

Evaluation of piezoelectric micromachined ultrasonic transducers (PMUT) for the broadband detection of ultrasonic elastic waves

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Summary: Elastic waves in solids are frequently used for material characterisation or non destructive testing methods. For the detection of elastic waves with high sensitivity piezoelectric transducers are commonly used. This investigation compares the performance of a piezoceramic based ultrasonic transducer and a piezoelectric micromachined ultrasonic transducer (PMUT) for the detection of broadband acoustic waves in the spatial and temporal regime.

Keywords: Elastic waves, Non-destructive testing, Piezoelectric sensors, PMUT, Ultrasound

Motivation

In the interest of sustainable and cost-efficient processes the development of non-destructive testing (NDT) methods are a central aspect of contemporary research. Methods based on ultrasonic elastic waves are prevalent in this field, requiring specialised transducers for the excitation. Design goals for the detecting transducer are e.g. high sensitivity and a high bandwidth. This high bandwidth is especially important for material characterisation methods, as applied and developed by the authors [1]. While high temporal bandwidth can be achieved at the expense of the sensitivity in traditional, bulk piezoelectric transducers, high spatial bandwidth can only be reached by decreasing the sensors active area. The authors employ a specialised transducer based on an oblong, cuboid piezoceramic [2] to detect guided elastic waves to a high wavenumber or spatial frequency. These transducers are not commercially available and build in a manual process, which is incompatible with standard manufacturing techniques. To be able to deploy the aforementioned material characterisation methods in e.g. industrial applications an alternative to this custom build detection method, the performance of a piezoelectric micromachined ultrasonic transducer (PMUT) [3] is evaluated. To assess the bandwidth of the PMUT, broadband guided elastic waves in an aluminium plate are used as a benchmark.

Experimental setup

Ultrasonic guided waves are excited in an aluminium plate utilising ultraviolet pulsed laser radiation focused via a cylindrical lens onto a thin line ($\approx 0.1\text{ mm}$) on the surface of the specimen [2]. Due to a sufficiently low optical energy density the radiation results in a purely thermoelastic excitation without damaging the sample. A measurement routine is performed by moving the line of excitation in equidistant steps (e.g. $\Delta z = 0.1\text{ mm}$) along the plate and recording a signal at each step with the transducer coupled to the specimen. The resulting data matrix contains information in space-time-domain.

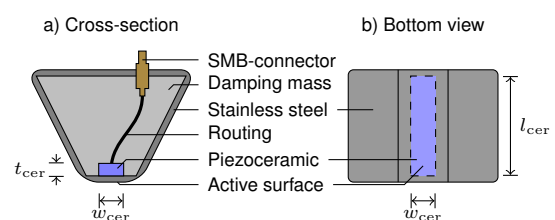


Fig. 1: Schematic of the piezoelectric transducer for the detection of broadband acoustic plate waves.

By applying a two-dimensional Fourier transform the data is transferred to the wavenumber-frequency-domain [4]. A depiction of the absolute value of the transformed measurement data shows detected propagating waves as ridges. The spatial and temporal bandwidth of the respective transducer can be assessed in these depictions by the range in which ridges are observed.

Piezoelectric transducers

For the purpose of detecting of propagating waves in the plate-like specimens with the measurement setup a piezoelectric transducer is designed (Figure 1). The active element is a strip-shaped piezoceramic (PIC255, PI Ceramic) with dimension $w_{\text{cer}} = 1\text{ mm}$, $t_{\text{cer}} = 0.5\text{ mm}$, and $l_{\text{cer}} = 12\text{ mm}$. A sufficient amount of damping mass inside the transducer enclosure enables a reliable detection of broadband acoustic waves. Due to the laser radiation being focused onto a thin line and the strip-shaped piezoceramic excitation and detection are adequately matched.

The universal piezoelectric micromachined ultrasonic transducer (PMUT) used in this study comprises a number miniaturised sensors with an adaptive channel and chip size. For the electromechanical transducers a piezoelectric thin film AlN on a silicon oxide membrane and its necessary electrical components are used [3]. The universal PMUT technology is a patent pending technology, aiming a fast and resource-friendly production of application adapted sensors with-

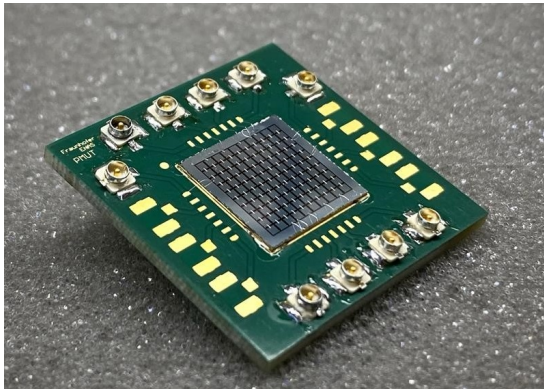


Fig. 2: PMUT with a membrane diameter of $100\ \mu\text{m}$ and a linear wire bonding on a printed circuit board.

out the setup cost for an application specific design and wafer run [5]. The design of the acoustic channels and chip size is based on piezoelectric transducer on a silicon wafer substrate divided into $1\ \text{mm} \times 1\ \text{mm}$ unit cells. Each of these unit cells contains the miniaturised membranes ($50\ \mu\text{m}$ to $200\ \mu\text{m}$) with piezoelectric aluminium nitride as electromechanical transducer. Using an automatic wire bonding process those unit-cells can be electrically connected to create the desired geometry of the active elements of the final sensor (see Figure 2). This procedure enables the manufacturing of multichannel sensors from one wafer substrate with individual channel geometries. [5] For this investigation one single channel with a geometry of $1\ \text{mm} \times 10\ \text{mm}$ and a membrane diameter of $100\ \mu\text{m}$ resulting a center frequency of $2\ \text{MHz}$ is used.

Experimental comparison

Figure 3 depicts a direct comparison of a measurement based dispersion diagram obtain with the piezoceramic transducer and the PMUT. Both measurements are recorded using the same $2\ \text{mm}$ thick aluminium plate and as well as the same process parameter and data processing algorithms. The depiction shows that both sensors have a sufficiently high sensitivity and therefore their measurement data provides clearly visible and distinguishable mode curves. The measurement using the traditional piezoelectric sensor contains modes up to $16\ \text{MHz}$ and $30\ \text{rad mm}^{-1}$, indicating that modes at least up to this frequency range are present in the specimen. The PMUT under consideration provides interpretable data up to $10\ \text{MHz}$ and $20\ \text{rad mm}^{-1}$ with reduced background noise.

Conclusion

The evaluation of a specially configured, universal piezoceramic micromachined ultrasonic transducer (PMUT) for the detection of elastic waves shows adequate spatial and temporal bandwidth. Given the fact that the PMUT examined in this work is not specifically build for this purpose, the test in the proposed application can be considered successful. Adapting the design of the PMUT to the task at hand, e.g. by

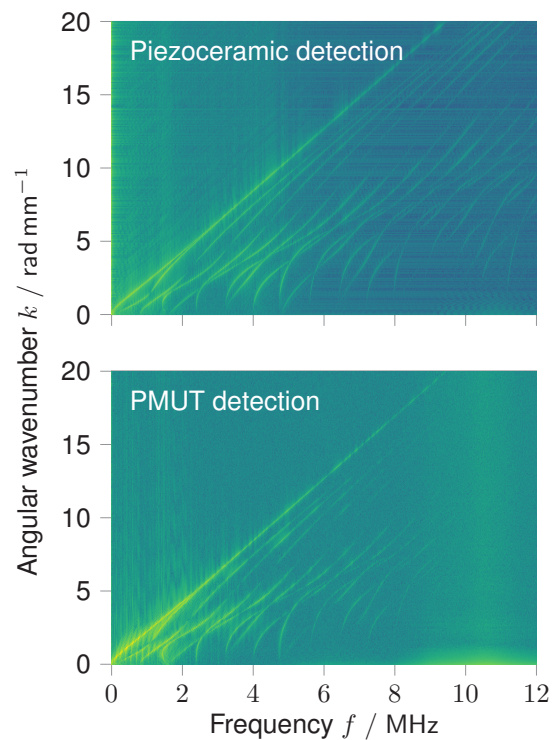


Fig. 3: Comparison of measured dispersion diagram of a $2\ \text{mm}$ aluminium sample using the piezoceramic based transducer and the PMUT as the detecting sensor.

adjusting the arrangement of the membranes, increasing the fill factor, using inner and outer electrodes and increasing the nominal resonant frequency, or using piezoelectric transducers with high piezoelectric coefficients and low permittivity such as AlScN, is expected to improve the results presented.

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