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Optical sensoring techniques for structural diagnostics

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ABSTRACT: Inspection methods, based on the use of laser light, for measurement of static or dynamic deformations, for surface profilometry and surface state analysis, and optical fibre sensoring techniques are briefly presented and their possible contribution to structural reliability pointed out.

1. INTRODUCTION

The application of coherent light technologies for the inspection, monitoring and diagnosis of structures is dramatically increased in the last decade. This fact is not due to a possible better understanding of their advantages, which were already well known:

- full-field measurements;
- non intrusive, non contact measurements;
- remote operation;
- high resolution;
- numerical storage
- excellent for qualitative results;
- real time continuous measurements;

but to the impressive development and cost reduction in the relevant technologies:

- pulse lasers with variable repetition rate;
- diode lasers;
- optical fibres;
- miniaturized digital cameras and consequent development of Electronic Speckle Pattern Interferometry (ESPI);
- thermoplastic film;
- computer supported analysis and interpretation, etc.

Holography has an extraordinary precision in recording images which can be studied and compared for diagnostics, allowing the detection of fissures, stress intensification areas, erosion and corrosion processes, etc down to the dimension of fractions of a micron.

Holography and interferometry can be used for determining if a repair work has been effective or not; controlling in real time the response of the structure to loads or monitoring in real time processes like welding and the related induced stresses; inspecting the internals of components via optical fibres and microprobes for endoscopy; etc.
The use of micro-endoscopes and radiation resistant optical fibres allows the inspection (e.g. measurement of deformation; control of dimensions; surface madification analysis; etc) of hard to reach regions of the structure.
Therefore, coherent light methods constitute a set of inspection and monitoring tools which may complement the classical techniques and greatly contribute to characterization of the actual state of the structure and of its modifications during its service life, by means of:

a. geometrical characterization and measurement af any physical dimension changes and material mass removed or added;
b. measurement of surface deformation and strain under various types of load: thermal, mechanical, environmental, vibration induced, shock, etc

The above knowledge is essential for safety assessment and management and for selection of timely and adequate actions of maintenance and repair.
According with inspection needs and structure characteristics, different techniques can be used (e.g. double exposure interferometry; real time interferometry; time averaged interferometry; sandwich holography; ESPI; surface contouring; optical correlation; optical fibre sensoring; ect.) which can assure resolutions ranging from millimetres to fractions of a micron. All of them are full field, non contact techniques and can be applied by remote operation: this constitutes a great advantage with respect to classical techniques which do interfere with the operation of the structure or plant and supply only point information.
Furthermore, all the images (e.g. interferograms; surface contouring maps; strain maps; etc) and data obtained are numerical, stored in computer mass memories and ready for analysis, further elaborations, comparisons. This means that they can be interfaced with complex computer programs like CAD (e.g. for reconstruction ,in 3D, of component shape or design of repair actions), graphical animation, or Finite Element Method Codes for stress and strain analysis (e.g. for comparing design stresses and actual stresses or for predicting structural effects of any kinds of load).
The possible applications of coherent light (laser) techniques can be thought of as belonging to the following main categories:

- measurement of static or slowly varying deformation;
- measurement of dynamic deformation;
- surface profilometry;
- surface state analysis;
- optical fibre sensoring

This means that a number of pieces of information of high interest for the estimation of the reliability of a structure can be made continuosly available in a format directly compatible with computing facilities.
Exemples are here given of some of the results obtained in each of these fields.

2. MEASUREMENT OF STATIC OR SLOWLY VARYING DEFORMATION

2.1. Absolute quantitative measurent of strain

Absolute strain values can bee obtained by numerical treatment of interferograms. A properly developed numerical code (ELISA) has been used for handling interferometric data and presentig results. The proposed procedure (three interferograms with different position of illumination and observation) enabled the achievement of high "quality factors" in the measurements. The agreement of interferometric strain values and the ones obtained by strain gauges and analytical solution (i.e. finite elements calculation) was very good (Lucia, Franchi etc,1989). The approach seems very effective for diagnostics and surveilllance purposes of structures as it allows a full field measurement of strain without any local averaging action (as resulting, for example, from the use of strain gauges).
It is worth mentioning here that in most cases it is not necessary to evaluate the complete deformation vector and one single interferogram, allowing the measurement of the displacement component along the bisector of the angle between the illumination and observation directions, is enough to have a quantitative monitoring of the structural behaviour. As a matter of fact, even a purely qualitative result (i.e. the interferometric fringe behaviour) is very often adequate to monitoring purposes.

2.2 Quick qualitative measuremt of strain

Interferograms may also supply quick, qualitative information which may be sufficient for early warning on structural degradation. During a long-running fatigue test (about 1million cycles at 1cpm) of a pressure vessel (SA508 and SA533 nuclear quality steel plus AISI 347 for internal clad), laser interferometry periodic inspections did detect the formation of a fatigue crack at the nozzle corner (thickness about 75 mm) showing a system of small, closed fringes. The result was important because acoustic emission (for environmental noise problems) and ultrasonics (for inspection difficulties due to the geometry on the corner region) did not give clear evidence of the nucleation and propagation of the defect.
Good results have also been obtained for the detection of residual stresses induced by the welding process on steel components.
The potentialities of laser interferometric techniques for improving structural safety can be inferred by the outcomes of the inspection and monitoring campaigns (by laser holographic interferometry and acoustic emission) that JRC has performed, on a trunk of aircraft fuselage undergoing fatigue damage, for an italian aircraft manufacturer. The use of a pulsed wave laser did allow to get rid of the disturbances due to environmental parasite vibrations (Zürn, Franchi, 1992).
The detailed results of the measurements are confidential, but it is possible to say that the techniques turned out to be effective. The use of double exposure holographic interferometry allowed the identification of regions where the previous loading process induced structural damage: the qualitative behaviour of the fringes showed the presence of a local decohesion between cylindrical shell and internal frame element (ISEI, 1992)
This kind of measurement could be envisaged for the primary circuit pressure components, during service, possibly by means of endoscopes and optical fibres

allowing to reach critical regions, even not directly accessible, while keeping laser and main instrumentation far away fron hot regions.

2.3 Real-time interferometry

Real-time interferometry is quite an effective tool for monitoring the evolution of strain distribution in critical regions, e.g. where local stress intensification is present, and the onset of service induced defects, which are more more likley to appear there then elsewhere; this technique could be applied during normal transients of pressure or temperature. Pseudo three-dimensional images of the deformed surfaces can be obtained which provide a very clear picture of the strain distribution, and further yield accurate quantitative results.
Fig.1a shows one image, out of the continuos sequence obtained on a composite material specimen during a temperature transient; irregular fringe patterns were immediately observed, during heating up, where structural anomalies or defects were present; closed shape fringes show the high strain region. Fig.1b shows the correspondent strain map (Solomos, Lucia, 1992).
It has also to be mentioned that this type of structural degradation may escape detection by ultrasonics.

2.4 Electronic Speckle Pattern Interferometry

Much activity has been focused, at JRC, on the improvement of the performances of ESPI (Electronic Speckle Pattern Interferometry), for micro-deformation analysis, and on development of a portable instrument.
ESPI enables micrometric static and dynamic surface displacements to be measured with an accuracy of fractions of a micron, less than the wavelength of visible light, and constitutes an interesting alternative to conventional holographic interferometry. It has the added advantage that, since it uses a video-electronic system for detection and processing, measurements can be made in real time and detection of micrometric deformation evolution can be easily performed. Tests have been carried out to define clearly advantages and limits of this technique.
An electronic speckle pattern interferometer with an endoscopic imaging system has been developed for non-destructive measurements in hidden or difficult to reach zones. The whole system is very flexible and the fields of application can range from industrial survey to medical diagnostics (Facchini, Zanetta, etc 1992).
A simple and accurate fibre optic interferometer, able to perform real-time measurement in hostile environment, has been realized with a minimum of optical components and adjustments. Preliminary tests were carried out in laboratory and further measurements were performed on buildings.

3. ANALYSIS OF DYNAMIC DEFORMATION

3.1 Vibration measurement by time-average interferometric techniques

The study of the vibration properties of a structure allows important conclusions to be drawn on the structure state. Holographic interferometry and related techniques offer a direct visualisation of the stationary vibration modes in real time. Fig.2 shows an interferogram depicting the vibration of an impeller excited by an acoustic wave at a frequency of 647 Hz. The interferogram has been digitally recorded with a system based on Electronic Speckle Pattern Interferometry.

3.2 Visualization of fast phenomena by pulse laser holography

Holographic interferometry by pulse laser can be used not only to get rid of vibrations, always present outside laboratory, but also for the visualisation of fast phenomena like bending wave produced by impacts. The availability on the market of pulse lasers with high repetition rate and possibility of double pulses with variable time gap makes it possible to obtain a fast sequence of interferograms.

4. SURFACE PROFILOMETRY

Surface profilometry consists of inspecting the object surface in order to obtain a detailed description of its three-dimensional contour. Optical contouring techniques have extensively been studied as their main characteristic is of being non-intrusive. These techniques have been applied to a variety of fields of metrology including topography, industrial measurements, robotics, visual graphics, three diemensional computer-generated modelling, etc.

4.1 Fringe projection contouring

Depth contouring can be performed (with resolution up to 50 microns) by projection of parallel fringes onto the object under inspection. The projected fringes are modulated by the surface shape. By appropriate digital precessing, a three dimensional map of the object surfce is obtained (Zanetta, Albrecht, etc, 1993).

4.2 Line projection contouring

The achievable resolution is of about 100 microns. The object is illuminated with a laser light line which scans the surface regularly. The line is modulated by the object shape which can be retrieved by means of an appropriate digital processing of the line profile. The resolution is lower than the one obtained with the fringe projection method, but the advantage of this last technique is that larger surfaces can be inspected.

4.3 CAD and 3-D graphic animation

The results of the measurement techniques applied to study surface and volume of an object, can be used as input data for computer codes such as Computer Aided Design (CAD), Finite Elements (FE) and 3D graphic reconstruction which enable the study of structures and components and of their behaviour.

5. SURFACE STATE ANALYSIS

A very early detection of surface alteration can be obtained by the use of local speckle correlation measurement. When the surface of an object is iluminated by laser light, its image shows a granular appearance known as speckle. Micro alterations of the surface structure (e.g. due to a very early stage of corrosion) induce modifications of the speckle image. By measuring correlation degree of speckle images taken at different times, it is possible to quantify and follow the alteration of the surface. In practice, speckle decorrelation has been detected as bright areas in the subtraction image of two speckle patterns recorded at different times. Since no refernce beam is necessary, the experimental set-up is very simple and insensitive to external disturbances (Zanetta, Facchini, 1993).

6. OPTICAL FIBRE SENSORING

The use of optical fibres for sensoring purposes is relatively recent, but much progress has been made since the first fibre optic sensors whose signal was only the fibre rupture signal. Now sensors are available for the measurement of several kinds of physical variables: displacement, deformation, vibrations, temperature, pressure, flux, radiation and even the concentration of certain elements in solutions or in the air. Two types of optical fibre sensors may be realized: phase modulation (i.e. interferometric) sensors and intensity modulation sensors. Both of them show the following remarkable advantages: they are passive devices and do not require extra power lines or local electronics; do not suffer from EM interference; are intrinsically simple and allow long distance interrogation; when used for monitoring structural variables, they can be stuck onto the surface or embedded into the material during fabrication (smart material). Development work has been carried out at the JRC/ISEI in the field of phase modulation fibre sensors (Tatti, 1995).

7. INFORMATION PROCESSING

It is worth pinpointing the critical role played, in the application of optical techniques, by information processing. By information processing we mean, from the one side, data and image analysis for obtaining in explicit form the information we need and, from the other side, the use of this information for inferring estimates on the state of the structure. An intelligent system for diagnostics by optical data analysis
should essentially be constituted by four parts:

1. analysis of experimental data and images for obtaining the explicit and object oriented representation of inspection results and, on its basis, the representation of the actual state of the structure (surface profile, strain map, temperature distribution etc);
2. theoretical analysis of the structure in order to have the representation of its theoretical state;
3. image bank containing similar cases or data and images (both from theoretical assessment and from experimental evidence) of previous analyes or inspections of the same structure;
4. comparison (theoretical vs experimental; experimental vs previous experimental) for diagnostics.

The comparison and diagnostics part could be seen as a decision support system, i.e it should contain a procedure for inferring intermediate or definitive conclusions on structural damage, basing not only on the accumulating data and images and on their comparison, but also on the domain knowledge.

8. CONCLUSION

Techniques based on the use of laser light and computerized methods for processing data and images constitute a powerful set of tools for structural diagnostics. The limitations due to vibrations and daylight have been removed by using pulse lasers and suitable electronic shutters. The ESPI technique too allows to get rid of the daylight problem and is very apt for continuous monitoring of critical regions, while radiation and temperature resistant optical fibre allow the holographic and interferometric inspection of regions difficult to reach. Optical fibre sensors are also available for continuos monitoring of several physical variables.
Practical limitations and difficulties of course still exist, but the advantages of these techniques are, in some applications, very clear.

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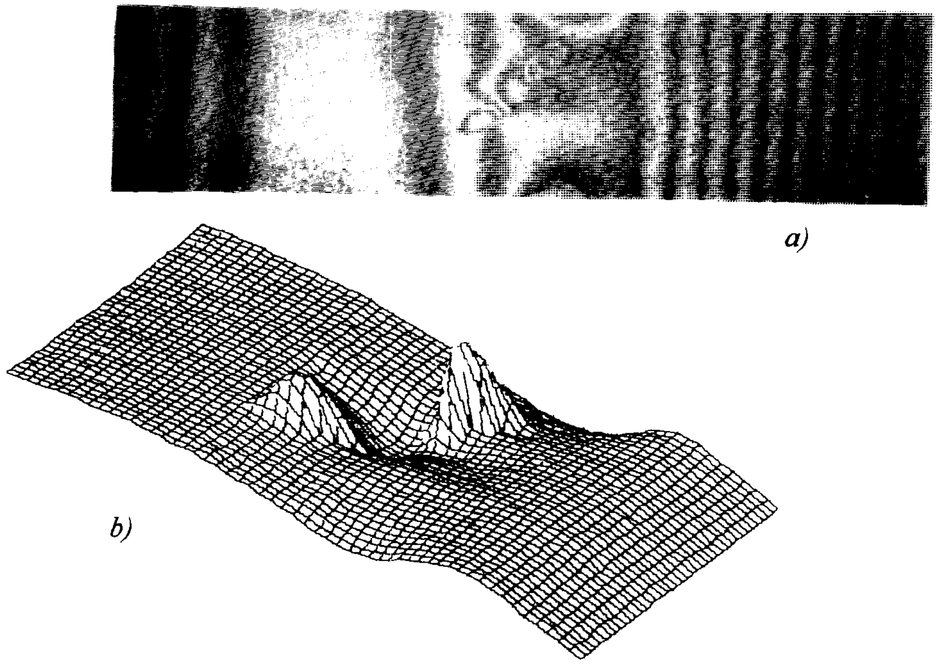

*Figure1 a: double exposure interferogram of a plate containing a buried defect;
b: 3-D plot of the evaluated deformation*

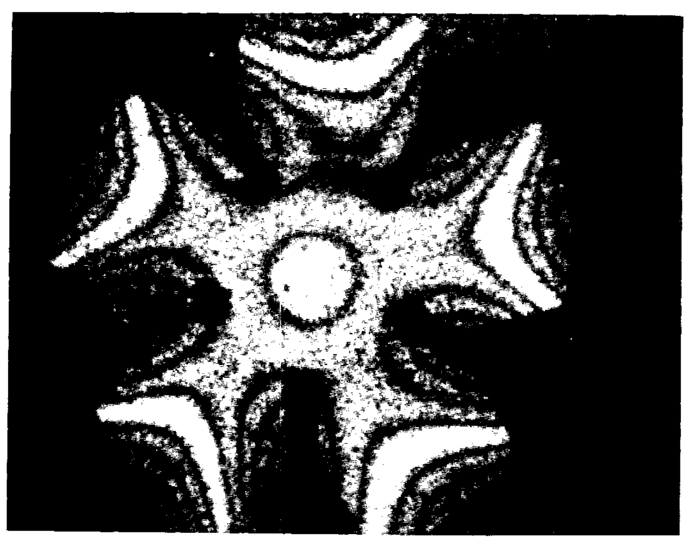

Figure 2: interferogram depicting the vibration of an impeller excited by an acoustic wave at a frequency of 647 Hz.