SHEAROGRAPHY: A FAST NDI METHOD FOR COMPOSITE STRUCTURES

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Abstract

In the NDI field, a strong interest belongs to the possibility to set up a fast, no contact and easy technique, that can be profitably used both for production and for maintenance purposes. The optical interferometric techniques are very promising from this point of view and then many laboratories are addressing their efforts to implement these kind of techniques. This report presents part of the results obtained from a research work supported by the Commission of the European Communities part of which was devoted to the development of a particular optical interferometric technique named: SHEAROGRAPHY. In this report a description of the technique is presented with limits and advantages and, from the point of view of the stimulation of the structure under inspection with the aim to get a light surface deformation, three different cases are presented. The first case is about the analysis of the state of damage of a solid laminate; the stimulation of the structure has been obtained by a small mechanical load; the result, in terms of loss of stiffness, was obtained comparing the derivatives of the deformation along a line perpendicular to the direction of load application when the laminate is undamaged, when it presents a single delamination and when it presents multiple delaminations. In the second case the debonding detection on a sandwich panel of CFRP skins and non metallic honeycomb core is presented. The stimulation has been obtained by a light heating by means of a flash of a 800 watt lamp. Perhaps the specific structure of the panel represents a very favourable situation for this type of inspection; as a matter of fact the defects were detected in a very simple way and with high precision. The last case presents the debonding detection in a panel of a real part of fuselage (tail unit of a medium-heavy helicopter); in this case the interesting result is represented by the possibility to exploit the natural vibrations due to the ground running conditions of a helicopter, in order to stress the structure.

Introduction

The optical interferometric techniques are always considered very interesting by NDT people because they present a lot of sure advantages; for instance: they allow to inspect a relatively large area in a single shot, they don't require any physical contact with the part under inspection and then no coupling media are necessary, they have a very high sensitivity and lastly, by comparison with the more traditional ultrasonic technique for the inspection of complex shaped parts, they allow to get a precise map of the defects without the need of complex and very expensive systems for the manipulation of the transducers. Only one condition is necessary and sufficient for the successful application of this kind of technique: the part in some way must undergo a small surface deformation and, when a defect is present in an area next to the surface in a way that it could interfere with this deformation, it results in a local additional surface deformation that can be easily detected by the very sensitive technique. The first optical technique, largely investigated mainly for purposes of NDE of composite parts, is the laser holography; its physical principle is completely described in lots of books and papers (one for all Ref. 1) and of course innumerable papers about its experimental application for defect and damage detection on composite structures can be found. Two examples for all are about its application to assess the impact damage in thin laminate of CFRP: with the most classical method of the double exposure of a photographic plate (Ref. 2) and with the so called real time holography (Ref. 3). However the holography, in spite of the undoubted advantages, mainly remained confined to the laboratory environment and this is because it presents some heavy limits, which reduces a lot its practical use. One of these is its hypersensitivity to the external disturbs for which the laser source, all the optical elements and the part under inspection must be insulated from the environment on an optical bench. In our opinion, a very important step forward the reduction of the aforementioned heavy limits of the optical techniques, is represented by the shearography.

The shearography

As an optical intepherometric technique the shearography is like the holography but is simpler then the latter because it doesn't need any really separate reference beam and then it requires a simpler optical condition. The basic principle of the shearography could be depicted by the scheme of figure 1 and described in the following way (Ref. 4).

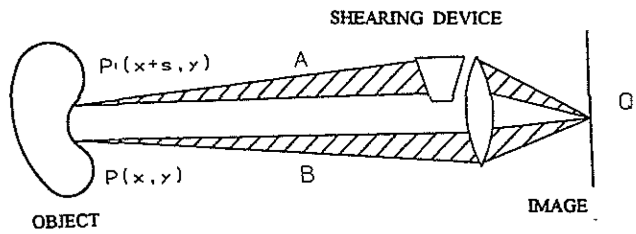

Figure 1. Scheme of the basic principle of the shearography.

From a laser source, a coherent monochromatic light beam is spread out to illuminate the object; the light beams reflected by two object points P and P' have a certain phase difference due to the different distance of the two points from the laser source. In the optical path from the object to the image, a shearing device is inserted in such a way that the beams from the point P(x, y) and P'(x+s, y), separated by the distance "s" called shear whose, impinge on the same image point Q which intensity will depend on the interference of the two beams A and B and in other words will depend on the phase difference ($\Delta\varphi$) between the two impinging beams (i.e. the starting phase difference at the points P and P' and the different path length of the beams A and B). The image Q is taken as a reference. The object is now subjected to a light load for which it undergoes to a light deformation which causes a shifting of the points P and P' and then a new point image Q* is obtained. If the two points move stiffly, the variations between the two optical paths (source-object-image) will be the same, therefore the former phase difference ($\Delta\varphi$) will be kept and Q will be equal to Q*; but if, next to one of the two object points, there is a defect for which the point moves of a different amount from the other one, the two optical paths will change of a different amount with the consequence that, in the area affected by the presence of the defect, $\Delta\varphi^* \neq \Delta\varphi$ and so the new interference condition will give a image point $Q^* \neq Q$. The image Q* is taken in its turn to be compared with the reference one Q. By the "point by point" algebraic comparison of the intensities of the image Q* with the image Q, it could be obtained a figure with interference fringes where each fringe represents the locus of points in which the phase difference is constant; in other words it could be obtained an image of fringes that visualise the derivative of the deformation of the surface of the object (while the holography fringes visualises the deformation itself). This fact is important for the reduction of the influence of environment on the inspection because some light rigid movements of the part due to external disturb haven't any effect on $\Delta\varphi$.

The reason why the shearographic image represents the derivative pattern is explained by the figures 2 and 3.

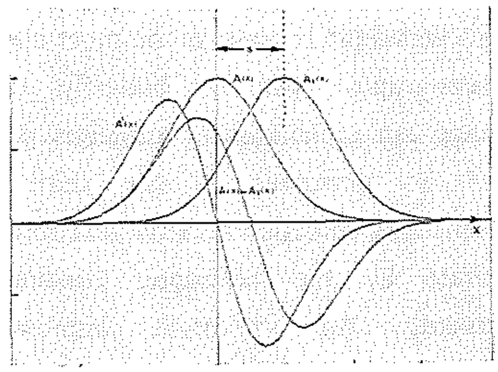

Figure 2. Comparison between A'(x) and $A(x)$-$A_1(x)$.

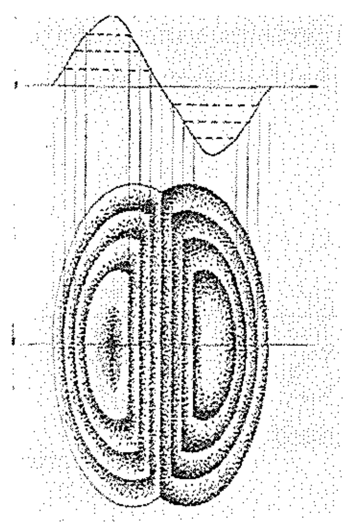

Figure 3. The butterfly image compared to a derivative.

In figure 2, the curve A(x) represents the profile of a deformation, $A_1(x)$ the same profile a part shifted of S, $A(x)$-$A_1(x)$ the "point by point" algebraic sum of the two previous curves and A'(x) the derivative of the curve A(x). For S sufficiently small it could be considered that the curve of the difference is proportional to the curve of the derivative. When the derivative increases of an amount equal to λ (wavelength of the light generated by the laser) a fringe is obtained, it is as schematised in the figure 3. This technique represents the most classical shearography with its butterfly shaped image. An application of a system like this will be presented in the third case (debonding detection on a tail unit forced to vibrate by the helicopter running on ground). An important improvement towards the possibility to process the image with the aim to make it easier to interpret, is represented by the so called phase step shearography (Ref. 5) which in principle could be explained with the scheme of figure 4 which presents a phase step device based on a Michelson interferometer.

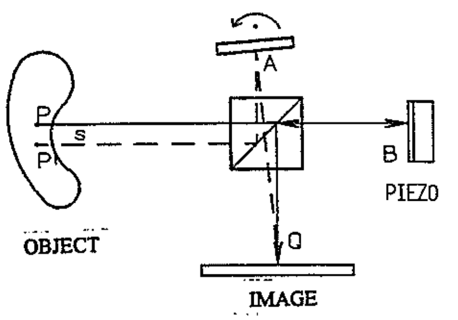

Figure 4. Scheme of the basic principle of the phase step shearography.

As before in figure 1 the light beams reflected by two object points P and P' must impinge on the same image point Q; the beam from P reaches the beam splitter and, considering only the transmitted component, it reaches the mirror supported by a piezoelement; it is reflected back to the beam splitter and to the image plane where a CCD camera provides for the acquisition and digitalisation of the picture. The beam from P' reaches the beam splitter and, considering only the reflected component, it reaches the rotating mirror (on whose angle of rotation depends the shear width "s") and then it is reflected to the image plane. The piezoelement supporting the mirror is driven in a synchronised mode with the acquisition of the image by the CCD camera in manner to change the optical path P-B-Q to get four images each out of phase of $\pi/2$ (0, $\pi/2$, π and 3 $/2\pi$). A specific algorithm, called four bucket algorithm, allows to calculate the $\Delta\varphi$ starting from the intensities of the four images (as an alternative of the former, another algorithm based on three bucket has been developed in which the phase displacement is in steps of $2/3\pi$). The possibility to know $\Delta\varphi$ both for the reference image Q and for the image Q* after the application of the load, represents the starting point for the development of specific software for the image processing with which operation like filtering and demodulation to eliminate the fringes were possible and in other words to eliminate noise, fringes and to obtain images easy to interpret.

Application of the shearography

Three different examples of application of the shearography are presented:

1. analysis of the state of damage of a solid laminate,
2. defect and damage detection on a sandwich panel,
3. defect detection on a real structure stimulated by vibrations.

Analysis of the state of damage

In the first example of application, the activities were focused to the analysis of the state of damage on a solid laminate; the part under test was a dynamic tension link of the main rotor of a helicopter; partially made of a solid laminate of about 30 mm thick, 700 mm long, 130 mm wide and with a hybrid stratification of CFRP and GFRP. In the thickness of this laminate and for a stretch of about 200 mm in length, due to severe bench testing, it could be given rise to a delamination which first propagates in one interface and after it is multilayer and extends to the adjacent layer when, in the mean time, a significant loss of stiffness is observed on the whole laminate. In a case like this and in a damage tolerance approach when a component must assure the safe performance even in presence of a damage, it is very important for the NDT techniques to clearly define the moment in which the component is approaching to the threshold of the tolerance for that specific damage. Because other more conventional NDT techniques like US for instance, are ineffective for discriminating between a delamination in one layer or in several layers laid one upon the others and the evaluation of the stiffness is rather complicate when the part is installed on the helicopter, shearography has been experimented to evaluate the gradient of the deformation on the laminate when it undergoes to a light load. Precisely three different laminates have been compared: one with multiple delaminations, one with a single delamination and one without any delamination. The surface of the laminate was lighted with a monochromatic coherent light of 514 nm of λ and the sequence of the operations was the following: with the tension link constrained at one end, a shear width of 20 mm in the direction of the application of the load was selected, the reference image Q is taken, a small load of 2 kg was applied at the second end (that 700 mm apart from the other) to bend the laminate, the second image Q* was taken in its turn and the algebraic sum between the two images was carried out obtaining the fringes picture. The image was processed and demodulated to obtain a image on which it is possible to get a profile; this profile is function of the shear width, the shear direction and the gradient of the deformation. This sequence has been applied to the three laminate keeping constant the shear width and direction; the so obtained profiles are proportional to the relevant deformation gradients. The figure 5 presents a graph of the three profiles along a line of 200 mm in the direction of the length and in the middle of the width of the laminate.

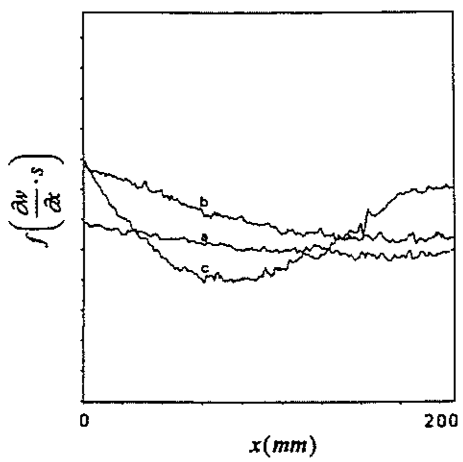

Figure 5. Profiles proportional to the deformation gradient (see the text for details).

Comparing the three curves, it could be observed that while the laminate with one delamination (curve "b") has a behaviour very similar to the that of the undamaged laminate (curve "a"), the profile of the laminate with multiple delamination clearly shows a significant loss of stiffness.

Defect detection in a sandwich panel

In the second case, the shearography was applied for the detection of defects like debonding and impact damage in sandwich panels. The part under inspection was a flat square panel of 800 mm of side; it is made of two thin skins of CFRP bonded on 0.5 inch thick non metallic honeycomb; in their turn the skins are made of unidirectional prepreg with a lay up of ±45° for a total cured thickness of 0.8 mm for the external skin and 0.6 mm for the internal one. In this panel both impact damage and debonding were simulated: the former by dropping an impactor with an hemispherical head from different heights, the latter by means of 4 permanent inserts of PTFE (2 discs of 20 and 2 of 40 mm in diameter and 0.7 mm in thickness). In this case the light deformation has been obtained by means of thermal loading by irradiation the panel with 800 watt white lamp placed at about 1 meter from the surface of the panel. As in former case, the surface of the panel was lighted with a monochromatic coherent light of 514 nm of λ and in one single shot and a corner of about 1/9 of the whole surface was inspected. The sequence of the operations was the following: after some attempts a shear width of 5-6 mm was chosen (but it could be observed that both the width and the direction of the shear were not so critical because equivalents results have been obtained with a wide range of shear and the direction, for this specific case, is ineffective), the reference image Q was taken, the area of the panel was lighted for 5 seconds with the 800 watt lamp, after 3-4 seconds of time for the homogenisation of the heat, the second image Q* was taken in its turn and the algebraic sum between the two images has carried out obtaining the image of figure 6a with fringes and in which the defects have the typical butterfly aspect. This image could be considered complete of the requested information, in fact the picture clearly presents both the simulated defects and the damage, but the image could be processed and improved to obtain the sequence of the images of figures 6b, 6c and 6d where: in 6b the image was demodulated to eliminate the fringes, in 6c the contrast and shadow were corrected to obtain a "flat" image and lastly in 6d the fringes were recalculated and presented in false colours for an immediate identification of defects and damage.

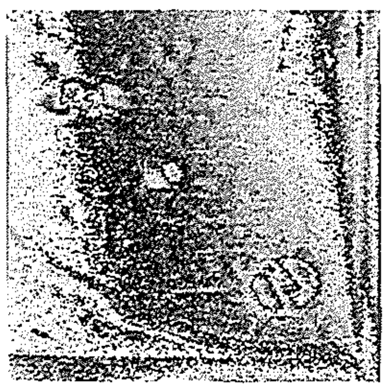

Fig 6a. Butterfly image of the sandwich panel with damage and defects.

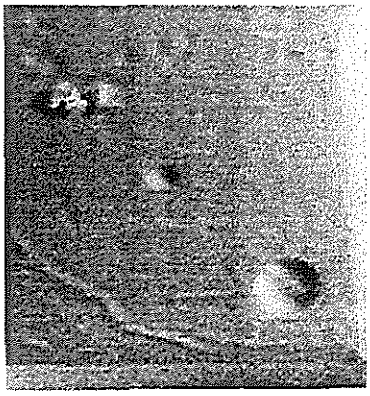

Figure 6b. The fringes of figure 6a are here eliminated by the demodulation.

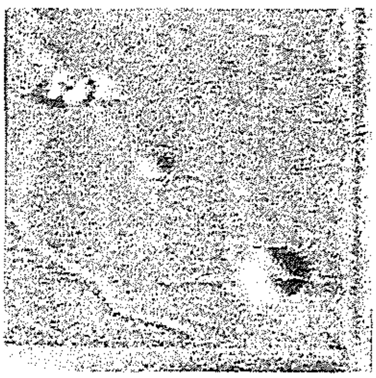

Figure 6c. The contrast and the shadow are here corrected to obtain a "flat" image.

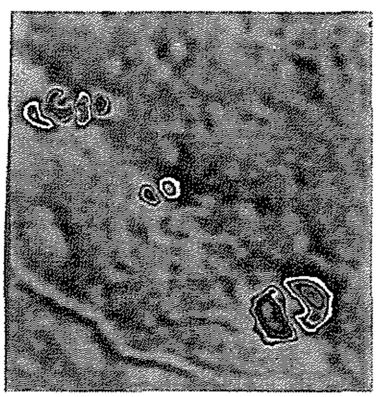

Figure 6d. The fringes in the areas of damage and defects are here recalculated.

Note: both the equipment and the image processing software for this test were prototypes developed by the NDT Development Group of Fokker Aircraft BV in Netherland; unfortunately this group is no more existing and even the software appears to be lost.

Defect detection on a real structure

In the last example of application, the shearography was used for the debonding detection on a side sandwich panel of a composite structure (i.e. tail unit of a medium-heavy helicopter). In this case, in order to stress the structure, the natural vibrations due to the helicopter running on ground were exploited.

Analysis of the condition of vibration.

With the aim to get information about the way to stimulate the structure to vibrate in a way similar to the natural one, it was necessary to understand the modes and the frequencies of vibration of the panel of interest. For this purpose, both a theoretical analysis and an experimental acquisition of the vibration spectrum have been carried out. The theoretical analysis has been carried out by means of a FEA of the panel of interest to get the model of the proper modes and frequencies of vibration. Without going into details of this activity, a meaningful results was that the central part of the panel of interest can deform with a significant amplitude at the frequency of about 196 Hz. The acquisition of the vibration spectrum has been done in order to get confirmation about the former data or to understand whether the structure itself, desired to avoid resonance avoiding in its turn to enhance the vibration loads forced in a panel by the running of a helicopter, could in some way modify both the proper vibration of the panel. The vibration data, in terms of acceleration collected up to 200 Hz in six different positions (the position of accelerometers on the side panel are depicted in figure 7) were recorded with the helicopter in four different ground running conditions: ground idle at 40% N.R. (Number of Main Rotor Revolutions), ground idle at 52% N.R.; ground idle at 61% N.R and flight idle (Condition at Minimum Power on Ground) at 100% N.R.

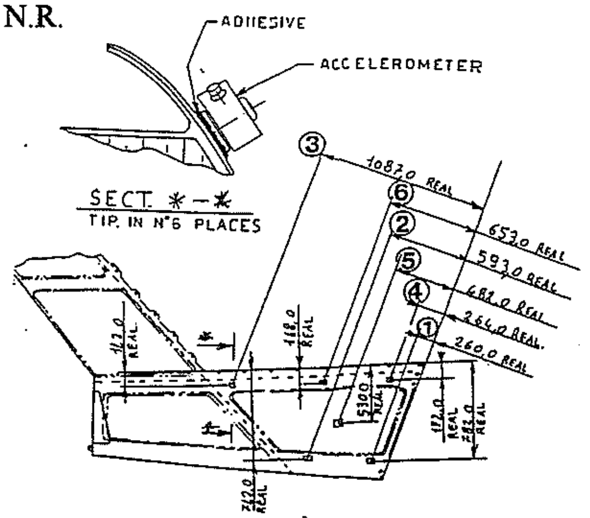

Figure 7. Positions of the accelerometers on the side panel of the tail unit.

Again without going into details of this activity for shortness purposes, the meaningful result was that, with the helicopter in flight idle with 100% N.R., the panel deforms in position 5 in three ways: at 124 Hz with a displacement of ≅8 μm, at 165 Hz with a displacement of 5 μm and at 190 Hz with a displacement of 9 μm and deforms in position 2 at 190 Hz with a displacement of 6 μm which is in a good agreement with the data from the theoretical approach.

Defect simulation.

In the middle of the panel of interest of a real tail unit and in roughly correspondence with the position of the accelerometer n° 5 of figure 7, a debonding was simulated in the following way: from the internal side of the structure, a core boring of 70 mm of diameter was carried out by removal of the internal skin and the honeycomb (leaving the external skin without damage), the cylinder of honeycomb was replaced and the internal skin was repaired by a cold bonding of a pre-cured patch.

Stimulation of the structure.

In the line of the power transmission to the tail rotor of the helicopter, there is a intermediate 42° gear box bolted to the tail unit; it is supposed that many vibration loads from this attachment are transferred to the structure and therefore the point of this attachment was used for the stimulation of the structure. The stimulation was obtained by means of a shaker controlled in manner to obtain a vibration answer of 190 Hz in the position correspondent to the accelerometer n° 5 which in its turn is the position of the simulated debonding.

Testing.

The surface of the panel was lighted with a monochromatic coherent light of 780 nm of wavelength generated by four laser diodes placed with the camera at 260 cm from the surface of the panel; the shear width was of 18 mm, in the vertical direction. In this case, the use of the phase step shearography is ineffective because this system requests the panel to be steady for the period of time requested for the acquisition of the four images for Q and the same for Q*. In case of vibration load, of course this cannot be assured. The system used in this case carries on a continuos acquisition of the images with a time average of them. In vibrating conditions the panel presents nodal lines and antinodal areas; while the latter move continuously and then the reflected light are randomly out of phase, the former are steady and this means that the reflected light has always the same phase, the time average is constant and therefore in the picture they appear as definite lines. The presence of the defect produces an alteration of the deformation modal pattern and consequently represents a sort of interference in the distribution of the nodal lines; the alteration of the nodal lines pattern is the indirect evidence of the presence of the defect. The result of this test on the panel of interest is depicted in figure 8.

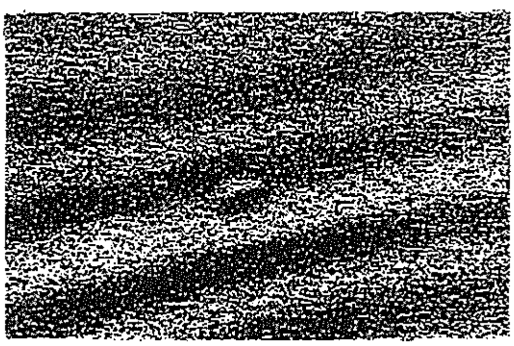

Figure 8. Shearographic image of the panel shimulated by vibration load.

Conclusion

As a conclusion about the first application of the shearography it could be observed that it represents an experimental and atypical use of a NDT technique. The evaluation of the deformation or of the gradient of deformation can be obtained with higher precision with other techniques, but in this application it is important to note the easiness, the quickness and the extremely low load employed to deform a laminate of a link designed to support tons.

About the second application, it could be observed that the structure of the panel perhaps represents the most favourable condition to demonstrate the capabilities of the shearography because it has a thin skin and then the defects easily result in a surface deformation; as a matter of facts it must be remarked the precision of the map of the defects simulated with discs of PTFE and moreover it must be taken into account the easiness and the repeatability of the inspection which gives justification to the increasing interest about this technique.

As a conclusion about the last example of application, it could be observed that the structure was stimulated to vibrate in a simpler way than in the real conditions (neither lower frequencies with wide displacements nor high frequencies have been taken into account and simulated); moreover in real conditions the wind of the blades and the heat generated by the engines surely could influence the reading (e.g. they influence the refraction index of the air) and this influence was not taken into account too during the test; however the positive conclusion of this experience is the demonstration of the possibility to detect some type of defects when they deform the surface of the structure during a natural vibration. This positive aspect suggests to continue the investigations and the development of the shearography to understand or to solve the problems connected with the influence of a wider vibration spectrum and the influence of the hot wind.

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