The On-Orbit Thermal-Structural Analysis of the Spacecraft Component Using MSC/NASTRAN

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Abstract

The predicting of thermally induced structural responses of high precision spacecraft components operating in space environment is a complex and interdisciplinary problem. Mainly using the MSC/NASTRAN software, an integrated resolution for the on-orbit thermal-structural response analysis of the spacecraft antenna reflector was presented in this paper. A unified finite element model was used in all associated analyses, including on-orbit heating loads analysis, view factor calculating, thermal analysis to obtain the temperature distributions, structural analysis to obtain thermally induced distortions as well as the best-fit analysis of the distorted reflector.

1. Introduction

The spacecraft components orbiting in the space environment would be exposed to continuous variations in both temperature level and temperature distribution because of the variations of solar radiation and shadowing conditions. The thermally induced structural responses would occur with the variations of the on-orbit thermal loads. Some thermal-structural responses could adversely affect the performance of the spacecraft component. These thermal-structural responses include the thermally induced structural distortion of high precision component, thermally induced structure vibration of the flexible component, etc. In order to meet the performance requirements of the spacecraft component sensitive to the thermally induced structural response, it is necessary to predict the on-orbit thermal-structural response with high accuracy. The predicting of on-orbit thermally induced structural response is a complex and interdisciplinary problem involved in several associated disciplines. The use of advanced composites in the spacecraft structures makes the on-orbit thermal-structural response analysis become more complicated. Only by means of reliable and efficient analysis techniques and analysis tools, can a good resolution be achieved.

The thermal-structural response analysis of a spacecraft component operating under space orbital environment involves following analysis work: 1) orbital heating loads analysis; 2) thermal modeling and the calculating of temperature profile; 3) structural modeling and the calculating of thermally-induced structural response. Traditionally, the temperature profile of a spacecraft component was obtained by means of thermal analysis software based on finite difference technique, while the structural response was calculated using structural analysis software based on finite element method. Because of these two kinds of analysis models are incompatible, the temperature data obtained from thermal analysis must be transformed before applying on the structural analysis model, so an interface program between thermal analysis software and structural analysis software must be developed[1~6]. This extra transformation work is a tedious and time-consuming process. In addition, in order to obtain on-orbit heating loads, generally a surface model should be established to calculate the radiation heat exchange. In order to achieve thermal-structural response analysis, a great amount of data transformation work between incompatible analysis model must be done. This not only makes the on-orbit thermal-structural response analysis become a challenging task but also results in compromised solution accuracy. In order to address this problem more efficient, a better resolution approach should be sought.

As general-purpose finite element engineering analysis software widely used in world aerospace industry, MSC/NASTRAN has not only powerful structural analysis function but also strong thermal analysis capability, so it provides a powerful tool for the predicting of the on-orbit thermal-structural response of the spacecraft component. In this paper, mainly taking the on-orbit thermal distortion analysis of the spacecraft antenna reflector as an example and taking the advantage of the potential thermal and structural analysis capacity provided by MSC/NASTRAN, an integrated resolution for the on-orbit thermal-structural analysis was presented.

2. An integrated resolution for the on-orbit thermal distortion analysis of the spacecraft antenna reflector

With the development of space technology, more and more high frequency antennas and high precision telescopes were used on all kinds of spacecraft. The demand on the surface shape accuracy of the reflector is also becoming more stringent. In order to meet the performance requirement of the high precision antenna, it is essential to have efficient analysis capability for accurately predicting the on-orbit thermal distortions of the reflector as well as their impact on antenna performance.

In this paper, in order to eliminate modeling disparities between thermal analysis and structural analysis when adopting finite-difference thermal analysis method, the finite element method was used to calculate the on-orbit transient temperature profile of the antenna reflector. The orbital heating loads were also calculated based on the finite element model. Therefore, a unified finite element model was used in all analyses, including heating loads analysis to give on-orbit thermal flux, view factors calculating, thermal analysis to obtain the temperature distributions and structural analysis to give distortion results of the reflector. In addition, the best-fit paraboloid of a distorted reflector shape was also obtained on the basis of the finite element model and the results of the thermal distortion analysis. This integrated on-orbit thermal distortion analysis procedure was shown in figure 1. In this integrated resolution, MSC/NASTRAN were used in both structural analysis and thermal analysis, in addition, the view factors were calculated by means of the VIEW3D module of MSC/NASTRAN. The MSC/PATRAN software was used to create finite element model of the antenna reflector and perform post-processing of analysis results. The programs used for calculating heating loads and performing best-fit analysis were developed by authors themselves.

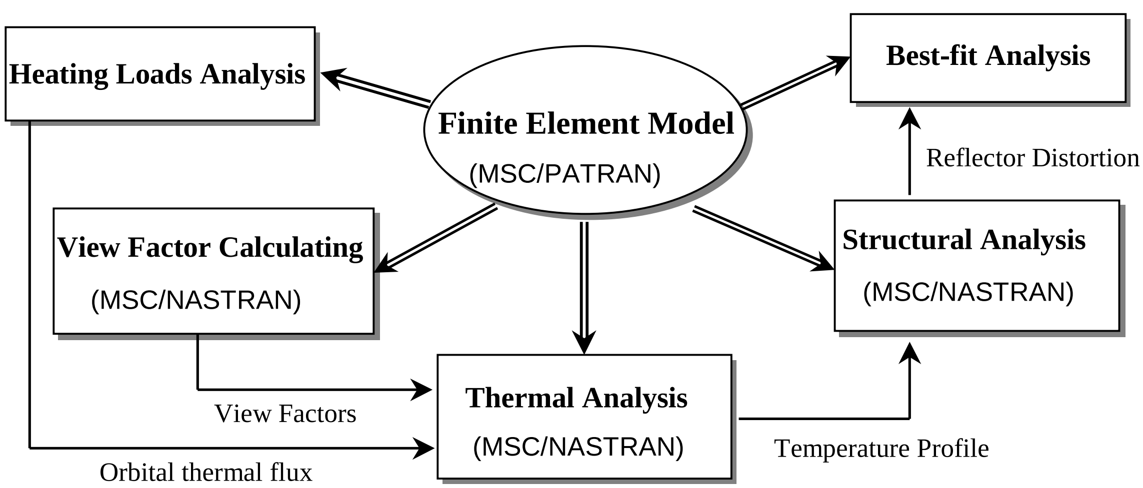

Figure 1. An integrated on-orbit thermal distortion analysis procedure

The spacecraft antenna reflector typically is constructed by composite honeycomb sandwich structure, while the finite element modeling and analysis of the sandwich structure is a challenging task. So the development of the reliable and efficient sandwich structure modeling techniques in both thermal analysis and structural analysis is the critical problem to predict on-orbit thermal distortion accurately.

In the thermal modeling of the sandwich reflector structure, a three-layer-model in which each layer respectively simulates the top face sheet, honeycomb core and bottom face sheet. In the face sheets, besides the composite laminates, the effect of the adhesives was also considered. The thermal control coating on the top face sheet was also taken into account. The aluminum honeycomb core was regarded as an equivalent continuum layer. The effective thermal property parameters of each layer were obtained by approximate calculating. In the calculation of the on-orbit temperature profiles, the heat conduction, heat capacity, the radiation exchange between space and the reflector, the radiation exchange among different parts of the reflector were taken into consideration. By means of this modeling method and using MSC/NASTRAN, the detailed temperature distributions on the reflector around the orbit can be obtained.

In order to calculate the heating loads in orbit, a program was developed by authors. Through this program, firstly, the grid and element information in the finite element model of the reflector was extracted to construct a surface model, then, according to given orbit condition, the shadowing situation of each surface element on the reflector was analyzed, so the type and the magnitude of the heating loads received by each element can be determined. At last, the thermal flux that put on each element of the concave surface of the reflector at any time in the orbit can be obtained. Because the elements that used in the calculating of the heat flux are same with those in the thermal analysis, the calculated thermal flux can be directly applied on the corresponding elements of the thermal analysis model.

In the structural analysis, because of the complexity of the composite sandwich structures and the high calculation accuracy requirement for the thermal distortion analysis, how to establish an accurate and efficient finite element model that can really simulate the sandwich reflector structure becomes a challenging part in the thermal distortion analysis. In order to support the thermal distortion analysis of the spacecraft antenna reflector, the structural modeling and analysis technique of the composite honeycomb sandwich structure that constitutes high precision spacecraft components were studied in detail by authors. On the basis of fully taking the in-plane stiffness of the honeycomb core into consideration, using combined composite face sheets - honeycomb elements, the finite element modeling method that can be used to accurately predict on-orbit thermal distortion was developed. In this modeling method, the honeycomb core is regarded as a homogeneous orthotropic material and modeled by three-dimensional solid elements. For the composite face sheets, the classical laminate analysis method was employed. In order to verify the analysis model, further tradeoff analysis and test measurement on thermal distortion of some specimen which have same structure with the antenna reflector have been done. The agreement of the thermal distortion results of the specimen between test and prediction is good. Based on these research work, it can be concluded that the thermal distortion analysis technique presented in this paper is reliable and efficient to predict distortion behavior of the sandwich spacecraft components under on-orbit thermal loading with high accuracy.

3. A practical application example

Applying the integrated on-orbit thermal distortion analysis technique presented in previous section, the thermal distortion analysis of a spacecraft parabolic antenna reflector - the ALT antenna reflector was performed. This antenna reflector will be used on a remote sensing device that operating in low earth orbit. It was constructed by sandwich shell with composite face sheets and the aluminum honeycomb core. Because of its high working frequency, the surface distortion of the ALT antenna reflector must be controlled within close tolerance, so the on-orbit thermal distortion analysis became a critical task in the design of this reflector.

During operating in orbit, the concave surface of the reflector will subject to 278s and 778s two periods of sunlight irradiation. When the spacecraft just come out of the shadow of the earth, some region on concave surface of the reflector were heated by sun and other region were shadowed by the reflector itself. The region heated by sun and the region shadowed continuously vary along the orbit. This results in relatively big temperature gradient existing along the surface of the reflector in some time. The calculating of the temperature profile of this reflector is a transient thermal analysis problem.

Firstly, the on-orbit heating loads were calculated. The heating flux that each element on the surface of the reflector received around the orbit can be obtained. Then the resulting heating flux were written into a data file with MSC/NASTRAN format, so the heating flux can be added on the corresponding elements of the finite element thermal analysis model. The view factors of the reflector were calculated using the function that MSC/NASTRAN software provides.

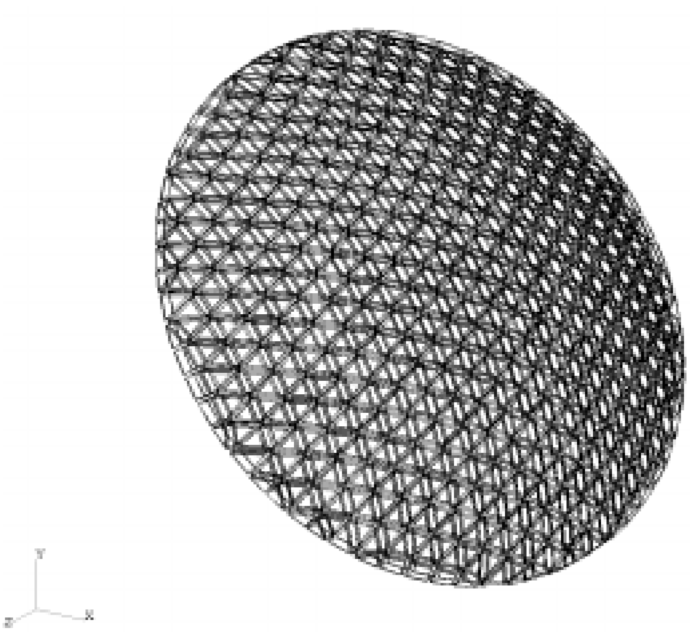

Figure 2. The finite element model of the ALT antenna reflector

After obtaining the orbital heating loads and view factors, the thermal analysis can be performed. In the calculating of the temperature profiles of the reflector, the heat conduction, heat capacity and the radiation exchange were considered. The finite element model of the ALT reflector was shown in figure 2. In this model, the face sheets were simulated by the triangular and the quadrilateral heat conduction plate elements and the honeycomb core was simulated by hexagonal and pentagonal heat conduction solid elements. In order to calculate the radiation exchange, the surface elements were added on the surface of the reflector. The finite element thermal analysis was performed using MSC/NASTRAN software.

Through the transient thermal analysis, the detailed temperature distributions of the reflector around the orbit can be obtained. Then these resulting temperatures were used as inputs of the calculating of the thermally induced reflector distortion and used to verify the adequacy of the thermal control designs. As an example, some results obtained from the transient thermal analysis of the ALT reflector were shown in figure 3 and figure 4. Figure 3 demonstrated the transient temperature profile on the surface of the reflector at certain time (t=300s). Figure 4 demonstrated the temperature history of four grids (two grids on the top face sheet and their corresponding grids on bottom face sheet of the reflector).

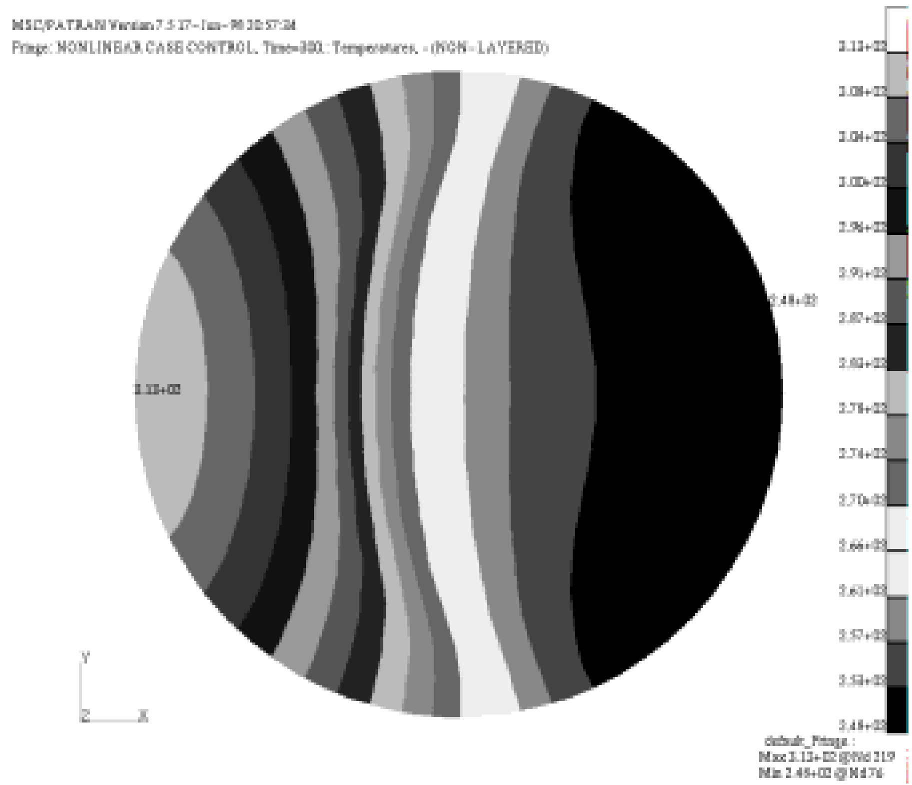

Figure 3. The transient temperature profile on the surface of the reflector (t=300s)

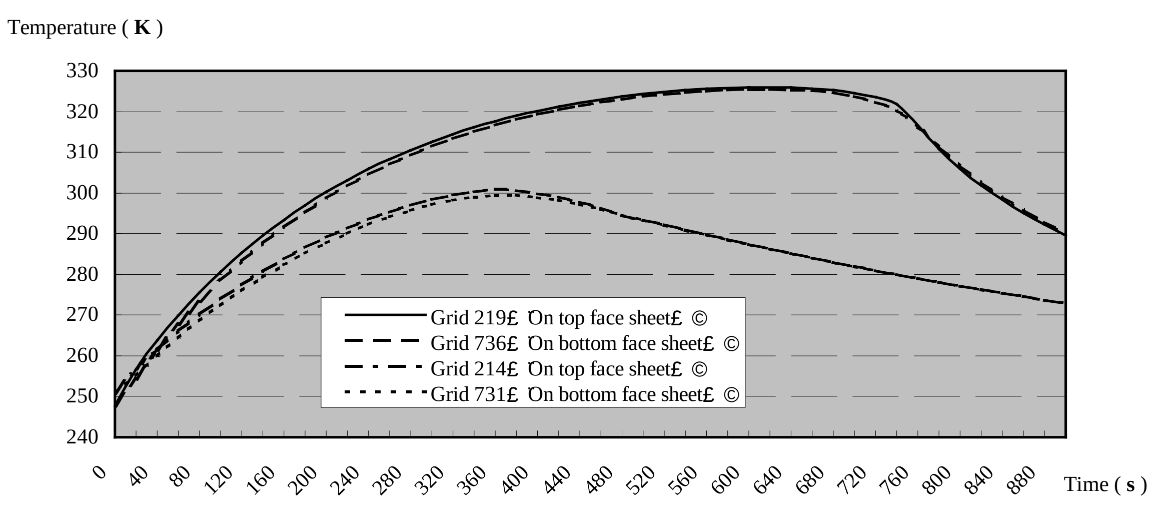

Figure 4. Transient temperature variation with time of four grids on the reflector

Based on the results of the thermal analysis of the reflector, some typical on-orbit temperature loads that probably induce relatively severe thermal distortion were selected, then the structural distortion of the reflector under these temperature load conditions were calculated using MSC/NASTRAN software. In the structural analysis model, the face sheets were modeled by the triangular and quadrilateral membrane elements and the honeycomb core was modeled by solid elements with orthotropic material properties. In this model, 744 composite membrane elements and 744 solid elements were employed in all. Because the in-plane stiffness of the honeycomb has great effect on the thermal distortion of sandwich structures, it was taken into consideration in the structural analysis model. The equivalent properties of the continuum core model were obtained by using the approaches described in the reference [8]. The finite element model used in structural analysis is similar to the model used in thermal analysis as shown in figure 2. The position of each grid is same in the thermal analysis model and structural analysis model, but the element type employed is different because of different modeling requirement came from the thermal analysis and structural analysis.

Through the thermal distortion analysis of the reflector, the surface distortion on the reflector at concerned time can be obtained. Figure 5 showed the contour of the displacement on the surface of the reflector at time of 300s. The corresponding RMS value of the surface distortion is $1.046\times10^{-5}\,m$ at this time. From obtained thermal distortion analysis results, it can be seen whether or not the design of the reflector meet the performance requirements of the antenna. In addition, through the tradeoff study to the results of the thermal distortion analysis under the conditions of different material selection, different structure style, different thermal control measure as well as different

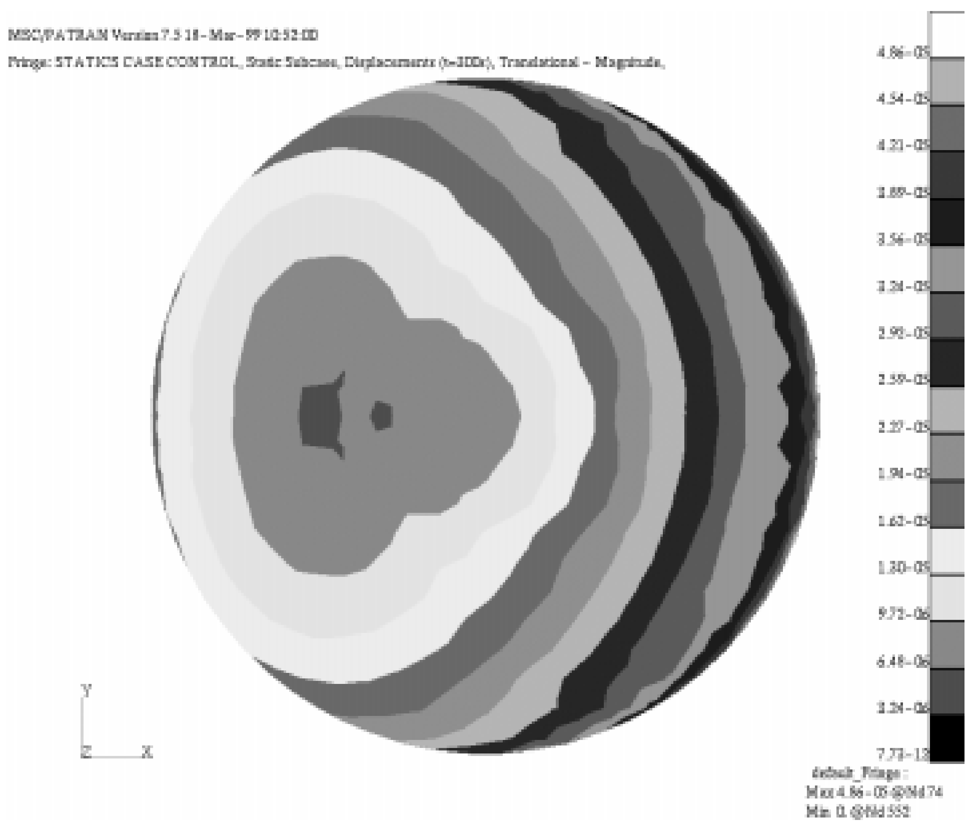

Figure 5. The contour of displacement on the surface of the reflector (t=300s)

on-orbit heating loads. A more reasonable design scheme of the reflector that meets the performance requirements of the antenna to the maximum extent can be achieved.

4. Conclusions

In this paper, an integrated resolution for the predicting of the on-orbit thermal-structural response of the spacecraft components was presented and a unified finite element model was used in all associated analysis disciplines to accomplish the thermal distortion analysis of the antenna reflector, so the analysis efficiency was improved greatly and the analysis accuracy increased. A practical example of the thermal distortion analysis of a spacecraft antenna reflector was given in this paper. The application demonstrated MSC/NASTRAN is a powerful tool to predict the thermal-structural response of the spacecraft components and the integrated on-orbit thermal distortion analysis technique presented in this paper provided a very good aiding tool for the analysis and design of the spacecraft components with high thermal stability requirements.

5. References

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