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MEASUREMENT OF STRESS WAVES PROPAGATION VELOCITIES IN SOLID MEDIA USING WAVELET TRANSFORMS

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ABSTRACT

Leakages in pressurized tubes generate stress waves that propagate along the walls of these tubes. These waves can be detected by accelerometers or by acoustic emission sensors. In order to determine the localization of the leakage one must measure the arrival time in the case of transient signals or the phase shift between two stress waves signals when they are stationary as well as their correspondent velocities. The distances between the sensors and the leakage are a function of the arrival time or the phase shift and the velocities. An experimental set up is being used to measure velocities of pulse type stress waves generated by a small steel sphere. The objective is to confirm that the theoretical values are being obtained by our measurement technique. The accuracy in the determination of these velocities depends on several factors like: sampling frequency that defines the time domain precision. Also, the signal to noise ratio of the electronics and the background noise determine how well we can separate the true signal from the noise thus the resolution in determining the velocity. No analog filters proved to be adequate for this task and the use of decomposing and denoising techniques based on Wavelet transforms proved to be fundamental and it is the main contribution of this work. Furthermore, the correct choice for the amplifier gain and for the accelerometer sensibility are important factors.

1. INTRODUCTION

Leakages in nuclear and industrial pressurized tubes and piping can cause great safety and economical burden as well as environmental problems. To overcome these problems, many researches are being conducted to develop methods to detect the existence of leakages and in some of these works the aim is to locate the leakage as well. In our present research the goal is to find techniques which will allow the localization of the leakage and hopefully the classification and sizing, Boaratti [1]. This paper presents a procedure to measure the velocities of stress waves propagating in a solid metallic media.

When a pressurized tube leaks, this leakage generates stress waves, which propagate through and on the tube walls. These waves can be captured by accelerometers and acoustic emission sensors attached to the external surface of these tubes. In order to determine the localization of the leakage one must measure the arrival time in the case of transient signals or the phase shift between two stress waves signals when they are stationary as well as their correspondent velocities. The distances between the sensors and the leakage are a function of the arrival time or the phase shift and the velocities.

According to Hunaid et alii [2], the propagation velocity of signals in water pipes could be calculated by using either time-of-flight method or the cross-correlation method. In the time-of-flight method, the propagation velocity is estimated based on the difference in arrival times of transient signals measured at two locations that are at a known distance apart. In the cross-correlation method, the propagation velocity is estimated based on the time lag between coherent continuous stationary signals measured at two points that are at a known distance apart. In both cases, the signals are generated using a source at a known location.

In the case of measuring arrival for transient signals by time-of-flight method one can read directly from the time domain waveform in the data acquisition instrument. However, when the stress waves signals are stationary random signals with noise the appropriate technique are either spectral cross correlations or higher order cumulants cross correlations.

According to Junger et alii [3], Kolsky [4] and Dunegan [5] there are more then one type of stress wave propagating in an infinite solid in a given moment. They report the existence of at least three types of waves, namely: *extensional waves* which velocity for steels is of the order of 5200 m/s; *shear waves* which velocity in steels is about 3200 m/s and flexural waves which velocity is smaller and dependent of material properties and geometry. Actually, Kosky [4] describes the presence of a longitudinal wave, in which the motion is along the direction of propagation, also called *dilatation wave*. He also describes another type where the movement is transverse and parallel to the wave front named *waves of distortion*. In addition, for a given geometry and boundary conditions, solution to the stress wave equation produce another wave, the so called *surface waves* which discovery is credited to Lord Rayleigh, being named *Rayleigh waves*, Keller et alii [6], Kolsky [4] and Rulf [7]. Junger et alii [3] report the existence of two modes of propagation in the axial direction of the wall of a cylindrical shell, one corresponds to flexural waves and the other to the longitudinal waves. One should notice that there is some ambiguity in the nomenclature among different authors. In the following sections we will try to correlate different definitions and propose a common nomenclature. At this point we define as *longitudinal waves* as being those waves which vibration is in the same direction as of the propagation direction and as *transverse waves* for those which have the vibration perpendicular to the propagation direction.

In this present paper we describe the determination of the propagation velocity of stress waves in tube walls using the time-of-flight method between two sensors. Since we have three types of waves propagating with different velocities through the tube wall, the main problem is to separate which part of the signals corresponds to each of the three types of propagating waves namely: longitudinal, transverse and Rayleigh waves. The precision and the resolution in determining these velocities depend on several factors such as: signals sampling frequency which determines the resolution in the time domain, the signal to noise ratio which determines the capacity to recognize which type of wave is embedded in the signal and consequently the resolution in the amplitude domain. To control the signal to noise ration one can only use the amplifier gain and the selection of sensors sensibility. Pos processing the signal using de-noising techniques based on Wavelet Transform is fundamental due to the transient form of the signals.

2. THEORETICAL BASIS

The general governing equation for stress waves propagating in an infinite, isotropic elastic media is given by Kolsky [4]:

$$\rho \frac{\partial^2 \Delta}{\partial t^2} = (\lambda + 2\mu)\nabla^2 \Delta \qquad (1)$$

Where ρ is the density, λ and μ are the Lamé's constants and Δ is the sum of the three normal strains, also called dilatation. From equation (1) using irrotational condition one can define the velocity c_1, and under no dilatation condition one can define the velocity c_2 as follows:

$$c_1 = \sqrt{\left[\frac{\lambda + 2\mu}{\rho}\right]} \tag{2}$$

$$c_2 = \sqrt{\frac{\mu}{\rho}} \tag{3}$$

For an infinite medium, c_1 is named "longitudinal velocity", and c_2 is called "transverse velocity". The surface velocity resulting from Rayleigh's solution for a semi-infinite medium produces the following surface wave velocity c_R where k_1 is the ratio between the surface velocity and the transverse velocity and ν is the Poisson's ratio :

$$c_R = k_1 c_2 \tag{4}$$

$$k_1^6 - 8k_1^4 + \left(24 - 16\left(\frac{1-2\nu}{2-2\nu}\right)\right)k_1^2 + \left(16\left(\frac{1-2\nu}{2-2\nu}\right) - 16\right) = 0 \tag{5}$$

Junger [8] develops the formula to calculate the longitudinal velocity, c_p (named as compression velocity) and the transverse velocities, c_s (named as shear velocity) for a thin shell tube which are:

$$c_p = \sqrt{\frac{E}{\rho(1-\nu^2)}} \tag{6}$$

$$c_s = \sqrt{\frac{G}{\rho}} \tag{7}$$

Where *E* is the material Young's modulus and *G* is the bulk modulus. They are related to the Lame's constant by the following expressions:

$$\lambda = \frac{E\nu}{1-\nu(2\nu-1)} \tag{8}$$

$$\mu = \frac{\lambda}{2\nu} - \lambda \tag{9}$$

$$G = \frac{E}{2(1+\nu)} \tag{10}$$

Fuller [9] and Xu [10] also demonstrate the use of equation (6) to calculate the longitudinal velocity for thin cylindrical shells.
Using the above equations, waves velocities are presented for different materials in Table 1 together with their typical material properties.

Table 1. Calculated theoretical waves velocities.

Material	ν	ρ (Kg m^{-3})	E (Pa)	λ (Pa)	μ (Pa)	c_1 (m/s)	$c_2 = c_s$ (m/s)	k_1	c_R (m/s)	c_p (m/s)
Steel	0.29	7800	198 10^9	1.0598 10^{11}	7.6744 10^{10}	5767.6	3136.7	0.9258	2904.1	5265
Iron (cast)	0.28	7700	105 10^9	5.2202 10^{10}	4.1016 10^{10}	4175.3	2308	0.92426	2133.2	3847
Aluminum	0.33	2700	70 10^9	5.1084 10^{10}	2.6316 10^{10}	6197.8	3122	0.93202	2909.7	5394
Hard rubber	0.4	1100	2.1 10^9	3.0 10^9	7.5 10^8	2022.6	825.7	0.9422	778	1508

3. DESCRIPTION OF THE EXPERIMENT

In our experiment we adopted the time-of-flight methodology to determine the velocities of an impact wave propagating in the wall of the tube. For this we constructed the experimental

setup. This setup is constituted of a 3 m long steel tube with 60 mm diameter and wall thickness of 2 mm, characterizing in this manner a thin cylindrical shell suspended at its ends by thin threads. To measure the impact and propagating waves, two accelerometers were used. Both were fixed using magnets on the tube wall. The first was fastened at "A" position located at 0.75m from the left end of the tube and the second was positioned at "B" position at 1.5 m or at "C" position at 2.25 m from the left end of the tube.
To generate the impact pulse a small steel sphere was used. This sphere was dropped down in a vertical free fall on the "A" position using an appropriate device to avoid external interferences and to guarantee the repeatability of the impact.
Several different impacts using the sphere were accomplished dropping from different heights and for different positions of the accelerometers in relation to the original configuration described above. Combinations of different gains in the charge amplifiers and sampling frequencies of the signals of 1MHz and 5MHz were also used. The objective was to verify the influence of these parameters in the quality of the acquired signal and consequently the capacity of measuring the different velocities of the signal.

4. RESULTS

We described below the main results obtained. We see below in the illustrations that it is possible to determine the longitudinal and transverse velocities of the waves propagating in a solid surface. Here specifically on the wall of a steel cylindrical shell. However we will notice that depending on the conditions chosen for the test the results can be better or worse depending upon which velocity one wants to observe.
For all cases the height of fall of the steel sphere was maintained constant at 33cm.
The computational tool for determination of the arrival instants of the propagating waves and of the time differences, we used the function SPTOOL and WAVELET included in MATLAB.
After denoising using Wavelet transform, in Fig. 1 we can observe the arrival of a wave (b) in $1.105\ 10^{-3}$ s at the accelerometer 2 resulting in a $\Delta t = 0.218\ 10^{-3}$ s, where Δt is the time differences of arrival of the impact and the propagating waves at the accelerometers. The distance between the two accelerometers is 0.75 m. This results in a speed of 3440 m/s. This speed when compared with the theoretical speed presented in Table 1 corresponds to the transverse wave speed. Notice that we know that a longitudinal wave exists and is propagating in the wall of the tube. However it does not appear in Fig. 1. Observe now in Fig. 2 point (b) that for the same test conditions with a larger gain in the charge amplifier of the accelerometer 2 we see a wave arriving in $1.027\ 10^{-3}$ s, which results in a $\Delta t = 0.143\ 10^{-3}$ s indicating a speed of 5245 m/s, which compared with the speeds of the Table 1 corresponds to the speed of a longitudinal wave. In the same Fig. 2 we found a point (c) in $1.104\ 10^{-3}$ s that results in $\Delta t = 0.22\ 10^{-3}$ s and consequently in a transverse speed of 3409 m/s.
Two facts should be noticed. Firstly, the increase of the amplifier gain improved the relationship between the signal of the propagating wave and the high frequency background noise generated by the electronics, by external electromagnetic radiation and other sources. Thus, the correct choice of the amplifier gain and of the accelerometer sensibility is an important factor in the capacity of detection of the longitudinal wave, which in this case presents a smaller intensity since the direction of the impact and the working direction of the accelerometer privileged the transverse waves. Secondly, in Fig. 2 we notice a peak between the points (b) and (c) that would take us to believe in the arrival of the transverse wave at this instant. However, this peak is related to the arrival of a new maximum of the same

longitudinal wave that propagates faster than the transverse wave. This effect is intensified when we increase the distance between the accelerometers as can be seen in Fig. 3, where we have now two maximums of the longitudinal wave arriving before the first transverse wave.

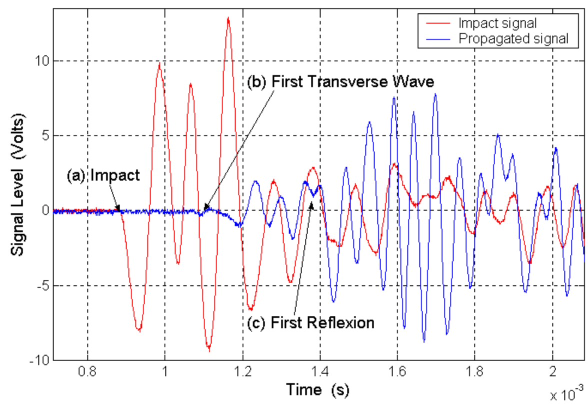

Figure 1. Distance between the two accelerometers of 0.75 m, 1Msamples/s and gain of 10 mV/ms^{-2}

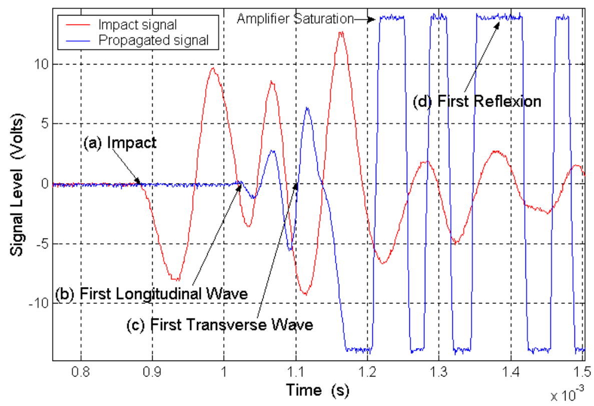

Figure 2. Distance between the two accelerometers of 0.75 m, 1M samples/s and gain of 316mV/ms^{-2}

In Fig. 3 as well as in Fig. 1 and in Fig. 2, we notice that the increase of the amplifier gain in the accelerometer 2 signal warrants a higher certainty in the determination of the instant of the longitudinal wave arrival. In order to decrease the effect of the high frequency noise, to facilitate a better visualization of the propagating waves, we filtered the signals using the Wavelet de-noising technique, represented by the red line in the Fig. 3. However, we notice that if the signal is very small, that is, it is of the order of the measure equipment sensibility, the use of the de-noising to eliminate the high frequency noise by itself did not allow us to recover the signal of the propagating wave in this point. In this case, the determination of the arrival instant of the longitudinal wave is not possible since it is lost among the signals. See in Fig. 3a point (b) that we estimated the arrival instant of the first longitudinal wave but we cannot be totally sure even zooming in the image. However, in Fig. 3b with a higher amplifier gain, the determination of this instant is assured.

In Fig. 1 point (c) and in Fig. 2 point (d) we observe the existence of singularities in the signals measured during the time interval that begins at 0.44 10^{-3} s and it finishes at

0.54 10^{-3} s after the impact time happened in the "A" position. These singularities are related to the first reflection of the longitudinal wave at the left end of the tube. This wave is arriving together at the accelerometer 2 with the direct waves coming from the impact at the "A" position. In Fig. 3a and Fig. 3b, points (d), we also found these singularities. Since in this case the accelerometer 2 is at the "C" position closer to the right end, we have reflected waves arriving from this end as well as reflected waves arriving from the left end, what explains a larger number of singularities in the measured signal.

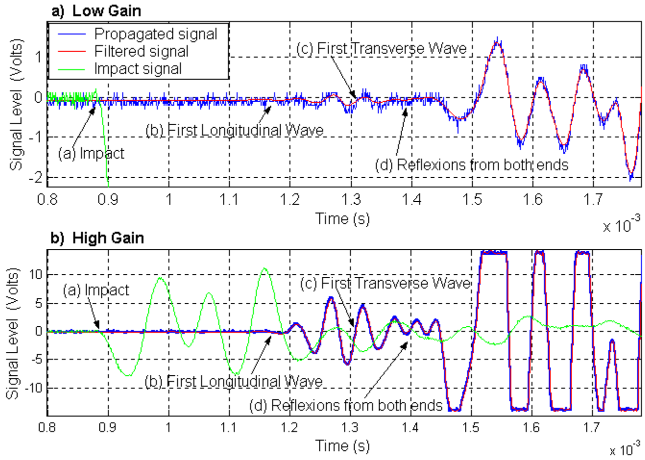

Figure 3. Distance between the two accelerometers of 1.5 m, 1M samples/s and (a) gain of 10mV/ms^{-2} (b) gain of 316mV/ms^{-2}

We observe that the increase in the sampling rate, in this case, did not improve the resolution in time, as expected, since with 1M samples/second it was already sufficient. What we observed was degradation in the signal-to-noise ratio, because with higher sampling rate more high frequency noise is acquired with the signal. We observe in this manner there is a commitment between the time resolution and the signal-to-noise ratio, which together with the choice of the amplifier gain are crucial to assure the detection of the waves propagating on the surface of the material.

With the objective of verifying the influence of the impact force in the propagating waves detection capacity, we decreased the height of the falling steel sphere from 33 cm to 16,5 cm., diminishing in this way the energy of the impact. It was verified that using adequate amplifiers gains for the accelerometers and repeating the same other previous tests characteristics, the results found in the shape of the signals as well as in the duration and speeds measured are identical. Again, the accelerometer sensibility and the amplifiers gain showed to be the two major factors important during the measurement. When we talked about the accelerometer sensibility we should take into account the way we fix it on the surface of the material, which can interfere in the repeatability of the experiment as well as in the decrease of the sensor sensibility. Such conditions are under study and we will present it in future works.

To verify that the relationship between the accelerometer working direction and its fixation mode on the material surface is a important factor in the detection capacity, since it can privilege a transversal signal in relation to a longitudinal signal, we set up the accelerometers in two configurations: In the first configuration the accelerometer 1 was maintained at the "A" position and the accelerometer 2 was fastened at the right end of the tube aligned with its axial axis. In the second configuration both accelerometers were fastened each of them at one of the ends of the tube, aligned with its axial axis. One of them at the right end and other one at the left end from the "A" position where impact took place. In both situations the longitudinal wave arrival instant visualization was now possible, resulting in both cases a speed of 5357 m/s. Here again we verify that besides the way the sensor is fastened, the fixation direction is also important to improve the signal that we want to measure.

3. CONCLUSIONS

As we verified, the method was shown to be efficient for the stress waves longitudinal and transverse speeds determination. However, care should be taken in the selection of the accelerometer sensibility, its working direction and the amplifier gain, so that the signal-to-noise ratio is large enough so we can identify the stress waves arrival instants. The working direction affects the sensibility of the measurement since it can privilege a longitudinal wave instead of a transverse wave, or vice versa. The sampling frequency is also a factor that should be taken into account in the improvement of the time precision. However if the precision is already enough, the increase of the sampling frequency did not show to improve the quality of the signal. The use of filtering tools, such as the de-noising Wavelet, with the objective of removing the high frequency noise was an efficient tool. Wavelet allows to improve the measured signal to noise relationship and to enable a better determination of the wave arrival time.

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