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

S. Ivashov a, *, V. Razevig a, I. Vasiliev a, T. Bechtel b, L. Capineri c

a Bauman Moscow State Technical University, 2nd Baumanskaya st., 5, 105005, Moscow, Russia
b Franklin & Marshall College, 17603-3003, Lancaster, PA, USA
c University of Florence, Via Santa Marta, 3, 50139, Florence, Italy

A R T I C L E   I N F O

Article history:
Received 7 June 2014
Received in revised form
16 October 2014
Accepted 23 October 2014
Available online 31 October 2014

Keywords:
Holographic subsurface radar
Non-destructive testing
Cryogenic fuel tanks thermal insulation
Polyurethane foam
Launch vehicle

A B S T R A C T

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.

© 2014 Elsevier Ltd. All rights reserved.

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...
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 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].
2. Holographic subsurface radars of RASCAN type

Design of subsurface radar is based on the classical principles of radiolocation. The radiated signal is reflected from local inhomogeneities, if their dielectric constant \( \varepsilon \) differs from the dielectric constant of the medium. The reflected signal is recorded by the receiving antenna and amplified. After appropriate signal processing, the result is displayed on a computer screen in real-time [13].

Traditionally, the type of subsurface radar used in common practice is impulse radar. In general, these repeatedly transmit one period of a sine wave signal (or impulse), and record the time domain return signal which contains reflected impulses. Currently almost all subsurface radars in commercial production are of this type. The main advantages of impulse radar are the high effective penetration depth into the surveyed medium due to the application of time-varying gain which amplifies the weaker later/deeper reflected arrivals, and the ability to make direct determination of reflector depths by measurement of the reflected signal time-of-flight if electromagnetic wave velocity in the medium is known or can be evaluated [13,14]. A significant disadvantage of impulse radars is the reverberation effect, i.e. multi-reflections of the transmit pulse between the radar antenna and strong reflectors such as the metal supporting structure to which thermal insulation or heat protection coatings are attached. In this case, the primary reflection of interest is obscured by multiple reflections (often called ghosts or phantoms) of the transmitted impulse signal [15]. Holographic subsurface radars of RASCAN type which are discussed in this article are free from this effect because they are continuous wave radar. RASCAN radars have also a distinct advantage in lateral resolution over impulse radars because of the specific design of the radar antenna which combines transmitter and receiver antennae into one lightweight/compact apparatus with small footprint.

Holographic subsurface radars get their name from the process of recording the interference pattern on the surface of the medium between the reference wave and the object wave reflected from subsurface targets. It is worth noting that for a long time there was widespread opinion that due to strong attenuation in typical media, and the inapplicability of time-varying gain to continues-wave radar returns, this type of radar was unlikely to find any significant application in practice [16,17]. However, the recent development of holographic subsurface radar of RASCAN type, their commercial production, and sufficiently wide practical applications have shown that for examination of low electrical conductivity media at shallow depths, this type of device has many advantages including real-time imaging plan-view, and high lateral resolution. Design details of various modifications of RASCAN radars and their areas of application are described in [12,18].

The principles of recording microwave holograms using RASCAN radar are easily explained by analogy with optics. Consider a plane monochromatic wave with a constant phase called the reference wave falling on a point object and being scattered. As a result of the summation of the incident or reference and scattered waves on a flat screen located at some distance behind the object, an interference pattern is formed, Fig. 7a. If the screen is normal to the propagation direction of the reference wave, the interference pattern forms a Fresnel pattern of concentric rings. In optics, after development of the pattern recorded on the flat screen, it can be illuminated by a reference wave, and a virtual image of the object is formed – seeming to float behind the screen, Fig. 7b. A similar phenomenon occurs when a microwave hologram of a point target in a uniform medium is recorded by the RASCAN subsurface holographic radar [12,19].

In some cases, microwave holograms recorded by RASCAN are remarkably similar to the optical holograms shown in the classical work of D. Gabor [20]. The essential difference is the much lower spatial density of interference lines on microwave hologram interference patterns [21]. This is because at approximately the same characteristic dimensions of the systems, the radar wavelength is several orders of magnitude greater than wavelengths in the optical waveband.

This principle has been fully implemented in RASCAN holographic subsurface radars. Fig. 8 shows the subsurface radar RASCAN-5/15000 which was used in the experiments described below. Radars of RASCAN-5 type are equipped with a quadrature signal receiver that
allows recording of complex microwave holograms of hidden objects. The radar transducer head containing both transmitter and receiver is connected through network cable to a microcontroller unit with USB link to a computer. The microcontroller unit drives the transmitter and receiver, digitizes data, and transmits to the computer.

3. Hologram reconstruction method

As mentioned above, RASCAN-5 radars record complex microwave holograms of subsurface objects. In many cases the recorded holograms resemble the actual subsurface target due to the high attenuation of electromagnetic waves in typical media and consequent loss of the outer fringes or rings of the interference pattern [21]. But in media with low attenuation, it is possible to improve the resolution of the microwave images by using a hologram reconstruction algorithm [23,24]. Fig. 9 represents a diagram of the recording of a microwave hologram using RASCAN radar.

The target is assumed to be flat, parallel to the scan plane and placed at constant depth \( z_0 \). The key relationships can be summarized as follows:

\[
F(k_x, k_y) = \frac{1}{(2 \pi)^2} \int \int E(x, y) e^{-i(k_x x + k_y y)} \, dx \, dy
\]  

(1)

\[
S(k_x, k_y, z_0) = F(k_x, k_y) e^{i(4 \pi \sqrt{\varepsilon/c} - k^2 + k_y^2) z_0}
\]  

(2)

\[
E_R(x, y, z_0) = \int \int S(k_x, k_y, z) e^{i(k_x x + k_y y)} \, dk_x \, dk_y
\]  

(3)

where \( E(x, y) \) is the registered hologram, i.e. the complex amplitude distribution registered by the radar receiver on the scanner aperture at \( z = 0 \), \( F(k_x, k_y) \) is the plane-wave spectrum of hologram; \( S(k_x, k_y, z_0) \) is the plane-wave spectrum at parallel plane at \( z = z_0 \); \( E_R(x, y, z_0) \) is the image reconstructed for plane \( z = z_0 \). \( \omega \) is the angular frequency, \( \varepsilon \) is the dielectric permittivity of the medium, \( c \) is the speed of the electromagnetic wave in the medium, and \( k_x \) and \( k_y \) are the spatial frequencies corresponding to \( x \) and \( y \), respectively.

In Eq. (1), the plane-wave spectrum of the registered complex amplitude distribution in plane \( z = 0 \) is obtained by two-dimensional Fourier transform of the complex amplitude. Eq. (2) relates plane-wave spectrum at a parallel plane at a distance or depth \( z_0 \). Eq. (3) gives the reconstructed distribution of sources by inverse Fourier transform of the plane-wave spectrum at depth \( z = z_0 \).

It should be noted that for this method to work, it is necessary to know the depth of the object. If the depth is not known, it is possible to conduct hologram reconstruction layer-wise, or repeatedly using a selected step in depth, while checking for the layer or depth where the target object is best-focused. In some complex cases, such as heterogeneous media with high levels of attenuation, this method will give the best focus on the artifact. However, determination of the location and depth (absolute position) of a subsurface object is typically difficult for all types of radar because measurements performed only on the surface of a half space create a reverse and ill-posed problem [25].

4. Sample of thermal protection coating

A sample of thermal insulation with artificial flaws was prepared by gluing polyurethane foam of 40 mm thickness on an aluminum alloy plate of 5 mm thickness. Design of the sample and positions of the flaws are shown in Fig. 10. The sample form was chosen in to match the real construction of spacecraft fuel tank insulation coating.

The dimensions of the sample were 500 by 400 mm. The sample was made in two stages. On the first stage, the central circle, 270 mm in diameter, was sprayed with adhesive, but with three round cuts on the bottom surface of the foam. At the cuts points, prime coating and glue are missing (usual total thickness=200 μm). Instead, the prime coating and glue were placed on the inner surface of the cuts. On the second stage, the rest of the sample was filled. This sample imitates the defects of gluing on the border between foam and metal.

5. Experimental results

The highest available frequency version of RASCAN-5 holographic radars, with operating frequency of 15 GHz, was used in the experiments. Choice of frequency band was determined by the low attenuation factor of polyurethane foam for electromagnetic waves and the need for high resolution to detect small anomalies. The dielectric permittivity of this material is essentially the same as for vacuum, i.e. about 1. According to data presented in [2], the complex permittivity of the foam sprayed on the external fuel
tanks of the Space Shuttle is $e = (1.05 - j0.003)$, and the density is only 4% of that for water. This is because the polyurethane foam consists mostly of pores filled by air. Laboratory experiments with RASCAN-5/15000 radar have shown that penetration depth in polyurethane foam is more than 16 cm that with margin exceeds the Space Shuttle foam insulation thickness [8].

However, it should be noted that the properties of the bulk polyurethane material depends on the fabrication process, and may vary within wide limits, so the density of its industrial samples lay in the range of 48–287 kg/m$^3$ [10]. Polyurethane foam has the lowest heat conductivity among all modern materials. Depending on its density, polyurethane foam thermal conductivity varies in the range of 0.019–0.033 W/m·K. Due to these characteristics, polyurethane foam is widely used as insulation material in various fields of industry, as well as military and space engineering.

Note that using frequencies around 15 GHz for diagnostics of other common structural materials is hardly possible because of the frequency-dependent attenuation of electromagnetic waves, i.e. generally a sharp increase of the absorption factor for frequencies above 10 GHz. Therefore, for diagnostics of building structures with concrete, wood, and plaster construction, it is more appropriate to use frequencies in the range of 1.5 to 7 GHz to obtain good results [12].

In the experiments on thermal protection coatings, manual scanning of the sample surface was performed, Fig. 11 [26]. It needs about 4–5 min to scan the sample with dimensions of 40 by 50 cm, Fig. 10. Scanning could be faster if electro-mechanical scanner is used. But there is no such aim in these experiments. The complex microwave hologram (real and imaginary components), as well as the digital reconstruction (1)-(3) for a signal frequency of 14.6 GHz are shown in Fig. 12.

Procedure of hologram reconstruction by our algorithm is very fast. It needs less than 1 sec. One can readily see on these microwave images the three flaws, and the round sample border created by the two-stage production of the test sample.

Vertical and horizontal stripes in Fig. 12 are the result of the reflection of electromagnetic waves, emitted by the radar in medium, from the end faces of the sample insulation, primarily from the border of the underlying aluminum plate, i.e. they are edge effects. Cyclical variation with distance in the reflected wave phase combined with the constant phase of the reference signal forms a striped pattern. This phenomenon is very similar to the “zebra effect” that was described and explained in [27].

Examination of heat protection coatings and thermal insulation of space vehicles that are glued to the metal surface of the base structure is a fairly specific task. This is because the metal surface is a perfect mirror for microwaves. The specular reflection ensures certain specificity in the process of hologram reconstruction and requires this be accounted for when interpreting the results.

For a better understanding of the processes occurring in a material relatively transparent to microwaves located above a perfectly reflective metal surface, an experiment was performed with two metal spokes that were inserted through the sides of the sample, Fig. 13. The spokes are labeled on this figure as numbers 1 and 2. Spoke 1 was inserted parallel with the metal surface at a depth of 13 cm (distance above the metal surface of 2.3 cm). The second spoke was inserted in the polyurethane foam at an average depth of 13.5 cm but with a slight dip relative to the surface to demonstrate the above-mentioned “zebra effect.”

To determine the true depth of the objects inside the foam, it is necessary to take into account the 3 mm Plexiglas sheet that covers the scanning surface to improving the sliding of the radar head. Another important effect is related to presence of the metal plate that underlies the polyurethane foam and reflects the microwave as an ideal mirror. The same as in optics, the mirror reflection of spokes must be observed behind the plate.

Upon reconstruction of the microwave holograms from the interference pattern recorded by the radar, the image is focused at a distance specified by the parameter $z = z_0$. Results of microwave hologram reconstruction for different depths in the experiments with the spokes are shown in Fig. 14.

In this figure, the two top images correspond to the original complex holographic interference pattern recorded in two radar quadratures, real and imagery. Images below correspond to
successively deeper hologram reconstructions: $z=0$, 2.7, 4.7 and 6.7 cm respectively. Depth 2.7 cm corresponds approximately to the depth of the object, 4.7 cm is the position of the metal surface, and 6.7 cm is a virtual image that corresponds to mirror reflection of the spokes from surface of the metal plate.

It is necessary to note that the contrast of the virtual image of spoke 1 with respect to the background has changed to the opposite sign in comparison with the real image of the object at a depth of 2.7 cm. This effect is associated with the phase inversion of the electromagnetic wave by 180° upon its reflection from the surface of the metal [28], leads to the polarity reversal in the virtual image contrast. Such complexities indicate that further investigation is needed to understand the details of microwave holograms recorded in dielectric media located above a metal surface.

6. Conclusions

Diagnosis of thermal insulation and heat protection coatings glued onto a metal surface is a very specialized task since the metal surface fully reflects the electromagnetic waves. For impulse radars, such targets are characterized by multiple reflections of signal between radar antenna and metal substrate which obscure the desired target in the recorded impulse radar images. Although holographic radar is free from this shortcoming, the presence of a perfectly specular reflective metal substrate beneath desired targets must be considered when interpreting the results of holographic imaging.

These experiments showed that the proposed diagnostic method for thermal insulation using holographic subsurface radars allows detection of internal defects within the coating. However, in the microwave images, the detected defects are subtle due to the low permittivity contrast between the defects and surrounding polyurethane.

It is possible that the sensitivity of the radar could be enhanced by increasing the operating frequency up to 24–25 GHz. This possibility is suggested by experiments with a lower frequency Rascan-5/7000 radar (frequencies in range of 6.4–6.8 GHz), which did not detect the defects in the sample used for these experiments. This suggests that increasing the radar operating frequency should enhance both spatial resolution and sensitivity, probably with little loss of penetration due to negligible loss in the low electrical conductivity, and low-scattering insulating materials.

Acknowledgments

Support for this work was provided by Ministry of Education and Science of the Russian Federation (grant #7.340.2011) and Russian Foundation for Basic Research (grant #12-07-00557).
References


