INTERFEROMETRIC MEASUREMENT OF THE PARTICLE VELOCITY DISTRIBUTION IN THE MATERIAL UNDER SHOCK LOADING

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Abstract: Laser differential interferometry is now widely used for the study of fast dynamic phenomena. The obtained interferograms provide the important data for the calculation of threshold strength in the materials under shock loading and allows to determine the beginning of their destruction. In the paper we analyse the procedure of the interferogram formation in such interferometer. The distribution of the particle velocities of the material under shock loading causes the quasi-monochromatic character of the interfering waves. In general case it occurred the result of interference of two quasi-monochromatic waves with different wavelengths and different bandwidths of spectral lines. We discuss the problems associated with the interference pattern contrast reduction that leads to the error in determination of the average velocity evolution. The results are illustrated by experimental data.
Keywords: velocity measurement, velocity dispersion, interferometry,
interferogram contrast

1   INTRODUCTION

Laser differential interferometry allows to get the information about the velocity and acceleration of the moving object under study. The object under study is illuminated by the coherent light, and the light reflected by the surface is analysed. Due to the motion of the object the reflected light has the wavelength which is shifted relatively the wavelength of the incident beam. If one combines two waves that were reflected by the surface at different time moments, they will form the interference pattern. In general case, when the object motion is not constant, these two reflected waves have different wavelengths due to the difference in Doppler shift caused by the object velocity.

$$\lambda_{1,2} = \frac{\lambda_0}{1 + \frac{2v_{1,2}}{c}} \qquad (1)$$

where c is the light velocity, $v_{1,2}$ are the object velocities at two time moments, and λ_0 is laser radiation wavelength.

The surface of the object under shock loading does not move as a unit. Different particles of the object move with different velocities, and so the light reflected from the spot larger than the particle size has quasi-monochromatic character:

$$E_1(t) = \int_{-\infty}^{\infty} f_1(\omega)e^{-i\beta(\omega)\cdot(c\cdot t_1)}d\omega$$

$$\qquad (2)$$

$$E_2(t) = \int_{-\infty}^{\infty} f_2(\omega)e^{-i\beta(\omega)\cdot(c\cdot t_2 - z)}d\omega$$

where ω is incident wave oscillation frequency, $\beta(\omega)=\omega/c$, $t_2=t_1+\tau$, where τ is the delay time, and $z=a\tau^2/2$ is the distance of the object motion during the delay time, and *a* is the target acceleration.

In fact $f_2(\omega,t) = f_1(\omega,t+\tau)$. For the fast processes this function can rapidly change in time. Therefore when studying by means of interferometry the fast phenomena occur under the shock loading of solid

body, we need to analyse the interference of two quasi-monochromatic waves with different wavelengths and different frequency distribution function.

2   THEORY

Schematically the evolution of the wavelength values and dispersions in time is presented in Figure 1. We distinguish two main types of the wave propagation processes in the material: stationary and non-stationary. In the stationary case when the front of compression pulse reaches the stationary phase inside the target the maximal bandwidth of the velocity distribution Δv occurs in the middle of the plastic wave front (Figure 1,a). However if the front of the compression pulse does not reach its stationary phase or for the given width of the target it already left it, the amplitude of interference signal will change up to the beginning of the pulse plateau. This is evidence that the velocity distribution function widens along the whole pulse front and even sometimes at plateau and on the back front of the pulse (Figure 1,b). We considered the general case when the waves have different dispersion (Figure 1,c). The last case is of particular interest, because its consideration allows to estimate the influence of the fast velocity dispersion change on the obtained result.

One can see from the Figure 1 that at the initial moment the waves are nearly monochromatic. The dispersion of the waves is enhancing in time. This leads to the reduction of contrast of the observed interference pattern. If the dispersion is not too large, the intensity oscillations can be observed up to the moment t_3 corresponds to the pulse plateau. At this moment the reverse of the intensity signal happens, and then the intensity pulsation is observed again when the target is decelerating. During this period the second wave reflected later from the target corresponds to the lower velocity.
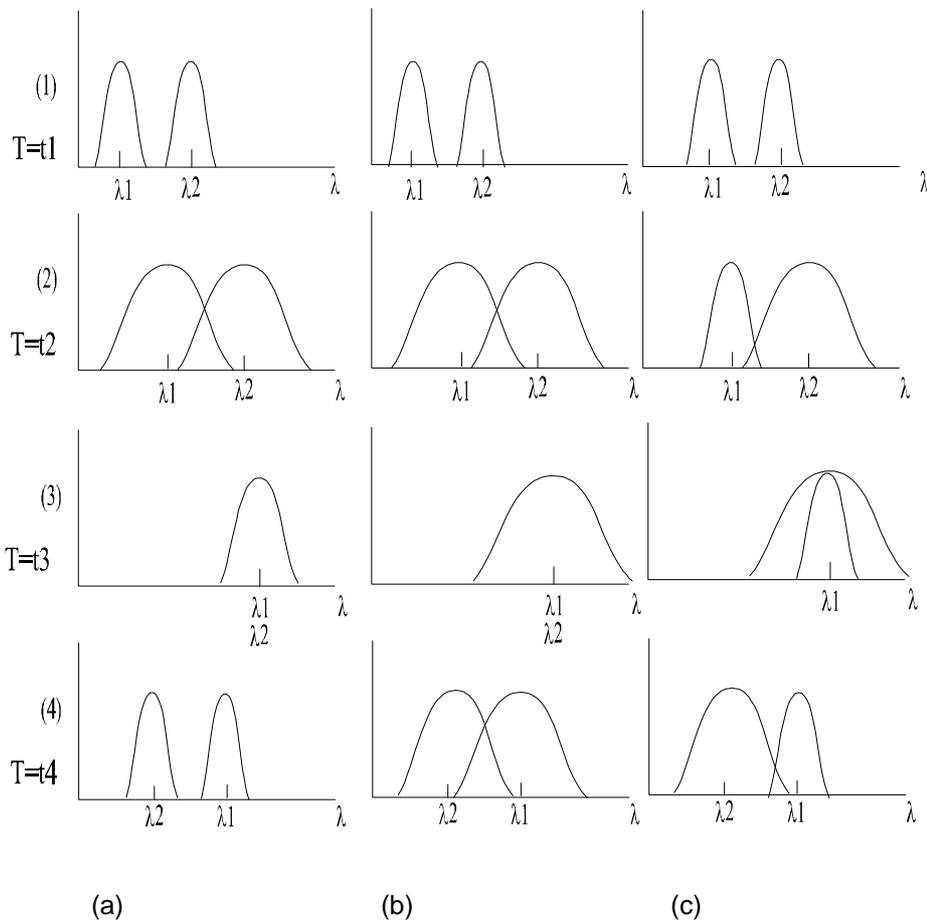

Figure 1. Typical change of the interfering waves dispersion and spectral disposal during the impact for stationary propagation (a) and non-stationary propagation (b, c). In (c) we consider the case of the velocity dispersion changes during the delay time.

We assumed that spectral density functions have Gaussian character

$$f_{1,2}(w) = \frac{1}{s_{1,2} \cdot \sqrt{2p}} \cdot e^{-\frac{(w-w_{1,2})^2}{2 \cdot s_{1,2}}} \tag{3}$$

where ω_1 and ω_2 are central frequencies, and σ_1, σ_2 are bandwidths of the spectral functions.
Let us consider that at the initial moment $f(\omega,0)=0$.
   The intensity of the interference pattern

$$I(t) = const + E_1 \cdot E_2^* + E_1^* \cdot E_2 \tag{4}$$

can be found by substitution of (1) into (4) and solving the integral taking into account that

$$\int e^{-x^2} dx = \frac{\sqrt{p}}{2} erf(x)$$

The resulting expression is:

$$I = const + 2 \cdot e^{-\frac{t^2 \cdot s^2(t)}{2} - \frac{(t+t)^2 \cdot s^2(t+t)}{2}} \cdot \cos[w_0(t+t) - w_0(t)) \cdot t + t \cdot w_0(t+t)] \tag{5}$$

where ω_0 is the incident light frequency.
In the case of monochromatic interfering waves the obtained expression simplifies to

$$I = I_0 \cos(\frac{4pt}{l_0}(v_1 - v_2)) \tag{6}$$

which is known as Barker's formula for this kind of interferometers [1].
The expression (5) allows us to understand the behaviour of the interferogram contrast, to explain the reduction of the contrast and even disappearance of the part of oscillations caused by quasi-monochromatic character of the interfering waves and by the difference in bandwidth of spectral functions of interfering waves. In Figure 2 one can see the temporal behaviour of the contrast $F(t, \tau, \alpha)$ depending on the delay time τ and difference α between the dispersions of wavelengths.
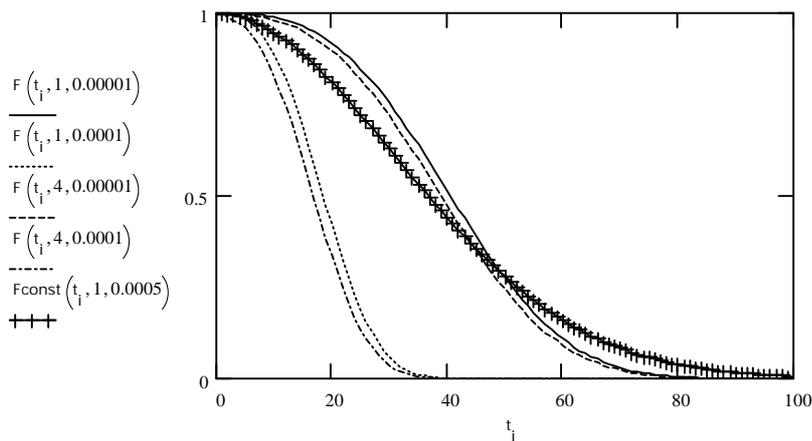

Figure 2. The dependence of interferogram contrast $F(t, \tau, \alpha)$ depending on time t, the delay time τ and the difference α between the dispersions of wavelengths. F_{const} corresponds to the case when the spectral dispersions are equal.

3   EXPERIMENTAL RESULTS

In our experiments the object under study is subjected to the shock loading from the pneumatic gun. The velocity of the bullet is hundreds meters per second. The central spot (of about 100 micron in diameter) of the object is illuminated by the laser light. The light reflected from the surface under study is splitted into two beams, one of which falls directly at photoreceiver and the other passes the delay arm [2]. Being recombined at the photoreceiver input these two beams form the signal I(t), which was recorded by the high resolution oscilloscope C9-4A.

In practice we had not one interferometer, but two of them. We used double frequency laser LGN-302 with the radiation spectrum consisted of two closely located frequencies with polarisation directed at 90° angle to each other. Two interference patterns were recorded simultaneously with a phase shift of 90°. Such a procedure allows us to get more precise information about the processes occurred under shock loading of the object. Especially this is useful for the determination of the reverse point, when the object starts its deceleration after the fast acceleration under shock loading. This reverse point occasionally can coincide with the interference extremum when one interferogram is recorded. However at the interferogram with the phase shift of 90° it will be clearly pronounced.

3.1   Oscillation contrast reduction.

Typical experimental result is presented in Figure 3 [3]. One can point out that the interferogram contrast is not constant along the velocity pulse. On this particular interferogram the contrast reduction is easily observed on the back front of the velocity pulse (point A). However such effect can be observed on different parts of interferograms (front and back) depending on the target material, the bullet velocity, and the interferometer parameters. The observed contrast reduction allow to make the conclusion that the interfering waves have quasi-monochromatic character caused by the particle velocity dispersion
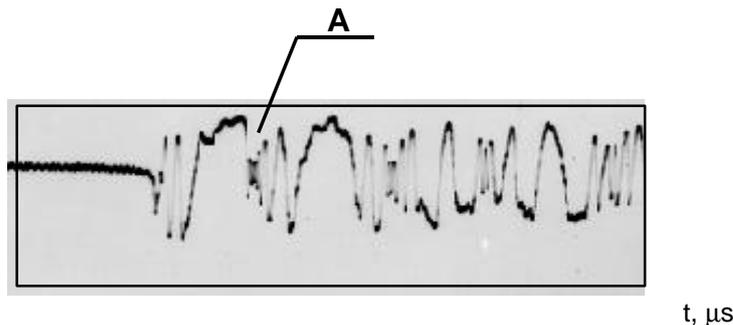

t, μs

Figure 3. Interferogram obtained for the shock loading of 2 mm thick target made from aluminium alloy V-95 PCH T2.

At this particular moment (point A) the contrast is minimal, and therefore the velocity dispersion of the particles of the object under study was maximal. The accurate measurement of the contrast value allows us to get the magnitude of the velocity dispersion that provides an additional tool in determination of the material properties.

3.2   Disappearance of part of oscillations

Another typical experimental result is shown in Figure 4. One can see that the back front of the pulse describing the object deceleration contains much more oscillations than its front part which corresponds to the object acceleration. The part of oscillations at the front part was not recorded while the oscilloscope resolution was sufficient.

Figure 4. The illustration to the interferometric signal disappearance occurred at the front part of the pulse (10 mm thick target made from alloy D-16).

The independent (not interferometric) measurements of the object maximal velocity confirm that in reality the object velocity was higher than the one calculated basing on the data from the interferogram corresponding to the pulse front part. In these independent measurements we assumed that the maximal velocity of the target is equal to the velocity of the bullet if they are made from the same material, and the target (object) is relatively thin. We measured the velocity of the bullet through the measurement of the time duration between the moments when the bullet crosses the paths of two laser beams. These beams are directed perpendicular to the bullet propagation line and separated from each other by 1 cm.

The disappearance of the intensity oscillations can be explained as a sudden rise of the velocity dispersion that led to the total contrast reduction.

Another explanation takes place if we consider the object as an ensemble of structures of different scale. The particles that participate in the process of the object destruction usually have a size of about microns. The diameter of the light spot that illuminates the target is about 100 micron. The amount of particles observed is enough to describe their behaviour by statistical distributions. The next scale of the structures in metals is about 100 micron which is compatible with the size of illuminated spot. The sudden beginning of motion of these 'large' particles can cause the total disappearance of interferometric signal. This phenomenon is probably consisted in the sudden energy transfer from the small particles to the large ones analogous to the phase transition in the materials. Its description is the topic for the material scientists.

4   CONCLUSIONS

We analysed the interferogram formation in laser differential interferometer for velocity evolution measurement. It was shown that in general case two interfering waves with different wavelengths have quasi-monochromatic character, and their spectral bandwidths are different. We received the dependence of the interferogram contrast on the particle velocity dispersion and its acceleration, i.e. the difference between the dispersions of the interfering waves. The obtained expression allows us to make the better description of the processes occurring inside the material under shock loading.

The reduction of the interferogram contrast can be explained by the particle velocity dispersion of the object under loading. The disappearance of the signal oscillations can be explained either by sudden widening of the velocity distribution function or by the introduction of effects caused by structures of larger dimensional scale.

ACKNOWLEDGEMENTS

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