World Academy of Science, Engineering and Technology
International Journal of Aerospace and Mechanical Engineering
Vol:8, No:4, 2014

Substructure Method for Thermal-Stress Analysis of Liquid-Propellant Rocket Engine Combustion Chamber

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***Abstract*—**This article is devoted to an important problem of calculation of deflected mode of the combustion chamber and the nozzle end of a new liquid-propellant rocket cruise engine. A special attention is given to the methodology of calculation. Three operating modes are considered. The analysis has been conducted in ANSYS software. The methods of conducted research are mathematical modeling, substructure method, cyclic symmetry, finite element method. The calculation has been carried out to order of S.P. Korolev Rocket and Space Corporation «Energia». The main results are practical. Proposed methodology and created models would be able to use for a wide range of strength problems.

***Keywords*—**Combustion chamber, cyclic symmetry, finite element method, liquid-propellant rocket engine, nozzle end, substructure.

I. INTRODUCTION

SPACE launch services market is efficiently developing in the sector of spacecraft delivery to geostationary and geostationary transfer orbits. These orbits are the most needed for launching of telecommunication and navigation satellites. Upper-stage rockets are used for satellite injection into these orbits [5], [6], [8], [9]. It is urgent necessity to develop the new upper-stage rockets and to modernize the old ones. Hence it is essential to replace a cruise engine.

Combustion chamber and nozzle end of a liquid-propellant rocket engine (LPRE) are the most important elements that determine operability of the whole construction [7]. The detection of the combustion chamber and the nozzle end critical zones and the analysis of deflected modes of these zones are of considerable practical importance [19]-[21].

II. THE CALCULATION PRINCIPLES

Fig. 1 represents a schematic view of the combustion chamber and the nozzle end of LPRE.

A cooled part of the structure can be described as a thin three-layer shell composed of a fire wall and an external structural envelope between which spiral cooling lines are located. These cooling lines are inclined to the vertical axis by a varying angle. The availability of these cooling lines and inlet branches does not permit to consider the structure as an axisymmetric structure. The radiation-cooled nozzle represents a one-layer axisymmetric shell.

According to the operating conditions, the structure has to bear under 7 loading cycles. Every loading cycle consists of three operating modes: triggering mode, stationary mode, stop mode. The gas dynamic problem and the problem of thermal-stress analysis are considered as unlinking problems. Distribution laws of temperature and pressure along a meridian of a fire wall for every operating mode were determined from the solution of the gas dynamic problem.

The revealed critical zones (Fig. 1) are:

- inlet headers in a supersonic section, a joint between a supersonic section of a nozzle and a flared jacket (see I–A);
- a joint between a copper part and a steel part of a fire wall in a supersonic section (I–B);
- a cooling channel in the throat area (I–C);
- a joint between a cooled part of the chamber and the radiation-cooled nozzle (II–D).

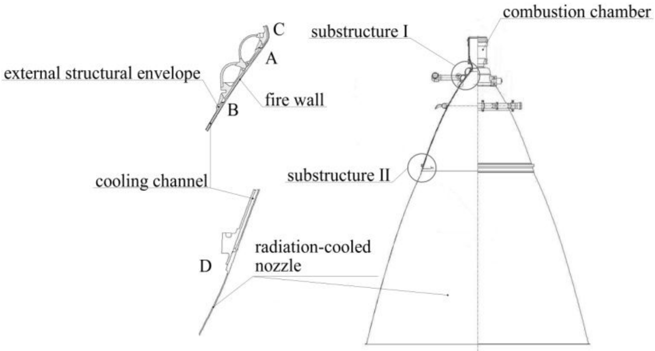

Fig. 1 Schematic view of the combustion chamber and the nozzle end of LPRE

In the course of solving the problem it was need to carry out a detailed analysis of a complex three-dimensional structure, for which a direct finite-element approximation was almost unrealizable because of a high dimensionality of the problem and because of the necessity of taking into account materially nonlinear material properties.

Besides that it was a considerable difficulty to solve the problem of numerical implementation of a cyclic loading with an allowance for three operating modes within every loading cycle.

For solving the dimensionality problem it has been decided to use a substructure method.

Since a finite-element modeling of a real geometry with an actual shape of a cooling channel is impossible at the moment because of a high dimensionality of the model, modeling of the combustion chamber was conducted on basis of a simplified design model for reducing the dimensionality of a finite-element model [1]-[3].

An axisymmetric structurally anisotropic model is used as a

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simplified design model [12], [13]. The essence of the method consists in «spreading out» of the cooling lines over a thickness and a circumferential direction. This makes it possible to consider the shell as a continuous. The thermal analysis and the strength analysis are considered as unlinking problems. The rigidity of inlet branches is not taken into account. Anisotropy factors are determined by using the condition of equivalent stiffness.

This simplification allows estimating rigid properties of the structure but does not permit to carry out a stress analysis exactly. This problem is solved by using the following method. Each cycle is divided into two stages. At the first stage an axisymmetric finite-element model is used. The calculation of deflected mode of the chamber is conducted. As a result of this calculation the nodal displacements on the boundaries of the substructure I and the substructure II are determined (see Fig. 1). At the second stage computed displacements are used as boundary conditions for two three-dimensional substructures with a real geometry. The kinematical boundary conditions are supplemented with the results of solving the stationary heat conduction problem. This makes it possible to reliably estimate the stressed state in critical zones. An elastic-plastic stress-strain curve for every used material and physical-mechanical material properties as functions of temperature are specified in a tabular form. Nonlinear calculation at the second stage is carried out by using the continuation method with respect to a load parameter [14]. A detailed description of the implementation of the calculation at every stage is given below. The problem is solved in the quasi-static statement. It is assumed that the load parameters vary linearly during the transition from one to another operating mode. The two-stage calculation is repeated. Firstly an axisymmetric problem is solved. After that the analysis of the substructures is conducted. In axisymmetric problem solving it is assumed that the influence of the plastic strains in critical zones on the behavior of an axisymmetric structurally anisotropic shell is inessential, that is why it is acceptable to carry out an axisymmetric problem solution on the assumption that the behavior is elastic. As for the substructures, the calculation is conducted with an allowance for the elastic-plastic deformations cumulated at previous stages.

Cyclic symmetry boundary conditions are used for analysis of the substructures because of a repeated in a circumferential direction position of the cooling lines. The use of cyclic symmetry conditions allows modeling a recurrent sector instead of the whole substructure [4]. On the assumption of the truth of the Saint-Venant's principle the meridional substructure boundaries are located at a sufficient distance from critical zones.

III. THE STAGE OF SOLVING BY USING A SIMPLIFIED AXISYMMETRIC MODEL

As stated above, the availability of cooling lines disturbs an axial symmetry. That is why the method of the replacement of the real structure by a structurally anisotropic continuous model is employed. Anisotropy factors are determined by using the condition of equivalent stiffness. The assumption that the stationary heat conduction problem and the strength analysis are unlinking problems, allows solving these problems sequentially. For solving the stationary heat conduction problem the isoparametric 8-node thermal finite element PLANE 77 is used [10], [11]. The finite-element model of the chamber consists of 30 327 elements and 101439 nodes (Fig. 2).

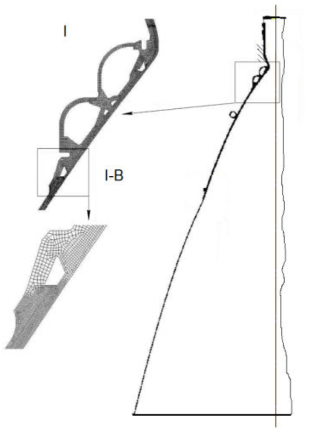

Fig. 2 The finite-element model of an axisymmetric structurally anisotropic shell

As a result of solving the distribution of temperature is determined. This distribution is used for the stress-strain analysis. The stress-strain analysis is conducted by using the isoparametric 8-node structural finite element PLANE 82. The nodal displacements, determined by using an axisymmetric model, are used as kinematical boundary conditions for the strength analysis of two three-dimensional substructures.

IV. THE STAGE OF SUBSTRUCTURE ANALYSIS

At the second stage it is conducted the analysis of the substructures by using the detailed three-dimensional models (see Figs. 3, 4).

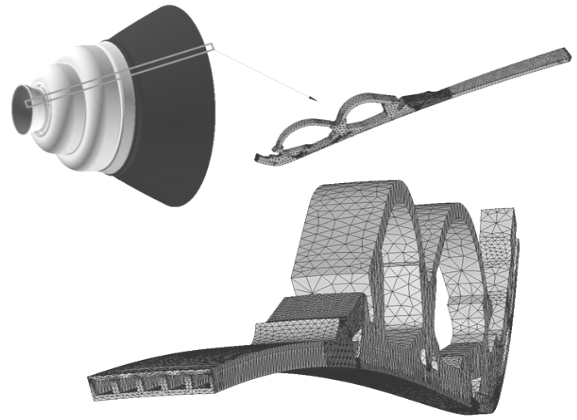

Fig. 3 The finite-element model of the substructure I

The use of cyclic symmetry conditions allows conducting the analysis of a recurrent sector instead of the whole substructure.

At this stage the nodal displacements, determined at the previous stage, are used as kinematical boundary conditions for the substructures. Since the number of nodes in the three-dimensional model is greater than in an axisymmetric model, the interpolation is applied for determining the rest of the nodal displacements.

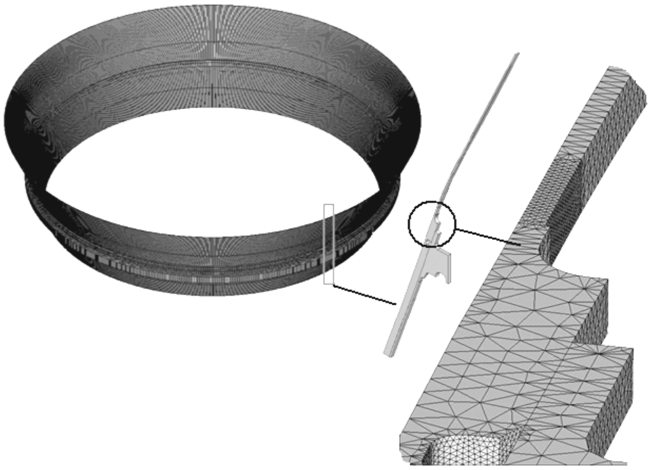

Fig. 4 The finite-element model of the substructure II

For the substructure I three critical zones are analysed. They are a joint between a supersonic section of a nozzle and a flared jacket (I – A), a joint between a copper part and a steel part of a fire wall in a supersonic section (I – B), a cooling channel in the throat area (I–C).

The finite-element model of the substructure I consists of 142601 nodes and 88960 elements (see Fig. 3). The analysis shows that the von Mises plastic strainon the stationary mode is above 5% in the region of the weld seam. The residual von Mises plastic strain [15], [16] is above 3% in the region of the joint.

The von Mises stress in the region of the weld seam on the stationary mode is on the average 40% of the ultimate strength for the material of the combustion chamber. And for the material of the nozzle retainer the von Mises stress exceeds 60% of its ultimate strength.

It is impossible to make a reliable conclusion about the degree of danger of residual stresses and strains in the region of a joint between a cooled part of the chamber and the radiation-cooled nozzle because of insufficient experimental data about fatigue life of the materials. The main reason of the large plastic strains is a high temperature gradient induced by a great difference between the thermal conductivity coefficients of the fire wall material and the nozzle initial retainer material. For reducing plastic strains it is recommended to use a material with a higher thermal conductivity coefficient for the fire wall of the nozzle.

The reason of considerable plastic strains in the cooling fins is high temperature gradients too. For reducing plastic strains in the region of the joint between a copper part and a steel part of a fire wall in a supersonic section it is recommended to use a material with a higher yield strength. For reducing temperatures of a fire wall and temperature gradients it is recommended to change the cooling channel geometry.

A cyclic strength assessment [17], [18] could be carried out if there are the experimental data about fatigue life of the materials. The developed algorithm allows conducting the strength analysis of the structure under cyclic loading.

Let us have a detailed look at the analysis of the joint between a cooled part of the chamber and the radiation-cooled nozzle (substructure II – D). The stationary heat conduction problem and the strength analysis are solved sequentially. For solving the stationary heat conduction problem the 3-D 10-node tetrahedral thermal finite element SOLID 87 is used. The element has one degree of freedom, temperature, at each node. The finite element model consists of 68495 nodes and 36704 elements (see Fig. 4).

For the strength analysis the 3-D 10-node tetrahedral structural finite element SOLID 187 is used. The element is defined by 10 nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The analysis is conducted for each stage sequentially with an allowance for the stresses and deformations cumulated at previous stages (prestress).

The results of the analysis of the critical zones are presented in Table I.

TABLE I
RESULTS

	Substructure	Von Mises stress, % of the ultimate strength for the material on the stationary mode	Residual von Mises plastic strain
I-A	Joint between a supersonic section of a nozzle and a flared jacket	76%	4.1%
I-B	Joint between a copper part and a steel part of a fire wall in a supersonic	42% for the material of the combustion chamber 64% for the material of the nozzle retainer	3.3%
I-C	Cooling channel in the throat area	55%	0.4%
II-D	Joint between a cooled part of the chamber and the radiation-cooled nozzle	54% for the material of the combustion chamber 45% for the material of the nozzle	0.3-0.4%

V. CONCLUSION

A solution strategy of the finite-element strength analysis of a combustion chamber and a nozzle of a perspective liquid-propellant rocket engine (LPRE) under cyclic loading on three operating modes has been suggested.

A possibility of substantial reducing the dimensionality of a finite-element model of a complex structure by using the substructure method and cyclic symmetry conditions has been shown.

The critical zones have been detected. The advices on improving the structure have been given.

ACKNOWLEDGMENT

O. V. Korotkaya thanks Dr. Prof. Sergey S. Gavryushin, Head of the Computer Systems in Manufacturing Automation Department of Bauman Moscow State Technical University for his useful advices and sensible suggestions; Dr. Prof. Dmitry A. Yagodnikov, Head of the Rocket Engines Department of BMSTU for an important information about liquid-propellant rocket engines; Evgeny E. Krasnovskiy, Ph.D., Assoc. Prof. of the Applied Mathematics Department of BMSTU for his assistance in practical realization.

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