Contents lists available at ScienceDirect
Aerospace Science and Technology
www.elsevier.com/locate/aescte

The crack detection and evaluation by elastic wave propagation in open hole structures for aerospace application

Marek Barski, Adam Stawiarski

Institute of Machine Design, Cracow University of Technology al. Jana Pawła II 37, 31-864, Cracow, Poland

A R T I C L E I N F O

Article history:
Received 30 January 2018
Received in revised form 2 May 2018
Accepted 28 July 2018
Available online xxxx

Keywords:
Plate with hole
Aluminum alloy
Elastic waves
Piezoelectric transducers
Damage detection
Estimation of crack length
Finite element simulation

A B S T R A C T

The rectangular plate made of aluminum alloy with a relatively large circular hole in the geometrical center of the structure is subjected to uniform tension. This loading causes that in the vicinity of a hole a process of crack formation is triggered. The crack is detected and evaluated with the use of elastic wave propagation method. The piezoelectric activator is located directly on the edge of the hole and the rest of sensors are placed at an equal distance from the activator. The crack is detected by comparison of the reference, obtained for the intact plate, and the actual signal (pitch-catch measurement). The appropriate damage magnitude measurement is proposed. Moreover, the system, which works without knowledge of an intact structure, is also discussed. In order to estimate and visualize the length of a crack, the advanced diagnostic imaging is introduced. The applied method is based on a visualization of sensing paths with an assigned value of correlation coefficients, computed for reference and actual signals. The effectiveness of the described system is verified with the use of numerical simulation and experimental test. The theoretical analysis is carried out with the use of the finite element method. The computations are performed for several assumed lengths of cracks. The obtained theoretical results, as well as the experimental analysis, confirm the fact that the crack can be detected at an early stage of formation. Moreover, a relatively good agreement between the real crack lengths and the ones obtained with the use of the proposed method is observed in the numerical analysis as well as in the experiment.

1. Introduction

Nowadays, the problem of automatic damage detection at the early stage of formation in different kind of structures becomes very important. First of all, such technologies ensure the higher safety, which is especially important in civil transport (aviation, railway transport). Moreover, such systems allow for a longer service life between necessary inspections, which significantly reduces the costs of exploitation. Finally, such systems allow for remote inspection of hard-to-reach parts of the machines, for example, the internal structure of the aircraft wing. Generally, the methods which enable a diagnosis of the structure, especially in online mode, are known as structural health monitoring (SHM) [1,2]. Among different possibilities, the application of the elastic waves seems to be the most promising due to the simplicity of the use of piezoelectric transducers in practice [3]. There are two main type of elastic waves, namely: Lamb waves [4], which propagate in thin-walled structures and Rayleigh waves [5], known also as surface waves. From a practical point of view, the Lamb waves are more useful, because they can propagate for a long distance without a significant loss of energy, thus it possible to inspect large areas. Probably, the one of the first scientists, who recognized the potential of the use of Lamb waves for damage detection, was Worlton [6] in 1957. Next, Ball and Shewring [7] in 1973 and Mansfield [8] in 1975 analyzed the possible application of elastic waves in the case of damage detection a in wide range of different strips and plates. Over the past twenty years, Lamb waves have been widely used to detect damage in railway rails [9], pipes and cylinders [10] or thin-walled structures like elements of aircraft skin [11]. The elastic waves can also be applied in the case of composite materials in order to detect defects, which are characteristic for this kind of materials, e.g. matrix cracking, delaminations or fiber debonding [12]. They can also be used to evaluate mechanical properties of composite materials [13], thickness measurement [14] or phase velocity [15].

Current work is devoted to the detection of cracks in the vicinity of holes with the use of elastic waves. The different cut-outs are one of the most important parts of all support structures. First of all, the existence of such holes is necessary for the weight reduction of the whole structure. The cut-outs also have to be made due to the installation of different pipes or wires, for example,

E-mail addresses: mbar@mech.pk.edu.pl (M. Barski), asta@mech.pk.edu.pl (A. Stawiarski).

https://doi.org/10.1016/j.ast.2018.07.045
1270-9638/© 2018 Elsevier Masson SAS. All rights reserved.

the hydraulic pipes inside an aircraft wing. A separate problem is the holes made for rivets. The existence of any holes causes that the continuum of material is disturbed and, as a result of external loading, the stress concentration arises in the vicinity of holes. As a consequence of such a state, the crack can appear. It is especially dangerous in case of structures, which are subjected to cyclic load. Moreover, the localization of holed structures very often makes the inspection difficult or even impossible. Thus, the undetected cracks can growth until the whole structure will be destroyed. Unfortunately, the number of papers devoted to the discussed above problems is not significant and they are mainly connected with the detection of cracks in the case of relatively small holes, for example, rivet holes. The analytical solution of Lamb wave scattering from a through-thickness hole is presented by McKeon and Hinders [16]. They use Kane and Mindlin's plate theory in order to obtain pattern of wave amplitude scattered from the hole. The similar work is presented by Grahn [17]. However now the scattering problem of an incident plane Lamb wave in a plate with circular partly through-thickness hole is investigated. In the next work by Zensheu Chang, Ajit Mal [18] the problem of crack detection in the neighborhood of a rivet hole is studied. In order to obtain the theoretical solution for the infinite plate with a circular hole, the hybrid (global–local) finite element (FE) method is utilized. The obtained results are verified experimentally. The main conclusion is that the existence of cracks on both sides of the hole changes the scattered wave, which is especially visible in a frequency domain. However, there is no information about the estimated length of a crack. The similar problem is investigated by Fromme and Sayir [19]. The theoretical analysis is conducted with the use of Mindlin's plate theory and the finite difference method. The damage is detected by the incident and scattered wave analysis. The existence of one-sided crack is visible by disturbance of amplitude measured around the edge of the hole. As before, there is no available estimation of the crack length. The fatigue damage in a rivet joints caused by cyclic load is studied also by Grondel et al. [20]. The signals received by piezoelectric transducers are analyzed with the use of Hilbert transform and time–frequency analysis. Additionally, with the Lamb waves, the acoustic emission is also applied. Like before, there is no clear estimation of the magnitude of the damage. The Lamb waves are also used by Mofakhami and Boller [21] in order to detect both-sided crack on the edge of a circular hole. The propagation of the elastic wave is simulated with the use of ANSYS9.0 finite element system. The time–spatial solution is obtained with the use of Newmark time integration method including an improved algorithm HHT. In this work, one can find the simple numerical model of piezoelectric sensors. Relatively original approach to the problem of crack detection in a rivet joint is presented by Shudong Liu et al. [22]. The authors use the wavelet transform and artificially neural networks in order to detect and localize the damage in a rivet joints. The wavelet transform is used to extract a robust and effective feature called energy ratio change from time domain signals. One neural network is first used to diagnose plate integrity. If cracks are detected, then the second neural network is called to determine their locations.

For last several years, there have been more sophisticated methods applied in order to detect the crack in comparison with those, which are discussed above. Here the paper by Ming Hong et al. [23] can be quoted. The authors extend the use of temporal signal processing to the realm of nonlinear Lamb waves so as to reap the high sensitivity of nonlinear Lamb waves to small-scale damage (e.g. fatigue cracks), and the efficacy of temporal signal processing in locating damage. Nonlinear wave features (higher-order harmonics) are extracted using networked miniaturized piezoelectric wafers and reverted to the time domain for damage localization. Masserey and Fromme [24] investigate the scattering of the coupled fundamental Lamb wave modes by fatigue cracks in structures with a circular hole. Experimentally the high frequency guided waves (2.25 [MHz]) were excited using standard angle beam transducers and the scattered field around the hole was measured with the use of laser interferometry. The propagation and scattering of the high frequency guided wave at the fastener hole were simulated using a three-dimensional, second-order, displacement-stress finite difference (FD) formulation. Yikuan Wang et al. [25] apply a nonlinear Lamb-wave-based method for fatigue crack detection in steel plates with and without carbon fiber reinforced polymer (CFRP) and small through-thickness circular hole. With the generation of the second harmonic, the damage induced wave nonlinearities are identified by surface-bonded piezoelectric sensors. Yi Yang et al. [26] presents experimental and theoretical analyses of the second harmonic generation due to non-linear interaction of Lamb waves with a fatigue crack. Three-dimensional FE simulations and experimental studies are carried out to provide physical insight into the mechanism of second harmonic generation. In this paper one can also find the numerical model of piezoelectric sensor. Chiu et al. [27] present a computational study of the interaction between the edge-guided wave and small crack on a circular hole in an aluminum plate. It is shown that edge waves traveling on the curved surface leak energy into the medium, unlike those traveling on a straight surface which do not attenuate, and the scattered field generated by their interaction with an edge crack is investigated. It should be noted that this work concerns relatively large circular hole with diameter $d = 40$ [mm].

To sum up, it is worth stressing that the mentioned above works are mostly concerned with small holes in rivet joints. The damage detection procedure is mainly based on the analysis of a scattered wave. Generally, there is no estimation of the actual crack length or the damage size. The currently presented work is devoted to the problem of detection and evaluation of crack length in the case of relatively large holes. It is assumed that there is known a system of external loads. Therefore, it can be predicted the most dangerous point where the damage may be initialized. Moreover, the direction of the crack propagation is also known. Thus, it is possible to design the SHM system, which is able to detect the damage and evaluate the size of it. The proposed system utilizes a pitch-catch measurement technique and the idea of signal correlation [28]. Additionally, this procedure can also work without a reference information obtained for intact structure. The preliminary approaches are described by Stawiarski et al. [29–31].

2. Experimental setup

A schematic of the experimental setup is depicted in Fig. 1. The investigated specimen is a square plate of dimension $l_p = 200$ mm and thickness $t_p = 2$ mm. In the geometrical center of the structure there is a circular hole of diameter $d = 50$ mm. The plate is made of aluminum alloy EN AW 1050A. The mechanical properties are presented in Table 1.

The plate is uniformly stretched in the vertical direction. Generally, in the case of high enough load level, this process causes that horizontal cracks appear on the both sides of the hole. Therefore, the main goal of this work is detection of the moment of crack initiation and further estimation of its actual length with the use of elastic waves.

On the surface of the plate there are installed 10 identical rectangular piezoelectric transducers Noliac CMAP06 with dimensions 3×3 mm and 2 mm height. One of them, placed on the edge of the hole, generates an excitation signal and the rest of piezoelectric elements register the dynamic response of the studied plate. The detailed position of the transducers will be discussed in the next part of this paper. The excitation signal is actuated by the arbitrary function generator HAMEG HMF 2525 25 MHz and amplified

Please cite this article in press as: M. Barski, A. Stawiarski, The crack detection and evaluation by elastic wave propagation in open hole structures for aerospace application, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.07.045