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Millimeter waves Radar: A way to see through the airplane covering?

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Abstract

The usability of Ultra Wide Band terahertz radar technique for inspection and imaging of objects of interest for the aeronautics industry is under investigation in this paper. Frequency-modulated continuous-wave (FMCW) radar principle and systems will be detailed along with its benefits and limitations depending on the architecture and characteristics of the system as well as the materials under inspection. Promising results and advances in the airplane covering see-through problematic are also demonstrated through measurements that have been performed with our imaging systems, demonstrating the suitability of FMCW radars for a new tool for Non Destructive Testing (NDT) applications for the aeronautics industry.

1. Introduction

Frequency modulated continuous-wave (FMCW) sensing technique was originally investigated in radars for locating a distant object by means of millimeter waves through simple data processing. They have been later implemented as a highly sensitive tool for defect detection either in NDT applications [1], target detection or security applications [2], or SAR imaging [3][4][5].

The unique potential of FMCW radar comes from many intrinsic benefits such as its high level of integration and compactness, its relatively low cost as well as the harmless character of the emitted radiation and their high penetration capabilities in adequate materials. These arguments make it a suitable candidate to take up on the most trusted techniques in the case of specific, demanding tasks. In addition, and contrarily to X-Rays based techniques, low frequency continuous wave NDT systems or thermographic imaging systems, FMCW data processing natively enables the capability to provide information on the propagation time delay and so gives a direct correlation with the object's distance relatively to the radar unit. 3D imaging is directly

assessable. The detection and location of damages, cracks, impact marks, delamination or inclusions is then achievable in compatible materials that are commonly used in the aeronautics industry, such as glass fiber based composite, honeycomb structures, polymers or ceramics either during fabrication or for maintenance processes.

Our study has been focused on the implementation and the capabilities of the reflection geometry setup, using a homodyne radar transceiver, since it turned out to be particularly appropriate for the see-through covering problematics. The large versatility in term of working frequency, available power and modulation frequency band is a great advantage for its implementation in Non Destructive Testing (NDT) applications.

2. Radar imaging Capabilities for NDT

2.1. FMCW radar architecture and principle

The FMCW radar architecture have been applied for various functions and from various technologies from Si-based fully integrated devices [6] to high frequency precision radars[7] where a similar architecture is implemented in most of the cases.

Figure 1 (a) describes the typical architecture diagram of a block integrated III/V radar, where, the first block of the system is a Voltage Control Oscillator (VCO) or a Phase Locked Loop (PLL) oscillator, which generates a saw tooth-like frequency sweep between a minimum and maximum values at low frequency. The multipliers chain then performs the up-conversion to bring the signal on the desired working frequency bandwidth which are typically centered around 100 GHz, 150 GHz, 300 GHz or up to 600 GHz. This high frequency signal is then considered as a reference signal and is emitted by a horn antenna. By modulating the

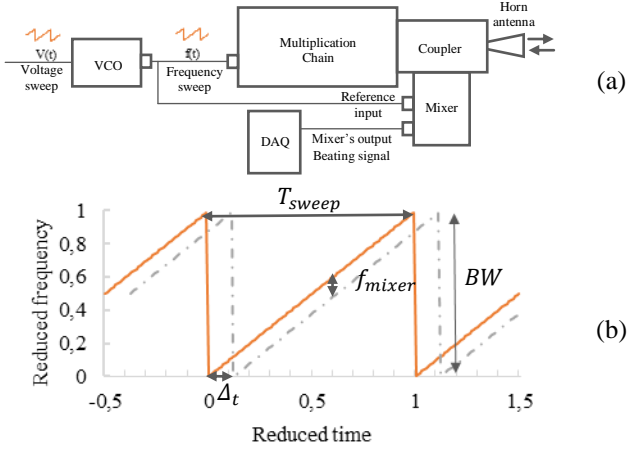


Figure 1 (a) FMCW Radar architecture in the case of a reflection mode transceiver (b) FMCW reference emission frequency sweep (solid line) and delayed reflected signal for a single object (dashed line)

frequency in such a way (see Fig. 1 (b)), the concept of the technique is equivalent to putting a unique "time stamp" on the emitted wave at every instant.

The reflected signal, delayed due to the propagation back and forth to the target, is guided toward the detection circuit thanks to the directional coupler linked to a multiplexer where it is mixed with the reference signal or one of its lower harmonics. This mixing will produce a beating signal, collected by a data acquisition unit (DAQ), at the frequency f_{mixer} , directly proportional to the propagation delay and so the distance to the object as showed in Equation (1).

$$d = \frac{c_0 \Delta_t}{2n} = \frac{c_0 f_{mixer}}{2n} \cdot \frac{T_{sweep}}{BW} \quad (1)$$

$$\delta_{res} = \frac{c_0}{2n BW} \quad (2)$$

Where Δ_t is the propagation-induced time delay, BW is the accessible bandwidth, f_{mixer} is the output beating frequency of the mixer and T_{sweep} is the frequency sweep period.

From equation 1, which states the relation between the distance and the beating frequency, the longitudinal resolution can be derived as equation 2 and only relies on the bandwidth of the radar transceiver.

2.2. Optical implementation for imaging

A quasi optical coupling system for beam focusing is

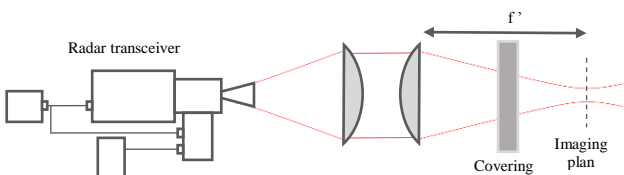


Figure 2 Optical configuration diagram for radar imaging in reflection mode with intermediate covering obstacle

implemented thanks to a PTFE lens doublet as showed in Figure 2. It enables the operator to focus the beam on the element of interest, beyond an eventual extra obstacle, to have the optimum resolution and signal amplitude by optimizing the back coupling of the reflected signal from the imaging area to the transceiver.

The gaussian beam model, which is quite adequate for such geometry gives, in this configuration, the relation between the beam waist diameter which limits the resolution and the focal length of the focalizing lens as follows:

$$\omega_0 = \frac{4 \lambda f'}{\pi D} \quad (3)$$

Where D is the diameter of the lens, f' its focal length and λ the wavelength related to the emitting frequency.

Due to this gaussian beam geometry, the resolution varies with the working frequency as well as the optical configuration since for example, imaging at longer distances from the radar transceiver will require a larger focal length, thus decreasing the resolution of the system.

2.3. System and 3D imaging results

In the imaging process, the frequency band selection is one of the key parameters with the adequate optical configuration, since higher frequency bands would allow larger bandwidth and so, improve the longitudinal resolution (see Equation 2) as well as the lateral resolution (see Equation 3). Nevertheless, a wide range of materials, such as glass fiber composites, polymers or ceramics remains, sufficiently transparent for millimeter wave radiation, but commonly displays significant absorption increase for higher frequencies, closer to 1 THz. This dimensioning results from a tradeoff between material penetrability and required resolution.

A wide range of samples based on glass and reinforced plastics with various types of geometry have been examined using a SynView imaging system on reflection mode and have been evaluated in the frequency domain with a 100GHz and 300GHz radar transceivers, as displayed on Figure 3. Carbon fiber doped samples, on the other hand, remains too highly reflective over all frequency range, preventing in depth or see-through inspection but allowing high sensitivity topographic inspection or coatings analysis.



(a)

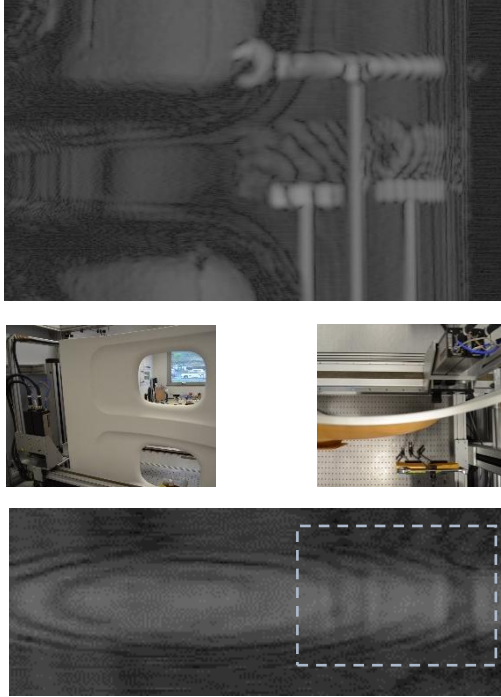


Figure 4 (a) 100 GHz image of a wrench and sponges with their support through a plane covering panel (b) SynView imaging system with plane panel installation (side view and top view) (c) 100 GHz Image of an altered aluminum tube that displays cracks on its right part (dashed frame).



(b)

Figure 3 (a) 100 GHz radar scan of a glass fiber composite test sample displaying inclusions (b) 300 GHz radar scan of the same test sample.

Focusing on the covering see-through problematics, the 100 GHz radar transceiver turned out to be the most adequate system to minimize the losses when passing through the fiber glass covering panel back and forth and enable imaging of objects with an adequate resolution of a few millimeters, as showed on Figure 4. Figure 4 (a) shows that metallic reflective objects, such as the wrench or the sample holders, are detected and identified through the panels as well as other objects that displays much lower reflectivity such as the two square sponges with different moistures levels. Reminiscences of the panel geometry remains distinctly discernible. Distances up to 15 cm between the imaging area and the covering panel is achieved with the related lowered resolution. Figure 4 (c) depicts the capability of see-through radar imaging to detect defects and alterations such as cracks or broken components through a cover, in this case, an aluminum tube displaying 2 breaks.

Depending on its depth, the matrix material, and its size, defects like foreign material, object, alterations or moisture contamination can be visualized through a covering structure of aeronautics. If a defect is not too deep in the sample, its location

and its shape can be correctly identified from the delay between the induced partial reflections at the surface and the defect itself.

3. Conclusions

Ultra Wide Bandwidth FMCW radars are known for their contactless NDT capabilities for the aeronautics industry. Here, they proved to be an adequate, compact and sensitive solution for remote sensing of inaccessible targets through plane panel thanks to the object identification as well as alterations and defects detection that have been demonstrated in reflective mode. Further ongoing works are oriented toward the testing of other types of materials. The implementation of a more versatile FMCW radar system amongst other optical NDT tools that would grant maximum degrees of freedom in order to get a resourceful imaging system is also under development.

Acknowledgements

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