Probing Material Properties via a pair of Piezoelectric Micromachined Ultrasound Transducers

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***Summary*—Ultrasonic methods have been widely employed for non-destructive testing and characterization of materials. This work investigates the potential of employing micromachined ultrasonic transducers in this context. Piezoelectric Micromachined Ultrasound Transducers (PMUTs) were used in a 5-layer acoustic model (PMUT-medium-specimen-medium-PMUT) to evaluate the feasibility of material characterization in air. A transmitter PMUT was electrically actuated to project ultrasonic waves through the air-sample-air interface before being incident on a receiver PMUT. The modulation of the amplitude at the receiver PMUT is then correlated to the specimen material type, which showed a clear distinction between metallic and polymeric materials. However, materials of a similar nature were not immediately distinguishable. The experimental findings are complemented by numerical simulations. These findings reinforce the feasibility of PMUTs to be deployed for non-destructive assessment of materials.**

Keywords—PMUT; AlN; Resonant Coupling; Material Probing; MEMS Characterization; Polymer NDT.

I. Introduction and Background

Ultrasonic methods have been widely employed as means of non-destructive testing of materials. A particular application context is related to monitoring the aging of materials, and especially polymers that can occur as a result of internal structure alterations due to exposure to high temperature and pressure loads or plasticizing agents. Those morphological changes are often translated to alterations of the crystallinity and elastic moduli of the matrix [1]–[3]. However, work on the early detection of material aging non-destructively is limited in the literature. The present study was initiated in this regard with an aim of evaluating the feasibility of PMUTs to characterize and monitor material parameters pre- and post-aging. The current study is a follow up to the evaluation of single and dual-port PMUT configurations employed to distinguish between various materials, in which 2 identical PMUTs of the design presented in previous work [4] were corroborated in a 5-layer acoustic setup consisting of a PMUT-medium-specimen-medium-PMUT stack.

II. Description of Method

The experimental setup included two 485 µm by 485 µm square AlN-on-SOI PMUTs with a primary design frequency of 492 kHz for the fundamental mode. The PMUTs were held equidistantly at either side of a 2 mm thick specimen by a bespoke jig (Fig. 1). The air medium between each PMUT and the specimen was set at 4 mm, which is the thickness of the chip carriers employed to electrically package the PMUTs for assembly onto their designated printed circuit boards (PCB). The transmitter PMUT was actuated by a frequency sweep about the primary resonance via a Zurich Instruments HF2LI Lock-in Amplifier. This launches an acoustic wave that is transmitted through the specimen film and surrounding air medium through to the receiver PMUT. Both receiver and transmitter PMUTs were designed with nominally the same dimensions. This 5-layer model [5] interrogation was applied to polyethylene of raised temperature resistance (PE-RT), polyvinylidene fluoride (PVDF), brass, copper and aluminum specimen, for a constant drive level and fixed air distance.

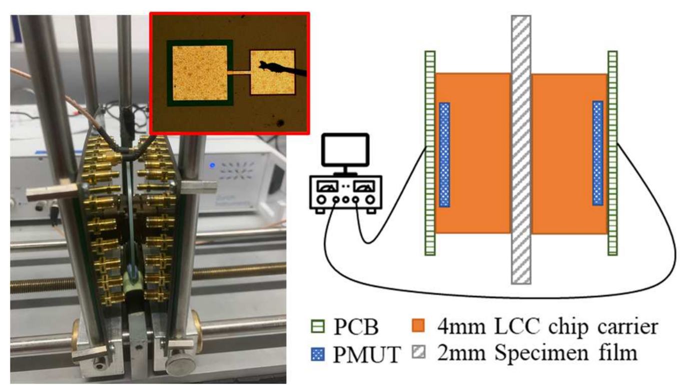

Fig. 1. Left: experimental setup; microscopic image of wirebonded PMUT unit shown in the red box. Right: diagram of the 5-layer acoustic model of 2 PMUTs, which sit in their respective chip carriers sandwiching a specimen film.

III. PMUT Characterization using 5-Layer Model

A. Effect of voltage without specimen

The effect of voltage on transmissivity of two PMUTs placed opposite one another and separated by an air medium was explored first. The receiver PMUT logged the fundamental resonance of the transmitter at 1V, 5V and 10V input voltage, depicted in Fig. 2., showing non-linear effects at higher input voltages. This is in agreement with holographic characterization of the PMUT out-of-plane displacement as a function of voltage.

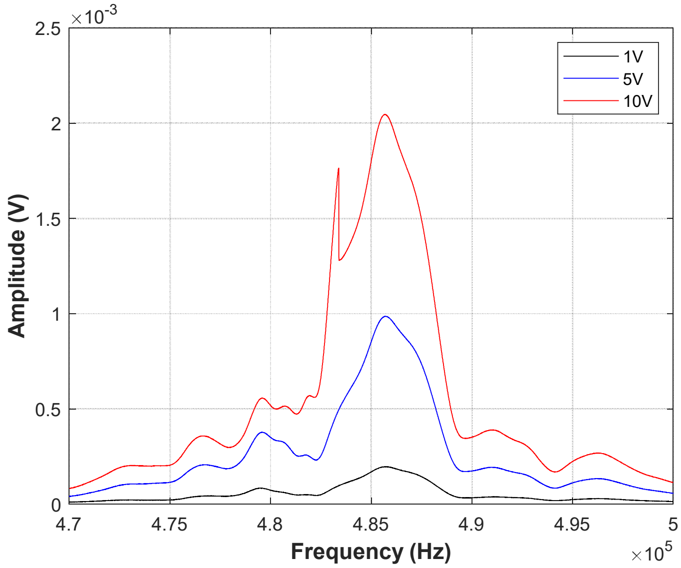

Fig. 2. Comparison of the effect of input voltage (AC) on the response of the system comprising two nominally identical PMUTs (one transmitting and another receiving) facing each other at constant seperation in air medium.

B. *Effect of distance without specimen*

Similarly, the two air-separated PMUTs transmissivity was tested at different separation distances, ranging from 8mm, which is the minimum distance constrained by the two chip carriers, to 30mm at constant 1V actuation voltage. The receiver's logged signals varied at each distance, but with a general trend of attenuating designed resonance with distance (Fig.3). There seemed to be a preferred distance at which the two nominally identical PMUTs (considering fabrication trench uncertainty of $\pm 25\ \mu m$ [6]) at which the 10 mm gap was the closest to target. It is also worth noting that each microchip includes an array of identical PMUTs, which could explain the smaller resonances around the design frequency as side-lobing of indirect actuation of units neighboring the receiver.

IV. Experimental Results & Discussion

A. *Probing vairous materials*

Introducing a solid specimen between the two PMUTs greatly reduces the logged signal by the receiver, as now the waves would principally travel through the specimen's matrix. As a result, a particular resonance shape is not detectable at 1V input voltage, and there were only traces of the resonance at 10V. Nonetheless, the probing of various materials, presented in Fig. 4, showed an obvious distinction between polymeric and metallic specimen in terms of their amplitude responses. Phase responses corresponding to metallic samples were also distinguishable from polymeric samples.

The logged amplitude responses were modulated by the transfer function characteristics of the transmitter and receiver PMUTs as well as the properties of the media probed. However, due to the low signal-to-noise ratio (SNR) of the measurements, specimens of a similar nature were not immediately distinguishable.

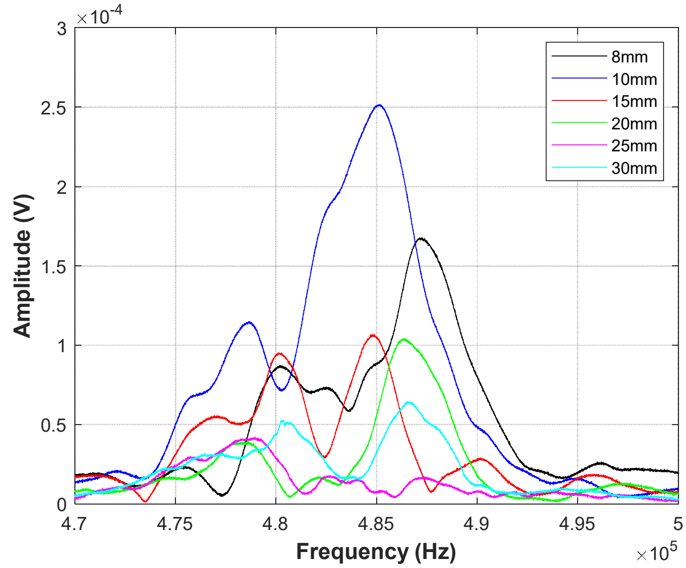

Fig. 3. Comparison of the effect of air gap seperation of two nominally identical PMUTs facing each other without a specimen, at constant 1V actuation voltage.

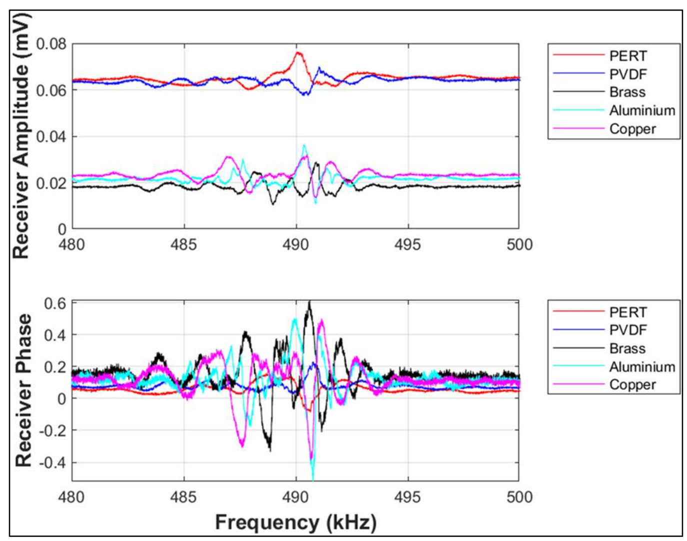

Fig. 4. Comapriosn of receiver PMUT amplitude and phase signals logged by the Lock-in Amplifier for PERT, PVDF, Brass, Aluminum and Copper.

B. *Simulation comparison*

The experimental setup was constructed and simulated via COMSOL Multiphysics® ignoring atmospheric attenuation reported distinct peaks at the design frequency of the receiver PMUT, while the difference between materials is only noticeable at the peak amplitudes (Fig. 5). Once again, polymeric samples logged higher amplitudes compared to distance and voltage applied to transmitter PMUT were in agreement with experiment. Lastly, the order of amplitude magnitudes relative to materials is consistent with the order reported for the same materials in a complementary study using a 3-layer acoustic model (PMUT-air-specimen).

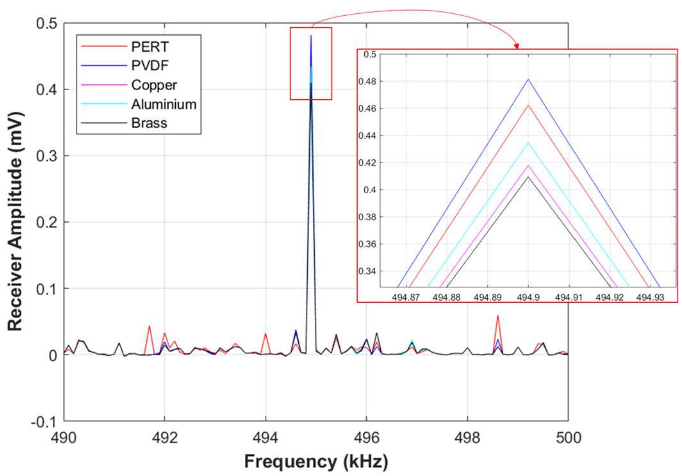

Fig. 5. COMSOL simulation output of the receiver amplitude, showing the signature for various materials superimposed at this particular air gap (4mm).

V. Conclusion

The current work is part of a series in utilizing MEMS for age monitoring of polymers in-service. A feasibility analysis was conducted for two nominally identical airborne PMUTs to be used for material interrogation through a 5-layer model. The findings suggest a relative distinction between polymeric and metallic specimens, whereas materials of a similar nature were not distinguishable at the given signal-to-noise ratio. The findings of this study point the areas of improvement for future work and reinforce the feasibility of PMUTs to be deployed for material characterization in the field.

References

[1] B. Craster *et al.*, "Exposure of various polymer-lined carbon steel pipe sections to a sour hydrocarbon fluid at a maximum service temperature: Methodology and observations," *NACE - Int. Corros. Conf. Ser.*, vol. 2020-June, pp. 1–16, 2020.

[2] H. Raheem, B. Craster, and A. Seshia, "Analysis of Permeation and Diffusion Coefficients to Infer Aging Attributes in Polymers Subjected to Supercritical CO2 and H2 Gas at High Pressures," *Polymers (Basel).*, vol. 14, no. 18, 2022, doi: 10.3390/polym14183741.

[3] H. U. Khalid, M. C. Ismail, and N. Nosbi, "Permeation damage of polymer liner in oil and gas pipelines: A review," *Polymers (Basel).*, vol. 12, no. 10, pp. 1–31, 2020, doi: 10.3390/polym12102307.

[4] H. Raheem, A. Seshia, and B. Craster, "Resonant Coupling of Piezoelectric Micromachined Ultrasound Transducers with Polymer Specimens in Different Media," *IEEE Int. Ultrason. Symp. IUS*, pp. 1–4, 2021, doi: 10.1109/ius52206.2021.9593551.

[5] M. Agrawal, "Ultrasonic Resonant Cavity Technique for Materials Characterisation,", PhD thesis, University of Cambridge, 2015.

[6] A. Cowen, G. Hames, K. Glukh, and B. Hardy, "PiezoMUMPs Design Handbook a MUMPs process, Revision 1.3.," 2014.