NON-DESTRUCTIVE TESTING OF SENSOR ENHANCED ARMOR

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ABSTRACT

The US Army is replacing conventional armor with new types of ballistic protection which are lighter in weight than the materials they replace yet offer the same degree of protection. A key component of this new type of armor is called Multi Functional (MFA) or Sensor Enhanced Armor (SEA) because the armor provides more capabilities than traditional ballistic protection for the soldier and ground vehicle. In this paper we shall concentrate on the real-time health monitoring of SEA.

We have developed a method which has been applied to several types of new ballistic protection. We use ultrasonic waves to excite the armor panel. We measure the response to the excitation when the ballistic protection is known to be undamaged and store the results in a database. To determine if the armor has been damaged, we measure it again and compare the new results to the contents of the database.

INTRODUCTION

The US Army is introducing new kinds of armor to protect Warfighters and their vehicles. These new types of armor provide the same or superior protection as compared to conventional armor, but they are lighter in weight. In many cases it is difficult to determine whether or not the armor has been damaged and to what extent its ballistic protection has been compromised. This new kind of armor is called Sensor Enhanced Armor, or SEA armor. We have developed a rather general method that has been applied to various types of SEA armor. The method has been able to distinguish between undamaged armor and damaged armor. In certain cases, it has been possible to distinguish between levels of damage severity.

DESIRED PROPERTIES OF THE METHOD

Before describing the method we have developed it is useful to consider what properties a desirable technique should possess:

1. The method should not add considerable cost or weight to the armor. Violating either of these conditions would make it difficult to implement the system.

2. The system should be operable in both the battlefield and at a parts depot. It is necessary to be able to determine armor health in both of these environments.

3. The method should not require extensive computation. Time in both a battlefield or parts depot environment is at a premium, and it is useful to be able to get the status

of the armor health in a minimum amount of time.

4. The method should not require comparison with a “golden part” or a CAD model. Either of these conditions places a restriction upon the variability in manufacturing of the armor panels, by requiring all parts to be relatively close to each other in some measurable characteristic related to armor health. It also requires a different “golden part” or CAD model for every different armor panel. It also causes a need to update these models every time a change is made in the size, shape or composition of an armor panel.

5. The method should have a low probability of false positives (indicating damage when there is none) and should be able to detect damage of one inch in length or more.

A CONCEPTUAL DESCRIPTION OF THE SYSTEM

The basic idea for the system is modeled after a common medical technique. People often go to a physician once a year for a general checkup. The doctor typically measures several basic markers such as blood pressure, cholesterol, blood sugar, etc and stores them in a database. This gives the doctor a baseline. If one of these critical measurements changes drastically one year, the doctor is alerted that some change has occurred in the patient. In a sense the new measurements from the patient are compared to a time when he/she was known to be healthy. Differences from the baseline indicate a change in the patient’s health and further testing may be required.

We have developed a system based on this model. It has been applied to several types of armor, but we shall limit our discussion to ceramic armor. The results for metallic armor are similar.

THE SYSTEM DEVELOPED FOR CERAMIC ARMOR.

We first install a pair of PZT transducers in the armor plate. These ceramic sensors have the property that when they are excited by an alternating electrical signal they vibrate, and conversely when they vibrate they produce electrical signals. We then send an electrical signal (a sine wave of a particular frequency) to one sensor (the “driving” transducer) which vibrates and sends these vibrations through the armor plate. The other transducer (the “receiving” transducer) converts these vibrations to an electrical signal which is then transmitted to a computer where an A/D converter is used to store the signal pattern. We typically send out 200 sine waves from 1 to 200 kHz in 1 kHz increments. This gives us 200 distinct measurements for the armor plate. There is always measurement error in each trial; however, by doing measurements over time and different ambient conditions and then averaging the results, the measurement errors can be substantially reduced.

The armor plate usually has a small set of frequencies which contain most of the energy of the 200 measurements, i.e. 90% of the total energy is contained in at most 40-50 distinct frequencies. We call these particular frequencies the “fundamental frequencies” and they form a reliable signature of the armor plate.[1] The average measured responses of the armor plate’s receiving transducer to the driving

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[1] The vibrational spectrum of a plate or armor coupon consists of its fundamental frequency and its overtones, in addition to its fundamental frequencies and overtones of the transducer. The fundamental frequency is a function of mass, thickness and length.

transducer's vibrations at each of these fundamental frequencies are called the "fingerprint of the armor plate". The fingerprint corresponds to measuring the patient's vital signs over time and storing them in a database.

Figure 1: Ceramic Armor after Ballistic Testing

At some point in the future we re-measure the armor plate using the same system. By comparing the new measurements with the fingerprint we may compute a metric score based on the deviation. When the armor plate is healthy the metric scores are usually in the range (0, 5). A score above 20 is a clear indication that something has changed in the armor plate. Figure 1 shows a ceramic armor plate after being shot twice. The arrows in figure 1 show the locations of the first and second shots. Although it appears that the first shot hardly damaged the armor plate, it caused the metric score to jump from less than 1 to almost 2000.

Figure 2 shows the response of the undamaged armor's receiving transducer when the corresponding driving transducer was vibrated at various frequencies by a sine wave generator. The plot shows the response of the plate's vibrations at each frequency from 1 to 200 kHz at one kHz increments. This plot shows that the energy is not distributed randomly; in fact, most of the energy is distributed between 80 and 120 kHz.

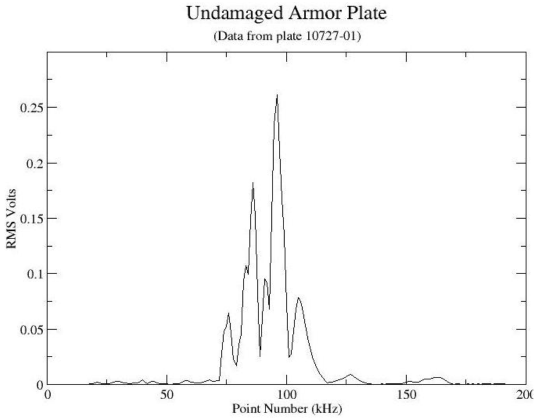

Figure 2: RMS Voltage vs Frequency for Undamaged Armor Plate

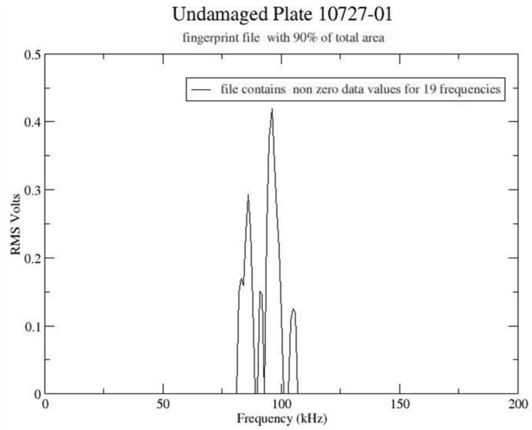

Figure 3: Graph of a fingerprint for the undamaged armor plate

Figure 3 shows the fingerprint file which is made by averaging the values from several replications data collection from the armor plate. The 19 non-zero frequencies in the fingerprint file contain 90% of the energy of the average response although they correspond to less than 10% of the total number of frequencies used in figure 2. These 19 frequencies represent the "vital signs" of the undamaged plate in the same manner that the medical tests of a general checkup do for a patient as part of his annual physical.

Figure 4 compares the frequency response of the plate for 3 distinct conditions:

- Undamaged (healthy)
- After damage by one ballistic round
- After damage by 2 ballistic rounds

Figure 4 shows that in the frequencies below 70 kHz or above 125 kHz, there isn't much difference in the frequency response of the plate before and after ballistic impact. The fingerprint in figure 3 ignores the data response of the plate except for the 19 fundamental frequencies displayed in figure 3. Since the fingerprint contains 90% of the energy of the average response vector, it captures the essence of the plate's reaction to the input of the ultrasonic waves of various frequencies. The frequencies that the fingerprint ignores contain only 10% of the energy of the system, and they play no significant role in determining the health of the armor plate. By inspection of figure 4 we note that both the locations and size of the maximum response of the plate change after ballistic impact. These changes may appear to be small and perhaps inconsequential. However they are quite significant to the fingerprint algorithm, and they correspond to major changes in the how the ultrasonic vibrations induce a response at the receiving transducer. The numbers in table 1 show that the metric clearly detects the damage from the first ballistic round and the subsequent damage from the second ballistic round.

Plate Status	Metric Score
Undamaged	0.82
After First Impact	1940.21
After Second Impact	2182.17

Table 1: Metric scores before and after ballistic impact

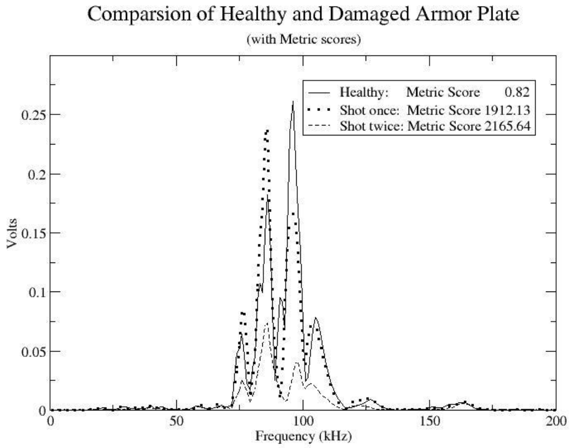

Figure 4: Data response of the plate before and after damage

HOW ACCURATELY DOES THE FINGERPRINT CAPTURE THE STATUS OF THE ARMOR PLATE?

The accuracy of the fingerprint method in determining the health of armor depends on the quality of the fingerprint data in representing the "ideal set of vibrations" from the plate. This assumes that a sufficient amount of the sources of variability from testing and environmental factors have been taken in account by testing under these conditions.

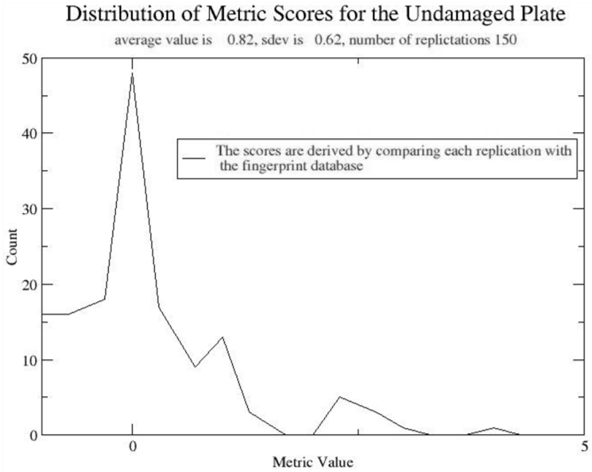

Figure 5: Distribution of the Metric Scores for the Undamaged Plate

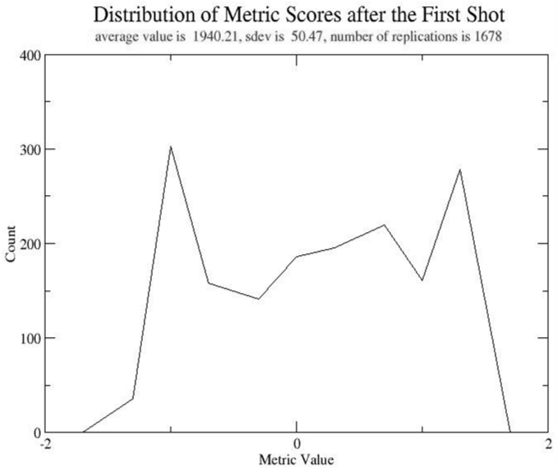

Figure 6: Distribution of the Metric Scores after the First Shot.

In figure 6, we see the score distribution of the plate after it has been shot once. Even though the damage to the plate appears to be minor (see figure 1), the average score is now over 1900, and the scores range between (1840, 2030), a range of roughly two percent. The metric clearly discriminates between the healthy plate and the damaged plate. The data used to generate figure 6 was collected on two different days, and it appears as if the distribution is bimodal, with peaks at a value of -1 and 1.75. The range of the testing values is less than 3% of the average value, so all the test replications indicate a damaged plate.

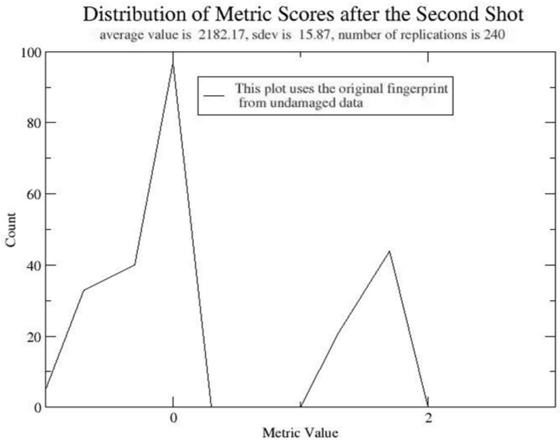

Figure 7: The Distribution of the Metric Scores after the Second Shot.

After the second shot, we see in figure 7 that the metric score has an average value of 2182.17, and the range of testing values is less than 2% of the average value. Based on this, the plate has clearly changed from its condition after the first shot. It should be noted that the fingerprint algorithm only measures the change in the plate's response to ultrasonic vibrations, and it is not able to determine the ballistic protection of the plate directly. Suppose we examine the plate after the first shot, and determine that the plate still provides ballistic protection. In this case we can declare the plate "undamaged" and compute an entirely new fingerprint just as we originally did, and use this new fingerprint in the same way as before.

Figure 8 shows that the new fingerprint based on data collected after the first shot has a distribution which resembles a normal distribution with an average value of 0.84. It can be used to determine if the plate changes from its configuration after the first shot. The data after the second shot was then analyzed with the new fingerprint. The results are shown in Figure 9.

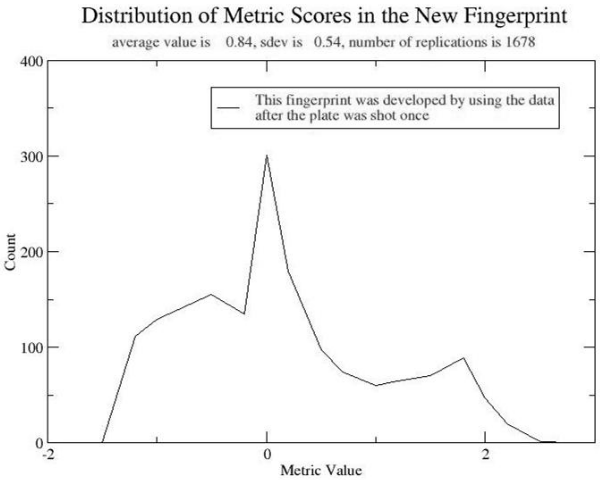

Figure 8: Distribution of the Metric Scores in the New Fingerprint

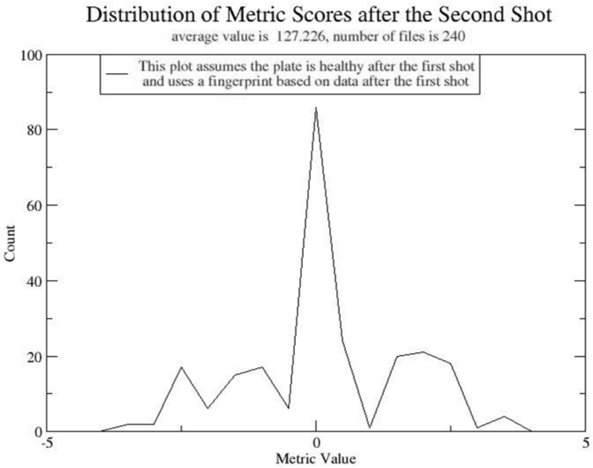

Figure 9: Distribution of the Metric Scores after the Second Shot Using the New Fingerprint

The increase in the average value from 0.84 to 127.23 with low variation in each case show that using the new fingerprint permits detection of additional damage (i.e. caused by the second shot) to the armor plate.

CONCLUSION

The authors have developed a novel real-time technique for assessing the health of armor. The fingerprint algorithm provides a convenient means for determining armor health. The algorithm requires very little computation and can be used on the battlefield or in a parts depot. It doesn't use a CAD model or a golden part, so it can doesn't require extensive modification for changes in the size, shape or composition of the armor plates. It is expected that this technique will be applicable in all types of armor.

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