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Non-axisymmetric Lamb wave excitation by piezoelectric wafer active sensors

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ABSTRACT

A Lamb wave-based structural health monitoring system requires the exact knowledge of the dynamical behavior of piezoelectric actuators. Since piezoelectric wafer active sensors (PWASs) with a disk-wrapped electrode are used in many practical applications, a detailed description of the radiation field is essential to enhance the damage detection sensitivity. It has been shown in the literature that the radiation pattern is often directional and frequency-dependent. While a uniform radiation occurs at low excitation frequencies of several tens of kilohertz, the radiation pattern becomes strongly non-axisymmetric when the excitation frequency increases. The theoretical considerations and experimental studies in this paper show that this effect can be attributed to the influence of the complex actuator shape with disk-wrapped electrode. Therefore, simulation procedures based on an integral approach and a pin-force model are compared with experimental measurements with a laser-Doppler vibrometer (LDV).

1. Introduction

Guided waves propagating in thin shell structures exhibit high sensitivities when they interact with structural elements such as geometric boundaries or stiffeners. Similar sensitivity can be observed when the waves hit a structural defect, e.g., a crack or delamination. Due to these properties, guided waves are widely used for the continuous surveillance of technical structures in a health monitoring framework [1–5]. An elementary part of such a monitoring system are piezoelectric transducers since they excite acoustic waves as a response to a voltage pulse via the inverse piezoelectric effect. Piezoelectric transducers are usually adhesively bonded on the surface of a structure or integrated into a composite during the manufacturing process.

The initial wavefield excited by these actuators is of particular importance because it determines the subsequent wave propagation in the structure and the capability of finding hidden defects. An example is a piezocomposite transducer, which excites a very directional wavefield due to the influence of its piezoelectric fibers [6]. Although piezocomposite transducers are more flexible than piezoceramic discs, they are less suited for the application in a general spatially distributed transducer network, because the wavefield in certain directions has almost zero amplitude. This makes the monitoring system blind in these directions. On the other hand, it is shown that rectangular transducers exhibit a corner effect that influences the near field around the transducer especially [7]. Thereby, exact knowledge on transducer dynamics should be used through the optimization of monitoring systems.

In recent years, a considerable amount of literature has been published on the modeling and experimental analysis of piezoelectric wafer active sensors (PWASs) trying to explain the transducer dynamics, e.g. [8–12]. Two classes of mathematical models can be marked out in the literature. The class of coupled models takes into account the coupling between the actuator and the substrate; this leads to mathematical complications due to the corresponding boundary-value problems, e.g. [9,10,13]. The second class are the so-called uncoupled models utilizing a predetermined form of the stresses generated by the actuators. This approach, arising from the classical pin-force model [14], uses concentrated forces applied for the approximation of stresses that are generated by PWAS in the media. Moreover, it was found in ref. [8] that the sensor response of a circular transducer on an isotropic plate is, to a certain extent unexpected, angular dependent.

The paper focuses on the investigation of the dynamical properties of circular PWAS with disk-wrapped electrode since they are widely used in practical applications. The generated wavefield exhibits a non-axisymmetric and frequency-dependent behavior due to the complex shape of the PWAS. The mathematical and the computer model are based on an integral approach [15], where a pin-force excitation [16] is applied to account for the transducers dynamics. Both, the simulation and the experiment consider a flat isotropic plate with surface-bonded PWAS. For the experimental

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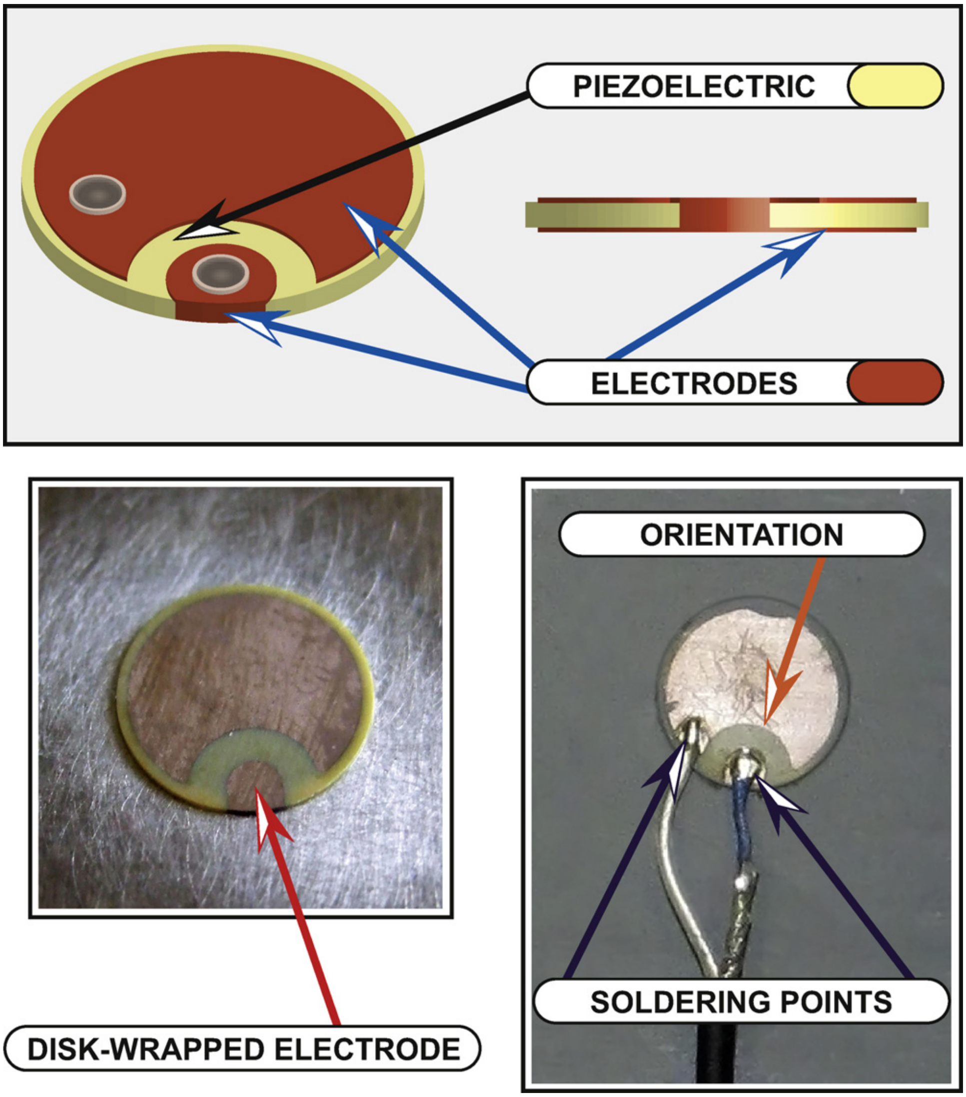

Fig. 1. Structure of PWAS: geometry, orientation coming from the electrode position and soldering points.

investigations a LDV is used. Furthermore, the influence of the soldering spot positions on the radiated wavefield is analyzed from experimental data.

2. Experimental setup

A typical PWAS used in practical SHM applications is depicted in Fig. 1. It consists of three layers, where the middle layer is made of piezoelectric material. The electrically conducting bottom layer is wrapped to the top surface so that an additional coupling layer between substrate and transducer providing the electric contact, e.g. a layer of brass, is not necessary. Due to the electrode wrapping, the geometry of the transducer becomes non-axisymmetric and more complicated. As a result, the PWAS gets an orientation with respect to the electrode position.

The impact of PWAS structure and the position of the soldering spot position have been investigated with the experimental setup shown in Fig. 2. LDV measures the out-of-plane component of the wavefield that corresponds to the A_0-mode motion in the considered low frequency-thickness range. For a detailed description of the experimental setup the reader is forwarded to ref. [17]. According to the dispersive nature of Lamb waves, a narrow band voltage pulse is applied. The Hanning-windowed toneburst with N_c cycles and a carrier frequency f_c is defined by

$$p(t) = \frac{1}{2}\cos(2\pi f_c t)\left(1 - \cos\left(\frac{2\pi f_c t}{N_c}\right)\right), \quad 0 < t < \frac{N_c}{f_c}. \tag{1}$$

Fig. 3 shows the design of the specimen; the Cartesian $\boldsymbol{x} = (x, y, z)$ as well as the cylindrical $\boldsymbol{x} = (r, \varphi, z)$ coordinates are introduced in such a way, that the origin of the coordinates coincides with the center of the PWAS. The z-axis is an outer normal to the surface of the specimen. The circular PIC151 actuator from PI Ceramic company has a radius of $R_0 = 5$ mm, a thickness of $h_{\mathrm{PWAS}} = 0.25$ mm and is bonded in the center of the $H = 1.5$ mm thick square aluminium plate of 600 mm width. The geometry of the region of the disk wrapped electrode is approximated by circles with the center at $\boldsymbol{x}_{\mathrm{DWE}}$ and radii of $R_1 = 2.3$ mm, $R_2 = 1.4$ mm as depicted in Fig. 3. For the simplicity of describing the PWAS orientation, polar parameters θ and $d = |\boldsymbol{x}_{\mathrm{DWE}}| \approx 4.1$ mm are used in the following; the soldering spot is located at the point $\boldsymbol{x}_{\mathrm{SP}}$.

The resulting out-of-plane particle velocities $\dot{u}_z(t)$ are recorded at each coordinate of the specimen by the LDV. For the central frequencies considered, the number of cycles $N_c = 5$ has been chosen. The measurements are performed at the surface $z = -H$, i.e. in the same place where the PWAS is attached but on the back side of the plate. Because of the large amount of data, a suitable signal