Combining radar and ultrasound imaging for surface echo compensation and augmented visibility of interior structures in NDT applications

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Abstract

Millimeter-wave radar imaging is a promising technique in non-destructive testing. When a small material defect is located closely to the test object’s surface, the strong reflection caused by the air-material interface can overlap with the defect’s weak reflection and mask it. If the image resolution is not sufficient, the defect cannot be resolved and will not be recognizable in the reconstruction image. To solve this problem, surface echo compensation techniques have been invented. However, these techniques are usually restricted to planar surfaces, which for most applications is not the case. This article presents a technique for surface echo compensation of arbitrarily shaped objects. We propose to combine radar and air-coupled ultrasound. Since air-coupled ultrasound is not able to penetrate solids, an air-coupled ultrasound imaging system is only able to detect the surface of a solid object. The idea of our proposed concept is to employ the ultrasound signal to compensate for the surface echo in the radar signal. The proposed method is based on the idea of using signals of equal wavelengths for both wave types and an amplitude calibration. Then, the resulting signals for radar and ultrasound are formally equal, which makes it possible to directly combine them numerically. That way, a modified radar image can be obtained which only contains the reflections from the inside and highlights interior defects.

KEYWORDS: Millimeter-wave imaging, terahertz imaging, ultrasound imaging, air-coupled ultrasound, radar, subsurface imaging, boundary compensation, polymers.

1. Introduction

Millimeter-wave and terahertz synthetic aperture radar imaging has become a promising technique for non-destructive testing (NDT) applications [1], [2]. It is able to penetrate many optically opaque materials and achieve image resolutions in the sub-millimeter range, while being no risk to the operator as is the case with X-ray.
A radar imaging system’s depth resolution is mainly limited by its bandwidth. When a material defect is located closely to the test object’s surface, the strong reflection caused by the air-material interface can mask weak reflections from closely behind it. If the resolution is not sufficient, the defect cannot be resolved and will not be visible in the reconstruction image. To overcome this problem, boundary compensation techniques were invented [3-6]. However, these techniques are only applicable to objects with planar surfaces, which for most applications does not hold.

To overcome the restriction of a planar boundary, this article presents a technique for surface echo compensation of arbitrarily shaped objects. We propose to combine radar and air-coupled ultrasound. Air-coupled ultrasound is not able to penetrate into solids. Therefore, an air-coupled ultrasound imaging system is only able to image the surface a solid object. The idea of our concept is to use this ultrasound signal to compensate for the surface echo in the radar signal. The approach was previously introduced in the context of security imaging [7] and is now applied in non-destructive testing.

2. Multimodal Imaging

In this section, the multimodal imaging concept for surface echo compensation is described. It was derived in detail in [7] but the main issues are reported here for clarity. The receive signal of a synthetic aperture radar imaging system when illuminating a dielectric, solid object is a superposition of all material inhomogeneities encountered by the electromagnetic waves. These occur at the object’s surface, at its rear and at inner defects such as contaminations or air inclusions, if there are any.

In contrast, when measuring the same object with a synthetic aperture air-coupled ultrasound imaging system, there will only be a reflection from the surface. This is because the acoustic impedance of solids is much higher than that of fluids such as air, and consequently, the reflection coefficient will be approximately equal to one (100%). Since scalar electromagnetic waves and acoustic waves follow the same mathematical formalism, the idea of the multimodal concept is to dimension the radar and ultrasound transmit signals in such a way that they are formally equal. Then, the ultrasound receive signal will be numerically equal to the surface component of the radar signal. By subtracting the two signals numerically, we obtain a modified radar signal which no longer contains the surface echo component.

In order to obtain equivalent signals, the amplitudes and phases of the electromagnetic and acoustic complex baseband signals must be equal.

The phase is

$$\varphi = kR$$

where \( k \) is the wavenumber and \( R \) is the distance between the transducer position and a respective voxel. When moving the transducers of both wave types along the same trajectory, \( R \) will be equal for both signals. The wavenumber \( k \) is

$$k = \frac{2\pi}{\lambda}$$

where \( \lambda \) is the wavelength. Thus, the wavelengths for both wave types have to be equal. The amplitude of a synthetic aperture imaging system depends on a number of influences such as transmit power, free-space attenuation directivity pattern and the test object’s reflection coefficient. However, these effects differ significantly for acoustic
and electromagnetic waves. To circumvent this, we propose to use antennas and transducers with equal, or at least similar directivity patterns and then normalize both signals with a metallic reflector plate. A metal plate acts as a perfect reflector for both wave types. Thus, the influence of free-space attenuation and transmit power are eliminated. The test object’s reflection coefficient can be assumed to equal one for air-coupled ultrasound. For radar, it depends on the object’s material. Therefore, in order to obtain equal amplitudes, the ultrasound signal has to be scaled with the radar reflection coefficient. More details on the system calibration can be found in [7].

3. Application to NDT

3.1 Multimodal measurement setup

A multimodal imaging system comprising radar and ultrasound was set up [7]. It is shown in Fig. 1.

The imaging system consists of two vector network analysers (VNA), for the signal generation of each wave type. VNA ZVA 24 from Rohde & Schwarz, combined with frequency extenders was used for the radar signal generation, whereas type ZVRE (also from Rohde & Schwarz) was used to generate the signals fed to the ultrasonic transducers. The imagers operate in a quasi-monostatic setup, with two transducers/antennas in close proximity. Sonoscan CF 125 transducers, which are commercially available piezo-electric transducers for air-coupled ultrasound, were employed. The antennas are spline horn antennas for the W-band (75 GHz – 110 GHz), fabricated at the authors’ institute.
2.2 Experimental results in an NDT scenario

A polyethylene (PE) test object was used for the demonstration. Fig. 2 shows a geometry sketch of the object and its cross-section.

Two drill holes of radius 2 mm simulate interior material defects. The $x$ and $z$ coordinates in the right hand side subfigure equal those of the measurement scenario, i.e. the test object was located at a minimum distance of 44.8 cm from the aperture plane. Since the object is invariant along the height direction, we only performed a line scan and imaged a cross section for the demonstration. The length of the line scan was 400 mm, sampled in a step width of 1 mm to meet the spatial sampling criterion. The employed wavelengths were in the range of 2.72 mm – 3.15 mm. This equals a frequency range of 94.9 GHz – 110 GHz for the radar signal, and a frequency range of 110.2 kHz – 127.8 kHz for the ultrasound signal for a speed of sound of 348.2 m/s in the laboratory.

The test object was measured with the multimodal setup and the receive data were processed using a backprojection algorithm combined with ray tracing, as described in e.g. [2].

For the computation of the modified radar data, the radar reflection coefficient is needed (see Sec. 2). When assuming normal incidence, the reflection coefficient $r$ is

$$r = \frac{n_2 - n_1}{n_2 + n_1}$$

where $n_1$ and $n_2$ are the refractive indices of the two materials. In our setup, a reflection coefficient of 0.2 was used. This is the reflection coefficient for the material interface air-polyethylene, with PE having a refractive index of ca. 1.5 and assuming a refractive index of approx. 1 for air. The assumption of normal incidence is made here because the quasi-monostatic setup will be able to capture only waves at normal incidence from the smooth surface.

Reconstruction results are shown in Fig. 3: Subfigures a) – c) show the reconstructed radar data, the reconstructed ultrasound data, and the reconstructed modified radar data,
respectively. All images are normalized to their maximum value and are displayed in logarithmic scaling. A dynamic range down to -20 dB w.r.t. the maximum value was chosen to suppress noise. The boundary contour is displayed in a white dashed line.

![Figure 3. Reconstruction results. a) radar reconstruction data, b) ultrasound reconstruction data, c) modified radar reconstruction data.](image)

Expectably, the radar image (subfigure a)) shows reflections from the surface, the drill holes and the rear boundary (cf. Fig. 2). The fact that only the upper, planar part of the boundary is displayed, is because of the relatively small aperture angle of the antennas. In contrast to the radar image, the ultrasound image (subfigure b)) only displays the boundary reflection. There are no reflections whatsoever from the inside. The highlighted image points at \( z = 45.5 \) cm are sidelobes of the boundary reflection. Results obtained with the proposed concept (subfigure c)) show that the surface is successfully cancelled, which verifies the proposed concept.

4. Conclusion

In this paper, a multimodal concept for surface echo cancellation in subsurface millimeter-wave imaging is presented. For the compensation, air-coupled ultrasound is used. Air-coupled ultrasound is not able to penetrate into solids, whereas radar is. As a
consequence, the radar receive signal, when inspecting a solid object, is a superposition of the echoes from the surface and those from the interior. In contrast, the ultrasonic receive signal only consists of the surface echo. The idea of the proposed approach is to use the ultrasonic echo to compensate for the surface component in the radar echo. Since scalar electromagnetic waves and acoustic waves follow the same formalism, the ultrasonic signal is formally equal to the surface echo of the radar signal when using equal wavelengths and a suitable amplitude calibration. Then, the two signals can be numerically subtracted and the subtraction signal only contains the interior echoes. With the proposed approach arbitrarily shaped surfaces can be cancelled. Experimental results with a polymer test object were presented to verify the proposed concept for NDT applications.

References


