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Wavelet-based data processing for comparative study of noncontact measurement techniques for vibroacoustics

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In vibration analysis of structures complex measurement information is required in order to perform modal analysis, therefore the choice of the measurement technique to be applied is essential. Non contact measurements are preferred to classical transducer based methods, mainly due to the absence of influence upon the structure under test. The various techniques available today in vibroacoustics produce results which are quite different in terms of spatial and temporal resolution or measured quantities and therefore a choice has to be made of the experimental tool best adapted for different fields of research (acoustics, mechanical structures, dynamics). In this paper, we present a comparative study of several optical, acoustical and numerical techniques for vibration measurement or simulation, namely Digital Speckle Interferometry, Laser Doppler Vibrometry and a FE model. The tests were made for the free and the forced vibrations of a highly dumped, non-metallic plate. In the data processing stage, discrete wavelet decomposition has been applied on the experimental data in order to match up the spatial maps of vibration amplitudes.

1. Introduction

Due to their continuous development in recent years, non-contact measurements techniques have become indispensable tools in several domains of vibration related research like experimental modal analysis, non-destructive testing, or identification of dynamic material properties.

Their major advantage over classical methods is that they don't influence the vibration data since there isn't any mass attached to the structure under test. For the measurement of small amplitudes of vibration amplitudes, the most appropriate optical techniques are those based on interferometric principles.

Although there is a variety of noncontact methods available today, they are producing complementary results, different in terms of measured quantities as well as spatial or temporal resolution.

This paper presents a comparative study of the results obtained through Speckle Interferometry (SI) and Laser Doppler Vibrometry (LDV). The analysis has a main interest in establishing a confidence factor for the detected or estimated mode shapes .
The research is done in the framework of two cooperative programs involving the participation of the Photomechanics Laboratory of INSA Rouen.

One of them [1] concerned the identification, based on SI and LDV measurements, of complex-valued material parameters with strong frequency dependence. Another program [2], whose concern is the reduction of noise radiated by a vehicle, a particular phase of the project is the validation through SI measurements of the modal shapes obtained from LDV and NAH experimental results.

The rectangular plate was chosen as a simple test object, allowing to obtain a good similarity of boundary conditions during the measurements in the participant laboratories.

2. Presentation of the techniques

2.1 ESPI

Speckle interferometry (ESPI) is a noncontact technique for the measurement of displacement and vibration amplitude fields at the surface of opaque and diffusive objects. It is based on the interferometric properties of coherent light and is derived from the principles of holographic interferometry[3].

The direct results of the mesurements are digital images of the object covered by interference fringes. These parametric images need to be processed by appropriate algorithms in order to obtain a quantitative estimation of the mesurand. The measuring scale lies between 0,2 and 50 microns. In the case of vibration measurements, the method sensibility is constant over the frequency domain.

The typical setup for a out-of-plane phase-stepped speckle interferometry system (also called TV holography) is presented in Fig.1.

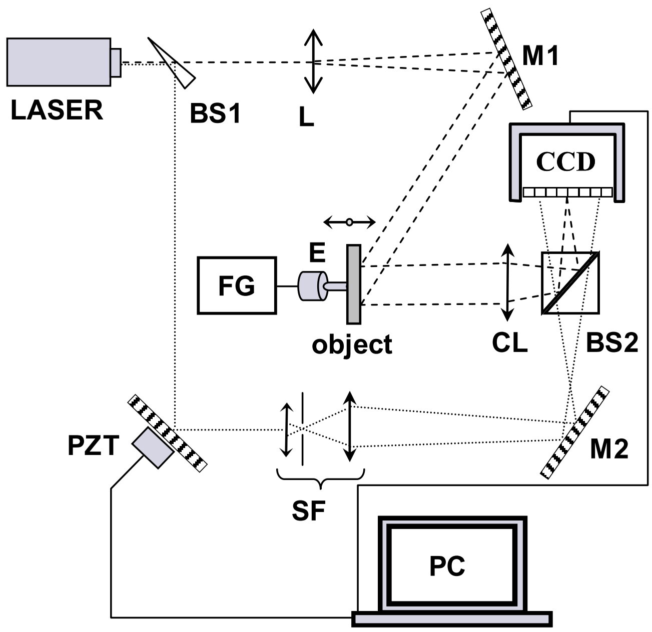

Fig.1 Phase stepped ESPI setup

In the speckle interferometry system we employed, the continuous laser beam (532 nm) is divided by beam splitter BS1 into object and reference beams. The object beam is expanded by lens L and directed onto the object surface by mirror M1. The light reflected back is imaged by the camera lens CL. The piezoelectric transducer introduces the 4 bucket phase step into the reference wave which is then expanded by spatial filter SF and redirected by mirror M2 to BS2. The two wavefronts are recombined by beamsplitter BS2 and directed onto the CCD sensor.

For each phase step, the system acquires an interferogram of intensity described by:

$$I_k = I_0\left[1 + m \cdot \cos(\varphi_{OR} + \Delta\varphi_R) \cdot J_0(\varphi_v)\right] \qquad (1)$$

where $\Delta\varphi_R = (k-1)\dfrac{\pi}{2}$, k=1,..,4 is the phase step introduced in the reference wave and $J_0(\varphi_v)$ is 0th order

Bessel function of the first kind, having as argument the optical phase induced by the object's vibration:

$$\varphi_v(x,y) = \vec{K}(x,y) \cdot \vec{A}_v(x,y) \quad (2)$$

which is the projection of the out-of-plane displacement on the sensitivity vector.

The processor calculates for each set of intensities the time average hologram, according to:

$$I_{TAV} = \sqrt{(I_3 - I_1)^2 + (I_4 - I_2)^2} \quad (3)$$

The hologram is displayed in real time on the system monitor.

The high frequency multiplicative noise due to the speckle effect can be removed by applying the algorithm described in [4].

The main inconvenient of speckle interferometry consists in a weak temporal resolution of the interferograms when compared to LDV or NAH. The results obtained from the 3 approaches complete each other, the temporal resolution of LDV and NAH allow access to the vibration phase, while the high spatial resolution of speckle interferometry allows the observation of local phenomena.

2.2 Laser Doppler vibrometry

The basic setup of a Laser Doppler Vibrometry (LDV) system is presented in Fig.2. It's based on a pointwise interferometer, with an acousto-optic modulator (usually a Bragg cell) in one of its arms. The control unit uses the output signal of the detector to compute the amplitude and the phase with respect to a chosen reference (usually the applied force) of the vibration velocity at the point of measurement.

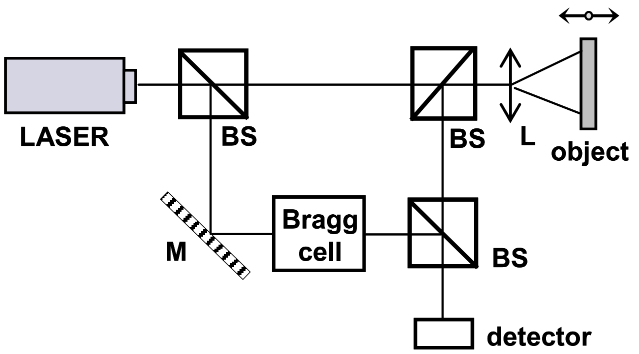

Fig.2 LDV setup

In LDV measurements, the excitation may be achieved either harmonically, by applying a sinusoidal force of adjustable frequency, or with an instrumented impact hammer – free vibration [5].

The intensity detected by the CCD sensor is

$$I(t) \propto 1 + \cos[2\pi(f_B - f_D)t] \quad (4)$$

where f_B is the frequency modulation introduced by the Bragg cell and f_D is the Doppler frequency shift, containing the information on the surface velocity at the measurement point:

$$f_D = \frac{2\text{v}}{\lambda} \quad (5)$$

LDV is basically a single point measurement instrument, but with several improvements, the system can explore successively a limited number of object points (scanning LDV). The measurement data for the different points can be presented as surfaces or color coded maps of velocity amplitudes and phases.

The software associated to the control unit may also use the time histories recorded for a set of different points on the object with impact excitation and compute an estimated modal basis.

Obtaining the vibration parameters for a vibrating point is an interesting advantage over full-field techniques like SI, but the estimated velocity amplitude map has a sensibly lower resolution.

Moreover it must be noted that the estimation of the amplitude map is less direct than direct measurements of time-average SI, that is why the computed modes should be validated by direct SI measurements.

3. Experimental setup

The tests were performed for the free vibration of rectangular plates. For the parameter identification experiments we used a sandwitch aluminium plate of 150 x 100 x 5.1 mm composed of 3 layers:

- aluminium layer 5 mm
- viscoelastic material (ISD112) 0.1 mm
- aluminium layer 0.3 mm

For the second project, a dural plate sized 450 x 350 x 5 mm served as test specimen.

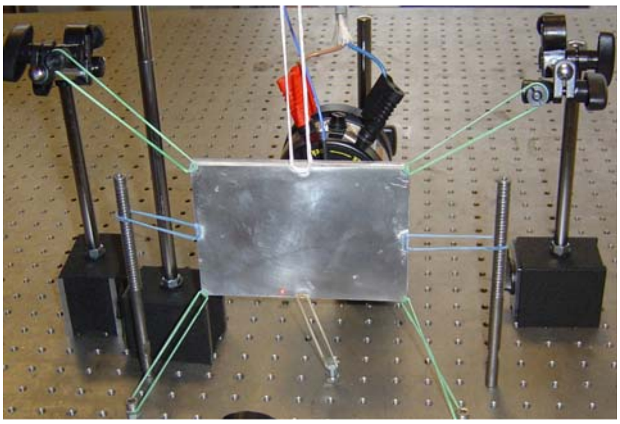

Fig.3 Test setup for the sandwich aluminium plate

In order to obtain free vibration, elastic strings were used, as shown in Fig.3.

3.1 Experimental data

For the pointwise excitation we used a signal generator which applied a sinusoidal voltage with controllable amplitude and frequency by means of a piezoelectric actuator.

The fringe patterns thus obtained containing the image of the vibrating surface were processed by an algorithm similar to phase unwrapping, which allows obtaining vibration amplitude maps like those presented in Fig.4(b).

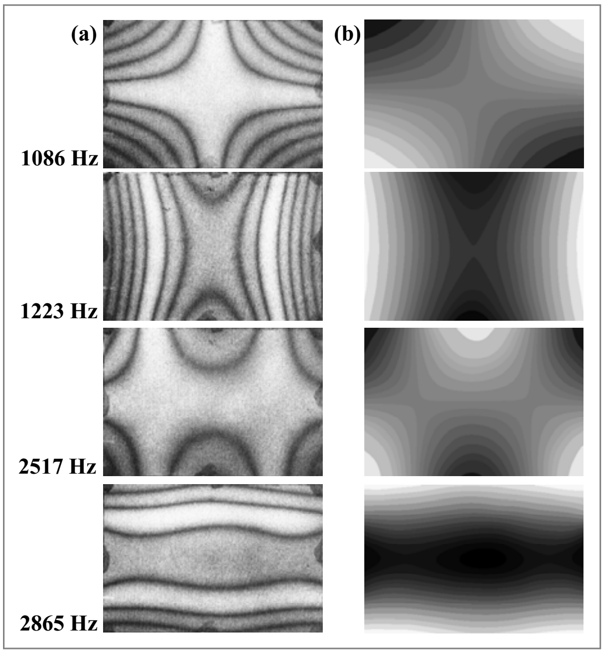

Fig.4 ESPI results: (a) fringe patterns; (b) amplitude maps

The LDV results are obtained from pointwise measurements. The experimentally obtained frequency response functions (FRF) allow selecting the amplitude and phase in the frequency range 100-3200 Hz with a step of 2 Hz.

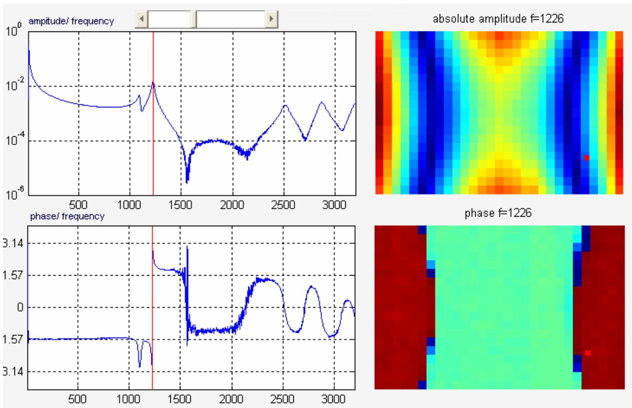

Fig.5 LDV results

The frequencies for which the velocity map and the phase map are computed from the FRF data have to satisfy the following conditions: a local maxima in the mean absolute value of the velocity amplitude map (this indicates a local resonance) and a maximum standard deviation of the phase distribution, (indicating uni-modal behavior).

In these cases, LDV velocity maps are theoretically proportional to the displacement amplitude fields provided by SI measurements.

4. Comparison

The comparison aims at quantifying the similarity of the velocity maps generated from LDV or NAH measurement data. The field of excellence for these techniques being other than to provide full field information on the measured vibration, we need to be able to estimate the accuracy of the estimated maps.

The investigated techniques yield results which are quite different in terms of measured quantities, temporal and spatial resolution. The main difficulty is that the data fields we intend to compare represent various parameters of the free vibration of a rectangular plate: time-average speckle interferometry with harmonic excitation provides vibration amplitude maps and measured frequencies, while Doppler vibrometry with shock excitation yields complex FRF from which we can estimate the velocity maps, for a sampled frequency domain and a limited number of measured points. Therefore a direct quantitative comparison isn't possible.

For the comparison we retained the most representative modes, that is those where we had a good visual similarity between the SI vibration amplitude maps and the LDV velocity maps.

In a preliminary phase of data processing, the amplitude and velocity fields were brought to the same size. In order to avoid interpolation of data, we chose to align all the amplitude maps to the smallest size, which is, for both cases, the LDV data. To this purpose, SI results were resampled by applying a wavelet decomposition. The coefficients corresponding to the scale of interest were retained for the reconstruction and the obtained amplitude maps were used for the comparison.

In order to insure the compatibility between the data fields, the values were normalized for the interval [-1;+1] and wherever it was necessary an inversion of sign was applied.

The comparison was performed by applying several general criteria and case specific criteria. First, the detected frequencies were investigated, using the relative average error criterion:

$$e_{rms} = \frac{1}{N}\sqrt{\sum_{k=1}^{N}\left(\frac{f_{1k}-f_{2k}}{f_{1k}}\right)^2} \qquad (6)$$

The criteria employed were adapted from modal analysis, where they're standard tools for comparison of the mode shapes obtained from different numerical models or from numerical and experimental tests.

The modal assurance criterion is a global comparison tool, described by eq. (7):

$$MAC_{kl} = \frac{(A_k \cdot B_l)^2}{A_k^{\,2} \cdot B_l^{\,2}} \qquad (7)$$

It is basically a correlation operator for two spatially scaled and range normalized amplitude maps [6].

When applied over two series of mode shapes, it delivers a matrix that quantifies the agreement between the elements. In a favorable case, MAC takes values close to 1 if applied to matching modes and tends to 0 for different orders.

The coordinate modal assurance criterion (COMAC) was applied in order to obtain a local comparison between the distribution fields:

$$CoMAC(i,j) = \frac{\left[\sum_k \left(\left|a_k(i,j)\cdot b_k(i,j)\right|\right)\right]^2}{\left[\sum_k \left(a_k^{\,2}(i,j)\right)\right]\cdot\left[\sum_k \left(b_k^{\,2}(i,j)\right)\right]} \qquad (8)$$

This criterion performs a cumulative comparison over the matched mode shape pairs able to detect eventual regions of systematic poor correlation [7], as exemplified in Fig.6 where a strong disagreement between the compared data can be observed on the boards of the plate.

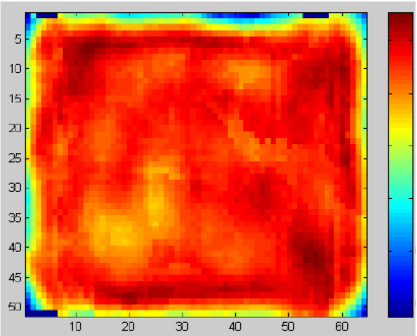

Fig.6 ECOMaC criterion

The data processing was run under Matlab programming environment; Fig.7 presents one of the graphical interfaces developped for this work.

The comparison was performed for SI and LDV results; the rms error between the SI and LDV frequencies is 23 Hz. The correlation-based criteria for SI and LDV data yielded satisfying values. The MAC elements on the principal diagonal are between 0.61 and 0.98, with an average value 0.89. The non-diagonal elements keep below 0.25. The lowest values in the CoMAC distribution are found in regions of the plate close to the nodal lines.

5. Conclusion

In this paper we presented a comparative study of the experimental results obtained from different non contact techniques for the case of a vibrating rectangular plate.

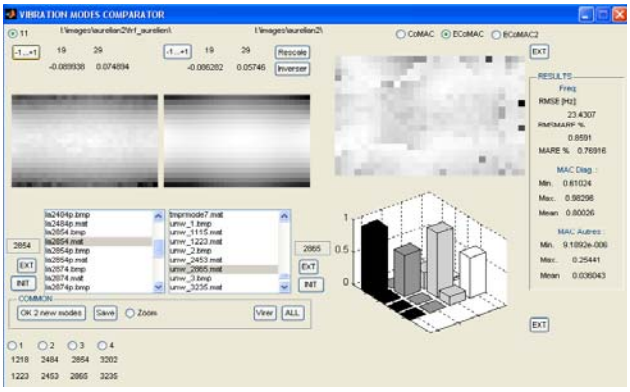

Fig.7 Comparison interface for SI and LDV data

The comparison is mostly concerned with the data fields directly obtained or computed from the measurement results.

Due to the net advantages of the technique in terms of spatial resolution, an enhanced factor of confidence is attributed to speckle interferometry amplitude maps.

In the pre-processing stage, the interferometric amplitude fields are rescaled by means of a wavelet transform in order to avoid interpolation of LDV data. Comparison is performed by applying amplitude based correlation criteria derived from modal analysis wih an overall good agreement between the compared data.

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