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Enhancing the bandwidth of piezoelectric composite transducers for air-coupled non-destructive evaluation

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ABSTRACT

This paper details the development of a novel method for increasing the operational bandwidth of piezocomposites without the need for lossy backing material, the aim being to increase fractional bandwith by geometrical design. Removing the need for lossy backing materials, should in turn increase the transmit efficiency in the desired direction of propagation. Finite element analysis has been employed to determine the mode of operation of the new piezocomposite devices and shows good correlation with that derived experimentally. Through a series of practical and analytical methods it has been shown that additional thickness mode resonances can be introduced into the structure by a simple machining process. The shaped composites described in this paper offer increased operational bandwidth. A simple example of a two step thickness design is described to validate and illustrate the principle. A more complex conical design is presented that illustrates a possible tenfold increase in bandwidth from 30 kHz to 300 kHz, operating in air without backing. An illustration of the applicability of this type of transducer technology for frequency agile guided mode non-destructive evaluation is then presented.

1. Introduction

With the current interest in harmonic affects in the biomedical imaging and non-destructive evaluation or naval mine hunting requirements for wideband actuators capable of detection and characterisation of targets, there is an increased need for sensitive transducers offering wide operational bandwidths. Traditionally, increased bandwidth in piezoceramic or piezoelectric composite/tradition of backing/loading materials [1,2] or by using electrical tuning or matching networks [3,4]. However, the addition of this backing reduces the overall sensitivity of the transducers. This paper details a preliminary investigation into the integrated design of piezocomposite devices for operation across a range of frequencies, without need for additional rear face loading.

Piezoelectric composite transducers are constructed of two constituent phases, incorporating an active piezoceramic and a passive polymer material. This transducer technology enables the designer to tailor the properties for specific applications. It is the addition of this polymer material, which offers an increase in transducer sensitivity and improved impedance matching to media of lower specific acoustic impedance, such as air and water, compared to piezoceramic sensors.

Fig. 1 illustrates a 1–3 connectivity piezocomposite consisting of active ceramic pillars embedded within a passive polymer matrix. The annotations 1 and 3 relate to the connectivity of the ceramic and polymer within the device respectively [5]. Namely, the number of directions in which it is possible to connect the material to the outer boundaries without intersection of the second material.

The standard method of manufacture for the 1–3 composite is the "dice & fill" technique developed by Savakus [6], whereby two sets of slots are cut orthogonally into a ceramic block. An epoxy resin is then poured into the slots to provide a passive polymer matrix. The composite is then lapped to remove the excess ceramic and epoxy and reduce the transducer to the desired thickness. An alternative method, developed by Bowen [7], involves injection moulding, whereby the powdered ceramic material is injected into a periodic mould with a chemical binder, the mixture is then subjected to high temperature until the ceramic sinters and reforms within the mould. The resultant structure of free standing pillars is then bound within a polymer matrix and poled. Injection moulding enables fine scale transducer structures to be manufactured that are unrealisable with standard dice and fill techniques, although at an increased initial cost.

The resonant behaviour of a 1–3 connectivity piezocomposite device is exceptionally complex due the periodicity of the piezoceramic pillars embedded within the polymer matrix structure. It is

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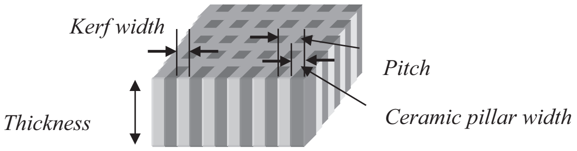

Fig. 1. 1–3 connectivity piezocomposite.

as a result of this regular structure that a number of vibrational resonance modes are generated, both in the thickness and lateral directions each with their own frequency of operation and mode shape.

1.1. Thickness mode resonance

The fundamental thickness mode resonance of a piezocomposite transducer is typically the most dominant mode active within the transducer structure. This mode is governed by the overall thickness of the device and is caused by the longitudinal vibration within the piezoceramic pillars, in the height or thickness dimension. The wavelength for this mode is equivalent to twice the thickness of the transducer thickness and the velocity is defined as the speed of the sound travelling longitudinally through the thickness direction. Hence, for a composite with defined thickness of d_t, the frequency of thickness mode resonance can be calculated by

$$f_t = \frac{n v_l}{2 d_t} \tag{1}$$

where

f_t is the resonant frequency in the thickness direction
v_l is the sound velocity in the thickness direction
n is the wave number.

In this case, n is limited to only odd harmonics (1,3,5...) due to the assumption that the transducer will always have significantly higher acoustic impedance than that of its surrounding media. These harmonics are due to additional reverberation within the composite structure, although the magnitudes are reduced through damping with increased frequency. All resonance modes exhibit a distinct impedance characteristic with respect to frequency. Fig. 2 illustrates a typical transducer impedance response, highlighting the two primary frequencies of interest, these being f_e and f_m, the electrical and mechanical resonances respectively.

The electrical resonant frequency is shown as the impedance minimum and is defined as the optimal frequency of operation for transmission [8]. This defines the frequency at which the transducer will displace most when excited by a driving voltage. Conversely, the peak on the impedance response illustrates the optimal frequency for reception [8] under open circuit conditions. The impedance characteristic shown in Fig. 2 also indicates the width dilation mode of the transducer, occurring at approximately 120 kHz resulting from the lateral resonance of the transducer.

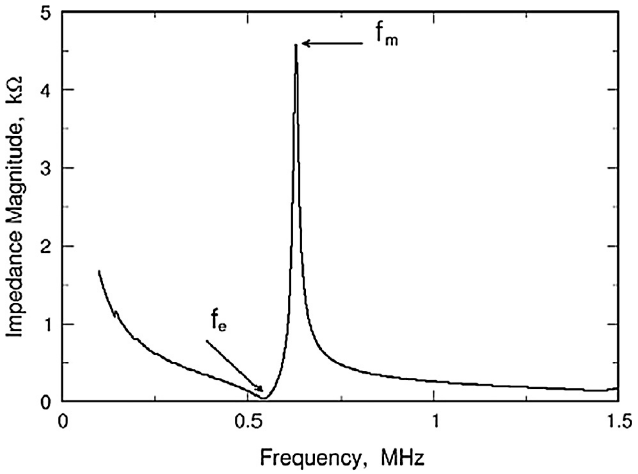

Fig. 2. Electrical impedance characteristic of a piezocomposite device.

1.2. Lateral resonance modes

Lateral modes differ from thickness or longitudinal modes in that instead of travelling in the thickness or 3 direction, these modes travel along the width of the transducer, in the 1 and 2 directions. To explain, the characteristics exhibited from piezoelectric materials depend upon the orientation of the poling axis. This orientation governs the direction of vibration exhibited by the piezoelectric material. 1 and 2 correspond to the x and yaxes respectively; while 3 relates to the zaxis and 4 through 6 refer to rotations around these axes. In piezoelectric ceramics, the conventional axis of polarisation is along the z-axis or 3 direction, hence the notation of axes can be shown as in Fig. 3.

Lateral waves are travelling perpendicular to the thickness mode and are governed by the velocity of sound in this direction. There are a number of different lateral modes active within a 1–3 connectivity composite transducer, these are *width-dilatational, inter-pillar* and *intra-pillar* modes. The influence these lateral modes exert over the transducer performance is governed by the *aspect ratio* of the transducer. Which is defined as the ratio of the ceramic pillar width to its height. It is not the intention of this paper to investigate these modes in detail, (this occurrence has been covered in greater depth by authors such as Gururaja et al. [9,10], Reynolds [11] and Gachagan [12]) only to comment upon there existence and influences. These modes are now discussed briefly.

Width-dilatational resonances are due to the overall width of the transducer structure and can propagate waves in either radial or transverse form, dependent upon the transducer geometry. Typically, these modes have little influence upon the transducer performance being in the low kHz range and therefore do not interfere with the thickness mode operation.

Inter-pillar resonances are modes that arise due to standing wave patterns being generated within the periodicity of the composite structure. Namely, as the piezoceramic elements within the structure vibrate in the thickness direction, 3, a certain proportion of this displacement is coupled into the lateral directions, 1 and 2, dependent upon the polymer material parameters. This lateral motion generates shear waves within the composite structure which can, depending on the ceramic and polymer periodicity, lead to standing waves within the device. These phenomena can cause significant problems in the design of transducers with low ceramic volume fractions, typically less than 30%. Substantial work has

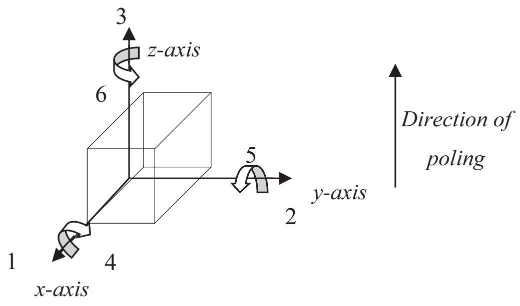

Fig. 3. Diagram of axes notation.