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Holographic subsurface radar for diagnostics of cryogenic fuel tank thermal insulation of space vehicles☆

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ABSTRACT

Analysis of critical conditions on the reusable spacecrafts *Columbia* (USA), and *Buran* (Russia) related to defects in insulation and heat-protection coatings have been performed. It is shown that the existing methods of non-destructive testing, including ultrasonics, failed to prevent the disaster of the Space Shuttle *Columbia* and serious incidents involving the spacecraft *Buran* during its only flight. A new method for using the holographic subsurface radar RASCAN-5/15000 which reveals the internal defects of the coating was proposed, and experiments on models of thermal insulation coatings were performed. The experimental results were displayed in the form of radar images on which defects in the heat insulation provided a good contrast. The article reflects preliminary study and further efforts are needed to improve resolution of the technology.

1. Introduction

The Space Shuttle *Columbia* disaster occurred on February 1, 2003, killing all seven crew members, Figs. 1,2. This and other incidents which fortunately did not lead to such catastrophic consequences have aroused interest in the development of new methods for non-destructive testing of insulation and thermal protection coatings on spacecraft and fuel tanks [1–4].

In the opinion of NASA investigators, one of the causes of the *Columbia* disaster was voids in the thermal protection coating on the shuttle's external fuel tank [5,6], Figs. 3,4. The external tank contains liquid oxygen and hydrogen propellants stored at minus 183 and minus 253 °C respectively. To reduce fuel vaporization and prevent icing of tank surface that could fragment and damage the shuttle, the tank is covered with insulating polyurethane foam [7]. The thickness of the foam is within the range of 25 mm to 50 mm [8]. If the super-cold external tank is not sufficiently insulated from the ambient warm and moist air, atmospheric water vapor condenses inside the foam voids.

According to this hypothesis, during the launch of *Columbia's* 28th mission, water that had condensed inside voids rapidly vaporized (boiled) as result of lowering pressure with increasing altitude following launch [6]. As a result of this explosive boiling, a piece of foam insulation broke off from the external tank and struck the left wing, damaging heat protective leading edge panel. When *Columbia* reentered the atmosphere after the mission, this damage allowed plasma (produced ahead of the craft during its flight in stratosphere) to penetrate and destroy the wing structure, causing the spacecraft to break up, Fig. 2. Most previous shuttle launches had seen similar, but more minor, damage and foam shedding, but the risks were deemed acceptable, Fig. 5 [9].

It is well-known that the tiled thermal protection coating of return vehicles such as the Space Shuttle is exposed to high mechanical, and especially thermal, influence on reentry. In fact, after the first flight of Columbia (April 12, 1981) 16 tiles were lost and 148 tiles were damaged [5]. Similar problems with more serious after-effects arose after the first and only flight of *Buran* (November 15, 1988). Post-flight inspection showed partial destruction to complete loss of thermal shielding tiles, Fig. 6 [3]. Such damage could lead to a repeat of the *Columbia* disaster in future missions.

Shedding of thermal insulation is connected with impurities and/or insufficient quality control in the bonding of foam or tiles to a space vehicle surface. Gluing tiles is carried out manually, and in these circumstances it is difficult to maintain the necessary quality control. A variety of control methods are described in detail in [3], mainly involving destructive testing by "tearing off".

Methods of ultrasonic diagnostics, which are widely applied for non-destructive testing of different constructions [1], are insufficiently effective at diagnostics of foam insulation due to polyurethane's high porosity, which leads to the high levels of incoherent acoustic scattering and attenuation [10]. Similar considerations apply

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Fig. 1. Space Shuttle *Columbia* take-off on 16th January 2003.

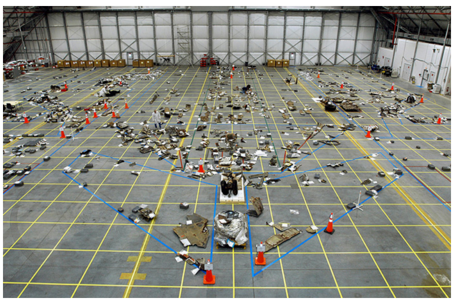

Fig. 2. Result of *Columbia* disaster on February 1, 2003. Remains of the spaceship collected on the ground were laid out in a hangar.

Fig. 3. Space Shuttle Columbia on the launch pad. Yellow design elements are thermal insulation coating of the external cryogenic tank [7].

to the silicate fiber tiles that shield the outer surface of the Space Shuttle and *Buran*.

Microwave diagnostics using holographic subsurface radars [4,11] could be a good alternative to ultrasonic testing. The basic advantage of microwave diagnostics in comparison with ultrasonic

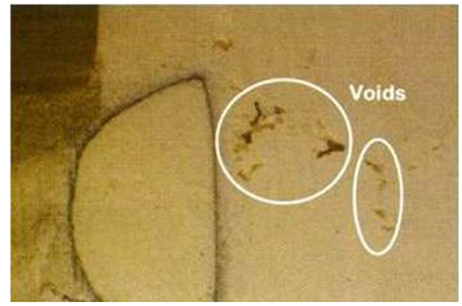

Fig. 4. Cross-section of thermal protection coating of shuttle external tank. Voids are visible inside of insulation polyurethane foam [6].

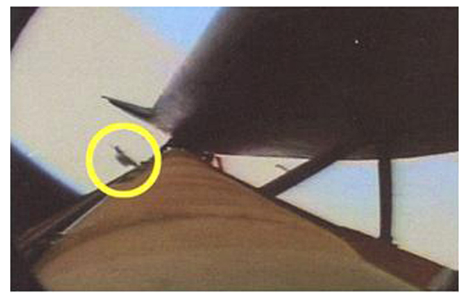

Fig. 5. A torn off piece of the insulating foam falls along the surface of the external fuel tank [5].

Fig. 6. Destruction of three the tiles placed directly behind 21st section of the wing leading edge of spacecraft *Buran* [6].

ones is the fundamental difference in physical properties effecting the propagation of electromagnetic versus acoustic waves in heterogeneous media. Electromagnetic waves reflect from heterogeneities only when their dielectric contrast is sufficient. Thus, electromagnetic waves propagate practically without loss in porous materials such as polyurethane foam insulation wherein the dielectric of air in pores almost matches that of the matrix foam [2]. Moreover, the pores dimensions are much smaller than the length of electromagnetic wave, so the foam can be considered as the continuous medium.

Thermal protection tiles are exposed to hydrophobization to prevent moisture penetration. New tiles are checked by immersing them in water for 24 hours followed by weighing [3]. However, this method is not suitable for testing of tiles already installed on the spacecraft, especially for critical post-flight inspection. However, in this case, it is possible to use microwave methods. In particular, this article considers the holographic subsurface radar RASCAN which has a high sensitivity to the presence of moisture due to the high relative dielectric constant of water (approximately 80) relative to air or foam (approximately 1) [12].