Bartolomeo Trentadue[1]

Experimental analysis of structural damage in tensile membranes

[1] DMMM – Politecnico di Bari, Viale Japigia 182, Bari, Italy, E-mail: btrentadue@poliba.it

Abstract:
Different numerical and experimental methods have recently been introduced in the literature for the diagnosis of structural damage by using location-dependent changes in the modal parameters (natural frequencies, damping factors and mode shapes). The main task is to determine the presence, location and extent of the damage. This work is concerned with the possibility of introducing, along with a manufacturing process, an on-line quality control for structural components before assembly using modal parameters. The assembly process is usually realized by welding joints or bolts. The structural reliability of the entire system results, therefore, is dependent on the reliability of the single elementary components as well as on the local quality of the welding processes. As a result, a non-destructive control provided together with the relevant assembly or manufacturing process can be important for the integrity of the whole system. The modal analysis techniques [Giannoccaro NI, Messina A, Trentadue B, Masciocco G, Montuori G. *Detection of Changes in Mechanical Components for Automobile Chassis Using Modal Data*. ATA International Edition, 2001; Messina A, Williams EJ, Contursi T. *J. Sound Vib.* 1998, 216 (5), 791–808] lend themselves well to the case because they are based on the measurement of parameters (natural frequencies and mode shapes). They are sensitive to the structural modifications but have a different sensitivity for the variations in the generic investigated zones of the system. To enact the real possibility of using such a technique, the defects that are troublesome for integrating the assembled or elementary component must be established. These defects have to induce some variations in the checked parameters (modal parameters) in order to be out of experimental repeatability of the same parameters connected with healthy structural systems. In this work, natural frequencies are shown and compared to a non-contact optical technique subsequently experimentally reliable when used in diagnostic routines connected with geometrically similar components from a molding process.

Keywords: image processing system, optical technique, vibration

DOI: 10.1515/jmbm-2018-2004

1 Introduction

Natural frequency tensile structure arms are easily excited by environmental factors. These factors could cause considerable displacement of a structure and compromise its safety.

Unfortunately, the change of the dynamic characteristics of the drilled components was rarely, if ever, considered in these kinds of structures. Due to the importance of safety, it is necessary to investigate the whole effects of the tensile structure components under the excitation of vibratory loads.

Butters and Leendertz [1] first adopted the electronic speckle interferometry method to demonstrate the out-of-plane vibration fringe patterns of a disk. Hohberg and Hogmoen [2], describing the light intensity of a fringe pattern by the zero order Bessel function, proposed that contours of constant phase can be plotted by combining the time averaged echo-planar spectroscopic image (ESPI) with the phase modulation technique. It was found that the ESPI method produced the best visibility and highest resolution of the fringe pattern. Therefore, in this paper, the ESPI technique was applied in order to acquire the fringe patterns of a final component for a tensile structure.

2 Speckle interferometry

The speckle technique used for this particular study [3] was based on the time averaged and image subtraction techniques as shown in Figure 1.

Bartolomeo Trentadue is the corresponding author.

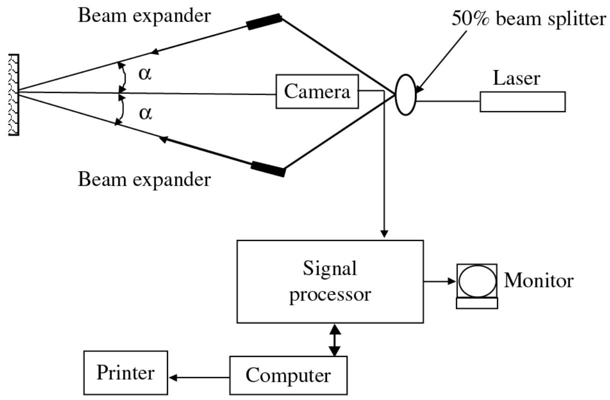

Figure 1: ESPI set-up.

The light intensity detected by a charge-coupled device (CCD) camera at time t can be expressed as:

$$I = I_0 + I_r + 2\sqrt{I_0 I_r}\cos(\phi + \Delta) \tag{1}$$

where I_0 is the object light beam, I_r is the reference light beam, ϕ is the random phase related to the surface roughness, $\Delta = 4\pi(1 + \cos\theta)(A \cos \omega t)/\lambda$, θ is the illumination angle of the object light, A is the vibration amplitude, ω is the vibration frequency and λ is the wavelength of the light source.

The reference image is not taken in the unloading state but in the excited condition. The corresponding brightness can be expressed as:

$$B = \frac{4N\alpha\beta\pi}{\omega}\sqrt{I_0 I_r}[J_1^2(\eta A)\cos^2\phi]^{\frac{1}{2}} \tag{2}$$

where N is the number of vibrating cycles in one exposure time, α is the slope of CCD camera's sensitivity curve, β is the conversion factor of the look up table of the image processing system, J_1 is the first order Bessel function, and $\eta = 2\pi(1 + \cos\theta)/\lambda$.

3 Acceleration transmissibility

In order to estimate the structural resistance to vibration, the acceleration transmissibility, TR, is measured and considered as a criterion to analyze the component behavior. The TR is used to describe how the acceleration is transmitted from the exciting device to the test specimen as a function of the frequency ratio $r = \omega/\omega_n$:

$$\mathrm{TR} = \frac{P(r)}{F(r)} \tag{3}$$

where ω_n is the natural frequency, $P(r)$ is the power spectrum of the output signal measured by an accelerometer attached to the specimen, and $F(r)$ is the power spectrum of the input signals measured by a force sensor attached to the loading device.

4 Experiment

As shown in Figure 1, there are three subsystems involved in the experimental setup for this study: the optical, vibration and image processing systems. The optical setup is the out-of-plane ESPI arrangement. The laser beam, coming from the 35 mW He-Ne laser of 632.8 mm wavelength, is split into two beams by the variable beam splitter. The variable beam splitter also adjusts the light intensity ratio of the two beams. The optical paths of the two beams must be equal. In order to make the optical collinearity easier, ground glass is added in the reference beam path. Two spatial filters are used for both beam paths to filter the optical noise and expand the laser beams. The vibration system was adopted to measure the natural frequencies and modal modes of the specimens. The exciting and response signals are detected by the force sensor and accelerometer, analyzed by the dynamic signal analyzer and post-processing software. Two different specimens were used in this paper, one without holes (A) and the other with holes. (B) Both specimens are made of steel with measurements of: length 150 mm, width 50 mm and hole diameters 20 mm (Figure 2).

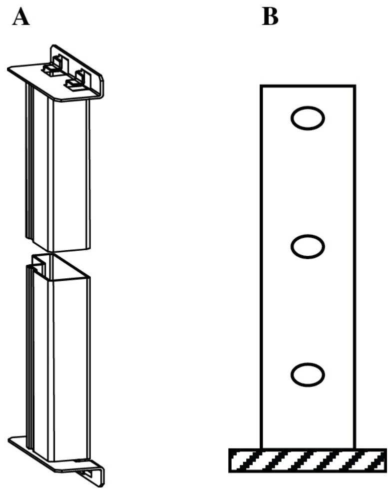

Figure 2: (A) Specimen without holes; (B) holed specimen.

In the beginning, the natural frequencies of the specimen were detected by the frequency response functions (FRFs) measured by the dynamic signal analyzer of the vibration system [4], [5].

The Star [6], [7] Modal and Suffer, both post-processing software, were used to fit the modal shape from the FRFs. The exciting force was then applied to the specimen when the fringe patterns of ESPI were viewed by the CCD camera. Finally, from the output contours of ESPI, the regions of maximum deformations can be decided.

5 Results and discussion

The contours of the vibration amplitudes [8] and the modal modes of the specimens without holes are shown in Figure 3 and Figure 4. The results for the holed specimens are shown in Figure 5 and Figure 6. The white numbers in the fringe patterns represent the fringe order of the dark fringes and the negative sign represents out-of-phase. The holes did not affect the mode shapes of the specimens because there is almost no difference in the deformations from the first to the fourth modes in the two different specimens (Figure 5 and Figure 6).

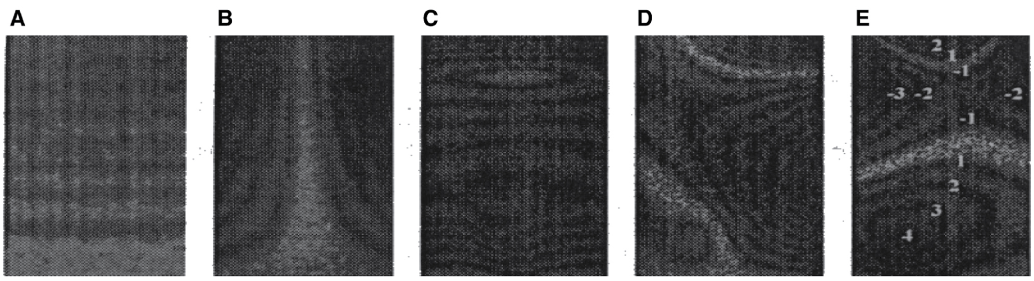

Figure 3: ESPI fringe patterns at different resonance modes (no hole specimen). (A) First mode (B) second mode (C) third mode (D) fourth mode (E) fifth mode.

Figure 4: Different resonance modes by modal analysis (no hole specimen). (A) First mode (B) second mode (C) third mode (D) fourth mode (E) fifth mode.

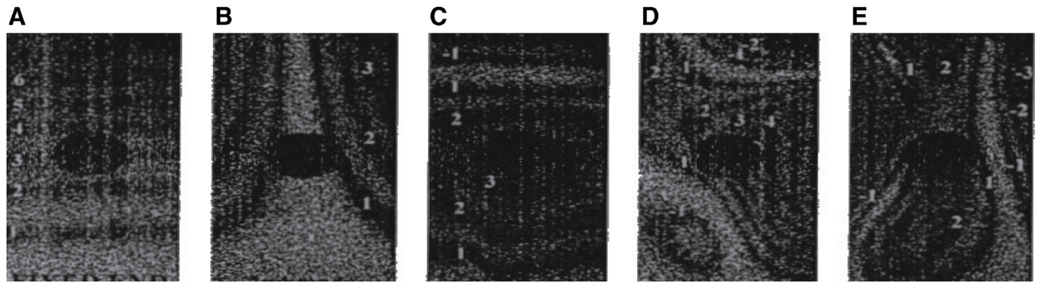

Figure 5: ESPI fringe patterns at different resonance modes (holed specimen). (A) First mode (B) second mode (C) third mode (D) fourth mode (E) fifth mode.

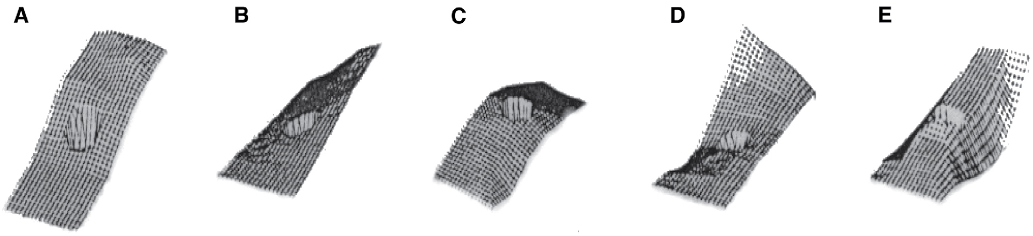

Figure 6: Different resonance modes by modal analysis (holed specimen). (A) First mode (B) second mode (C) third mode (D) fourth mode (E) fifth mode.

The fifth mode, alternatively, was influenced by the presence of the holes as observed in Figure 5E and Figure 6E. The frequency results obtained from modal testing are plotted in Figure 7 and seem to be very similar for both. Particularly, the resonance frequency is directly proportional to the square root of the stiffness and inversely proportional to the mass.

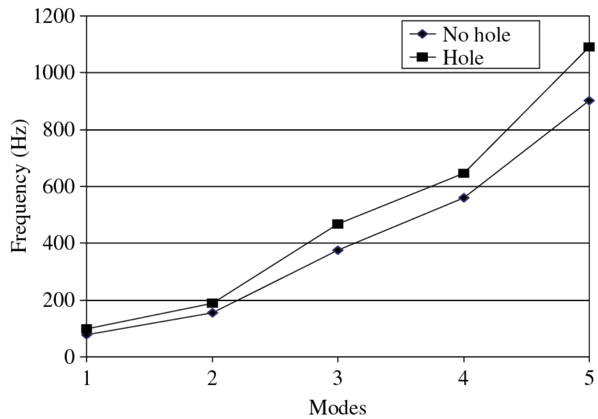

Figure 7: Frequency distribution.

In Figure 8, the TRs were measured, calculated and plotted. They represent the approximate maximum acceleration transmitted for one unit of exciting force from the exciting device to the specimen for the first to the fifth modes. The higher the transmissibility, the easier the specimen can be excited for the frequency and therefore deformed into the mode shape.

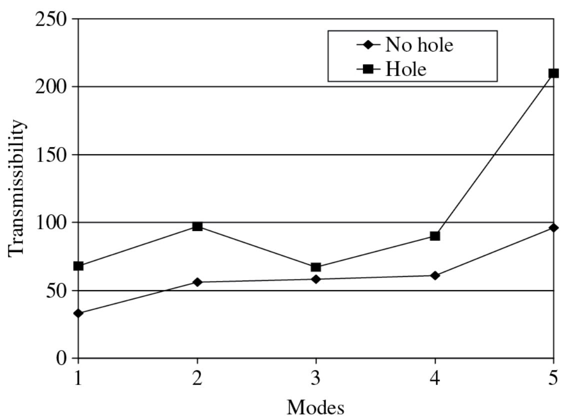

Figure 8: Transmissibility distribution.

As shown in Figure 8, the TR for every mode becomes larger for the no hole specimen (except in the third mode).

This means that the hole creates a reduction of the weight that seems to provide better behavior considering the proportions between the diameter of the hole and the size of the specimen.

6 Conclusion

From the studies of vibration problems shown above, several achievements were reached. The speckle technique showed very good visibility and resolution compared to other optical technique [9] while having a very easy setup. It also seems to be very reliable for this kind of measurement as it could be easily applicable on an already mounted structure.

Comparing the optical technique with the modal tests, the dynamic characteristics of two different specimens (hole and no hole) were analyzed.

The changes of the first four mode shapes are not significant however, changes in the fifth mode shape are.

The natural frequencies are very similar for both specimens. By analyzing the TR results, we found that the specimen weakened in anti-vibration capability in the case of the specimen without hole, showing a unique and interesting result related to the specimen and hole dimension.

Future applications will be concentrated on similar analyses considering different defects such as slots and irregular holes.

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