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Piotr Duda, Toshiya Nakamura

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ABSTRACT

The purpose of this work is to develop a method for solving inverse transient-state thermal and strength non-linear problems in complex shapes. Non-linearity is caused both by the material temperature-dependent properties and radiation. The proposed algorithm reconstructs the whole transient temperature and thermal stress distribution based on temperatures measured in the element selected points. Measured transient temperature values are generated during a numerical simulation of aerodynamic heating on the atmospheric reentry capsule. Both constant and temperature-dependent properties of the material are assumed. A comparison is presented between the transient temperature distributions obtained based on the material constant and temperature-dependent properties. Finally, the developed method is used to identify the transient temperature and stress distribution in the atmospheric reentry capsule assuming temperature-dependent properties of the material. The proposed approach is expected to be a good solution for improving spacecraft structures.

KEY WORDS: inverse method, transient heat transfer, thermal stress, reentry capsule

1. Introduction

Thermal and strength analyses performed in the aerospace or power industries indicate that high temperature gradients can create considerable thermal stresses [1, 2]. The cyclic character resulting from the cooling and heating of the elements under consideration creates the low-cycle fatigue phenomenon, which can lead to crack formation [3, 4]. In order to avoid this kind of damage, the most favourable option would be to measure the values of these stresses directly on the most loaded surface. This, however, is often very difficult in practice. In order to establish the stress distribution in heated or cooled elements, it is necessary to determine the transient temperature distribution in their volumes. The fundamental problem of calculating the temperature distributions in newly designed components and those already in service is the difficulty in determining some of the thermal boundary conditions. For slabs made of a liquid-cooled, fibre-reinforced polymer, a convection boundary condition appears on the cooled internal surface and a complex radiation-convection condition – on the fire side [5]. A thermochemical model is constructed to determine these boundary conditions. If some of them are unknown, the temperature distribution can be calculated by means of the inverse boundary method. It involves using additional temperature measurements instead of the unknown boundary condition. For simple-shape elements and constant material properties, analytical methods of solving the inverse heat conduction problem (IHC) may be used [6, 7].

The assumption of the material temperature-independent properties is a frequent simplification in thermal and strength studies. Calculating pressure vessels operating in transient states, material properties are assumed at the mean cycle temperature [8]. This shortens the time needed to determine the allowable number of load cycles. Similar problems arise in the thermal-structural design of a spacecraft entering the Earth's atmosphere. The thermal load (the heat flux) caused by intense aerodynamic heating is difficult to predict. Consequently, predicting the thermal stress distribution, which is very important in structural design, is also a very difficult task. The IHC approach is expected to be a good solution for improving spacecraft structures. Material properties are assumed to be independent of temperature for simplicity of the solution presented in [9]. In order to cover the reentry flight adequately, a transient-state thermal analysis was carried out for a period of 1200 seconds after the capsule reentry into the atmosphere.

Solving multidimensional inverse problems concerning complex-shape elements or temperature-dependent physical properties requires numerical methods [10, 11, 12, 13, 14].

The temperature distribution reconstructed in this manner makes it possible to calculate stresses in the analysed elements as accurately as possible [15]. The algorithm for determination of the temperature and stress distribution based on temperatures measured in selected points of the analysed element can be used in monitoring systems. Such systems have a significant impact on remnant life predictions, highlighting hot zones and enabling modifications of the element operation [16].

The purpose of this work is to develop a method for solving inverse non-linear heat transfer problems. Non-linearity is caused both by the material temperature-dependent properties and radiation. The developed method is used to identify the temperature and thermal stresses in the atmospheric reentry capsule. Additionally, errors arising from the assumption of temperature-independent properties of the material are presented.