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IMPLEMENTATION OF AN ULTRASONIC, ADHESIVE BOND TEST BED: SAMPLE PROBLEMS:
ALUMINUM TO ALUMINUM AND HONEYCOMB STRUCTURES

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ABSTRACT

The complex problems of predicting adhesive bond strength for both adhesive and cohesive defects have been studied using an ultrasonic, experimental test bed system. This experimental test bed incorporates the ultrasonic and computer equipment necessary to acquire and process data from various types of adhesively bonded test specimens. The computer hardware and software have been developed to allow the design of reliable pattern recognition algorithms for the prediction of adhesive bond strength. Two different types of adhesive bonded structures were studied. First, the problem of inspecting the adhesive bond joint in an aluminum to aluminum step-lap specimen to predict the bond strength that could be affected by adhesive or cohesive defects was studied. A set of 164 bond specimens was used to design an algorithm that is 91% reliable for separating the specimens into a good class or a weak class. A Fisher Linear Discriminant function was selected by the test bed system as the optimal pattern recognition routine for the classification problem. The second structure studied is the honeycomb configuration. Specimens were acquired that contained many of the typical adhesive defects common to honeycomb structures. A feasibility study was conducted to determine the test bed's potential for solving honeycomb inspection problems.

INTRODUCTION

Adhesive bonding is rapidly becoming an important part of joint technology because of its inherent nature to provide more uniform stress transfer, increased fatigue life, and a reduction in structural weight. These characteristics are particularly important in high performance structures utilizing aluminum to aluminum and aluminum to composite joints as those found in aircraft. Adhesives are often suitable for solving many joining problems compared to the more common techniques of welding, riveting, and the use of other mechanical fasteners. One of the major limitations on the use of adhesives as a structural element, however, is associated with the difficulty encountered in making an accurate determination of bond quality or potential performance after the joint has been completely assembled. An important part of using adhesives is to develop a nondestructive evaluation technique that makes use of a single ultrasonic measurement for predicting the potential bond performance level.

Recently many investigators have studied this difficult problem of ultrasonic inspection of adhesive joints. The more successful techniques for determining bond strength where gross flaws are not present have been with the aid of computerized, sophisticated signal processing and feature extraction [1-8]. Though a tremendous advance in the state of the art of ultrasonic adhesive bond inspection has been made, there still exists much work to be done in the area of producing a complete bond flaw prediction algorithm which includes all bonding defects. The solution to this problem is the goal of this study. The problem of developing a complete bond flaw prediction algorithm has been attacked by assembling an ultrasonic design tool and experimental test bed for the prediction of adhesive bond defects. This system includes ultrasonic equipment, computer hardware, and software for the design of adhesive bond defect prediction algorithms which could account for a variety of bonding
flaws. Two sample adhesive bond problems have been studied using this test bed system. Some of this work was presented at the Ninth World Conference on Nondestructive Testing [9].

The first sample problem which called for the classification of bonding defects in an aluminum to aluminum structure, was quite successful. A computerized algorithm was developed that provided an overall reliability of 91% for classifying adhesively bonded bond defects. The second sample problem which involved the classification of bond defects in honeycomb structures is in its preliminary stages. Data acquired to date clearly indicates a strong potential for successful classification.

TEST BED CONCEPT

The test bed idea was conceptualized out of need for a means to study new ultrasonic inspection problems that could not be solved using traditional techniques. These inspection problems required advanced, state of the art, methods for solutions. A test bed is a self-contained assemblage of equipment, controlled by a computer, to acquire data, process the data and design classification schemes for new ultrasonic inspection problems.

The test bed system provides a systematic approach to a new problem in ultrasonic nondestructive evaluation. Once a new inspection problem has been defined, the ultrasonic test bed can be implemented. For example, in the case of an adhesive bond problem, the first step is to perform a parametric study using Brekovskik's layered media program [1, 11] to model the bond structure. This study will provide a resource base for selecting pertinent features, plus determine a transducer selection criteria. The test bed equipment is used then to acquire data using the appropriate transducer from a set of training specimens. This data can next be reduced by signal processing to provide the desired features values. After the training set's feature vectors have been determined, a collection of computer augmented pattern recognition algorithms that are included in a package called "Generalized Approach to New Problems in Ultrasonic Inspections" (GANPUI) [12] can be instituted to find the optimal classification technique. Then a different set of specimens, a test set, are inspected by the test bed system and classified by the newly designed bond defect prediction algorithm to determine the algorithm's reliability. If the reliability is not adequate, the process is started from the beginning using new data acquisition techniques, selecting different features, and instituting other pattern recognition algorithms.

TEST SPECIMEN DESCRIPTION - HONEYCOMB

Two specimens were used in order to investigate the feasibility of this test bed to identify flaws in Honeycomb Structures.

The specimens are described in Fig. 2. Specimen A has two kinds of programmed defects, unbonds and damaged honeycomb. The unbonds were simulated by thin pieces of teflon. Specimen B contains two kinds of unbonds. Skin Unbond (SU) - where the teflon was placed between the facing and the adhesive, and Core Unbond (CU) - where the teflon was placed between the adhesive and the Honeycomb core.

TEST BED SYSTEM

An ultrasonic pulse echo immersion system was used for the data acquisition procedures required in this experimental test bed. A block diagram of the ultrasonic equipment is shown in figure 3. The system consists of an Aerotech UTA 2 Pulser/Receiver driving the ultrasonic inspection probe. This pulser/receiver also amplifies the returning ultrasonic RF signal and has a gate circuit to separate and output a specific part of the ultrasonic waveform. The gate signal was used in this test bed as a means to trigger the analog to digital converter.

A Tektronix 7704 oscilloscope is used to display the ultrasonic RF waveform along with the gate signal. A computer controlled XY scanner is incorporated into this test bed system as a tool to acquire automatically and accurately, ultrasonic data for a variety of bond specimen configurations.

Transducer Parameters for Adhesive Bond Inspection

The selection of the ultrasonic probe to be used for the inspection of the adhesive bond structure is a critical phase in the assembly of the ultrasonic equipment. The main concern when selecting the inspecting transducer is to provide the proper frequency content for accurate feature value selection. A theoretical modeling approach to the adhesive bond system was conducted on a computer to determine the significant features of the ultrasonic signal which was reflected by the bond layer. Once the features are selected, a transducer acceptance criteria is established to insure visibility of the features chosen. For example, if discrimi-
Figure 1. Step-Lap Joint Test Specimen (SI conversion: 25.4 mm = 1 in.)

Figure 2. An Aluminum Core - Aluminum Facing Honeycomb Structures Containing Programed Defects
nating features are determined to occur at five and twelve megahertz, then the search probe must have a frequency bandwidth which includes these frequency nodes to be acceptable.

Computer Hardware

The automatic data acquisition system for adhesive bond inspection is developed around a Digital Equipment Corporation PDP 11/05 minicomputer with various peripherals including a RK05 disk drive, a RX01 floppy disk drive, dual cassette drives, a Decwriter teletype and line printer, a Tektronix 4014 video terminal and a 4631 hard copy unit.

Analog to Digital Converter

The analog to digital converter used in this test bed is a Biomation 8100 unit capable of sampling intervals to .01 usec. Digitizing ultrasonic RF waveforms at this rate will yield approximately ten points per cycle on a ten megahertz pulse. The converter is an eight bit machine and thus digitizes to an accuracy of one part in 256, and can store 2,048 amplitude-time points in its memory at one time.

TEST BED PROTOCOL

Data Acquisition Details

The data acquisition procedure used for ultrasonically inspecting the test specimens is as follows. The transducer was automatically located over each of six inspection points on the bonded specimen, and these signals were spatially weighted and averaged to account for the shear stress distribution in the step-lap joint [13]. A one and a quarter inch water path separated the transducer from the specimen. At each location, five amplitude-time signals, which included a reference reflection from the top of the aluminum-water interface, and an echo from the adhesive bond layer, which was composed of the superposition of both adherent-adhesive interfaces, were gathered by the analog to digital converter. These signals were averaged to eliminate some of the random noise generated by the system. The result of the averaging is a single reference and bond line echo which is stored in the computer's memory. A program is then called which calculated the Fourier transforms of the reference and the bond line echoes. The reference spectrum is divided, point by point, into the bond layer's echo spectrum using a complex division algorithm. This division results in the transfer function for the bond layer [10]. The transfer function is then used to determine various feature values because the transfer function is a function solely of the bond layer and is independent of the transducer. The features from the amplitude-time signals and the transfer functions are stored and later used in the pattern recognition algorithm. The pattern recognition algorithm function which accepts the feature values from each bond layer and classifies the bond specimen according to the presence or absence of defects. The data acquisition for the honeycomb specimens was similar to that used in the aluminum to aluminum adhesive bond work.

Signal Processing

An important phase in the development or implementation of an adhesive bond prediction algorithm is signal processing and data reduction. This is done before the feature values are determined to provide better, more accurate values. There are several noise influences in this experimental test bed system. One source is noise picked up by the transducer from the specimen and its surroundings. Another source of noise is from the measurement equipment. And the quantization noise caused by the finite quantization levels of the A/D converter. Random noise can be significantly reduced by averaging the ultrasonic RF waveform many times as it is passed to the computer. A moving average is beneficial in reducing high frequency noise in the ultrasonic signal. And low frequency noise can be accounted for in the frequency domain or by a DC offset setting in the A/D converter.

The major data reduction technique used in this test bed is Fourier Transforming the ultrasonic RF signals. The Fourier Transform changes amplitude-time information into the amplitude-frequency domain. The Fourier Transform is a good data reduction technique because, for example, a 512 point amplitude-time signal can easily be represented by
a 50 point Fourier transform spectrum. Thus a significantly reduced feature vector is able to represent the signal in the frequency domain. Furthermore, the ultrasonic signal might be described by only a few characteristic features such as peak frequency, 6 dB down bandwidth, and a number of significant depressions. These features can then be used in a pattern recognition algorithm to classify the ultrasonic signal’s origin.

Feature Selection

One of the more critical steps in the implementation of any pattern recognition techniques is the selection of the best features to distinguish the different classes being studied. To aid in feature selection, a theoretical, computer-generated model, based on Brekhovskikh’s layered media theory [12] was developed to provide a large set of idealized ultrasonic transfer function data for a variety of adhesive bonding situations. These transfer functions provided a means to select the distinguishing features. These features were then compared with the same features from the actual bond specimens to determine their usefulness. Features found promising by other authors [2, 3, 4, 5, 6, 14, 15] were also considered and either incorporated into the algorithm or rejected. The features used were primarily extracted from the transfer function as shown in figure 4, and are described in more detail in reference [16].

Algorithm Development

After the entire set of bond specimens have been ultrasonically inspected and the data stored in the computer, the bond defect prediction algorithm may be developed. A fairly large set of specimens must be used to produce an accurate bond defect prediction scheme. The data set which in this study included 154 bonds was Fourier transformed and the transfer functions were calculated. The data set of features were then separated into two random groups, the training set and the test set. The first set of 64 specimens was used in the Fisher Linear Discriminant [3] function to calculate the optimal coefficients for the linear discriminant function. The same data set is then substituted into the Fisher Linear Discriminant function’s equation and the scalar result for each bond specimen is calculated. These scalar results are then correlated with their respective failure modes and a threshold for the good bond-bad bond boundary is derived. The final task is to test the second set of 90 unknown bond specimens with the linear discriminant function so as to determine the bond defect prediction algorithm’s reliability. If the reliability is not acceptable, the process must be restarted using improved data acquisition, better signal processing and possibly different features.

RESULTS - ALUMINUM TO ALUMINUM STUDY

Two sources of feature values were considered for this sample problem of adhesive bond defect prediction. First, a more classical technique of selecting features from the Fourier transform frequency spectrum was considered, but this method is dependent on one transducer as described by Rose and Thomas [8]. Their method used Fourier spectrum features in a Fisher Linear Discriminant function to classify adhesively defective bond specimens and was 91% reliable for the design transducer. See figure 5. Any other transducer produced poorer results. Figure 5 also presents the results from an earlier study conducted by Rose and Thomas [8] to predict “adhesive defects” in aluminum to aluminum, step-lap specimens. This study differed from the present study because the present study includes cohesive defects as well as adhesive defects. A second more desirable technique of directly selecting most of the features from the transfer function of the bond system was considered because of its inherent transducer independence. Both methods of selecting features used the same training set and test set of specimens. Both methods considered a two class problem, good or bad bonds. The bad bonds in this study were either adhesive defects or cohesive defects. The adhesive defects were caused by surface contamination as in the earlier study [8], and the cohesive defects were manufactured by undercuring the adhesive.

Features from the earlier study [8] were used to find adhesive problems and new features, determined by a theoretical study, were added to find the cohesive problems.

The first method of selecting features from the Fourier transform provided rather reliable results, but again these results are only good for a single transducer. The training set of specimen's defect was predicted with 97% reliability by the Fourier transform alone. Then the test set reliability dropped to 74% when using only the Fourier transforms for feature value determination (figure 5). In this case, as in the second case, a Fisher Linear Discriminant function was designed to predict the adhesive bond defects.

The second method, using the transfer function provided a 91% reliability for the same 64 bond specimens used in the previous training set. The algorithm was designed to produce an optimal loss function reliability, which in this case was 97%. The loss function analysis concept allows for the incorrect prediction of good bonds, but does not tolerate incorrect prediction of weak bonds. Sometimes adjusting the pattern recognition algorithm to produce best function results decreases the total reliability of the algorithm. A test set of 90 bond specimens was inspected and the transfer function based algorithm provided an 84% reliability, which was better than the Fourier transform based algorithm for the same specimens (see figure 5). Also, the loss function results for this test set using the function approach was 91% reliable.

Preliminary Results for Honeycomb Study

The preliminary results for the Honeycomb specimens are summarized in fig. 6. Fig. 6 also compares these data with other NDT methods, i.e. Neutron Radiation (NRT), Optical Holography (OH), Ultrasonic: Resonance - Fokker Bond Tester (FBT), Pulse Echo (PE) and Through Transmission (TT). All defects have been detected and differentiated by the combined effort of the NDT methods presented in Fig. 6.

Neutron Radiography Fig. 6a can detect clearly core Unbonds but not Skin Unbonds. Honeycomb defects are detected by NRT but not as clearly as by x rays (RT) 17, 18

Optical Holography can detect clearly all three types of defects presented in Fig. 6b - i.e. Damaged Honeycomb, Skin Unbonds, Core Unbonds and differentiate them clearly from the situation of
Relative Amplitude

A - Peak Frequency
B - Dip Frequency
C - Dip - Peak Frequency
D - Dip/Peak Amplitude
E - DP1 - DP2 Frequency
F - 6 dB Down Bandwidth

Figure 4. Features Selected from Transfer Function

<table>
<thead>
<tr>
<th>Training Set</th>
<th>Test Set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reliability</td>
</tr>
<tr>
<td>Rose and Thomas Fisher Algorithm (adhesive defect only)</td>
<td>96%</td>
</tr>
<tr>
<td>Fisher Algorithm Using Fourier Spectrum Features</td>
<td>97%</td>
</tr>
<tr>
<td>Fisher Algorithm Using Transfer Function Features</td>
<td>91%</td>
</tr>
</tbody>
</table>

Figure 5. Sample Problem Results Compared with Results of Previous Adhesive Bond Study

Figure 6a. Neutron Radiographs of Specimens A & B of Fig. 2b.
Figure 6b. Optical Holography NDT Results for Specimens A & B of Fig. 2b.

Note: Flaws with less than 0.5 inch diameter were not detected.

Figure 6c. Fokker Bond Tester Results of Test Specimen A & B of Fig. 2b. Prof. #1214: Adhesive FM-123-5
the Good Bond (Fig. 6b). The optical Holography method can not differentiate between the three types of defects.

The specimens of Fig. 2b were bonded with the FM123-5 adhesive. It seems that for this adhesive the Fokker Bond Tester is quite limited as the B-Scale Amplitude for different bonded areas is dispersed and it can hardly differentiate between a situation of Unbond or a Void and a situation of Bonded areas, Fig. 6c.

The UTPE and UTTT together can differentiate between the four situations (good bond, SU, CU, damaged honeycomb). The PE technique can differentiate clearly between the damaged honeycomb and skin unbond on the one hand and Good Bond and Core Unbond on the other hand. But it does not differentiate clearly between bond and CU or between damaged honeycomb and SU (Fig. 6d). The Through Transmission can differentiate clearly between damaged honeycomb and Skin Unbond and between good bond and Core Unbond. But it does not differentiate clearly between SU and CU, (Fig. 6e).

We see that the Ultrasonic test method has the full potential to detect and differentiate between the different types of defects. A detailed study of the different parameters of the Ultrasonic signal may detect and classify the defects in an honeycomb structure by a single measurement. Commercial interests prefer the PE technique as this technique needs access to only one surface and is more economical then the through transmission technique. The new sophisticated technique may in the future predict a sub-standard bond strength in a honeycomb structure.

CONCLUSIONS

A major concern of the adhesive bonding industry has been the nondestructive evaluation of the bond layer in an assembled structure. This study has produced a computer augmented, ultrasonic test bed system which is designed to attack and solve problems in classifying adhesive bonding defects. The types of problems considered are not the gross flaws such as delaminations or debonds by the more subtle defects such as improper surface preparation and adhesive under-cure. State of the art ultra-
sonic data acquisition procedures, sophisticated signal processing and feature extraction methods, and advanced pattern recognition techniques are incorporated in the test bed system.

A sample problem of identifying improper surface preparation or adhesive under-cure in aluminum to aluminum step-lap joints has been solved using the ultrasonic test bed system. An overall reliability of 91% has been achieved for this classification problem. The success of this sample problem clearly indicates the potential of the ultrasonic test bed to solve many of the adhesive bonding inspection problems plaguing the industry today.

REFERENCES


