Shock wave velocity measuring system based on vernier VISAR-type interferometers

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Abstract. The paper presents a multi-line diagnostic system for measuring the surface velocity in shock physics experiments. This system is designed for simultaneous measurement of surface velocity at multiple points. It is free from ambiguity caused by harmonic dependence of interference signals on the velocity and has a time resolution of 0.8 ns.

Studying extreme states of matter exposed to intense pulsed loads is rather complicated due to a number of setup features of the experiment. The uniqueness of experiments and inability to repeat them under identical conditions place heavy demands on output data. An important scientific problem in the physics of extreme states of matter is the investigation of physical and mechanical properties of materials exposed to intense dynamic loads, produced by powerful explosion shock waves, hypervelocity impacts or laser pulse. The most informative contactless method in such experiments is Doppler interferometry, which allows to carry out continuous surface velocity measurement. At present quadrature-differential VISAR systems are the most widespread laser systems for velocity measurement [1].

They have earned a reputation as reliable, convenient and relatively inexpensive devices providing sufficient accuracy and time resolution for most measurements.

The most advanced systems use quadrature-differential systems, which allow compensating additive and multiplicative noise, and providing opportunity to change the measuring range and the use of optical fibers for radiation transport [2].

However, such measuring systems have a number of limitations due to properties of optical layout. In particular, the standard interferometers of Michelson scheme are designed for the simultaneous measurement of the velocity of only one point on an object (more precisely, they measure the average speed of $\sim 10^{-5}$ cm^2 area). Another problem is the consequences of interference contrast losses due to insufficient detectors time resolution.

Contrast loss is usually observed at short shock front (< 10 ns) and can lead to significant errors in the recorded absolute value of velocity.

The propose of this work is to remove these deficiencies of diagnostic system and to provide the complexity of the motion dynamics data processing on the hardware and software level. This was done by creation of quadrature-differential unequal arm interferometer (KDNI) system.

Structurally, diagnostic system contains the optical units of light frequency analysis (interferometers) and electronic components of photoelectric conversion (photo receivers)
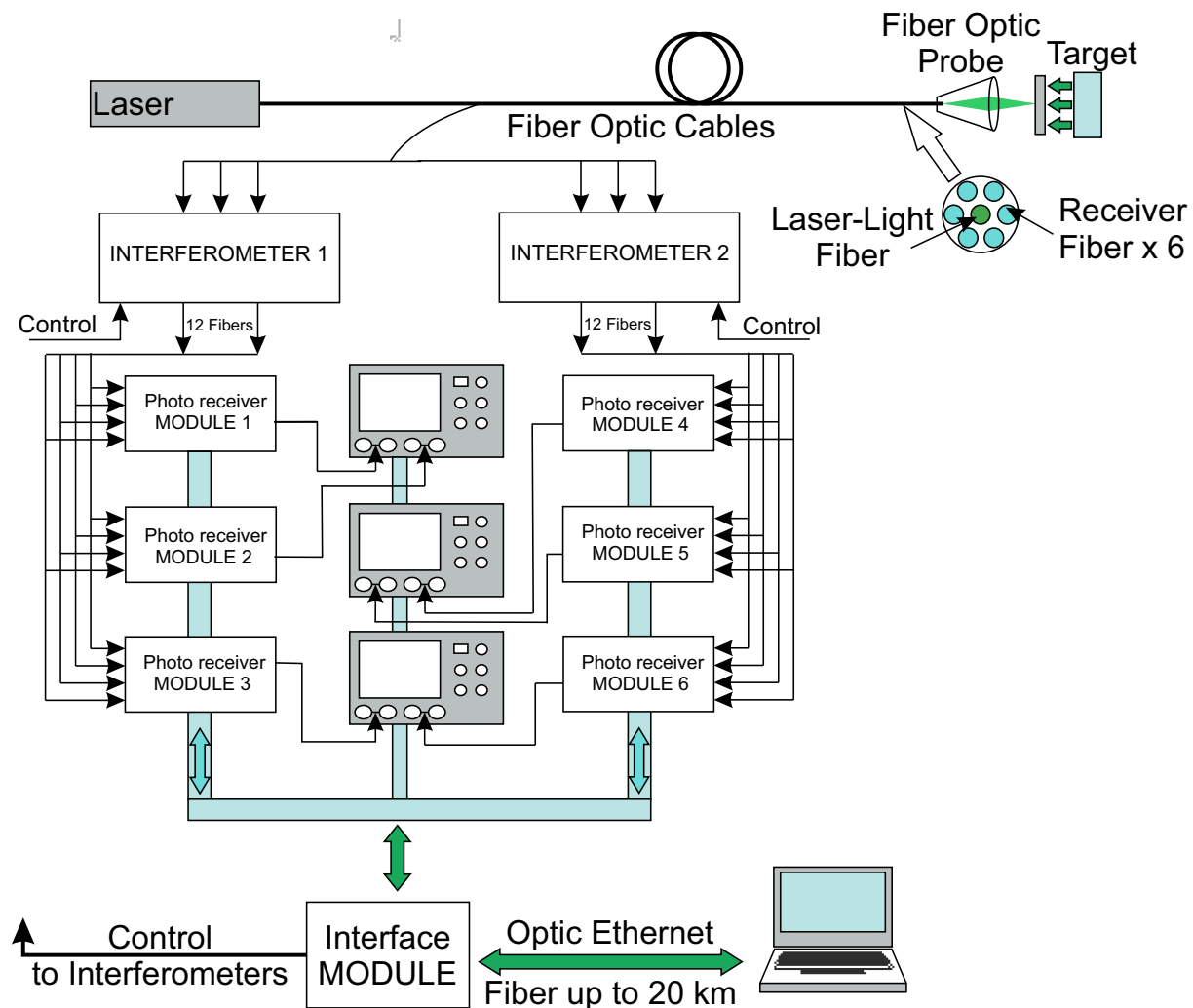
Figure 1. General scheme of the laser system for measuring the mass velocity of condensed substances in shock wave experiments.

interconnected by fiber optic cables, and control unit (interface module). This setup is designed for using the second harmonic of a continuous single-frequency Nd^{3+} solid-state laser $\lambda = 532$ nm) as probing.

Figure 1 shows an embodiment of the system for measuring the speed of a single point. In this case, the probe radiation is transported to an object through the central fiber, and reflected light is transported to interferometers by the six outer fibers.

Figure 2 shows the general scheme of the interferometer system. Interferometer is formed by mirrors M1–M3. Radiation injected in it by collimator. A face of the glass block (optical delay line, etalon) covered by multilayer dielectric coating with an intensity division ratio of 50/50 is used as the splitting mirror 2. The opposite face of the etalon is covered by antireflection layer. The system of quadrature-differential polarization coding is formed by phase plate ($\lambda/8$) attached to the mirror M3 and polarization beam splitters PBS.

Mirror M3 is fixed on a three-coordinate piezoelectric actuator that enables independent remote mirrors alignment on two corners in the range of 600 μrad and modulate the length of M2–M3 interferometer's arm in order to calibrate the measuring channels.
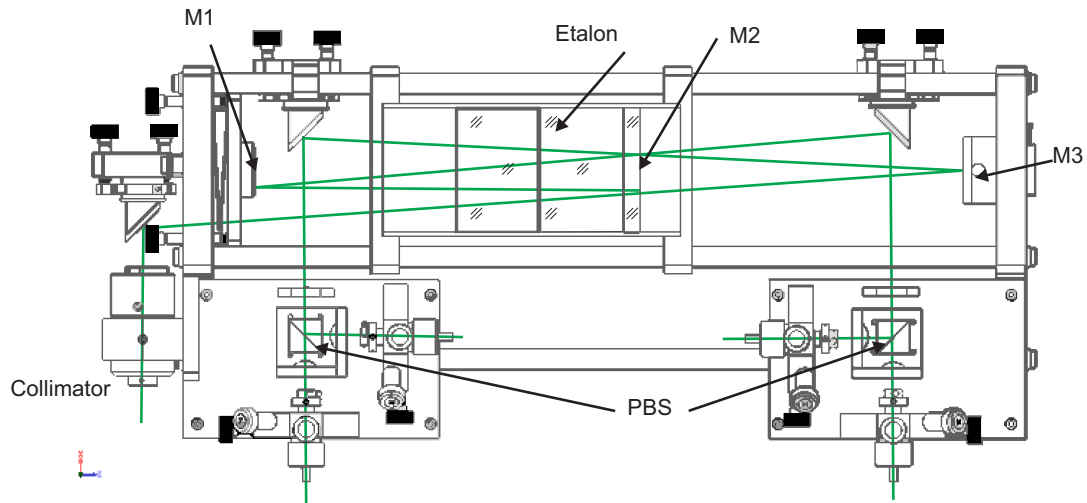
Figure 2. Optical layout of the interferometer.

When the velocity of the reflecting surface changes, the waves that interfere at the splitting mirror 2 have different frequencies owing to a time delay in the etalon. Changes in the light intensity I at the interferometer output is related to changes in the velocity V of the reflecting surface via a harmonic dependence that is similar to the instrument function of a conventional two-beam interferometer

$$I = I_0\, cos(\varphi(t)),$$

where

$$\varphi(t) = \frac{1}{c\lambda_0}\Big[8\pi\ell(n - 1/n)(1 + \delta)V(t)\Big],$$

where ℓ is the length of the etalon, c is the velocity of light, n is the refractive index of the etalon material, I_0 is the intensity of light entering the interferometer, λ_0 is the initial wavelength of laser radiation,

$$\delta = -\frac{n}{n^2 - 1}\lambda_0 \frac{dn}{d\lambda}\Big|_{\lambda=\lambda_0}$$

is the correction factor that takes into account the chromatic dispersion in the material of the etalon.

Thus, photo-current value has periodical dependence on the velocity, characterized by a scale factor of the interferometer, i.e. changing the velocity on one interference fringe:

$$K = \frac{\lambda_0\, c}{4\ell(n - 1/n)(1 + \delta)}.$$

Optimal velocity range for VISAR-type systems in typical shock wave loading experiments is proportional to K and ranges from 0.1K to 10K. The etalons included in the KDNI, are cylinders made of BK7 glass with a diameter of 75 mm and a lengths of 10, 35, 60, 110 or 160 mm. Coefficients K for this set of etalons lie in the range of 300-4600 m / s.

By replacing the etalon, the system can be tuned over a measurements range. However, such adjustments are associated with rebuilding of the system, and futher alignment of the mirror M2 in relation to the mirrors M1 and M3. In Michelson interferometer system (figure 1) infinitely

wide fringe provides maximum interference contrast, which can only be achieved if the geometric paths difference in two interferometer arms is $\Delta L = \ell(1 - 1/n)$.

It specifies the position of the mirror M2 as a function of the etalon thickness. Absence of system reconfiguration after etalon changing allowed us to use the hollow aluminum cylinder containers for the etalons. The position of etalon within the container is adjusted in such a way that when the container is fixed in a special attachment inside the interferometer, mirror M2 is in the optimal position and additional adjustment is not required.

The basic control of the system can be performed remotely from a PC with help of specialized software and a remote control unit. Built-in Ethernet interface allows adjusting interferometers, monitoring its elements condition remotely, and performing remote recording of digital signals. High-speed photomultipliers (Hamamatsu R9880) allow to use a laser with power < 1 W as a probe source during operation with low reflection surfaces, including diffuse surfaces.

Rise time of the detection system is 0.8 ns, which is sufficient for shock front restoration in the vast majority of shock physics experiments, though the possibility of interference contrast loss on sharp front still remains. In this case, data can skip on one or more interference periods, resulting in an incorrect determination of the velocity and, although, the changes of the velocity behind the shock front are possible to track, measured velocity will be shifted from the real velocity on a multiple interferometer constants K.

This problem of fringe "skipping" is inherent to all traditional VISAR-type systems. The reason is a harmonic dependence of interference signals on the velocity, which demands the need for the entire previous velocity changes information to be known to determine its current value. The velocity is proportional to the current value of the phase. In case of contrast loss caused by insufficient time resolution of the registration system, phase information will be lost, causing ambiguity in the velocity values determining.

Usually, the problem of "skipping" is solved by using a priori information about maximum velocity of the object. Such information can be obtained by additional experimental, in particular contact, methods. In the absence thereof such information, the data obtained during the experiments lose their validity and can be recognized as erroneous.

Contrast loss can be removed by shortening the length of the etalon L. It allows to solve the problem if velocity of the surface in the shock front changes at a value less than interferometer constant K. This solution in actual experiments is, however, not applicable due to the direct connection between the interferometer constant and velocity resolution.

The optimal solution is to use a measuring complex of two interferometers with different constants K. They can be used in two ways. If K of first interferometer was chosen so high that the "skipping" was not observed, and the second K was chosen in order to achieve optimal velocity resolution on the temporary region, all time dynamics of velocity with an acceptable resolution can be uniquely reconstructed. This solution, however, has a significant drawback. Due to the low sensitivity of the first interferometer, its data cannot be used for anything other than velocity jump determining at the shock front, which drastically reduces the overall efficiency of the vernier interferometry system. In addition, estimating the length L sufficient to eliminate skips is not always possible a priori, especially in investigation of samples with unknown physical parameters.

Another way to use such system is because the ambiguity of velocity behind the shock front is discrete. The actual velocity differs from that calculated directly from interferometer data on integer interferometer constants K. This fact makes it possible to create vernier system with two close but not multiple interferometer coefficients. Each of the interferometers will be exposed to the fringe "skipping" but collaborative processing of interferometers data can allow to determine the value of the jump and restore the entire velocity profile (except for the time interval of the shock front, where time resolution of the detector does not allow to track changes in the intensity). The procedure of shock front restoration in this case is a selection of the
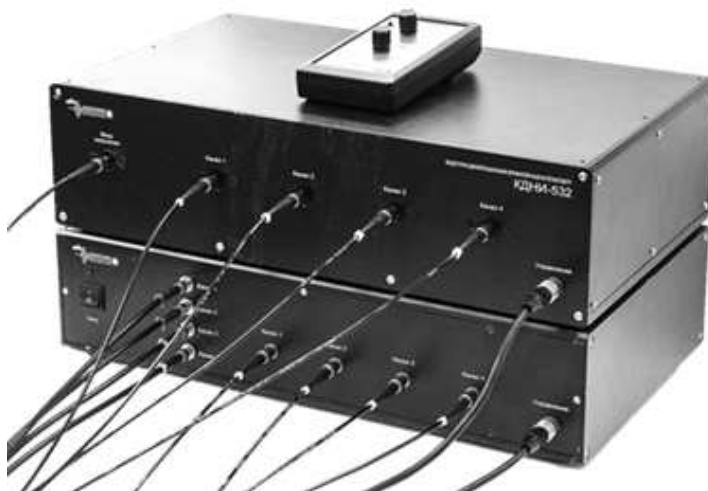
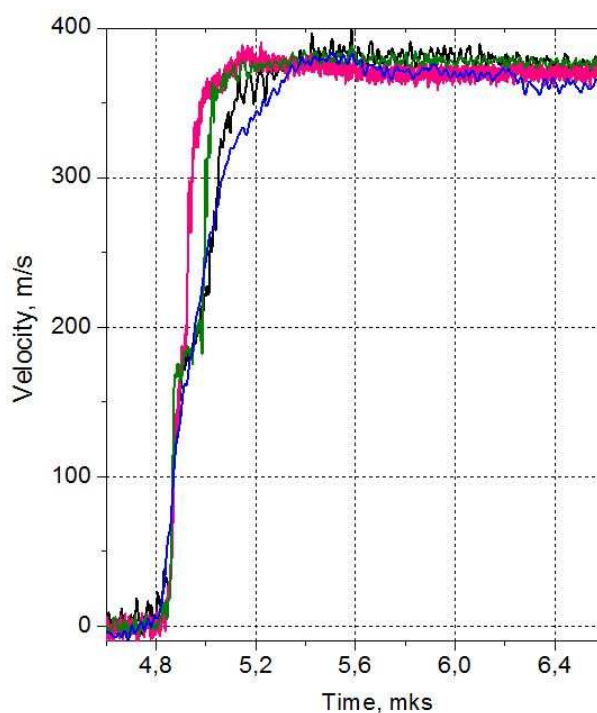**Figure 3.** Appearance of the interferometer.

Figure 4. The profile of granit's surface velocity.

number of skipped periods for each of the interferometers to match the graphics behind the shock front, obtained for different interferometers. This method of selecting the coefficients of the interferometer can improve the accuracy and dynamic range of the measuring system, the total reliability of the data will increase significantly as compared to currently used systems because of "skips" compensation and because of the duplication of the experimental data for further processing.

Often, experiments are required to have information about temporal dynamics of the velocity

at several points of the surface. Examples of such experiments are one-dimensional experiments of samples loading, where one needs to be confident in the planarity of the shock front, and investigation of stepped samples by optical pyrometry. To solve this problem we developed an optical scheme of the interferometers, which allows each of them to carry out an independent analysis of up to 7 optical channels. This is achieved by forming the cluster of seven beams at the input of the interferometer, each of which comprises light reflected from one point of the investigated surface. The cluster passes through the interferometer and enters into a group of optical fibers, serving to deliver radiation to a multi-channel photodetection system. Thus, it is possible to record simultaneously the speed at several points of the object surface (or a number of different objects).

An example of the KDNI experimental data is shown in figure 4. This graph is the result of the impact on the granite plate steel strikers accelerated to a speed of 400 m/s. Different colors correspond to different KDNI channels. The reason of significant difference of the elastic precursor for different channels and the lack of further oscillation is granular structure of granite and heterogeneity of its composition. Granite contains a large number of stress concentrators pores, cracks, grain boundaries. Micropores existing in the initial state are partially closed under elastic compression, which leads to plastic deformation and fracture elimination. When the threshold is exceeded, plastic deformation object is destroyed.

Acknowledgments

References

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