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Measuring predictability in ultrasonic signals: An application to scattering material characterization

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ABSTRACT

In this paper, we present a novel and completely different approach to the problem of scattering material characterization: measuring the degree of predictability of the time series. Measuring predictability can provide information of the signal strength of the deterministic component of the time series in relation to the whole time series acquired. This relationship can provide information about coherent reflections in material grains with respect to the rest of incoherent noises that typically appear in non-destructive testing using ultrasonics. This is a non-parametric technique commonly used in chaos theory that does not require making any kind of assumptions about attenuation profiles. In highly scattering media (low SNR), it has been shown theoretically that the degree of predictability allows material characterization. The experimental results obtained in this work with 32 cement probes of 4 different porosities demonstrate the ability of this technique to do classification. It has also been shown that, in this particular application, the measurement of predictability can be used as an indicator of the percentages of porosity of the test samples with great accuracy.

Contents

1. Introduction

When scattering materials are subject to ultrasonic non-destructive testing (NDT), the ultrasonic pulse undergoes some variations that are related to the internal grain microstructure of the specimen. Each grain behaves like a scattering center, producing an echo that when superimposed on other echoes coming from other grains can even hide the echoes produced by a possible defect. Similar situations are found in other related fields such as ultrasound B-mode scans (where the grain noise is called speckle) and in radar with clutter [1].

In the literature, a wide range of solutions has been proposed to enhance the detection of small cracks or defects and to reduce (or even eliminate) the effect discussed in each of the above situations. Some of these solutions are signal averaging, auto- and

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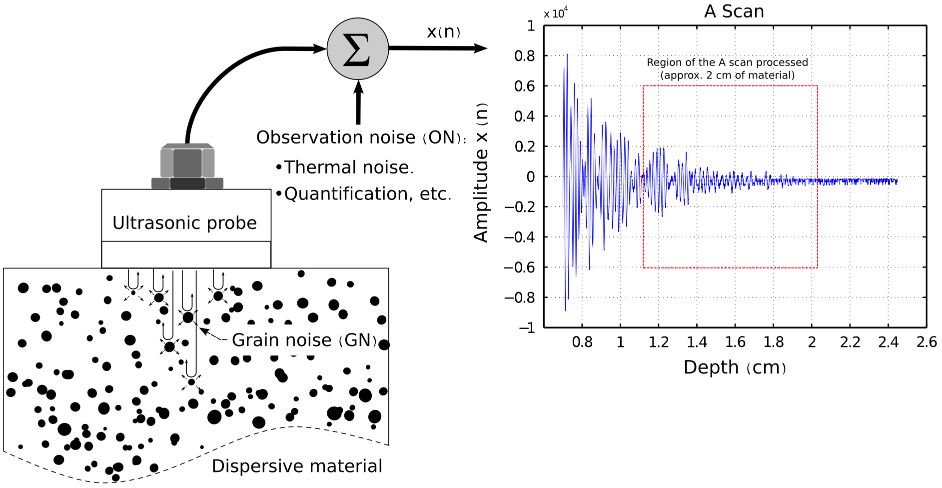

Fig. 1. Pulse-echo model of an ultrasonic inspection of scattering materials and an example of the resulting signals.

cross-correlation, matched filtering, frequency spectrum analysis [2], spectral correlation [3], and wavelet transformations [4]. The aforementioned analyses discard the information encoded in the grain noise; however, this information can be used to recognize potential differences among materials, tissues, or surfaces. This approach has been employed to characterize materials by extracting temporal signal statistics [1], the resonance frequency [5], and even the penetration depth [6]. Our work continues with this line of thought and proposes a new approach that attempts to extract information about the nature of the signal, thereby characterizing the signal modality. Signal modality characterization is a key concept of a multidisciplinary research topic that includes different concepts such as signal linearity, stationarity, and stochasticity [7]. The applications of signal modality characterization are becoming more and more relevant in signal processing and machine learning. Specifically, signal modality has been tested in the analysis of EEG data and weather information, but it has never been used in ultrasonic testing.

In order to apply signal modality algorithms to ultrasonic signals, a brief review of the typical noise sources that appear in ultrasonic inspection must be made. The vast majority of noise sources can be approximated by random processes (thermal noise, quantification, etc.), but some of the sources have a distinctly deterministic pattern (vibrations, grain noise, or speckle). Fig. 1 illustrates how coherent and incoherent noises are combined as a function of the inner material structure in a typical ultrasonic inspection of scattering materials. Measuring the predictability of the resulting signals can give information about this blend and, thus, about the material characteristics.

The remainder of this work is organized as follows. Section 2 proposes an alternative index based on higher-statistics which avoids some of the drawbacks when measuring predictability in ultrasonic signals. Section 3 describes and mathematically formulates three algorithms that are typically employed in chaos theory when studying determinism. These will be used for comparison with the proposed predictability index. All these algorithms are tested in Section 4 with a theoretical ultrasound model. In Section 5, we focus on a real ultrasonic application where different kinds of scattering materials are classified by measuring their degree of predictability. Finally, the conclusions are summarized.

2. Analysing the predictability of ultrasonic scattered signals using higher order statistics

Ultrasonic scattered signals are not simply deterministic or stochastic, but rather a combination of both [8]. Predictability can be viewed as the signal strength of the deterministic component of the time series with respect to the whole time series. A feasible alternative for characterizing the predictability of the signal is to use the correlation between points. Second-order correlation (autocorrelation) cannot give enough information about higher order interactions among parameters that govern the model that leads to the time series. Due to the complex physical interactions taking place in the ultrasonic inspection of a highly scattering material, we propose using higher order statistics to measure the predictability of the time series.

Let us model the ultrasonic register as a discrete stationary stochastic process $\{\tilde{x}(n)\}$. We can define what will be called a displacement sequence,

$$\{\widetilde{S}_m(n)\} = \{\tilde{x}(n)\} - \{\tilde{x}(n+m)\} = \{\tilde{x}(n)\} * h(n) \tag{1}$$

where m is the time delay, $*$ denotes the discrete convolution of the stochastic process $\{\tilde{x}(n)\}$ with the linear time-invariant system $h(n) = \delta(n) - \delta(n+m)$, and $\delta(n)$ is the discrete Dirac delta function.

The statistical properties of $\{\widetilde{S}_m(n)\}$ can be analyzed as a function of the statistics of the input process $\{\tilde{x}(n)\}$ and the impulse response of the filter $h(n)$, previously defined. We can obtain the 4th order cumulant of $\{\widetilde{S}_m(n)\}$ ($c_4^{S_m}(k_1,k_2,k_3) = E[S_m(n)S_m(n+k_1)S_m(n+k_2)S_m(n+k_3)]$) using filter relationships of a colored process [9]:

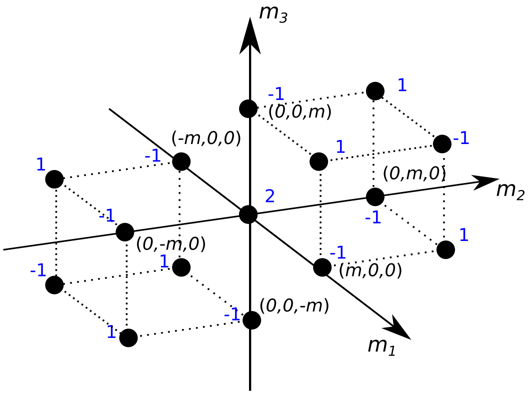

Fig. 2. Graphical representation of the 4th order cumulants of $h(n)$. The black dots indicate unique values where $c_4^h(m_1,m_2,m_3)$ is non zero (the blue numbers next to the dots indicate the amplitude of the cumulants at these lags). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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