Materials Letters 62 (2008) 3700–3703

Contents lists available at ScienceDirect

Materials Letters

journal homepag xe: www.elsevier.com/locate/matlet

Identification of highly oscillatory ultrasonic NDE echoes through evolutionary algorithm

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ARTICLE INFO

Article history:
Received 6 December 2006
Accepted 9 April 2008
Available online 20 April 2008

Keywords:
Ultrasonic NDE
Characterisation methods
Sensors

ABSTRACT

The performance of ultrasonic non-destructive estimation (NDE) is strongly dependent on the axial resolution of ultrasonic echoes. However, the highly band-pass signals commonly used in ultrasonic NDE systems pose significant limitations upon the time resolution enhancement due to seriously oscillatory cost function under classic estimation methods. In the present paper, a novel approach to improve the fidelity of sinusoidal NDE signals is presented which incorporating the pre-whitening of the non-linear least-squares (LS) cost function with the evolutionary optimization to facilitate the efficient search of global minimum. Simulation results are presented, demonstrating the feasibility of the proposed algorithm.

1. Introduction

With its advantages of non-destructive, convenience and low-cost, ultrasonic inspection technique has the potential of being applied for NDE inspection system of multilayer structures, bonded or composite materials, as several researchers have published their related works [1–5]. The ultrasound echoes reflected from tested materials can provide useful information of characteristics of target objects. Nonetheless, time domain analysis of pulse-echo signals is seriously limited by the band-pass nature of the ultrasonic transducers, which producing slowly fading and highly oscillatory response.

To characterize the patterns of overlapping echoes from a noisy received waveform that consists of attenuated and delayed reflection replicas of a known sinusoidal signal, there has been a large amount of literatures published [1–4]. Demirli and Saniie[5] developed a generalized parametric ultrasonic echo model, composed of a number of Gaussian echoes corrupted by noise, and algorithms for accurately estimating the parameters. Daewon Kim[6] proposed a model based approach using the least mean square (LMS) and the expectation maximization (EM) algorithm to classify the NDE ultrasonic signals. However, these Gaussian model-based approaches may not be suitable for the system using the highly band-pass signal where global searching of the global minimum will be seriously hindered by the strongly oscillatory and multimodal least-squares (LS) cost function. There are also some attempts concerning the problems induced by highly band-pass signals.

Manickam [7] proposed a gradient-based approach based on alleviating the oscillation of the signal's non-linear least-squares (NLS) cost function by allowing the amplitude to be complex valued. Nonetheless its performance may be affected by the precision degradation of the initial estimates under complex-valued amplitudes. Wu [8] dealt with the problem by adopting the relaxation-based scheme and initial estimation refining. However, both methods need the number of effective echoes as a priori, which is difficult, if not impossible, for many practical applications. Another drawback is the relative heavy computation burden contained.

Due to its immunity to local maximum problems that arise with a multimodal likelihood function, evolutionary algorithms (EA) has found extensive applications in different fields such as automatic control, adaptive filter and artificial neural networks [9]. In this paper, a novel method based on pre-whitening [10] of the likelihood function and the evolutionary algorithm is presented to tackle the difficulties caused by the highly oscillatory signals and thus facilitate the global search of the resulting highly non-linear problem. Moreover, to remove the dependence on the prior knowledge of the effective number of echoes, the effective echo number is included into the signal parameter vector together with the time-delay as well as the amplitude of individual echo. Numerical experiments are then carried out to demonstrate the effectiveness of the proposed method.

2. Proposed method

2.1. Theoretical model

In the ultrasonic echoes identification problem we consider, the received waveform consists of delayed and attenuated replicas of the

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doi:10.1016/j.matlet.2008.04.050

backscattered sinusoidal signal. This is the result of multiple reflections and attenuation of the signal caused by media interface or defects. We assume that the received sampled signal can be expressed as:

$$y(nT_s) = \sum_{l=1}^{L} \alpha_l s(nT_s - \tau_l) + e(nT_s), \quad n = 0, 1, \ldots, N-1 \tag{1}$$

where T_s is the sampling period and is equal to the reciprocal of the sampling frequency f_s. N is the sampling number. $s(nT_s)$ represents the known reflected sinusoidal signal and can be obtained from the thick samples where individual echoes are well separated. $e(nT_s)$ denotes the zero-mean Gaussian random noise. $y(nT_s)$denotes the received echoes composed of L replicas of $s(nT_s)$ with different amplitudes $\{\alpha_l\}_{l=1}^{L}$ and delays $\{\tau_l\}_{l=1}^{L}$. Then the echo characterization problem here is to estimate the parameter vector $V = \left(\{\alpha_l, \tau_l\}_{l=1}^{L}\right)$ when the sinusoidal input has highly oscillatory correlation function. By converting the problem into the frequency domain, Manickam *et al.* proposed the following frequency domain non-linear least squares (NLS)-type cost function [7].

$$\arg\min_{V=\{\alpha_l,\tau_l\}_{l=1}^{L}} \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} \left| Y(k) - S(k) \sum_{l=1}^{L} \alpha_l e^{j\left(-\frac{2\pi\tau_l}{NT_s}\right)k} \right|^2 \tag{2}$$

where $Y(k)$,$S(k)$,and $E(k)$, $k=-N/2,-N/2+1,\ldots,N/2-1$, is the discrete Fourier transforms (*DFT*s) of $y(nT_s)$, $s(nT_s)$ and $e(nT_s)$ respectively. Different from the approaches in which the effective number of the reflected echoes L is assumed to be known [2–3], the proposed method includes the L to generate the new parameter vector $W = \left(L, \{\alpha_l, \tau_l\}_{l=1}^{L}\right)$. Furthermore, aim to accelerate the optimization process by normalizing the behavior of different convergence modes in frequency domain [10], we apply a spectral whitening strategy under which the frequency domain NLS criterion is divided by the corresponding frequency amplitude response of the received signal to form the new cost function as:

$$\arg\min_{W=\left(L,\{\tau_l,\alpha_l\}_{l=1}^{L}\right)} \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} \frac{|Y(k) - S(k) \sum_{l=1}^{L} \alpha_l e^{j\left(-\frac{2\pi\tau_l}{NT_s}\right)k}|^2}{K_w}, \quad \begin{cases} k_w = |Y(k)|^2, & |Y(k)|^2 \geq T_y \\ K_w = 1, & |Y(k)|^2 < T_y \end{cases} \tag{3}$$

where T_y is the threshold set to avoid the overflowing caused by the near zero $Y(k)$.

2.2. Proposed method

In view of the different types of signal parameters containing the amplitude, time-delay and echo number, the evolution operation of the corresponding parameter is designed accordingly. The proposed evolutionary estimation algorithm can be expressed as:

(1) Initialization. For the parameters of multiple echoes, with an initially set echo number L_0, p individuals $\boldsymbol{W_i}$, $i=1,\ldots,p$ are randomly produced from uniformity distribution across [−0.5 0.5], in which the 2 L+1 dimension floating-point weights of each candidate acts as a parent for next evolution operation.

(2) Echo amplitude and time-delay parameters evolving. We define the fitness function as:

$$E(\boldsymbol{W_i}) = \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} \frac{|Y(k) - S(k) \sum_{l=1}^{L_i} \alpha_{l,i} e^{j\left(-\frac{2\pi\tau_{l,i}}{NT_s}\right)k}|^2}{k_w}, \quad \begin{cases} k_w = |Y(k)|^2, & |Y(k)|^2 \geq T_y \\ K_w = 1, & |Y(k)|^2 < T_y \end{cases} \tag{4}$$

Compute the fitness of every individual $E(\boldsymbol{W_i})$, $i=1,\ldots,p$ in the evolution mass, and then produce p new individuals $\boldsymbol{W_i}$, $i=p+1,\ldots,2p$ by adding a L-dimension Gaussian random vector with mean zero and variance proportional to $E(\boldsymbol{W_i})$ to the echo amplitude factor $\{\alpha_l\}_{l=1}^{L}$ and time-delay part $\{\tau_l\}_{l=1}^{L}$ respectively. To alleviate the computational burden during parameter searching, constraint is imposed to limit the range of the time-delay of new offsprings within a suitable

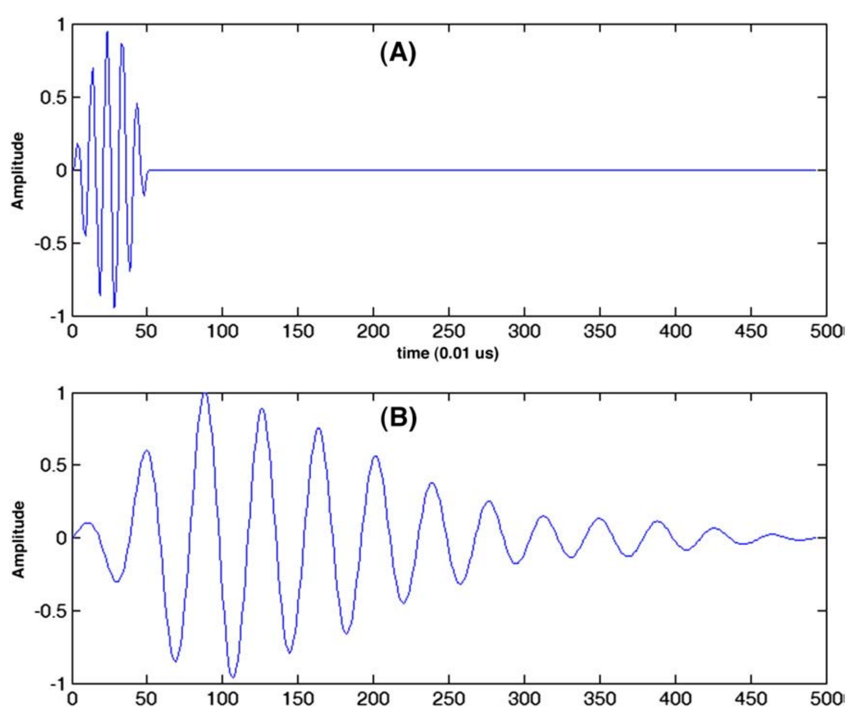

Fig. 1. Numerical waveform (A) and physical ultrasonic echo (B) adopted as transmitted signal.

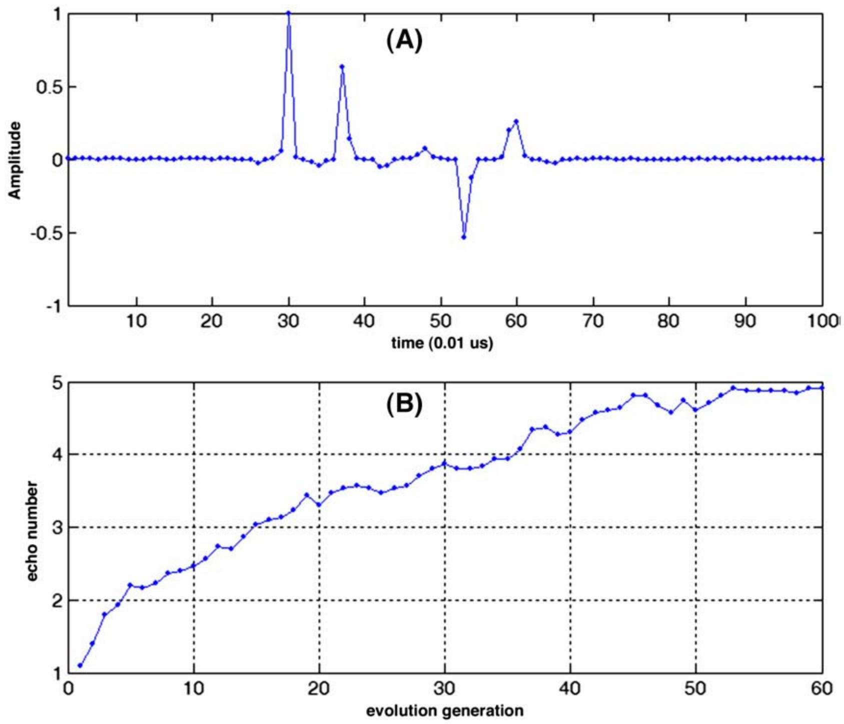

Fig. 2. Estimation result of the first experiment over 30 independent runs.

bound N_b as $0<\tau_l<N_bTs, l=1,2..L$. Meanwhile, in view of its integer nature, the time delays newly produced are converted to the nearest integer number.

(3) Echo number parameter evolving. New offsprings are selected to perform echo number parameter variation according to the *echo number variation probability* Ψ. The original echo number of the chosen offsprings is added or subtracted by one according to uniform probability to form the new L_i equals L_i+1 or L_i-1, while that of the other offsprings remaining unchanged.

(4) Selection. To evaluate the fittest candidate among all the offsprings, compute the fitness values of the new individuals $E(\boldsymbol{W_i})$, $i=p+1,\ldots,2p$. A series of c pairwise comparisons are carried out between each vector and randomly selected opponents [9]. Let $\boldsymbol{W_i}$ be the vector being conditioned upon. Let $\boldsymbol{W_0}$ be the randomly selected opponent vector. Assign a "win" to $\boldsymbol{W_i}$ if $E(\boldsymbol{W_i})<E(\boldsymbol{W_0})$. Sort all of the vectors by their associated value of wins $[0, \ldots, c]$. Then select p individuals from the whole $2p$ individuals as the new generation mass.

(5) Repeat (2) until the end condition is satisfied.

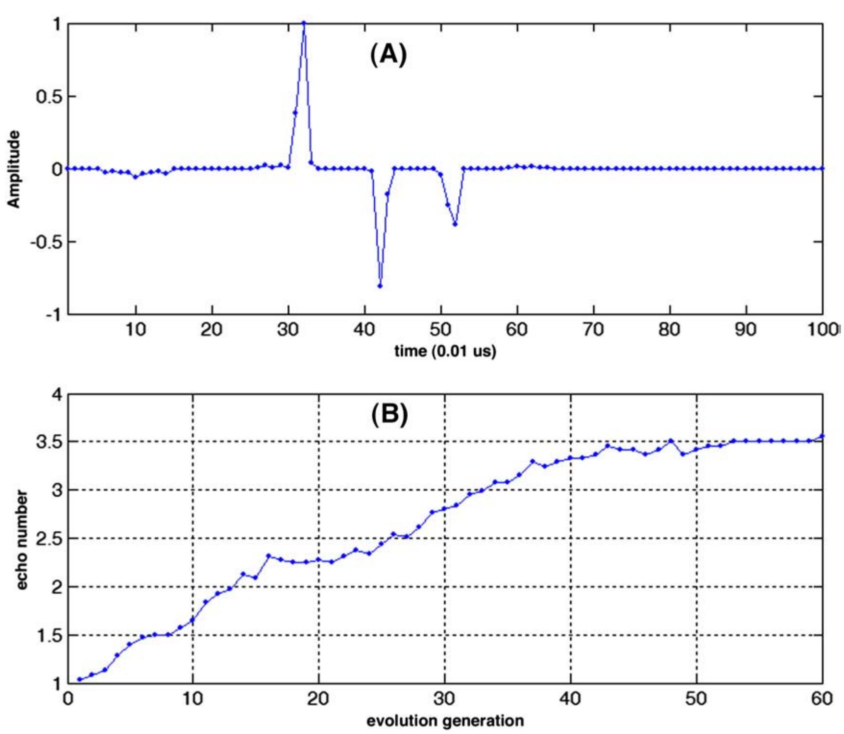

Fig. 3. Estimation result of the second experiment over 30 independent runs.

3. Experimental results and discussion

In this section, numerical experiments are carried out to evaluate the effectiveness of the described algorithm. Firstly, a windowed sinusoidal signal expressed as following is adopted as transmitted signal (See Fig. 1(A)).

$$s(nT_s) = a(nT_s)\sin(2\pi f nT_s), \quad 0\le n\le N$$

where f = 10.0 MHz, N = 500 denotes the centre frequency and sample number of the transmitted signal, fs = 100 Msps, $T_s = 1/f_s$. The window function is

$$a(T_s) = \begin{cases} \sin\left(\frac{2\pi nT_s}{T_w}\right), & 0\le n\le W \\ 1 & W<n\le N \end{cases} \tag{6}$$

where $T_w = 100T_s$, W = 50. The simulated highly superimposed echoes $y(nT_s)$ consisting of k delayed and attenuated replicas according to

$$y(nT_s) = \sum_{m=1}^{k} w_m s(nT_s - \tau_m) + e(nT_s) \quad n = 0, 1, \ldots, N-1. \tag{7}$$

The effective number of the echoes is 4, with time-delay at $30T_s$, $37T_s$, $53T_s$ and $60T_s$ associated with the amplitude of 1.0, 0.73, -0.59 and 0.47 respectively. A real-valued zero mean additive white Gaussian noise $e(nT_s)$ is added into the input, producing a signal to noise ratio (SNR) of 20dB.

The population size p, the *multipath number variation probability* Ψ and the initial multipath number L_0 is set to 600, 0.25 and 1 respectively. With the time delay bound set as N_b = 100, the time-delay parameter is limited to the range [$1T_s$, $100T_s$]. The evolutionary process is designed to terminate after 60 generations.

The mean parameter estimation results of 30 independent simulation trials via the proposed method are provided in Fig. 2(A), which indicating that highly overlapped echoes are discriminated correctly. In Fig. 2(B), the mean converging process of the effective echo number in 30 independent tests is shown. As Fig. 2(B) indicating, the iteratively evolutionary estimation process yields the final result around the physical echo number of 4, confirming the validity of the proposed joint estimation scheme.

Secondly, we use a physical sinusoidal ultrasonic NDE echo $s(nT_s)$ (See Fig. 1(B)) to produce the simulated highly superimposed echoes according to Eq. (7). With fs = 100 Msps and N = 500, the centre frequency of the $S(nT_s)$ is 2.5 MHz with a bandwidth of 0.4 Mhz. The effective number of the echoes is 3, with time-delay at $32T_s$, $42T_s$ and $52T_s$ associated with the amplitude of 1.0, −0.83, −0.47 respectively. The SNR is set at 35 dB.

The configuration parameters of the evolutionary algorithm are the same as the first case.

As can be seen from the parameter estimation results of 30 independent simulation trials in Fig. 3(A), complete separation of echoes is achieved. Meanwhile, the mean converging process of the simultaneous estimation of the effective echo number in 30 independent tests is shown in Fig. 3(B). It reveals that the estimation behaviour generally converges to the final result around the physical echo number of 3, demonstrating the effectiveness of the proposed method.

4. Conclusion

In this paper, we proposed a frequency domain weighting NLS approach to overcome the oscillatory nature caused by sinusoidal ultrasonic NDE signals and further develop an evolutionary strategy to search the global optimum efficiently. The design of the spectral whitening as well as the evolutionary optimization operation is provided. Numerical simulation results with highly oscillatory signals demonstrated the feasibility of the presented approach. Ultrasonic NDE experiments on physical multiple-layer bonded materials will be carried out in the future to further verify the proposed method.

Acknowledgment

This wok was supported by the Nature Science Foundation of China (NSFC) (No. 10704063).

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