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Enhanced time of flight THz imaging via a de-noising procedure based on band pass filtering

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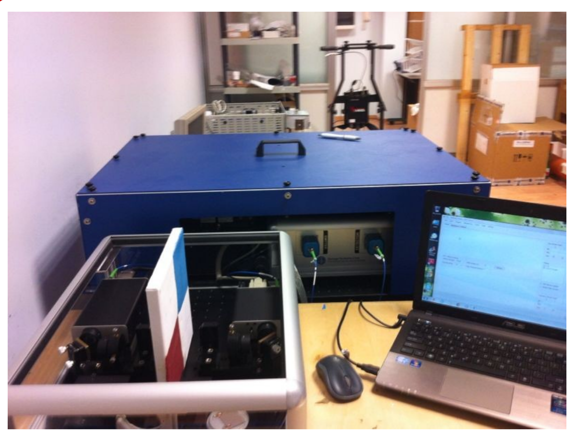
Abstract – Time of flight imaging by means of Terahertz waves deserves huge attention in a wide range of applications, among which diagnostics of art works, food quality control, composite material assessment and so on. In all these contexts, the common requirement is to obtain high quality images from which one can infer the material inner structure and localize hidden anomalies. This issue involves the need to reduce noise, which may corrupt data collected without purging ambient water vapor. In this frame, we compare two filtering approaches, which do not require knowledge of noise level or reference measurements. The first method exploits the concept of the actual frequency bandwidth of the data, while the second one is based on the Singular Value Decomposition of the data matrix. Experimental results state the improvements, in terms of imaging, offered by the filtering procedures. In particular, we present results regarding a specimen of a composite material covered by an ice-phobic coating, which has been designed at CIRA and analyzed by means of the Fiber-Coupled Terahertz Time Domain (FiCO) system available at IREA.

FICO SYSTEM DESCRIPTION

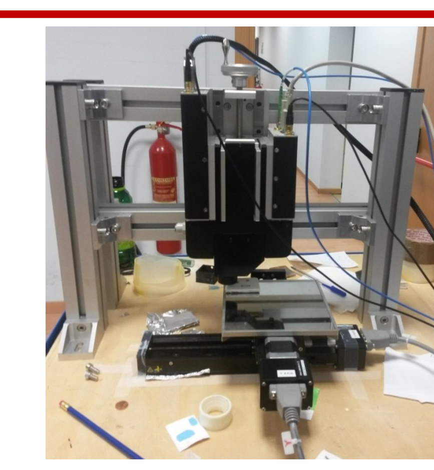


FICO system

The Zomega FICO system allows spectroscopy and imaging and it is schematized as made up of three main components: a) the laser source; b) the base unit; c) fiber optic coupled transmitting and receiving probes reconfigurable in transmission and normal reflection mode.

The system collects signals into a 100 ps observation time window, which can be moved along a time scan range of 1ns according to the path length between transmitter and receiver. The waveform acquisition speed can be up to 500 Hz and the maximum dynamic range (DNR) is 30dB, while the typical DNR is 20 dB. The effective frequency range is from about 50 GHz to 3 THz.

The system has been potentiated by means of an automatic positioning system enabling to scan a 150 mm x 150 mm area with physical resolution, i.e. smallest step size, of 12 μm.



FICO imaging stage

DE-NOISING APPROACHES

FFT based approach

The procedure takes into account the effective frequency bandwidth of data and consists of three steps

a) the direct fast Fourier transform (*FFT*) is used to obtain the frequency spectrum of all the THz traces gathered along a line or a surface

b) the effective frequency range is fixed as the range where the amplitude of spectra, as normalized to its maximum value and plotted in logarithmic scale, is no lower than 3dB

c) the selected portion of the spectrum of each THz signal is transformed by means of the inverse FFT (*IFFT*)

Hence, let $s(t)$ be the raw THz waveform measured at the generic measurement point, the filtered signal is given as

$$\hat{s}(t) = IFFT\left(\Pi\left(FFT\left(s(t)\right)\right)\right)$$

where Π denotes the band pass filter designed to select the effective spectrum of the signal.

It is worth observing that the restriction of the spectra at the effective frequency range of the signals affects the depth resolution. According to the diffraction theory, this is, indeed, ΔR = v/(2B), where v is the wave speed in the probed medium and B is the considered bandwidth [1].

This procedure has been previously exploited to perform THz imaging of majolica tiles [2].

SVD based approach

The procedure uses the Singular Value Decomposition (SVD) of the data matrix A [3].

Let us assume that N waveforms are measured and each signal is represented by means of M sampling points. The N x M data matrix A can be represented as

$$\mathbf{A} = \mathbf{U}\Sigma\mathbf{V}^T = \sum_{i=1}^{Q}\sigma_i u_i v_i^T$$

where U e V are orthogonal matrixes having size N x N and M x M, respectively; ∑ is the N x M diagonal matrix containing the singular values of A and $Q = min\{M, N\}$ is the rank of A.

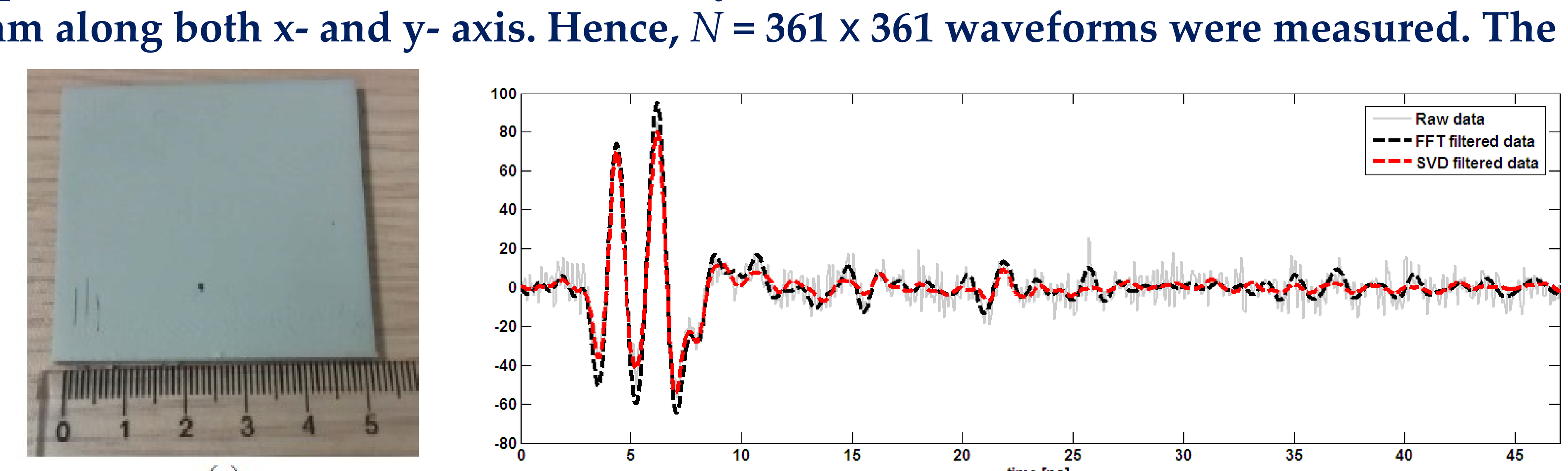
As the singular values are in a decreasing order, we can expect that the first ones represent the most significant part of the collected waveform, while the smallest ones are referring to less important information as well as to the noise. Accordingly, the noise filtered data matrix Â is obtained by truncating the SVD at a threshold $P < Q$

$$\hat{\mathbf{A}} = \sum_{i=1}^{P}\sigma_i u_i v_i^T$$

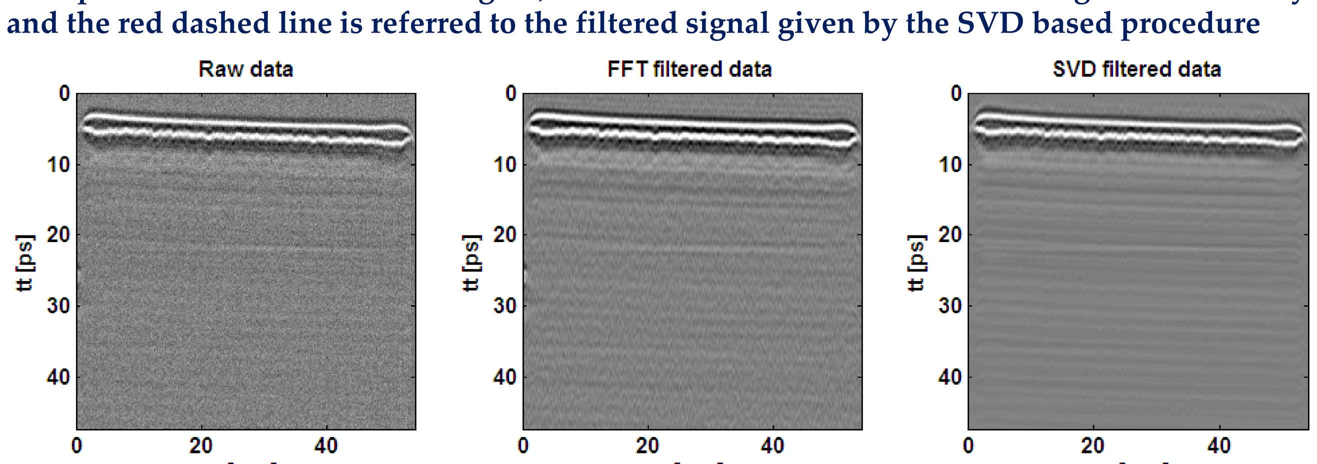
Here, we set P in in such a way to filter out all the singular values 20 dB lower than the maximum one. It is worth observing that this procedure does not restrict the signal spectra.

THz IMAGING

We performed THz imaging of a 50 mm x 50 mm x 4 mm specimen of a composite material covered by an ice-phobic coating [4], designed and manufactured by the research team of the Italian Aerospace Research Centre. The THz survey was carried out in the normal reflection mode, the measurement area is 54 mm x 54 mm wide and the spatial offset between two acquisition points is 0.15 mm along both x- and y- axis. Hence, N = 361 x 361 waveforms were measured. The observation time windows is about 50 ps wide and is sampled by M = 804 points.

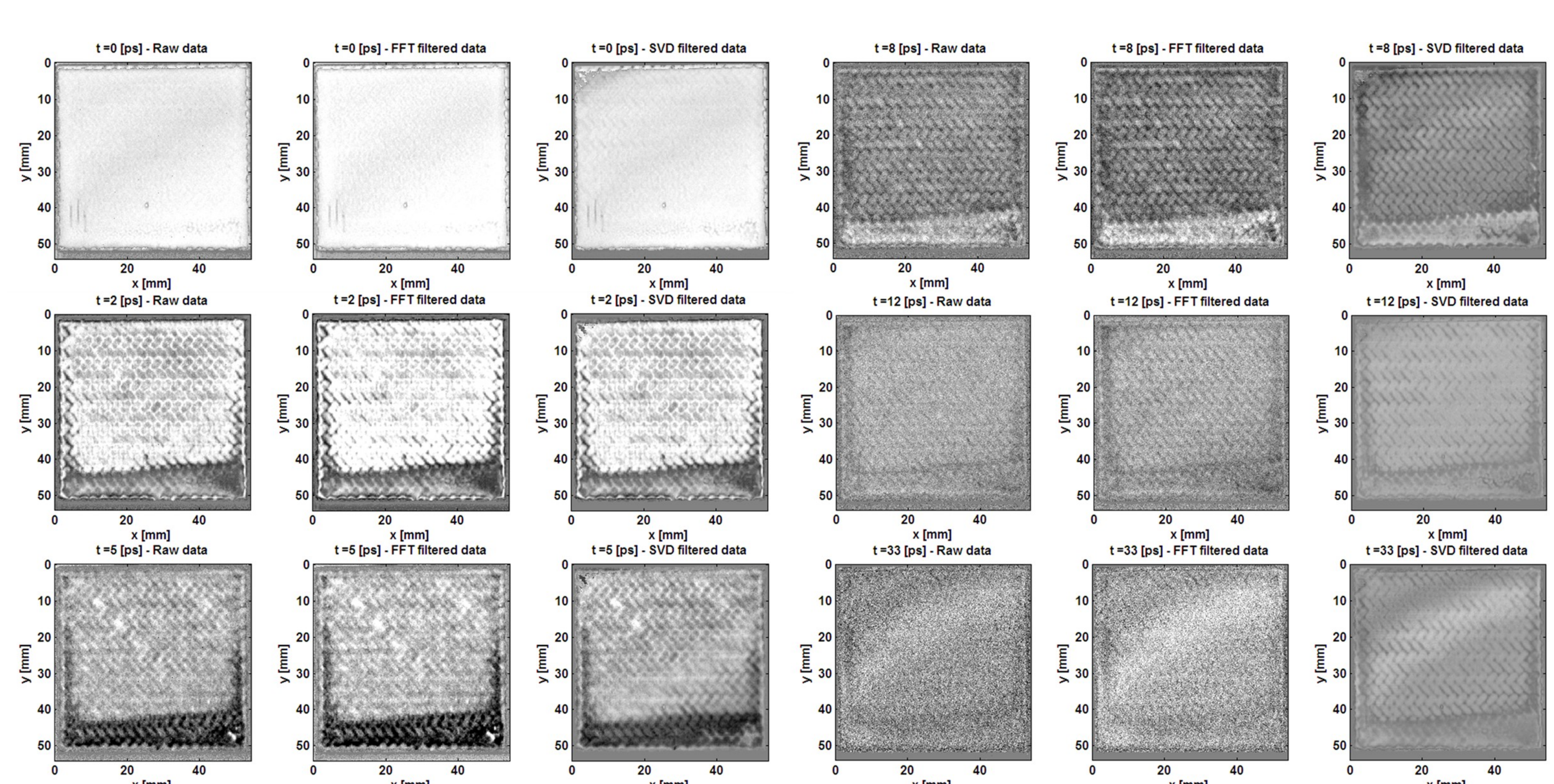


THz survey: a) specimen image; b) comparison of the raw and filtered waveforms referring to the central point of the specimen. The gray solid line represents the raw measured signal, the black dashed line is the filtered signal obtained by using the FFT based approach and the red dashed line is referred to the filtered signal given by the SVD based procedure



Raw and filtered radargrams referring to the measurement line passing through the center of the sample along the y-axis

The waveform collected at the center of the specimen suggests that raw data are sufficient to obtain a satisfactory image of the surface of the ice-phobic coating (first peak) and consequently of the defects present on its surface. Moreover, they allow a good visualization of the interface between the ice-phobic coating and the composite material, which is represented by the second peak. Conversely, both the filtering procedures are worthwhile to improve the image of the inner texture of the specimen. On the other hand, the provided radargrams show that the SVD based procedure outperforms the FFT based approach, since it allows to remove the random oscillations completely



THz images provided by raw and filtered data for increasing observation times. These images have been obtained by applying a topography correction procedure, which performs an alignment of the first reflection by setting the zero time, i.e. t=0 ps, at the beginning of the ascending front of the first peak occurring in each one of the measured waveforms.

These images corroborate that both the filtering procedures allow:

- an improved visualization of the inner specimen texture
- the FFT based procedure introduces a slight loss of spatial resolution (see images at t = 2 ps)
- the SVD based approach allows a better noise rejection and provides more clean images, especially when the observation time increases

References

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