STUDIES OF THE EFFECT OF SURFACE ROUGHNESS IN THE BEHAVIOR OF ULTRASONIC SIGNALS IN AISI-SAE-4340 STEEL: SPECTRAL AND WAVELETS ANALYSIS

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The present work focuses in the characterization of ultrasonic signals through spectral and wavelet analysis; in particular the effects of surface roughness in AISI-SAE 4340 steel samples. A Tektronix Oscilloscope model TDS 1002 was utilized for the signal capturing and the signal characterization was performed within the Matlab 7.0 environment. Steel samples of AISI-SAE 4340 were prepared through mechanical methods with different roughness in the front face, and such roughnesses were measured using a Mitutoyo Surfest-211. The samples were inspected applying the Contact Pulse-Echo of normal pulse method, using probes of 5, 7.5 and 10 MHz, with an equal diameter to 0,375 inches. Special care was taken with the number of measurements per sample were taken with each probe in order to observe the possible effects of the measurement process on the signals. This was done with the purpose of avoiding possible measurement induced errors, and therefore improving the repeatability of the signals being produced. The analysis of the signals through both methods (spectral analysis and wavelet analysis) allowed determining and establishing quantitatively diverse characteristics of the samples. Very particular behaviors where detected in this type of steel, which varied according to the frequency of the probe. The complementation of both methods contributed to a more complete evaluation and characterization of the samples. This study therefore serves as a possible initial step for true quantitatively characterization of materials with different internal and surface defectology. Further studies in this area have already commenced and their findings will be presented in future articles.

KEYWORDS: Ultrasonic testing, surface roughness, NDT, Spectral Analysis, Wavelet.

INTRODUCTION

Currently, industry produces components and parts with several degrees of surface finish (the surface finish depends on the fabrication process). Depending on the material, it can also be expected for the surface finish to be affected during its operational lifetime. This article focuses on the effects of surface roughness on direct contact pulse-echo ultrasonic testing performed on AISI/SAE 4340 steel. This type of steel is frequently used in components and parts that undergo high levels of dynamic stress, such as shaft, lever axis, torsion bars, cast for plastic injection, etc.

When performing ultrasonic testing by direct contact, the surface's roughness of the sample material is an important fact to consider. A high surface roughness may reduce the energy transmitted to the sample by the ultrasonic pulse, therefore reducing the amplitude of the measured signal [1, 2]. As a result, the capability of discontinuity detection, such as cavities, cracks, etc., is reduced to an extent. If the surface roughness is less than the wavelength of the sample pulse, noise will be generated and the transmitted pulse amplitude will be reduced, but the shape of the pulse will be kept. On the other hand, if the variation in the surface is larger than the wavelength of the sample pulse, the pulse will be distorted. This means that any variation of the surface condition of a sample material will affect the ultrasonic pulse used in the inspection. Therefore, it is important to evaluate changes in the pulse due to a series of roughness that may approach that generated in a component during its operational lifetime, in this way generating a based for comparison.

The study of a signal in the frequency domain represents a fairly common practice within Non-destructive testing (NDT). Once a specific attribute of the material to be studied is chosen, the changes in the frequency spectrum resulting from the variation of such attribute can be analyzed. This type of analysis has been amply utilized in the NDT of different materials, among them steel alloys [2, 3]. While the time domain representation of the signal can be obtain directly from the measurement instruments, the frequency domain representation can be obtain through Fourier analysis [3]. Spectral analysis has obtained, in recent years, wide acceptance as a mathematical technique used in the evaluation of defectology and characterization of materials, in particular when utilizing ultrasonic testing [4, 5, 6, 7, 8, 9]. When an ultrasonic pulse propagates through a material, it interacts with its micro-structural components (grain, inclusions, cracks, etc.). These interactions can be quantitatively correlated to their sizes and geometries, as well as to the wavelength of the incident pulse. This interaction can be evaluated as a change in the frequency allocation of the transmitted echo (spectral analysis of the echo), or of the signal of noise (spectral analysis of noise) [1, 2, 3].

Thavasimuthu et al. [10] stated that for the direct contact pulse-echo method, the effects of the surface roughness over the amplitude of an ultrasonic signal, with the presence or absence of discontinuities has not been adequately discussed in available literature. The before mentioned systematically studied stainless steel samples, improving the estimation of the size of the discontinuities within the sample (when compare to traditional methods). This was achieved by the indexing of specific signal characteristics in the time and frequency domain. Thavasimuthu's group noted that when the surface roughness increased, the smaller discontinuities offered an improved reflectivity at low frequencies, and that the larger discontinuities performed similarly at higher frequencies. It was also observed that although one would expect that the reflected signal's amplitude varied based on the discontinuities size, the reflected signal's amplitude was similar for both small and large discontinuities. Therefore a multi-frequency approach was recommended in order to properly estimate the correct size of the discontinuities. Similar studies of the effect of surface roughness have been made for the immersion method with similar conclusions [11]. On the other hand, Nicoletti and Sorli [12] measured the effects of surface roughness based on the ultrasonic reflection coefficients generated by the transmission method. This technique monitors linearly the surface topography of the steel samples with different roughness levels, through both immersion and direct contact transmission methods, providing in this way an easy and secure method for distinguishing a "bad" or "good" surface roughness.

Wavelet Analysis (WA) is a relatively new approach for studying transient non-stationary signals. The advantage of this mathematical approach is that the signal can be analyzed simultaneously in both time and frequency domain through the application of scaling factors. Petculescu et al [13] and others have used Wavelet transform in order to improve upon ultrasonic spectral analysis, by performing de-noising of the signals and other methods available when applying wavelet transform. WA thus can supplement the observed frequency domain variation due to surface roughness and permit a more complete evaluation of the steel patterns under study.

The present article intends to evaluate the ultrasonic signals obtained from AISI-SAE 4340 steel patterns, with four distinct levels of surface roughness in the frontal face. The range of surface roughness variation was limited to 12 micrometers since it is the usual range encountered in a component's surface finish deterioration during its operational use. The direct contact pulse-echo method was utilized for obtaining the signals which were then digitalized and process with Matlab 6.5. The spectral and wavelet analysis of each one of the signals allowed thus establishing quantitatively the variation of diverse parameters, which served in the characterization and evaluation of the surface roughness effect.

METHODOLOGY

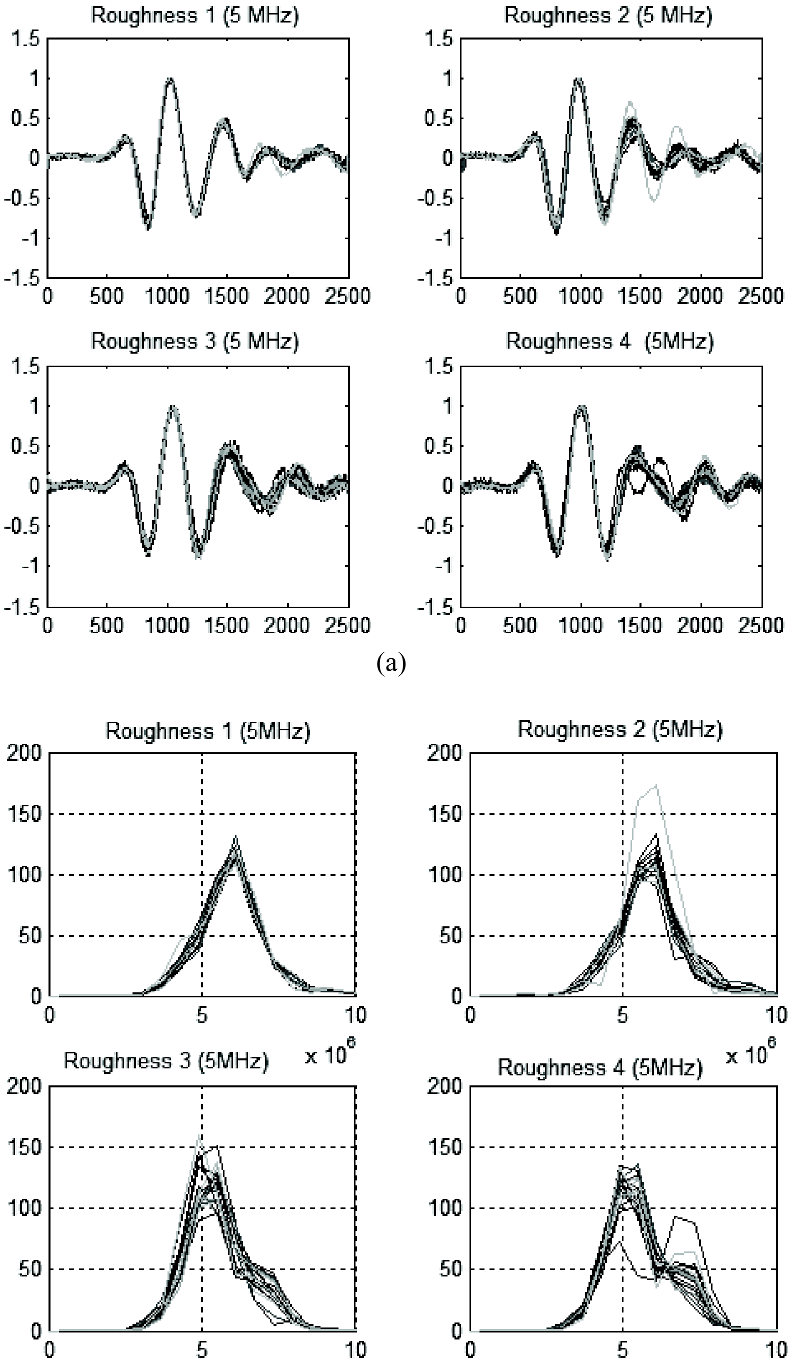
AISI/SAE 4340 steel patterns were constructed, with 300 x 120 x 20 mm dimensions and different surface roughness in the front face. The surface roughness of the front surface was achieved by mechanical brushing and corroborated by using a Mitutoyo Surfest-211. The back wall roughness of all steel patterns was kept constant at 0.5 micrometers. The values of the surface roughness of the different patterns are 0.5, 2, 8, and 12 micrometers, and will be referred to in this article as roughness R1, R2, R3 and R4 respectively.

A Krautkramer ultrasonic flaw detector model USN52L was used in order to apply the well known direct contact pulse-echo was use. The method consists of transmitting ultrasonic wave pulses through a sample material and capturing the echoes reflected from a discontinuity or the back wall of the test sample. Three probes with different central frequency where used in the experiment in order to appreciate the effect of the probe's frequency on the results, the chosen probe's frequency were 5 MHz, 7.5 MHz and 10 MHz, all with 0.375 inches of diameter. A Tektronix TDS 1002 oscilloscope was used for signal capturing and digitalization. 2500 points samples were capture with a sampling period of $4x10^{-9}$ seconds ($2.5x10^{8}$ sampling frequency). The third back wall echo was capture since it provides a cleaner pulse representation without the noise generated by the initial pulse transmission into the pattern.

In order to properly process the signals, 20 samples were taken for each steel pattern. This was done in order to corroborate the repeatability of the measurement and better understand the effects of measurement induced error. The samples where then normalize and their DC offset removed since amplitude variation was not the main focus of the experiment but the possible variations on the frequency and time domain. Additionally the samples were horizontally centered with each other in order to remove pulse capturing shift. Finally the pulses or samples were process through standard spectral analysis and wavelet analysis. An 11 level decomposition was performed on the wavelet analysis using the Daubechies (DB) 5 wavelet. The signal processing was accomplished with MATLAB version 6.5.

RESULTS

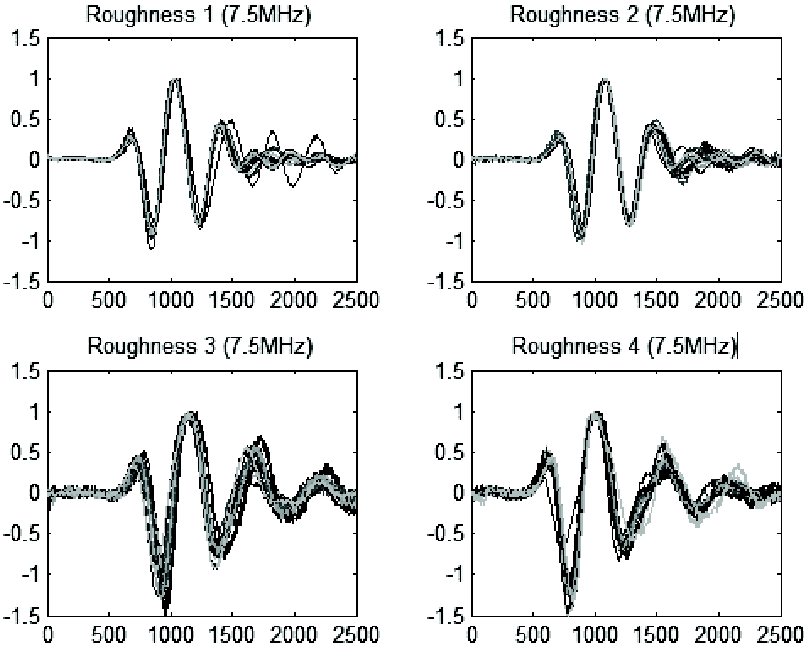
The following figures illustrated the signals and their spectral and wavelet analysis results:



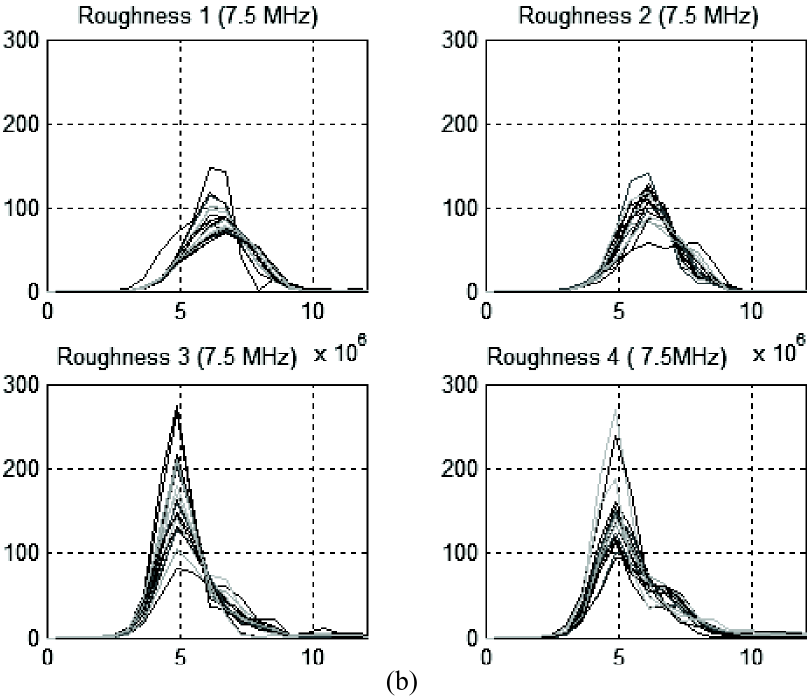
(a)

(b)

Figure 1 a) Signal capturing of the back wall echo using a 5 MHz probe
b) Spectral of frequency of the back wall echo using a probe of the 5 MHz

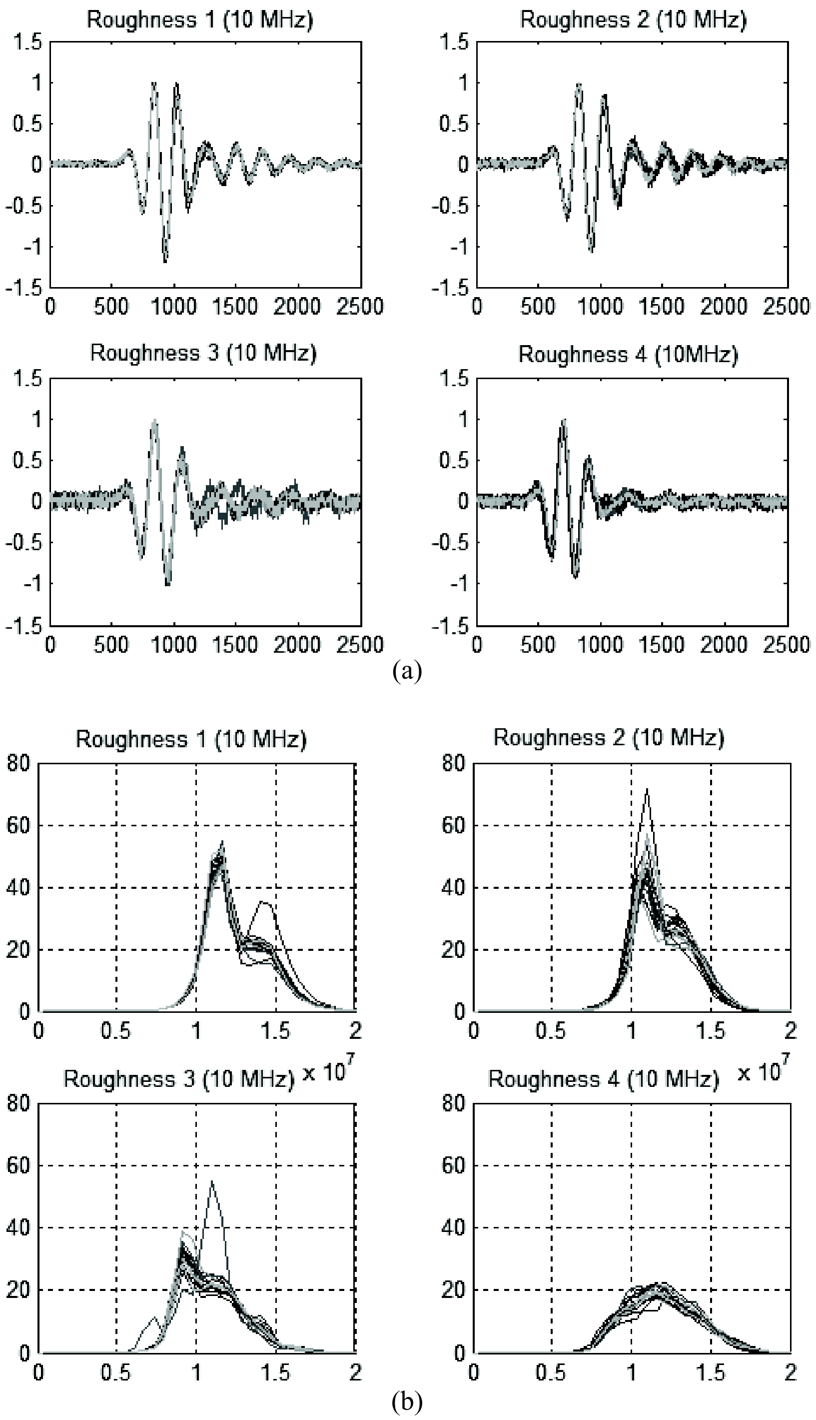


(a)



(b)

Figure 2 a) Signal capturing of the back wall echo using a probe of the 7.5 MHz.
b) Spectral of frequency of the back wall echo using a probe of the 7.5 MHz



(a)

(b)

Figure 3 a) Signal capturing of the back wall echo using a probe of the 10 MHz.
b) Spectral of frequency of the back wall echo using a probe of the 10 MHz

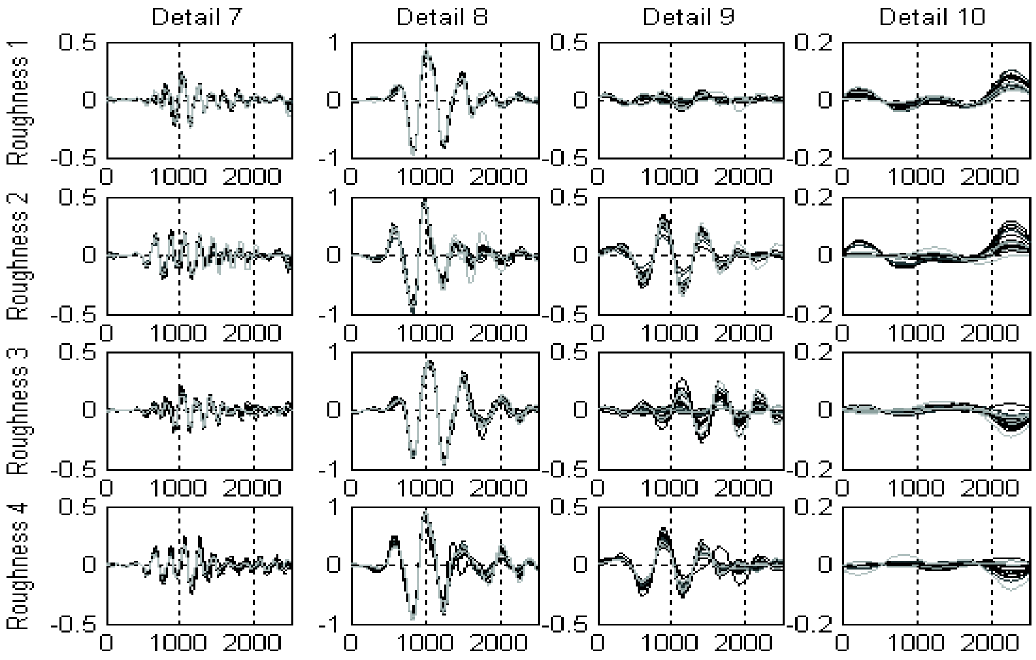


Figure 4 Wavelet analysis of the back wall echo using a probe of the 5 MHz

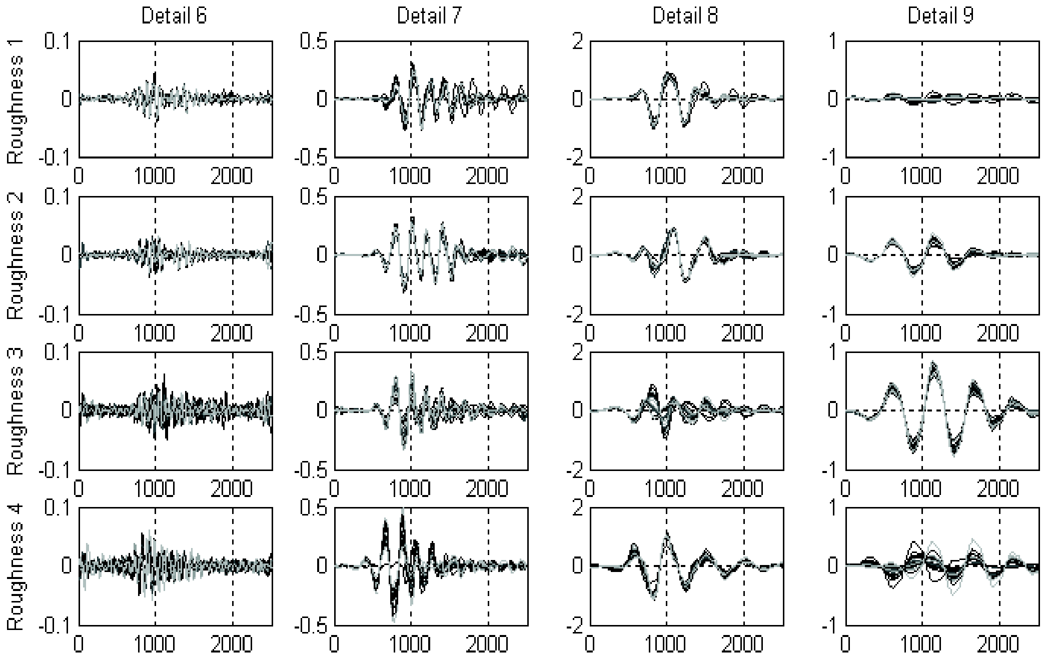


Figure 5 Wavelet analysis of the back wall echo using a probe of the 7.5 MHz

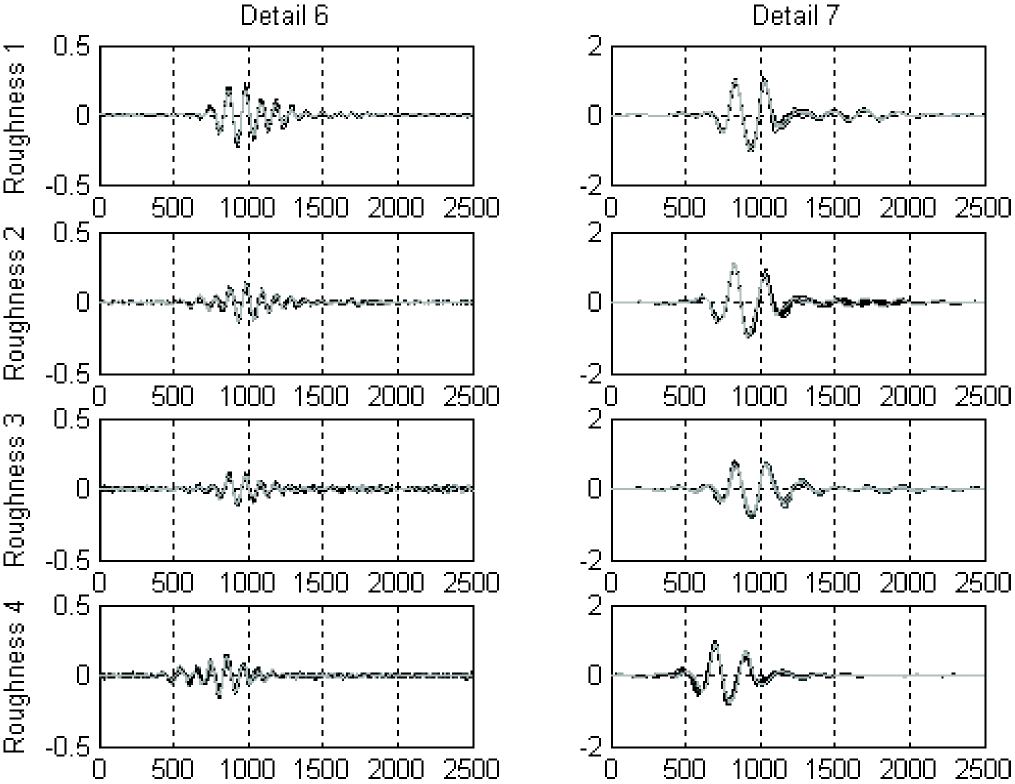


Figure 6 Wavelet analysis of the back wall echo using a probe of the 10 MHz

DISCUSSION

Figures 1 a) and b) correspond to the signals introduced by the 5 MHz probe, in time and frequency domain. Each graph shows a total of twenty pulses obtained from each one of the evaluated patterns, in order to illustrate the repeatability of the measurements and their influence in the observed variations. No clear determination of the effects of surface roughness can be observed in the time domain. Meanwhile the spectral analysis shows that a clear influence in the energy distribution of the signal exists. In general a energy peak can be found near 6 MHz and a tendency to shift to lower frequencies when then surface roughness is increased can also be observed**.** It should be noted that from these samples it seems that surface roughness has little or no influence in the energy's amplitude. For the case of R3 and R4 we note that the energy divides into two sections, which is especially apparent for the R4 case. In Figure 4 shows details 7 thru 10 of the wavelet decomposition for the same signals. From these representations it can be noted that detail 9 and 10 offer the best opportunity for a classification of the signals in their different surface roughness. Detail 9 shows a clear difference between R1 and the rest of the signals, insinuating that the introduction of surface roughness can be readily determine. In detail 10 the form of the signal, especially towards the end of the graphs, illustrates a clear difference between roughness R1 and R2, and the remaining roughness R3 and R4. It seems that for the 5 MHz frequency that while this first level wavelet analysis reveals some interesting features of the signals and permits in some measure classify the signals by their surface roughness, it is the standard spectral analysis which permits a more clear classification scheme.

For the case of the 7.5 MHz probe, Figure 2 a) and b), it is noted that the repeatability of the measurement is somewhat less consistent than the one observe for 5 MHz, although no major distortions are noted among the signals in general. In this case the spectral analysis shows clear variations no only in the position of the peak frequency but also in the amplitude, which in combination allow for a strong classification scheme. The resulting plots show that an energy peak is present around 6.5 MHz. The wavelet decomposition details 6 thru 9, seen in Figure 5, also reveal a tendency for shifting towards the left side axis, particularly for the cases of details 6, 7 and 8. Meanwhile detail 9 offers a clear differentiation of the first three surface roughnesses R1, R2 and R3. Surface roughness R4 seems so have a distortion effect for the case of detail 9 which insinuates that only for a certain range of surface roughness detail 9 can be useful for classification.

The case of the 10 MHz probe signals varies from that of the previous two probes. The time domain signals observed in Figure 3 a) illustrates that the second significant peak of the signal can be readily utilized for surface roughness classification since a clear relation can be observed between its amplitude and the surface roughness. On the spectral side, Figure 3 b), two relative maximums can be noted, which change seem to superimpose one over the other with the increase of surface roughness, achieving a maximum around 11.5 MHz. Also a diminution of the maximum occurs as the surface roughness increases, to the point of having a strong effect in the spectral representation of R4 when compared to the others. On the wavelet analysis side, seen on Figure 6, a shifting effect is observed for the particular case of R4, while the others seem to preserve similar characteristics.

CONCLUSIONS

Surface roughness plays an important role in ultrasonic testing analysis since it distorts the measured signals. The ability to properly identify the distortions introduced to the signal by surface roughness allows for a much clearer determination of a discontinuity's size and geometry. Both spectral and wavelet analysis provides some insight in methods for properly classifying the surface roughness present in the material being studied. It was shown that there is no clear advantage of one method one over the other, and even a direct time domain inspection can reveal the existence of surface roughness (as seen on the case of the 10 MHz probe). It is also important to mention that special care must be given at the moment of capturing the echoes and that multiple measurements necessary for a proper evaluation, all this with the objective of increasing resolution and sensibility necessary for this type of evaluation.

The experiments and analysis presented represent a first step of an in-depth study of the possible contributions of spectral and wavelet analysis in combination for determining internal discontinuities and abnormalities in steel alloys. These experiments and analysis show encouraging results and further studies and observations should definitely be undertaken.

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