MODAL ANALYSIS OF PLATE STRUCTURES USING DIGITAL SPECKLE PATTERN INTERFEROMETRY

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ABSTRACT

The Digital Speckle Pattern Interferometry (DSPI) is a well suited technique for non destructive testing and non-contacting vibration measurements. Specklegrams are resulting from the interference between the light diffused by the object under laser illumination and a laser reference beam. The specklegrams are recorded by means of a CCD camera and can be stored in a frame graber using a digital image processing board. During vibration, the phase of the object is moving and so is the speckle pattern too. This phenomenon is used to detect the frequency of the vibration. The measurement of the mode shape can then be made by comparing the vibration and the steady-state specklegrams. In this paper, a phase shifting DSPI technique is applied which leads to less noisy images in comparison with classical DSPI. Experimental results obtained by the DSPI technique are compared on the case-study of a thin plate with experimental results obtained from a classical modal analysis using an impact hammer and with computational results using the finite element method. This comparison shows that the DSPI provides valuable insight for industrial applications such as the vibration analysis of turbomachinery blades.

NOMENCLATURE

a	aperture diameter of the optical system
$\{\mathbf{d}\}$	displacement vector
d_s	speckle size
E	elasticity modulus
f	focal length of the optical system
I_B	background intensity
I_M	modulation intensity
α_i	phase shift
λ	wavelength of the coherent light
ϕ	phase
$\Delta\Phi$	phase change
ρ	volumic mass

1. THE SPECKLE

When an optically rough surface is illuminated by coherent light, the grainy aspect of the surface is called the speckle. In the case of subjective speckle, an optical system is used to project the grainy surface. If we use a CCD chip to analyze the speckle pattern, the size of the speckle grain is given by (figure 1):

$$d_s \simeq \frac{\lambda\, f}{a} \tag{1}$$

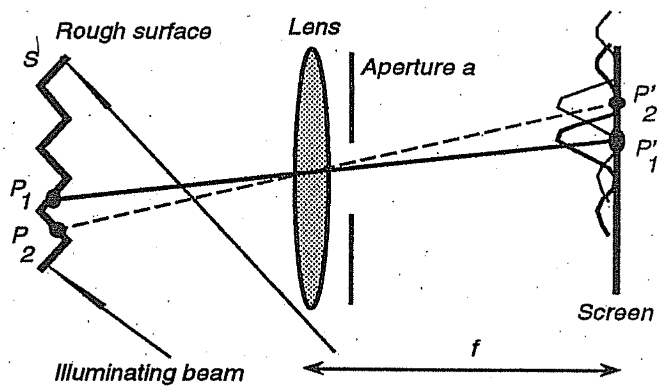

Fig. 1: Formation of subjective speckle

1.1. Speckle Interferometry

As shown in figure 2, if we add a reference beam, it is possible to record the interference pattern between the subjective speckle of the object and the reference beam. The result of the interference is called a specklegram [1]. The interferometer shown in figure 2 is out-of-plane sensitive. Any displacement $\{\mathbf{d}\}^T = \{d_x, d_y, d_z\}$ is then coded to a phase change $\Delta\Phi$:

$$\Delta\Phi = \frac{2\pi\, d_x}{\lambda}\,(1 + \cos\theta) \tag{2}$$

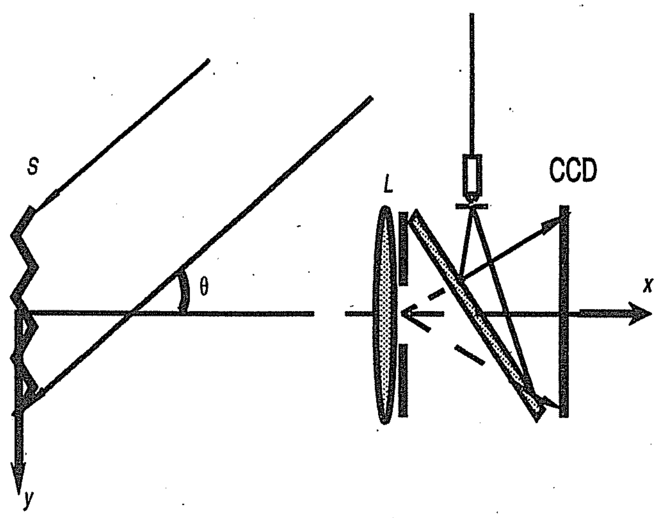

Fig. 2: Out-of-plane sensitive interferometer

The intensity of the light can be written as :

$$I(x,y) = I_B(x,y) + I_M(x,y)\ \cos(\phi(x,y) + \Delta\Phi) \quad (3)$$

where I_B and I_M are respectively the background and the modulation intensities and ϕ represents the phase.

1.2. Digital Speckle Pattern Interferometry

In DSPI, the images are seized by a CCD camera and transferred in a frame grabber using a digitizing board. The specklegrams are then compared before and after deformation using an appropriate software. It is possible to add or subtract the specklegrams but to study objects under vibration, it is very suitable to record time-averaged specklegrams. When the structure is vibrating at a much higher frequency than the CCD frame frequency, the resulting image is a superposition of the different positions of the vibration. The observed fringe pattern is very noisy because of the speckle but it is possible to increase the quality of the fringes by subtracting the image of the object in a resting state. The vibration nodes are the brightest fringes because the intensity of the fringe map is modulated by the J_0 Bessel function, resulting from the integration of the vibration along a frame time of the CCD [2-5].

Another possibility to enhance the contrast of the fringes is to use the phase shifting method [6]. In this case, a phase shift α_i is generated to calculate the phase. The resolution of equation (3) for the three unknowns I_B, I_M, ϕ needs at least the application of three phase shifts. To ensure the accuracy of the solution, the "four bucket algorithm" [6] is used to solve the system as shown in equation (4). This also allows to compute the actual value of the phase shifts.

$$I_i(x,y) = I_B(x,y) + I_M(x,y)\ \cos(\phi(x,y) + \alpha_i) \quad (i = 1, \ldots, 4) \quad (4)$$

Then, if $\alpha_1 = \frac{\pi}{2}, \alpha_2 = \pi, \alpha_3 = \frac{3\pi}{2}, \alpha_4 = 2\pi$, it follows :

$$\phi(x,y) = \tan^{-1}\left(\frac{I_1(x,y) - I_3(x,y)}{I_4(x,y) - I_2(x,y)}\right) \quad (5)$$

The phase interferogram of the vibration is subtracted from the resting state phase interferogram. The fringe pattern resulting from the subtraction is much more contrasted.

In the experimental set-up, the phase shift is generated using a calibrated piezoelectric transducer in the reference arm. The measurement range is between tenths to tens of micrometers. The accuracy is depending on the quality of the fringes and is typically about 200 nm.

2. COMPARISON OF DSPI AND HOLOGRAPHIC INTERFEROMETRY

In holographic interferometry, there are mainly three methods to study objects under vibrations : time averaged holography, real time holography and stroboscopic holography [7,8].

For the first two cases, the holographic image of the resting state object and the object under vibration are compared. The main problem of this method is that either the hologram has to be placed at the same position before and after development or it is necessary to develop the sensitive material in-situ (thermoplastics, photopolymers...) [9]. As in DSPI, it is then possible to detect in real time the mode shape vibrations when scanning the frequency of excitation.

This is not true in the case of time averaged holography where the fringes are frozen resulting of the recording of the object under stationary vibration. In this case, it is not possible to detect the mode shape but the contrast of the fringes is very good [10].

The main advantage of the DSPI system is that the CCD camera is used to produce and to analyze the fringe map whereas in holographic interferometry, it is necessary to record again the holographic interferograms with the CCD camera if an automatic analysis of the fringes is needed. Moreover, the DSPI system is less sensitive to external perturbation because of its lower resolution.

3. CORRELATION OF FINITE ELEMENT AND EXPERIMENTAL RESULTS

A practical case study was undertaken to compare experimental and finite element results. The structure used for this purpose is a thin cantilever plate with overall dimensions of $74.4 \times 50 \times 1$ mm (figure 3). The plate is made of aluminium ($E = 6.725\ 10^{10}$ N/m^2, $\rho = 2640$ kg/m^3).

3.1. DSPI Experimental Results

DSPI as an optical full view method is a non-intrusive and non-contacting technique. The DSPI experimental set-up is shown in figure 4. The plate is excited by a speaker driven with a sinusoidal wave generator. The piezoelectric transducer has been calibrated and is also computer controlled by a Digital to Analog Converter (D.A.C.). During the frequency scanning, the plate vibrates through different mode shapes. When detected, the mode can be studied using a phase shift routine.

3.2. Finite Element Model

The plate was modelled with the FE program Samcef [10] using 200 four-noded quadratic elements resulting in a total of 1265 degrees of freedom (DOFs). The degree of correlation between the FE and the DSPI results had to be improved by a better modelisation of the boundary conditions. It was found that the release of the rotational DOFs around x-axis (figure 3) at the clamping allowed a good correlation between the first ten calculated and DSPI experimental eigen-frequencies. DSPI experimental results are shown along with FE mode shapes in figure 5.

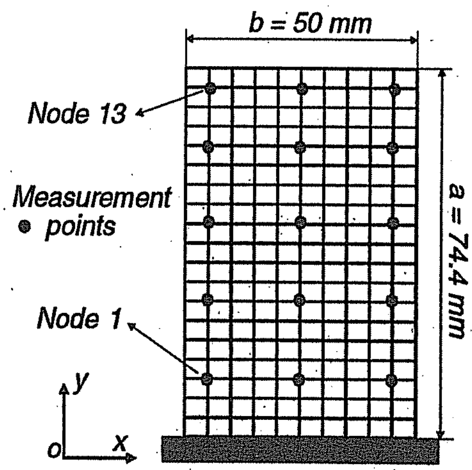

Fig. 3: FE model of the plate

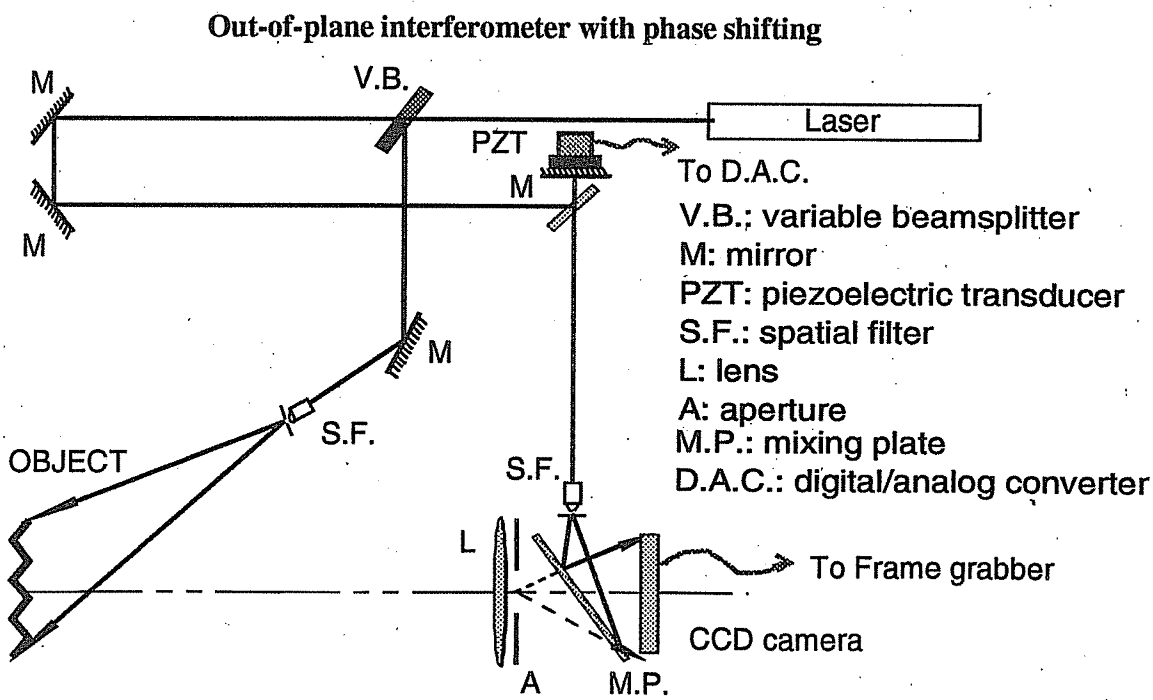

Fig. 4: DSPI measurement set-up

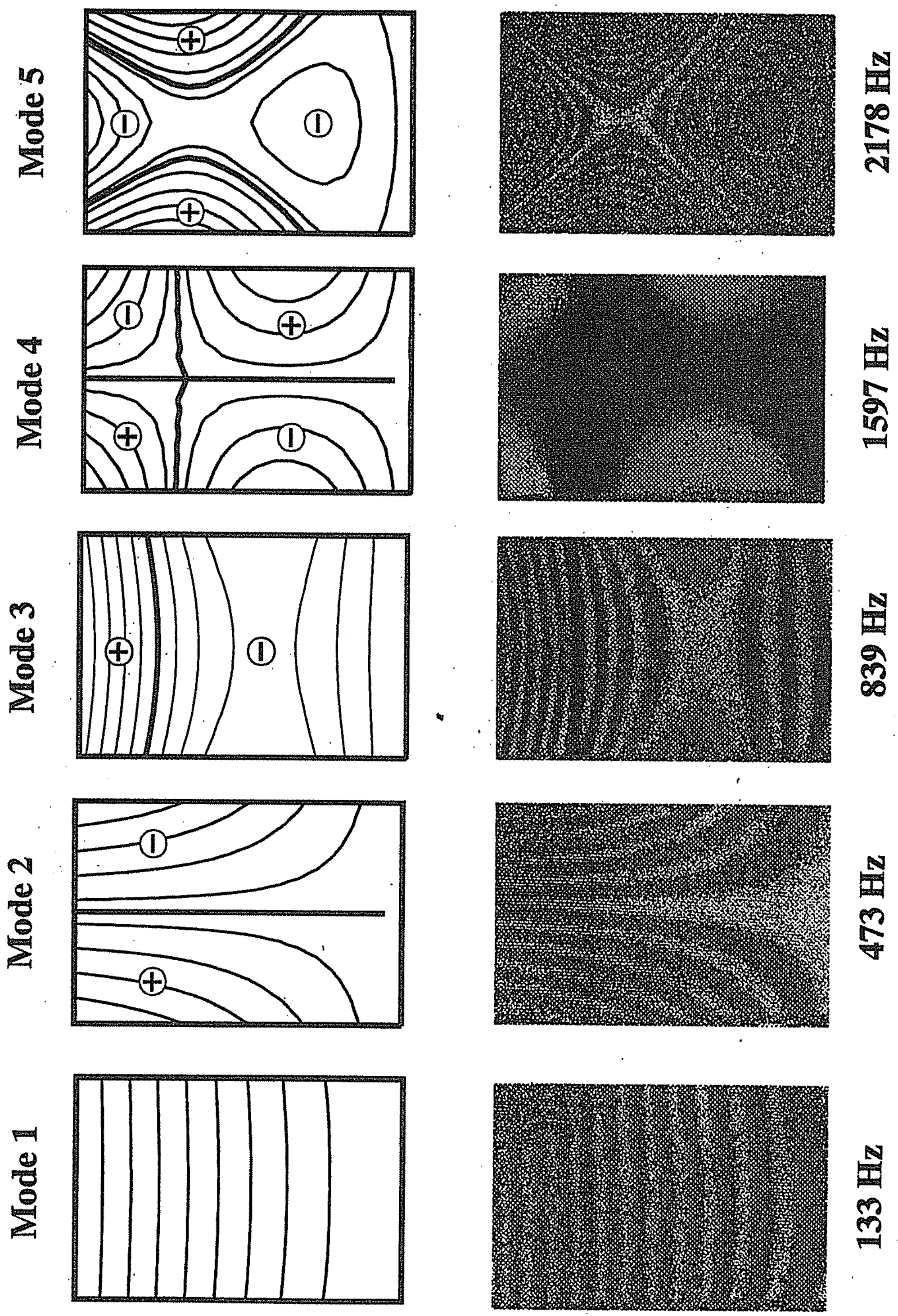

Fig. 5: Comparison of DSPI and FEM mode shapes

3.3. Impact testing

A classical modal analysis using an impact hammer was also performed on the plate as shown in figure 6. In order to limit the influence of the accelerometer mass (0.65 grams excl. cable) on the plate, the roving hammer technique was used with the fixed measurement point at node 1 (figure 6). A total of 15 response coordinates were measured on the plate. Each of the 15 Frequency Response Function (FRF) curves was measured at 2048 frequencies for a baseband frequency range of $0-2047$ Hz. An example of a measured FRF is shown in figure 7.

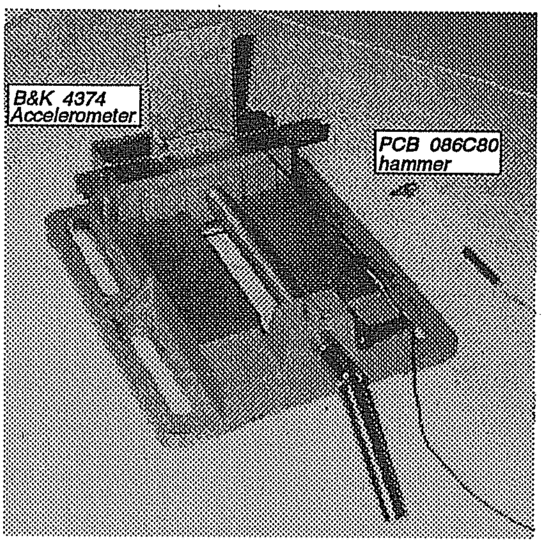

Fig. 6: Impact testing measurement set-up

A modal parameter extraction was performed using the least squares complex exponential method (L.S.C.E.) [11]. The degree of correlation between the FE and the experimental models was investigated by comparison of natural frequencies (table 1) and by visual inspection of mode shapes (figure 5).

Furthermore, the calculation of the mode shape correlation coefficient or Modal Assurance Criterion (MAC) between impact testing and FE analysis gives the following result :

$$MAC = \begin{pmatrix} 0.9876 & 0.0026 & 0.0442 & 0.0006 \\ 0.0018 & 0.9955 & 0.0000 & 0.0673 \\ 0.0122 & 0.0000 & 0.9750 & 0.0000 \\ 0.0015 & 0.0394 & 0.0000 & 0.9372 \end{pmatrix}$$

3.4. Discussion and remarks

When dealing with small structures such as compressor or turbine blades, classical experimental techniques suffer from many limitations.

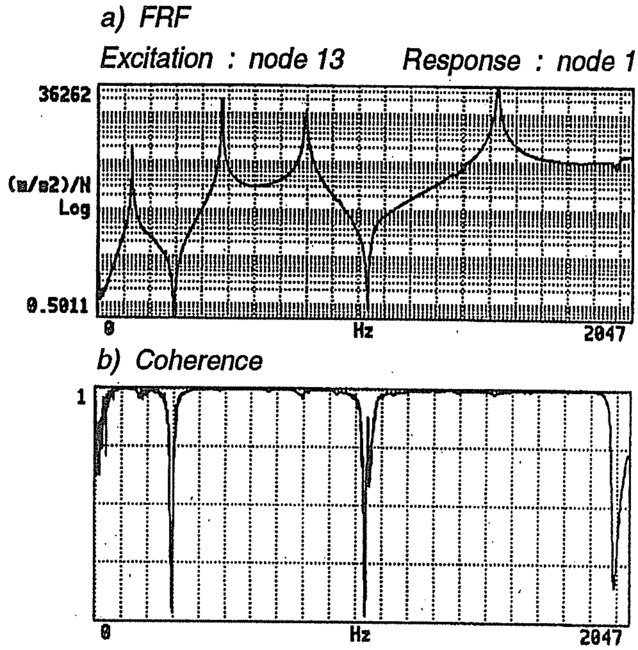

Fig. 7: Measured FRF and coherence function

Table 1 : Measured and predicted natural frequencies

Mode n^0	FE (Hz)	DSPI (Hz)	DSPI Error (%)	Impact testing (Hz)	Impact testing Error (%)
1	131.9	133	0.83	128.1	-2.88
2	473.3	473	-0.06	472.9	-0.08
3	841.2	839	-0.23	796.5	-5.31
4	1598.1	1597	-0.07	1531.2	-4.19

First, the use of an attached device such as an electrodynamic shaker or a piezoelectric exciter is not appropriate for the modal analysis of small structures as it may modify tremendously the modal properties of the structure. Also, an electrodynamic exciter is limited by its working frequency range. The impact hammer technique is a simple means of exciting the structure into vibration. However, other difficulties arise from the transient nature of vibration under which the measurements are made. Another problem derives from the difficulty to control the position of the impact and its orientation relative to the normal of the surface.

Furthermore, the use of accelerometers (or strain gages) also disturbs the dynamic behavior of the structure. In the previous case study, when the fixed hammer instead of the roving hammer technique is chosen, the plate resonances are found to be at slightly different frequencies as the measurement point is moved. This effect is all the more marked since the resonance frequency is high.

As a non-contacting measurement technique, DSPI does not suffer from the same limitations as intrusive techniques. It has a higher spatial resolution than measurement systems using piezoelectric transducers. However, it still needs the development of specific data processing in order to perform modal parameter extraction. Compared to holographic techniques, the DSPI technique is very fast.

4. CONCLUSION

The DSPI method can be recommended as a well adapted technique for the experimental modal analysis of small structures. It extends the application range of other classical techniques. Today, the most significant engineering application is probably the modal analysis of compressor and turbine blades. However, when the portability of the system and the automatic data processing will be insured, it will be able to provide valuable insight for other industrial applications in mechanical and aeronautical engineering. The DSPI method is now under development to design an automatic fringe analysis software leading to the displacement at every point of the structure. Future research will also be focused on the use of DSPI results for structural model updating.

5. REFERENCES

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