Published: “Insight”, Journal Brit. NDT Soc. Jan. 2000

A New Computational Remote Acoustic Impact NDT System for the Inspection of Composite Materials and Detection and Quantification of Corrosion.

John M. Webster & T. Thevar
Holographics Inc.,
4401, 11th St. L.I.C.
New York 11101
E-mail: john_webster@compuserve.com
&
Jackie M. Mew
Computer Science Division
University of Portsmouth, Portsmouth UK.

Abstract

The Remote Acoustic Impact Doppler (RAID) NDT system that is discussed in this paper is unique and employs a proprietary design acoustic transducer which produces an air coupled shock or pressure wave. The result of the design configuration employed is that a single brief, but extremely high velocity shock wave of broadly unidirectional characteristics is launched into the air and used to impact and excite the object undergoing testing[1].

The technique depends upon the hypothesis that any change in substructure will locally affect the surface frequency response spectrum. Thus, surface relaxation frequencies for any given material are dependent upon the underlying substructure of the object.

Remote interrogation of the relaxation frequencies is accomplished with a highly customised scanning laser Doppler velocimeter. The acquired time domain signal is processed to a Fast Fourier Transform (FFT). A velocity based image is computed and presented on a monitor overlaid on an image of the object. Advanced techniques for computerised automatic analysis of the images have been developed. Our results show both deep subsurface defects in solid as well as honeycomb materials.

1. Introduction

Defects in composite structures usually manifest themselves at a subsurface level. Impact damage will frequently cause delamination of the structure between laminates or skin/core interfaces. Delamination or bond weaknesses also occur in metal laminates. In a not dissimilar manner corrosion often manifests itself in such regions as lap joints in aircraft bodies where the defect lay between the bonded or fastened layers of metal[1].

For the detection of defects in composite materials, a frequent technique to detect defects is the simple “tap test” where the operator taps the surface and listens for the audible response. In this case the subsurface structure is effecting the excited resonance response of the surface; hence the sound change according to the subsurface structure. In a similar manner, delamination in metals or the presence of hidden corrosion will effect the surface response; albeit perhaps not audibly. In any case the tap test is a very subjective method of NDT, although there are scientific principles which can be exploited with modern technology. The RAID system has been designed to achieve this.

The system is totally remote and requires no physical contact with the object undergoing testing; it has been demonstrated to operate at a stand-off distance of three meters. The system employs a proprietary design acoustic transducer that produces an air coupled shock or pressure wave, similar to that produced from a small explosion. This is achieved by discharging a high voltage capacitor within a period of less than 5 microseconds. The discharge is contained within a small ceramic chamber with an annular design anode providing an exit for the resultant hot gasses. The result of this configuration is that a single brief, but extremely high velocity shock wave of broadly unidirectional characteristics is launched into the air and used to impact the object undergoing testing[2&3]. The objective of the brief impact is to excite natural relaxation frequencies in the object and avoid any "blanketing" effect that would be present if continuous wave white noise was applied.

As discussed above, surface relaxation frequencies for any given material are dependent upon the underlying substructure of the object. Remote interrogation of the relaxation frequencies on the surface of the object undergoing NDT is accomplished with a highly customised computer controlled scanning laser Doppler velocimeter employing special analysis programs. The technique depends upon the hypothesis that any change in substructure will locally affect the surface frequency response spectrum. The tapping analogy is very limited in satisfying an explanation because an important aspect of this technique is that it does not limit itself to the excitation of a single spot, but impacts a large area of the structure.

The scanning laser Doppler vibrometer obtains an analogue velocity time domain signal from each of up to 500 x 500 data points. This is passed into the processing computer where it is processed to a Fast Fourier Transform (FFT), which is effectively a frequency spectrum over the selected bandwidth recorded. This data is then stored in the computer as individual frequency bands. Each of the individual FFT lines might be considered as a snap shot of the object undergoing testing vibrating at that individual frequency. There can be over 6000 FFT lines employed up to a frequency of 200 kHz. This data is later analysed to select only the relevant information carrying frequency bands and a velocity based image is computed then presented on a monitor overlaid on an image of the object which was simultaneously grabbed by a CCD camera located in the vibrometer.

One of the aspects of this research program has been the development of a system for the analysis of this large quantity of data. Typically a defect in a given material might exhibit oscillations over several relatively narrow bands of the recorded spectrum. The problem was to devise a computer algorithm[4&5] which would separate out the few frequencies containing the defect information whilst rejecting the remaining mass of the recorded frequency spectrum and thus reducing noise. The process has been likened to searching for the proverbial needle in the haystack. Along with the analysis program, we have developed a technique of post processing the recorded data and to "zoom" into selected regions of the time domain trace; this does speed up the whole data acquisition process and again reduces any noise problems.

An FFT applied to this situation can be considered as a frequency spectrum with a predetermined number of discreet frequency lines of information over the chosen frequency range. An alternative way is to describe it as a data stack with potential image forming data in the horizontal X&Y axis and frequency information in the vertical or Z axis, as illustrated in Figures 1 & 2. For simplicity, the diagram only shows three primary areas of a complex situation in which image information was contained in small groups of frequencies ranging from 10 kHz to

25 kHz. In very brief and simplified terms, the analysis algorithm operates on the principle that the bandwidth of a defect will be greater than that of noise, thus it searches for vertical links within the data cube and extracts the relevant frequencies. It then applies a weighting factor to compensate for the lower velocities that occur at higher frequencies.

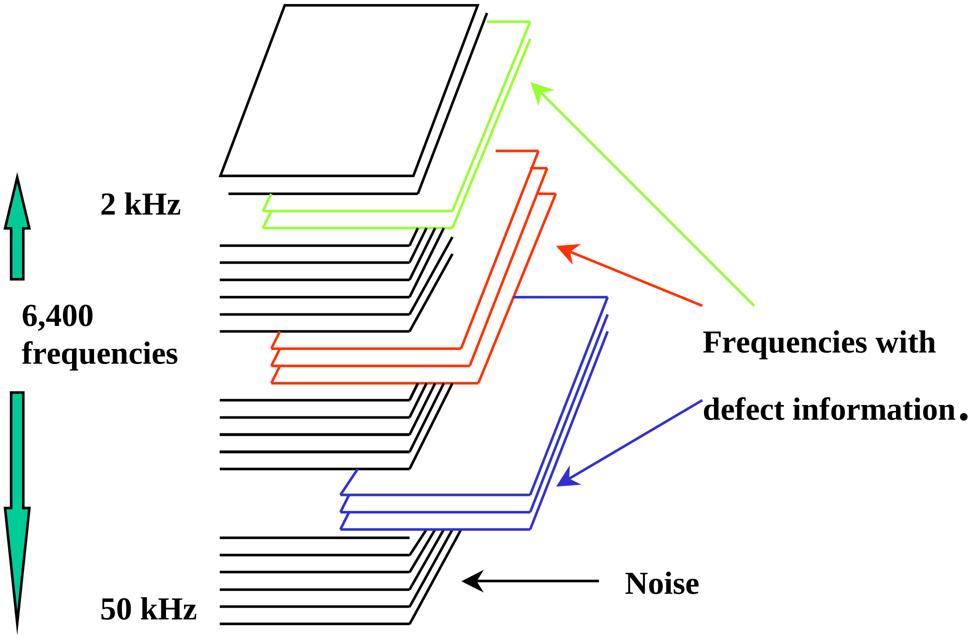


Figure 1. Selection of defect frequencies

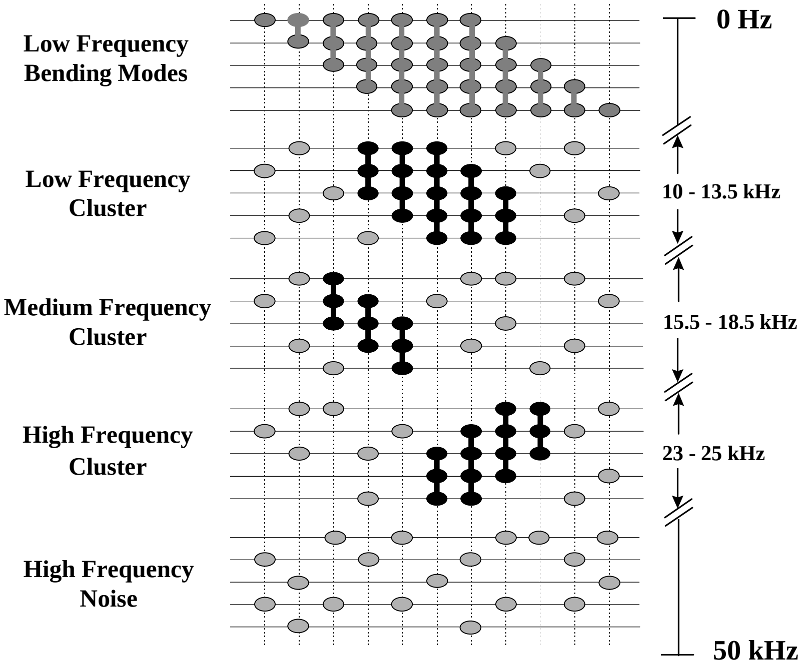
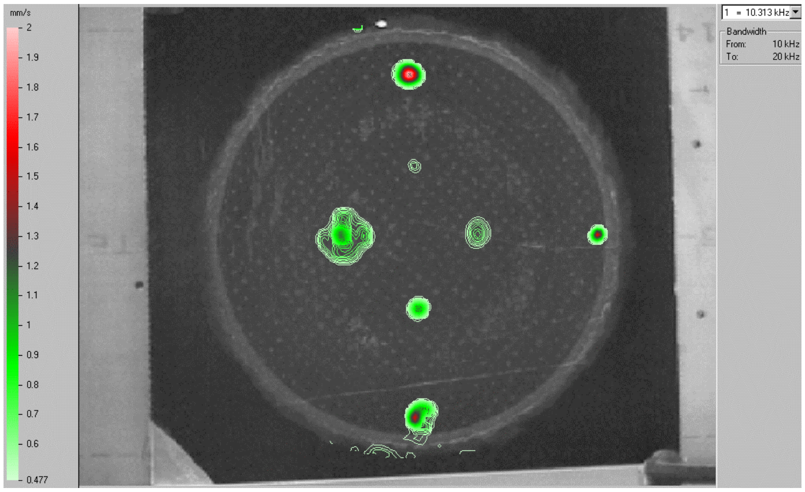


Figure 2: Schematic representation of the random noise, bending modes, and signal in the frequency spectrum obtained in a typical scan.

2. Results: Composite & Metal Bonds

The RAID technique has been successfully applied to the location and characterisation of defects in a wide variety of composites, ceramic and metal bonded materials including the situation where kiss contact delaminations are present. This presentation only permits room for a few examples. Figure 3 shows a defect in a carbon composite nomex honeycomb cored material in which a parametric repair has been carried out. The defects in this test specimen were simulated by the presence of Teflon shims, which give the effect of a kiss contact situation. In some cases the defect was on the rear face between the skin and the nomex core and in other either below the surface skin or on the scarf of the repair. Note the defect information has been overlaid on the recorded image obtained from the CCD camera located within the vibrometer



1 = 10.313 kHz

Bandwidth
From: 10 kHz
To: 20 kHz

Figure 3: Seven defects in Parametric Repair Panel.

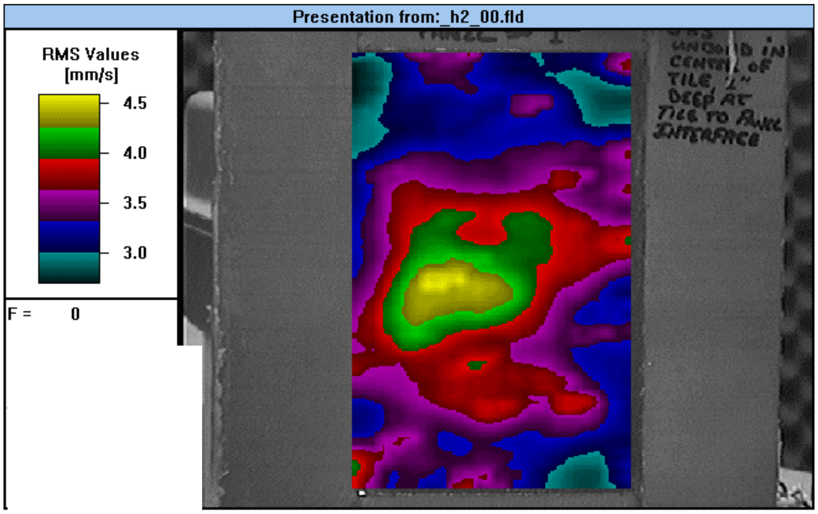


Figure 4: Delamination revealed in the 50 mm thick black shuttle tile. The defect area is clearly delineated

Figure 4 shows a debond in a 50 mm thick heat insulation soft ceramic tile of the type used to protect during re-entry of space vehicles. The RAID system has also reliably detected subsurface cracking in other modern foam materials now used in airframe construction. Applied to metal weak bonds, figure 5 shows a weak bond in a rib to skin joint in an aluminium helicopter rotor blade. The computer has been used to enhance the image of the defect region.

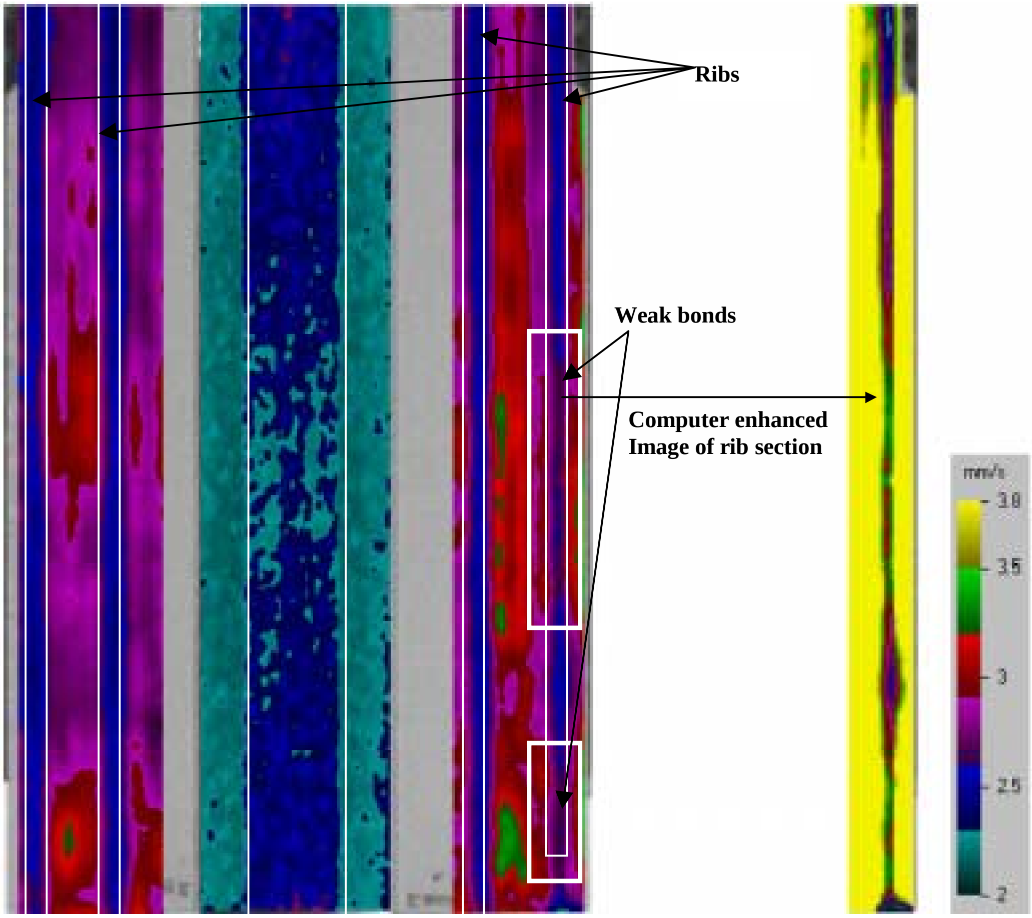


Figure 5: Application of RAID to detect weak bond in metal joints

3. Application of RAID to the detection & quantification of hidden corrosion

Corrosion in aluminium structures is largely calendar driven and is an increasing problem in our ageing air transport fleet where a structure weakened by metal loss in a pressurised cabin situation, could potentially threaten the safety of the aircraft. Currently there are aircraft in regular service that are over thirty years old[6,7&8] An example of this is the US fleet of KC135 Tanker aircraft, which are actually the old Boeing 707's with a future service life projected to be another 35 years**.** Reliable detection and quantification of metal losses under field conditions does present a difficult situation. Currently, no reliable and practical method exists, although there are considerable efforts now directed towards a solution. This technology presents promising early results in detection and quantification of corrosion in lap joint situations.

In very simplified terms, the system operates very much as it does in the field of composites. The effect of the presence of corrosion will affect the local relaxation frequencies. A rather over simplified analogy is a drum surface: The frequency produced by the drum will be the sum total of the boundary conditions, the skin thickness and the tension of the skin. In the case of hidden corrosion the metal skin thickness is a function of the metal losses due to corrosion, the boundary condition will be the extent of the corrosion whilst the tension is a function of the corrosion by product. Aluminium oxide has a lower density and a larger volume than the original metal, thus causing a tension on the surface.

Initially corrosion samples were obtained from the US Airforce Logistics command. The results were promising and corrosion was detected, however, no attempt was made to quantify at this stage of our work. As a result of these tests, we made up a lap joint in the laboratory and simulated metal by the removal of metal: 5%, 10%, and 15% respectively. The result is illustrated in Figure 6. This result clearly shows all three regions of simulated corrosion spots overlaid on a CCD record of the lap joint sample.

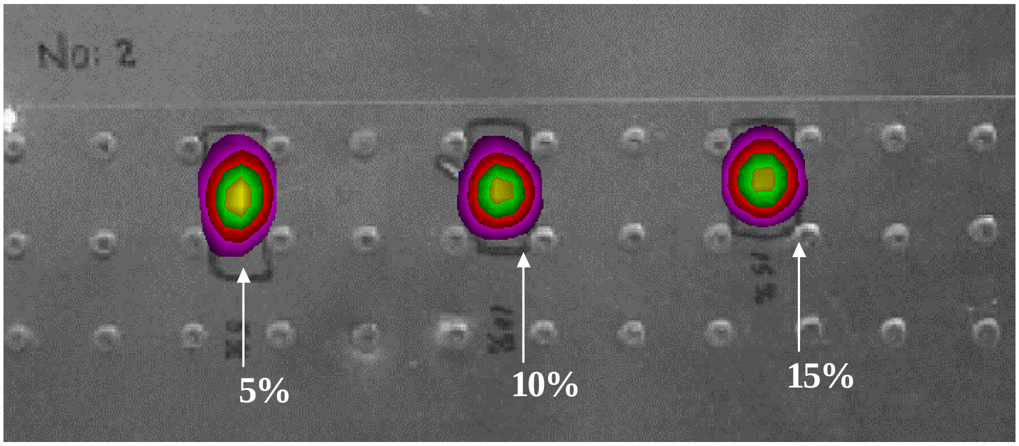


Figure 6: Lab joint panel manufactured with 5%, 10% and 15% metal thinning. Note: all three regions are clearly revealed.

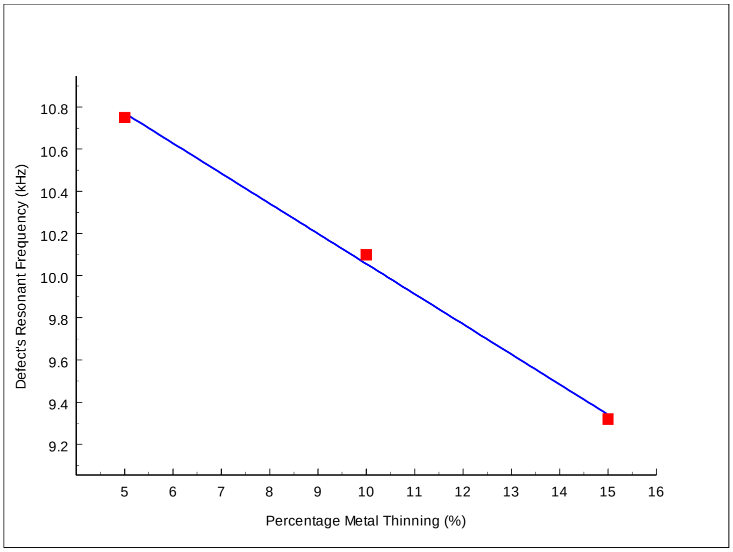


Figure 7: Graph of metal thinning against resonant frequency for the results in figure 6

From the data contained in the rich data set on the computer record of the scan, we extracted the FFT spectrum of each data point of the primary antinodes in each of the fault regions. What is to be noted here is that the peak response for each of the different defects is in an entirely different region of the vibration spectrum and relates directly to the metal thinning in that region. Figure 7 is a plot of the metal loss condition against the resulting frequency. It conforms to the equation for membrane resonant frequency, w_n, given by[9]:

$$w_n = B\sqrt{\frac{Et^2}{\rho a^4 (1-v^2)}}$$

where B is a variable dependent upon the shape of flaw and edge conditions, E is the Young's modulus, t is the thickness of plate, ρ is the mass density, a is the dimension of plate, and v is the Poisson's ratio.

1. J.M. Webster et al. Optical technique for the detection and imaging of subsurface defect in composite structures using Remote Acoustic Doppler. J. Sci. Imaging. No1. Vol. 46. 1998.
2. J. M. Webster. Acoustic Wave Generating Apparatus. US Patent No. 5,616,865 1997.
3. .J. M. Webster & J. M. Mew Method & Apparatus for Non-Destructive Inspection of Composite Materials and Semi-Monocoque Structures US Patent No. 5,505,090 1996
4. J. M. Webster, et al., "The detection of subsurface defects in composite structures & metal structures by the application of remote acoustic Doppler technique" - First Pan-American Conference on Non-destructive Testing, Sept. 14-18, 1998, Canada.
5. J. M. Mew et. al. ASNT Spring Research Conference 1998
6. R. A. Smith, Non-destructive evaluation for corrosion in ageing aircraft. Part 1, Insight, Vol. No. 37, No.10, 1995
7. J. P. Komorowski et. al., "Quantification of corrosion in aircraft structures with double pass retroreflection", Canadian Aeronautics & Space Journal, Vol. 42, No. 2, 1996.
8. D. Perry, Sandia National Lab, "Emerging NDE technology for ageing aircraft", ASNT Spring Conference and Research Journal, 19989
9. C. M. Harris, "Shock and vibration handbook", Fourth edition, 1996.

Acknowledgements

This work was sponsored by DARPA Phase III # DAAH01-98-R152 Contract "Development of an Optical/Acoustic Method for the Remote non-destructive Inspection of Large Area Composite Materials for Structural Defects". "Approved for Public Release Distribution Unlimited"