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NUMERICAL TIME REVERSAL PROCESSING FOR IMPACT DETECTION USING SURFACE BONDED PIEZOCERAMIC

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ABSTRACT

Time reversal processing for measured sensor signal can be applied to detect not only structural damage but also impact loading of the structure. In this study, a model based impact detection method for structural health monitoring is proposed. Impact identification capability of the numerical time reversal processing is demonstrated by using a rectangular aluminum plate with nine surface bonded piezoceramic sensors. Illustrative numerical simulation results indicate that the proposed method can be successfully identifying both exact impact point and time.

INTRODUCTION

Different kinds of impact loading, such as fluid force for turbo machinery or piping, aerodynamic force for airplane, dynamic force for operated vehicle, etc, induce structural defects of the mechanical parts of the system, which degrade structural integrity of the system. Nondestructive testing for detecting structural defects ensures safety operation of the industrial mechanical system. After localizing the impact loading point on the structure, only a small region of the structure should be inspected in order to assess structural integrity. A great deal of research is currently in progress on identifying the impact for structural health monitoring. Some of them are based on the inverse problem formulation, in which impact loading is estimated by the numerical iteration using the measured response of the structure due to impact [1-3].

Recently, a sophisticated paradigm for solving inverse problem of the acoustical wave propagation in the medium, "time-reversal processing," is presented by Fink and developed by his research group [4-7]. Time reversal processing for measured sensor signal can be applied to detect not only structural damage but also impact loading of the structure. However, time reversal processing was mainly used to structural damage detection [6-10].

Fink et al. successfully apply time-reversal processing to detect the defect in the titanium and duralumin blocks immersed in the water for industrial ultrasonic testing applications such as aircraft and engine components [6]. They also perform the detection of the flaws in the plate [7]. In reference [7], they used a laser impact on a plate to generate an incident pulse. Resultant guided wave generated by the pulse is scattered by a defect and reflected by the boundary of the plate. Then, transducer array located on the plate can generate electrical signals corresponding to the scattered wave. Applying time reversal processing to the measured electrical signals, time-reversed electrical signals are used as excitations for each transducer element of the array where each electrical signal is measured. Time-reversed waves travel back through the plate and are refocused on the point corresponding to the target defect. The location of the target defect can be detected by a laser interferometer.

The other method for detecting structural defects based on time reversal processing is presented by Leutenegger [8, 9]. In his research, experimentally measured signals from defective structure are time-reversed and used as the input signals for the numerical simulation. Time-reversed waves travel back through a model structure in the simulation and are refocused on the target defect. Leutenegger experimentally performs the measurement for a cylindrical tube with a defect by using 100

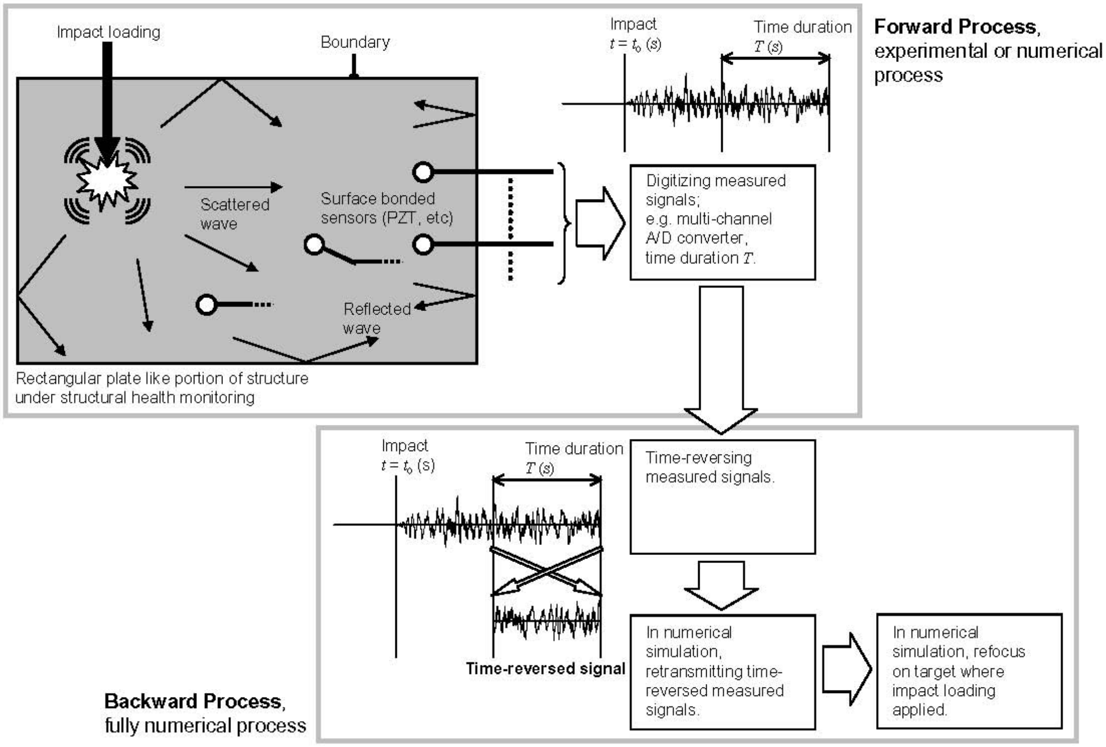

Figure 1 Block Diagram of Impact Detection Based on Time Reversal Processing.

transducer elements located at the end of the tube. The numerical simulation for identifying the defect is performed by using a finite difference method.

Adachi and Sakota present a damage detection method based on time reversal processing [10]. The differences between the authors' work and the references [8, 9] are as follows. In reference [10], 1) model based damage detection for a rectangular plate is presented; 2) time-reversal processing is successfully performed by using a commercial finite element code (ANSYS University Ver.7.0, high option); and 3) a small number of transducer elements (up to nine surface bonded piezoceramic sensors) is used.

Wang et al. [11] present the theoretical and experimental investigation of the influence of the dispersion effect of wave propagation [12] on time reversal processing for a rectangular plate.

This paper aims at proposing impact detection method based on time reversal processing. This work is expansion of the authors' previous work [10]. In the next section, the time reversal processing is briefly introduced. Then the basic concept of impact detection based on time reversal processing is presented. An illustrative numerical example to demonstrate the feasibility of the proposed method is performed for a rectangular plate with nine surface bonded unimorph piezoceramic sensors.

THEORETICAL BACKGROUND

Wave Propagation

The governing equation of wave propagation in a non-dissipative homogeneous elastic medium is given by following matrix form in the sense of the finite element analysis [10, 13].

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \boldsymbol{K}\boldsymbol{x}(t) = \boldsymbol{f} \qquad (1)$$

where $\boldsymbol{x}(t)$ is the nodal displacement vector due to elastic wave propagation that is induced by the impact loading $\boldsymbol{f}$. The matrices $\boldsymbol{M}$ and $\boldsymbol{K}$ are the mass and stiffness matrices of the elastic medium, respectively. The equation contains only a second-order time-derivative operator and assuming harmonic wave propagation. Therefore, if $\boldsymbol{x}(t)$ is solution of the equation, then $\boldsymbol{x}(-t)$ is also solution of the same equation [4, 5].

The impact loading is applied at a point on the structure and generates elastic guided wave in the structure. Resultant guided wave is scattered and then reflected by the boundary. The advantage of the guided wave is that the inaccessible regions of the structures can be tested, because waves propagate along the structure due to its nature. The transducer located on the structure generates the electrical signal corresponding to wave propagation in the structure. The measured signal is time-reversed and used as the input for the same transducer. Time-reversed waves travel back through the structure and are just refocused on the point where initial impact loading is applied.

Impact Detection

Impact identification based on time reversal processing of acoustical wave propagation in the solid medium consists of the following two processes, forward and backward processes. Figure 1 shows the block diagram of impact identification.

Forward process (experimental or numerical processes)

Elastic wave field in the structure is induced by an impact loading $\boldsymbol{f}$ at $t = t_0$ (sec) and resultant wave front is diverging from the source in which the impact loading is applied. The elastic wave is scattered and reflected at the boundary of the structure. The transducers on the structure generate the electrical signals corresponding to the nodal displacement ***x***(t) due to wave propagation. After digitizing the measured signals, it is stored during the time duration *T* (sec).

Backward process (fully numerical process)

The stored signals are time-reversed and retransmitted by the same transducers in a reversed chronology ***x***(*T*-*t*). Time-reversed waves travel back through the structure and then refocused on the target where the initial impact loading is applied. From Eq.(1), the impact loading ***f*** can be reconstructed and estimated.

In the case of damage detection, Fink et al. experimentally perform both forward and backward processes [6, 7]. Forward process is experimentally performed and backward process is numerically performed in references [8, 9].

In this paper, in order to demonstrate the feasibility of the proposed impact identification method, both forward and backward processes are just numerically performed for a rectangular plate with nine surface bonded unimorph piezoceramic sensors (Fig.2).

NUMERICAL EXAMPLE

Finite Element Model of Plate

Figure 2 shows the layout of the rectangular aluminum plate with nine surface bonded piezoceramic sensors. Each piezoceramic sensors are numbered from #1 to #9. Finite element model of the rectangular plate should represent elastic wave propagation accurately. Under the limitation of the element/node numbers of available commercial finite element code at the authors' laboratory (ANSYS University Ver.7.0, high option), the element length is determined by considering the criteria presented in reference [13]. Table 1 shows the properties of a finite element model and Table 2 shows the material properties of the plate and piezoceramic sensors. In the numerical simulation, three-dimensional solid structural elements (SOLID45 for the plate and SOLID5 for piezoceramic sensors) are used. These elements are 8 nodes (SOLID45) and 4 nodes (SOLID5) elements with 3 dof at each node: translational displacements in *x*-, *y*-, and *z*-directions.

Following subsections, the feasibility study of time reversal processing for the model based impact detection is numerically performed. An incident pulse at *t*=0 (sec) due to impact loading is representing by a half sine cycle. According to the element length shown in Table 1, elastic wave filed is generated by the half sine cycle at a frequency of 25kHz applied at the "input" point shown in Fig.3.

Simulation of Time Reversal Processing

Resultant wave filed scattered inside and reflected at the boundary of the plate are simulated by ANSYS University (Ver.7.0, high option) just after applying 10(V) half sine cycle at a frequency of 25(kHz) as an incident pulse at *t*=0 (sec) to the "input" point shown in Fig.3. Figure 4 shows the calculated measured electrical signals during 0(sec) to 0.003(sec) at the piezoceramic sensors #1 - #9 in forward process of impact detection (Fig.1).

In order to demonstrate the refocusing of the incident pulse in backward process of impact detection, the calculated measured signals during 0 (sec) to 0.0015 (sec) (time duration *T*=0.0015 (sec)) are inverted in time. The amplitude of time-reversed signals is 10000 times and retransmitted by the same sensors (piezoceramic sensors #1 - #9). Figure 5 shows time-reversed signals whose amplitude is 10000 times from the calculated measured signals shown in Fig.4.

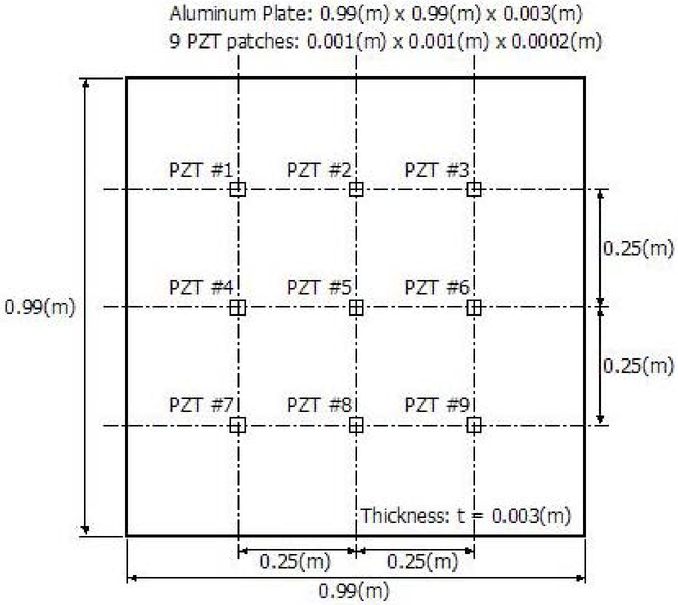

Figure 2 Plate with Nine Surface Bonded Sensors.

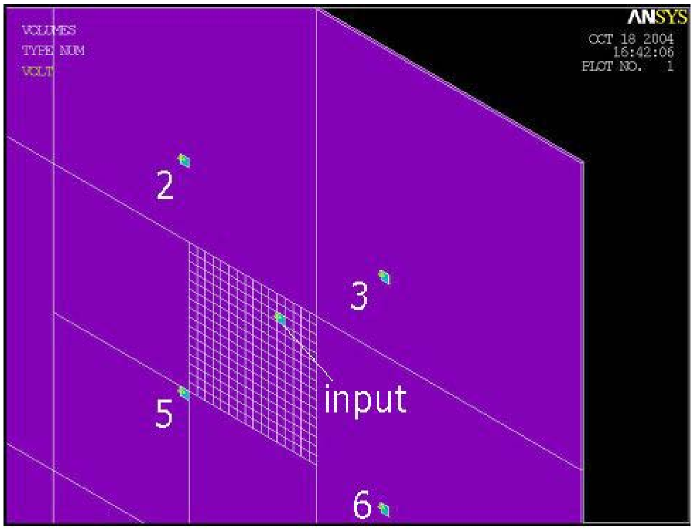

Figure 3 Input Location ("Input") of Incident Pulse.

Table 1. Finte Element Model of Plate.

Element Length	0.01(m)	
Element Type	Plate	SOLID45
	PZT	SOLID5
Elements	9810	
Nodes	20044	

Table 2. Material Properties of Plate and Piezoceramic Sensors.

	Material	Density (kg/m^3)	Young's Modulus (N/m^2)	Poisson's Ratio	Piezoceramic Constants(m/V)
Plate	Aluminum	2800	7.4×10^{10}	0.33	
PZT	C-82 (equivalent to PZT-5H)	7400	6.1×10^{10}	---	$d_{31} = -2.71 \times 10^{-10}$ $d_{33} = 6.30 \times 10^{-10}$ $d_{15} = 7.75 \times 10^{-10}$

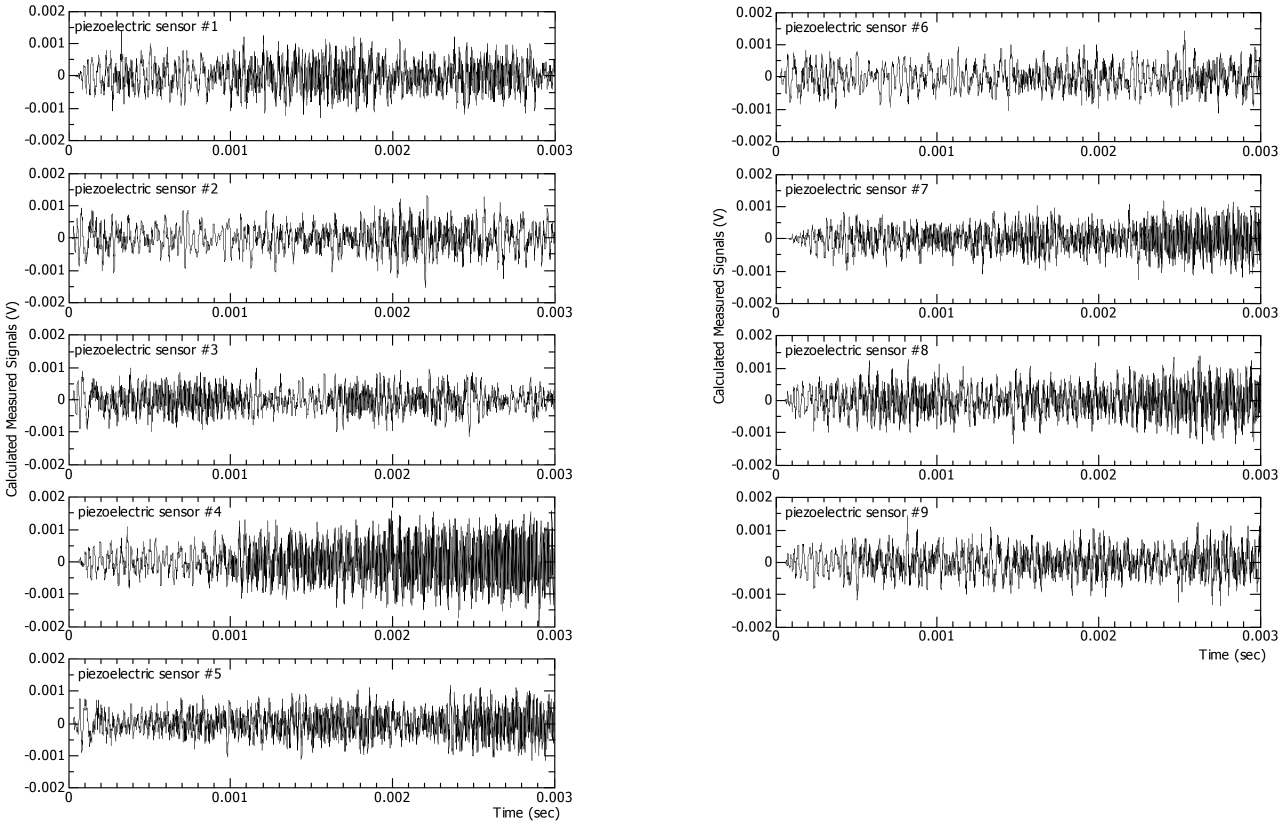

Figure 4 Calculated Measured Signals at Nine Surface Bonded Piezoceramic Sensors in Forward Process.

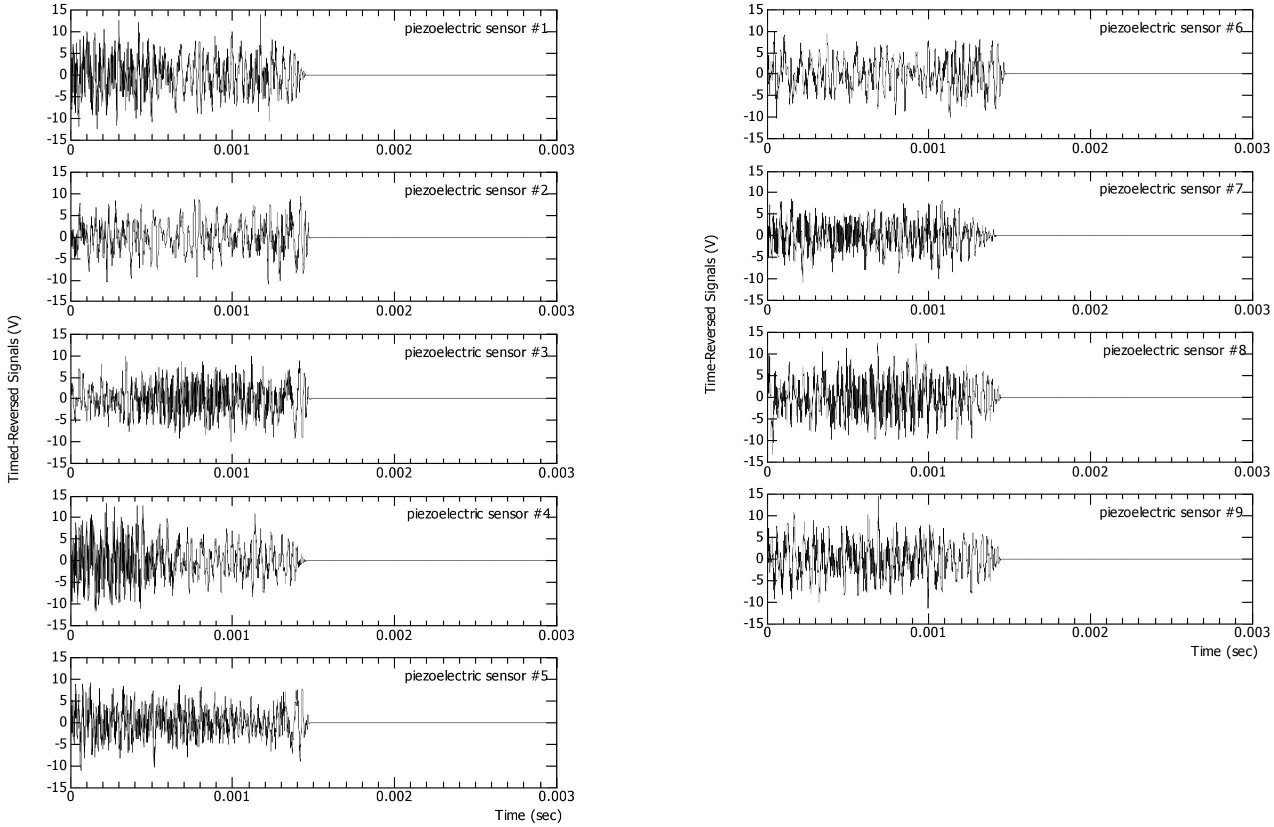

Figure 5 Time-Reversed Signals at Nine Surface Bonded Piezoceramic Sensors in Backward Process.

In backward process, in order to identify the initial impact loading, the vertical displacement of the each node of the plate is calculated just after retransmitting the time-reversed signals.

Figure 6 shows the vertical displacement at 4 nodes just around the element shown in Fig.3, where initial incidental pulse is applied. Figure 6 shows the refocusing at the "input" point in backward process. Since calculated measured signals shown in Fig.4 include calculation error in the numerical simulation for forward process, the resultant reconstructed nodal vertical displacements in time series shown in Fig.6 are noisy response signals. However, the pulse like signal is only reconstructed just at *t*=0.0015(sec) at 4 nodes just around the "input" point shown in Fig.3. This means that the exact location and time of the impact are identified by the proposed method.

CONCLUSION

This paper investigates impact identification capability of the numerical time reversal processing. The proposed method requires the numerical simulation model for the structure should be monitored for identifying the impact. The illustrative numerical simulation results indicate that the proposed method can be successfully identifying both exact location and time of the impact.

The main contribution of this paper is summarized as follows: (1) model based impact detection for the rectangular plate is presented and (2) exact impact point and time can be identifying by the numerical time reversal processing.

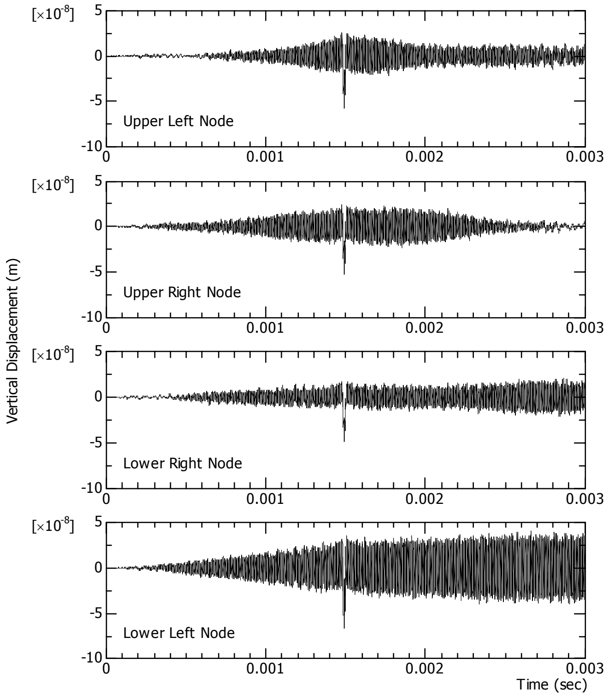

Figure 6 Vertical Nodal Displacement at "Input" Point in Backward Process.

After identifying the impact point on the structure, only a small region of the structure should be inspected in order to assess the structural integrity.

ACKNOWLEDGMENTS

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