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Laser vibrometry based on analysis of the speckle pattern from a remote object

A.A. Veber · A. Lyashedko · E. Sholokhov · A. Trikshev · A. Kurkov · Y. Pyrkov · A.E. Veber · V. Seregin · V. Tsvetkov

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Abstract A novel technique is represented that allows one to measure vibrations from a distant object with micron and sub-micron amplitudes in real time.

The method is based on the speckle interference phenomena and speckle pattern analysis. The scheme allows us to use a single photodiode as a photo-detector and to obtain information from an analog signal without any additional post-processing, which significantly simplifies the device realization compared with the available today laser vibrometers based both on interferometric and on speckle pattern analysis principles.

The scheme investigated was implemented as a device and several studies of the practical applications were carried out.

1 Introduction

Nowadays vibrometry is one of the standard methods of nondestructive testing and it founds a variety of applications. It is used in industry for quality control and optimizing of production; for diagnostics of electric motors and equipment; for construction inspection etc. Besides contact vibration sensors laser vibrometers became more and more widely used because they have several advantages, namely: absence of a mechanical influence on the investigated object, possibility of application for objects difficult of access etc. One of the main advantages is a high sensitivity by amplitude up to 4 pm [1]. Generally laser vibrometers are based on interferometric schemes, which makes a device highly sensitive to object surface quality, to environment factors and to constraints on the mutual location of a vibrometer and object investigated.

There are a variety of nondestructive testing methods based on the analysis of speckle pattern from a remote object. The speckle pattern contains data about relief, deformation, displacement and vibration of the surface [2]. The speckle pattern is an interference pattern being formed when a shaggy surface is illuminated by coherent light. The pattern actually presents a set of high intensity spots. The higher the coherence of the light source the higher contrast of the speckle pattern. The speckle phenomenon is well known and detailed information can be found e.g. in [2].

The schematic of a vibrometer based on the speckle pattern analysis is presented on Fig. 1.

The movement of an object can be represented as a sum of three types of moving: longitudinal to optical axis of receiving system, transversely to the axis and tilt. Let us assume that the surface of an investigated object is flat and rough in the mean and coherent light source and receiving system "looks" normally to the object from the same point. In this case the speckle pattern will be invariable to the longitudinal movement; moves following the object while transverse movement and rotates on the angle of 2θ while the tilt rotates on the angle of θ [2]. As was shown in [3] using the scheme presented on Fig. 1 only tilting can give considerable changes in speckle pattern which can be detected.

Vibration of the object is a superposition of all three types of movement which occur simultaneously. In practice when the object starts to vibrate the appropriate speckle pattern becomes oscillating with a proper frequency and amplitude. Devices based on the analysis of the speckle pattern work on the scattered radiation from the object, and is less sen-

A.A. Veber (✉) · A. Lyashedko · E. Sholokhov · A. Trikshev · A. Kurkov · Y. Pyrkov · A.E. Veber · V. Seregin · V. Tsvetkov
General Physics Institute, GSP-1, Vavilov str., 38, Moscow 119991, Russia
e-mail: alexveb@gmail.com

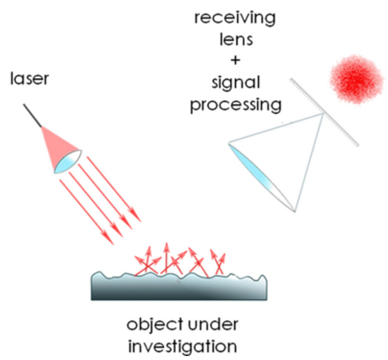

Fig. 1 Common scheme of a vibrometer based on the analysis of speckle pattern

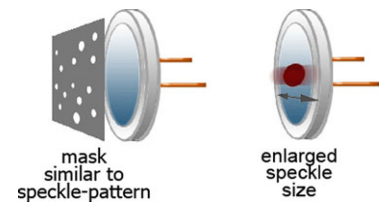

Fig. 2 Possible ways to register speckle pattern oscillations when using a photodiode

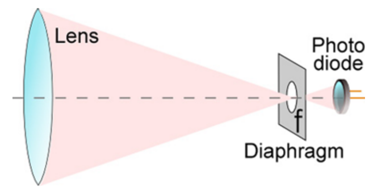

Fig. 3 Receiving system with spatial filter

sitive to fluctuations of atmosphere as compared with interferometric vibrometers; they have fewer restrictions on the object surface and laser characteristics.

Usually these devices include:

1. High-speed video-camera with an appropriate post-processing function, which makes it more expensive and inapplicable for on-line observations. For example Z. Zalevsky et al. implemented a device based on high-speed CCD-camera and successfully applied it for remote listening of human voice etc. [3].
2. Special photodetectors with an amplifier, which allows detecting directly oscillations of either whole speckle pattern [1, 4] or single speckles [5]. Using of non-standard detectors does not allow using this scheme widely.

We propose an optical schematic that enables one to detect the vibrations of a speckle pattern and consequently object vibrations, while using a commercially available photodiode. Our method keeps all the advantages of devices based on the speckle pattern analysis, but it is simple to implement and the sensitivity of the oscillations amplitude is up to 100 nm from a 50 m distance.

2 Experiment

As was mentioned above, there are different ways to record the oscillations: to measure oscillations of speckle pattern as a whole or oscillations of single speckles. While using a photodiode as a detector it is necessary to provide sufficient oscillations of sensitive area irradiance. You can either put a mask in front of the photodiode, which, in an ideal case, has to be the same in structure as the observed speckle pattern, or make the size the photodiode area comparable to speckle size (Fig. 2). In the both cases, changing of speckle pattern will result in changing of photocurrent, which can be easily detected by common methods.

3 Experimental setup

In our research we tested both proposed schemes. At first the investigations of registration of single speckle oscillations by photodiode was carried out. Increasing of the speckle size by varying of lens seems to be the easiest way in this case. However, this method is hard to realize due to insufficient irradiance of the active area of photodiode and the low value of the signal.

To overcome these restrictions it was proposed to place a low frequency spatial filter (diaphragm) at the focal plane of the lens. Thereby on the surface of the photodiode only larger speckles remain, of which size and quantity depend on the sizes of the spatial filter.

The scheme of measuring system was as follows: in the image plane of the lens with focal distance of 7 cm and 5.6 cm in diameter the Ge-photodiode was placed, in the focal plane was placed a diaphragm (Fig. 3). T he minimal distance to the object in this case was 5 m; therefore the image plane is almost invariable while increasing distance to the object and the photodiode position was fixed. Collimated emission of the cw single-mode, not a single-frequency Yb^{3+}-fiber laser ($M^2 < 1.1$, $\lambda = 1.08$ μm, FHWM = 0.2 nm) was used as a coherent light source. Since single-mode operation spatial coherence is high, the coherence length is about 0.5 cm. Output power of the laser was varied in the range of 0.1 to 1.5 W. The received signal was amplified by the low-noise audio pre-amplifier and was registered by conventional audio card of a PC. As a source of vibrations a loud-speaker was used. The schematic of the experimental setup is presented on Fig. 4.

It was found experimentally that the 50-μm diaphragm has been optimal in terms of the signal-to-noise ratio; about 10 speckles falls on the photodiode surface in this case (Fig. 5). When reducing the diameter of the diaphragm the

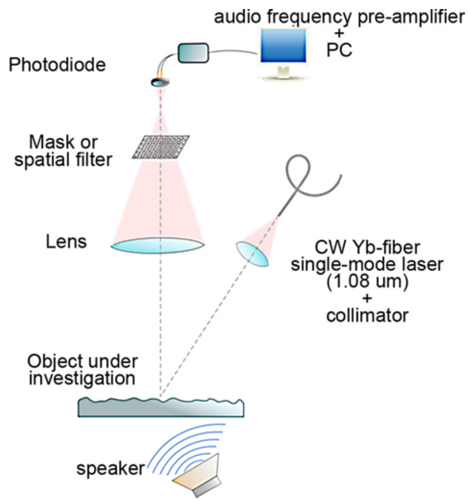

Fig. 4 Experimental setup

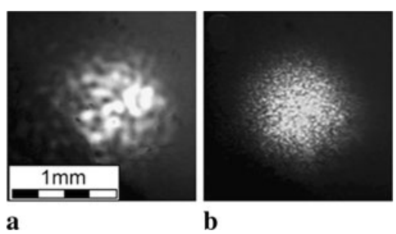

Fig. 5 Observed speckle pattern at the photodiode surface: (**a**) with spatial filter; (**b**) without spatial filter

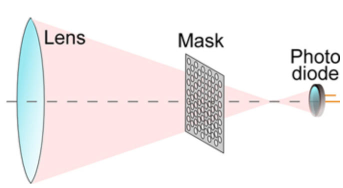

Fig. 6 Receiving system with a mask

useful signal decreases significantly otherwise the amount of speckles on the photodiode and noise are increasing.

However, if we compare the size of the observable speckle pattern with active area of the photodiode (3 mm) it becomes clear that the observable photocurrent changes cannot be the result of speckles moving over the surface of photodiode but the result of moving speckle pattern over the diaphragm surface. In this case the key function of the diaphragm is a mask but not a filter.

As the next stage of research, the optical scheme with application of a mask (hereinafter scheme B) placed between lens and photodiode was implemented (Fig. 6).

A long-focus lens with $f = 250$ mm and aperture $f/3.5$ was used as a receiver lens. To adjust to the object the focusing ring of the lens was used. The speckle pattern strongly depends on the parameters of the studied object, therefore

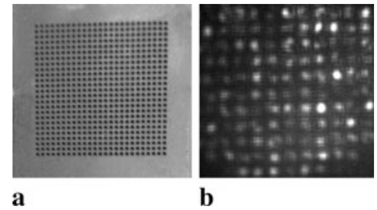

Fig. 7 (**a**) Mask used in the scheme B; (**b**) observed image after the mask

in the general case it is impossible to place the mask of the same structure before the photodiode.

It should be noted that the size of speckles is determined by several parameters: parameters of the lens used, the observation plane of speckle pattern, laser wavelength and a degree of radiation coherence. The mask represented the set of regularly arranged holes with a diameter of 0.4 mm (Fig. 7a); it was placed between receiving lens and photodiode in a rather arbitrary position. In this case additional Fraunhofer diffraction of the speckle pattern due to mask occurs [6] and a number of beams with different intensity are observed after the mask (Fig. 7b).

Hamamatsu G8421-03 InGaAs photodiode was used as a photodetector. The same Yb-laser was used as a coherent light source.

The use of mask allowed one to measure oscillation of several speckles simultaniously and we got a much higher signal-to-noise ratio compared to scheme A.

3.1 Device implementation

Both principles have been implemented as a device. The device made by scheme A (Fig. 8a), hereinafter device A, consist of two units: laser unit (below) and receiving unit (on top) which are connected to each other by precise tilt stage. Due to the use of 50-µm diaphragm a rather precise alignment of the two parts is necessary.

The use of a mask greatly simplified the design and allowed us to make the device in a single package (Fig. 8b), hereinafter device B. This design does not require accurate alignment.

4 Experimental results

Some experiments were carried out to compare the two devices, to estimate sensitivity and to find possible applications.

4.1 Frequency analysis of different materials

In these experiments device A was used to measure forced oscillations of different materials. We used the loud-speaker test signal, influencing the object investigated. The signal

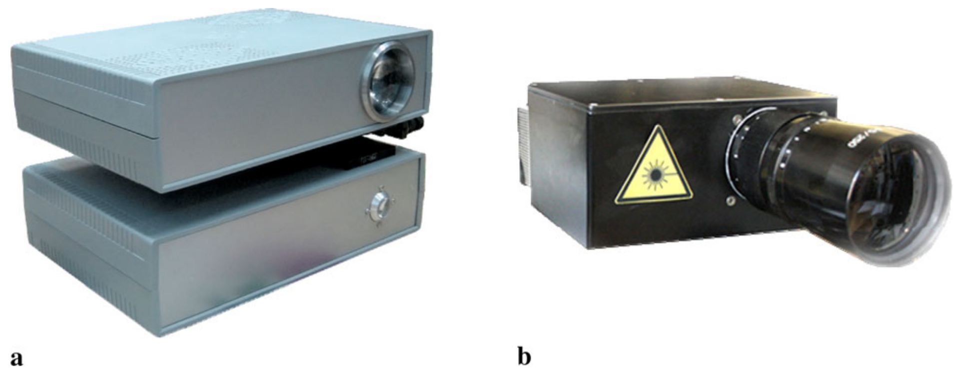

Fig. 8 Implemented laser vibrometers: (**a**) the scheme based on the spatial filter (300 × 200 × 260 mm). (**b**) Scheme based on the mask (220 × 340 × 110 mm)

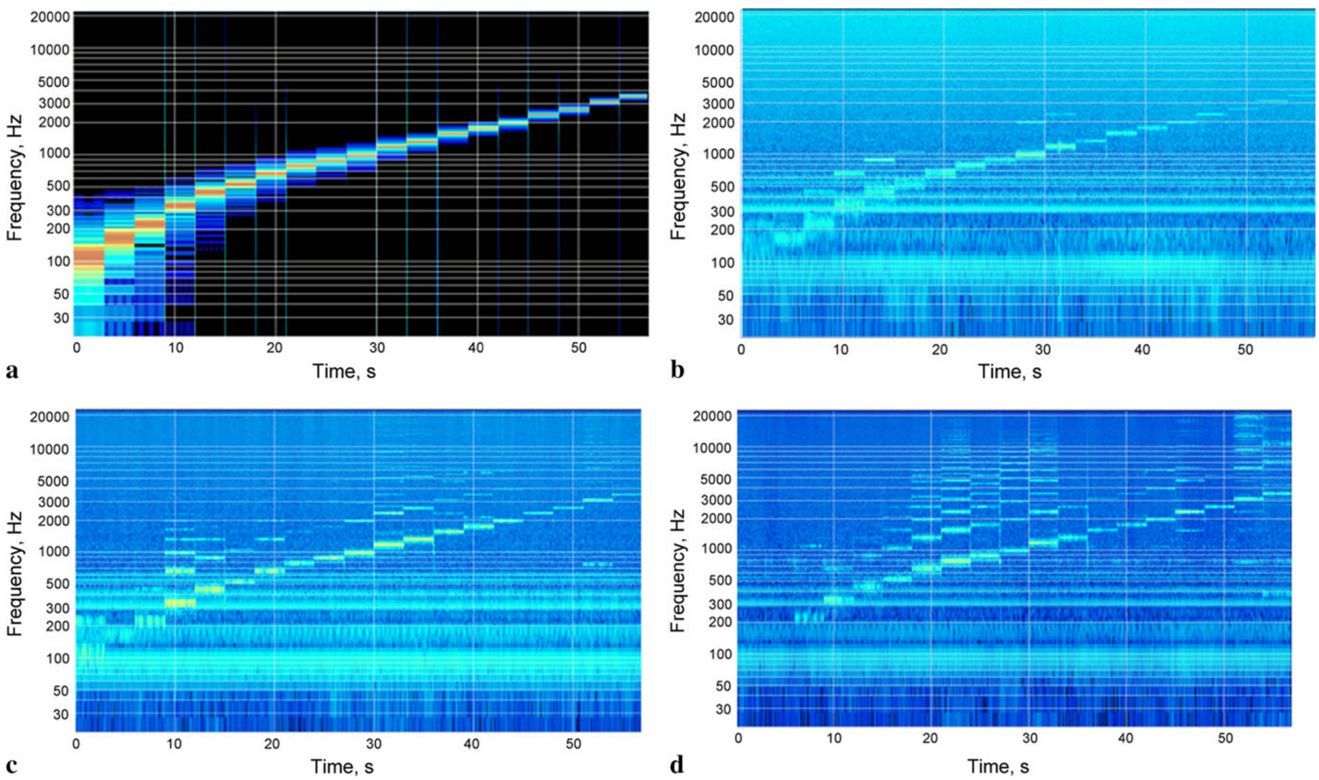

Fig. 9 Spectra of test signal (**a**) and obtained signal from paper (**b**), cellophane (**c**), ash (**d**)

was the set of sound segments with increasing frequency (Fig. 9a). The laser beam and the receiving lens were aimed on the same point of the object and oscillations were measured from a distance of 5 m. This experiment was carried out for various materials: paper, foil, cellophane, plywood etc.

Spectra of paper, cellophane and ash are shown on Figs. 9b, c and d, respectively. It is seen that the influenced frequencies remain in the spectra but additional frequencies, depending on the resonance properties of materials, have appeared. Signal intensity and signal-to-noise ratio also depend on the material of investigated object and can be characterized by contrast on Fig. 9.

A permanent signal at 100, 160, 300, 400 Hz is a result of self-vibration of the device due to an active cooling system. This disadvantage was eliminated in device B by using of passive cooling.

The cellophane vibration spectrum exposed by sound of 3136 Hz is presented on Fig. 10. Obviously it is a proper frequency of the investigated sample and exciting of other proper oscillations was observed.

Thus the device can be used to measure the response of different materials under external influence. This can be applied to find various defects which change the frequency properties of the investigated object.

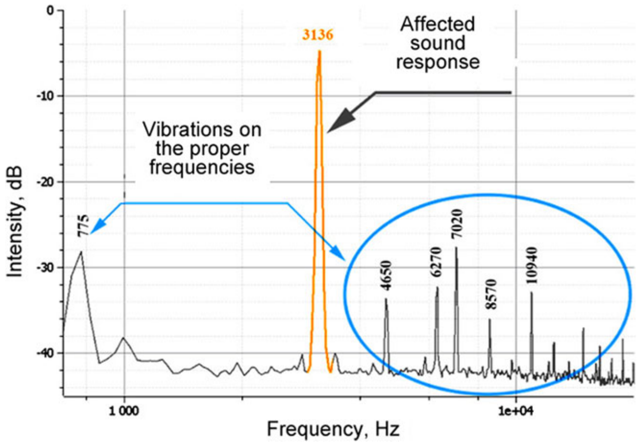

Fig. 10 Cellophane vibration spectrum exposed by sound of 3136 Hz

4.2 Sensitivity estimation and comparison of two schemes

The sensitivity and operating range of the devices were not measured directly, but they could be estimated from the experiment mentioned above. The sensitivity is enough to sense the oscillations of a sheet paper (with density 80 g/cm^2) under the influence of sound pressure of 50 dB (low human voice). The amplitude of the oscillations in this case is theoretically estimated to be ~ 0.1 µm. Devices A and B are able to measure the signal from a distance of 10 m and 50 m, while using the laser output power of 1.5 W and 0.5 W, respectively. The considerable disparity of sensitivity might be explained by differences in receiving lens and photodetectors, as the Ge-photodiode (scheme A) is less sensitive to 1.08 µm radiation. The experiment proved that the scheme with a spatial filter (scheme A) is less effective even under the same conditions.

The sensitivity in current implementation of the device is about one order lower than in Chen-Chia Wang et al. work [1] and can be compared with Zalevsky et al. device [3]. We suppose that the sensitivity can be improved considerably in future, e.g. by using of lock-in amplifying technique.

To obtain precise information about operating range and sensitivity direct measurements are needed.

Background noise of devices is strongly dependent on the stability of the used laser output power. Main condition in this case is the absence of any fluctuations in preferable frequency range, otherwise additional noise peaks or bands will occur due to laser. In used Yb-fiber laser no fluctuations of output power were detected in the frequency range of 100–10000 Hz to within 0.01%.

The signal-to-noise ratio was 2.5 and 12.6 for devices A and B, respectively. These measurements were done at 50 dB sound pressure to the sheet of paper. The distance from the object was 20 m in both cases.

It is important to note that the signal was obtained directly from the device without any additional processing. The frequency range was limited only by the pre-amplifier and was 200–5000 Hz. 1.08 µm laser was used but any other wavelength was also suitable with appropriate photodetector.

5 Conclusions

The novel design of a laser vibrometer based on speckle pattern analysis from a remote object is proposed in the paper. The scheme is simple and can be fully implemented on commercially available components. The signal obtained from the device does not need additional processing which makes it possible to use such devices for on-line diagnosis and monitoring.

Devices based on the proposed scheme can be successfully applied to solve various vibrometry problems with appropriate calibration and minor refinement.

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