DEVELOPMENT OF A MANUAL AIR-COUPLED ULTRASONIC INSPECTION INSTRUMENT FOR USE ON AERONAUTICAL STRUCTURES UNDER IN-SERVICE CONDITIONS

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ABSTRACT. This paper describes the development programme for a portable non-contact inspection system, suitable for in-service inspection of aeronautical structures. The instrument is powered from a rechargeable battery pack which provides over six hours of continuous usage. The transducer front end is a lightweight, hand-held assembly in which a pair of piezocomposite transducers are housed. Angular adjustment of the transducers enables the instrument to operate into a variety of materials, with metallic and composite materials of primary interest. Importantly, a single channel oscilloscope has been incorporated to provide visual interpretation of the processed received signal. Defect detection is demonstrated in a number of aerospace samples, with the resultant C-scans presented where appropriate.

INTRODUCTION

Conventional ultrasonic inspection techniques employ some form of liquid coupling to efficiently transfer the energy between the ultrasonic sensor and the structure under test. The requirement for this coupling layer is a severe hindrance on acquiring fast, reliable in-service inspection data. Over the past decade, significant research activity in the field of non-contact ultrasonic inspection techniques has been reported [1-4]. The principal application is for pre-production inspection of materials and has been successfully applied in the aerospace industry [1,4]. An alternative inspection technique is to generate and receive ultrasonic Lamb waves in the material under test [1,2]. This approach is extremely attractive for in-service inspection as access to only one side of the test specimen is required. However for practical in-service applications, such an inspection instrument must be portable, reliable and robust. Unfortunately, meeting all these requirements, and hence bridging the gap between laboratory and industrial systems, has proved to be difficult for many air-coupled transducer technologies.

This paper describes the development of a prototype portable inspection instrument suitable for application in the aerospace industry. This work builds on the foundations of a laboratory based Lamb wave system [2] and advances the technology to operate under
battery power. The ultrasonic transducers are constructed using 1-3 piezoelectric composite technology [5] and designed to operate at a frequency of 600kHz. In order to generate and receive the fundamental antisymmetrical Lamb wave in a plate, mechanical adjustment of the transducer angle with respect to the surface of the test specimen is required [2]. An electronics package has been designed to supply an excitation signal to the transmission device and provide both amplification and processing for the received ultrasonic signal. Defect identification is either through visual observation on the integrated oscilloscope or by the emission of a continuous audible tone. System performance has been successfully demonstrated through C-scan images from both metallic and composite test specimens.

**ULTRASONIC TRANSDUCER ARRANGEMENT**

**Transducer Development**

The ultrasonic transducer design and manufacture was pivotal to the successful development of the prototype instrument. A number of the authors have promoted the use of 1-3 connectivity piezocomposite transducers for use in non-contact inspection systems [1,2,5,6]. Moreover, significant research effort was afforded to the development of a novel matching layer system, which has been reported to improve pitch-catch transducer efficiency by over 30dB [7]. Another important design issue is to ensure that the electrical resonance of the transmitter matches the frequency of the mechanical resonance of the receiver to maximise sensitivity. These design concepts were applied to the ultrasonic transducers utilised in the instrument and furthermore, 15mm diameter was selected as the lateral dimensions of the transducers to conform to the size constraints for the hand held front end. The transducers were characterized in terms of their electrical impedance response, surface displacement and insertion loss.

The transducer surface vibrational characteristics were measured using a scanning laser vibrometer [8]. Figure 1 presents the measured characteristic for the transmission device at an operating frequency of 595kHz. The magnitude response is illustrated in Figure 1(a), where the largest displacement is located in the center and tapers out to the transducer edges, which is constrained by the epoxy bond to the transducer casing. A reasonably uniform corresponding phase characteristic is shown in Figure 1(b). It is also possible to measure the vibrational response of the reception transducer, but this should be acquired at the system operating frequency to evaluate the practical system performance. This frequency corresponds to the receiver mechanical resonance (i.e. the frequency of maximum reception efficiency) and the resulting measured surface vibrational characteristic, presented in Figure 2, demonstrates both a lower absolute surface displacement, although the magnitude and phase responses are reasonably uniform.

As a final test, the transducer insertion loss was measured [6]. This figure of merit was acquired by axially aligning the two transducers, with a separation distance of 100mm, and measuring the peak signal response of the receiver directly on an oscilloscope. The transmitter was excited by a 10V, 20-cycle tone burst at 600kHz and the measured insertion loss was 28.4dB. This represents an efficient air-coupled transducer system and is comparable with previously reported data [6].
Mechanical Holder Design

The transducer holder design was approached from the consideration of producing a robust mechanical arrangement, whilst ensuring that the system was compatible with hand held operation. The adopted approach is illustrated in Figure 3. An angular adjustment mechanism (AAM) was incorporated into the top face of the holder (not shown) and is used to adjust the transducer angle between 0° and 15°. A tensioning spring was incorporated to maintain the transducer angle and provide stability to the mechanism during operation. Two windows have been cut from the base of the holder to provide a
FIGURE 3. Mechanical holder design illustrating ultrasonic transducer arrangement.

channel for ultrasonic propagation. Furthermore, a baffle has been included to inhibit direct propagation between the transmitting and receiving devices and this has been manufactured from PTFE to enable the holder to be freely manoeuvred over a test specimen. The transducer housing was constructed from grey nylon with protective front and back panels included to prevent damage to the transducers or inadvertent user interference of the AAM. Obviously, the transducers cannot be entirely protected due to the necessity for an air propagation channel between the transducers and the test sample.

ELECTRONICS DESIGN

Transmission Electronics

The transmission electronics for the portable Lamb wave system is facilitated using digital circuitry to gate a Sine wave oscillator in order to generate a tone burst of a fixed number of cycles and duration. This pulse is then used to switch a high power d.c. supply and thus excite the transducer. Figure 4 illustrates these components using a block diagram approach. For this system, the chosen pulse repetition frequency is 100Hz, to allow the transducers time to ring down between firings and conserve the battery life of the power source. The main obstacle in the design of the power amplification stage, is the generation of a sufficiently high d.c. level for the amplifier power supply. The approach adopted here employs three dc-dc converters, which are connected in parallel to boost the actual 24 volt system battery up to 285 volts. These converters have a current draw of approximately 100mA, which means that the power supply should operate from the given battery supply for approximately 10 hours.
Reception Electronics

The schematic shown in Figure 5 illustrates the constituent sections of the reception electronics design. The package incorporates an ultra-low noise pre-amplifier, with a gain of approximately 60dB, operational bandwidth of 2MHz and an input impedance of 50Ω, all coupled to an exceptionally low input noise voltage of less than 2nV/√Hz. An additional amplification stage is incorporated into the system and this voltage controlled variable gain amplifier is controlled from a switch on the instrument front panel. The electronics package provides a degree of frequency filtering using a simple RLC filter, with an adjustment capacitor to trim the centre frequency of the filter to the desired frequency of operation. The 6dB bandwidth of this filtering stage was measured to be 100kHz, around a 600kHz centre frequency. Finally, a comparator is utilised to threshold detect the envelope of the amplified and filtered signal, by comparing the envelope signal with a pre-defined dc level.

FIGURE 5. Receiver system schematic.
Completed Electronics Package

The electronics package incorporating both the transmission and reception electronics and the system battery is housed in an aluminium case. The instrument front panel is located on the side of the case containing the user control features (on/off switch, gain and buzzer volume) and enabling connection to the transducers and an external data acquisition package, if required. A single channel oscilloscope has been incorporated to provide visualization of the processed envelope signal. This configuration is depicted in Figure 6.

SYSTEM PERFORMANCE

Instrument Calibration

For each test sample the instrument must be re-calibrated to ensure that the angular position of the transducer is appropriate for Lamb wave generation in that material. Both audible (buzzer) and visual (oscilloscope) means are utilised to determine the transducer angle which corresponds to the maximum Lamb wave response in the sample. Figure 7 illustrates a typical envelope signal, which was acquired on a 3mm thick carbon fibre reinforced polymer (CFRP) composite test sample. Signal A in the Figure represents the calibrated Lamb wave signal generated by the instrument. It should be noted that the calibration procedure must be carried out on a defect-free area of the sample under test.

FIGURE 7. Typical Lamb wave signals generated by the prototype instrument illustrating (a) the calibrated signal and (b) the signal over a defect.

Defect Detection

It is interesting to note the reduction in signal level when the transducers operate over a 10J impact damaged area. This scenario is depicted in Figure 7 in which the calibrated signal, A, can be compared to the signal over a defect, B.

The system performance was evaluated through an investigation into its defect detection capabilities in a both metallic and CFRP composite test samples. Automated non-contact C-scans have been performed to identify simulated defects and Figures 8(a) and 8(b) demonstrate the detection of impact damage in a 3mm thick CFRP composite plate and 30mm square, 10% thickness reduction in a 3mm thick aluminium plate. From these results it is clear that this non-contact inspection instrument has identified both defects.

CONCLUSIONS

This paper has discussed the design and development of a non-contact portable inspection tool designed for in-service operation in the aerospace industry. The system is powered from a rechargeable battery pack, which has demonstrated an operating life of over six hours before requiring to be recharged. This figure is down on the estimated 10 hours of battery life when considering the transmission electronics in isolation. Although, this predicted figure did not take into account the ancillary components of the instrument.

The system has been used to interrogate a number of aerospace test samples within the laboratory environment. The instrument has successfully detected inclusions and impact damage on CFRP samples and thickness loss in metallic and CFRP samples.
Further testing will be performed by EADS to evaluate the system performance under practical operating conditions. However, the limitations of this instrument are also understood and the inevitable slightly inferior performance relative to the equivalent laboratory system using power amplification must be appreciated. Furthermore, single sided Lamb wave inspection is generally not suitable for use with honeycomb samples. Notwithstanding, commercial realisation of this non-contact portable inspection tool is considered to be the next logical step.

REFERENCES