Application of PNLMS and DTW to analyze overlapped Lamb waves

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Abstract. A method based on Proportional Normalized Least Mean Square (PNLMS) and Dynamic Time Warping (DTW) is present in this paper for the analysis of the overlapped Lamb waves. The damage information, including location, severity and type, can be assessed based on the characteristics of damage reflected Lamb waves. However, the damage reflected waves can be easily masked by the waves reflected by the boundary, especially for the scenario when the damages adjoin to boundaries. The overlapped waveform are difficult to analyse using conventional filtering methods since the waveforms reflected by damages and boundaries have identical frequency characteristics. The methods developed in the area of audio echo-hiding processing has been introduced to solve this problem. Improvements has been made with considering the requirement of Lamb waves-based damage detection. The results from numerical simulation show that the presented method is superior to conventional methods in both stability and accuracy.

1. Introduction

Lamb waves seem to be an advisable choice for detecting defects in structures like plates, since their energy may be shared into reflected and transmitted wave packets, the proportion in amplitude of which will depend on the characteristics of defects. However, the characteristics of multiply modes and dispersion of Lamb waves can cause the damage scattered signal overlaps with other wave forms. A baseline subtraction approach based on baseline signal can obtain the damage scattered signal directly while the result has large error. And this approach is difficult to give satisfactory result in actual circumstances due to influence factors, such as noise effects and temperature changes. In addition, baseline signal is not available every time[1].

Echo-hiding technology utilizes the biological characteristic of human hearing, places several closely-spaced echoes into original audio data to realize specific form of data hiding. Overlapped Lamb waves processing is similar to the decoding processing of echo hiding. They have similar mathematical model. Adaptive signal processing has been applied to information extraction of
echo-hiding[2]. Overlapped Lamb waves consist of damage scattered wave and boundary reflection. It can be regarded as the output signal of propagation system. The characteristics of this system are related to propagation path. Therefore, overlapped Lamb wave processing can be seen as a problem of system identification. Impulse response of this system is required for extracting damage signature. Thus, the key point of the research is transformed into a simulation of impulse response of the propagation path. A robust and efficient method is therefore proposed to realize the simulation of impulse response of the excitation signal propagation path in an unknown structure, which is based on Proportional Normalized Least Mean Square (PNLMS).

2. Mathematical model and adaptive algorithm

If boundary reflection and damage scattered signal belong to the same mode, the waveform of boundary reflection is similar to the waveform of damage scattered signal without mode conversion. The difference between them can be simplified as the propagation time and amplitude value. Aiming to the overlapped issue, some other fields have provided us several mathematical models based on the simplification mentioned above. Therefore, mathematical model of information extraction in echo hiding is used as a reference[3]. We define that the overlapped wave \( y(t) \) is expressed by input wave \( x(t) \) and impulse response of propagation path \( h(t) \) as,

\[
y(\tau) = x(\tau) * h(\tau)
\]

\[
h(t) = \delta(t) + a\delta(t - t_0)
\]

Where, \( a \) is the amplitude factor, \( t_0 \) is the time-delay required, \( \delta(t) \) is the unit-impulse function.

The derivation of proportional normalized least mean square (PNLMS) algorithm began with the least mean square (LMS) algorithm. Least mean square algorithm is a kind of adaptive signal processing method. Its essence is a search algorithm which is designed for getting the minimum point of mean square error (MSE) function.

LMS algorithm is an initial adaptive algorithm, followed variable improved algorithms are based on LMS. However, classical adaptive algorithms utilize the same step-size value for all coefficients, such as the normalized least mean square (NLMS), this shortcoming makes it inaccurate to simulate sparse impulse response, namely most coefficients of response take values near zero and only a few have significant values. Then proportionate NLMS (PNLMS) was proposed for the simulation of sparse impulse response.

Impulse response \( h(t) \) in mathematical model proposed above is classified as sparse response. The simulation of it is accomplished by adaptive algorithm. Aiming to the sparse characteristic of \( h(t) \), PNLMS might be the optimum choice[4].

After the simulation of impulse response based on PNLMS, resulting impulse response always contain several peaks with different amplitude. The moments corresponding to these peaks in time domain represent various possible time-delay. Therefore, a similarity test is needed to identify the optimum peak. Amplitude factor corresponding to every time-delay is calculated for obtaining a complete impulse response. The calculation of amplitude factor was based on the mathematical model. There are two unknown terms in mathematical model, time-delay and amplitude factor, amplitude factor corresponding to each possible time-delay can be obtained as the time-delay was known to us. Therefore, a calculated impulse response can be reconstructed with the time-delay and amplitude factor mentioned above. Then we can make the reconstructed impulse response convolves with input signal to obtain a series of output signal. A similarity test between each output signal and expectation signal which is based on DTW is performed then.
3. Numerical verification

In order to verify the capability of proposed method, experiment was conducted with a 600 mm×600 mm×1 mm 2024-T3 aluminum plate, material parameters of which is shown in Table 1. The four edges of aluminum plate were free. The damage is a circular hole with the radius of 2.5 mm (Figure 1). When the PZT A was excited, PZT B received a signal which was composed of incident wave, damage scattered signal and boundary reflection. And baseline signal for the pristine condition of plate, namely nondestructive condition, was recorded. However, these received signals were interfered by experimental environment and influenced by noise as a consequence of it. In order to eliminate the effects of noise, Singular Value Decomposition (SVD) was used for noise elimination issues.

| Table 1. Material parameters of aluminum plate |
| E(GPa) | μ | ρ(kg/m³) | h(mm) | CL(m/s) | CT(m/s) |
| 72.4 | 0.33 | 2780 | 1 | 6211 | 3129 |

![Figure 1. Scheme diagram. (unit: mm)](image1)

![Figure 2. Obtained impulse response of propagation path AB](image2)

The baseline signal was used as input signal. And at the same time, overlapped signal was used as expectation signal. The input parameters of adaptive system were set. These parameters mainly consist of input signal, expectation signal, the order of adaptive system and convergence factor of PNLMS. Therefore, the order of adaptive system is the effective length of input signal and the value of convergence factor is a random number between 0 and the reciprocal of the maximum eigenvalue of the input signal correlation matrix. Then the iterations started until the final impulse response was obtained (Figure 2). Several peaks with large amplitude value of impulse response were marked and numbered. Hence, the moment corresponding to each peak represents a possible time-delay. The amplitude factor corresponding to each peak was calculated. The possible time-delay and calculated amplitude factor can be reorganized as a new impulse response. Similarity test based on DTW was implemented between the expectation signal and the convolution result of input signal and new impulse response. The actual propagation distance of damage scattered signal is 0.3695m, while the estimated result given by the proposed method is 0.3706m. The error is 0.0011m. The relative error is 0.298%. The method is accurate enough.

4. Conclusion

In this paper, a new approach for overlapped GW signal processing using PNLMS and DTW was proposed. First, with the prior knowledge of material properties, plate thickness and the sites of actuators and sensors on the plate, the propagation distance of boundary reflection was obtained.
Second, the simulation of excitation signal propagation path was achieved. The obtained impulse response includes vital information about the damage. Because the baseline signal is not available every time, a simulation signal is selected as input signal. Its effectiveness was demonstrated using experimental results, where the proposed method was capable to process overlapped waves.

Advantage of the proposed approach against conventional methods is clear. It is a suitable method for homomorphic overlapped Lamb waves. The robustness of proposed approach was proved by complicated experimental signals. It was also shown that the absent of baseline signal cannot interfere the processing of overlapped issue. Therefore, it can be considered as an effective tool for single mode Lamb wave signal processing. The drawback of the method is that the method is not suitable for multi-modal Lamb waves.

This method originated from hidden information extraction in echo hiding. The key point of the method lies in adaptive signal processing. Compared to the conventional method, it provides a new tool for overlapped Lamb wave processing.

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