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A 2D-FFT signal processing technique to enhance the contrast of air-coupled ultrasonic C-scans

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Abstract

In this work, a Fourier-based algorithm to enhance the contrast of air-coupled ultrasonic C-scans is presented. The performances of the developed algorithm are checked on C-scans recorded in order to monitor the state of conservation of ancient paintings. Experiments on simulated and real ancient paintings have confirmed the ability of the algorithm in recognizing small corrupted regions, replacing them with synthetic values and finally filtering out the high frequency noise. The processed images show an enhanced contrast and an higher signal to noise ratio and appear pretty easy to be interpreted.

Keywords: 2D Fast Fourier Transform, air-coupled C-scans, contrast enhancement.

1. Introduction

In almost all current ultrasonic inspection methods, ultrasonic waves have to be conveyed from a transmitter, into the object to be tested and then to a receiver. This procedure usually requires the use of a good acoustic coupling agent between the transducers and the material to be inspected. Nevertheless, in many applications the presence of a couplant may be undesirable and impractical or simply its use can damage and/or contaminate the investigated object (e.g. aerospace materials such as honeycomb structures, foams, porous and hygroscopic materials, wood and paper based products. On the other hand, if air is chosen as the coupling medium, several problems must be overcome in setting-up a feasible technique [1]. Besides the ultrasound attenuation, which is larger in air than in any other liquid media, the main problem is the acoustical impedance mismatch between air and the most common materials. The amount of transferred energy after each interface is really small and advanced techniques have to be designed to minimize losses at every stage and to achieve an acceptable signal to noise ratio for the inspection. The main techniques are: the use of un-dumped resonant transducers, to maximize the conversion between electric and kinetic energy; the implant of final matching layers, to reduce losses due to the impedance mismatch; the use of low-noise preamplifiers, to minimize any noise pickup on the cables; the optimized electrical design of the receiver circuitry, mainly accomplished by using tunable narrow band filters matched to the toneburst frequency; the use of advanced signal processing techniques, such as the pulse compression technique [2], in order to achieve a good time resolution, even using chirps of longer duration.

In the next section, a description of the air-coupled application will be given, as well as a short presentation of the employed technology and of the adopted procedure; in the same section, the main artifacts of the air-coupled C-scans, which we are dealing with, will be shown. Then, after a brief review of the Fourier theory, the developed algorithm to enhance the quality of the obtained air-coupled C-scans will be described in detail. Finally, some examples of application of the proposed algorithm will be displayed and discussed.

2. Air-coupled application

Before coming deeper to the algorithm, it is useful to give an explanation of the kind of application which we are dealing with. Wooden panel paintings are the object of the present investigation. A wooden painting can be thought as a layered structure with a support [3]; the last one provides a base for the paint. During its life, the painting is subjected to variations of ambient parameters, like temperature and humidity. In dependence of these daily variations, the different materials that constitute the painting expand and contract themselves of different amounts. In time, the ground (made by several layers of gesso and animal glue) becomes more and more fragile, loosing its former elasticity. Hence, it can not follow the deformations of the wood support any more: cracks appear on the ground and propagate through the painting surface, severely damaging the aesthetics of the art work. Other typical defects that can occur are detachments between layers. If the ground has lost its elasticity, the occurrence of cracks and/or delaminations is unavoidable. The aim of the present research is to develop an air-coupled technique in order to check the state of conservation of paintings [4,5,6].

The ultrasonic pulser/receiver NCA-1000 2E is implemented in the measurement system; the device is based upon the synthesis of an amplitude modulated chirp with a Gaussian profile. Dealing with air transmission and propagation to highly absorbent materials, in order to extend the detection range for a given peak-power and still have an acceptable time resolution, the cross-correlation technique [2] is used. Piezoelectric transducers have been utilized; they represent one of the best solutions to the air-coupled issue and are developed at the Ultran Laboratories [1]. We utilized three couples of transducers, characterized by 200, 500 and 1000 kHz as center frequencies.

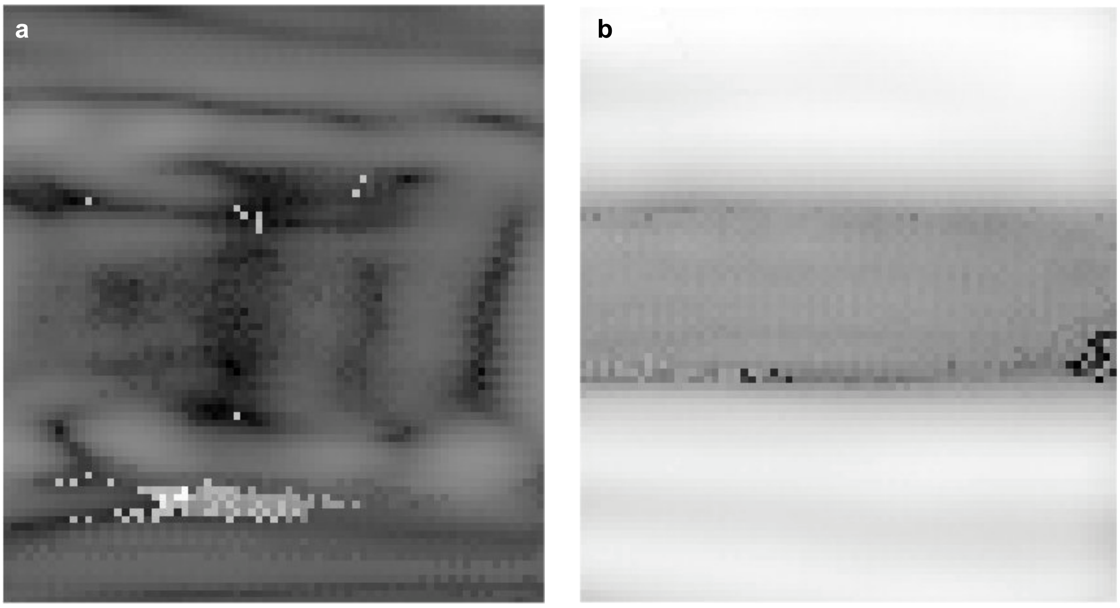

Fig.1.a and b – Original air-coupled C-scans with corrupted regions

Home made models - with simulated defects such as cracks and delaminations - and real paintings were analyzed in single-sided configuration. The transducers were tilted by a proper angle to generate guided waves in the panel and a commercial scanning device was used to control the position of the non-contact transducers. The generated guided waves allowed us to properly detect the presence of a defect in almost all the models tested: the presence of a delamination destroys the correct propagation of the guided wave. The received signal is processed by the system for each position, and data regarding a precise time interval of the compressed pulse are stored. The main information is represented by the Integrated Response, the area underneath the gated time interval. The added benefit of using the cross correlation as the basis for ultrasonic pulse measurements is that, due to the time integration involved, a large signal-to-noise ratio enhancement can be achieved. Nevertheless, the cross correlation procedure leads to instability of the measured parameters of the gated time interval.

For these reasons, C-scans show sometimes regions of incoherent values that affect the quality of the image as a whole, as it is possible to see in the non processed C-scans showed in Fig.1.a and b and related, respectively, to a home-made maple model with a rectangular delamination (a) and a passing horizontal delamination between the wood support and the ground. As it is possible to realize by simply observing the extension of the corrupted regions, it is difficult to cancel the influence of these regions by applying classical filters, such as average or median filtering procedures.

3. Fourier theory and 2D Fast Fourier Transform (2D FFT) based algorithm

A 2D-FFT based algorithm has been developed in order to deal with the above mentioned artifacts. Actually, the used algorithm is a modified version of a previously developed routine designed by the author to properly face missing fringe regions in shadow moiré fringe patterns [7]. Before coming deeper into the core of the algorithm, it is useful a brief introduction regarding the Fourier theory.

A periodic function can be expressed as the sum of sines and/or cosines of different frequency and amplitude (the Fourier series). A function of finite duration (like an image) can be expressed as an integral of sines and/or cosines, multiplied by proper weighted functions (the Fourier transformation). Nowadays, several transformations are coming into use in several applications such as image restoration, coding, pattern description and so on; nevertheless, the Fourier transformation maintains an important role in the image processing. The Fourier transformation of a continuous function f(x,y) of real variables x and y is defined as:

$$\Im[f(x,y)] = F(u,v) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x,y)\exp[-j2\pi(ux+vy)]dxdy \quad (1)$$

The u and v variables are thought as frequencies variables; in fact, being $\exp[-j2\pi kx] = \cos(2\pi kx) - j\sin(2\pi kx)$, where $k = u,v$, the F(u,v) function is composed by the sum of infinite sines and cosines. The inverse transformation is definite as follows:

$$\Im^{-1}[F(u,v)] = f(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} F(u,v)\exp[j2\pi(ux+vy)]dudv \quad (2)$$

The Fourier transformation can be seen as a reversible change of coordinates in which the image is represented; during the transformation the information is totally preserved. It is like if in the Fourier space the image is observed from a different point of view. The extension to the discrete case is easy, and one has to speak now about Discrete Fourier Transform (DFT) or Fast Fourier Transform (FFT). The new system of Fourier coordinates in which the image is represented allows one to operate in the Fourier space and manipulate these data, in order to measure particular frequency components in the space domain or to properly modify its values.

The proposed algorithm operates in three steps: during the first step the corrupted regions are located. This operation is accomplished in different ways depending on the artifact nature; each way has a different degree of automation. It is possible: 1) to manually design the mask by simply using Boolean operations, 2) to operate on the histogram function of the image in a manual or totally automatic fashion, or 3) to locally process the image in a semi-automatic way, recognizing which gaps are related to corrupted regions, having previously informed the software on which kind of gray level steps are supposed to belong to corrupted zones and which are not. Actually, the designed mask is not a binary mask, but a labeled mask, which allows us to manage each region of bad values independently by each other ones. The result of the mask creation, regarding the corrupted C-scans previously displayed in Fig.1.a and b, is shown in Fig.2.a and b, respectively.

Fig.2.a and b – Created masks to highlight the corrupted regions

After having recognized the artifacts, the next step is represented by the filling operation of the highlighted regions by coherent values; this is performed by properly operating on the spectrum and on the space information. The corrupted values related to each bad region are first replaced by constant values. The proper gray level is calculated by locally processing data on the borders of each zone. At this point, a low-pass filter is designed by using the spectrum of the C-scan so manipulated. The filter is designed by thesholding the image spectrum. The threshold value is calculated by statistical considerations on a region of the spectrum characterized just by noise. Applying the so designed filter on the image, and retaining the information related to the masked data, it is possible to further replace the bad regions with values smoothly varying in passing from the masked to the not masked areas; but the boundary zones are still far from being well connected and joined together. Now, the iterative space-frequency procedure starts. Before performing this operation, a new low-pass filter is designed, by following the criteria above exposed. The image is then iteratively Fourier processed; for each iteration, the following operations are accomplished:

- low-pass filtering of the current image;
- logical application of the mask to the result, in order to locate and isolate the values filling the previously highlighted bad regions;
- image processing of the temporary result. Each region is properly scaled using the information retrieved on its boundaries to accelerate the convergence of the algorithm.
- upgrade of the current image. Using the mask, the current image is upgraded for what concerns the masked regions. In other words, previous values of those regions are substitute with the new ones. These operations will continue until a proper condition is reached, that is - in few words – until the mean variation of the gray level value per pixel, considering the current and the previous image during the algorithm iteration, is lower than a pre-defined value.

The result of the iterative procedure on the C-scans displayed in Fig.1.a and b, on the ground of the created masks that one can see in Fig.2.a and b, is shown in Fig.3.a and b, respectively.

After being restored the continuity of the image, the high frequency noise is removed in the last and third step. This operation is performed by designing - in the way above described - a low-pass filter and applying it on the final result of the iterative procedure now exposed. The final results, regarding the usual C-scans (Fig.1a and b), are shown in Fig.4.a and b.

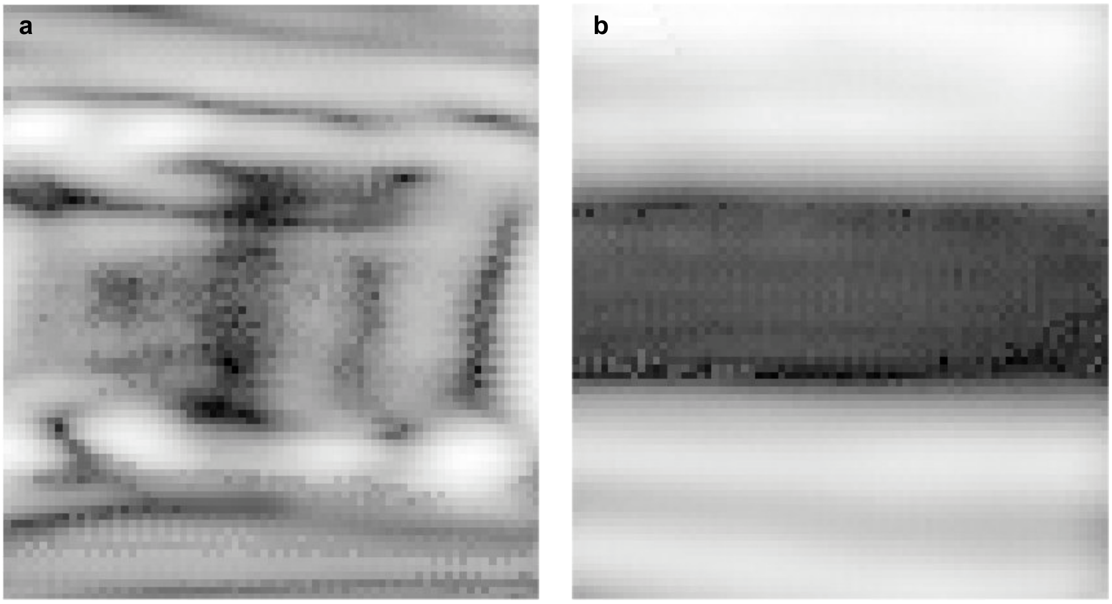

Fig.3.a and b – Result of the space-frequency iterative algorithm to fill the bad regions

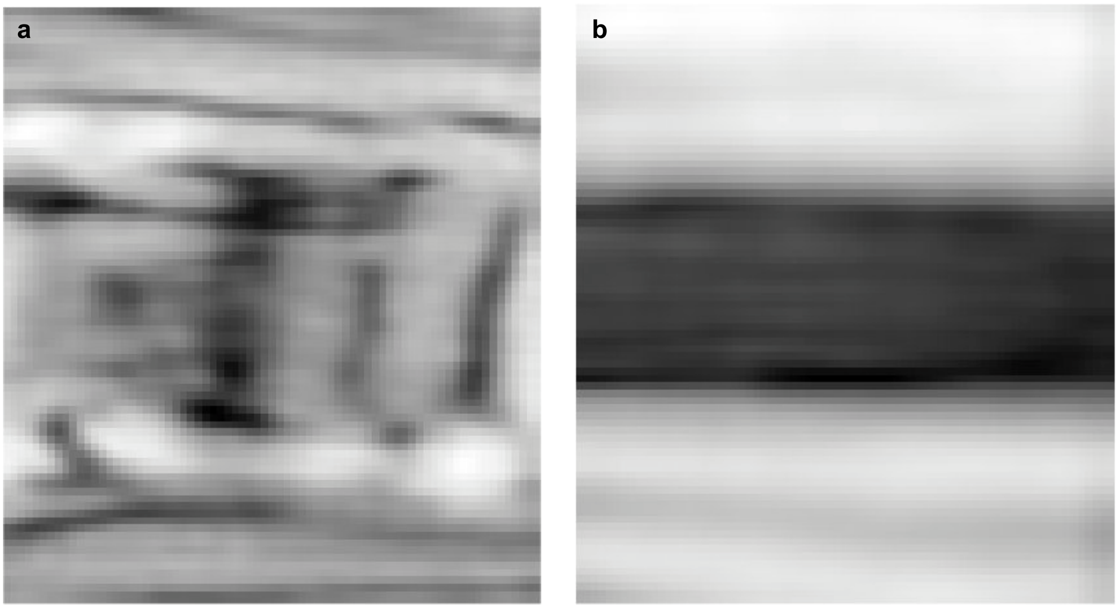

Fig.4.a and b – Final results of the algorithm application

4. Results of the algorithm application and discussion

In the Fig.5, an application of the described algorithm on a real ancient painting is shown. The object of the investigation was a six hundred year old painting coming from a private collection (Fig.5.a - the scanned region is highlighted by a white box). The single-sided C-scan, performed by using the 200 kHz couple of transducers (Fig.5.b), showed various corrupted regions due to the really weak received signal and to the correlation operation involved in the energy measurement. Nevertheless, it was possible to enhance the contrast of the scan by applying the proposed algorithm and the result is displayed in Fig.5.c. The darker regions of the scan represent zones of the interface between the mahogany support and the ground that are characterized by weak adhesion or incipient delamination. The difference in the received energy between a sound and a defective region was about 30 dBs.

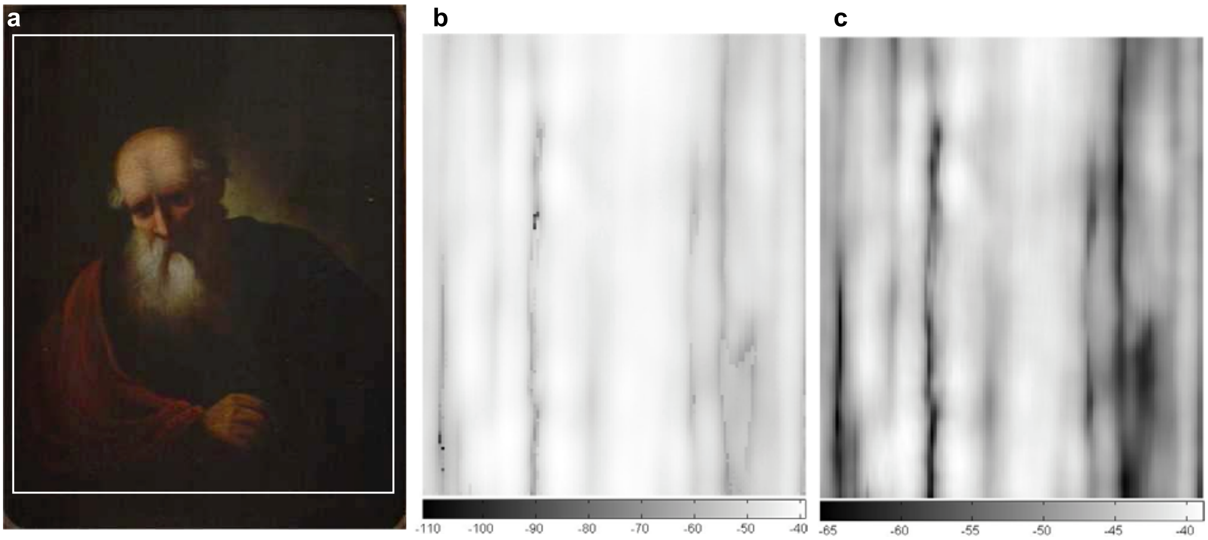

Fig.5.a, b and c. a) Investigated wooden painting, b) original C-scan and c) enhanced C-scan

5. Conclusion

In this work, an algorithm based on the use of the Two Dimensional Fast Fourier Transform has been presented. The aim of the algorithm is to enhance the contrast of ultrasonic air-coupled C-scans. Due to the inherent weak signal received and to the burdensome procedure in processing the information of the received wave packet, these scans present corrupted regions that highly influence the quality of the measurement. The algorithm proposed allows us to detect the presence and the location of these corrupted regions and to profitable fill them with coherent values; this is accomplished by iterative operations in the frequency and space domains, in detail above described. The performances of the algorithm have been proved by means of real and home made wooden panel paintings. The objective of the research was to check the state of conservation of these art works and to localize the presence of defects such as delaminations and cracks between the layers that constitute the structure. Results on real and home made models have been presented; they show that the routine developed is fit and effective to the present application.

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