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Dynamic optical method for local strain measurements: principle and characteristics

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RESUME : L'analyse spectrale d'un réseau par diffraction oblique est utilisée ici pour déterminer les déformations locales lors de chargements en dynamique. Afin de séparer les faisceaux diffractés durant l'événement dynamique, nous associons à chaque état de chargement une orientation particulière du faisceau laser incident. Expérimentalement cela est réalisé à l'aide d'éléments acousto-optiques. Ces éléments permettent l'enregistrement de vingt-quatre états de déformation à une fréquence maximum de 500000 images par seconde. L'ensemble des figures de diffraction est recueilli sur un même plan film puis traité automatiquement à l'aide d'une caméra CCD. Avec une technique de dépouillement adaptée, la sensibilité en déformation atteint quelques 10^{-4} . Des essais en dynamique sont présentés afin de montrer les performances de cette méthode optique de mesure des déformations.

ABSTRACT : A spectral analysis of a grating using optical diffraction with an oblique incidence is employed to determine the local strains for dynamic loading. In order to separate the diffracted beams during the dynamic event, we associate with each strain state a particular orientation of the incident beam. For the conception of the optical device, we use acousto-optics elements which allow the recording of twenty four strain states at a maximum frequency equal to 500,000 frames per second. The diffraction figures are collected on the same photographic plate which is quasi automatically analysed with a digital image processing using a CCD camera. With a specific analysis device, the strain sensitivity reaches some 10^{-4} . Simple dynamic tests are presented to show the performance of this optical strain measurement method.

1 INTRODUCTION

The optical strain measurement methods allow non contact and non destructive evaluation. Recent developments of the digital image processing [1] have given a new future to these optical methods. The grid method [2], one of these powerful tools, allows to obtain by the comparison of the geometry of two crossed gratings (pitch and orientation of each grating) with the initial one, the magnitude and the orientation of the principal strains and the solid rigid-body rotation [3]. The grid interrogation is performed by a numerical or an optical spectral analysis using a Fourier transform [4][5]. This strain measurement method is very efficient for soft materials, for studies in hostile environment. This method presents no limitation for large strain measurements and few specific analysis like the phase shifting technique [6] give a strain sensitivity of 10^{-5} which is comparable of the one obtained from strain gauges. The use of the method is still now restricted to static investigations. We present an extension of this optical method adapted to the local measurement of a dynamic strain.

2 PRINCIPLE

In this method, we use the oblique incident diffraction phenomenon. We can see on Fig. 1, for an orientation of the incident laser beam, the elliptical distribution of the light spots obtained after diffraction. We can also determine this geometrical distribution with the following equations.

Fig. 1 Diffraction in oblique incidence oblique incident diffraction equations

This system of three equations associates the position of the light spot on the screen to the pitch and the orientation of the grating, the two orientations of the measurement base and the three positions of this base. It is necessary to record the zero order for the determination of the orientation of the measurement base and the diffracted order ± 1 associated with two grating families for the measurement of the strain components. At each step of recording, we have to solve 15 equations with 14 unknowns. These unknowns are: The 4 geometrical characteristics of the grating, the 2 angular positions of the measurement base, the 3 components of the position of the measurement base, and the 5 distances between this base and each spots. The comparison of these 14 unknowns with the quantities at initial state gives the components of the strain tensor, of the rigid body rotation and of the rigid body displacement.

3 RECORDING DEVICE

In order to separate on the same photographic plate the spots of each step of the dynamic event, we associate with each of these steps a specific angle of the incident laser beam (Fig. 2).

Fig. 2 Optical device

For the conception of the optical device, we have not retained the solution with rotating elements (turbine, mirrors, etc...) which seems complex and we have preferred to employ opto electronic components which are easier to use.

During the dynamic event, the variation of the orientation of the incident laser beam is achieved with an acousto-optic deflector. This element, devoid of mobile parts, allows to record the strain states at a maximum frequency of 500,000 frames per second. To obtain a sequential information we use an acousto-optic shutter which can produce a minimum exposure time equal to 30 ns. A holographic optical element, with 24 holographic lenses, allows to rotate the laser beams leaving the acousto-optic deflector, in the direction of the grating. This holographic element gives cylindrical beams with a diameter equal to 10 mm. This diameter allows a displacement of the small measurement base of a few millimeters. Finally, after reflection on the specimen, the diffraction figures are all collected on the same photographic plate. For a test, we expose two plates: the first one with the five groups of diffracted spots at the initial state, the second one at the deformed states.

Some simulations have been made to show the diffraction figure when the specimen is strained[7].

4 ANALYSIS DEVICE

To determine the position of the 5x24 spots recorded on the photographic plates, we use a digital image processing. First we calculate these positions by a classical technique using a photographic lens on a CCD camera (384 x 288 pixels), which records the whole field of the photographic plate (Fig. 3).

In order to appreciate the strain sensitivity of this analysis method, we are interested in a test with no strain. After analysis of the photographic plates, we obtain (Fig. 4) a strain sensitivity of this classical analysis method of approximately 2×10^{-3} .

Fig. 3 Acquisition and analysis device

Fig. 4 Strain sensitivity results

We can verify that this strain sensitivity is directly associated to the precision of measurement of the position of the spots, and of course, of the CCD camera quality. A CCD camera with a spot position error of 1 pixel and a 120 x 90 mm photographic plate gives a spot position error of 0.15 mm. The ratio of this position error on the size of the plate gives a sensitivity of the same order of the one experimentally determined.

If we want to obtain a better strain sensitivity, we must discretise more finely the plate (more pixels on the CCD, subpixel position sensitivity). We have chosen to move the photographic plate with a very good precision and to look at its spots with a microscope lens.

The acquisition device (Fig. 5) consists of a XY displacement table with 0.01 mm sensitivity for moving the plate, and the same CCD camera for the acquisition of the spots. We have illustrated in the same diagram (Fig. 6) the strain sensitivity obtained with this spot by spot analysis method and with the first whole field method.

Fig. 5 Acquisition and analysis device

Fig. 6 Strain sensitivity comparison

With this new analysis technique, the strain sensitivity can approach to 2×10^{-4} which represents an improvement of magnitude 10.

5 EXPERIMENTAL INVESTIGATIONS

For all these experimental investigations the diameter of the measurement base is about 1 mm. These tests are performed on a polycarbonate specimen and the experimental data are analysed using the spot-by-spot technique.

First we have glued on the specimen a strain gauge on one side and made a grating of 300 lines per millimeter on the other, then we have applied this measurement method to static loading using a uniaxial tension test [7]. We have compared the strains optically determined with those obtained from classical extensometry and formed a very good agreement between these two sensors.

In order to show the performance of the strain measurement method, we have performed simple dynamic experiments. We have created an impact using the potential energy of a mass which hits the moving grip of the specimen loaded in tension first and in compression in the second test (Fig. 7). For these dynamic tests we have made a grating of 200 lines per millimeter on the strain gauge for better agreement on the localisation of the two sensors (Fig. 8).

Fig. 7 Dynamic loading system

Fig. 8 Sensors disposition for dynamic tests

For the recording we use an Argon laser ($\lambda=514.5$ nm) and a photographic plate with a 400 ASA sensitivity. Because of the duration of the impact, the frame rate (i.e. the frequency of the acousto-optic deflector) is chosen equal to 1,5 kHz for the first test and 35 kHz for the second. The time exposure is respectively 100 μ s (15% of the frame rate) and 2.8 μ s (10% of the frame rate). We can see in Fig. 9 and Fig. 10 the good agreement between the strains measured with this optical method and those given by a strain gauge.

Fig. 9 Dynamic uniaxial tension test

Fig. 10 Dynamic uniaxial compression test

In Fig. 11 and Fig. 12 we can see the strain rate range of these two dynamic tests calculated from the grating response.

Fig. 11 Dynamic uniaxial tension test

Fig. 12 Dynamic uniaxial compression test

It is important to note that the same performances of the method developed can be obtained for faster dynamic conditions. The frame rate and the exposure time can be adapted to the loading speed. The frame rate can be equal to 500 kHz and the exposure time can be very short even with conventional equipment. For example, a study of the energetical efficiency of our experimental device shows that the use of a 260 mW laser power allows the recording on a plate of 400 ASA sensitivity with a minimum exposure time equal to 0.5 μ s. In these conditions the developed recording device can be applied for the strain measurements on dynamic loading of a minimal duration equal to 50 μ s and if we want to obtain a strain sensitivity of some 10^{-4} during the dynamic event, the maximum strain rate approach 1000 s^{-1} .

6 CONCLUSION

This measurement method performed by an interrogation of the grating using the optical diffraction with an oblique incidence allows to determine not only the classical parameters given by the optical diffraction in normal incidence (the strain tensor) but also the rotations and the displacements of the measurement base. The use of acousto-optic elements allows to separate easily the information during the dynamic event. The acquisition of this information by digital image processing using a CCD camera gives a quasi-automatic analysis.

The optical device allows to record states at up to 500,000 frames per second and does not require expensive equipment. The direct determination of strains without any contact is well adapted to the analysis of impact loadings, with the measurement directly obtained from the specimen and not from the bar as in the Hopkinson's test, to study behaviour laws in dynamic loading or to control structures under vibratory regimes.

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