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DYNAMIC RESPONSES OF PLATE AND SHELL STRUCTURES STUDIED BY NONDESTRUCTIVE TESTING METHODS

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Abstract. *The advanced non-destructive testing of shell structures is conditioned to characterisation of guided waves propagating in a thin-wall solid. It is very important from this point of view to know the response of these elements on different type of a loading. Therefore the new powerful diagnostic methods are continuously developed.*

Stress waves were generated by focusing the pulse laser beam or by means of the exploding wire. The full-field visualisation of the displacements caused by generated mechanical waves was carried out by double-pulse holointerferometry (DPHI) with a ruby laser as a source of light.

The time history of the ultrasonic waves in different points on the shell surface was studied by the pair of miniature piezoelectric transducers.

The aim of the paper is to contribute to non-destructive structural monitoring of the thin shell components..

Key words: Stress wave propagation; thin-wall structures; double-pulse holointerferometry; laservibrometry; finite element method; impact generation; guided waves; non-destructive testing.

1. Introduction

Thin-walled structures, in particular, of plate and shell structures are widely used in various fields of engineering (chemical, nuclear power plants, aircraft, launch vehicles etc.). Structural health monitoring of shell components represents set of diagnostic approaches and therefore a new non-destructive testing methods are developed. Their correct interpretation contributes to study a preservation of safe long-time service life without failure or fracture.

While the stress wave propagation laws are reliably determined only for simple geometry bodies e.g. for thin disks, plates, bars, walls etc. [1], for bodies with more complicated geometry e.g. for cylindrical shells the laws have not been determined reliably up to this time [2]. It is necessary to combine various experimental and numerical methods to achieve new results. Our attention in this paper will be focused on using optical methods, numerical finite element method (FEM) and acoustic emission (AE) method to investigate transient wave phenomena in plates and shells.

For our purposes suitable optical methods are Double Pulse HoloInterfeometry (DPHI) and laserinterferometry. Both are non-contact, the first one offers full-field of view on the object under consideration, the second is pointwise measuring method. DPHI enable us to record and to study transient phenomena e.g. stress wave propagation in solids [3], [4].

Holointerferograms - the results of DPHI - seem to be, at first sight, an ideal way to depict the deformations they measured. Their conversion into numerical data, however, is not an easy task. The main problem consists in interpretation of the interference fringes mainly in the case of curved surfaces [5].

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The other problem is that the usual sensitivity DPHI with ruby laser as a source of light is *only* 174 nm. This was the reason for our activity to combine the full-field holography information with pointwise quantitative measurements by piezoelectric transducers (PZT). It allows to obtain information about wave propagation in shells (plates) and gives data for easy evaluation of wave velocities and geometrical dispersion.

Generally it is possible to say that a successful research of stress wave propagation in solids is conditioned by the optimal impact generation. We used for our purposes two different type of impact loading by a focused ruby laser beam or by special elements with exploding wires.

Various physical processes may take place when a solid surface is exposed by a focused laser beam [6]. The very located heating shock caused a thermal expansion which generates thermoelastic stresses. At higher powers, material may be ablated from surface and a plasma formed, while in the sample local damage may be formed. It is possible to generate all types of surface and guided wave by the focused pulse laser beam but in thin plates and shells Lamb waves dominate [7].

The second type of the loading - by exploding wires – enables us both a normal impact and an oblique impact generation on the plate (shell) under investigation. These experiments used discharging capacitors to explode the wires. Discharging a capacitor through a very small wire placed in a small hole of a loading sample is an "easy" way to make a very intensive mechanical impact [8].

2. Experiments and procedures

Double pulse ruby laser was used simultaneously as a source of light for holointerferometry and as a source of guided waves. Two cylindrical shells with diameter 112mm and 200mm, length 300 mm and average thickness 0.635 mm made of carbon steel were studied. The examined shells were slightly opened to enable us focusing a part of ruby laser beam on its inner surface. The optical setup for holography record of the loaded shell is shown in Fig.1.

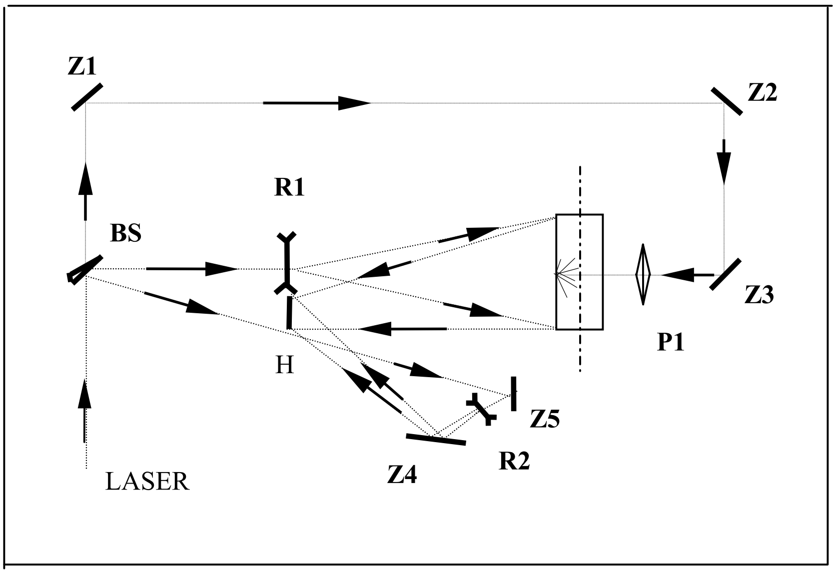


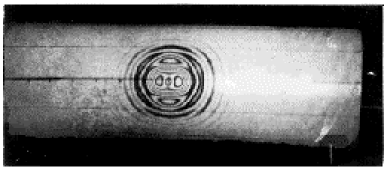
Fig.1

The laser beam is splited by the beam splitter BS to three beams. The main beam is, after reflection from the mirrors Z1, Z2, Z3, focused by the lens P1 on the inner surface of the shell. This beam caused a short mechanical and thermal impact on the shell surface. The second beam becomes divergent by passing through the negative lens R1 after reflection from the first surface of the beam splitter. This is the object beam. The third beam is the reference beam reaching hologram H after reflection on the rear inner face of the beam splitter BS via two mirrors Z4, Z5. This optical arrangement was designed both to study the outer surface deformations of the cylindrical shell and to evaluate the deformation of the nearest geneatrix located on the shell to the hologram.

The shell is loaded by focused ruby laser beam almost simultaneously with the record of its undeformad state. The second ruby laser pulse is deliberately delayed with respect to the first one between 1μs – 800μs. It is possible to record a set of interferograms by this way. The hologram reconstruction was carried out by using of a He-Ne laser. The recorded fringes are interpreted as iso-amplitude lines of radial displacement of the shell. Two consecutive fringes have a difference in amplitude of $\lambda/2$ where $\lambda = 0.6943\mu m$ is the ruby laser wavelength.

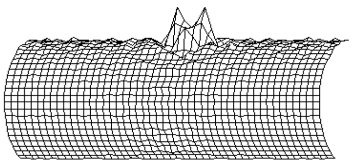
The interferogram of the „forzen“ propagating guided waves 30µs after impact in the shell with diameter 112mm is shown in Fig.2a. The Fig.2b shows the result of finite-element simulation of the impacted shell in the same time [10]. The interferogram of the shell with diameter 200mm is shown in Fig.3. It was recorded in the same time after laser beam impact like previus interferogram. Comparing by the different curvature.

A sound wave generated by interaction of focused ruby laser beam with inner surface of the investigated shell is seen in Fig.4. The *half sphere* of this sound wave was recorded 70µs after the impact. The changes in the optical path length were caused by the changes in the refraction index between two exposures of hologram. It is possible to observe the guided wave visualised by the fringes on the inner shell surface as well. The interaction of mechanical and sound waves exists only for very short time after impact owning to the difference of wave velocities in steel and air.



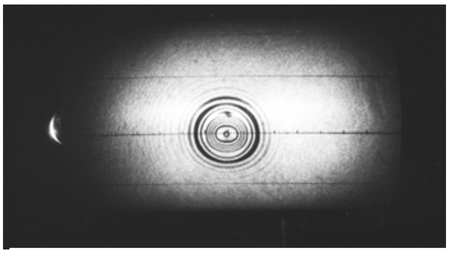
30µs

Fig.2a



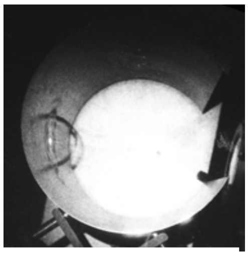
30,5µs

Fig2.b



30µs

Fig.3



75µs

Fig.4

In the case of the perpendicular impact on the surface of an isotropic metal plate the propagating bending wave is recorded as a set of the concentric circle fringes as long as there isn't an influence of the boundary conditions. However the response of the shell for the same impact is completely different. The circular shape of fringes is preserved only for extremely short time after impact in the case of cylindrical shells. Then the concentric circle fringes change their shape to an oval. Later it is possible to see two peaks propagating axially and symmetrically to the loading point. This *geometrical anisotropy* is closely coupled with the shell curvature. It is almost impossible to interpret quantitatively interferometric pattern in holointerferograms in Fig.3, e.g. for evaluation of the *guided* wave velocity.

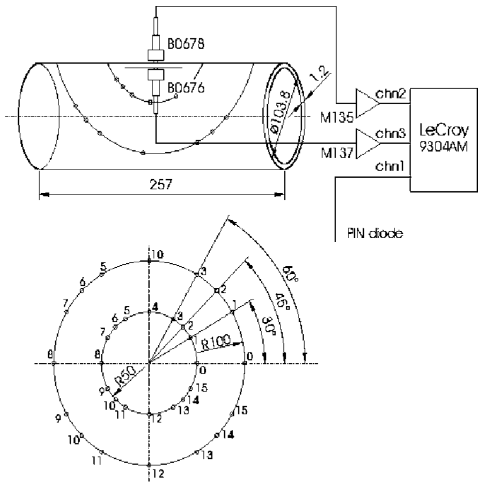


Fig.5

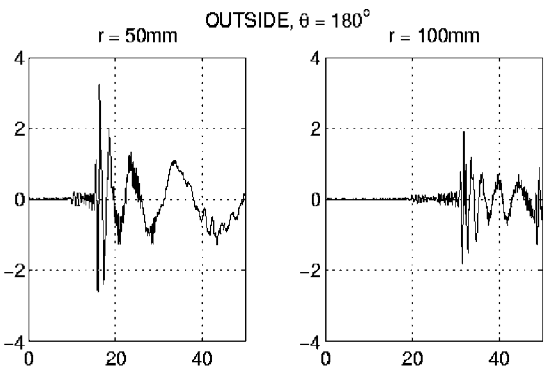


Fig.6

Therefore the velocity history was detected by means of PZT sensors fixed on the shell [8].

It was tried to distinguish experimentally the velocity changes of the flexural waves propagating in the carbon-steel shell (diameter 103.8mm and 1.2mm thickness). The point-like PZT sensors were fixed together on both external and internal surface of the shell in the opposite position -see Fig.5. Ultrasonic waves were generated by a point-focused Nd-Yag laser pulse on the external surface and its position was changed on the two concentric circles with the radius R= 50 and 100mm. The transducer pair was fixed at the circumcentre.

The laser pulse vaporised the black paint film cover and induced the wave propagation. A small low-energy part of this beam was detected by PIN diode. It was used as a trigger of signal recording. The typical signals were detected on the external/internal surface along the tube and two of them are shown in Fig.6. The symmetric modes (first arrival, low-amplitude part), Rayleigh wave and antisymmetric modes (high amplitude peaks and low-equency tail) may be distinguish. The average velocity is c = 3.2097mm/μs. The velocity deviations are not influenced by the source-receiver orientation and their values are under 2%. It is under the accuracy of the distance measurement. These results indicate that the curvature sensitivity of flexure waves in shells (with the ratio h/R approx. 0.02) and the source-receiver distance versus radius >0.50 is not detectable and the first part of the signal with 2MHz bandwidth does not differ from the waves in the plate of the same thickness.

The above mentioned impact generation by focused ruby or Nd-Yag laser beam has many advantages eg. it is the source of mechanical broadband pulse. The laser beam splitting enables impact generation in the different places simultaneously. By using a double pulse lasers gives a chance to study interaction of two mutually delayed pulses by propagation in structures. The important advantage is the exact triggering of the record of a transient phenomena. Among the disadvantages belongs that the object surface properties have significant influence on generated impulse amplitude /influence of the absorbing layer/ and that focused laser beam loading causes visible mechanical damage of loaded surface. It is necessary take into account that the impact reproducibility become poor and the laser pulse energy may fluctuate in the repetition regime up to 20%.

Generally it is valid that in the investigation of stress wave propagation by holointerferometry the loading by focused pulsed laser beam is effective for the structures thickness approx. up to 2-3mm.

One of the most important things in the experimental research of transient phenomena is the method of generating the well known and well defined impact.

The experimental study of wave propagation in the structures with higher thickness requires for impact generation mostly a mechanical or electromechanical loading. The mechanical impact can be realized by the different types of impactors eg. by the ballistic pendulum, by drop hammer or by shooting.

We have chosen the second type of loading – the impact generation by exploding wire. At first, we analyzed the parameters of electrical circuit, secondly the shape of the loading element. The time history of the generated force was measured by means of miniature strain gages glued to a thin aluminum bar. The size of it (10mm in diameter and 2 500mm in length) is determined so that the waves propagating through the bar can be considered as a planar waves. The loading elements of various dimensions were glued on the front of the bar. The wire explosion generates stepwise compression elastic waves both in the loading element and in the Al-bar.

The impact reproducibility was studied by using ofthis method. The maximum of the generated force varied, depending on the shape of the element, approx. in values 600 - 1700N and 15 - 25μs. The signal recorded by means of the Al-bar was used like input signal for finite element simulation.

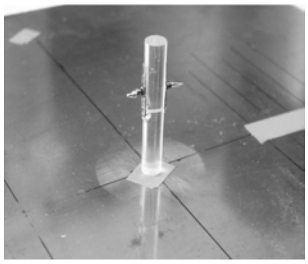
A special element with a thin bronze wire glued to the plate in its center is shown in Fig.7. The thin carbon steel plate (280x280x5 mm) representing isotropic dispersive medium has been used to study guided wave propagation by double-pulse holointerferometry.

The first ruby laser pulse serves both for triggering pulse in the electronic circuits with the exploding wire and simultaneously for the holography record of the undeformed state of the plate. Triggering is realized by means of a small portion of ruby laser beam detected by the PIN photodiode. The second pulse is launched at a preset time (variable from 1-800μs).

The time of the beginning of the mechanical impact is delayed approx. 11.5 μs after the triggering pulse. The delay includes the effects of the finite length of the loading element and the influence of parameters of the electric circuit. This delay must be taken in to account when comparing the experimental results with numerical simulation.

The holointerferogram of “frozen” guided waves 55μs after the triggering pulse is shown in Fig.8. The wide fringes represent "hills" or "valleys", the sign of displacement is ambiguous. The appropriate sign must be determined from experiment where direction of the loaded force is known. 3-D projection of the “frozen” guided wave of the double-pulse holointerferogram (Fig.8) is shown in Fig.9 [11].

The detailed evaluation of the interferogram is shown in Fig.10. The transverse displacement is plotted versus the radial distance from the impact center.



Fig,.7

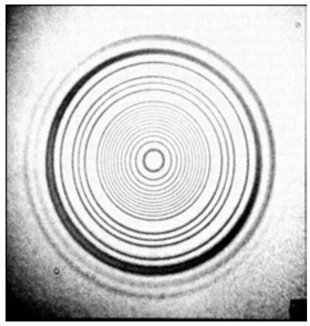


Fig.8

Comparing the numerical and experimental results, it is necessary, first, to focus on the relations between the positions of *the numerical and experimental* “hills” and “valleys”. A very good agreement was observed for the first minimum, the second maximum, and the second minimum of the propagated guided wave in all recorded times – see Fig.10. Quantitatively the computed peak values correspond to experimental results very good as well [12].

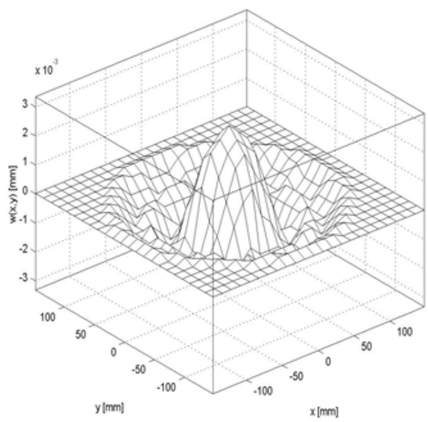


Fig.9

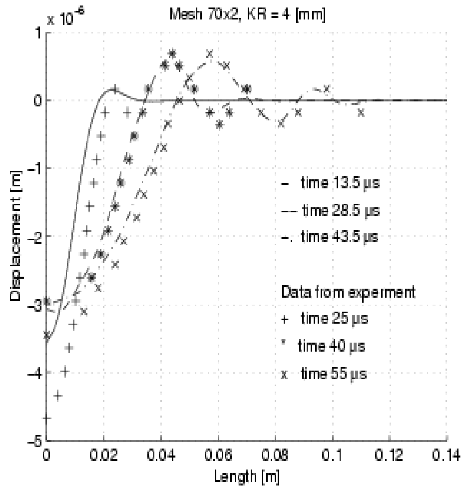


Fig.10

3. Conclusion

The present paper is focused on solving of the several tasks. The first task concerns to the mutual temporal shift for the guided waves propagating in a thin cylindrical shell. The waves were generated by focused pulsed laser beam. By comparing of the shapes of the recorded signals in various directions for the same distance from the source were found out differences of velocities of propagation in the radial, axial and another directions. The evaluated differences correspond to the distance change only up to ±1 mm. It represents approximately 2% of the distance between the sensor and the source. It was estimated that error of evaluation of the distance along with the influence of the sensor aperture represents 1 to 2%.

The second part of the paper deals with the comparison of the experimental and numerical results of the transverse displacements of dynamically loaded plate. Double-pulse holointerferometry was used to visualise guided wave propagation in the plate under investigation. Some of the experimental results were compared with numerical simulations. The comparison of the FEM solutions with experimental results showed very good agreement at least up to about 60 μs.

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