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Determination of stratospheric component behaviour using Finite Element model updating

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ABSTRACT

In general, it is difficult to analyse equipment for space applicability due to the fact that realistic tests on Earth are technically difficult and expensive. To prove the reliability of space systems, a combination of numerical analysis and expensive pre-flight tests is used. However, this paper discusses a new methodology in which a combination is made of low-budget ground tests with a newly developed finite element model updating technique which can deliver a time efficient added value or alternative to the expensive and time-consuming pre-flight tests during thermal analysis. In addition, this contribution shows the influence of several design parameters on the accuracy of thermal simulations for space applications and discusses how this accuracy can be optimised. The methodology is verified within the HACORD project of the REXUS/BEXUS programme.

1. Introduction

Scientific ballooning has been developed in the early 19th century, a few years after the invention of the hot air balloon by the Montgolfier brothers. This technique has been used frequently for scientific measurements since the entrance of low-density polyethylene balloons in the 1930s [1]. Even today, high altitude balloons are widely used in several disciplines e.g. atmospheric sciences, aeronautics, Earth observatory and physics on Earth and other planets [2]. The thermal design of spacecraft or balloon experiments is vitally important due to the extreme environmental conditions and zero-failure tolerances [3–5]. In general, thermal designs of balloon experiments are based on a combination of knowledge gained through previous experiments, empirical data and numerical simulations. Occasionally extra information is found by interpolating the environment at high altitude [6,3,5]. The use of accurate numerical models is essential to perform accurate simulations and to be able to design insulation techniques [7,8].

Finite element (FE) models, as explained in section 2.3, are widely used for virtual modelling and the prediction of the dynamic and the thermal behaviour of materials and lightweight structures [9,10]. These predictions are essential in the preparation of atmospheric balloon experiments [11,4,12]. Since atmospheric and space experiments are generally very expensive, it is important to have an excellent knowledge of the interaction between the experiment and its environment in advance, which is efficiently gained through reliable simulations. In general until now, these simulations are made only in steady state conditions and are mapped to a structural analysis [7,10]. Recent research compares these models manually with complex ground experiments which simulate the space environment as for example the NIRVANA facility, but these experiments are expensive to perform [10]. Next to its importance for predicting the response of the system, simulations are also crucial to increase confidence in advanced experiment set-ups operating in extreme conditions present in the upper atmosphere [8]. All material parameters and thermal loads of the experiment should be known in order to generate accurate estimations of the thermal behaviour [3].

Recent research, as performed by Liu et al. [13] tries to further improve these numerical models by using transient, time-dependent simulations in which the temperature and time-related parameters during the flight are approximated more accurately. The next step to improve the accuracy of the numerical models and predict the behaviour of balloon experiments is the combination of the numerical models with experimental measurements using numerical updating techniques like finite element model updating, known of system dynamics [14] and recently adapted to use for thermal models by Peeters et al. [15].

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Nomenclature

c_p	Specific heat constant pressure	Pr	Prandtl number (dimensionless)
g_c	Gravitational acceleration	Ra	Rayleigh number (dimensionless)
Gr	Grashof number (dimensionless)	ΔT	Temperature difference from surface to air
h	Heat transfer coefficient	B	Coefficient of thermal expansion for air
k	Thermal conductivity of air	ρ	Density of air
L	Height or length of plate	μ	Dynamic viscosity of air
Nu	Nusselt number (dimensionless)		

For example, one of the important parameters in thermal radiation simulations which is essential to estimate correctly is the emissivity. This parameter is difficult to approximate correctly due to the influence of complex geometrical shapes [16].

The combination of an FE model of the structure with experimental data has major benefits because the experimental criteria can be relaxed due to the integration of the numerical model. Simple and fast to perform ground tests deliver enormous potential for FE updating, as part of a structural condition assessment program to use for correct approximate behaviour at extreme conditions.

The objective of this contribution is to predict the thermal insulation and heat distribution in the HACORD (High Altitude Cosmic Ray Detector) balloon experiment while being exposed to stratospheric conditions using two ground tests which are easy to perform: an actual long duration stratospheric flight and numerical simulations. The flight is made within the REXUS/BEXUS[1] programme using a balloon with a floating time of more than two hours at an altitude of 28.2 km.

To ensure accurate numerical simulations the finite element updating technique introduced in [15] is used for non-destructive evaluation. The technique is adapted for more general 3 dimensional thermal problems. The prediction results are validated using the real experimental data retrieved by thermal sensors during flight. The goal of this contribution is to validate if it is possible to better predict experimental device behaviour in space by using a straightforward thermal load and freezer experiment, performed in atmospheric conditions as input for an FE model updating routine. The described methodology can be used to accelerate the design process of atmospheric balloon experiments [5] and helps to improve the design process of future spacecraft [3].

2. Materials & methods

In the following section, we will describe the measurement techniques, the developed numerical model and the designed updating algorithm. The chapter starts with a brief description of the experimental box itself, after which the model and experiments will be discussed.

2.1. Experimental device description

The HACORD experiment consists of four Geiger–Muller tubes for the detection of cosmic ray particles and a PCB with an ARM® mBed™ micro-controller, a digital and analogue thermal sensor, three pressure sensors and the necessary power and communication electronics. The full system is packed in a polycarbonate box containing 8–20 mm of Styrofoam insulation and a reflective space blanket on the inside of the box to encapsulate the thermal heat of the PCB. The experimental components are shown in Fig. 1. A wireframe view of the full experiment is shown in Fig. 2 with the PCB (green), the Geiger–Muller tubes (red), the clamps (red), the Ethernet connector (red) and the power connector (yellow).

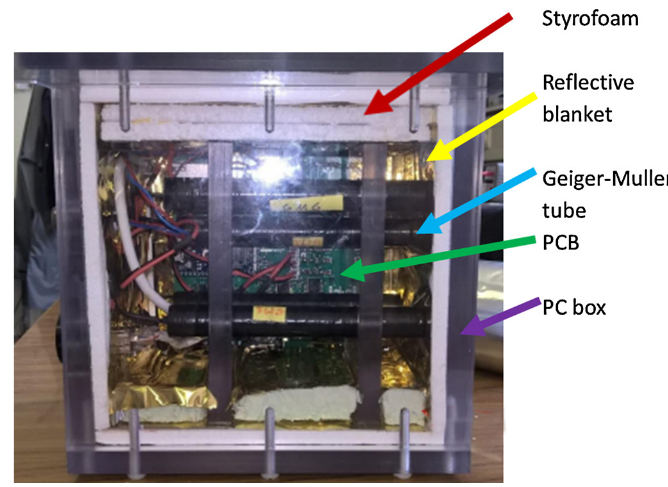

Fig. 1. Side view inside the experiment with in white the Styrofoam and in gold the reflective blanket.

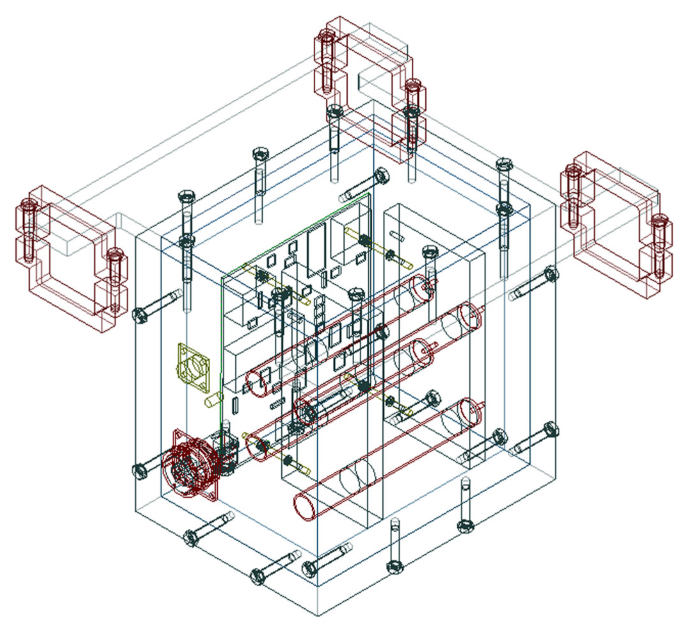

Fig. 2. Wireframe visual of the experiment design. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

2.2. Description measurements

Three different types of measurements are performed: thermal load tests using a thermal imaging camera, a freezer test of the experimental box and finally the balloon flight.

[1] More information about the REXUS/BEXUS (Rocket/Balloon Experiments for University Students) programme can be found on www.rexusbexus.net.