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Nonlinear elastic wave spectroscopy with MLS perturbation signal

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Abstract

The article describes a test procedure based on the fundamental principle of Nonlinear Elastic Wave Spectroscopy. Without integration of all test stages into one automated measurement station and without Maximum Length Sequence (MLS) perturbation signal, this method would be otherwise lengthy and unfit for practical application. Material nonlinearities are elegantly quantified in a single coefficient. Furthermore, in the same measurement Eigenfrequency of the sample can be estimated with greater accuracy than in conventional methods. The method is applied on thermally loaded mortar samples.

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Keywords: Nonlinear Elastic Wave Spectroscopy (NEWS); Maximum Length Sequence (MLS); building materials; Eigenfrequency; non-destructive testing; ultrasound

1. Introduction

Acoustic waves introduced into the specimen are changed and reflected as they interact with inhomogeneities. Amplitudes of reflected echoes and resulting time of flight is in classical defectoscopic approach used to locate inhomogeneities. However, more sophisticated methods focus on information contained within the frequency domain, to estimate dynamic modulus of elasticity and other material properties.

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The purpose of Nonlinear Elastic Wave Spectroscopy (NEWS) [1,2] is to assess severity of micro-cracking from ultrasonic wave propagation. Material nonlinearities manifest themselves as resonant frequency shifts, harmonics and dumping coefficients. These methods are extremely useful for basic research. However, sweeping the whole frequency spectra with sine waveforms requires extensive test times. In practical applications is preferred Nonlinear Wave Modulation Spectroscopy (NWMS), in which additive and subtractive sideband of the two-toned excitation signal are monitored. The procedure described and tested in this article utilizes broadband pulse-compression signal, with variable amplitude to measure the change of fundamental frequency.

1.1. MLS test signal properties

Most tested systems are assumed to be linear time-invariant (LTI), in order to simplify non-destructive evaluation. Dynamic nonlinearities present themselves primarily at higher amplitudes of the signal. Therefore, the test signal should have minimal crest factor and high power spectra at specified harmonics to improve Signal to Noise Ratio(SNR) and reduce nonlinear behavior. Maximum Length Sequence with well-defined power spectra, crest factor of 1 and excellent autocorrelation property, make an ideal candidate for NDT. However, there are some general requirements if Maximum Length Sequence is to be used as an excitation signal. In order to prevent time-aliasing, the period T of sequence N must be greater than system setting time (length of expected IR) See Eq. 1. Where n corresponds to number of bits in the shift register.

$$N = 2^n - 1 \geq f_{gn} \cdot T \tag{1}$$

The second requirement concerns signal sampling. Maximum length sequence can be sampled at higher frequency as long as f_s/f_{gn} is integer. In literature, a power spectrum of MLS is often incorrectly assumed to be discrete and therefore flat. In real applications, sampling frequency f_s is greater than generation frequency f_{gn}. Such oversampling of original sequence results in power spectrum with Sinc-squared function envelope, dropping to zero at sequence's generation frequency and its harmonics. The energy in the MLS is clearly spread over the harmonics in a non-uniform manner.

Keeping this in mind, the system impulse response $h(t)$, is retrieved by cross-correlating the system output $y(t)$ with the original signal $x(t)$. Where $R_{x,y}(t)$ is the cross-correlation operator of x and y and * denotes the convolution See Eq. 2[2].

$$y(t) = L\{x(t)\} = h(t) * x(t) \rightarrow R_{x,y} = R_{x,x} * h(t) \cong h(t) \tag{2}$$

1.2. Application of MLS in NDT

Over the past two decades, pulse-compression techniques are applied in the field of NDT. Most of them are chirped signals and its aperiodic autocorrelation properties are used to obtain impulse response (IR). Other pulse-compression techniques, based on periodic pseudorandom sequences, use cyclic correlation to reconstruct IR. Compared with classical, non-correlated signals, they offer quantization noise immunity, SNR enhancement and noticeable hardware cost reduction.

In 1979, Schroeder introduced Maximum length sequences (MLS) technique for identification of LTI systems. It is now considered to be one of the most successful approaches. Shortly after that, Eysholdt and Schreiner presented a novel method for to recovering of individual transient responses at high stimulation rates. Lam and Hui were the pioneers, who suggested using MLS in the field of NDT [4,5]. MLS has been utilized for many applications, since then. In the field of electrical engineering, performance of switching power supplies is tested by MLS [6,7]. For its immunity to noise, it is used in room acoustics to test absorption coefficients of various materials [8,9]. MLS is used for piezoelectric sensors testing and to measure Modulus of Elasticity [10]. In impedance spectroscopy MLS signal is used for rapid measurement across the frequency spectra [11]. Lastly, radar technologies in nautical engineering and medical grade ultrasonic imaging instruments are all based on pulse compression signals. Techniques based on