Experimental Investigation of the Acousto-Ultrasonic Transfer Characteristics of Adhesively Bonded Piezoceramic Transducers

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ABSTRACT

For the development of optimised health monitoring systems and smart materials, the understanding of the interaction of piezoelectric transmitting and receiving transducers with the structure is essential. This paper reports on the development of an experimental technique to determine the acousto-ultrasonic transfer characteristics of adhesively bonded piezoceramic transducers. Five millimeter diameter piezoceramic discs with and without brass backing were glued to one and two millimeter thick aluminium plates. Narrow and broad band excitation pulses were applied to the transducers in a frequency range between 50 kHz and 1 MHz, a frequency regime suitable for guided wave ultrasonic non-destructive evaluation applications. The electro-mechanical transfer properties of the ultrasonic transmitter elements were determined using a heterodyne Doppler laser vibrometer as a non-contact receiver device and Rayleigh-Lamb wave theory to describe the propagation behaviour of the waves in the structure. It is found that the transfer characteristics are extremely complex including sharp and narrow as well as broader but less pronounced frequency regimes of high energy transfer. It is shown that the major features of the transfer functions for different experimental configurations are similar, but the magnitudes of the peaks and their locations in frequency space are different for individual transducer/substrate combinations.

1 INTRODUCTION

The successful application of advanced materials such as composites and the introduction of preventive maintenance schemes largely rely on the accurate assessment of the integrity of the structure before loading and during service. Consequently, there exists an increasing demand for reliable and effective non-destructive evaluation (NDE) methods in modern engineering applications.

In recent years an ultrasonic NDE technique, known as acousto-ultrasonics (AU) has received considerable attention (e.g. Duke 1988, Vary 1991). The general objective of the AU technique is to determine an experimental parameter, the so-called stress wave factor (SWF), that describes the relative efficiency of stress wave energy transfer from a transmitting to a receiving transducer. Experimental results have confirmed the potential of the AU approach to provide a measurable parameter which enables the quantitative assessment of the integrity of a structure. Since AU techniques attempt to measure either absolute or relative velocity as well as attenuation of the interrogation pulse, signal validity and reproducibility require the utmost care in the test setup and procedure. The major challenge in this context is to separate the material's response from external factors such as inherent transducer properties and transducer-to-specimen interactions.

Considering the basic AU measurement system sketched in Fig. 1, the transfer function of the measurement system, $G(\omega)$ can be formulated as:

$$G(\omega) = \frac{V_{ou}(\omega)}{V_{in}(\omega)} = T_{ou}(\omega)D(\omega)T_{in}(\omega) \tag{1}$$

where ω is the circular frequency, V_{ou} represents the measured system response, V_{in} describes the frequency characteristics of the excitation pulse, T_{in} and T_{ou} are the electro-mechanical transfer functions of the transmitter and receiver elements, respectively and D represents the propagation behaviour of the stress waves within the structure. As mentioned above, the challenge in developing effective ultrasonic NDE techniques is to quantify the transfer characteristics of the transmitter and receiver elements, T_{in} and T_{ou} that the output characteristics of the measurement system V_{ou} can be directly related to the wave propagation properties within the (damaged) structure.

Much effort has been devoted to the modelling of the transduction behaviour of ultrasonic elements in the low as well as high frequency range (e.g. Allan et al 1991, Dual 1994, Rose et al 1994, Varadan et al 1997, Wilcox et al 1998). High frequencies, typically in the MHz regime, are used in conventional ultrasonic flaw detection applications using broad band excitation pulses. The low frequency regime, where the resonance of the free transducer elements are much higher than the frequencies employed, has recently attracted much attention in ultrasonic NDE techniques using structural waves, (e.g. Cawley 1997, Komsky and Achenbach 1993, Rose 1995, Sayir 1992). These applications using mainly narrow band excitation signals and fixed transducers have shown great potential in building accurate, reliable and efficient ultrasonic measurement systems for the quantitative assessment of the integrity and serviceability of structural elements such as fibre-reinforced laminates. A number of factors associated on one hand with the transducer-to-specimen interaction such as applied pressure and type and amount of couplant for conventional transducers or thickness and viscoelastic properties of the adhesive layer for adhesively bonded transducers and on the other with the properties of the transducers themselves such as bandwidth, resonance frequencies, internal damping and electrode characteristics, make it difficult to quantitatively model the electro-mechanical behaviour of the system. Even in the low frequency range, where the transducer-to-specimen interaction should be minimal, considerable deviations were measured between predicted and experimental transfer functions (Dual 1994).

In this paper an experimental technique is presented which enables the determination of the transfer function of adhesively bonded piezoelectric transmitters. Transducers with and without backing material are glued to isotropic plates of various thicknesses. Narrow band excitation signals in a frequency regime suitable for guided wave ultrasonic NDE applications are applied to the transducers and a heterodyne laser Doppler vibrometer is used as non-contact sensor device to measure the system response at various locations. The transfer function of the transmitter elements are calculated using the Rayleigh-Lamb solution to describe the propagation behaviour of the waves in the plates. The main objectives of the present study are: 1) to introduce the experimental procedure as a possible calibration technique for transmitter elements used in acousto-ultrasonic measurement systems and 2) to show the common features and highlight the differences of the transfer functions for various transducer/substrate configurations.

2 EXPERIMENTS

Fig. 2 shows the experimental set-up used for the measurements in the present study.

Piezoceramic transducer elements (manufactured by Ferroperm, PZT 27, discs: diameter 5-mm, thickness 2-mm) with and without backing material (brass cylinders: diameter 5-mm, length 5-mm) were glued to commercially available aluminium plates (AS 5005-H34). Transducer, backing material and aluminium plates were glued together using a two component, fast curing Epoxy adhesive (manufactured by Permabond). For the electrical connection, copper wires (diameter 0.01-mm) were either soldered to the transducers or glued to the backing material. Additional masses like solder or wires were kept as small as possible in order to minimise their effect on the measurement results.

Narrow band burst or broad band sweep pulses were either generated in the digital function generator or computed in the personal computer and downloaded into the function generator. The centre frequencies and bandwidths of the individual excitation pulses were chosen such that a frequency resolution of approximately 300 Hz resulted in the frequency range between 50 kHz and 1 MHz. Typical excitation and response pulses and the magnitudes of their Fourier spectra are shown in Figs. 3a and 3b. The signals were repetitively triggered at a repetition rate of 40 Hz which was chosen such that no interference between individual experiments occurred, i.e. that the pulse of the previous experiment had been damped out. The excitation pulse was amplified to a level of approximately 1 kV_{pp} and then applied to the transducer. The out-of-plane velocity at the measurement locations were measured using a heterodyne Doppler laser vibrometer. Its sensitivity was set at 25-mm/s/V for the entire frequency range. The output of the function generator and the laser vibrometer were fed to the oscilloscope. The signals were averaged several hundred times in the oscilloscope and then transferred to the personal computer for storage and data processing. The experimental configurations tested are summarised in Table 1.

The transfer function T_{in} was computed according to (2) which directly follows by rearranging equation (1)

$$T_{in}(\omega) = \frac{V_{ou}(\omega)}{V_{in}(\omega) T_{ou}(\omega) D(\omega)} \qquad (2)$$

where T_{ou} represents the transfer function of the laser vibrometer. According to the manufacturer's specifications and independent validation experiments, its magnitude was set to have the constant value of one over the entire frequency range.

As mentioned above, D(ω) describes the propagation characteristics of the travelling stress waves in the structure. For the present study only the lowest flexural branch of the Rayleigh-Lamb wave modes was considered. This can be justified since: 1) the longitudinal components generated are very small, 2) the cutoff frequency for the second mode is approximately $f_c \sim 800$ kHz for the 2-mm thick plate and $f_c \sim 1.6$ MHz for the 1-mm thick plate and 3) the measured transfer functions at different locations within the plates using this most simple dispersion relation for data analysis are almost identical which is illustrated in the following section. In the case of introducing the presented methodology as a general calibration tool for piezoelectric transmitter elements used in guided waves quantitative NDE applications a multi-layer spectral method (e.g. Liu et al 1998, Liu et al 1999) is going to be used for processing the measured response signals to accurately model the influence of guided wave aspects.

3 RESULTS AND DISCUSSION

Fig. 4 shows the magnitudes of the two transfer functions for the measurement locations (50, 0) and (100, 0) of experimental configuration 4 in Table 1. Each transfer function is comprised of more than 2000 data points. In this extremely fine resolution the transfer functions show many complex features which are represented in almost perfect agreement for the two measurement locations. This statement is also correct for other measurement locations and other experimental configurations. This demonstrates on one hand the sensitivity and reproducibility of the measurement system and on the other is a strong indication that considering only the lowest flexural branch of the Rayleigh-Lamb wave modes in calculating $D(\omega)$ in equation (2) is a valid procedure.

In the areas of good electro-mechanical transduction the magnitudes for larger distances are generally slightly smaller which reflects the effect of the material's damping which is not included in the theoretical model.

The most prominent features in the transfer functions are the presence of three frequency regimes with high magnitudes around 200 kHz, between 550 kHz and 650 kHz and around 780 kHz. In all experimental configurations the maximum energy transfer occurs at the first transducer-to-specimen resonance frequency. Between the high amplitude bands frequency regimes exist where obviously almost no energy is transferred from the transducer into the structure. These results indicate that 1) a detailed knowledge of the transfer characteristics is essential to enable the design of optimised ultrasonic measurement systems for quantitative non-destructive evaluation applications and 2) the development of quantitative models accurately describing the electro-mechanical transfer characteristics of piezoelectric transmitters is a difficult task.

In Fig. 5 the influence of the frequency content of the excitation signal is demonstrated by comparing the transfer functions measured at a distance 50 mm away from the transmitter for experimental configurations 3 and 4. The comparison of the scale factors used to normalise the maximum amplitudes of the corresponding signals indicates that the maximum energy transfer of configuration 3 using narrow band burst excitation is approximately 4.3 times larger than the one of configuration 4 using broad band sweep excitation. The curves show that the major features for the two excitation modes are similar but that they behave rather differently on a local scale.

By using narrow band excitation it is possible to have optimised energy transfer in the area of the major transducer-to-structure resonance frequency which is represented by the large first resonance peak compared to the amplitudes at other frequency regimes of high energy transfer. For the broad band excitation the transmitter transfer function has similar magnitudes in all high transduction regimes. Thus, the fact that specific transduction modes are excited selectively using a narrow band signal results in more complex transfer characteristics since various local deformation modes within the transmitter element and the transducer-to-structure system seem to be excited which are slightly less dominant for an excitation signal using a broader frequency regime. This may limit the potential of the frequency regime corresponding the first resonance peak in quantitative NDE applications using narrow band excitation since even small changes in the transfer characteristics of the transducer-to-specimen system due to external (e.g. temperature, moisture) or internal (e.g. aeging of transducer, electrodes or adhesive joints) influences may substantially change the excitation efficiency and therefore jeopardise the reliability of the measurement system. This indicates that apart from the characteristics of the transducer elements and their locations also the frequency content of the excitation signal has to be considered in the design of acousto-ultrasonic measurement systems.

In Fig. 6 the magnitudes of the transfer functions of identical transmitters bonded to substrates with different thicknesses are compared. The scale factors used for normalising the amplitudes show that the peak magnitude for the 1-mm thick plate is approximately seven times larger. As expected, the frequency regimes of high transduction efficiency are shifted to higher frequencies for the thicker substrate. But the transfer functions, although showing similar global features, are quite different on a local scale. This implies that it is a challenging task to develop models predicting the behaviour of a piezoelectric transmitter bonded to one substrate based on its measured or calculated transfer characteristics for another transducer/substrate configuration. A comparison of the results for experimental configurations 1 and 2 in Table 1 shows that this statement is identically true for transmitters with and without backing materials bonded to the same substrate.

4 CONCLUSIONS

The experimental investigations of the acousto-ultrasonic characteristics of adhesively bonded piezoceramic transducers have shown that:

- the transducer-to-specimen transfer functions are very complex with frequency regimes of high and low amplitude electro-mechanical transduction characteristics whose magnitudes and locations in frequency space are different for the individual transmitter/specimen configurations.
- the knowledge of the transfer characteristic is essential to enable the efficient development of optimised acousto-ultrasonic measurement systems.
- the development of quantitative models accurately describing the transducer-to-specimen interaction is a challenging task.
- the presented measurement technique based on the use of the heterodyne Doppler

laser vibrometer as a non-contact receiver device and a theoretical model to represent the propagation behaviour of the stress waves in the structure has great potential to be used as a possible calibration methodology to determine the transfer characteristics of piezoelectric transmitter elements.

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Table 1: Summary of experimental configurations investigated

Exp	Thickness [mm]	Backing Material	Excitation Pulse	Measurement Locations (x,y) in [mm]
1	2	no	narrow band	(50,0), (100,0)
2	2	yes	narrow band	(50,0), (100,0), (0,100)
3	1	yes	narrow band	(50,0), (100,0), (150,0), (200,0), (0,50), (0,100)
4	1	yes	broad band	(50,0), (100,0), (150,0), (200,0), (0,50), (0,100)

FIGURE CAPTIONS

Fig. 1: Schematic diagram of a basic AU measurement system

Fig. 2: Schematic diagram of the measurement system used in the present study

Fig. 3: Time and frequency representation of typical excitation and response signals: a) narrow band burst excitation, time space scale factors: 0.01 for excitation, 0.75 for response, frequency space scale factors: 0.0006 for excitation, 0.0074 for response, b) broad band sweep excitation, time space scale factors: 0.01 for excitation, 2.00 for response, b) broad band sweep excitation, frequency space scale factors: 0.0021 for excitation, 0.046 for response

Fig. 4: Acousto-ultrasonic transfer characteristics for experimental configuration 4 measured at distances d = 50 mm and d = 100 mm from excitation point.

Fig. 5: Acousto-ultrasonic transfer characteristics for experimental configurations 3 and 4 measured at a distance d = 50 mm from excitation point, scale factors: 0.0035 for narrow band excitation, 0.041 for broad band excitation.

Fig. 6: Acousto-ultrasonic transfer characteristics for experimental configurations 2 and 3 measured at a distance d = 50 mm from excitation point, scale factors: 0.0035 for thickness 1 mm, 0.0245 for thickness 2 mm.