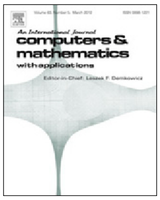
Computers and Mathematics with Applications 72 (2016) 879–892

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

journal homepage: www.elsevier.com/locate/camwa



Iterative time reversal based flaw identification

Robert Seidl [a,*], Ernst Rank [a,b]

[a] Chair for Computation in Engineering, Faculty of Civil, Geo and Environmental Engineering, Technische Universität München, Arcisstrasse 21, 80333 München, Germany

[b] Institute for Advanced Study, Technische Universität München, Germany

ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form 23 May 2016
Accepted 26 May 2016
Available online 16 June 2016

Keywords:
Full waveform inversion
Iterative adjoint-based optimization
Flaw detection
Ultrasonic non-destructive testing
Adjoint method
Time reversal

ABSTRACT

In the field of ultrasonic non-destructive testing, ultrasonic impulses are used to detect flaws in components without causing damage. Based on performing experiments alone, it is possible to infer the state of the component – but this usually provides only limited details about the interior damage such as its position, dimension or orientation. Furthermore, the amount of sensors that can be used to record the signals is restricted to only a few because of the shape and the dimensions of a typical specimen and considerations such as costs, additional mass and structural integrity. Further information about the flaw is hidden in the recorded experimental signals. The idea of the proposed method is to use the experimental data together with a wave speed model of a healthy component and to try to adapt the model to generate these experimental measurements. Formally, the problem is posed as a nonlinear optimization, and the wave speed model is adapted in such a way that the discrepancy between the experimental measurements and the model output is minimized. Moreover, to overcome the problem of only a few available sensor measurements, a combination of multiple simulations corresponding to generally performed multiple experiments in SHM practice is used to improve the accuracy. Following this approach, the position, dimension and orientation of a flaw can be detected for an emulated damaged aluminum plate. For cases when there are only few sensors available, it is shown how a combination of similar experiments can be used to improve the inversion results.

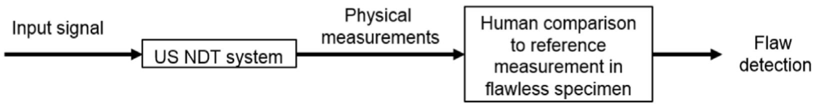
1. Introduction

The goal of structural health monitoring (SHM) is to implement a damage detection and characterization strategy for physical structures. In this context, a damage is defined as a change in either material or geometric properties of the structural system. SHM is concerned with observing the state of such a system over time, using response measurements from an array of sensors — and its goal is the extraction of damage-sensitive features from these measurements. The principal techniques are vibration-based and wave-propagation-based. In the scope of nondestructive testing (NDT), samples are examined using electromagnetic, radiation, sound, and inherent material properties. Application areas are weld verification, radiography in medicine or structural mechanics. In the latter, a structure undergoes a dynamic input such as a tap of a hammer or a controlled pulse and displacement or acceleration is measured at different sensor locations. Then, the observed output is compared to the expected output of a healthy structure. Thus, differences in outputs may indicate an inappropriate model or failed components. Possible methods include radiological, electrical, magnetic, and ultrasonic (US)

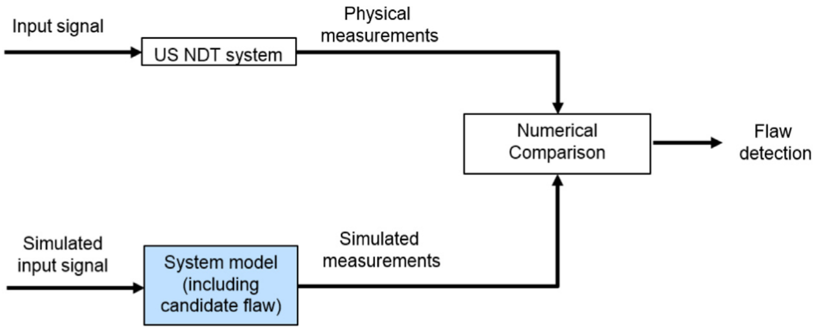
---

[*] Corresponding author.
E-mail addresses: robert.seidl@tum.de (R. Seidl), ernst.rank@tum.de (E. Rank).

http://dx.doi.org/10.1016/j.camwa.2016.05.036



(a) Expert based.



(b) Flaw model based.

Fig. 1. Different NDT devices, after [10].

methods. Typical examples are X-ray tomography, thermography, eddy current or ultrasonic testing. Test specimen can range from homogeneous to strongly inhomogeneous structures consisting of carbon-fiber-reinforced polymer (CFRP) or fiber composites. For current applications see [1–6]. The most widely used testing method is ultrasonic NDT. It is based on the propagation of low amplitude waves through the material, measuring the travel time and intensity of the waves at specific sensors. In general, only radiological and ultrasonic techniques are able to detect internal flaws accurately. For an introduction into ultrasonic NDT see, [7–9]. Ultrasonic NDT is extensively employed in the aerospace industry and in the scope of the nuclear, oil and gas sectors. Because of the short time duration of the signal, Ricker wavelets with center frequencies ranging from 0.1–20 MHz and wavelengths in the range of 1 to 10 mm are used to transmit US waves into materials to detect internal flaws. The advantages of ultrasonic NDT are that it is suitable to detect flaws deep inside the part, allowing to detect extremely small flaws (in order of the wavelength of the source). Further, it serves to estimate the size, orientation and shape of defects. In principle, flaws and other discontinuities hidden in the structure produce reflective interfaces and can thus be detected using ultrasonic NDT.

Conventional ultrasonic NDT methods were parameter-based, because earlier devices were not able to store the entire signal for every sensor. The idea is to assume that the measured signals can be described sufficiently accurate by a set of parameters. Examples for such parameters are the maximum peak-to-peak amplitude, arrival time, rise time or duration of the signal, see [11] for a general overview. In the conventional approach, the physical measurements – or some selected features – are compared to reference measurements in the flawless specimen by a human expert who then decides if there is a flaw in the specimen or not, based on man-made criteria. This standard NDT device has the capability to detect damage, but usually not to provide detailed information on the damage parameters. The basic setup for a purely experimental NDT device is shown in Fig. 1(a).

More recently, it became possible to store the complete signals, allowing to couple experimental data with numerical simulation models. [10] introduced an approach that is based on a combination of experimental measurements and a simulation model. Fig. 1(b) shows this model-based NDT system where a flaw is identified based on a comparison to a computational model that assumes various candidate flaws. Their position is varied to find the best fit. The key idea of this approach is to use the concept of time reversal, see [12]. It is based on the reversibility property of wave propagation, which allows developed signals to propagate back in time to determine the original source that emitted them. If the source is very local, this procedure is called refocusing. It can be divided into three parts. First, a known source generates waves in the structure and the time-varying response of the structure is measured at certain points and times. Second, using a computational model of the structure, the measured signals are played back into the structure to construct a time reversal solution for each set of flaw parameters. A specific measure is used to find the initialization time at the original source. Third, the flaw identification problem is posed as an optimization problem: "*Among all crack candidates, find the crack which yields the best wave refocusing at the true source location*." See [10,13] for more details.

Time reversal methods have been used extensively in the field of seismology, see [14–18] and were adapted for NDT, see [19,20]. Recently, this approach has been extended to the so-called *full waveform inversion*, which is used to create high-resolution wave speed models. It performs forward modeling to compute the differences between the acquired seismic data and the current model—as well as a process similar to reverse-time migration (RTM) of the residual dataset to compute a gradient and to update the wave speed model. See [21] for more details. As the parameter space for these wave speed models is often extremely high-dimensional (one parameter may be assumed for one finite element in a 3D finite element model) the method relies on adjoint-based techniques to compute the gradient efficiently. Similar methods have been used in many