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Original Research Article

Guided waves for monitoring of plate structures with linear cracks of variable length

B. Zima, M. Rucka *

Department of Mechanics of Materials and Structures, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, ul. Narutowicza 11/12, Gdańsk 80-233, Poland

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ABSTRACT

Damage occurring at the work of plate structures may grow to a considerable size. The joint action – the detection of a defect at the earliest possible stage, the monitoring of its growth and the determination of its critical size in the context of structural reliability allows optimizing the cost of the maintenance and repair of structural elements. Thus the development of monitoring systems for permanent observation of fault evolution is of great importance among civil, mechanical and aerospace engineering communities. This paper focuses on a diagnostic system dedicated for plate structures with a variable length linear crack using the guided wave-based technique and a novel ellipse-based binary damage imaging algorithm. The emphasis is put on the relationship between the configuration of embedded piezoelectric transducers and the extent of a defect possible to identify. Numerical and experimental results show that the proposed diagnostic system has a great potential for the implementation in monitoring systems dedicated for the evaluation of damage growth.

1. Introduction

Plates are widely used as components of civil, mechanical or aerospace structures like bridges, silos, machines or aircrafts. Diagnostics of such plane areas should provide information not only about the presence of possible damage but also its precise localization and extent. Recently various non-destructive testing (NDT) methods have been developed for damage detection in metal or composite plates, including vibration-based methods and ultrasound-based methods. Vibration-based damage detection methods make use of dynamic characteristics of a structure. The approach particularly useful for accurate damage localization utilizes structural mode shapes and their further analysis by the wavelet transform. Spatial wavelet analysis was applied for damage localization in beams [1] and metal plates [2] as well as in composite plates [3] and composite elements with non-linear geometry [4]. Ultrasound techniques are based on generating stress waves. High-frequency ultrasonic testing can be used for evaluation of adhesive joints of plates providing detail representation of defect areas [5]. An extension of ultrasonic wave testing from local to global approach of sending and sensing waves is the wave propagation-based technique. Intensive experimental investigations with the use of Lamb waves were undertaken

* *Corresponding author.*
E-mail addresses: beazima@pg.gda.pl (B. Zima), mrucka@pg.gda.pl (M. Rucka).
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from the early 1960s [6]. A wide range of studies has already been reported on the Lamb wave scattering from damage in metal plate structures [7–9], composite materials [10] or shell-like structures [11].

The initiation of structural damage may be caused by different reasons, like progressive degradation due to operational and environmental loadings, corrosion, fatigue or impact. The detection of a defect at the earliest possible stage, the monitoring of its evolution and the determination of its critical size in the context of structural reliability allows optimizing the costs of the maintenance and repair of structural elements. Therefore, there is a need to develop monitoring systems for permanent observation of fault evolution. A promising solution referring to automatic monitoring systems is the method based on guided waves due to their ability of propagation over long distances and inspection of large areas with a small number of permanently attached sensors [12,13].

The monitoring system based on guided waves consists of two parts: the hardware, i.e. an array of embedded piezoelectric transducers with a data acquisition system and the software, i.e. a damage imaging algorithm for defect localization on the basis of registered wave propagation signals. One of the most common damage imaging algorithm is based on the so-called ellipse method, used in many previous research. Tua et al. [14] constructed elliptical loci of possible line crack positions based on the time-of-flight of crack-reflected waves. Michaels and Michaels [15] used the ellipse method to create damage images based on signals from a sparse array of piezoelectric transducers attached to a plate structure with through holes. Kudela et al. [16] presented an algorithm of damage detection in composite plates with a 16.6 mm crack using damage influence maps based on signals from a clock-like configuration of sensors. An extension of the ellipse method for anisotropic plate structures with the use of distributed sensor network was performed by Moll et al. [17]. Yu et al. [18] presented results of damage detection in an aluminium plate with a 19 mm long crack. They used a summation algorithm and a correlation algorithm based on ellipse creation. In the paper [19] a problem of damage detection in plates was investigated using triangular configuration of piezoelectric transducers. Damage was analyzed by means of an additional mass in the form of two disc magnets. Different kinds of damages (additional mass, drilled hole, 10 mm notch) and various configurations of sensors (strip, cross, square, circle) using the ellipse method were studied by Wandowski et al. [20]. Lu et al. [21] developed a probability-based damage imaging in a welded tubular steel structure with a 12 mm defect. Yan [22] proposed a Bayesian damage localization approach for plate-like structures, quantifying the identification uncertainties. A new damage localization algorithm using chirp technique for dispersion pre-compensation was studied by Zeng and Lin [23].

Most of the above reported works deal with the problem of the detection of point defects or line defects of a small size, not exceeding several millimetres. This study focuses on the evaluation of the extent of line-crack defects of considerable size. The guided wave-based diagnostic system consists of an array of embedded piezoelectric transducers and a new ellipse-based binary damage imaging algorithm. The developed algorithm is used to investigate numerically and experimentally steel plates with variable length damage. The main aim of the study is to investigate the relationship between the configuration of transducers and the extent of the defect possible to identify.

2. Ellipse-based binary algorithm for defect imaging

The idea of the ellipse method is to determine a probable position of a defect based on wave reflections identified in the registered signals. The method uses geometric relationships between the mutual position of sensors and the distance of propagation path calculated based on the time-of-flight (ToF) of scattered waves. In the ellipse method, more than two pairs of sensor–actuator are necessary to provide unambiguous information regarding the location of damage. The reflections in signals are assumed as a result of structural defects which provide scattering of waves. On the base of the known value of the wave group velocity and the identified value of the ToF for the scattered wave it is possible to calculate the actuator–damage–sensor distance. All solutions of a constant distance create an ellipse in the plane. The distance excitation point–damage–registration point, which is the sum of position vectors of each point lying on the ellipse (Fig. 1), can be computed as:

$$d_i = \Delta t_i c_g, \tag{1}$$

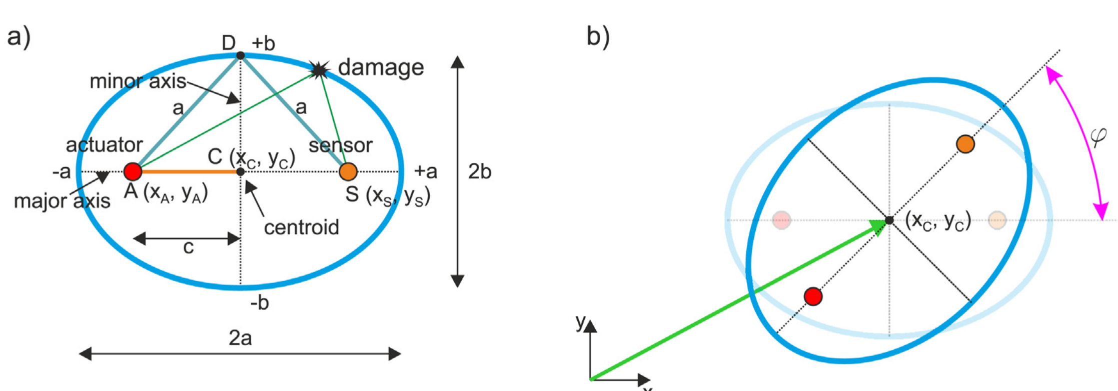

Fig. 1 – Schematic view of ToF-based ellipse method: (a) geometric relationship for ellipse method; (b) translation and rotation of ellipse.