Multichannel laser radiation collection and transport system for particle velocity measurements in shock wave experiments

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Abstract. VISAR type measuring laser systems are used for the determination of surface velocities in high-speed processes. Their operational characteristics mostly depend on the efficiency of collection of scattered radiation. In this paper we present results of the comparative analysis of several radiation collection schemes along with experimentally obtained data on the scheme parameters effect on collection efficiency and recording length.

1. Introduction
One of the most popular methods for measuring shock wave velocity is based on VISAR systems usage [1]. VISAR is a reliable measuring instrument, its various modifications have been successfully used in experimental studies on fast and transient processes. Modern measuring systems allow to perform multichannel high-precision velocity measurements of the investigated moving surface Moreover, utilization of the nonius scheme allows to eliminate the velocity ambiguity due to its step increase upon shock wave reaching surface of the sample. [2].

Operating principle of VISAR type systems based on Doppler shift of light reflected off of the surface of a moving object. During the experiment, the surface of the object often rotates, so that usage of specular reflective surfaces is unreliable. This allows operation with rough unpolished surfaces, or with objects without reflective coatings. On the other hand, the reflection of rough surfaces is close to Lambert reflectance, so that efficiency of light collection is low.

Experimentally measured light collection efficiency $\mathcal{E}$ is of the order of $10^{-5}$ (10 μW of radiation was collected per 1 W of radiation delivered):

$$\mathcal{E} = \frac{P}{P_0}$$

where $P$ is the power of the radiation collected from the surface of the investigated object, when the object is illuminated by laser radiation with the power $P_0$.

Lasers with a power of 2–10 W CW can be used as sources of probing radiation, photomultipliers are used for recording. With that said, powerful local heating is unacceptable for the unstable and sensitive to heating objects.

Possibilities of operation on samples with scattering surfaces without an additional reflective ones are also limited by the obtainable efficiency of radiation collection. The signal-to-noise ratio depends on the amount of collected radiation, which directly affects the accuracy of the results obtained.
2. Light collection and transport systems
In this regard, usage of the appropriate light collection and transport system (LCTS) is essential in order to obtain meaningful experimental results. Adequate LCTS should provide high collection efficiency along with long recording length (the distance beyond which the signal level drops to the noise level). Three LCTS were used as optical sensors setups: LCTS on a free beam, fiber LCTS without collimating optics, and LCTS fiber with the fiber optic sensor.

2.1. LCTS on a free beam
The most simple LCTS scheme is a mirror with a hole and collecting lens located at the focal distance from the object (Fig. 1). Laser radiation passes through the hole and focuses on the investigated object. The scattered light returns through the collecting lens and forms a parallel beam, which is reflected from the mirror to the interferometer.

![Figure 1. The scheme of transportation and collection of radiation using a mirror with a hole.](image)

The movement of the object results in its surface leaving the focal plane of the lens. In this case, the scattered radiation collected by the lens stops forming a parallel beam and begins to diverge. This leads to the fact that the power of the collected radiation decreases rapidly as the studied object moves. This imposes restrictions on the effective length of the signal recording.

For the analysis purposes scheme with following parameters was tested: lens focal length 15 cm and distance between the collecting lens and the mirror with a hole is 4 m. The effective length of the signal recording for such scheme was calculated to be 3.5 mm.

Operational characteristics of the LCTS on a free beam were determined in test experiment on the shock-wave loading of the aluminum plate. The result of the experiment is shown in Fig. 2. After 3.5 µs the signal is lost and the time dependence of the velocity becomes unreliable. Thus the length of the effective signal recording assessed as 3.4 mm.

Multipoint measurement setup using a free beam scheme is extremely complicated, as it requires bulky optical system consisting of a large number of optical elements. However multipoint measurements could be significantly simplified by the use of optical fiber systems for the optical signal transport.

2.2. Fiber LCTS without collimating optics
LCTS without collimating optics is the system of fiber-optic transport of radiation from a laser source to a test object and an interferometer.
In this case, the polished ends of the optical fibers are located at the distance of 2-5 mm from the surface of the test object (Fig. 3). Radiation from the laser source is transported to the surface of the test object using one optical fiber, another fiber (or few others) are used for the collection of scattered radiation and it transport to the interferometer. In the most simple case fibers can be fastened in rigid plane plate made of plastic or even plywood. In that case collection efficiency assessed to be no more than \(2 \times 10^{-4}\).

For such similar test experiment on the shock-wave loading of an aluminum plate was conducted (Fig. 4). The length of the effective signal recording was 0.82 mm.

Described scheme is easy to use, cheap, allows multipoint experiments, but at the same time it has low effective signal recording length and a large measurement area, as it is determined by the fiber numerical aperture (Measurement area is 1.44 mm\(^2\) for NA = 0.22 and the 3 mm distance between the fiber and the object).

2.3. **Fiber LCTS with a fiber-optic sensor**

Convenience of fiber transport of radiation with the collecting lens systems efficiency can be combined with the applications of probes, i.e. fiber based optomechanical systems (Fig. 5). Disposable fiber-optic probes are built on a base of the metal case with a through hole for radiation transport and mounting holes. Probe is set on a special table at some distance from the surfaces of the test samples parallel to them.

Lens with a 10 mm diameter and a 10 mm focal length is glued in the case for radiation collection, the other side of probe contains thread, which holds hollow plastic adjustment screw. In the screw through hole assembly of the optical fibers is fixed.

The ends of optical fibers in the probe, are aligned along the optical axis of the lens; fibers axes are equally distanced from it and grouped together.

The probe design allows to adjust the distance between the faces of the optical fibers and the lens, as well as to adjust the angle sensor’s axis and surface of the researched object.

The choice of fibers for the sensor is dictated by the requirement of maximum collection efficiency and acceptable collimability of radiation at the fiber output for radiation processing in the interferometer.

A fiber with a larger diameter collects radiation more efficiently because of the larger cross-sectional area of the core, but using larger diameter fibers leads to increased radiation losses at the interferometer input. Modelling in Zemax software have shown that the use of fibers with a core diameter of 200 µm is optimal. Additionally, studies have been conducted on the possibility of using standard telecommunication fibers with a core diameter of 62.5 microns as they are significantly cheaper and more technologically advanced.
Characteristics of single lens probes with different fibers were determined by the measurements of dependencies of the radiation collection efficiencies on the distance between the sensor's collecting lens and the test surface on different positions of the ends of optical fibers relative to the collecting lens. Various combinations of transferring and collecting optical fibers were used: transferring and collecting fibers with 62.5/125/250 µm diameters (core/sheath/protective coating) (Fig. 7, a); transferring fiber with 62.5/125/250 µm diameters and collecting fibers with 205/230/340 µm diameters (Fig. 7, b); transferring and collecting fibers with 205/230/340 µm diameters (Fig. 7, c). Matte polished aluminum plate surface was used as reflective test surface.

The highest radiation collection efficiency is provided by probes using 205/230/340 µm optical fibers for both input and output and 13 mm distance between faces of the optical fibers and collecting lens with 30 mm distance between the target and the lens. With this configuration, the collection efficiency was $5.6 \times 10^{-4}$.

Test experiment was conducted on the shock-wave loading of an aluminum plate using single lens sensor. In the experiment the sensor was set so that the distance between the collecting lens and the surface of the researched sample was 25 mm. The distance between the ends of the optical fibers and the collecting lens is 13 mm. Optical fibers with 205/230/340 microns diameters were used for transferring supply and collecting of the radiation. The results of the experiment are presented in Fig. 6. the effective length of the signal recording was 6.0 mm.

Such configuration, according to measurements of the efficiency collection, allows achieving an effective recording length of up to 25 mm. However, destruction of the target during the experiment sets practical limit to the recording length.
3. Conclusion
Three types of LCTS for VISAR interferometric systems were studied.

LCTS based on the single lens fiber-optic probe has the longest effective recording length. Changing the distance between the ends of the optical fibers and the collecting lens allows to achieve an effective signal recording length of the tens of millimeters order.

The highest radiation collection efficiency achieved by using single lens probe was $5.6 \times 10^{-4}$. At the same time, the effective recording length was 16 mm with, the distance between the ends of the optical fibers and the collecting lens 13 mm.

Conducted test experiments confirmed the effectiveness of disposable single lens fiber-optic probes for particle velocity measurements in multipoint experiments on shock-wave loading.

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References
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