EAN 2018
56th conference on experimental stress analysis

Application of Laser Shearography to Vibration Mode Shape Analysis of Composite Panel during Acoustic Load

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Keywords: Laser shearography, modal analysis, acoustic loading, acoustic fatigue.

Abstract. Acoustic fatigue is important topic of durability in aerospace. Progressive wave tunnel was built to carry out the tests of acoustic fatigue properties of flat composite panels. Vibrations were induced by sound wave. The mode shapes of the vibrations of panel were measured by laser shearography in a form of shearograms – fringe patterns of the out-of-plane surface displacement gradients. Finite-element modal analysis of the panel was performed. FE based displacement gradients were compared with shearograms. Excited vibration mode shapes can be qualitatively estimated on the basis of these comparisons. Few suggestions to enhance both the resolution of shearograms and FE analysis were made.

Introduction

Experience in aircraft industry has shown that the wide band high intensity noise pollution produced by jet exhaust, propellers etc. can cause structural fatigue failure in regions close to the source of the noise [1]. Even though no catastrophic failure of an airplane has occurred due to the acoustic fatigue yet, nevertheless, the economic importance of this topic is not inconsiderable. The major expenses caused by acoustic fatigue are spent on maintenance, inspection and loss of aircraft use. Designing against acoustic fatigue is therefore the key process to prolong the intervals of inspection and thus to lower operational costs.

An air inlet duct of a jet engine is a typical example of the part of an aircraft which is exposed to high intensity sound loading. Development of modernized version of the air inlet is one of main goals in project *TE02000032* (*Advanced Aerostructures Research Centre project*) of the Technology Agency of the Czech Republic. In this case, composite material is proposed to be used as a replacement of aluminum alloy, partly for the reason of low fatigue endurance of aluminum alloy. Testing of material properties, with special focus on the high frequency fatigue behavior, is therefore needed to be carried out. For this purpose, acoustic fatigue testing device, called progressive wave tunnel (PWT), was designed, optimized and constructed [2, 3].

Vibrations of a flat panel clamped on the edges are induced by progressive sound wave. The mode shapes of the vibrations of the panel determine the locations of the stress peaks, where fatigue damage is prone to occur. The displacement field of vibrations of the panel is thus desired to be measured. A potential indirect technique for the mode shape measurement is laser shearography [4, 5] with the alternatives such as the field of accelerometers or digital image correlation techniques.

Theoretical background

Acoustic fatigue is basically fatigue damage caused by the vibrational response of the structure subjected to high intensity noise. The acoustic loading is generally not very effective in inducing high amplitude of displacements or stresses in structures. The combination of very low stress amplitudes and high frequencies of vibrations is practically harmless for the duration of service life of the majority of structures thanks to the nature of S-N curve for high-cycle fatigue. The exceptions are the structures exposed to extreme sound level, such as aircraft, rocket or space shuttle, and structures such as pipeline systems, with natural frequencies close to the exciting sound frequencies. In these cases, the vibration frequency is high enough to cause fatigue damage in not negligible amount of service time.

The laboratory testing of materials is focused on three topics –vibration response of the structure subjected to acoustic loading, acoustic fatigue life and fatigue damage propagation under acoustic loading. The latter is very important in damage tolerant philosophy, for prediction of fatigue crack propagation [6].

Laser shearography is a full-field optical inspection system that uses interference of monochromatic laser light for detection of slight surface deformation due to subsurface discontinuities. It is an active non-destructive method, which measures the response of a material to an applied stress [7]. Detectable surface displacements are in the order of nanometers. Conventional application of laser shearography is the visualization of change of structural stiffness, such as disbond, delamination or change in structure. Examples of these applications are in Ref. [8, 9].

Phase stepping laser shearography works with the Michelson cube for laser interference. The specimen is illuminated with two laser beams, with focal points laterally shifted by the length of a shear vector. The process commonly consists of 4 steps, when the interfering light waves are shifted against each other by a known phase of $\frac{\pi}{2}$. The intensity $I(x,y)$ of reflected light is measured on CCD for each step:

$$I_i = I'(x,y) + I''(x,y) \cdot \cos\left[\phi(x,y) + \frac{\pi}{2} \cdot (i-1)\right], \tag{1}$$

where I', I'' are the distributions of light intensity of the two lasers, ϕ is a distribution of phase value. The phase value is calculated as

$$\phi(x,y) = \tan^{-1}\left(\frac{I_4 - I_2}{I_1 - I_3}\right). \tag{2}$$

Then, the material is stressed, and the steps are repeated, with the phase value post stress denoted as ϕ'. Relative phase difference of the pre-stressed state and post stress state is calculated as

$$\Delta = \phi - \phi'. \tag{3}$$

The relative phase difference represents the relative change of the out-of-plane displacement δw in the direction of shear vector. The out-of-plane gradients of displacement $\frac{\delta w}{\delta x}$ and $\frac{\delta w}{\delta y}$ can be measured by choosing the perpendicular orientations of shear vector for two consecutive measurements

Deformations of plate. Let us define the rectangular coordinate system with axis x and y in the plane of the panel and the z axis in the out-of-plane direction. The displacement components are denoted as u, v, w respectively. For simplicity, the deformation state of the tested panel can be described using Kirchhoff-Love theory of thin shells [10]. Its postulates are the negligibility of normal stresses σ_z, conservation of the thickness of the plate during a deformation, conservation of the straightness and normalness of the straight lines normal to the mid-surface after the deformation. [11]. As a consequence, the displacements of the mid-plane of the panel are zero in the xy plane, $u = v = 0$. The rotations of the deformed mid-plane are

$$\omega_x = \frac{\partial w}{\partial x}, \quad \omega_y = \frac{\partial w}{\partial y}. \tag{4}$$

Experimental setup

Device setup. The PWT device is composed of a pair of loudspeakers TVM ARA-389-00/8 with a preamplifier Dynacord S1200, transition parts, a rectangular tunnel of wooden fiberboard and a controlling PC. The tested panel is clamped on a hole on the side of the tunnel. The basic instrumentation consists of two microphones located in the tunnel and an accelerometer mounted by an adhesive wax to the center of the panel. PWT device is shown in Fig. 1

Fig. 1 Progressive wave tunnel (PWT) device

Test specimen. A flat octagonal shaped composite panel (729×729 mm) was designed with lay-up orientation of $[45/-45/0/45]_s$ and with an artificial defect. Thickness of the panel is 1,8 mm. The interlaminar defect was created by inserting a circle foil (D = 200 mm) between the middle layers at the center of the panel. The panel was manufactured in Aero Vodochody Aerospace company using Hexply 8552/AGP193-PW prepreg. The octagonal shape and the dimensions of the panel are derived from the optimization of a testing stand for high velocity impact testing [12]. The final shape of boundary of the panel is a compromise between the symmetry of circular-shape and the enforcement of prescribed clamping boundary condition of a rectangular shape. The choice of the same shape and size of specimen is driven by later possibility of acoustic fatigue testing of impact-damaged specimen.

Experimental procedures. Odd natural frequencies were estimated from the power spectral density of the response of the center of the panel to the white noise signal loading. Dantec Q-800 laser shearography system was used to measure the gradients of deformation on the estimated frequencies. The panel was illuminated by two dispersed laser beams with horizontal shear vector and excited by the sound of a chosen frequency. Horizontal gradient of panel deformations was derived from the phase difference of the reflected and interfered laser signals in the CCD sensor. The vertical gradients were obtained analogically by setting the shear vector to the vertical direction.

Numerical simulation

Finite element (FE) simulations were performed using the NX Nastran software package. The composite panel was modelled using 2D orthotropic material properties and composite lay-up with plies orientation defined by the production drawing. Literary values [13] were used as material properties. Two variants of the panel were modelled, one with the artificial defect and the other without defect. The meshes are shown in Fig. 2 and Fig. 3. The defect was modelled by two separate layers using only half of the lay-up. Both layers had the thickness of 0,9 mm (half of the thickness of intact panel). These layers were connected to the rest of the panel on circular boundary of modelled defect. Natural frequencies and mode shapes has been extracted from the Normal Modes/Eigenvalue Analysis (SOL103) using Lanczos method with the limitation to the first 60 eigenvalues.

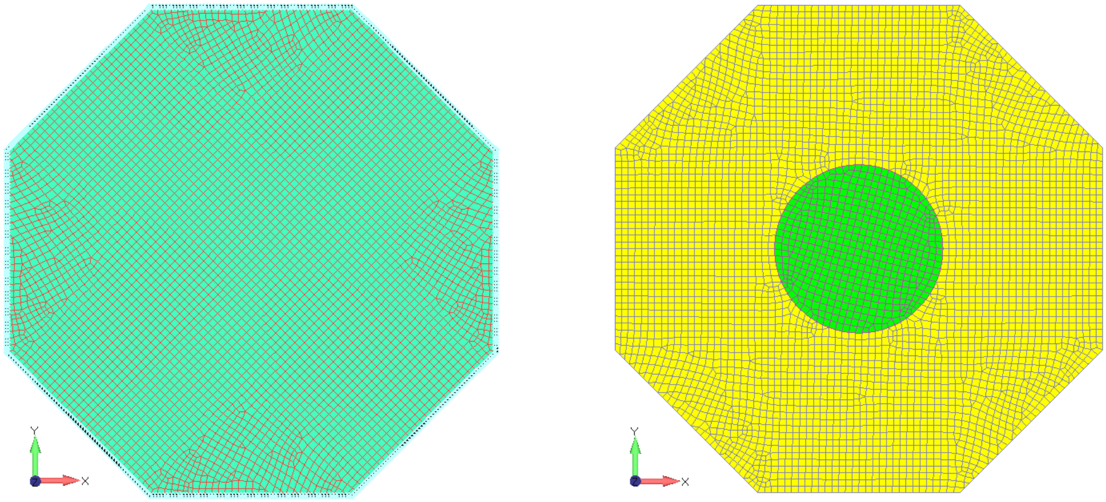

Fig. 2 Variants of the meshes of the panel. a) Panel without artificial defect. b) Panel with artificial defect. The area with defect is marked by green color.

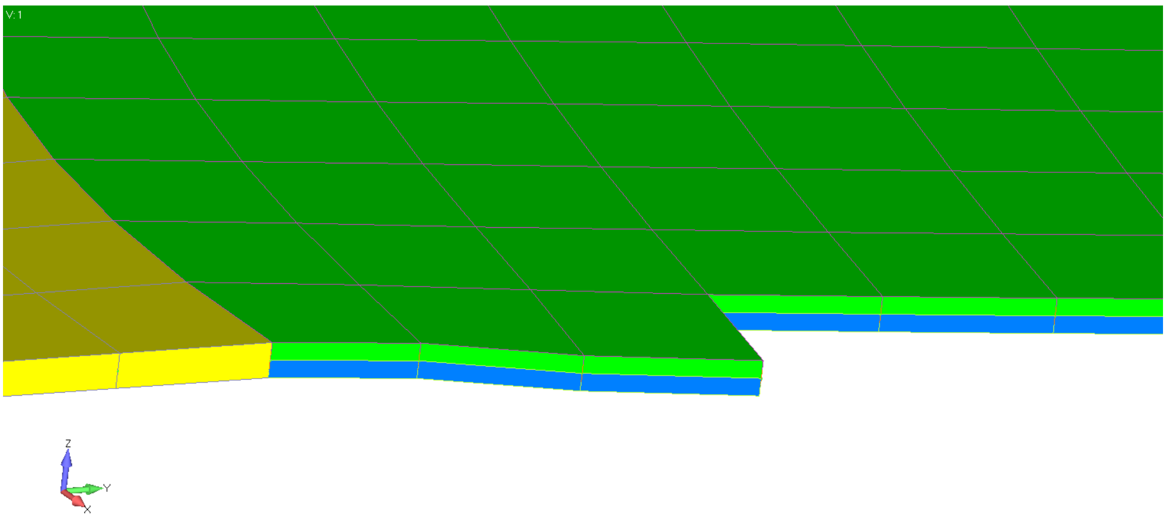

Fig. 3 Detail of the meshes of the defected panel at the edge of artificial delamination. Green and blue layers are separated

Results. As stated in the theoretical background, laser shearograms depict the gradient of out-of-plane displacement. Kirchhoff-Love theory of thin shells states, that these gradients can be easily obtained as the components of the rotation output vector from FE simulation. NX Nastran uses more sophisticated Reissner-Mindlin formulation of shell elements [14], however the differences of results of both theories are negligible for thin shells, so the assumption of the Kirchhoff-Love theory may be considered as accurate enough.

As a result, the shearograms can be directly compared with the corresponding Rotation output value of NX Nastran. The limitation of this comparison is its purely qualitative interpretation. The field of displacements cannot be determined by this method.

Horizontal and vertical gradients of deformation from the laser shearography and from FE simulation were compared. Few examples of the comparison are in Fig. 4, Fig. 5 and Fig. 6.

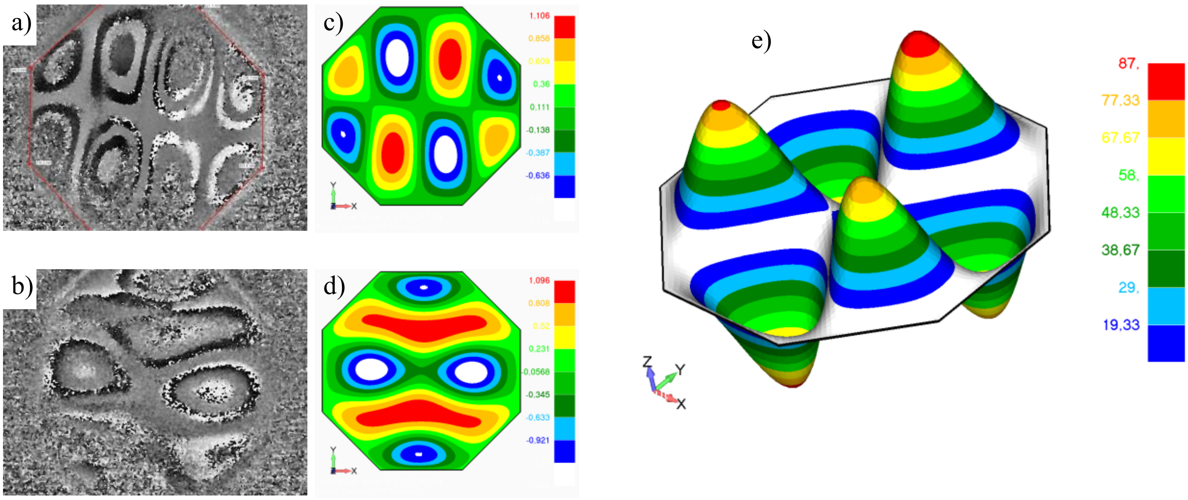

Fig. 4 Comparison of the gradients of deformation determined from laser shearography: a) shearogram –shear in *x*-axis direction, b) shearogram – shear in *y*-axis direction, both for exciting frequency 184 Hz, c) FE simulation – output vector Rotation R2, d) FE simulation – output vector Rotation R1 and e) the mode shape from FE simulation, mapped with output vector Total Translation, FE simulation output is for eigenfrequency 273 Hz.

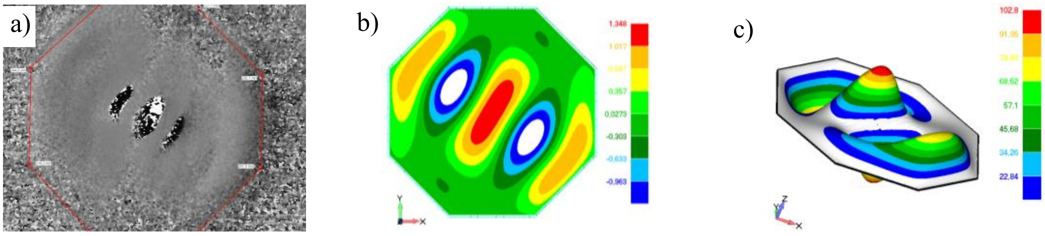

Fig. 5 Comparison of the gradients of deformation determined from laser shearography: a) shearogram – shear in *x*-axis direction for exciting frequency 500 Hz, b) FE simulation – output vector Rotation R2, c) the mode shape from FE simulation, mapped with output vector Total Translation, FE simulation output is for eigenfrequency 329 Hz.

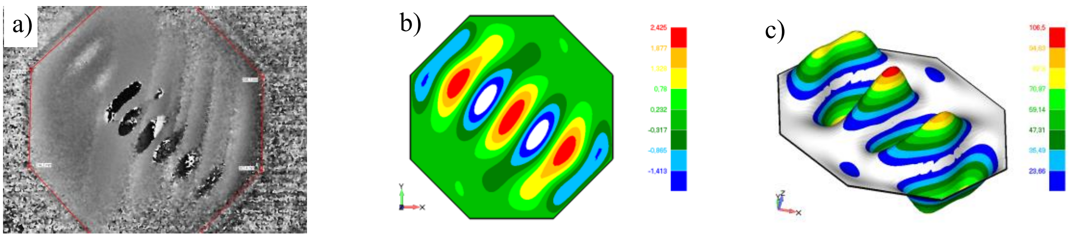

Fig. 6 Comparison of the gradients of deformation determined from laser shearography: a) shearogram –shear in *x*-axis for frequency 967 Hz, b) FE simulation – output vector Rotation R2, c) the mode shape from FE simulation, mapped with output vector Total Translation, FE simulation output is for eigenfrequency 650 Hz.

Discussion. The similarity between the experimental and numerical deformation gradient, represented by shearograms and FE Rotation output components is very good. Better similarity of the gradients of deformation was achieved using the model of undamaged panel. This may be a sign, that the adhesive forces of the separated surfaces might be strong enough to restrain from the total separation of these surfaces. Another but non-exclusive explanation of indicated phenomenon is that the mass forces of the oscillating plate are lower than the atmospheric pressure, which prevents from the separation and dilatation of the unbonded surfaces. However, the excited vibrations had to be very small because of the effective range of measuring technique and thus this result cannot be generalized. It is assumed that with rising amplitude of vibrations both the adhesive forces and the atmospheric pressure will be exceeded and different vibration modes may appear.

This method can be used to the qualitative determination of the mode shape, however with limitation to the cases, when linear behavior is expected. The accuracy of FE simulation is also limited, mainly due to the lack of experimental supporting data of the material properties of the panel. For example, the stiffness of the composite was described by external literary values [13], which may significantly differ from the properties of the tested specimen. There is a clear mismatch between the numerical eigenfrequencies and experimental exciting frequencies of matching shapes. Apart from the possible inaccuracy of stiffness description, numerical eigenfrequencies can be significantly affected by the boundary conditions. For example, the edges of the panel might have been not ideally clamped. Alternatively, the vibration mode shapes on Fig. 5 and Fig. 6 may have been excited by overtones of basal natural frequencies. Consequently, the differences between numerical estimation of frequency and experimental observation would lower to more acceptable range. FE frequency response analysis of the panel should yield more accurate results.

The absolute range of the displacements is needed to be determined by a different technique. Another drawback is the level of noise in the gradients of deformation from shearography, which can be effectively lowered by the use of shearographic system with more laser beams.

Conclusions

Experimentally measured shearograms can be compared with the components of Rotation output vector of the FE modal analysis. The quality of the interpretation is effectively limited to the scope of measuring displacement range of laser shearography. Other limitation factors of this approach are given by the level of noise in shearograms and by the accuracy of supporting data of FE simulation. Better results could be obtained using more advanced shearographic system, with more laser beams and higher imaging resolution and lesser influence of the noise. On the other hand, the reliability of the FE simulation could be improved by the use of experimentally measured material properties. FE based frequency response analysis of the panel is also desired to be studied.

Acknowledgement

This work was supported by the Technology Agency of the Czech Republic (TA ČR) TE02000032 / Advanced Aerostructures Research Centre project.

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