Defect Detection Studies on Time Reversal Theory in Pipelines

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Abstract. This paper investigates the use of time reversal processing techniques to compensate for multimodal and dispersive effects in a low-power structural health monitoring system for pipelines. We demonstrate the use of time reversal as a pitch-catch operation between two transducer arrays to illuminate changes caused by damage on a pipe. The response is then propagated backwards through the medium from the same array. We demonstrate how this method provides a metric for classifying the magnitude of damage in a pipe while relaxing the restrictions on excitation frequency and bandwidth that are imposed on many other nondestructive techniques.

1. Introduction

In order to enhance the detection capability of guided wave for small and anomalous defect, some signal process methods, such as the time-frequency reassignment and the wavelet transform, had been tried to improve the signal-to-noise ratio. However, it is not enough for those signal process methods to identify a defect if the defect waveform is too small. Some researchers used multi-channel transducer array to focus the ultrasonic energy on the defect (Fink, M, 1992). Some are achieved by calculating the input time delays and amplitude factors in advance which depend on the exciting condition, frequency, distance and the properties of the pipe. Then, each element of the array is excited with an appropriate delay and amplitude so that a focused wave would hit the defect and produce an echo with large amplitude. However, the course of scanning the pipe to find an unknown defect is complicated.

In this paper investigates has been used for time reversal processing techniques to compensate for multimodal and dispersive effects in a low-power structural health monitoring system for pipelines. The ability of time reversal to focus improves as the number of modes and propagation paths as well as waveform dispersion increase. This stands in contradiction with traditional ultrasonic structural health monitoring systems that use low frequency and small bandwidth excitations. The peaks of the Time Reversal Change Focusing show a clear indication of the presence of damage in the pipe. According to the principle of time reversal, a set of test system is set up to retransmit the signal from the sound source received by different sensors to the medium according to the reverse process of its time history, so that the signal arrives first and then arrives first. At the same time, returning to the source of the wave, the reconstruction of the sound source signal can be realized effectively, and then the parameter analysis is performed.

When the depth of the defect penetrates the wall thickness, the reflection coefficient of the guided wave increases linearly with the increase of the circumferential length. By analyzing the influence of the defect length on the reflection coefficient of the guided wave, the size of the defect can be approximated.
The signal time reversal method can realize the focusing gain of the signal, and can improve the signal-to-noise ratio of the acoustic signal in the solid medium. It is important practical significance for the further application of the ultrasonic guided wave in the nondestructive detection of pipeline defects. Has a specific guiding role.

2. Time reversal change focusing

Current structural health monitoring techniques are often based on the comparison of current structural responses with a baseline “healthy” response case. Variations from the baseline case alert the presence of damage. Unfortunately, operational and environmental conditions may cause the variations in the “healthy” response and, therefore, it is generally necessary to have baseline data for all possible operational and environmental conditions. For most structures, there exists a complex array of possible functional conditions, making it necessary to perform front-end data mining for all of the structural response characteristics. Furthermore, the necessary data storage increases the cost/decreases the efficiency of these diagnostic techniques. The concept of using a Time Reversal Method (TRM) has recently been proposed as a baseline-free diagnostic technique in attempts to address these problems. Currently, the TRM has been successfully implemented to detect the presence and location of damage and has the potential to determine extent and type of damage.

To implement the TRM for damage diagnosis, a transducer array is setup and used in a pitch-catch arrangement (a signal is actuated from one transducer and recorded at another). Each transducer must work both as a sensor and an actuator, so typically piezoelectric (PZT) transducers are used. The time reversal process is shown in Figure 1.

The TRM needs a complex actuator/sensor array. Although PZT transducers alleviate some of the problems associated with actuation and sensing at the same position, other complexities still exist. In particular, the hardware (power amplifier, data acquisition) necessary to support both actuation and sensing at all sensor locations is quite high. Therefore, an MTRM is required to develop.

The MTRM is as shown in Fig.2 Step by step, the procedure is as follows (where the modified steps are denoted in bold font):

1. A Lamb wave tone burst is sent from transducer A and recorded at transducer B.
2. The received signal at B is reversed in time [i.e., VB(t)→VB(-t)].
3. The time reversed signal is sent from A to B where it is recorded.
4. The received signal at B is time reversed and compared to the original signal actuated

Although the MTRM is similar to the original TRM, only one actuator is necessary for the process. Over a large structure, instead of actuating and sensing between every transducer, only a few actuators are necessary within a grid of sensors. The MTRM can be validated by analyzing the process in Fourier space. For the transducer arrangement in Fig.4, the signal received at B due to an input signal at A can be represented by
\[ \hat{V}(\omega) = \hat{I}(\omega)G(\omega) \] (1)

where \( \hat{\cdot} \) denotes the Fourier transform of the function, \( I \) is the input signal at A, and \( G \) is the structural transfer function (defined in the later section). In Fourier space, the time reversal of the signal at B is defined by

\[ \hat{V}(\omega)TR\hat{V}^*(\omega) \] (2)

where \( \hat{\cdot} \) denotes the complex conjugate of the function. Therefore, the time reversed signal at B (step 2) can be represented by

\[ V_{tr}(\omega) = \hat{I}(\omega)G^*(\omega) \] (3)

In the proposed MTRM here, the time reversed signal is actuated from A to B (step 3), resulting in

\[ \hat{V}(\omega) = \hat{V}_{tr1}(\omega)G(\omega) = \hat{I}(\omega)G^*(\omega)G(\omega) \] (4)

Time reversing the final signal \( \hat{V}_{tr2}(\omega) \) (step 4),

\[ \hat{V}_{tr2}(\omega) = \hat{I}(\omega)G^*(\omega)G(\omega) = |G(\omega)|^2 \] (5)

and transforming the signal back into the time domain,

\[ V_{tr}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{I}(\omega)|G(\omega)|^2 e^{j2\pi\omega t} d\omega \] (6)

Such that \( |G(\omega)|^2 \) is independent of \( \omega \) (as discussed later), the signal at the end of the time reversal process is directly related to the originally actuated signal as found by

\[ V_{tr}(t) = C|I(t)| \] (7)

Where \( C = |G(\omega)|^2 / 2\pi \) is the same result as found for the original TRM.

2.1 Finite element modeling

The finite element simulation has been extensively and successfully used in studying the interaction between guided wave and defects in structures. It is possible to model the pipe by means of a reduced three-dimensional membrane finite element model. The basis for such simplification is the simple nature of the mode shapes of the excited L (0.2) mode and the conversion modes at 70 kHz.

The pipe model with a circumferential crack is illustrated schematically in Fig. 1. The pipe length is 5.0 m. The axial distance between the center of the crack and the pipe’s end A is 2.5 m. A crack, 2 mm in width and 60 mm in length, is modelled by removing the full wall thickness. Except for auto-meshing in the vicinity of the defect, meshes of identically sized linear quadrilateral membrane elements are used. There are 28 elements around the 360-deg circumference in the pipe model. The considered pipe in this paper is designed with outer diameter 159 mm, wall thickness 5 mm. Young’s modulus is 2.1693e11 N/m², material density is 7932 kg/m³, and Poisson’s ratio is 0.3.

To demonstrate how the time reversed method works in guided wave detection of a pipe to focus on the defect, a circumferential is considered. At first, a five-cycle 70k Hz toneburst in a Hanning window is chosen for the input. If the toneburst is concurrent applied at all nodes of the end A as a sequence of prescribed displacements in the axial direction of the pipe, then L(0,2) mode is generated in the pipe (as shown in Figure 3).
2.2 Results of reflection study

The detection of the reflected waves is achieved simply by monitoring 28 nodes around a circumferential ring. The axial distance between the monitor ring and the pipe end A is 3mm. Typical received signal is shown as Figure 2. Except for $L(0, 2)$ mode, other flexural modes emerge due to mode conversion at the defect. These flexural modes and $L (0, 2)$ mode propagate at respective different velocities in the pipe. Therefore, each mode’s travel time from the defect to one receiving node would be different. It leads to complex waveforms received at all receiving nodes. It is difficult to distinguish certain mode from these signals. Moreover, the reflection energy is distributed to all modes, which results in that the amplitude of each mode from the little defect is too small to identify.

2.3 Defect circumferential locating

The experiment was being set up. The pipe used in the experiment was 5000mm in length, 159 mm in outer diameter and 5 mm in wall thickness. Five artificial oblique cracks, 2mm in width, 60 mm in...
length and 1.5mm in depth, was machined on the pipe, which is 2500mm far from the excited end. The angle θ between the crack and 0-deg line as shown in figure 5 is 90 degrees.

A PZT transducer ring is fixed on the excited end to excite guided wave. 10 PZT transducers used as 10 time reversal transducers are mounted around the pipe circumferentially. Each time reversal transducer is sized with 12×6×0.5 mm. A 5-cycle’s 70 kHz toneburst in a Hanning window is chosen for an input signal and is applied on the PZT ring.

![Figure 5. Comparison of the reflection coefficients for circumferential cracks](image)

The reflection coefficients of L \( (\omega, 0) = 0, 2 \) mode for pipes with different cracks are compared in figure 5. The comparison shows that the reflection coefficient of L \( (0, 2) \) mode obtained by the time reversal method is larger than that obtained by the conventional guided wave inspection method. The reflection coefficient of L \( (0, 2) \) mode decreases with length circumferential cracks in the time reversed processing. For the circumferential crack, the non-axisymmetric geometry of the crack results in a strong mode conversion phenomenon when L \( (0, 2) \) mode is excited for inspection. Other modes, such as F \( (1, 3) \), F \( (1, 2) \) and F \( (2, 3) \) modes which can exist at the excited frequency, will share the wave energy too. When these modes are included in re-emitted signals, as should be expected, the reflection coefficient of L \( (0, 2) \) mode can be enhanced to a higher level. The reflection coefficients of L \( (0, 2) \) gotten is least 6.6 times larger than the reflection coefficient of the original detection signal.

3. Conclusions

Time reversal method of ultrasonic guided waves has many outstanding advantages in the use of pipes. Time reversal allows the signal from the sensor to compensate for the dispersion and multi-mode conditions of the guided wave. This allows the researchers to have a larger bandwidth when selecting the excitation signal. Different frequencies can be selected as the excitation frequency, which can achieve long The distance is detected and a good signal to noise ratio is obtained. The damage of the medium can be effectively determined according to the different peaks of the signal. The magnitude of the peak amplitude determines the extent of the damage.

Based on the analysis above, some important conclusions are obtained as follow: Using the time reversal method for the guided wave inspection of a pipe can realize energy focusing on a defect in the pipe. The reflection coefficient increases with widening the intercepting window when the time reversal method is used to enhance the inspection ability of guided waves. Numerical results for the method presented here will guide the experiment in the future. Time reversal method has broad application prospects in structural damage monitoring of pipeline damage and other structures.

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