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Ultrasonic Nondestructive Evaluation of Composite Materials using Fractal Graphs

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ABSTRACT

In nondestructive evaluation of composites, ultrasonic C-scan technique is perhaps the most versatile and widely practised. In recent years, automated C-scan has become possible, which incorporates advanced features as digitisation and storage of analog data, in real-time. However, C-scan images are still evaluated by visual inspection. In the present work, Fractal theory is proposed as a viable supplement to this human inspection. A simple fractal algorithm has been implemented for such an exercise.

1. INTRODUCTION

The aerospace industry, since its inception, has a demand for materials having light weight, high strength, high stiffness and good fatigue resistance. Composite materials meet these requirements quite efficiently. Assessment of their reliability through identification and evaluation of damages in these materials is complicated because of simultaneous existence of different defect modes. The ultrasonic methods are versatile and relatively inexpensive for such a task and are playing an important role in helping to identify damage mechanisms (in composites) to characterise the role played by them in the final failure process. The most popular among the ultrasonic methods is C-scan. In recent years, with the availability of high speed analog-to-digital (A-D) cards, attention has been focussed on automated C-scan through interfacing and control by computers.

In the present investigation, automated ultrasonic C-scan, developed in-house, has been performed as (i) composite specimens implanted with artificial flaw and (ii) composite specimens containing impact damage. Multidimensional clustering technique is employed for systematic grouping of datasets pertaining to any individual feature or a feature set. Features, both in time and in frequency domain, are extracted from the received waveform during the scanning procedure. C-scan images are obtained from the clustered output by assigning proper grey level to each location scanned, corresponding to the group to which it belongs. This clustered data is also processed by the fractal algorithm for quantitative evaluation of the images. Encouraging results have been obtained from this analysis which show that fractal graphs are quite useful in quantitative evaluation of the C-scan images. This concept also evaluates the usefulness of features in identifying defects in composite materials.

2. EXPERIMENTAL SETUP

This setup is an automated ultrasonic C-scan system, developed in-house, consisting of a high resolution type ultrasonic flaw detector (UFD) (USIP 12, Krautkramer-Branson make) interfaced with a microcomputer (PC-AT) through a high

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speed analog-digital (A-D) converter card. A schematic diagram of the setup is shown in Fig. 1. The computer also controls two stepper motors driving two lead screws with zero backlash to facilitate precision movements of the ultrasonic probe in two mutually perpendicular directions (say X and Y). A high speed A-D converter card (SONOTEX STR* 8100) with a maximum sampling rate of 100 MHz is used to digitise RF signals. The transducer (probe) used in this investigation is of broad-band type, with a nominal frequency of 6 MHz. The time gate is set over the entire portion of the desired echo to avoid any loss of information. The signal within the time gate is digitised at 512 points. Features in frequency domain, i.e., the amplitudes of different frequency components of the waveform are extracted by performing FFT on the digitised data. The frequencies of harmonics would vary from $1/(n\Delta t)$ to $1/\Delta t$ in steps of $1/(n\Delta t)$, where Δt is the sample interval and n is the number of samples. The amplitude of first fifty harmonics along with peak amplitude of the waveform in time domain are stored for further analysis. At each location, peak detection and harmonic analysis is repeated ten times and their average is taken to minimise the time-dependent error.

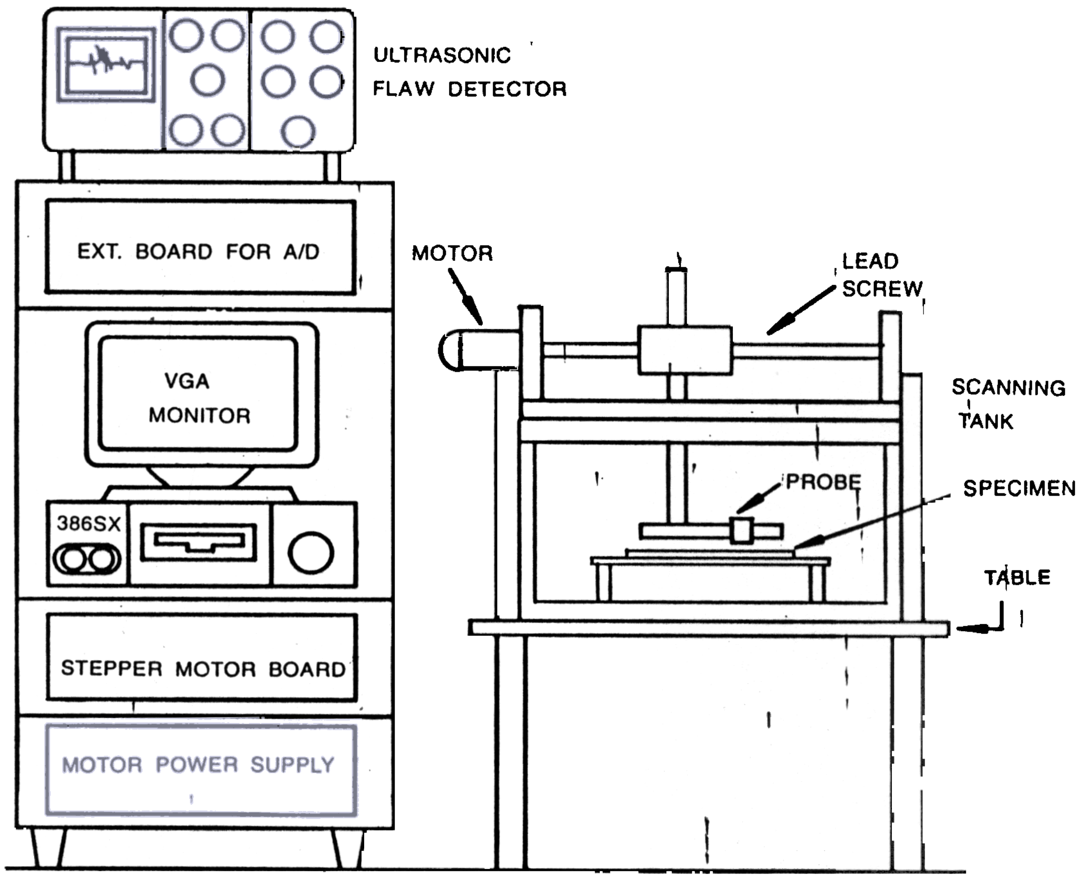


Figure 1. Schematic diagram of automated ultrasonic C-scan system

3. CLUSTER ANALYSIS

Cluster analysis is a systematic technique for sorting data units into different groups. For a given data set D of ne events (X_1, X_2, ..., X_{ne}) to be classified into K clusters, the process of clustering is stated as to seek the clusters C_1, C_2, ..., C_k, such that every X_i, $i = 1, 2, ..., ne$, falls into one of these clusters and no X_i falls in two regions. Mathematically,

$$C_1 \cup C_2 \cup C_3 = D \quad (1)$$

and

$$C_i \cap C_j = 0 \text{ for } i \neq j \qquad (2)$$

Operational objective of cluster analysis is to sort the observations into groups on the basis of their natural association. Most cluster analysis methods define this natural association or similarity measure between events as a distance. The commonly used similarity measure is the Euclidian distance, defined as

$$d(x_j, x_k) = \left[\sum_{i=1}^{n} (X_{ij} - X_{ik})^2 \right]^{\frac{1}{2}} \qquad (3)$$

where

X_{ij} = Score achieved by the j^{th} data unit on the i^{th} variable.

$(X_j) = [X_{1j}, X_{2j}, \ldots X_{nj}]^T$ is the vector of scores for the j^{th} data unit.

n = Number of variables.

In the present investigation, hierarchical clustering method with agglomerative procedure has been adopted. The criterion of Ward[1] (based on within group variance) for similarity determination has been employed. In this, the clustering procedure starts with each data unit as a separate cluster or group and, at each successive stage, two groups are merged for which the increase in the sum of within group deviations is minimum. The code incorporates stored data matrix approach as proposed by Wishart[2]. The procedure continues till the number of clusters is reduced to the present value. The clustering technique can be one-dimensional or multidimensional depending on the number of features being handled. In the present study, the total number of clusters is taken as ten for all the cases. The final output of the analysis contains coordinates of the points scanned and the cluster number assigned to it which is later used for image display.

4. FRACTAL ANALYSIS

Fractal theory can be successfully employed in quantitative assessment of digital images. In relation to ultrasonic application, the problem is to evaluate C-scan images in a quantitative way by this concept. Mandelbrot[3] describes fractal as a 'shape made of parts similar to the whole in some way'. The defining characteristic of a fractal is the fractal dimension (FD). The FD of a surface corresponds quite closely to the intuitive notion of roughness. A rough surface has a smaller FD than a smooth surface. An M x M two-dimensional digitised image consists of M^2 pixels having individual intensity values attached to each pixel. A three-dimensional representation of this two-dimensional image incorporates the third dimension as intensity of each pixel. Thus any two-dimensional digitised image can be represented as a fractal having an FD between two and three while an image with constant intensity is similar to a cube with no dents and its fractal dimensions will be three as per definition.

4.1 Estimation of Fractal Dimension from Fractal Graph

The FDs of any digitised image can be readily evaluated from its fractal graph. The fractal graph is the plot of log normalised multiscale intensity difference (NMSID) *vs* log (NSR). The normalised reference scale (NSR) corresponds to normalised scale range vector. It consists of reference scale that generally corresponds to the possible distances between any pair of pixels in the image. The NMSID corresponds to normalised multiscale intensity difference vector. It consists of different absolute intensity difference averages around each NSR i.e.,

$$\text{NMSID} = [ndi(1), ndi(2), \ldots, ndi(k), \ldots, ndi(n)]$$

where

n = Number of possible different distances between any pair of pixels in the domain.

Thus ndi for any k^{th} (out of n) distance i.e., NSR(k), can be evaluated as:

$$ndi(k) = \frac{\sum_i \sum_j | I_i - I_j |}{npn(k)} \qquad (4)$$

where

I_i and I_j are the intensities of the i_{th} and j_{th} pixels of the domain which are separated by a distance of NSR(k).

Both i and j are varied from one to the total number of pixels in the domain.

npn = Normalised pair of pixels number vector.

npn consists of elements that are the number of pair of pixels with scale (distance) values similar to reference scale. Thus, $npn(k)$ corresponds to the number of pair of pixels having distances equal to NSR(k).

Plotting lot NMSID vs log NSR for $k = 1,2,..,$ n results in a curve consisting of n pairs of points. A linear fractal graph represents a perfect fractal, otherwise a least square linear regression on it gives the slope H of the resultant curve. The FD is then calculated by the relation

$$FD = 3 - H \quad (5)$$

5. RESULTS & DISCUSSION

Composite specimens are prepared by hand layup technique in the laboratory. In all, three different types of glass (balanced woven cloth)/ epoxy specimens are used in this investigation. Out of the three specimens, two are implanted with artificial flaws, such as teflon insert and resin rich zone whereas the third specimen contains impact damage. However, due to the limitation of space, the results of the composite specimen containing impact damage only are reported here. The detailed results of all the other cases studied will be available in the PhD thesis of D.Datta, currently under progress. The damage is induced by the impact of a bullet of hemispherical nose of 10 mm diameter on the specimen in a gun barrel setup. The velocity of impact is around 45 m/s.

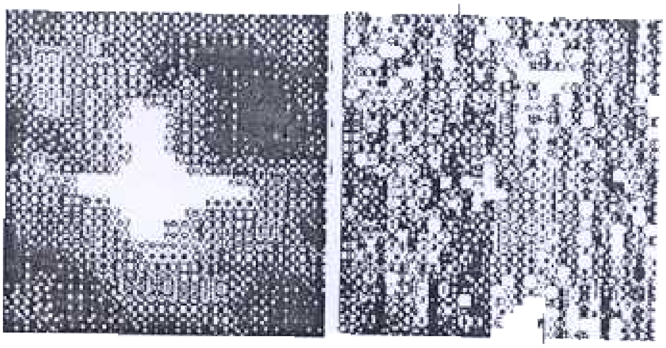
A square area of 29 mm x 29 mm is selected around the damage region for scanning. During scanning, the distance between each successive point scanned in both X and Y directions is maintained at 1 mm. Thus, total number of points scanned are 900 and the scanning is performed through transmission mode.

The dataset with different features is classified into ten clusters and the hard copies of C-scan images are drawn using a scale of grey levels. The dark region of the image corresponds to the good regions in the scanned plate while the light portions represent flawed regions. The fractal graphs are drawn for each image and respective fractal dimensions are evaluated as outlined earlier. It is clear from the fractal graphs that the images do exhibit fractal behaviour up to a NSR range of 11.4. It may be noticed that the FD is sensitive to any significant change in the image. The slopes and intercepts of the least square linear fit are listed in Table 1.

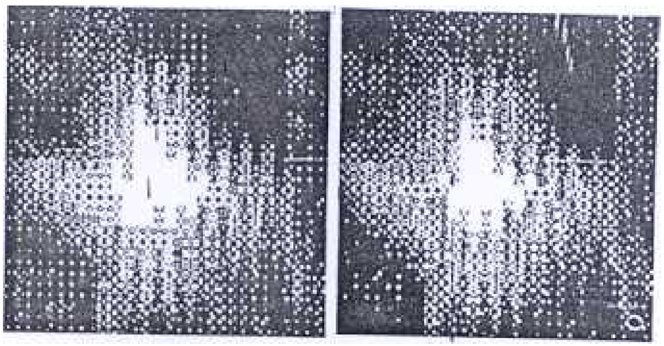
Table 1

Feature	Slope = H	Intercept	FD = 3 - H
Pk amp	0.615		2.385
0.58 MHz	0.128		2.872
1.56 MHz	0.686		2.314
1.75 MHz	0.684		2.316
2.34 MHz	0.653		2.347
8.79 MHz	0.126		2.874

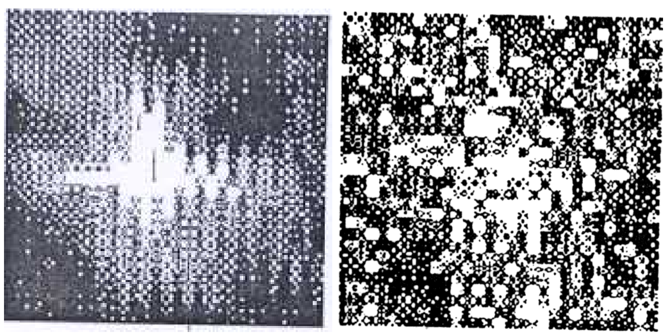
The C-scan images of the glass/epoxy specimen with impact damage, for peak amplitude, harmonic of 0.58 MHz, 1.56 MHz, 1.75 MHz, 2.34 MHz and 8.79 MHz are shown in Figs 2(a)-2(f), respectively. The corresponding fractal graphs are shown in Figs 3(a)-3(b). Figure 3(a) contains fractal graphs of the first three images (2a-2c) and Fig. 3(b) contains fractal graphs of the remaining images [2(d)-2(f)]. Both the graphs are drawn in same scale for comparison. Here the peak amplitude image as well as some of the harmonics within certain frequency range (1.5 - 3.0 MHz) represents the damage clearly. The harmonics above and below this range are less sensitive to the damage as can be seen from both their image and respective fractal dimension. This also verifies the idea that each feature interacts with the damage in



(b)



(c) (d)



(e) (f)

Figure 2(a)-2(f). C-scan images of impact damaged glass-epoxy specimen: (a) Pk amp, (b) 0.58 MHz, (c) 1.56 MHz, (d) 1.75 MHz, (e) 2.34 MHz, and (f) 8.79 MHz.

a distinct manner as observed by Rose, et al[6,7]. The fractal graphs and FD also consolidate the same.

6. CONCLUSION

The above analysis shows that the fractal graphs provides quantitative idea of defects in a C-scan two-dimensional image. This investigation recommends that the study of frequency domain

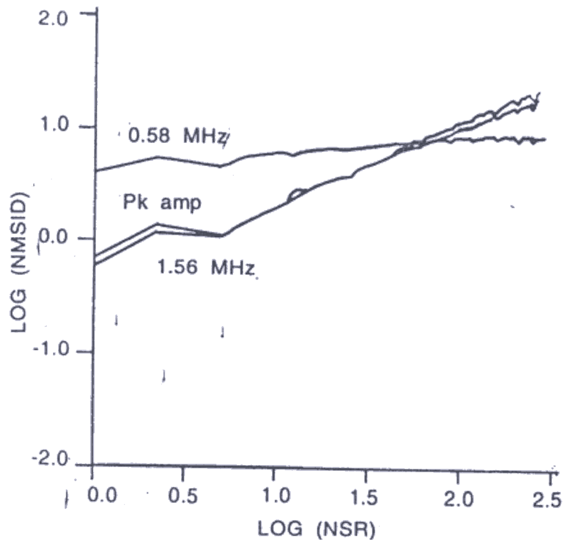


Figure 3(a). Fractal graph for images (2a-2c)

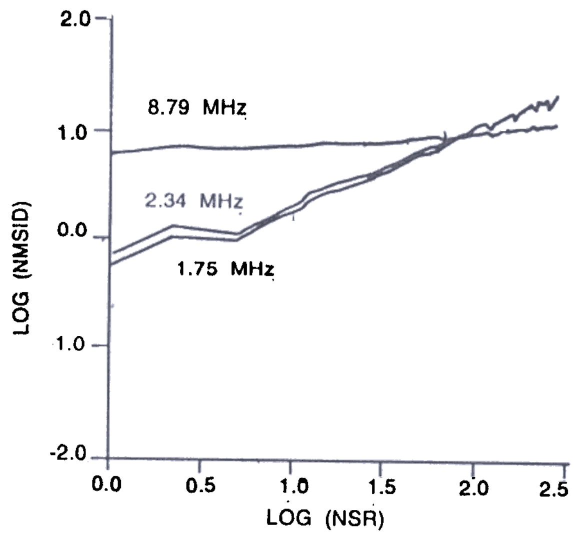


Figure 3(b). Fractal graph for images (2d-2f)

features, may be useful in addition to time-domain features, such as peak amplitude and time-of-flight in evaluating the defects in composites. Fractal graphs and FD can help in evaluating C-scan images in a quantitative manner and thus may form the basis of a fully automated nondestructive evaluation procedure.

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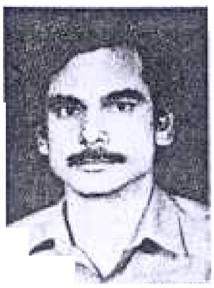
Contributors



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