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Fully-flexible Thin-film Ultrasonic Array for use in Industrial NDE Applications

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***Abstract*— Ultrasonic inspection is the go-to tool for many industrial NDE applications. Ultrasonic arrays have been employed in NDE since the 1980's. However, with the rise of complex, computer-generated geometrical structures, the demand for arrays with the ability to conform to these structures is more pressing than ever before. The work here reports on the development of a truly flexible ultrasound array that allows previously uninspectable objects to be ultrasonically inspected.**

A novel, thin-film, piezoelectric material is deposited onto a flexible substrate using reactive sputtering of a metal-oxide-based alloy [1]. Additive manufacturing processes are then employed which allow for the mass manufacture of flexible arrays with consistent acoustic output and build quality, capable of operating in the region of 1-100 MHz. The arrays are subsequently demonstrated and tested on a variety of geometries such as moderate-diameter pipes and more complex test pieces. Moreover, these arrays are also demonstrated as permanently installed sensors, providing a solution to improved continuous monitoring with more information available to the industry.

Data presented here includes sensitivity analysis and performance of a 64 element 15 MHz ultrasonic array. This was carried out using industry-standard NDE equipment, and common laboratory ultrasound apparatus. Preliminary testing has given strong indication that fully-flexible ultrasound arrays may be the future of industrial condition monitoring.

Results demonstrated an array with effective performance following repeated flexion, indicating that they can withstand repeated conforming to test surfaces. The arrays tested achieved an average center frequency of 34 MHz, and average bandwidth at -6dB of 76%.

Keywords*— *non-destructive evaluation, fully flexible, array, piezoelectric, thin film.

I. INTRODUCTION

Non-destructive evaluation is a group of analytical techniques widely employed in the scientific and technological communities; it allows for the detailed inspection of assets whilst avoiding the risk of causing permanent damage to the material, or system, under test. A major branch of NDE is ultrasonic testing (UT), a volumetric inspection method which comprises the propagation of high-frequency sound waves through a medium, and subsequent evaluation of the reflected signals to characterise the thickness or internal structure of the test piece [2]. This makes it possible to detect internal flaws which may weaken the structural integrity of the asset in question before they become critical.

Typically, ultrasonic transducers are manufactured using polymers or bulk ceramics such as *lead zirconate titanate* (PZT) and *barium titanate* ($BaTiO_3$) as the core piezoelectric material [3]. These ceramics are inherently brittle and only perform well in environments with flat, smooth surfaces. Inspection, therefore, of assets with complex geometries and tightly curved surfaces (e.g. turbine blades and pipe elbows) is currently extremely difficult and costly if not, in certain circumstances, impossible. As an example, turbine blades require bespoke, single-use arrays designed with contours to fit a specific part of the blade; removing this restriction is therefore highly desirable.

This paper presents a solution to the difficulties faced by the available ultrasonic inspection apparatus through the development of a truly flexible thin-film ultrasound array which can conform to complex geometries.

II. TRANSDUCER FABRICATION AND EXPERIMENTAL SETUP

Frequencies typically employed in NDE are in the region of 1-10 MHz. These frequencies allow for good penetration of the test material since lower frequencies experience less attenuation, and do not scatter as much from large grain sizes in materials under inspection. One disadvantage of low frequency ultrasound, however, is the poor special resolution, and thus inability to resolve minor flaws, or image and inspect thin samples [2]. This could be addressed with a material capable of operating at a wider range of frequencies.

The piezoelectric material at the core of the flexible ultrasonic array reported here utilises a thin-film manufacturing technique. Thin-film piezoelectric materials such as *Aluminium Nitride* and *Zinc Oxide* are two compounds most commonly used in this area. Normally, the fundamental resonant frequencies of the piezoelectric films would be in the region of 1 GHz [4, 5], rendering the material impractical for NDE applications. However, with the introduction of a thin, flexible, metallic substrate and mass loading applied to the material, it has been possible to reduce the operating frequencies to <50 MHz, making it feasible for use in medical and industrial settings [6].

This is in itself advantageous; frequencies exceeding 10 MHz are rarely employed in contact testing due to the fragility and thinness of the ceramic element required. Thin-film materials are intrinsically high resolution and therefore experience no reduction in integrity at higher frequencies, therefore presenting a solution to this issue. The broadband nature of the films may allow for simultaneous low-frequency and high-frequency inspection of assets, which can be post processed to show images with depth from low frequency, and the resolution from high frequency – all from a single transducer.

In this paper, the thin-film material presented is deposited via reactive sputtering of a metallic-oxide-based alloy, and several additive processes are incorporated for the production of multiple array assemblies, making the entire manufacture process highly scalable. Applied to NDE, this would allow for continuous monitoring of large assets; multiple arrays could be installed in situ across an entire system or site, resulting in reduced operator access to potentially hazardous working environments [7].

To create the flexible ultrasonic arrays, the thin-film material was deposited on a thin metallic substrate. Onto this, a 64-element array was screen printed with pitch, element width, and elevation specified at 1.2 mm, 0.8 mm, and 5 mm respectively. A secondary layer with designated circuitry and connector was affixed to the array to complete the flexible printed circuit (FPC).

Initial characterisation of the sensor was performed by adhering an array to a flat aluminium bar with thickness 6.3 mm. This was connected to industry-standard inspection equipment (Mantis from EddyFi, France) as shown in “Fig. 1”; drive settings of the Mantis are detailed in the table shown below.

TABLE I. TABLE OF MANTIS DRIVE SETTINGS

Mantis Drive Settings	
Voltage [V]	85
Pulsing Frequency [MHz]	15
Filtering [MHz]	1 - 25
Scope	Internal
Cabling	IPEX

These settings remained the same throughout the experiment, with the only variable being the pulse width, and thus the driving frequency, of the Mantis.

To demonstrate the flexible array in practice, tests were carried out with lengths of steel tubing and industrial samples exhibiting curvatures typically found in practical environments. These test pieces effectively demonstrated the flexibility of the sensor, and the capability of obtaining thickness measurements from challenging structures. See “Fig. 2”, and “Fig. 3” for reference.

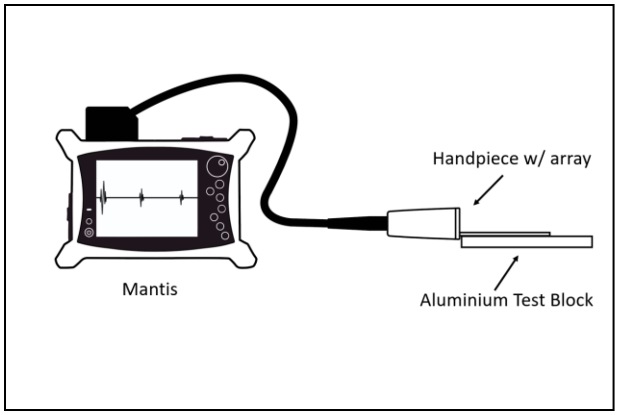

Fig. 1. Experimental setup for characterisation of flexible array.

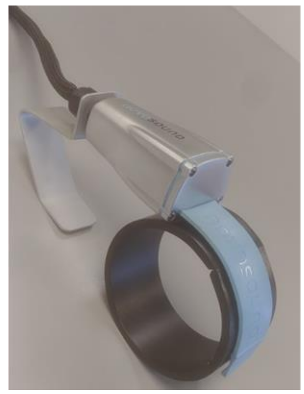

Fig. 2. Demonstration of array conforming to medium-diameter pipe.

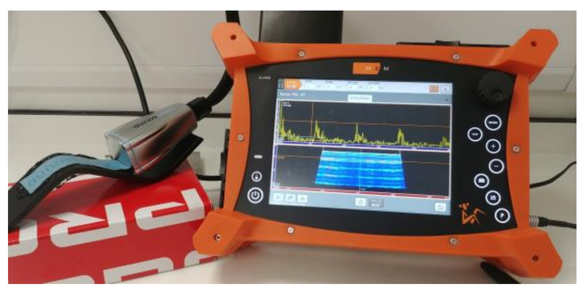

Fig. 3. Wall-thickness measurements achieved through curved sample with typical industrial testing apparatus.

III. EXPERIMENTAL RESULTS

Operating in pulse-echo mode, the array was pulsed through the aluminium bar; back-wall echoes were recorded and analysed offline to extract performance information of the array. Shown below is an example of a typical A-scan extracted from the Mantis “Fig. 4”. Using a python script, Fourier analysis was performed on the data to obtain the frequency spectrum, and thus the -6dB bandwidth could be calculated, an example Fast Fourier Transform (FFT) is illustrated in “Fig. 5”.

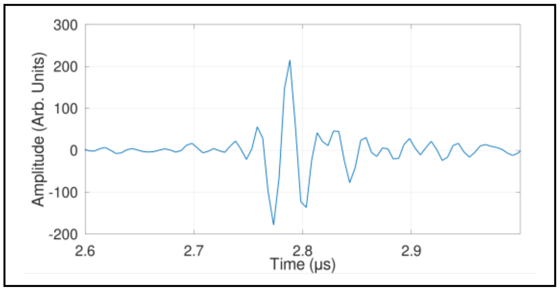

Fig. 4. Graph showing a typical pulse from the array through aluminium. Units of amplitude arbitrary as the Mantis displays this as a percentage of the screen height.

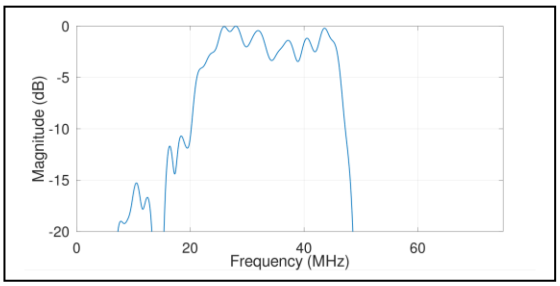

Fig. 5. Frequency spectrum obtained following Fourier analysis.

When pulsing at 15 MHz drive frequency, this array performed well through an aluminium test block. For most industrail NDE applications this would serve as a sufficient means of insepection. Moreover, further development of the piezoelectric material, combined with mass loading and improved coupling will lower the centre frequency whilst increasing the operational bandwidth, allowing the tranducer to perform optimally at a lower frequency range. This will permit the operator the option of multi-frequency inspection from a single transducer which, may drastically increase the data-collection capabilities of NDE equipment.

The average centre frequency and -6dB bandwidth for an array at the aforementioned drive frequency were calculated to be 34.1 MHz, and 76%, respectively.

IV. Summary and Conclusion

The ability to ultrasonically inspect complex structures \remains one of the major challenges faced by NDE. The novel, thin-film fully-flexible ultrasonic arrays presented in this paper have demonstrated a potential solution to overcome these challenges.

Whist the results detailed in this report have shown that the arrays manufactured from the current material have the capability and adaptability to inspect various assets with different compositions and geometries, further development will allow for better measurements, and extensive testing in real-life environments. Development of the proprietary core material will reduce the operating frequency to the optimum range for NDE applications, whilst improving durability, flexibility.

Acknowledgment

The processes for material deposition and array manufacture which have been discussed throughout this report are covered by the patents referenced, respectively [8], [9].

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