Development of an automated assessment technology for detecting damage in body armour

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Abstract

Hard ballistic body armour plates are designed to withstand the impact of a bullet and protect the wearer, if this happens the armour is clearly damaged and so is retired from service. Mishandling however, such as dropping the armour, may cause minor and difficult to detect damage which compromises the effectiveness of the plate. Current methods of inspection involve shipping the plates to a central location, performing a thorough inspection and returning them to service if uncompromised; this is costly and requires redundancy of equipment for when not in service. Acousto-Ultrasonics (AU) is a method of Structural Health Monitoring (SHM) in which ultrasonic waves are excited in a structure by a transducer and receivers record the response, any deviation from a baseline measurement give an indication of damage within the structure. Within this paper the development and testing of a novel handheld prototype device is presented, which gives a simple yes/no answer to if there is damage on the plate. This inspection is quick and easy to perform by unskilled personnel. Low profile sensors have been utilised combined with a novel flexible circuitry with built in memory which does not compromise the effectiveness of the armour.

Keywords

Damage detection, Acousto-Ultrasonics, Non-Destructive Testing, Lamb Waves, Health Monitoring, Guided Waves, Instrumentation

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Introduction

Ballistic body armour is used by several militaries and law-enforcement agencies worldwide. There are two main types of armour available; 'soft' amour that is manufactured from woven materials such as Kevlar for protection against stab attacks and low velocity projectiles (e.g. hand guns). 'Hard' armour which is typically manufactured from ceramic and composite materials, on the other hand is used for protection against high velocity projectiles (e.g rifle rounds)[1].

Currently, the UK Military employs a hard combat body armour known as 'Osprey'. The Osprey plate is made up of a ceramic strike faced backed with composite fibre reinforcement (the exact material details have been omitted due to commercial sensitivity). Through use and mishandling of body armour the ballistic protection may become compromised. Although compromised plates have shown that they may be able to resist a threat[2], the level of protection is very difficult to determine therefore any damage to armour results in its withdrawal from service[3]. Generally, aging is perceived not to be a significant contributing factor to the degradation of hard armour but may effect soft armour[4].

Currently, there is very little technology to assist with the evaluation of robustness of armour panels in the field and hence the ballistic protection that they offer. The main method used to check armour for any obvious damage is visual examination [5]. In order to conduct a more thorough inspection of the armour, the armour has to be removed from service and transported to a laboratory for inspection, at considerable cost[6]. This is also an inconvenience to military operations where additional armour units are required to compensate for the units taken out of service.

A variety of techniques have been employed to non-destructively evaluate the integrity of armour which include resonant ultrasound spectrometry, C-Scans, infrared thermography and microfocus x-ray computed tomography[7]. The current method used for inspecting body armour plates is x-ray imaging. Although this method is a non-destructive technique, it is a time-consuming process as the only a small area of each plate can be imaged at a time to achieve the required fidelity. These images are then 'stitched' together to create a composite image. This image is then inspected by an operator manually for any visible damage. In all, this inspection method is expensive, lengthy and prone to human error[8].

There is a keen interest both within the UK[9] and abroad[6] for technologies that are able to conduct a rapid, low-cost assessment of the condition of body armour within the field. At the time of writing, there are limited technologies that try to achieve this. Plextek have developed their AIMS system to assess the condition of body armour[10] which they state removes the need for regular x-ray analysis. The system uses a small inertial sensor to detect impacts sustained by the plate. Although this technique will give an assessment of use of the system, what this technology does not do is give an assessment of the condition of the armour plate, thus x-ray inspection would still be required when damage is detected. Therefore, it may be possible that false-positives are produced. Furthermore, only impact damage is considered which means that damage from other sources may go undetected.

Haynes et al.[11] presented a development of an automated x-ray system that could be employed in the field for assessment of armour plates. The system employed a bespoke algorithm that processed the x-ray images to reveal the presence of cracks.

A technique that has showed much promise for the detection of damage in composite structures and assessment of hard ballistic armour is ultrasonic guided waves[12]. Meitzler et al.[13] used lead zirconate titanate (PZT) transducers to excite flexural modes of the plates in the order of tens of kilohertz. Although the motivation of the research was to produce a handheld device, all testing was conducted on laboratory-based equipment. Modal responses were measured for damaged and undamaged plates where metrics such as amplitude and frequency content were then compared.

Godinez-Azcuaga et al.[14] used guided ultrasonic waves to assess the condition of ballistic protective inserts in personal armour. Pitch-Catch ultrasonic techniques were applied to detect damage by moving sensors across the ballistic insert both in transmission and through-thickness configurations. Power spectrums were analysed to determine the presence of damage.

Godinez-Azcuaga et al. [15]presented an automated damage assessment system for ballistic protective inserts using low-frequency ultrasonics. The system uses a large frame and conveyor belt to place ballistic inserts under cylindrical roller transducers that acted as through thickness transmitters and receivers. The ultrasonic waves were compared using a cross-correlation method which allowed the presence of damage to be determined which was verified with X-ray inspection.

Despite all of these technology developments, a suitable device for in-service use has yet to be developed and employed. Many of the aforementioned technologies require either background knowledge and training of operators, large space for operation or require specific health and safety requirements (as in the case of x-rays).

This paper presents the development of an automated ultrasonic-based technology which is handheld and can be used in the field with no formal training. This was achieved through initial lab equipment testing, the development of a large bespoke MK I system which then led to the development of a handheld MK II system.

Technology Overview

The presented technology uses Acousto-Ultrasonics (AU), which are also referred to as guided lamb waves, to inspect the body armour panels. The basic principle of AU is outlined in Figure 1. Transducers are excited with an electrical signal which induce a surface wave in the armour. The wave travels across the surface of the armour plate where it is received by another transducer; being converted back into an electrical signal for analysis. This wave is excited a number of times and the recoded waves averaged to reduce recorded noise.

When the armour plate is in an undamaged condition, the received wave should not differ from previous inspections (baseline measurements - Figure 1 (a)). When damage is present, the wave interacts with the damage and the wave is disrupted, resulting in a difference in the waves received thus indicating damage is present (Figure 1 (b)).

Although, this technique is most sensitive to damage that lies within the source-sensor path, it is possible to detect damage outside of this, as the wave reflects off the damage, assuming the waves do not attenuate before they can be received.

[insert Figure 1.]

Figure 1: Demonstration of AU principle (a) AU inspection on an undamaged ballistic plate (b) AU inspection on a damaged plate

A technique which quickly and clearly identifies the presence of damage whilst performing AU is cross-correlation[24,25,29,30]. The technique compares the similarity of the two waveforms returning a value between one (where two waves are identical – indicating no damage) and zero. A value below one indicates that there is a change in the wave, which if below a certain threshold indicates that damage is present. For further reading on the coefficient, the reader is referred to Lynn[31].

The AU principle of damage detection has been applied to a variety of structures and materials in a range of work using lab-based equipment[12,16–26]. Researchers such as Fu et al[27] have also created lightweight, low power wireless devices capable of applying the technique. A fully wireless device is however infeasible for military application due to the additional size as all hardware is permanently on the armour and the presence of a radio signature due to wireless communication. There are some devices commercially available for conducting AU inspection, such as the products from Acellent[28]. This technology is primarily aimed at infrastructure and transport meaning although their sensors are low profile making them well suited for armour the hardware is bulky so not suited for field operation. To the knowledge of the authors there is currently no technology that can conduct inspection on a handheld, battery-powered device which returns a simple 'Pass/Fail' result, that is capable of out-performing the current x-ray inspection process, demonstrating it is an excellent solution for battle field inspections.

The concept of the developed device is presented in Figure 2. With the aim of applying a system to body armour a few considerations had to be made:

- Lightweight and low-profile transducers and circuitry for wearer comfort and not to interfere with battlefield operations
- On-board memory for storing 'baseline' measurements.
- Wired connection, hence not giving a battlefield radio signature
- Simple operation with no requirement for prior knowledge
- Low cost

[insert Figure 2.]

Figure 2: Device concept

As a design consideration was the cost, using typical ultrasonic sensors was impractical as they tend to be in the order of hundreds of pounds (as demonstrated by the sensors used by Godinez-Azcuaga et al.[14]). They are also not at all low profile, small sensors being around 10mm high. Trials were conducted with Murata SMD Diaphragm Piezo transducers pictured in Figure 3 which showed sufficient fidelity could be achieved. These low-profile transducers (0.22mm) are 12mm in diameter, cost around 20p and have gained popularity for SHM recently[32]. Although they are resonant between 8kHz – 10kHz sufficient ultrasonic waves can be produced and received by these transducers in the order of hundreds of kilohertz.

[insert Figure 3.]

Figure 3: Murata SMD Diaphragm Piezo transducers[33]

Lab Based Equipment Testing

Test setup

Prior to the manufacture of a bespoke prototype, an investigation was conducted with commercially available lab-based equipment. Four piezo transducers were attached to an Osprey body armour plate that was in 'new' condition using cyanoacrylate adhesive (locations of the transducers are shown in Figure 4b). Each transducer was excited with a 5-cycle sine wave at frequencies 50kHz – 300kHz in 50kHz increments. Each frequency was excited at an amplitude of 20Vpp using an Agilent 33210A function generator while the other transducers recorded the wave packets using a Mistras Group Ltd (MGL) PCI-2 Acoustic Emission system with a sample rate of 10MHz. The acquisition of all the receiving channels were triggered from the excitation signal with a repetition rate of 5Hz, allowing the wave packet to attenuate before exciting the next wave packet. 150 baseline signals were taken at each amplitude and frequency and averaged to improve the signal-to-noise ratio. Prior to impact, AU was conducted on the armour plate which acted as a baseline measurement.

The instrumented plate was subjected to a 30J impact using a 20mm hemispherical impactor in an Instron Dynatup 9250HV drop weight test machine. The impact energy was chosen to simulate dropping the 3kg plate from 1m. After conducting the impact test, an AU inspection was conducted. These measurements were compared with the baseline measurements using the cross-correlation technique.

Results

On conducting a visual inspection of the Osprey plate, there was very little, if any, damage present (Figure 4 (a)). Visually it appeared in the same condition as it did prior to impact. To verify the presence of damage, a dye-penetrant test was conducted which revealed cracking over the plate, shown in Figure 4 (b).

[insert Figure 4.]

Figure 4: Ballistic plate subjected to 30J impact (a) no damage visible, (b) cracks visible after dye-penetrant testing

The results of the cross-correlation of waveforms acquired before and after the impact are shown in Figure 5 (a) where the maximum cross-correlation coefficient for each transmission path at each excitation frequency can be seen. For each path and frequency there was a significant drop in correlation (below 1) indicating the presence of damage. A waveform pair is also presented for visual comparison in Figure 5 (b).

[insert Figure 5.]

Figure 5: (a) Maximum normalised cross-correlation coefficients against excitation frequency for each transmission path, comparing pre-impact and post-impact wave packets. (b) Tx1Rx2 50kHz Pre and post impact waveforms. (Note: Tx refers to transmission, Rx refers to receiver)

Mk. I System

Mk. I Design

The Mk. I prototype, shown in Figure 6 was developed to test, refine and debug desired hardware and associated software. The system was controlled via USB using bespoke software. Each channel was designed to act as both a transmitter and receiver. As a transmitter the system could construct either continuous sine waves or sine wave packets using Direct Digital Synthesis (DDS) between 50kHz – 150kHz in 1kHz increments, with a maximum amplitude of 20v peak-to-peak. As a receiver, the system could sample at 1 MHz with a 12-bit resolution and variable gain.

[insert Figure 6.]

Figure 6: Mk. I prototype

The Mk. I was a ‘dumb’ system that still required the connection of a laptop and subsequent signal processing to determine the presence of damage. This was an interim step between the commercially available lab-based apparatus and a bespoke hand-held prototype.

Mk. I Testing

As with the prior testing a series of impact tests were conducted on a virgin Osprey plate using the Mk. I prototype system. From the initial testing, it was found that the best amplitude response was achieved at 125kHz, enabling the number of averages to be reduced to 32 with a 9.6Vpp. Reducing the excitation amplitude was desirable for any future hand-held system to reduce power consumption.

To investigate the system's ability to differentiate between impacts that cause damage and those that do not, a series of impact test were conducted starting at 1J, increasing in 0.5J increments. After each impact, an AU inspection was conducted to determine whether damage was present. This was repeated until a significant drop in the normalised cross-correlation coefficient was observed at 8J as shown in Figure 7.

[insert Figure 7.]

Figure 7: Cross-correlation coefficient results after each impact with increasing impact energy for MK I testing

At this point, the plate was removed from the impact drop tower and visually inspected. As shown in [insert Figure 8.]

Figure 8 (a), there was no apparent damage to the plate based on a visual assessment alone. The plate was returned to the manufacturer for x-ray inspection, the technique used for assessing damage for in-service plates. The x-ray inspection inspected sections of the plate in-turn resulting in a composite image being created, presented in [insert Figure 8.]

Figure 8 (b). The manufacturers concluded that no damage was present on the plate based on x-ray image.

Subsequently, the results of the detected damage were verified by conducting a dye-penetrant test which highlighted the presence of cracks, as shown in [insert Figure 8.]

Figure 8 (c) in a similar guise to the plate previously impacted in Figure 4.

[insert Figure 8.]

Figure 8: Armour plate with sensor ID's marked, impacted with 8J of energy (a) visual appearance – no apparent damage, (b) manufacturers x-ray inspection – no apparent damage, (c) plate after dye penetrant testing - damage visible – highlighted in boxes). Impact location shown as cross

Mk. II System

MK. II Design

Based on the development of the Mk. I device, a hand-held Mk. II device was created, which is shown in Figure 9 (a). The Mk. II could transmit and receive wave packets with a receiving sampling rate of 1MHz. A USB link enabled transmitting and receiving settings to be adjusted but unlike the Mk. I, much of the functionality of the system was set prior to use and did not need to be connected to a PC to operated.

[insert Figure 9.]

Figure 9: Mk. II prototype, (a) The assembled Mk. II, (b) Layout of the control panel

To achieve a low-profile system, a novel flexible circuitry was developed as shown in Figure 10. The circuitry was able to adapt to the contours of the armour as well as being suitable for being adapted for monitoring a variety of protective apparel. Four transducers were mounted on the circuitry as well as memory for storing baseline measurements and metadata and a cable connector. The flexible circuitry also meant that the transducers could either be applied during the manufacturing of new armour units or retrofitted to existing in-service plates.

[insert Figure 10.]

Figure 10: Flexible circuitry with sensors, memory and connector installed

When plugging the circuit into Mk. II, the onboard memory gives a readout of the details of the unit as well as all the transmitter and receiver settings, removing the need for prior knowledge of testing and parameters. The control panel on the Mk. II, shown in Figure 9 (b) was designed to be simple to use with limited prior knowledge. Only four buttons are on the control panel; On/Off, Sensor check - excites each sensor in turn in the audible range, Mode – enables switching to a 'debug' mode when a PC is connected via USB and a Run inspection button.

MK. II Testing

Following the development of the MK.II prototype, a test was conducted to demonstrate its' ability to detect damage. A baseline set of data was taken before impacting the plate, averaging the measurements 32 times with an excitation frequency of 125kHz and a sample rate of 1.25MHz. Each transmitter was driven with an excitation amplitude of 20Vpp. As with the experimental work with the Mk. I system the initial impact was at 1J, which was increased at increments of 0.5J until the MK II system detected a significant drop in correlation. It was impacted just above the cross of the flexible circuit with a 20mm hemispherical indenter.

The MK II system detected a large drop after a 7J impact, as can be seen in Figure 11. Once complete dye penetrant was used to identify if damage was present in the armour. Clear cracks were visible, as shown in Figure 12.

[insert Figure 11.]

Figure 11: Cross-correlation coefficient results after each impact with increasing impact energy for MK II testing

[insert Figure 12.]

Figure 12: Armour plate after impact with sensor ID marked. Damage present after dye penetrant testing. Cracks are highlighted in boxes. Impact location shown as cross.

Discussion

Through testing using lab-based equipment it was shown that AU was a suitable method for detecting the presence of minor damage on Osprey hard combat body armour. In addition to assessing the applicability of AU within these panels the testing assessed Murata SMD Diaphragm Piezo transducers applicability. They were shown to function well and given their major advantages of price and size when compared to traditional ultrasonic sensors they are perfect for this application. The initial testing also showed that the frequency of excitation did not greatly impact the output of the cross correlation, this may have been due to the large quantity of cracking present on the plate ensuring wave modification was caused at any frequency.

The testing of the MK I and MK II showed very similar results; that a smaller damage could be detected on the armour with either system. This testing was all at a single frequency, 125kHz, which was chosen as it gave the highest amplitude response. This single frequency successfully identified the presence of damage in the testing conducted however testing a range of frequencies may be more successful for smaller damage. A threshold on the cross correlation of 0.9 would correctly identify the presence of damage in all the testing presented within this paper, for each pulse and receive combination. Additional testing is required to ensure that external factors, such as temperature, would not result in false positives. Testing would also need to consider smaller damage or damage outside the array, which may not lower the cross correlation enough to cross this threshold.

The MK II system and flexible circuitry was developed in order to fulfil several criteria in order to make it suitable for use on body armour in a battlefield situation. Its lightweight and low-profile nature as well as being low cost makes it possible to fit/retrofit to many armour plates without being detrimental to their operation. Furthermore, the wired connection means there is no risk of a radio signature. The simple handheld device means plates can be inspected in-between use by non-trained personnel without need to transport the armour. The onboard memory enables any system to inspect the armour without need for a large database of plates and their associated baseline measurements.

The testing presented within this paper showed very encouraging results for this technology, however there are further areas that need investigation. Firstly, the effect of external factors such as temperature and damage to sensors need to be considered and accounted for. Different damage mechanisms must also be considered as within this study only localised impact to the front has been considered, side and rear must also be tested.

The MK II system has many potential applications outside of body armour, for example within the aerospace and automotive sectors. Further applications should be sought out in order to trial the system in a large range of structures.

Conclusion

This paper has presented a novel handheld device capable of conducting AU testing and be operated by an unskilled user. The device utilises a low-profile flexible circuitry enabling it to be applied to personal protective armour without compromising its size or giving it a radio signature. The MK II system has been shown to be an appropriate method of damage detection in hard armour plating without compromising the ability of the armour to perform its purpose, this has been shown through impact testing on the front side of the structure. Further testing is required to build confidence in the technology before it can be considered for large scale application. In addition to this, structures from other industries, for example automotive and aerospace, should be trialled to assess the systems effectiveness at identifying the presence of damage.

Funding

This work was funded by a Small Business Research Initiative (SBRI) through Innovate UK in partnership with the Ministry of Defence (MoD).

Acknowledgements

The authors would like to acknowledge Stuart Bailey at Morgan Advanced Composites for facilitating the acquisition of the Osprey plates and conducting the X-ray inspection.

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