondary power supply is one order of magnitude higher than that under the single environment, so it is not enough to carry out qualification test only.

2. Simulation analysis of the three axes is performed to obtain equivalent stress. As an initial condition, the equivalent stress is applied to the static stress analysis module, and the rotational angular velocity is exerted on the three axes respectively to obtain the simulation results of the triaxial 6-DOF random vibration. It breakthroughs the restriction of having no separate simulation modules of a triaxial 6-DOF. The stress-strain matrices obtained under transient thermal simulation and triaxial six-degree-of-freedom were added to the finite element model of the secondary power source, and the simulation results of the coupling effect between the two were obtained.

3. Based on the principle of stress superposition, the thermal stress distribution matrix from transient thermal simulation and stress-strain distribution matrix from a triaxial 6-DOF are applied to the finite element model at the same time to obtain the combined simulation of transient thermal simulation and a triaxial 6-DOF. It provides an idea for multi-stress simulation in extreme environments.

But the interaction between the transient thermal shock and the triaxial 6-DOF is not clear enough. Therefore, the coupling effect between them cannot be reflected. Further studies on the coupling effect will be carried out in the future.

Acknowledgement
Thanks to financial support from Equipment Pre-research Project (41402010201).

References
[1] Xu Ning, Wang Qingchao, Liu Zhansheng and Yang Fan 2016 Transient thermal impact research on turbine rotors based on thermoelastic coupling Journal of Harbin Engineering University 37(7) pp 936-942
[2] Ren J W, Tan Y H and Wu B Y 2016 Experimental Investigation and CFD Simulation of Heat Transfer of Slot Film Cooling under Transient Thermal Shock Conditions Journal of Propulsion Technology 37(9) pp 1704-1711
[3] Zhang Long and Huang Chunyue 2017 A study on the reliability of double-bump solder joints based on Patron and frequency domain analysis under random vibration load Journal of Vibration and Shock 36(6) pp 203-205
[4] Kong Xianghong and Wang Zhijin 2014 Thermal Shock Load Induced Space Structure's Vibration Analysis Method Computer Simulation 31(5) pp 67-70
[5] Yang Xin and Chen Haibo 2017 Vibration characteristics of an axially moving beam under thermal shocks Journal of Vibration and Shock 36(1) pp 8-15
[6] Liu Maocuan 2017 Coupled Analysis Research on Thermal and Vibration Environment Oriented to Highly Accelerated Stress Screening Xidian University pp 58-66
[7] Xu Shinan and Wu Cuisheng 2019 Simulation of Multi-Field Coupling on Hypersonic Missiles Journal of Astronautics 7 pp 768-775
[8] Wang Yingze, Liu Dong, Wang Qian and Shu Chang 2015 Thermoelastic response of thin plate with variable material properties under transient thermal shock International Journal of Mechanical Sciences 55 pp 474-478
[9] Liu Fang, Lu Ye, Wang Zhen and Zhang Zhiming 2015 Numerical simulation and fatigue life estimation of BGA packages under random vibration loading Microelectronics Reliability 55(12) pp 2777-2785
[10] Wang Baolin and Han Jiecai 2012 Fracture mechanics associated with non-classical heat
conduction in thermoelectric media *Science China (Physics, Mechanics & Astronomy)* 55(3) pp 493-504

[11] Guo S L and Wang B L 2016 Thermal Shock Cracking Behaviour of a Cylinder Specimen with an Internal Penny-Shaped Crack Based on Non-Fourier Heat Conduction *International Journal of Thermophysics* 37(2) pp 1893-1899

[12] Shi En’bing, Su Jianxin, Zhang Lifang, Deng Xiaozhong, Ren Xiaozhong and Cheng Chen 2020 Thermo-mechanical Coupling Simulation Analysis of Cycloid Gear Multi-tooth Form Grinding *Journal of Mechanical Transmission* 44(4) pp 101-106

[13] Sun Yue 2016 Research on Control of Three-axis Six Degrees of Freedom Vibration Test System *Nanjing University of Aeronautics and Astronautics* pp 18-25

[14] Jiang M S 2019 *Introduction and improvement of workbench* 19.0. (Beijing: Posts & Telecom Press)

[15] Zhu Shengping 2016 Study on Thermal Simulation for Current Transducer of Hall Effect Based of ANSYS *Shanghai Jiao Tong University* pp 26-55

[16] Peng Xingwen, Feng Zhigang and Wang Dong 2019 Thermal Analysis for Power Module of Fiber Laser on FEM *Electro-Mechanical Engineering* 35(1) pp 25-28

[17] Zhou Jiacheng and Liu Fang 2017 Thermal Stress Analysis of the PCB Assembly in Vehicle under Different Thermal Based on Finite Element Method *Journal of Wuhan Textile University* 30(6) pp 76-80

[18] Phillips A W, Zucker A T and Allemang R J 1999 A comparison of MIMO-FRF excitation/averaging techniques on heavily and lightly damped structures *Society for Experimental Mechanics, Inc, 17th International Modal Analysis Conference* 2 pp 1395-1404