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Circular sensing networks for guided waves based structural health monitoring

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ABSTRACT

In this paper, results of damage localization performed for four sensing network configurations are compared. Process of damage localization is based on guided waves propagation phenomenon. Guided waves are excited using piezoelectric transducer and received by scanning laser vibrometer. Different excitation frequencies are also investigated. In experimental investigations two types of piezoelectric transducers are used as guided waves exciters. Frequency–magnitude characteristics of symmetric and antisymmetric modes are created for both types of transducers. These characteristics allow a choice of an excitation frequency for efficient generation of selected wave mode. The amplitude of second mode in this case has negligibly small value. Finally, sensing networks in the form of circle with three different diameters are realized based on piezoelectric transducers. Damage localization algorithm is prepared in MATLAB® environment as well as in C++.

1. Introduction

Structural Health Monitoring (SHM) is well known technique that allows us to assess the state of structures in real time. In many cases elastic waves propagation method is utilized for SHM. This is a very promising technique that is very sensitive to small damage in early stage of growth. Owing to this sensitivity, the damage can be detected early before it is dangerous to the structural integrity.

In many cases elastic waves are generated and received using piezoelectric transducers [1]. They are very light, thin and can be used as actuators and sensors, which makes them very attractive for SHM applications. Elastic wave propagation method was utilized for damage localization in very simple structural elements like rods [2,3], beams [4], pipes [5,6]. However, large number of papers are related to topic of damage detection and localization in metallic as well as composite plates: [1,7,8]. Elastic wave propagation method was utilized in order to localize damage also in more complicated structures. In Ref. [9] damage localization was performed in aluminum honeycomb panel. Damage detection was also conducted in the case of bolted steel members [10], riveted spacecraft like panels [11], three-story bolted frame structure and fuselage rib structure [12]. As far as composite structures are concerned the research was focused on panels with stiffeners [13] and wing box [14,15].

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Generally two approaches of elastic wave propagation method are used in terms of actuation and sensing methods: pitch-catch [16,17] and pulse-echo [16,4]. In pulse echo approach a special case can be distinguished—the phased array technique [1,5,9]. It takes advantage of wave interference phenomena in order to directionally excite and sense elastic waves. Giurgiutiu and Soutis in Ref. [18] introduced third approach called the thickness mode. The same authors also distinguish fourth approach called impact/AE detection. This method is used for impact source location and it is a passive method in contrary to the three active methods mentioned above.

Elastic wave-based methods allow to detect such damage as fatigue crack [19,20], corrosion [7,11], delamination/debonding [2,4,21], impact caused damage: for example crushing over multiple honeycomb cells [9], delamination or broken fibers [16]. Very interesting is the investigation of moisture absorption influence on Lamb wave propagation in viscoelastic carbon fiber reinforced plastics/polymer CFRP [22]. SHM systems can be used in many fields like aerospace structures [11,12], civil engineering structures (e.g. bridges) [23], wind turbines.

Application of SHM systems in aerospace structures is a great challenge because a lot of works has to be done according to many types of certification that is needed to approve such a system on an aircraft (especially in passengers aircrafts). However, from some time attention of researchers is focused on SHM applications for Unmanned Air Vehicles (UAV) [24]. Certification of SHM system for the UAV could be simpler than in the case of an aircraft, because human life is not directly in danger. Some examples of SHM system developed for UAV can be found in the literature [25–27]. The monitoring of adhesively-bonded CFRP composite joints through the use of ultrasonic guided waves is proposed in Ref. [25]. The components examined are representative of the wing skin-to-spar joints of UAV. Other, non-wave-based, SHM solutions for the UAV were also reported in the literature. In Ref. [26] reconfigurable multivariable MEMS array is proposed for monitoring of loads and spatial orientation of UAV (accelerations, rotational rates, magnetic fields, temperature and pressure). Interesting application of fiber optics technique in order to monitor structure of UAV can be found in Ref. [27].

Summarizing, a lot of work has been done in the area related to the SHM systems based on elastic waves propagation. However, some of the fields still are not sufficiently covered by the research, for example the problem of optimal transducer placement in SHM systems. Most papers are related to general problem of sensor placement but are not related to the SHM sensing problems. In Ref. [28] the problem of proper placement of visual sensors across a sensor field for covering targets with arbitrary location and orientation is investigated. In Ref. [29] a multi-objective optimization method using genetic algorithm was proposed for sensor array optimization. Based on information theory, selectivity and diversity were used as the criteria for constructing two objective functions. A statistic measurement of resolving power, general resolution factor, and visual inspection were used to evaluate the optimization results with the aid of principal component analysis (PCA). Authors of paper [30] deal with localization errors in distance-based multi-hop localization procedures of one-dimensional sensor networks through the Cramer–Rao lower bound (CRLB). The fundamental behaviors of localization errors were analyzed and it was shown that the localization error for a sensor is locally determined by network elements within a certain range of this sensor. In Ref. [31] authors investigated problem of wireless sensors placement. The effectiveness of the wireless sensor networks depends to a large extent on the coverage provided by the sensor deployment scheme. A sensor deployment scheme based on glowworm swarm optimization (GSO) to enhance the coverage after an initial random deployment of the sensors was presented. In Ref. [32] authors investigate the coverage problem in directional sensor networks (DSN). Authors categorize available studies about coverage enhancement into four categories: target-based coverage enhancement, area-based coverage enhancement, coverage enhancement with guaranteed connectivity, and network lifetime prolonging. In Ref. [33], the multi-type sensor placement for SHM was intvestigated. The investigation was focused on simultaneous placement of strain sensors and accelerometers based on application demands for SHM system.

Many papers can be found that are related to problem of the optimal sensor placement for parameter estimation in structural dynamics. In Ref. [34], the effect of spatially correlated prediction errors on the optimal sensor placement was investigated. The information entropy was used as a performance measure of the sensor configuration. The optimal sensor locations were formulated as an optimization problem involving discrete-valued variables. Analysis showed that the spatial correlation length of the prediction errors controls the minimum distance between the sensors and should be taken into account when designing optimal sensor locations. In Ref. [35], the author concluded that the process of planning of sensor placement can be realized by a finite element model before a modal test will be performed. Author proposes method in order to select the most relevant degrees of freedom which should be monitored by sensors. It uses two criteria based on observability of mode shapes and on information shared by sensors. A set of sensors is obtained by maximizing the norm of a Fisher information matrix and by avoiding the redundancy of information between the selected degrees of freedom. In Ref. [36], process for determining the optimal sensor placement in Structural Health Monitoring system of a suspension bridge is conducted. Four different optimal sensor placement methods have been investigated, including the effective independence (EI) method, the effective independence driving-point residue (EFI-DPR) method, the minimized modal assurance criterion (min MAC) method and the principal subset selection-based extended EI (PSS-EI) method. Then, three criteria, which are modal assurance matrix (MAC), condition number (CN) of mode shape matrix and determinant of Fisher information matrix (FIM), were employed to evaluate the effect of the optimal sensor placement methods, respectively. The result showed that the PSS-EI method developed has the ability to guarantee the highest determinant of FIM, a relatively small off-diagonal term of MAC and agreeable CN, as well as the deployment of sensors in a uniform and symmetric fashion for the studied bridge. In Ref. [37], a new approach to optimal placement of sensors in mechanical structures is presented. In contrast to existing methods, the presented procedure enables a designer to seek for a trade-off between the presence of desirable modes in captured measurements and the elimination of influence of those mode shapes that are not of interest in a given