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Shear horizontal piezoelectric fiber patch transducers (SH-PFP) for guided elastic wave applications

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ABSTRACT

A new type of a lightweight piezoelectric transducer is proposed for selective excitation of horizontal polarized shear (SH) waves. Based on piezoelectric fibers the transducers are flexible, i.e. show structure conformity. The novel approach allows to introduce significant surface tractions by a transducer with double layer crossed fiber arrangement without the need of heavy seismic masses. The transducer operating principles are explained and the performance of a first transducer version is demonstrated by laser vibrometric measuring of the waves emitted into a plate. Numerical modeling of the identical arrangement shows nearly perfect agreement with measurements for the main features while differences in some details helps to understand how the first transducer version can be improved. The transducer exhibits, depending on its aspect ratio, a rather high directivity and a strong mode selectivity.

1. Introduction

This paper presents new seminal Piezoelectric Fiber Patches (PFP) which are suitable to generate horizontal polarized shear waves (SH) in lightweight structures as e.g. in airplanes. In lightweight structures it is not possible to install conventional SH-transducers due to their height, weight and the physical principle of the wave excitation. Additional conventional transducers are limited in their excitation frequency. The present paper introduces therefore the operating principle of a new lightweight SH transducer based on Piezoelectric Fiber Patches (PFP), which we call SH-PFP. The functionality of these transducers has been already demonstrated by modeling [1] while in this paper we demonstrate their operation also experimentally.

The paper is organized as following. First, we introduce the advantages and possibilities of the new sensors. Second we discuss the options for Guided Wave (GW) excitation with piezoelectric wafer transducers. Then the operation of the piezoelectric fiber patches is introduced shortly and the idea how SH waves can be generated by SH-PFP is explained. This is followed in Chapter 5 by describing the laser vibrometry wave field mapping [2,3] set up and the modeling tools which are both used in the results section to give insight to the transducer operation. The paper is concluded by a discussion and outlook.

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2. Discussion of idea, advantages and application spectrum

The Non-Destructive Testing (NDT) denotes a procedure to verify, whether a material or object has still the properties relevant for its intended use without changing it significantly. This test is usually performed in time intervals by bringing the object and test equipment together. In contrast to that, Structural Health Monitoring (SHM) denotes either the permanent monitoring of a structure with sensors or the periodic reading out of such permanently installed sensors. Signal changes are considered as an indication for structure changes, which could be an indication of a defect in its early stage. For both methods, NDT and SHM, ultrasonic waves can be used advantageously.

In isotropic homogeneous (bulk) materials only two ultrasonic wave modes exist which are polarized parallel and perpendicular to the propagation direction, respectively. At boundaries mode conversion occurs in general, but shear waves polarized parallel to the surface are simply reflected without mode conversion.

When two surfaces are parallel to each other as in plates and tubes, the situation is more complicated. The wave propagation in such structures, also called Wave Guides (WG), can be envisaged either as superposition of multiple reflected and mode converted bulk waves or more appropriate as superposition WG modes. There is a series of such modes which are dispersive in general, that is, they are characterized by a frequency dependent wave speed. They can be classified as symmetric (S_i) and antisymmetric (A_i) Lamb modes and horizontal polarized shear waves (SH_i) of order i ($i=0, 1\ldots$). The lowest order mode (SH_0) is non-dispersive,

e. a. it propagates with a wave speed independent of frequency.

Ultrasonic testing is commonly based on piezoelectric transducers coupled by a fluid layer to the structure. For insonification under an angle the waves are sent into the structure by a wedge. In this way longitudinal and vertically polarized shear waves are exited. Successive reflections and mode conversion complicate the received time signal. This complication can be avoided by using horizontally polarized shear waves, which are commonly excited with corresponding piezoelectric transducers glued to the surface or with Electromagnetic Acoustic Transducers (EMAT) (e.g. [4]).

The NDT and SHM of shell like structures with ultrasonic guided waves (GW) is challenging since normally a mixture of different wave modes propagates and that these modes are in general dispersive. Multiple scattering at structure inhomogeneities as boundaries leads to an unpredictable mixture of signal contributions which can be considered as coherent noise. The common strategy against the large number of guided wave modes consist the limitation of the applied frequency to the range below the first cut-off frequency where only the lowest order Lamb waves A_0 and S_0 can propagate. Alternatively, transducer can be used, which excite preferentially only a specific mode b**y** matching the transducer size to the wavelength of the preferred mode at the given frequency [5–8].

An ingenious way of wavelength matching is proposed by Manka [9], who introduced a comb like electrode structure prescribing a periodic excitation. By exiting several wavelength within the transducer aperture, the emitted pulse has a corresponding length and is narrowband. This leads to better mode selectivity compared to piezoelectric wafer active sensors, where only a half wavelength is prescribed by the transducer lateral extension. But the higher pulse length is connected with a lower spatial resolution which can be a disadvantage. Another approach [10,11] combines high mode selectivity with the emission of short pulses: several separate electrodes are excited with corresponding phase matched delays. The additional benefit at no extra cost is a one dimensional (forward/backward) directivity.

Directivity of transducers helps to get a clearer view of the wave phenomena contributing to the detected signal. Also the directionality of the wave scattering at various defects (e.g. [12]) could be exploited more effectively. Therefore the natural directivity determined by the type and shape of the transducers was characterized extensively [9,13]. In ultrasonic testing of bulk materials, Phased Arrays (PA) are commonly used to focus and steer ultrasound. The simple transfer of the linear array arrangement to waveguides works only for weak dispersion and gets problematic for normal dispersive behavior of the guided waves [14]. Wilcox [15] circumvents that problem for metallic waveguides by arranging a number of omnidirectional electromagnetic transducers in a circular shape. There were proposed also other means to control the direction of radiated waves: wavenumber-spiral transducers [16] and wedge shaped sectorial transducers [17,18].

As already mentioned, the lowest order shear horizontal wave mode SH_0 is non-dispersive for all frequencies. It can be excited in metals by electromagnetic transducers (EMAT) [4]. For GW excitation also a number of configurations based on magnetostriction where described [19–21]. Here, the shear stress is generated in a strong magnetostrictive material glued to the structure. This material is subjected to two magnetic fields: a large static field plus a perpendicular alternating field. These transducers generate an in-plane shear stress and are very effective in selectively exciting shear horizontal modes. But the need for a strong magnets makes them bulky and adds weight to the sensor. This might be not a big problem for NDT or SHM in pipes but will not be acceptable for large SHM sensor networks installed in lightweight structures as e.g. in airplanes.

The requirement of lightweight SHM systems motivated the search for SH transducers based on piezoelectric materials. One proposed approach is based on piezoelectric shear disks, where the shear is normal to the surface [22]. They exert parallel forces in the surface and therefore excite - when appropriately shaped – shear waves. But with a free back side without some “seismic” backing, this force is rather small.

3. Short review of guided wave excitation with piezoelectric wafer patches

In the most general approach to understand the excitation of ultrasonic waves in a solid, is to solve the coupled problem of the elastodynamic fields and the exciting fields. These exciting fields can be e.g. the magnetic fields in magnetostriction and in Lorenz force excitation of ultrasound (both present in electromagnetic acoustic transducers EMAT), the electric fields in piezoelectric materials or thermal fields. The solution of the coupled problem is challenging if the ultrasound is generated inherently in the component like in the surface acoustic wave (SAW) devices for filter applications and also in photo acoustic [23] and particle acoustic [24] generation of ultrasound.

We are interested here in the simple cases, where the elastodynamic solution in the solid can be decoupled from the source. We follow the notation of Achenbach [25] and use Cartesian coordinates. The space position vector $\vec{r}=x_i\vec{e_i}$ is described by its components x_i in a rectangular coordinate system with the unit vectors $\vec{e_i}$. The vector components $u_i(\vec{r},t)$ describe the particle displacement at the position $\vec{r}$ and at time t. The elastic stress tensor is described by its components σ_{ij}. The partial deviation $\partial_i=\partial/\partial x_i$ is denoted by a comma before the index as e.g. $\partial u_i/\partial x_j=u_{i,j}$ Similar, the dot over a function denotes the partial deviation to the time t as in $\partial u_i/\partial t=\dot{u}_i$

The tensor of elastic strain is defined by

$$\epsilon_{ij} = (u_{i,j}+u_{j,i})/2 \tag{1}$$

With the Newton's law and the material stress–strain relation $\boldsymbol{\sigma} = \boldsymbol{c\epsilon}$ (c denots the stiffness tensor) the wave equation results

$$\rho\ddot{u}_i-(c_{ijkl}u_{k,l})_{,j}=f_i \tag{2}$$

This equation, together with initial conditions at $t=0$ and boundary conditions at the body surface determines the possible solutions. For a homogeneous isotropic material with the Lame Constants λ and μ Eq. (2) simplifies to

$$\rho\ddot{u}_i-\mu u_{i,jj}-(\lambda+\mu)u_{j,ji} = f_i \tag{3}$$

We assume that the transducer is attached to the surface and exerts surface tractions

$$t_i = \sigma_{ij}n_j \tag{4}$$

with n_j as the components of the surface normal vector. This surface traction serve as the boundary condition.

To envisage, which surface traction can be exerted by a piezoelectric material, it is helpful to visualize deformation schemes of piezoelectric wafers when they are in their free state. Fig. 1 lists in its first row: the orientation of the electric field (field direction), the orientation of the polarization (polarization direction) and the relevant strain orientation $\epsilon_{ij}\neq 0$ (strain/shear). Here and in the following we use both the full index notation “*ij*” ($i,j=1..3$) and the shortened (Voigt) notation, where the index pair is replaced by one index “*i*” within the range 1…6. The mode name “*kl*” in this table is composed of the orientation of the excitation electric field “*k*” and the relevant deformation direction “*l*”.

When the wafers are mounted at the surface, this free motion is restrained by the structure and the piezomaterial exerts