Interferometers for studying small vibrations

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Experimental methods for decreasing the mechanical noise level in interferometers used for detecting small vibrations are examined. The increase in the power of sources of coherent radiation has led to a situation in which the sensitivity of interferometers is, to a large extent, determined by mechanical fluctuations and not by the Poisson fluctuations in the light flux. Techniques have by now been developed that significantly decrease the level of mechanical noise. Similar techniques permit interferometers to be used in the presence of quite intense microseismic noise.

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Contact-free optical methods for studying vibrations of solid bodies open up new possibilities in a number of experiments. Osterberg[1] replaced one of the mirrors in a Michelson interferometer with a silvered piezoelectric quartz plate and observed contrast changes in the interference pattern during harmonic vibrations of the plate. In this manner, it was possible to measure the amplitude of vibrations that did not exceed a wavelength of the light wave. A more sensitive method involves detecting instantaneous displacements of the interference pattern, caused by vibrations of a mirror, with the help of a fast-response photodetector. The electric signal that arises can be amplified and separated from the noise background with the help of a narrow band filter. In this manner, vibrations with an amplitude that is significantly less than the minimally detectable static displacements of the interferometer mirror can be detected. The possibility for accumulating the signal over a time $T \sim \Delta f^{-1}$, where Δf is the transmission band of the filter, assures a higher sensitivity than that available with recently developed methods of holographic interferometry.

The limiting sensitivity of the method was investigated by Bershtein[2] and Gorelik.[3] It was assumed that the signal arising from the mirror vibrations can be detected if its power exceeds the power of the noise in the transmission band of the narrow-band filter used. The source of the fluctuations is shot noise in the photodetector, caused by the discrete nature of the electric charge. In this manner, it is possible to estimate the minimum detectable vibrational amplitude:

$$a_m = 0.16\lambda\sqrt{\frac{\beta e\Delta f}{i}}, \qquad (1)$$

where λ is the wavelength of the light used, e is the electron charge, i is the average magnitude of the current in the photocathode, β is a coefficient that accounts for the amount by which the noise of a real photodetector exceeds the Poisson noise, created by the flux of light quanta. (For an ideal detector $\beta = 1$, while for a photomultiplier $\beta = 2$–3.) The validity of the estimate (1) was checked experimentally. With a nonlaser light source it was possible to detect vibrations having an amplitude of $3 \cdot 10^{-11}$ cm using an analyzer with a bandwidth of $\Delta f = 1$ Hz.

The advent of sources of quite intense coherent radiation greatly increased the number of areas in which optical methods can be used for detecting small vibrations. It became possible to investigate specimens with nonmirror-like surfaces, since the light scattered by them turns out to be sufficient for detecting an interference pattern.

Laser vibrometers, constructed in various ways,[4,5] have been successfully applied in research on the acoustics of solids. Differential interferometers[6] that detect the difference in the displacement of two points in a specimen have been used effectively for studying elastic surface waves in crystals and isotropic bodies. Nevertheless, the expectations of a significant increase in the sensitivity of interferometers have been only fulfilled partially. Thus, the result mentioned above was improved by two orders of magnitude, although estimates made on the basis of shot noise suggested that a greater limiting sensitivity could be obtained with existing laser power (10^{-14} cm for a source power of 0.5 *W*). The reason stems from the fact that when the source power increases, a different kind of noise, fluctuation of laser radiation and microseismic vibrations of the apparatus, become dominant.

In order to compensate for parasitic vibrations, many workers[7-9] used an electromechanical tracking system that displaces the reference mirror of the interferometer. The mirror is attached to a piezoelectric element that controls the signal from a special servoamplifier. The system was constructed in such a way that slow (in comparison with the signal being studied) displacements of the apparatus were compensated by a displacement of the reference mirror and did not cause any changes in the interference pattern. The capabilities of such systems are limited by the small mirror displacements that are attainable. Increasing the dimensions using sectioned piezoelectric elements lowers

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the natural frequency of the transducer and limits the possibility of compensating for rapid perturbations. In order to overcome this problem, it is suggested[10] that a sectioned piezoelectric element, consisting of a collection of discs, the outputs of which are insulated from one another, be used. The different parts of the compound piezoelectric element are connected to the servoamplifier through specially chosen correcting filters. This procedure significantly improves the phase-frequency characteristics of the piezoelectric element-mirror system and increases approximately by an order of magnitude the stable amplification in the feedback circuit.

With this method, it was possible to compensate for the microseismic oscillations appearing in the apparatus with amplitudes ~1 μm in the frequency band above 1000 Hz. Another method for overcoming mechanical noise is use of differential interferometers,[6] which measure the difference in the displacements between two points in the object being studied. In this case, noise caused by translations of the object is eliminated. The requirements on the system compensating for low frequency perturbations in differential interferometers are significantly lower than for the usual interferometers. The tracking system generally need not be used in situations that do not require especially high sensitivity.

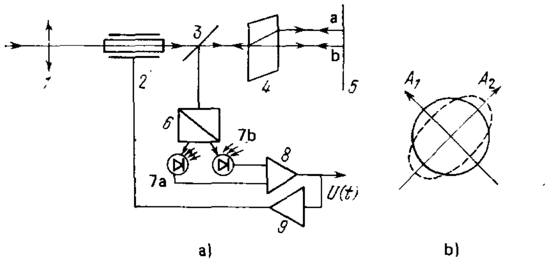
Noise arising from amplitude fluctuations in the laser radiation is decreased by a method for subtracting out noise, for which a special photodetector was used in Ref. 7. An additional interference pattern was used in Ref. 9 for the same purpose. These techniques are especially useful in setups wherein comparatively powerful unstabilized lasers, which have a high level of mechanical fluctuations, are used. Fluctuations in the light frequency lead to the appearance of differences in the optical path and are equivalent to a displacement of the object by an amount

$$\Delta x = \Delta l \frac{\Delta \lambda}{\lambda}, \tag{2}$$

where Δl is the difference in the length of the interferometer arms. A slow frequency drift is not important, since the resulting path length differences are eliminated by the tracking system by displacements of the reference mirror. This noise is in general absent in interferometers having arms of equal lengths ($\Delta l = 0$). In differential interferometers, the difference in the arm lengths is usually very small.

The methods for decreasing the mechanical noise level, enumerated above, are successfully combined in a differential polarization interferometer,[11] used for measuring small dynamic stresses in solids.

A block diagram of the experimental arrangement is displayed in Fig. 1 a. The light beam from a helium-neon laser passes through a long focal length lens 1, focusing the light on the surface of the object 5, and hits the electrooptical modulator 2. The modulator, containing a KDP crystal and oriented at an angle of 45° to the plane of polarization of the incident light, introduces a controlled phase difference between the ordinary and extraordinary rays that arise in it. Having passed through the splitting plate 3, the light beam hits the calcite plate 4, where the ordinary and extraordinary rays are separated in space and are focused at the points a and b in the object, respectively. The distance between the points a and b can be changed by rotating the plate 4. This method for splitting beams in the interferometer by a smooth change in their separation was successfully used[12] for high-precision measurements of the degree of spatial coherence of laser radiation. The light scattered by the object, having passed through the calcite crystal in the opposite direction and reflected from the splitting plate 3, falls on the analyzer 6. The initial phase difference between the beams with orthogonal polarization is chosen with the help of the modulator 2 so that the light incident on the analyzer 6 would be circularly polarized (Fig. 1 b). When the object 5 is stressed, the difference in the paths traversed by the rays changes and the circle becomes an ellipse (shown by the dashed line in Fig. 1 b). The principal surfaces of the analyzer that direct the light to two identical photodetectors 7a and 7b are oriented along the axes of the ellipse. In this manner, a deformation or inclination of the object unbalances the photocurrents reaching the inputs to the differential amplifier 8. The signal $U(t)$ from the amplifier 8 is applied to the recording system, as well as to the servoamplifier of the tracking system 9. The time constant of this circuit can be changed depending on the requirements of the experiment. The signal from the amplifier 9 is applied to the electrooptical modulator so as to compensate for the displacements of the object, restoring the circular polarization of the light at the input to the analyzer 6. In the case of rapid vibrations of the surface of the body being studied, the feedback circuit does not have time to compensate for the perturbation and the corresponding signal appears at the output of the apparatus. A LG-38 laser was used as the light source. The tube discharge current was decreased in order to decrease the amplitude fluctuations. In working with a specularly reflecting object, the laser light flux is attenuated by neutral filters in order to avoid overloading the photodetector. When scattering objects are used, the total light flux can be used.



a)

b)

FIG. 1. a) Block diagram of a differential polarization interferometer; b) nature of the polarization of light at the input to the analyzer.

A high degree of compensation for amplitude fluctuations is achieved in the interferometer due to the total symmetry of the channels. The decrease in the fluctuations at the output of the differential amplifier, com-

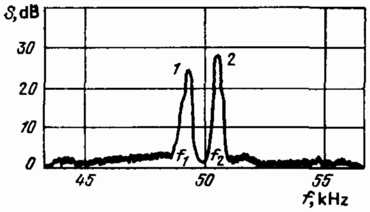


FIG. 2. Spectrogram of the vibrations of a plate, observed through a layer of liquid. 1—spectrum of the vibrations being studied; 2—control signal.

pared with a single channel, attains two orders of magnitude. Nevertheless, amplitude fluctuations remained a limiting factor in studying vibrations with frequencies below 200 kHz.

With the help of the arrangement described above, it was possible to detect reliably vibrations of a piezoelectric plate with a mirror-like surface with an amplitude of 10^{-11} cm at a frequency of 170 kHz with the band-width of the analyzer being $\Delta f = 300$ Hz. Scaling this magnitude to the standard bandwidth of 1 Hz gives an estimate of the minimum detectable amplitude, $a_m = 6 \cdot 10^{-13}$ cm. This scaling, however gives only a rough estimate due to the nonuniformities of the noise spectra.

The operation of a polarization interferometer in the presence of strong external noise is illustrated in Fig. 2, wherein a spectrogram of the vibrations of a light mirror, submerged in a liquid, is shown.

The mirror vibrations at the frequency f_1 were caused by an acoustic wave propagating in the liquid. Observations were made through the free surface of the liquid. The mirror was placed at a depth of 10 cm. The peak at the frequency f_2 represents a control signal created by the modulator. Its magnitude is equivalent to vibrations with an amplitude of $5 \cdot 10^{-7}$ cm and exceeds the noise level of the apparatus by more than one order of magnitude. The basic source of noise in such an experimental arrangement is the irregular motion of the free surface of the liquid, which leads to modulation of the path length difference of the interfering beams. Under usual laboratory conditions, random variations of the optical path length difference significantly exceed a wavelength of the light and make it impossible to carry out interferometric measurements with the usual scheme. The use of a differential interferometer permits, as can be seen from Fig. 2, detecting under such conditions vibrations with amplitudes that are small compared with λ. Of course, the sensitivity of such an experimental arrangement turns out to be much lower than the limiting value.

In conclusion, we will discuss one more possibility for lowering the noise level. In the interferometers mentioned above, the initial difference in the arm lengths (working point) was chosen so as to ensure the greatest sensitivity. This corresponds to a phase shift of $\pi/2$ between the reference and object beams. A change in the initial difference in the path lengths decreases the sensitivity of the apparatus, but the signal-to-noise ratio can sometimes be improved. As noted in Ref. 13, displacement of the working point towards low intensities (i.e. in the direction of the dark band) improves the ratio of signal-to-Poisson noise. A similar conclusion is also valid for noise caused by fluctuations in the laser power. The most promising application of the displaced working point method is for interferomenters that have a symmetrical optical scheme and a differential connection of photodetectors. In a polarization interferometer, such a scheme for making measurements can be realized by changing the construction of the analyzer.

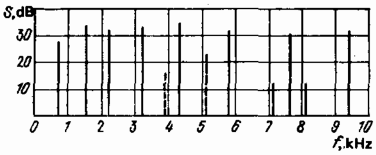


FIG. 3. Spectrum of natural frequencies of a steel plate, obtained with the help of a polarization interferometer.

A polarization interferometer was used for studying small deformations of solids and vibrations of liquid surfaces caused by acoustic waves. Inasmuch as such an apparatus detects the difference in the displacements of two nearby points on the surface, it actually appears as a sensitive gauge for local inclination. The profile of the deformed surface can be reconstructed from the slope distribution. The interferometer makes possible detection of vibrations of the body being studied under conditions when it is difficult to use the usual type of detectors, for example at high temperatures or when the specimen is cooled in a Dewar. The interferometer is especially convenient for studying the spectra of characteristic vibrations. For this purpose, vibrations are excited in the specimen over a wide range of frequencies with the help of a transducer, to which a signal is applied to the analyzer of the electrical signal spectrum. In this manner, the entire spectrum of natural frequencies is detected at the same time and it is easy to see any changes in it. Fig. 3 shows the spectrum of frequencies for a steel plate.[11] The solid lines indicate the principal bending modes and the dashed lines indicate other types of vibrations.

Modern laser interferometers for detecting small vibrations are highly sensitive devices and are successfully used in experiments for studying small vibrations of elastic bodies.

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