Continuous monitoring of deformations in mines using laser interferometer–deformograph

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Abstract. The article gives a detail description of the deformation graphing equipment designed at the Institute of Laser Physics, SB RAS, for the geodynamic monitoring of stress state in mine galleries and other underground openings, and for the analysis of ground surface vibrations before earthquakes and other seismic events. The more comprehensive study of separate rock mass blocks uses the advanced modification of the prototype deformograph introduced into service on Talgar testing ground in Kazakhstan. The programming support of the equipment is described.

1. Introduction

The Institute of Laser Physics, SB RAS, has developed and introduced a high-precision laser deformography equipment intended for geodynamic monitoring of stresses and strains in rocks in mines and ground vibrations before earthquakes and other seismic events [1–3]. The measurement equipment is based on the layout of the Michelson unequal-path interferometer with the shift of optical frequency range into radio frequency range using the method of optical heterodyne detection. The equipment performs continuous recording of time variation in the phase of a light wave due to Doppler effect when the light wave is reflected from a moving mirror (mounted on a test object) [4, 5]. The shift is determined as the difference of phases of two radio signals from light-detecting device in reference and measurement optical channels to electronic circuit of phase detector. A variation compensation unit for refracting index of air enables measurement in underground excavations without auxiliary vacuum or excess pressure beam waveguides at measurement error ~ 2X10⁻⁹ (ΔL/L). The limit sensitiveness of shift of the equipment is λ/4096 μm (where λ = 0.6328 μm is the gauge length of laser). The deformograph is designed for operation in the mode of continuous recording and short-term shutdown for the routine maintenance at a frequency of once per 3 months. Hermetic enclosures of mechano-optical and electronic units ensure long-term operation of the equipment under conditions of 100% moisture content of air.

At the present time, two deformography equipment sets have been put into practice. The first set operates on the testing ground of the seismic station Talaya situated on the south-west side of the Baikal Lake (51°40′N, 103°38′E), the second set is run at the geophysical observatory Talgar in Kazakhstan (43°18′N, 77°14′E). The second, later version of the deformograph possesses higher sensitiveness and sampling frequency [6]. This paper describes performance and measurement procedures of the latter version of the deformography equipment.
The deformography equipment is a set of optical, mechanical and electronic units. Figure 1 shows the layout of a two-channel laser deformograph, including laser, laser power supply, interferometer, mechano-optical compensation block, automatic laser frequency and phase control, electronic unit of phase shift measurement and data transmission, mirrors at the ends of optical paths and mechano-optical block of wavelength standard. Also, the measurement equipment includes a software support for the recording system and utility programs for the data pre-processing. The crucial components of the system are described below in this paper.

Figure 1. Layout of laser deformography equipment set.

2. Laser block
The laser source provides radiation for heterodyne detection and frequency measurements with the difference between optical frequencies of 1 MHz phase-locked with the frequency of a reference generator. The laser sources are represented by two He–Ne lasers with the wavelength of 0.6328 μm and capacity of 1 mW meant for continuous operation within 10–15 thousand hours. The phase synchronization and stabilization of the difference frequency between measurement and heterodyne lasers uses the system of frequency–phase control over piezoceramic elements, on which mirrors of laser cavities are mounted, by means of changing the optical lengths of the cavities and, thus, the laser radiation frequency. The structure of this block allows room for additional phase-locked He–Ne laser or laser frequency standard to stabilize operating wavelengths of basic lasers.

3. Interferometer block
The interferometer block changes phases of optical signals into electric signals proportional to the change in length of optical path of probing beams along measurement lines. The interferometer contains three independent optical channels, one of which is the reference channel, and the other two are the measurement channels. They are based on the layout of Michelson interferometer where the reference beam is the heterodyne laser radiation with the frequency shifted by 1 MHz relative to the measurement laser frequency. The reference optical channel receives electrical signal with the operating frequency of 1 MHz relative to which measurement of phases of information electrical signals from the photo-detectors of the measurement channels is executed. Figure 2 shows the optical circuit of the interferometer. Beam 1 means the measurement radiation, beam 2—heterodyne radiation. The reference signal is sent from photo-detector PD3, the measurement signals are from photo-detectors PD1 and PD2.

The block includes passive temperature drift compensation, which reduces instrumentation error of the measurement circuit under outward temperature variation down to < 0.01 μm/deg. The heterodyne radiation is sent to mirrors 2 and 3. The radiation beam passes optical paths between errors 1–2, 2–3 and 3–4. In such sequence, thermal distortions of sections of metal plate where optical elements 1, 2
and 3 are placed (and, accordingly, the change in the optical path length) are equal to thermal distortions of sections of the plate between optical elements 5, 6 and 7 and the contact zone of the plate and the measurement block legs fastened to the plate.

**Figure 2.** Optical circuit of the two channel interferometer. Description is given in the text.

The block can also use optical fiber waveguides to feed measurement radiation to the measurement optical circuit. The fiber optics simplifies operation of the equipment and eliminates tuning of the optical circuit after replacement of active laser elements and rigid fastening of the laser source on the plate.

4. **Mechano-optical compensation block**

The block of mechano-optical compensation of air influence measures relative fluctuations in the refractive index of air in the course of deformation measurements. The sensing device in the compensation block is designed as the heat-compensated length standard, which enables measurement without frequency-stabilized laser sources.

Such design enables elimination of air influence and compensation of measurement error caused by the change in the measurement wave length of the probing laser radiation. The sensing device is manufactured as a self-sustained unit and can be arranged at a distance to 10 m from the interferometer.

The compensation block circuit records the change in the length of optical path equal to the spacing of mirrors mounted on the length standard. The geometrical distance between the mirrors only changed by the value of thermal distortion of the material the length standard is made of, and is immune to the influence of deformations of a test object.

The basic circuit of the mechano-optical compensation block is shown in Figure 3. The block is composed of interferometer and thermally compensated length standard. The interferometer transform optical signal into electrical signal with the value proportional to the change in the refractive index of air and to the variation in the laser radiation wave length. This value is introduced automatically as a deformation measurement correction. The interferometer has two measurement channels based on the layout of the Michelson unequal-path interferometer with the transmission of phase data from the optical range to the radio frequency range using the method of optical heterodyning.

**Figure 3.** Basic optical circuit of the mechano-optical compensation block.
The length standard 1 m long is made of 36 N alloy thermally treated in a special mode and with a thermal expansion coefficient of $8 \times 10^{-7} \, 1/\text{deg}$, and is equipped with an auxiliary passive thermal compensation unit made of aluminum alloy. Such design ensures constant distance between the reflectors with an accuracy of $1 \times 10^{-9} (\Delta L/L)$ under the variation in air temperature in the range of $\pm 10 \, \text{deg}$.

5. End reflectors
The end reflectors of the laser deformograph (ER1 and ER2 in Figure 2) ensure sustainable measurements at essential angular and linear displacements of a test object (plate) at which they are mounted. The reflectors include prisms with additional alignment units on optical wedges, which allow considerable relaxation of prism manufacture accuracy standards. The operating light aperture of the reflectors is 25 mm.

6. Phase meter
The phase meter is intended for primary transformation of two input electrical signals with the frequency of 1 MHz fed from the channels of the optical circuit into a digital signal with the value proportional to the phase shift between these signals. The deformograph uses the 24-bit 6-channel phase meter with the measurement accuracy of $\pi/1024$ at the frequency of 40 kHz and $\pi/8192$ at the frequency of 5 kHz.

7. Software support
The software support of the laser deformograph is composed of two OC WINDOWS program packages for recording and pre-processing of data.

The data acquisition system includes phase meter, seismic signal recorder, data collection server, data visualization program, configuration manager and display. The data acquisition system receives data from the measurement systems, performs decoding, storage and visualization of the data, and detects seismic events based on LTA/STA criterion.

The data pre-processing program performs editing and on-line analysis of the deformograph data aimed to detect anomalous deformation processes. The analysis embraces digital arrays of data on variation in phase signals obtained from the two independent measurement channels and one compensation channel of the deformograph. Deformations in the two independent orthogonal directions are detected by means of program-aided diminution of the phase signals recorded in a digital form in the measurement channels and the compensation arm, with an adjustment coefficient proportional to the ratio of geometrical lengths of the measurement and the compensation arms. Moreover, the analysis includes a time series of the difference deformation between the first and second measurement arms, obtained by direct deduction of the phase signals of the phase meter.

The onward detailed processing of the resultant series uses the dedicated utility programs.

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