Utility of feature mapping in ultrasonic non-destructive evaluation

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Feature mapping presents us with a novel philosophy in ultrasonic non-destructive evaluation that utilizes maximum information from different data acquisition and signal feature domains for possible complete material characterization and defect analysis in a variety of different materials and structures. Feature mapping is a powerful technique that covers a wide area of data acquisition and analysis techniques applying both physically and statistically based principles. This procedure, beyond standard normal beam applications, employs many seldom used but interesting data collection procedures such as critical angles, surface waves, plate waves and backscattering techniques. It forms these into an extremely versatile data acquisition protocol, followed by detailed analysis through a state of the technology signal processing, pattern recognition and expert system and /or artificial intelligence implementation practice. This Paper explains the various existing possibilities for clever physically based data collection, and the types of feature domains and features available for anomaly representation in materials. Typical results are discussed to illustrate the capabilities and utilities of the feature mapping techniques, including a normal beam longitudinal wave high frequency area ratio feature mapping (F-map) system, oblique incidence shear wave amplitude F-maps, and plate leaky wave amplitude F-map results for interfacial weakness in an adhesive bond structure. Also discussed are the results from a normal beam longitudinal wave amplitude and frequency bandwidth F-map for crack detection in a composite material, as well as a backscattered energy F-map for defect edge detection in composite materials.

Keywords: non-destructive evaluation; feature mapping; guided waves

Non-destructive testing (NDT) techniques are required to detect and identify anomalies so that possible failure situations can be avoided without rejecting structurally good material. Of the many NDT techniques available, ultrasonic imaging is one of the most accepted techniques, since a two-dimensional image of the anomalies can be visualized. Detection of most anomalies can be performed by a classical B- or C-scan inspection of the structure [1]. To identify the particular anomaly type, however, more information must usually be extracted from an ultrasonic signal. A feature mapping (F-map) system, was designed to obtain this additional information[2,3].

The basic hypothesis of an F-map system is that each anomaly type will interact with an ultrasonic wave in a unique way. These variations must be detected, quantified into features and then used in the identification procedure. The features should contain information that correlates with shape, size, orientation and/or included material of the anomaly[3,4]. Data acquisition methodology is extremely important in providing an opportunity for physics and mechanics to play an important role in feature selection. Benefits of such items as mode conversion, oblique incidence, plate wave generation, etc. can be realized. Feature sources[3] for almost any kind of data acquisition, that have proven useful, are the time and frequency domains, transfer function and an analytic spectrum. Many feature types can be defined from these feature sources. Signal processing and pattern recognition techniques also play an important role in the extraction and interpretation of ultrasonic feature values.

Factors influencing ultrasonic imaging

The ultrasonic inspection technique has excellent potential and resolution capabilities for locating and analysing a larger variety of anomalies in many different locations, compared to such other NDT techniques as dye penetrant, radiography, etc. Even in the application of ultrasonic NDT, many different directions can be taken. One of the most obvious would be associated with precise imaging, where shape, size and orientation information could be used for the identification of the anomaly type. Perfect imaging, however, may not be possible because of the physical limitations of a test technique. The primary limitation is the resolution of the ultrasonic beam. The axial resolution is limited by the maximum frequency that can propagate through a material without any significant loss of energy. The lateral resolution capability also decreases as the ultrasonic beam spreads while propagating through a medium. Also, precise imaging

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requires information from all sides of an anomaly, which may not be possible for many structural configurations.

Another significant problem with acoustic imaging is the inhomogeneous anisotropic nature of composite materials where exact wave velocities for the positive determination of reflection, refraction and skew angles are difficult to obtain. All of these limitations can restrict the imaging capabilities and in some cases cause artefacts or imaging errors. But even if precise shape, size and orientation information were obtained, proper identification may not be possible. It may also be necessary to ascertain the type, i.e. whether the anomaly is air filled or is some type of foreign inclusion. Information about the surface condition (rough, smooth, pitted, etc.) may be necessary for exact identification of the material contained in the anomaly. The total characterization of the anomaly is important in evaluating the final effects on structural performance. Therefore, precise imaging may not be the answer for anomaly identification, even if perfect imaging was possible.

Feature based systems

The goal of the feature mapping technique is to go beyond the direct acoustical imaging modalities using amplitude, arrival time and/or phase information, to a somewhat different approach. This new approach uses feature mapping or feature imaging to describe anomalies in materials. The motivation behind the development of the feature mapping technique is that each anomaly type will interact with an ultrasonic wave mode in a special way and this information can be extracted from the ultrasonic response through a detailed analysis of the signal and can be used to quantify these parameters using appropriate features. The additional information about the reflector obtained from the ultrasonic response function can augment the overall imaging process by characterizing a particular area inside a structure. The exact amplitude, arrival time and phase information is not always essential during anomaly identification in feature mapping. A typical feature mapping system is outlined in the following paragraphs.

The feature scanning technique, F-scan, was developed to display characteristics of the ultrasonic response function for a particular material. A mechanical scanning system is employed to collect ultrasonic responses throughout the entire structure. Signal processing algorithms such as time averaging, spatial averaging, the synthetic aperture focussing technique (SAFT) and split spectrum processing are applied to enhance the signal information from the electronic and material noise. Features can be extracted from time and frequency domains and in deriving the relevant features special-attention is paid to the digital signal processing computational requirements of the fast Fourier transforms (FFTs), to obtain frequency response, and other routines such as deconvolution, correlation and Hilbert transforms for obtaining the envelope of RF signals, etc. An F-scan consists of feature values being displayed as a function of transducer position. The entire F-map process is implemented on a digital computer system with many peripheral devices that are used in the data collection, data storage, feature extraction, pattern recognition and resulting displays, as shown in *Figure 1.* A subset of F-scanning is the traditional C-scanning, which uses a particular feature value, the peak amplitude in a gate, to generate an image'.

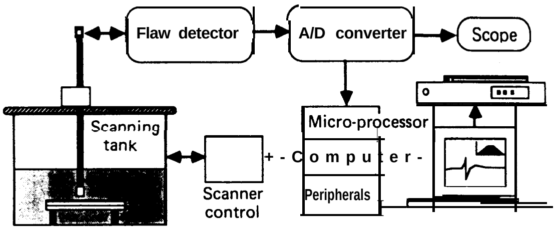


Figure 1 **Schematic representation of the different components of a feature mapping system**

The feature mapping technique goes beyond F-scanning, by identifying a specific anomaly type from an ultrasonic response rather than by just plotting a particular feature *versus* position. The F-map process has four major steps associated with it[3]. First, physical models of the anomalies are developed to give data acquisition suggestions and expectations of the changes in feature values. Second, the proper data is collected and feature values are extracted. Third, the actual variation in feature values are compared using statistical principles such as probability theory. Fourth, a decision algorithm is developed using pattern recognition techniques like cluster analysis, discriminant functions, etc. The final result is a map showing anomaly type at a given position.

The operator supervises the computer in the feature analysis and pattern recognition process to see if the results correlate with the physical model. Differences between the actual feature values and the expected feature values as derived from the physical model can occur because of difficulties in adequately describing the interaction of the ultrasonic wave with the specific anomaly geometry. The computer analysis with operator supervision allows a necessary feedback loop for the fine tuning of the identification algorithm.

Non-destructive inspection of materials is a dynamic process; the inspection tools must be capable of handling changes. New fibres, matrix systems, adhesives and metal alloys are being developed daily. These new material systems change the ultrasonic response of the anomalies. In some situations, the anomaly possibility is eliminated making one anomaly identification procedure unnecessary. Also, new anomaly types can be formed, creating a need for new identification procedures. The F-map process has the speed and flexibility to keep up with the changes in the material systems.

Data acquisition possibilities

Several data acquisition possibilities during feature scanning are described in the following paragraphs. An appropriate choice of the inspection technique depends upon the geometry and nature of the structure under scrutiny.

These data collection techniques are associated with physically based features that can be valuable in both material and anomaly classification analysis. *Figures 2-4* illustrate some immersion possibilities and *Figure 5* some alternatives where complete immersion is not possible. The basic physics and mechanics of wave propagation can be considered in any computer-aided system design. The most common industrial technique of through trans-

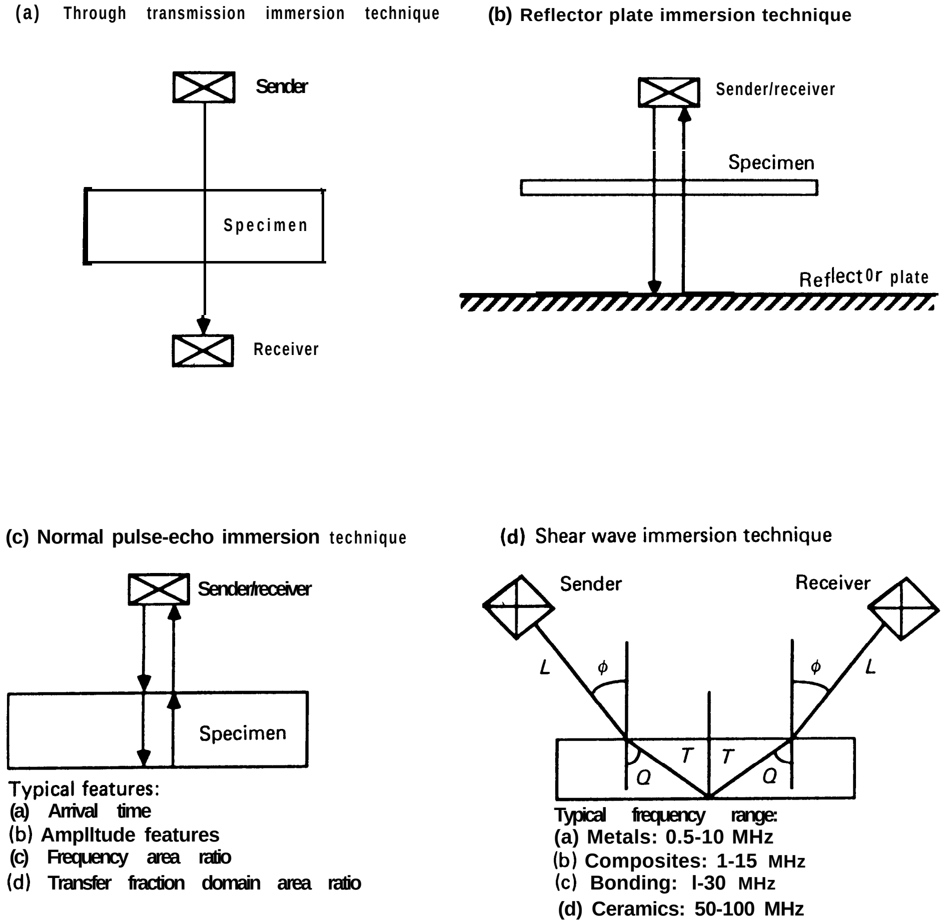


Figure 2 Data acquisition possibilities. Each of the techniques can be utilized for collecting data to exploit the physics and the mechanics of the inspected material. (a) Through transmission immersion technique; (b) reflector plate immersion technique; (c) normal pulse-echo immersion technique; (d) shear wave oblique incidence technique

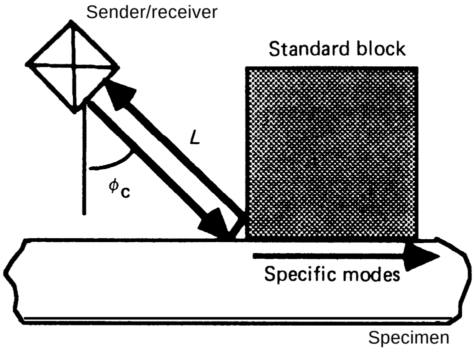
mission testing is represented in Figure *2a*. Defect detection is possible by simply observing a loss of energy through the test specimen. Depth information, on the other hand, is not available. A reflector plate double through transmission procedure is shown in *Figure 2b*. Again, defect detection is possible but reflector location information is lost. A benefit of this technique is the single transducer utilization as both sender and receiver.

The popular normal beam pulse-echo technique is shown in *Figure 2c*. This technique is one that can be traditionally used in C-scan testing. Defect presence and depth information can be obtained by way of proper gate and threshold selection (see Reference 1 for more details). A more sensitive oblique incidence shear wave immersion technique is illustrated in *Figure* 2d. By selecting a suitable incident angle of a longitudinal wave, it becomes possible to produce a shear wave with excellent sensitivity to subtle defects, such as interfacial weakness compared to a longitudinal wave in the structure. In all of the techniques illustrated in *Figures 2a–d*, the features that are most useful include, for example, arrival time of an echo, amplitude or amplitude ratio, a frequency area ratio (i.e. looking at the area under the power spectrum of a frequency range off;! to f_3 divided by the area under the power spectrum curve from f_1 to f_2), and also a transfer function domain area ratio.

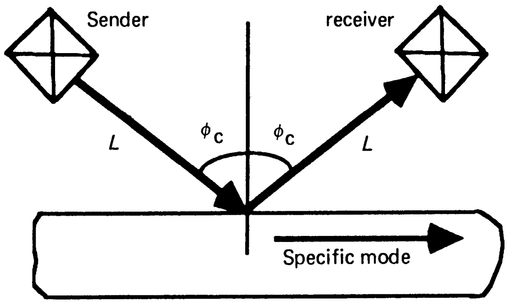
A whole series of data collection procedures that makes use of a critical angle measurement are illustrated by *Figures 3a* and *b*. Assuming a uniform homogeneous test material, the critical angle technique can provide us with a measure of the material properties of the test specimen; namely, the particular wave velocity in a particular direction. As the incident angle is increased for a longitudinal wave input, the received energy values can be plotted. A first critical angle can be obtained when the longitudinal wave angle reaches 90”. As the incident angle increases, additional critical angles can be obtained if the shear wave angle reaches 90”. Additionally, as the incident angles increase even further, various critical angles and surface or plate wave modes can be obtained, depending upon the geometry of the structure. As shown in the figures, either a single probe or dual probe technique can be employed. The scanning mechanism for this particular data collection procedure involves simultaneously moving a transducer and standard block over the specimen being scanned or two transducers over the test structure. If properties of the material are known, the data collection procedure would include a set-up at a particular critical angle of a particular mode of propagation. Any deviation from this critical angle indicating a change in material property can be recognized by a change in the amplitude of the received echo[5,6].

A plate wave data collection procedure is illustrated in *Figure 3c*. In this case, a sending transducer is mounted at a special angle to achieve a particular plate mode in the test structure. By way of a leaky wave leaving through a fluid, a receiving transducer can receive the signal information of interest [7]. Typical features could include a plate wave velocity measurement calculated from the arrival time information, as well as an amplitude ratio

(a) Critical angles using corner techniques

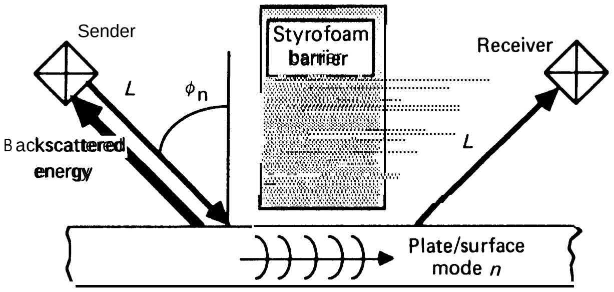


(b) Alternate reflection factor or critical angle techniques



Typical features:
(a) Critical angle of particular mode of propagation
(b) Amplitude of received echo

(c) Plate, surface and/or backscatter F • map analysis

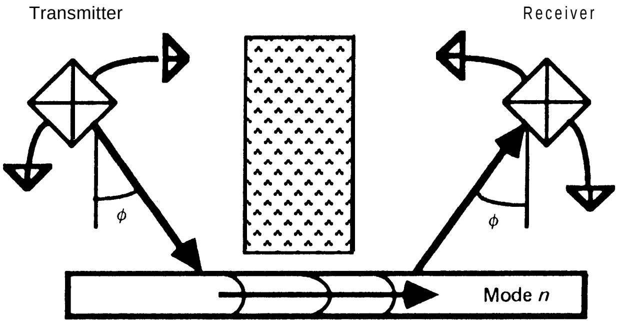


Typical features (for specific modes) :
(a) Wave velocity
(b) Amplitude ratio
(c) Frequency response

Figure 3 Other oblique incidence possibilities: (a) longitudinal, shear or plate mode critical angle set-up using a standard block; (b) critical angle or reflection factor measurement using a pitch-catch arrangement; (c) plate surface wave or backscatter measurement technique

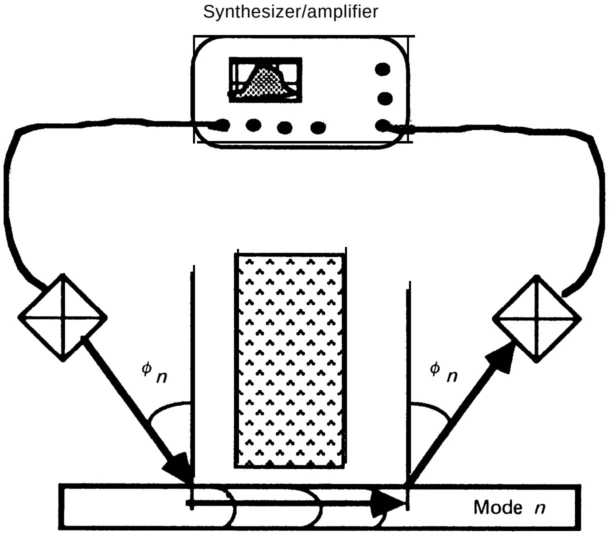
of sender to receiver. Pulse shape changes through the plate by way of frequency response measurements can also be useful. All of these features can be used to indicate the presence of either material changes or an anomaly in the test structure, since reference information on these features would be known precisely for certain structures.

An additional oblique incidence technique for producing surface waves is also illustrated in Figure *3c*. This



Typical features:
(a) Preferred angle
(b) Amplitude of leaky wave

(a) Angle perturbation technique (frequency constant)

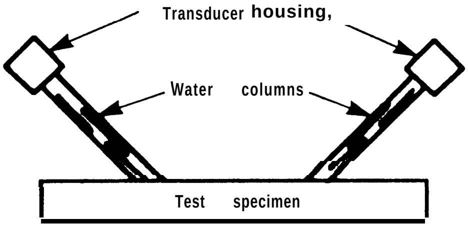


Typical features
(a) Preferred frequency
(b) Amplitude of leaky wave

(b) Frequency perturbation technique (angle constant)

Figure 4 Perturbation techniques for detecting subtle material property changes

(a) Squirter pitch-catch global inspection technique



(b) Contact methods

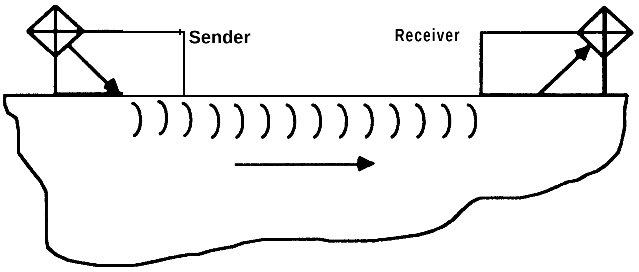


Figure 5 Some practical alternatives in the case of structures not suitable for traditional immersion modes of testing

technique is valid provided that either the wavelength to thickness ratio is very low (< 1.0) or that the specimen is considered as a half space. A surface wave velocity measurement can tell us something about the material properties of a test specimen'. A clear understanding of dispersion associated with non-homogeneities through the depth of any material can be useful in case hardening applications and other similar instances where inhomogeneity within the material is critical. Also interface waves can be applied to many situations where normal beam utilization is inaccessible due to physical limitations. For example, in the case of 'T' joints bonded to a flat surface. Here, an interface wave can be generated along the bond and useful features obtained'.

A back scattering procedure is also represented in Figure *3c*. In this case, the back scattered energy at a specific oblique incidence could often provide us with information on the fibre volume fraction, porosity content, delamination, etc. of a composite material[10].

Looking ahead to some additional new and advanced data collection possibilities, two very interesting wave mode perturbation techniques are illustrated in Figures *4a* and *b*. Perturbations using angle and frequency are possible. A careful measurement of the preferred angle or frequency could provide us with knowledge of any material property change or degradation, or any anomaly type within the structure.

Alternative data collection possibilities to the traditional immersion technique are shown in Figures *5a* and *b*. Squirter systems, couplant flow systems and various contact methods may also be used to employ the normal beam, shear wave, critical angle, plate wave, surface wave, back scattering or frequency perturbation techniques. Additionally, phased array probes with electronically controlled time delays can be used for accurately angling the ultrasonic beam or for producing surface waves.

Feature extraction and analysis

Once the data acquisition methodology has been selected, and the data acquired and stored in the computer, the next step is to efficiently and thoroughly analyse the data for information which correlates with the defect location, size, shape and type of anomaly. Such analysis techniques have been extensively dealt with in previous work[3,4,11] and hence shall be only briefly discussed here.

The various feature sources which can possibly be utilized effectively in ultrasonic NDE have been enumerated in *Table* I. Quantified information in the form of specific feature values are derived by looking at the physical as well as the statistical behaviour of an ultrasonic signal within the selected feature domains. The feature extraction process also serves as a data reduction step which is essential in the feature mapping process. A few of the typical feature types useful in ultrasonic NDE are defined in *Table* 2 but this list is certainly not exhaustive.

Table 1 **Typical feature domains available for analysis**

(a) Time domain of the RF waveform
(b) Power spectrum in the frequency domain of the signal
(c) Analytical spectrum in the frequency domain of the signal
(d) Phase angle in the frequency domain of the RF signal
(e) Echo dynamic profiles obtained through motion of the transducer towards and away from the defect
(f) Transfer function domain using the initial pulse of the transducer as the reference or any other normalization signal

Table 2 **A few of the feature types used in the feature mapping technique**

Time domain

1. Peak amplitude of the rectified RF signal (PA)
2. Positive peak amplitude of the RF waveform (PP)
3. Negative peak amplitude of the RF waveform (NP)
4. Stress reversal ratio ratio of PP and NP (SRR)
5. Energy in time domain area under rectified RF signal (ET)
6. Rise time of the rectified RF signal (RT) : (0.1 PAN–0.9PAN)
7. Fall time of the rectified RF signal (FT) : (0.9PAP–0.1 PAP)
8. Pulse duration of RF signal (PD): (0.1 PAN-O.1 PAP)
9. Number of peaks in the envelope (NP)

Power /analytical spectrum

1. Peak frequency of the frequency spectrum (PF)
2. Central frequency of the frequency band (CF)
3. Energy within a specified frequency band (EF)
4. Frequency area ratio of any two frequency regions (FA)
5. Bandwidth at $-x$ dB of the peak frequency (BWX)
6. Standard deviation of spectrum, second moment (SDF)
7. Skewness of the spectrum, third moment (SKF)
8. Kurtosis of the spectrum, fourth moment (KTF)
9. Slope of the regression least squares line fit (SLF)
10. Phase angle at frequency x (PAX)
11. Phase angle at x% of envelope (PAX)
12. Unwrapped phase angle at x% of envelope (UPAX)
13. Slope of the phase angle curve at frequency x (SPAX)

Echo dynamic profiles

1. Rise dynamics time (RDT)
2. Fall dynamics time (FDT)
3. Rise dynamics distance (RDD)
4. Fall dynamics distance (FDD)

While analysing the distribution of the feature values over a training specimen and to arrive at a conclusive decision algorithm for identifying a specific anomaly, pattern recognition techniques are useful. The utilization of cluster analysis, discriminant functions, etc. help to distinguish the good region in a specimen from the defects. Also, during the implementation process in a practical environment, expert system routines comprising of all of the different steps involved can be used to streamline the whole process.

Feature map sample results

Let us consider an adhesive bonding inspection problem with a weak interface between a metal and an adhesive. A new ultrasonic specification was developed utilizing short wavelengths to try to detect the change in the surface preparation of the bond interface. The most important component was a special higher frequency transducer with a centre frequency of 30 MHz and – 12 dB bandwidth limit from 20 to 40 MHz. This was highly focussed so that the beam width was 0.001in (0.025 mm). The return echoes were digitized at 500 MHz using a Tektronix 7912 digitizing unit. This unit can record 512 data points, or 1.02 μs of data, which was sufficient for recording the front wall echo (FWE), and both the bond line echoes (BLE1 & BLE2) separately. Data was taken in 2.5 mm increments over a test coupon that measured 25 mm x 100 mm.

This time, differences between the two surface preparation types were observed in the frequency area ratio features. The feature used was:

$$\frac{\text{Area under the amplitude spectrum (30.0-38.0 MHz)}}{\text{Area under the amplitude spectrum (22.0-30.0 MHz)}}$$

The F-map (see **Figure** 6), shows an area where bad surface preparation occurred. These results correlate well with the expectations derived from a physical model assuming the interface to be a very thin layer (1 μm) of specific material property embedded between the adherent (aluminium) layer and the adhesive (epoxy) layer. This theoretical analysis was based on Brekhovskikh's wave interactions with layered media techniques [12]. The conclusion drawn from these results was that the small pores of the well prepared specimens were too small to absorb or scatter the high frequency waves. However, the large pores of the poor surface preparation specimen were detectable with frequencies > 30 MHz. Additional work must be conducted to draw final conclusions in this study, but the tools for carrying out this inspection technique are now in place.

Moving on, let's consider some additional F-map results to demonstrate the overall utility and the wide range of possibilities with F-map analysis. An unusual F-map result is presented in Figure 7 for shear wave utilization using oblique incidence of a longitudinal wave. Here a 15 MHz signal was used to investigate the interface between an aluminium-epoxy bond. The increased sensitivity of the shear vibration mechanism is evident from the poor interface area F-map result. A plate wave F-map result on the same bond specimen is presented in Figure 8, with the reception possible by observing a leaky wave. Hence these techniques present us with a potentially excellent global inspection tool which could substantially improve the speed of in-service inspection. Also, the utilization of these different modes of wave propagation and the effective excitation of the material particles from different angles, can provide us with improved sensitivity for many types of anomalies.

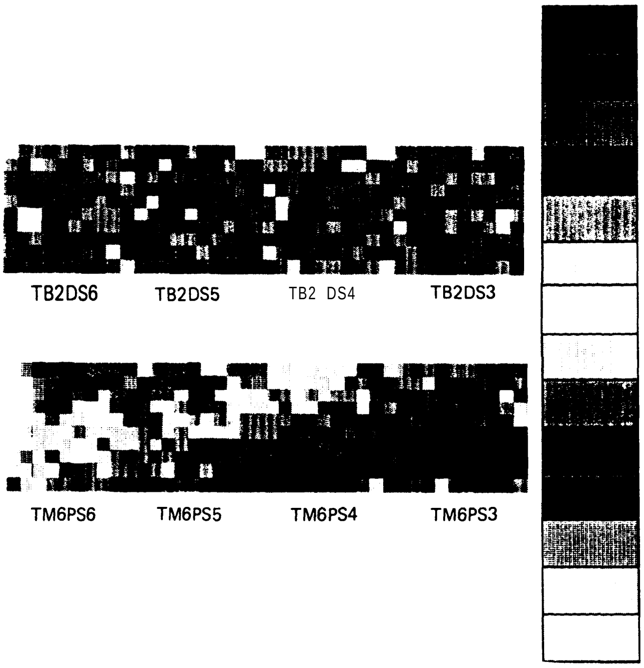


Figure 6 **Ultrasonic high frequency normal beam longitudinal feature mapping result of a good and a bad bond surface preparation. The feature selected was frequency area ratio (FAR): (30.0-38.0 MHz) / (22.0-30.0 MHz). (Lower feature values indicate possible bad surface areas)**

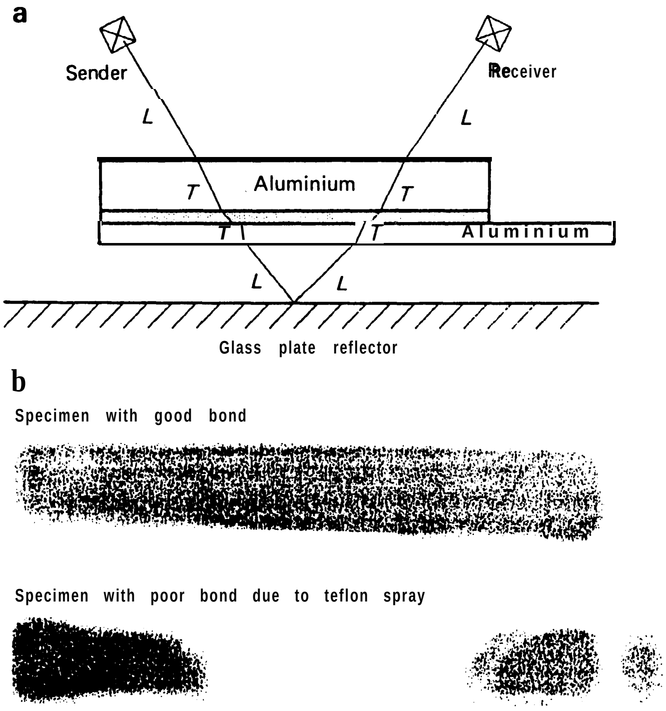


Figure 7 **Unusual oblique incidence shear wave amplitude F-map result. (a) Use of shear waves and reflector plate technique for defect location; (b) typical result using the shear waves in F-mapping (shear waves are more sensitive to interfacial weakness)**

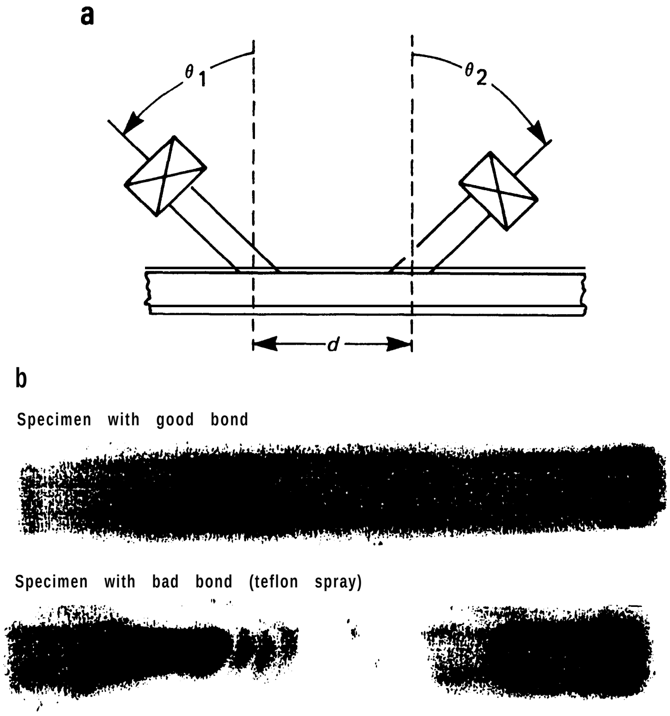


Figure 8 **Leaky plate wave result. (a) Plate wave utilization in non-destructive testing; (b) results using plate waves for detecting interfacial non-uniformities**

Let us further consider an oblique incidence shear wave F-map result for a specimen with subtle interface weakness areas, as shown in Figure 9. In the inspection of adhesive joints, subtle irregularities during surface preparation of the adherent can lead to bonds in which the two surfaces are in good contact, i.e. no delaminations, but still have poor connection at the interface. Due to lack of material property changes at either side of the interface, conventional C-scans using normal longitudinal waves, radiographic technique, etc., fail to distinguish these defective regions from a well-bonded region. Due to poor adhesion, such defects cannot carry any shear loading and hence are extremely susceptible to failure. An obliquely incident shear wave, incident at 30° to the interface, generated through mode conversion of a longitudinal wave incident at a specific angle of 15° from water on the upper aluminium plate, was used to evaluate the interface quality. The physical principle underlying this option is that shear waves produce displacement components 'tangential to the interface' during interactions at the interface and hence possess additional sensitivity to subtle changes in smooth boundaries, such as would occur in a defective bond. The utilization of shear waves for evaluating interfacial integrity has been substantiated through an analytical analysis? Data was acquired using experimental configurations as illustrated in *Figure 2d* and a broad-banded ultrasonic transducer of central frequency 17 MHz. *Figure* 9 represents a high resolution F-map of the interface echo obtained through such a technique. Here the dark regions along either side of the specimen represent subtle interfacial weaknesses for which shear waves show an increased sensitivity.

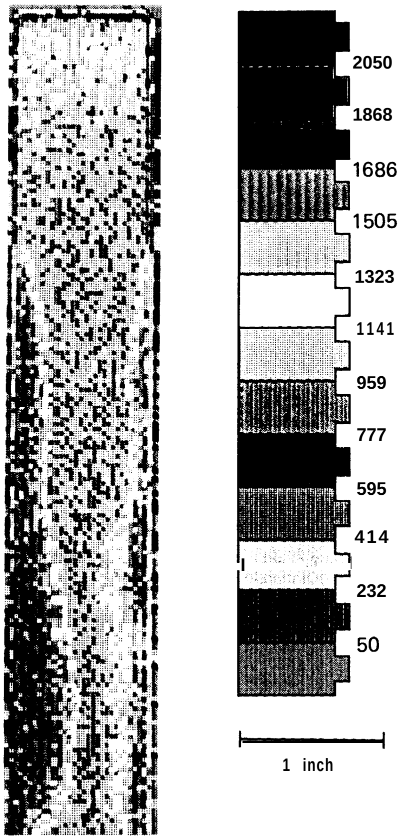


Figure 9 Oblique incidence shear wave F-map showing subtle interfacial weakness in an adhesively bonded test specimen (30°, 17 MHz)

Now we shall consider a few F-map possibilities for composite materials. The feature mapping technique is adaptable to almost any type of material available today. Due to the increased applications of fibre reinforced composites in industry and due to their complex lay-ups and the degree of anisotropy involved, non-destructive evaluation becomes more involved. It is now important to distinguish between the different types of anomalies so that a pragmatic judgement can be made on the performance potential of these composite structures. It has been shown elsewhere[4] that by applying feature analysis techniques, anomaly classification in composite material might be possible. Another example of the utility of F-mapping in composites is illustrated by *Figures 10a* and *b*. Damage analysis in composites is invaluable in studying fracture mechanisms, crack propagation, impact damage, etc. and it is important to be able to identify the damage and be able to isolate the damage on an individual ply basis. Here, several graphite epoxy composite coupons, each having a notch as a stress concentration zone, were then biaxially loaded in a two-dimensional loading device following different loading cycles. It was critical to obtain the crack propagation pattern from this composite. *Figure 10* presents F-map results using two different features derived from the echo reflected from the back wall of the specimen. The first F-map shows the damage along the plies orientated along −45° but does not clearly show any other damage zone. An alternative feature, i.e. the bandwidth at 12 dB of the amplitude spectrum in the frequency domain typically exhibits a damage zone, though to a lesser extent, on the plies oriented at +45°, and thus provides the analysis with additional critical information, demonstrating a clear advantage of the use of feature mapping in NDE.

Let us consider another feature map result (see *Figure 11*) of a delamination edge in a composite material.

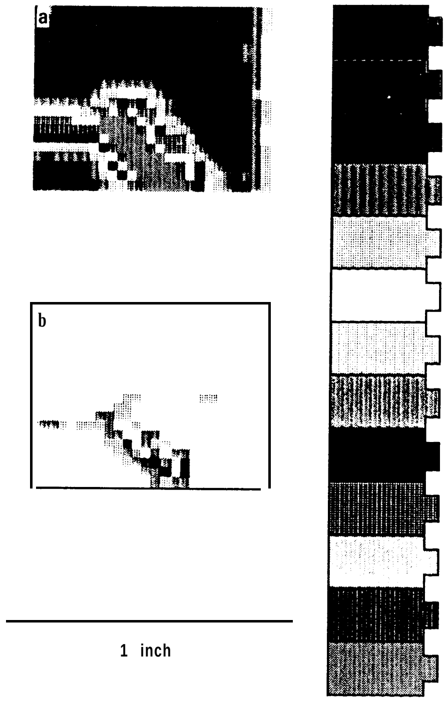


Figure 10 Normal beam longitudinal wave F-scans of a biaxially loaded composite coupon showing crack propagation. (a) Peak amplitude of the back wall echo; (b) -12 dB bandwidth of the amplitude spectrum

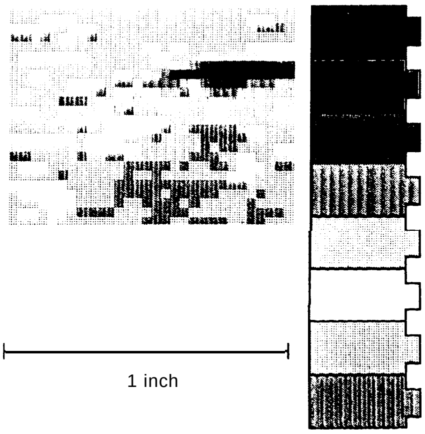


Figure 11 Backscattered energy F-map defect edge detection in a graphite epoxy composite. The dark region represents the higher amplitudes of backscattered energy from the edges of the defect

Delaminations are of great concern due to their severe detrimental effect on performance. The utilization of backscattered waves at oblique incidence to detect delaminations and cracks in fibre reinforced composite material is an interesting prospect, due to its sensitivity to anomalies with sharp edges. The utility of a backscattered echo in estimating porosity levels in such composites has already been realized [10]. Also, backscattered echoes are easily identified and are isolated from specular reflection due to their angle of incidence. Here such an evaluation technique was employed to inspect a unidirectional graphite epoxy composite with very thin teflon inserts t0 simulate delamination. The total thickness of the composite was 1 mm and a 2.25 MHz narrow band transducer was used at 12” inclination in the experimental set-up, as shown in Figure *3c*. By monitoring the backscattered echo, the energy scattered back from the edge of the defect is recorded and is imaged as shown in Figure ***11.*** Thus, application of backscatter to examine subtle delaminations or other anomalies possessing sharp edges may have a distinct advantage over the traditional longitudinal wave normal incidence techniques.

Concluding remarks

A whole list of techniques and features can be used in F-scanning, all based on physical model analysis and the physics and mechanics of wave propagation. Many of the feature mapping techniques are currently being applied in actual material characterization and anomaly identification work. Only a few examples are illustrated here. The potential value of F-mapping and feature based systems is being considered in a variety of different fields, including such areas as piping and vessel applications in the power generating industry, composite and bonding applications in the aerospace industry, tissue classification in medical ultrasound, ceramics and powder metallurgy in advanced material characterization work and offshore structural inspection.

We will now briefly comment on some F-map implementation considerations. Implementation accuracy and computational efficiency is extremely important in acquiring good and reliable results for both plane and contoured structures. A brief list of computationally critical parameters is given in Table 3. Great care is essential in system design and in the utilization of physics and mechanics.

Table 3 Computational efficiency considerations in the F-mapping technique

(a) Scanning speed of the data acquisition system
(b) Data storage device capabilities
(c) Analog-digital converter speed
(d) Feature extraction speed
(e) Number of feature sources and features analysed
(f) Computer speed and excessive number crunching
(g) Graphics display and printing speeds
(h) Software for interactive menu set-up, etc.

Table 4 F-map accelerators

(a) Increase speed of scanning through faster motors and ‘on the fly’ type of data acquisition
(b) Fast multiplexing of arrays of probes
(c) Using direct memory access boards, etc. for data transfer
(d) Utilization of high speed number cruncher such as array processors using parallel processing
(e) Utilization of hardwired feature extractor and signal processing modules
(f) Using super microcomputers for data analysis and random access disk systems such as optical disks
(g) High speed colour graphics display and raster storage devices for continuous output to thermal printers
(h) Efficient and logical software

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