Application of direct optical heterodyning methods for studying the processes of chondrite targets destruction by laser radiation

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Abstract. We have represented a system description used to study of the kinematic parameters of processes of destruction of chondrites under the action of intense shock waves. Interferometric method of measuring speed PDV was the basis for a compact, easy-to-use device intended for the analysis products of target destruction. Using the Fourier transform method of analysis, the dynamic rates of expansion for chondrite targets in interaction with high-power laser radiation and the dependence of the shock wave velocity on the thickness of the target were obtained.

1. Introduction

The collision of asteroid-cometary bodies with the Earth poses a significant threat to our planet [1].

After scaling experimental modeling of the destruction of chondritic meteorites by powerful shock waves allows to develop effective mechanisms of antimeteorite protection. Using pulsed laser radiation, it is possible to create shock waves of the necessary intensity for small objects in laboratory conditions.

In present interferometric diagnostic methods are widely used for studying the processes of shock-wave loading of the matter. These methods allow to conduct a non-contact measurement of the object surface velocity under the action of a shock waves. The surface velocity contains information about phase transformations, shock wave parameters, strength properties. It included in the state equation (as mass velocity and pressure).

For problems related to processes of fragmentation and dusting of objects methodic PDV (Photonic Doppler Velocimetry) is usually used. It is based on the fiber interferometers using for the formation of a heterodyne beat signal. This signal is a result of mixing reflected from the object and reference laser radiation [2, 3]. These methods are immune to external influences, accurate, easy to implement. Moreover, the applied algorithms of signal processing allow to analyze fragments and drops distributions (by speed and size). All of the above make the PDV method an optimal tool for studying the kinematic parameters of processes chondritic targets destruction by laser radiation. Experimental installation

Shock wave breaking of chondrite targets experiment was conducted using “Saturn” device in RSRI RAS. “Saturn” device is multistage laser system with automatic stimulation of active medium based on Nd³⁺ - phosphate glass. Nd³⁺ laser operating in Q-switching mode is used as a main
generator. Its emission is amplified by preamplifier initially and then by 5 consecutive phosphate glass stages with diameter of 15, 20, 30, 45, 45 mm.

The device is capable of separating beam into two parts which allows to study the glass destruction process by several shock waves. Cuneiform plates made of glass are used for this purpose. Avalanche photodiode, calorimeter and CCD device are used to measure exiting emission characteristics.

Device emission lasts 30 ns with typical energy about 10 Joules which is equivalent to 300 μm spot with power density of $10^{11} - 10^{12}$ W/cm$^2$. Targets, which are made of volcanic rock of various composition (chondrite and andesite), are shown in Fig. 1. Some of samples was polished or covered with aluminum (1.5 μm coating) to improve the emission collection.

![Figure 1. Target photography before and after interaction with emission. Aiming in the center of the target.](image)

New diagnostic scheme was developed in order to explore processes of breaking targets by shock waves. Principal structure of this scheme is shown in Fig. 2.

![Figure 2. Principal scheme fiber interferometer with direct optical signal conversion](image)

Main ideas behind this scheme are listed below. Emission of single frequency continuous laser is conducted to the object of interest through the optical fiber cable. Beam is separated into two parts after passing through the circulator. The first part of the initial beam interacts with the object of interest and is reflected by its surface, then this emission enters the collimator. Both parts combine
after the first one passes through the circulator and the second one passes through attenuator. Difference in frequencies of two parts of initial beam caused by Doppler effect produces beats after parts combine. These beats are registered by ET-3500AF photodetector (9 GHz bandwidth) and then the signal with the frequency equal to the Doppler shift is outputted to the LeCroy WaveRunner 640 Zi oscilloscope (4GHz bandwidth). It worth saying that this method requires the usage of single mode fibers and laser with small wideband in order to obtain the necessary contrast [3].

The beat frequency is related to the object’s velocity by the following formula:

$$f_b(t) = \frac{2v(t)}{\lambda}$$ (1)

Where \(\lambda\) is wave length of probing emission.

Relatively low price of this device comes from using of telecommunication equipment. This is also the reason to choose a semiconductor laser with 1.55 µm wavelength as a source of probing emission. Moreover, such choice of wavelength results much lower beat frequencies compared to usage of visible spectrum wave (it uses in devises like VISAR). Thus, it is possible to register the signal on equipment with smaller bandwidth. In this case, maximal velocity which this devise is capable to measure is limited by oscilloscope bandwidth \(f_{out}\) and is equal to \(V = \frac{\lambda}{2}f_{out} = 3100\ m/s\).

2. Results

A series of measurements of the rear surface velocity for chondrite and andesite targets with different thicknesses values was made. The results are oscillograms describing the dynamics of expansion rates for chondrite targets in interaction with high-power laser radiation. The processing of the received signal was made by software, created in a high-level programming language MATLAB.

To track changes in frequency over time Windowed Fast Fourier Transform was used [4]. The result of its application are spectrograms containing information about the time dynamics of the signal spectrum. The maxima in the spectrum, which stand out against on the noise background, correspond to the target surface velocity and / or the fragments reflecting the laser radiation. To obtain the dynamics of the object speed from the spectrum, it is necessary to perform a recalculation using formula (1). Time and speed resolution are determined by processing parameters. Especially important is the choice of the window type and length.

![Figure 3. Signal recorded with an oscilloscope.](image-url)
At the Fig. 3 – Fig. 6 the example of result of experimental data processing is given. At the Fig. 3 signal recorded with an oscilloscope is given.

On the spectrogram shown in Fig. 4, there are 2 processes. Velocity which is about 20–50 m/s corresponds to the first process. Oscillation with frequencies, which corresponds to this velocity (dozens MHz) is related to instability in reference laser radiation. Average velocity of target explosion after interaction with laser radiation is equal to 100-130 m/s. Spectral power density cutoff was made to obtain more evident time dependence of shock wave velocity.

![Spectrogram](image)

**Figure 4.** Spectrogram of the studied signal

So signals with spectral power density not less than 99% of the maximum was considered. The results of processing are shown in fig. 5.

![Spectrogram](image)

**Figure 5.** Spectrogram of the studied signal after cut-off

So the time dependence of the target surface velocity was obtained (Fig. 6). Obtained dependence is typical for studying processes, its form remains even after radiation energy and target thickness are changed.
Experiment results show that the average shock wave velocity depends weakly on the laser pulse energy. Thus, the beam energy increase by a factor of two leads velocity increase by 5-10%. Perhaps, it is due to the aspect ratio value, since the focusing spot diameter is comparable with the thickness of the target.

![Graph](image)

**Figure 6.** Time dependence polished andesite target surface velocity after interaction with pulsed laser radiation (target thickness is 430 μm pulse energy 9.6 Joules, spot 300 μm, pulse duration 30 ns).

Another oddity is the relation between the shock wave velocity and the thickness of the thick target (Fig. 7). Heating of the target crystalline substance with the energy of plasma flame may explain this oddity. As is well knows, heating the crystalline substances, unlike gases, decreases its speed of sound. The wave moves through matter from the more to the less heated layers that is why it accelerates. Later, it decelerates due to decay of the shock wave at large thicknesses. The error in thickness measurements is determined by the error of used micrometer. The inaccuracy in velocity measurements is related to the averaging of results obtained for same thickness targets.

![Graph](image)

**Figure 7.** Relation between the shock wave velocity and different targets thicknesses. Focusing spot diameter is 300 μm, power density of the laser emission if $4 \times 10^{11}$ W/cm$^2$.
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