Microcracks UHMWPE assessment using the wavelet transform

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Abstract. Previous studies have indicated that one of the main problems in the prosthesis inserts of ultra-high-molecular-weight polyethylene UHMWPE, is the destruction apparently by delamination, due to wear. Fatigue in polymeric materials is the leading cause of failure due to the cyclic or random application of the load in a component. Damage inspection techniques, such as ultrasound and microtomography, are used to detect internal microscopic damage. However, the high cost of these two techniques allows us to propose new inspection methods. The present work shows a simulation of signal processing techniques, as well as the use of the wavelet transform to obtain a representative image of the possible emergence of microcracks. The results show a low-cost test of the acoustic impedance contrasts, which represent the changes in velocity propagation in the medium, which translates into cracking.

1. Introduction
The research on the emergence of microcracks in materials such as ultra-high molecular weight polyethylene (UHMWPE), is a constant concern in the field of wear fatigue in tibial inserts [1-2], in particular, a case of Mexican phenotype was focused in the design of an experimental apparatus for testing a total knee prosthesis [3] and in the development of new methodologies for modelling and analyzing using Finite Element Method (FEM) of the contact zones into the metallic femoral insert and UHMWPE tibial insert [4]. There are methods used for the detection of cracks in tibial inserts of UHMWPE [5]; none of them gives accurate results of the behaviour implants. The factors related to the emergence of cracks, microcracks and fractures have been investigated from several perspectives such as their formation, detection, autonomic repair, as well as detection techniques such as non-destructive tests (NDT) [6], visual inspection tests, optical coherence tomography, microscopy, deformation measurements, ultrasonic testing, acoustic emission, conventional X-ray radiography, computerized X-ray microtomography and thermal/infrared techniques [7]. The structural damage of the polymer can be classified into macro and microscopic levels. Microscopic damage at scale, such as micro-fissure occurs as a result of the impact and internal tensions. The microscopic damage is the leading cause of failure of the material due to its nature of being detected and due to the induced fragmentation of the structure leads a reduction of mechanical properties such as strength, rigidity, and dimensional stability. In general, fatigue in polymers is the main cause of failure of the inserts due to the cyclic or random load application.
The principal method used to detect micro-crackling is the computerized X-ray microtomography, which allows identifying and characterizing internal failures, gaps, delamination, microcracks, as well as having a better spatial resolution [8]. However, its drawback is in its high cost.

This work combines several signal processing techniques known as ultrasonic pulse-echo [9-13], adaptive noise cancellation [14-19], cross-correlation [20-22] and the Wavelet Transform [23-28] to propose a new methodology to visualize non-invasive and low cost the emergence of microcracks in UHMWPE inserts. This work is organized as follows: Materials and Methods shows the steps used to implement a signal processing applied to the pulse-echo technique; The results exhibit simulating echo signal, which represents the possible emergence of a crack by acoustic impedance contrast on one specimen of UHMWPE; Discussion and conclusions present the limitations of this method and its contribution to this research.

2. Materials and methods

The echo peak signal delivered by the piezoelectric transducer is generated using MATLAB® and represents the acoustic impedance contrast found within the UHMWPE material. In this signal is added a noise signal that is also generated using MATLAB®. To eliminate all the noise and to be able to reconstruct the signal, different algorithms in signal processing techniques are used. The echo signal processing is shown in Figure 1.

![Figure 1. Method of processing the echo signal.](image)

The adaptive filtering process is seen in Figure 2. The input signal $x(n)$ represents the sum of the original signal and the noise signal $d(n) = x(n) + N(n)$. The noise signal that is added to the signal of interest is processed using the adaptive filter of the minimum mean square error (LMS). The filter LMS
algorithm is a stochastic gradient development by Widrow and Hoff. The output of the adaptive filter $y(n)$ represents the multiplication of the weight vector $w(n)$ by the reference signal $N'(n)$.

$$y(n) = w^T(n)N'(n) \tag{1}$$

The adjusts of the coefficients and the weight vector to minimize the error signal $e(n)$ is given by filtering algorithm. The estimated error is given by the difference of the desired echo signal and the output filter.

$$e(n) = d(n) - y(n) \tag{2}$$

The $w$ vector is calculated iteratively until the error is minimized.

$$w(n + 1) = w(n) + \mu x(n)e(n) \tag{3}$$

The size of the step $\mu$ help to the stability and speed of convergence for the adaptive algorithm LMS and to obtain the reconstructed output signal $Vo(n)$.

Then it is applied the cross-correlation to the $Vo(n)$ signal with a known waveform $s(n)$ to determine the similarity between the two signals and improve the noise signal ratio, Figure 3.

$$r_{Vs}(\tau) = \sum_{n=-\infty}^{\infty} V_o(n)s(n - \tau) \quad \tau = 0, \pm 1, \pm 2, ...$$

**Figure 3.** Cross-correlation of the reconstructed signal with the known signal.

In order to have a profile of the output signal $V1(n)$ of Figure 3 and display the signal in time-frequency simultaneously, the Wavelet Transform is used, which through the help of variable length windows, which is it adapts to changes in the signal frequency of interest, a signal representation is obtained by translating $\tau$ and scaling of the wavelet mother $\psi(t)$ selected and multiplied by the signal $V1(n)$ as shown in Figure 4.

$$CWT(s, \tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} V1(t)\psi \left( \frac{t-\tau}{s} \right) dt \quad s \neq 0$$

**Figure 4.** Wavelet transform of the $V1(n)$ signal with the mother wavelet.

### 3. Results

Analysis with wavelets allows scaling and shifting of the wavelet where precise low-frequency information is required, with shorter regions where high-frequency information is needed. This representation shows the places where there is an acoustic impedance contrast, which represents the emergence of a microcrack in the material.

The signal obtained at the Rx receiver of the ultrasonic transducer is shown in Figure 5, which contains three echoes with noise and is created using MATLAB®, with a sampling frequency of 1000 Hz. The first echo (Figure 5(a)) represents the direct signal that travels on the surface of the material and is generated by the ultrasonic transmitter Tx. The second echo (Figure 5(b)) constitutes the possible emergence of a crack resulting from discontinuity in the propagation medium, and the third corresponds to the background echo. The amplitudes of the echoes (Figure 5(c)) depend on the intensity of the signal resulting from the contrasts of acoustic impedance in the medium. Finally, show the results of the proposed methodology of the adaptive filter using the LMS algorithm, the cross-correlation and Wavelet Transform are shown in Figure 5(d).
Figure 5. Time-frequency analysis of the wavelet modulation with the signal: (a) Original signal with echoes and noise; (b) Adaptive filtering of the original signal; (c) Cross-correlation of the filtered signal; (d) Wavelet transform of the reconstructed signal.
4. Discussions
The signal processing technique that we have described has proven to be a solution to obtain a representative image of the possible acoustic impedance contrast inside the UHMWPE. As already mentioned, is a new method non-invasive that display the wear due to fatigue, a better option is the microtomography computed X-ray. This technique obtains fine cuts using a sweep to build a 3D image. This mapping gives information about the micro-cracks in the subsurface. However, this effective technique has a higher cost. The new methodology proposal has certain limitations of posit detail image, However, demonstrates successfully the possible detection of the occurrence of microcracks using a mixed of signal processing and the use of the wavelet transform at a low cost.

5. Conclusions
In this work, it was proposed to simulate the pulse-echo technique, which is one of the highly proven ultrasonic techniques. The results of this work show an essential contribution in the possible detection of the emergence of microcracks in the UHMWPE with the help of signal processing techniques and the use of the wavelet transform, resulting in an image in time and frequency. In the image obtained it can visualize the contrasts of acoustic impedance and the depth where the microcracks appear. With the propagation velocity of the longitudinal wave in the UHMWPE and the times where the velocity changes of the medium occur, its depth can be determined.

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