SENSITIVITY ANALYSIS OF TEST SIGNAL WITH RESPECT TO THE TRANSDUCERS POSITION IN ULTRASONIC NDT TESTING

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ABSTRACT

The state of the art of non-destructive acoustic tests provides information on the type of transducers and on the number of tests to be conducted in order to obtain satisfactory mappings on the surfaces of the elements under test, to trace shape and size of defects, both in Test Method for Transparency (with emitter and received transducer arranged in corresponding points on two opposite surfaces) either by using Tomographic Methods [3].

The main problem in this type of analysis is related to the strong attenuation of the signals in reception, which often have amplitudes of the same order of magnitude of noise. For this reason, in this work we use cross-correlation between emitted chirp signal and the relative received signal, that allows to assess significant amplitudes.

For this paper one refers to tests using Test Method for Transparency applied on a grid of points. The aim of this work is to assess how the relative position between the transducers and the defects affect the accuracy of the results obtained. To implement this study, we use orthogonal chirp signals. The study is performed using a specimen of steel of dimensions (34×135×8) mm³ with three defects consisting of holes of 1 mm diameter with different depth. To do the simulations we used the commercial finite element software COMSOL in the frequency domain.

In a second phase experimental verifications will be made to verify the obtained results and to tune the model. The instrumentation is as follows: function generator NI PXIe-6251 (NI PXI-1042 chassis), TiePie Arbitrary Wave Form Generator, Handyscope HS5 and Krautkramer SEB 10 KF-3 @10MHz double probes.

Key words: Acoustic NDT, piezoelectric transducers, Finite Element Method, linear Chirp

1. Introduction

The ultrasonic inspection technique is one of the most common non-destructive testing techniques employed in the steel industry due to the favourable propagation conditions that such material ensures. In particular, ultrasonic NDT is extensively exploited in verifying the quality of forged steel to be used in the energy industry.

Among NDTs, Ultrasonic Tests are based on the principle that the propagation of any wave is affected by the medium through which it travels. Thus, changes in measurable parameters
associated with the passage of a wave through a material can be correlated with changes in physical properties of the material itself [1, 2]. Elastic waves propagate in different manner through solid materials and cavities, thus enabling fault detection. 

Due to media dissipative effect, elastic waves are strongly attenuated, so it is important that the emission cone of the signal source is less divergent as possible. If \( d \) is the diameter of the emission source and \( \lambda \) is the wavelength of the wave, for \( d >> \lambda \) the wave is emitted with a not very divergent cone. As \( \lambda \) is in inverse proportion to frequency \( f \), it is understandable how high frequency signals enable waves to be highly directional [1].

In this paper, the potentiality of an approach to ultrasonic investigation involving the analysis in the frequency domains of several parameters associated with acoustic waves propagating through the material has been analyzed.

The metallic sample is inspected by means of ultrasonic Test Method for Transparency in order to verify the presence of internal irregularities or flaws. In particular, in the transparency technique a mechanical impact is applied on the surface of the metal element and a receiver is located in the opposite surface of the structure. The technique is based on the detection of elastic waves and their conversion into electrical signals. This is accomplished by directly coupling piezoelectric transducers (accelerometers) on the surfaces of the structure under test. Sensors are coupled to the structure by means of a couplant fluid. Usually for this type of measures on metal material, the applied excitation frequency ranges from 2,25 to 20 MHz (we use 10MHz), and its propagation velocity in a mean is a function of the elastic characteristics of the mean itself (Young modulus, and Poisson coefficient) and of its density. Dishomogeneities in the structures (cracks, degraded regions, etc.) produce variation of the propagation velocity; reflections, refractions, partial absorption and attenuation of the wave. The analysis of such phenomena can be useful to evaluate the presence of such dishomogeneities.

Having available techniques that are able to detect millimetric flaws also in small metal objects ensures confidence about the quality of the forged part: the object is accepted or rejected according to the result of the ultrasonic inspection.

Due to the attenuation of the acoustic signals that occurs in materials in receiving the signals become comparable with the noise. So the standard method that use impulsive signal do not always assure the inspection capability requested in order to assess faithfully the integrity of the sample.

It is therefore very important to develop procedures that are able to guarantee contextually a signal-to-noise ratio (SNR) and a resolution sufficiently high to allow the detection of defects of the specified dimensions.

The amplitude of the echo signals of a chirp pulse compression system can be increased without changing the amplitude or duration of the transmitted signals if matched nonlinear pseudochirps (square waves) are used instead of linear chirp signals. Nonlinear frequency modulation has the additional advantage of reducing the side-lobe levels of the compressed pulses. The use of pseudochirps leads to a decrease of hardware effort for the signal generation hardware.[4]

To accomplish this aim, in the present work a Test Method for Transparency is presented for the ultrasonic NDT of a sample small metal \( (8\text{mm} \times 34\text{mm} \times 135\text{mm})[1,2,4,5] \). The main idea underlying the proposal is the exploitation of wide-bandwidth high-energy excitation signals to enhance both the resolution and the penetration of the ultrasonic inspection with respect to the standard pulse-echo technique [4,5]. In this work we use the transparency testing that requires access to two surfaces because the receiver is in the opposite surface of the transmitter. The first pulse that arrives at the receiving transducer will be diffracted around the periphery of the eventual defect.

For the simulations the Finite Element Software COMSOL Multiphysics has been used to model a 3D three-dimensional model of a metal sample, already built and tested in laboratory, in order to calibrate structural parameters.
The shapes and sizes of the defects are similar to those of the metal samples that are used to calibrate the instrumentation as required by standards ASME (American Society of Mechanical Engineers) for the calibration blocks of welding ferritic [11].

The paper is structured as follows: in Chapter 2-nd the main features of the Test Method for Transparency scheme of ultrasonic NDT application are explained, while Subsection 2.1 describes in detail the linear chirp signal properties.

In Chapter 3-th The FEM model developed with the commercial software COMSOL multiphysics which has been developed and the elaborations results are presented. While in Chapter 4th we will discuss the use of the feature of cross-correlation with the signal emitted by the piezoelectric transducer and the signal of receiver transducer.

In Chapter 5th we will describe the used method to evaluate the sensitivity of results respect to the position of the transducers and the position of the defects and we will discuss how you assessed the sensitivity of the test results for different positions of the nodes of the lattice points of application of waves relative to the position of the defects.

Finally, in Chapter 6-th some conclusions and perspectives are drawn.

2. Test Method for Transparency scheme of ultrasonic NDT

The sample is not a prototype for which the exact nature of the material of the specimens is not certain: it is presumably Iron (5900 m/s). Therefore first tests were made to characterize the material of the specimen under examination. Using ultrasonic techniques on healthy sample were made tests for the determination of important ultrasonic transfer characteristics: the speed of transmission and the attenuation of signals in the specimen, applying ultrasonic signals on the two surfaces A and B, appropriately mapped.

The presence of the defect is localized in three-dimensional coordinates in the volume \( V(x, y, z) \), through the directions of two-dimensional localization of the defect on the two surfaces: A \((x, y)\) and B \((y, z)\).

On the specimen were made of the holes of 1mm diameter and different depth, using a precision drill to simulate the presence of defects. In Fig.2 the positions of the holes that simulate defects are shown.

To characterize the material and evaluate the attenuation and the speed of transmission of signals have been made of the preliminary tests, using the pulse signals with the standard pulse-echo technique.
A transducer Olympus RM-V203 of 10 MHz with a signal generator 500 PR Pulser-Receiver have been used. It consists essentially of a cylinder of piezoelectric material capable of converting an electrical pulse applied to one of the base surfaces in an acoustic wave that propagates in the direction of the axis from the opposite surface.

The Panametrics Model 500PR Pulser-Receiver is a high quality, general purpose ultrasonic pulser-receiver. It features full performance in a compact package that is small enough to easily fit into a briefcase. The front panel controls of the Model 500PR permit easy adjustment of pulse height, waveform damping, receiver gain, and pulse repetition rate, as well as operating
mode (pulse-echo or through transmission). A high pass filter selectable via a rear panel switch can be used to change excitation pulse recovery time and reject low frequency noise. The Model 500PR weighs only 1.25 Kg in a 61 x 163 x 213mm package.

![Image of echo signal on surface A](image)

**Fig. 4: Echo signal on surface A**

In the handbooks for iron theoretical value of the wave propagation velocity is 5900 [m / s] and the cast iron it oscillates between 3500 ÷ 5600 [m /s]). The flight time for the specimen thickness of 0.008 [m] was calculated as:

\[ t = \frac{\text{specimen thickness}}{\text{wave propagation velocity}} = \frac{0.008[m]}{5333[m/s]} = 1.5 \, [\mu s] \]

Examining the applied signal and the reflected signals of the sample healthy, free of defects, through the criterion of the thresholds, was measured actual transmission speed of the specimen 5333.33 m / s and an attenuation of 5.7 Np/m.

![Image of echo signal on surface B](image)

**Fig. 4: Echo signal on surface B**

### 2.1 Linear chirp signal

On the basis of the tests performed it was verified that the output signal is too attenuated and comparable with the noise, so that it is detectable only if suitably amplified. It was therefore attempted to study in what way you can reduce the problem. It is therefore thought of using a linear chirp signal selecting signal duration less than the flight time [7 8].

The chirp signal is one of the most diffused waveforms used in pulse compression applications. There exist several types of chirp signals [13]. Here, we exploit the linear one described by the expression: \( s(t) = \alpha(t) \sin (2\pi f_0 t + \Phi(t)) \),
where $\Phi(t) = \frac{B}{2T}t^2 - \frac{B}{2}t$ is the quadratic phase term and $\alpha(t)$ is a windowing function that modulates the amplitude of $s(t)$ and that is non-vanishing only in the interval $t \in [0, T]$.

Due to the characteristic of linear chirp, the amplitude modulation also acts as a frequency band-pass filter. The matched filter’s impulse response, that is the reference waveform used to correlate the output data $d(t)$, in the simplest cases equals $s(t)$ itself, but here we consider the chance to vary the windowing function: $\Psi(t) = \beta(t) \sin (2\pi f_0 t + \Phi(t))$. For the simulations we have generated the signal using the Matlab Commercial Software. The signal amplitude was of 250 V e the frequency range was 9MHz ÷12MHz. The cross-correlation function of $s(t)$ and $\Psi(t)$ gives the approximation of the unit pulse, $\delta(t)$. The simplest window is the rectangular one, but it is well known that exhibits high sidelobes. To reduce the Leakage phenomena and the sidelobes of the signal spectra, we use an appropriate window for the matched filter: Tukey elliptical window [9,12]. This choice proved to be the most convenient simulation, since the transmitted energy is easily maximised without requiring optimisation of the coded excitation signal. The reduction of sidelobes is then accomplished through the processing of the received signal.

![Fig. 5: Linear chirp signal](image)

3. The FEM COMSOL Multiphysics Model of the 3D metal sample

The propagation of an elastic wave through the metal sample has been simulated by means of the Finite Element Method (FEM), using COMSOL Multiphysics [4]. The instrument is based on piezoelectric transducers technology, and it can be arranged to generate ultrasonic waves in the metal sample under test. Therefore the FEM model developed with the commercial software COMSOL multiphysics which has been developed and the elaborations results are presented.

In the examined cases, the instrument has been simulated as made up of one excitation transducer and one receiving transducers located in the front and back sides of a sample, as shown in Fig. 6. The acquisitions are repeated for each position of the excitation.

We used a mesh of points 4x24, for a total of 96 points to avoid having to take account of the effects of edge, the points were spaced 5 mm from 5mm x =5mm and y = 10mm.

For the simulations the Finite Element Software COMSOL Multiphysics has been used to model a 3D three-dimensional model of a metal sample, already built and tested in laboratory, in order to calibrate structural parameters.

The model has been solved in the frequency domain to reduce the number of variables of the problem with respect to an analysis in the time domain, in order to decrease the size of resolution matrices, the time processing and the computational errors. We used COMSOL Multiphysics using analysis: 3D Acoustic-Piezoelectric Interaction, Frequency Domain interface commercial software COMSOL. This type of analysis carried out the study of the distribution of the magnitude of the acoustic pressure field, in the frequency domain, with a Multiphysics Analysis...
that combines the analysis of the sound pressure in the frequency domain, Mechanics of Solids, the Electrostatic and the interfaces of piezoelectric devices. The material of which the transducer transmitter and receiver are composed, is (Lead Zirconate Titanate PZT-5H) and has the following characteristics: Density: 7500 [kg / m^3]; for this type of material the software COMSOL associates of 3x3 matrices to the following characteristics, since their values change in function of the direction: Density 7500[kg/m^3], Speed 3000[m/s], while for the Elasticity [Pa]; relative permittivity and coupling coefficients [C/m2] the software COMSOL provides full features. In Fig. 6 the Comsol geometric model of the metal sample with the transducer transmitter and receiver for the case of healthy path of acoustic waves is shown. The transducer emitter and receiver were modeled with two cylinders with dimensions equal to those of the used commercial transducers.

In the drawing made with COMSOL, are shown the holes, which simulate defects cylindrical with diameter of 1 mm, made in the following points:
- Point defect 21: x = 30 mm y = 13 mm, depth 6 mm
- Point defect 22: x = y = 65 mm 15 mm, 8 mm deep
- Point defect 24: x = 120 mm y = 15 mm, 4 mm deep

Moving the transducer emitter and receiver on the contact surface and maintaining their axes always aligned, it is possible to repeat the tests for each position, therefore the acoustic waves emitted by the emitter transducer will follow a path generally different. In particular in the presence of a defect relative to the positions of the transducers associated in the points 21, 22, and 23, the receiver transducers detect different signals, compared to the signals received in correspondence of paths salts. See Fig. 7.

Fig. 6: Comsol geometric model of the metal sample
Given the simplicity of the model, were examined different types of mesh between those standards Comsol as shown in Fig. 8. Through an optimization study the mesh to define the most suitable size of the tetrahedral elements was chose: "finer mesh" of COMSOL.

In the transducer and in the sample COMSOL software allows you to view the distributions of several variables: such as displacement or pressure for each value of the frequency. For example in the following Fig.9 and Fig.10 the distribution of the displacement for a frequency value of 9.995e6Hz is shown.
4. Cross-correlation

We use of the feature of cross-correlation with the signal emitted by the piezoelectric transducer and the signal of receiver transducer to map the defects of the sample. In fact with the simulations it was verified that, even for thicknesses of the order of millimeters, using the linear chirp signal it could detect the different paths, due to the presence of faults, with a precision greater than in the case of signals imprinted type impulsive. This is due to the possibility to transmit a greater rate of energy using the linear chirp signal in reception of signals thereby obtaining more distinguishable from noise [10]. Therefore we will discuss how you assessed the sensitivity of the test results for different positions of the nodes of the mesh points of application of acoustic waves, relative to the position of the defects. To evaluate the sensitivity of results respect to the position of the transducers we performed a series of tests using a mesh of points more detailed (with dimension of square elements of the mesh of 0.5mx0.5mm). Therefore we calculated the maximum value of cross-corelazione between the input signal and the output signal previously obtained with Comsol software. To convert signals in the time domain, the signals obtained in frequency domain by Comsol were post-processed: anti transformed with the IFFT.
In the Fig. 11 the input voltage signal and the output voltage signal are shown for a measuring point relative to healthy path without defect.

Therefore we constructed the maps of distributions of this feature in the case in which the transducers are exactly positioned in correspondence of the defects shown in Fig.12.

After we constructed the maps for four cases where the mesh of the measuring points is offset by ±0.5 mm along the axis x and y, and ±0.707 mm in the direction parallel to the diagonal of the sample.

As the, Fig.13, Fig.14 e Fig.15 show, the comparison between the map obtained by positioning the transducers exactly in correspondence of the defects and the maps relative to the four examined cases latter, detect the presence of defects with an position error which, however, is less than 0.5 mm on either the x and y axis.
5. **Sensitivity of results respect to the position of the transducers**

To quantify the sensitivity of the mapping of the feature as a function of the distance of the position of the transducer with respect to the exact location of defect, we used a simple method to evaluate objectively the sensitivity of obtained results. For the three cases examined we were taken into account the points of measurement with the transducer away from the defect to the values: [0.5 0.707 1.5  2 2.12]. For each of these values of the distance, the average value of cross-correlation to the measured points has been calculated. The Fig. 16 shown the trends of the cross correlations from the transducer position in correspondence of the defect.

For the three defect examined, we calculated have been taken into consideration the points of measurement with the transducer away from the defect to the values and for each of these values of the distance, it is calculated the average value of cross-correlation to the measured points. No reported in the figure are the trends of the cross correlations from the transducer position respect to the defect in proximity of the defect, for a maximum distance of 2.12 [mm].
6. Conclusions

In this paper, the experimental results have not been reported as we had proposed to make, because the description of the methods and FEM models used are already in itself a considerable part of the discussion, for which the experimental part is meant to develop it in a later work. We have verified the positioning of the transducers relative to the position of the defects can modify the results even when it is made a priori analysis to optimize the mesh of the measuring points required according to the size die defects. Using the same mesh with square elements of equal size, but with the nodes that are not centered on the defects, you can make an error of assessment on the coordinates of the position of the defect, which may not exceed the amount equal to the size of the mesh optimal previously adopted in function of the size of the defect.

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7. References


