Images formed by laser metrology of complex substructures: new concept in non-destructive inspection

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Abstract: The present paper presents the results of the remote recording, analysis and study of defect detection with laser Doppler vibrometry (LDV) coupled with shockwave excitation. The non-destructive inspection (NDI) procedure employed is based on the vibrational excitation and evaluation of test objects with defects of both known and unknown parameters. Additionally the potential advantages are presented of using whole field laser Doppler vibrometry (WFLDV) being developed. To evaluate the procedure the technique has been applied to a number of different samples that have been tested by this system of NDI. The test samples included multilayer and sandwich composites, ceramic and aluminium structures containing in service occurring or preprogrammed defects. Additionally included is an example of corrosion occurring at second and third layers in an airframe structure together with an example, manufactured to simulate metal loss, by introducing a 'defect' represented by a machined thickness removal of 2% at the central part of the test object.

Keywords: NDI, Laser anemometry, Acoustic imaging, Laser animometry

INTRODUCTION

Early defect detection is a major requirement in a variety of industries. For example, the maintenance of deployed aircraft and the inspection of composite radar dome on ships and other vessels. Methods exist for such non-destructive inspection (NDI) problems but these are usually slow, manual and at a reliable level often limited to the defects located at the upper layers of the structure yielding less reliable results for deeper levels. Furthermore, intimate contact with the test object is usually required, which is not always possible or practical.

Advances in the technology of sensing and signal processing have removed some of the obstacles that have kept such methods from being applied to large structures. For example, highly developed methods that apply acoustics and remote impacting techniques to image internal structure can now be integrated with advanced laser sensing techniques, leading to a non-contact method of probing materials.[1]

The present paper demonstrates that NDI based on laser Doppler vibrometry[2] (LDV) using short impulse (shockwave) excitation of the object; the resulting surface relaxation frequencies are interrogated by a scanning LDV. The system operates in a totally remote and non-contacting mode. It is evident that the character of these frequencies depends upon material and its construction conditions and therefore can serve as a natural signature for any particular structure. In the systems that are currently available the interrogation is performed on a point by point scanning basis over the entire inspection area. The signal retrieved from each local point of measurement can then used to build a map of the

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surface velocity and frequency. This image clearly reveals the location and spatial distribution of the structure and defects that exist on or below the upper layer or joints.

However, there can be a down side to using scanning LDV systems. Although the scanning method makes possible the inspection of objects with well organised vibrational mode structures, it can be tedious and time consuming usually requiring several minutes to scan a reasonably large area. Besides the inconveniently long duration of the scan it can generate false data for objects with a temporally complex structure and mode pattern or where there is body motion.

These problems can potentially be solved with a multichannel whole field laser Doppler vibrometer (WFLDV), where the interrogation is performed simultaneously at a multitude of locations over the test area of the object. The proposed concept brings the advantages of scanning LDV to the inspection of objects with vibrational mode characteristics of any degree of complexity, making the interrogation process much faster; in fact virtually instantaneous, thereby improving the reliability of the retrieved data. Eventually the concept for whole field operation instead of local point LDV permits generation of the whole picture of the vibration process in one 'snap-shot'. Effectively the method exhibits the features of a scanning LDV without the disadvantages of time delay in acquiring the data.

NON-DESTRUCTIVE METHODS FOR STRUCTURAL INTEGRITY INSPECTION

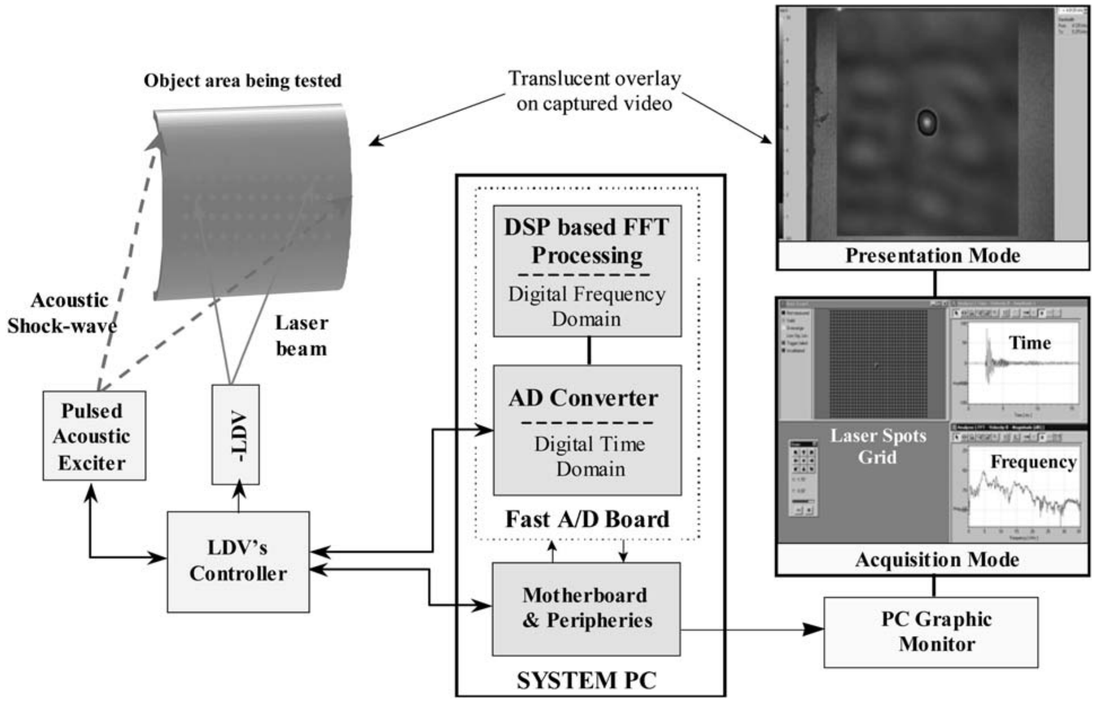
A variety of methods exist for aircraft and other structural integrity evaluation. Most current NDI methods are based on high frequency ultrasonic or pulsed eddy current techniques,[3] both detecting usually only the first or at best second layer defects. Also radiographic techniques[4–6] although giving reliable results, require bulky equipment or operate with highly localised scanning. Furthermore, radiography is a potentially hazardous procedure requiring clearing the area of operation. While some optical systems are used to visualise defects such as corrosion, for example *D* sight,[7] other, non-visual systems have been proposed for defect detection in the second and even third layer. These methods, which include fibre optical detectors[8] built into the structure and laser ultrasound,[9] are however, strictly local and therefore, are limited to examination of defective areas only leaving the structure as a whole unexamined.

There is a potential for holographic interferometry to be used together with shockwave excitation, the holographic camera replacing the laser vibrometer.[10] This method permits whole field inspection of large size structures. The procedure records a double or multiple exposure hologram of the object under inspection in its original and stressed conditions.[11,12] At the reconstruction stage such a holographic interferogram forms an interference fringe pattern, which essentially reproduces a contour pattern of the out of plane vibration modes. The location of the defective area can be identified through unaccounted variations in the fringe pattern, as the vibrational modes are different in the area of a defect. Pulsed lasers do permit this technique to be applied in industrial environments. The main limitations are that holography is not as sensitive to out of plane motion as a laser vibrometer and there is no velocity or frequency information.

LASER DOPPLER VIBROMETRY WITH SHOCKWAVE EXCITATION

Existing LDV methods, in contrast to holographic interferometry and most other methods of NDI, measure the local velocity of the target surface and, therefore, do not require the inducing signal be single frequency. Whereas, broadband excitation of the target permits a study of its response over different spectral ranges and as a function of time, thus making the test results significantly more extensive and useful. Finally, LDV allows discrimination of the useful signals from those related to whole body motion, making the system viable in virtually any environment.

One method of detection and characterisation procedure is to stimulate the material under inspection with air coupled acoustic chirping over a previously specified frequency range.[13] A yet superior method is to excite the object undergoing testing with a remotely generated air coupled shockwave.[13–15] The former chirping system being more applicable for use with thin structures, the latter coupling much more energy into the structure, can be applied to thick or stiff materials. As discussed above, the technique is based on the physical phenomenon that any change



1 System architecture for shockwave excitation method with LDV interrogation of surface relaxation frequencies

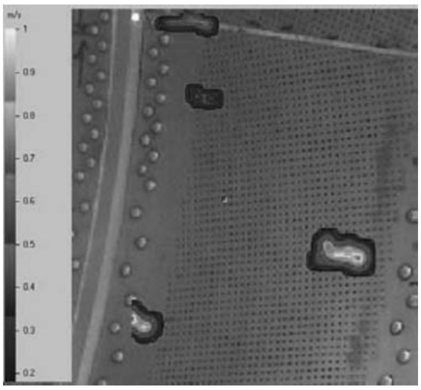
in substructure will locally affect the surface frequency response spectrum. Thus, the surface relaxation frequencies for any given material can serve as a signature for this specific structure.

Much of the present work has been with physically stiff or thick composites or aluminium where the best results for defect detection in conditions such as corrosion, delamination conditions, occur when, as discussed above, a brief but high velocity shockwave of broadly unidirectional characteristics is launched into the air and used to excite the object undergoing testing. Remote interrogation of the relaxation frequencies is then accomplished with a scanning LDV; the time domain signal acquired by the LDV is processed to a fast fourier transform (FFT). A velocity based image is then computed and presented on a monitor as an overlay of an image of the object. Advanced techniques for computerised automatic analysis of these images have been developed[14] and briefly discussed below. Figure 1 illustrates the system architecture for this NDT technology. Results have revealed disbonding and delamination, as well as deep subsurface defects such as corrosion. Some typical examples are illustrated below.

Figure 2 illustrates the set-up for the inspection of a jet engine casing. Because of the difficulties of geometry and opportunity, in this case it was decided to transmit the shockwave through the object to be tested as opposed to the normal frontal excitation where it is directed at the surface of the object to be tested. The transmitted shockwave excitation produced virtually identical results to frontal use.

The casing (Figs. 2 and 3) is a double skinned aluminium honeycomb sandwich construction. The object of the test was to detect disbonds or crushed core defects. This particular casing had previously formed part of a test rig and had acquired a number of defects during its life. A typical NDI result is

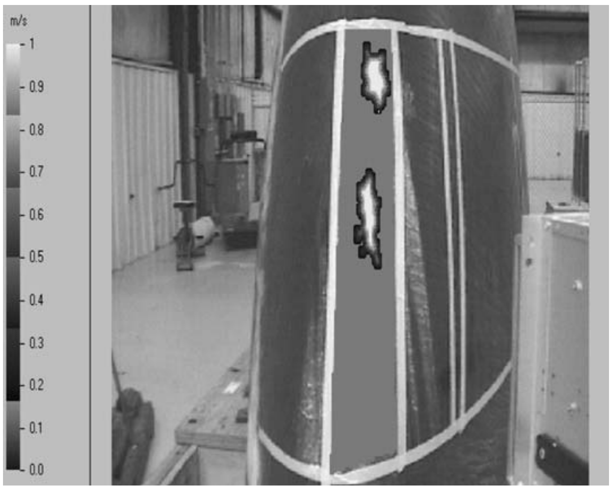
2 Jet engine casing undergoing testing: scanning LDV is in foreground and shockwave generator behind casing



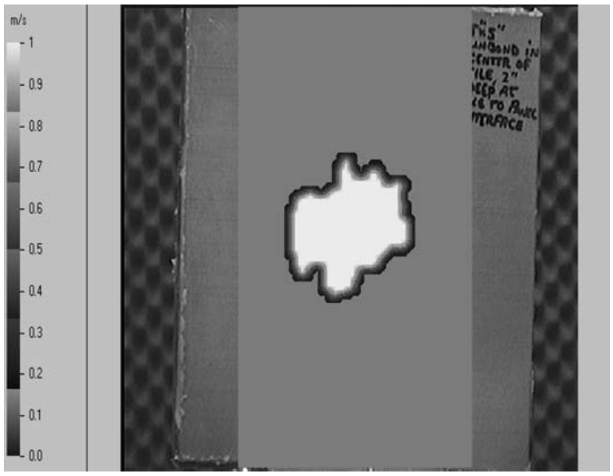
3 This result, which is casing shown in Fig. 2, obtained using scanning LDV with transmitted shockwave excitation, shows four small defects

illustrated in Fig. 3 showing four defects outlined with isolines.

Airborne warning and control (AWAC) aircraft radomes are a fibreglass construction order to be radio transparent with a skin over a honeycomb composite structure. These are subject to damage when in flight from such occurrences as bird strikes or hail storms and thus require regular inspection particularly along the leading edges of the rotating dome. A scanning LDV system using the shockwave method of excitation described above was employed to make a trial inspection of a dome section located in a laboratory/workshop at Tinker Air Force Base (AFB), Oklahoma. The result, using frontal excitation, is illustrated in Fig. 4 and shows two separate defects clearly delineated, both of which were later



4 Airborne warning and control aircraft radome section undergoing NDI using LDV with shockwave excitation: result shows two defects present probably caused by bird strikes

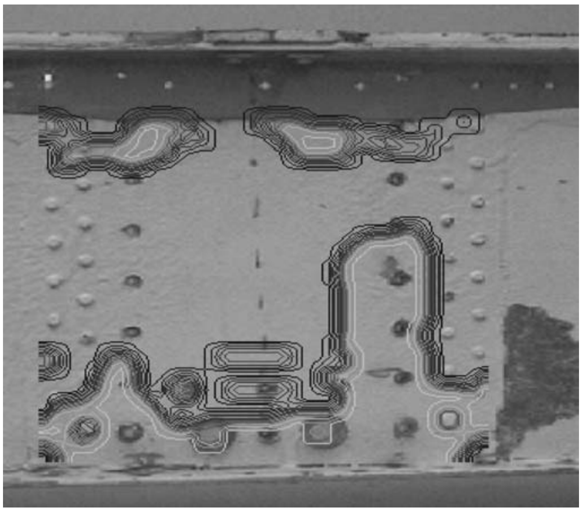


5 Soft highly pours ceramic heat shield tile with 300 mm debond at centre

confirmed by alternative methods of contacting NDI. The system has reliably located ‘kiss contact’ delamination defects, a condition normally very difficult to detect.

This technique has been also successfully applied to the detection of delaminations in both honeycomb/carbon sandwich and solid carbon composite materials, also to hard insulation lagged structures found in other industries including marine situations. Many composite materials are difficult to inspect for defects; in particular highly porous soft ceramic heat insulating materials or foam fall into this category particularly where debonding detection is the objective of the test. The LDV/shockwave technique was successfully applied to a 50 mm thick soft highly pours ceramic heat shield tile of the type used on B2 aircraft. The test sample was an actual tile attached to a substrate by the manufacture but with a 300 mm preprogrammed debond centrally located. The result is shown in Fig. 5. A series of similar tests were successfully applied to an array of space shuttle heat shield tiles, which are of somewhat similar construction.

Figures 3–5 all illustrate the LDV/shockwave technique of NDI applied to what is essentially corrosion or delamination in either metals or composite structures. It is also essential to detect and measure metal losses occurring in subsurface corrosion between layers of metal within airframe or marine structures at the earliest possible stage. Corrosion between layers of metals is difficult to detect often because the corrosion product may be present and, it being several times the volume of the original metal, gives a pressurised pseudocontact



6 Corrosion detected in floor beam of helicopter

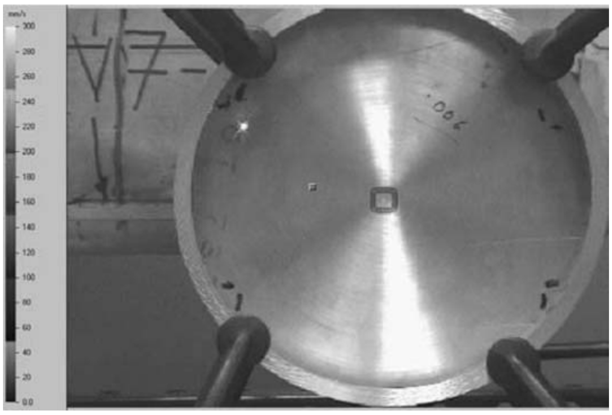
condition between the corroded metal sheets comprising the structure. Thus, when excited for the purpose of NDI, the different layers are not free to move independently as they would be in a simple debond or delamination situation, nevertheless the resulting surface relaxation frequencies are locally altered and it is suggested that it could be used to compute the metal loos due to the corrosion.

An opportunity presented itself to test a support beam taken from the floor of a Boeing helicopter. The beam was a complex structure comprising several layers in its make-up. The author's record shows the presence of corrosion and is illustrated in Fig. 6. The object size was several meters long. The author scanned a length of ~1 m at a time to cover the entire length, for the purposes of this illustration only a typically corroded region of ~40 cm is shown. This presence of corrosion was later confirmed by destructive inspection.

To verify the technique and complement the experimental programme simple targets with simulated defects were modelled and measured. To simulate the effects of a corrosive inner core causing metal loss, two circular plates were chosen. From one plate a core was machined from the centre to produce a thinner section by removing 2% of the metal.

The result of the plate with the 2% metal removed is shown a normal in Fig. 7, which has a clear record of the preprogrammed metal loss delineated at the centre. In the case where there was no preprogrammed metal loss the plate was totally clear.

A finite element model that consists of one circular element and many annular elements was used to

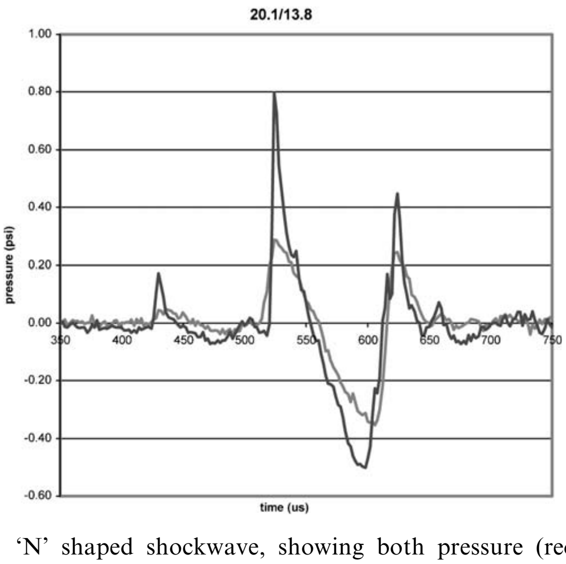


7 Result (NDI) of metal disc with 2% metal thinning region at centre: simulated defect is clearly shown in centre of plate

conduct the free vibration analysis study. The present work is discussed in detail elsewhere.[15] The result shown in the present paper illustrates the most severe of the condition experimentally examined where only 2% material loss was preprogrammed into the centre section.

SHOCKWAVE EXCITATION

The shockwave employed to excite the structures undergoing testing was generated by a high voltage electrical spark from a storage capacitor producing a discharge of a few microseconds duration via specially designed spark gap and discharge circuit. The shockwave was focused over an area of ~1 m on the object undergoing NDI. The standoff distance



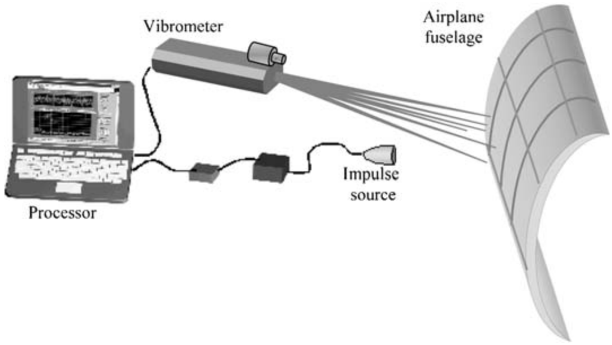
8 'N' shaped shockwave, showing both pressure (red) and blast recording (black) used was normally about meter. The discharge characteristics of the unit used in the work described are illustrated in Fig. 8, where both the impacting pressure wave and the subsequent negative pressure pulse are shown as a normal 'N' shockwave. This record shows actual acoustic pressure was in the region of $\sim$0.8 psi at the object distance of 1 m. The small prepulse shown on the trace is an artefact of the equipment design used at that time, since the early work has been eliminated and several improvements have been made in the system design including a discharge of shorter duration coupled with a new design concept for the spark gap resulting in a much higher acoustic pressure together with a more compact transducer unit than the one used to make the records illustrated in the present paper.

Synchronisation of the vibrometer to the arrival of the shockwave at the test object was accomplished by taking a sample of the acoustic transducer trigger signal via a time delay a generator to the LDV trigger input. The delay generator was set to account for the flight time of the shockwave.

DESIGN OF WFLDV

The LDV system operation and its application for detection of defects LDV is a well established technique for the measurement of velocities of macroscopic objects and widely used for the investigation of fluid flow structures and vibration sources.[16] The technique is non-invasive and capable of absolute measurements over large dynamic ranges of velocities (up to10^5 m s^{-1}) and vibrations (from dc to 1 MHz). A LDV vibrometer is basically an interferometer in which the light beam emerging from the laser is divided into two beams, one of which is used as a transmitting or interrogating beam and the other is used as a local reference beam for coherent detection. The transmitting beam is focused to a spot on the target; the returned light scattered from the target is combined with the local reference beam at the detector for coherent detection. At present, LDV systems are large, expensive, delicate and difficult to align. These disadvantages limit LDV for many applications.

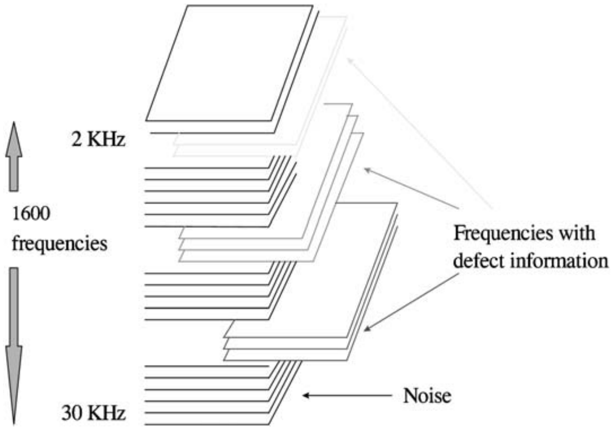
To overcome some of these problems a multichannel WFLDV has been developed;[17] currently this system can acquire 16 data point at any one instant. The concept brings the advantages of scanning LDV to the inspection of objects with vibrational mode characteristics of any degree of complexity, making the interrogation process much faster and thereby improving the reliability of the retrieved data. Eventually, the concept for whole field operation instead of local point or scanning LDV permits the generation of the whole picture of the vibration process in one process. Moreover, the configuration of the WFLDV makes it insensitive to gross mechanical instabilities of the object under inspection by optically normalising the retrieved data using one selected channel. Effectively the method exhibits the features of a scanning LDV without the disadvantages of time delay. To enhance the operational efficiency of the WFLDV and its capabilities in data analysis, the system incorporates specially developed software that will allow the comparison of the vibrational mode data with calculated values.



9 Conceptual view: WFLDV

The systems experimental concept is diagrammatically illustrated in Fig. 9, comprises an LDV head, a charge coupled device (CCD) camera, impulse transducer and a data processing board. The LDV operates by sending an array of laser beam from a single source. These beams strike the surface of the object, while the impulse source induces broadband vibration. The scattered laser light is collected by the LDV receiver optics and mixed with a reference laser beam at a detector array, generating a heterodyned signal at the output, whose frequency is dependent on the surface velocity. Thus, the system simultaneously interrogates all of the illuminated spots and retrieves information about the vibrational characteristics of the entire area, thereby mapping the spatial structure of its vibrational modes. Obviously the potential of the WFLVD in industry and research is far greater in its application that discussed in the present paper.

The complete system, used in a NDI situation, operates similarly to that illustrated in Fig. 1. It has been determined that a 625 channel receiver can be built based on an avalanche photodiode.



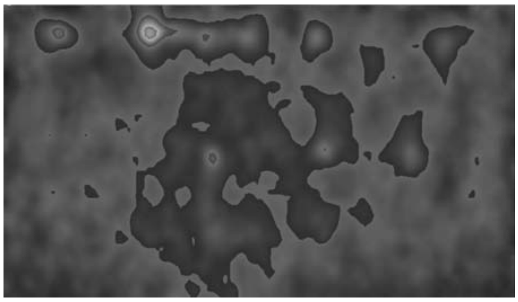
10 The software selects the frequency subsets indicating defects, as defined during the calibration process for specific materials and applications

SOFTWARE FOR DATA REDUCTION

Two types of the software are required for systems operation. The software controls the system, and extracts and processes the data in the frequency domain.

The time domain signal received from each laser beam location will be processed to an FFT at either 1024 or 2048 sample frequencies. The bandwidth for recording will be optimised to match the particular type of sample undergoing the test. Depending upon the type of object used, a spectrum of signals of a range of frequencies will be selected from a range from say 3 up to 100 kHz, covering the region where a defect may be expected to resonate. From this recorded data, a velocity map at each one of the 1024, possibly up to 2048 frequencies recorded by the LDV, of the object vibrating in an out of plane motion could potentially be constructed. From the total recorded data, it is possible to produce a root mean squared (RMS) velocity map over the entire bandwidth.

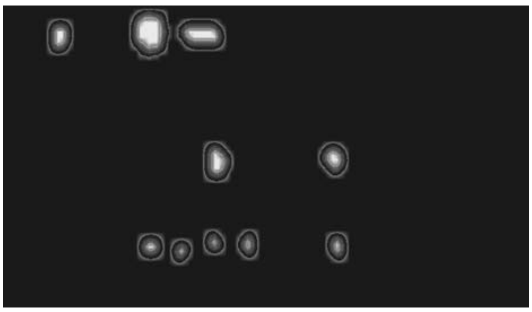
To overcome the masking effect that would be present if all the frequencies were overlaid in a composite image, special analysis software has been developed to extract only those recorded frequencies, which contain information pertaining to any defects present, and to reject the remainder in a data reduction process. The relevant data are then optimised and presented using a process that can be termed as 'normalised selective RMS'. This 'normalisation' process is added to compensate for the lower velocities at the high frequencies. Thus, the final velocity based image comprises only the defect carrying frequencies, with the velocity values compensated to hold an equal value. The above images shown in the present paper that illustrate defects were obtained by using a prototype analysis program. The essential elements of this software package are briefly outlined.



11 This figure shows the entire RMS presentation of a test-scan with all recorded frequencies present. The pre-programmed defects are masked b y noise from non-information carrying frequencies

Figures 11 and 12 show the results of applying the system to the NDI of a carbon composite honeycomb test panel supplied by the United States Air Force (USAF) containing preprogrammed defects of varying severity and depth. These images illustrate the process of the analysis program with the normalised selective RMS feature. Figure 11 is the RMS of all recorded frequencies, in which certain defects with relatively high frequency response have been masked due to their relatively low velocity; additionally bending modes recorded in other frequencies masks defects. Figure 12 shows the defects present after the data have been subjected to the analysis software.

A further development of this analysis program has permitted a select region of the time domain signal to be isolated for processing to an FFT. The advantage in this is the avoidance of noise that can occur in the later region of the received time signal.



12 This record shows the result after analysis processing of the test-scan shown in Figure 12. It clearly revealed are all ten pre-programmed defects

DISCUSSION AND CONCLUSIONS

Together with presenting images obtained with a scanning LDV, the present paper has emphasised the potential of WFLDV/shockwave technique as a way forward for NDI of a variety of materials including such defects as debond or delaminations in composite, ceramics and metal structures, including multilayer structures where there may be corrosion and related defects or damage within the structure. The ability of the system to detect corrosion, probably where the corrosion product was still present has been shown. The results with the circular disc also show that metal thinning alone, without corrosion product, can be detected and imaged at a very low metal loss of -2%. The results suggest that the technique has the potential for early detection and quantification of local metal thinning such as that occurring with subsurface corrosion. The basis for this argument is that surface frequency (relaxation frequencies) naturally excited must be a product of the underlying supporting structure, the thickness, tension and the boundary conditions. It has been shown these can be measured, providing sufficiencies of data points are obtained and a program based upon a suitable algorithm is formulated and designed for the data reduction and analysis. It has also been demonstrated that the inspection of large objects can be made in field environments.

All measurements were made without physical contact with the test object. By proper scaling of equipment the standoff distance can be several metres; the author has operated at distances up to 3 m with evident success. However in the results shown in the present paper a standoff distance of $\sim$1 m was generally used.

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