Journal of Sound and Vibration 413 (2018) 383–394

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Localization of multiple defects using the compact phased array (CPA) method

Volkan Y. Senyurek [a,*,1], Amin Baghalian [b,1], Shervin Tashakori [c], Dwayne McDaniel [c], Ibrahim N. Tansel [b]

[a] Department of Electrical & Computer Engineering, University of Alabama, Tuscaloosa, AL, USA
[b] Department of Mechanical & Materials Engineering, Florida International University, Miami, FL, USA
[c] Applied Research Center, Florida International University, Miami, FL, USA

ARTICLE INFO

Article history:
Received 26 April 2017
Received in revised form 12 October 2017
Accepted 27 October 2017

Keywords:
Phased array
Beam forming
Lamb wave
Total focusing method
Damage localization

ABSTRACT

Array systems of transducers have found numerous applications in detection and localization of defects in structural health monitoring (SHM) of plate-like structures. Different types of array configurations and analysis algorithms have been used to improve the process of localization of defects. For accurate and reliable monitoring of large structures by array systems, a high number of actuator and sensor elements are often required. In this study, a compact phased array system consisting of only three piezoelectric elements is used in conjunction with an updated total focusing method (TFM) for localization of single and multiple defects in an aluminum plate. The accuracy of the localization process was greatly improved by including wave propagation information in TFM. Results indicated that the proposed CPA approach can locate single and multiple defects with high accuracy while decreasing the processing costs and the number of required transducers. This method can be utilized in critical applications such as aerospace structures where the use of a large number of transducers is not desirable.

1. Introduction

Guided-waves based structural health monitoring systems are widely used in civil, mechanical, and aerospace applications. Guided waves, can propagate over long distances and inside curved walls with low attenuation and high sensitivity [1,2]. In particular, Lamb wave based methods play a critical role in detection and localization of damage in the structural health monitoring (SHM) of pipes and plate-like structures. These waves are utilized in transducer arrays for localization of defects since they can scan large areas and provide a mapping of defects of the scanned surface. Typically, complicated electrical devices and/or detection algorithms are required for successful damage detection and localization using transducer arrays.

Generally, in SHM, detection and localization are carried out based on information that is collected from time of flight [3,4], energy transmission [5], reflections from defects [6,7], changes in wave modes [8], electro mechanical impedance information

* Corresponding author.
E-mail addresses: vsenyurek@ua.edu (V.Y. Senyurek), abagh004@fiu.edu (A. Baghalian), stash002@fiu.edu (S. Tashakori), mcdaniel@fiu.edu (D. McDaniel), tanseli@fiu.edu (I.N. Tansel).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.jsv.2017.10.037
0022-460X/

[9–11] or acoustic emission [12,13]. Regarding transducer arrays, a single transducer pair is not enough to determine the exact location of damage in plate-like structures. Transducer arrays are typically used to obtain a map of defects in a structure. Different algorithms and approaches can be used for this purpose.

Among the array systems, the sparse array method is highly suitable for large but simple structures [14]. In this method, transducers are mounted in different locations on the surface of the target structure. Typically, at least three or four sensors are required to find the location of the damage [15–18]. In the sparse approach, multiple numbers of tests have to be performed, where in each test, one of the piezoelectric elements acts as an actuator and the remaining piezoelectric elements work as sensors. A virtual image of possible locations of damage on the target surface can be formed from all sensors. The image contrast can be negatively influenced by low signal to noise ratio (SNR), direct arrivals, scattered waves, and reflections from boundaries. Regarding the low SNRs, it should be noted that the excitation is omnidirectional and emitted waves propagate in all directions. As a result, a very small portion of energy is radiated in each direction and therefore, reflections from a damage location to the sensors will be very low in energy. Thus, in most of its applications a high voltage was applied for the excitation to increase the SNR value. For instance, Konstantinidis et al. [19] and Prado et al. [20] used peak-to-peak voltages of 190 V and 120V for the excitation, respectively. However, baseline subtraction can improve the resolution and alleviate the problem [21]. Yet, the sparse arrays are not suitable for small and complex structures which do not have enough space for placement of transducers.

When dealing with smaller structures, the compact array configuration can be an alternative for sparse arrays. Various arrangements of compact transducer arrays, such as circular, rectangular, and linear configurations have been proposed to minimize the footprint of transducers on small structures. These arrays generally use a single transmitter and multiple receivers (STMR) [22]. Different algorithms, such as the phase reconstruction algorithm [23], minimum variance distortion-less response (MVDR) [24,25], and total focusing method (TFM) have been used in the compact array systems [26]. These arrays can also work as multi-transmitter multi receiver (MTMR) systems.

Phased arrays are another group of methods in array based SHM systems which work like radar systems. In these methods, real beam forming is carried out by steering the outputs of all transducers in a controlled manner to trace the whole surface of a structure similar to a radar system. That is, in this approach through real beam forming a powerful wave energy is emitted in a predetermined direction by exciting all the actuators at the same time. Short inspection times and high SNR values are the main advantages of this method. In linear ultrasonic phased arrays focusing the energy in the desired directions requires expensive and complex electronic phase or pulse shifters and multiplexers for excitation of all transducers at the same time [27–29].

Virtual beam forming methods were developed to resolve difficulties associated with real beam forming and simultaneous excitation of transducers. In virtual beam forming the transducers are excited one at a time and there is no need for the concurrent excitation of all transducer elements. The recorded responses in different sensor locations are post processed to obtain the required information in a desired direction by filtering the unwanted information related to the other directions [18], [30]. However, massive post processing and low SNR value are the two main disadvantages in the group of virtual beamforming or steering based techniques.

This study proposes the application of an incremental three stepped steering approach using a compact phased array (CPA) with total focusing method. The proposed method eliminates the need for multiplexers, pulse, and phase shifter devices that are used in phased array systems. The method is based on creating beams in desired directions by using two transducers at a time and a third PZT element for sensing. The results are then processed by using the standard and modified TFM. Finally, by adding the information collected from all directions, a complete map of defects can be acquired. The theoretical background, experimental setup, and the performance of the proposed SHM system will be discussed in the following sections.

2. Theoretical background

2.1. Lamb waves

Elastic mechanical waves can be efficiently produced on plate-like structures using piezoelectric elements. These waves are referred to as guided waves since they are guided and bounded by two surfaces of the plate. Vertically polarized ultrasonic guided waves that travel in plates are called Lamb waves. In plate structures, Lamb waves can propagate in asymmetric and anti-symmetric modes. Symmetric and antisymmetric Lamb waves have symmetrical and anti-symmetrical movements about the mid-plane of the plate, respectively. The wave propagation speed is not necessarily the same for symmetric and anti-symmetric modes even at the same frequencies. The velocities of the waves can be calculated when the excitation frequency and the plate thickness are known. The characteristics of the Lamb waves depend on excitation frequency, access angle, dimensions of the plate, transducer's characteristics and the material of the structure [31,32].

2.2. Array radiation pattern

Transmission of the waves produced by phased arrays was first studied in 1905 for enhancing transmission of radio waves during World War II. Since that time, phased arrays have been used in many areas, such as ultrasonic applications, optics, and acoustics. In general, array configurations consist of multiple transducer elements that are carefully arranged to achieve a desired radiation pattern. The radiation pattern of a linear array made by identical transducer elements can be found