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Optical fibre interferometric system for Doppler effect measurement

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A novel idea of optical fibre laser Doppler velocimetry especially useful for non-contact testing of rotation elements is presented. The main idea of the system is based on an application of interferometric measurement of Doppler effect by a specially constructed optical fibre interferometer. The standard single-mode coupler, connected with laser diode operated at 0.68 μm, has been used as the main optical element. A suitable selection of a target distance from the specially constructed optical head makes the system work as a single-reflection Fabry-Perot fibre interferometer. Such device provided polarisation stability as well as good environmental shielding. The special numerical processing of interferometric output signals by a technique based on FFT gives a possibility of rotation element testing. The theoretical investigation was compared with experimental data obtained for the commercially available magnetic hard disc and the dynamically tuned electromechanical gyro.

Keywords: optical fibre interferometry, laser Doppler velocimetry, vibrometer.

1. Introduction

The optical fibre laser Doppler velocimetry (LDV) is a technique used for the velocity measurement of fluid flows. The two-dimensional directional LDV using a special technique based on generation of heterodyne signals of differential carrier frequencies has been described in literature [1,2]. The capability of simultaneous measurement of three orthogonal velocity components has also been presented in 3D LDV fibre optic system using wavelength and time division multiplexing techniques [3–5]. Recently, the presented system, based on optical fibre low-coherence interferometer, gives a possibility of measurement of the velocity distribution along depth, directly from a width of the Fourier spectrum of the interference signals [6]. Development of the above technique is based on a velocity vector component measurement directly from a peak position of correlation signal between two backscattering lights [7]. Other LDV applications are vibration measurements, by an unbalanced Michelson interferometer [8], self-mixing interference effect [9], or electronic speckle pattern interferometer [10].

In all the above situations, a compact and a simple probe is feasible by introducing optical fibres into the system. However, the use of optical fibres introduces the problems with obtaining efficient and stable system. If fibre LDV is used for a detection of moving surface [11], the use of interferometric Michelson configuration with polarisation maintaining fibre [12] or special interferometric processing [13] is needed for environmental stability and elimination of high frequency detection, respectively. Recently, fibre optic sensor using a frequency modulated laser to simultaneously measurement of both the position and velocity of a refracting target has been presented [14]. However, this system needs an expensive FFT spectrum analyser operating for sufficiently high resolution.

In this paper, we present theoretical and experimental results of a new LDV system using single-reflection Fabry-Perot (SRFP) fibre interferometer. The special design of a compact optical head provides polarisation stability, as well as good environmental shielding. The unique numerical processing of interferometric output signals by the technique based on FFT gives an easy possibility of rotation element testing – especially ‘face run-out’ of spinning disc or precession parameters of the whirling mass. The experimental data obtained for the commercially available magnetic hard disc and the dynamically tuned electromechanical (DTEM) gyro are presented as examples of the system application.

2. Principle of operation

Usually the fibre single-mode directional coupler is used as Michelson interferometer for Doppler effect measurement. In this paper, the above configuration has been modified to obtain a sensor which operation is based on optical fibre Fabry-Perot interferometer. The basic principle of this sensor is illustrated in Fig. 1. A coherent light from laser source is introduced into a single-mode directional coupler, one output end of which is inserted to immersion oil to attenuate reflected beam. Then, the only optical beams exist-

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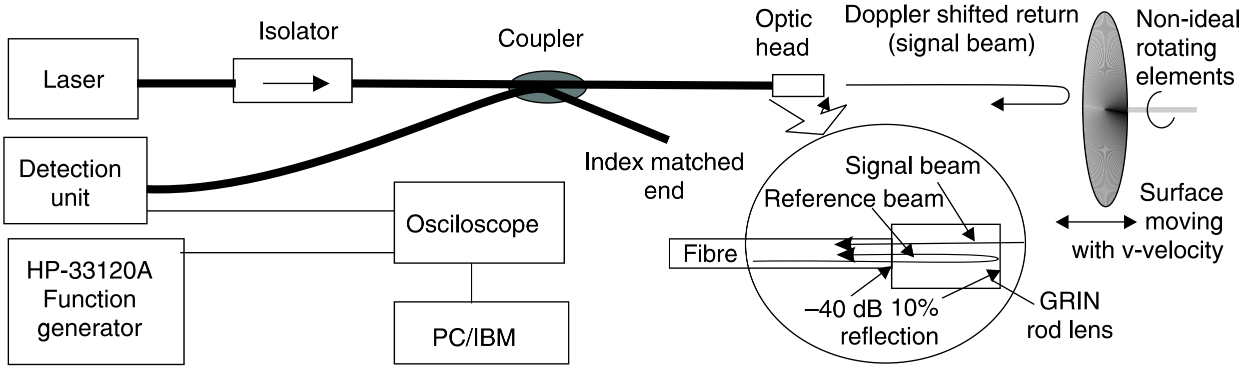

Fig. 1. Schematic view of the SRFP fibre interferometer.

ing in the second output arm can interact. This fibre arm contains special optical head at its end, which collimates output beam on moving target and reflects about 10% of beam (Fresnel reflection) from output surface of the head. The optical head includes GRIN rod lens glued to optical fibre with a low inherent back reflection (< –40 dB). Thus, light beam reflected from the target (signal beam) is coherently added to the Fresnel reflected one (reference beam), and this signal reaches a photodetector via the same coupler. Till now, the presented system is equivalent to the system previously described in Refs. 11, 12, 13, and 14. The novelty of the presented system consists in suitable choosing of the target distance from the optical head. For a proper system operation, this distance should fulfil the following condition

$$\frac{L_c}{2} < 2d < L_c, \tag{1}$$

where L_c is the coherence length of the used sources and d is the distance between an optic head and a moving target.

Then, from the beams set occurring in a cavity between the target and optic head surfaces, only the first reflected beam can coherently interact with the Fresnel reflected beam. Of course, such approach needs a suitable selection of a laser source for a given application and can limit it substantially. However, such a system is in fact a single-reflection Fabry-Perot (SRFP) fibre interferometer where both interacting beams propagate continuously in one optical fibre in the same time and direction, thus they have identical polarisation states. Moreover, they feel the same external environmental perturbations, hence such fibre interference protects polarisation stability and good environmental shielding [12].

For a moving target, the reflected (signal) beam undergoes a Doppler shift which can be easily decoded by a suitable signal processing. The interferometric processing by an applied additional optical fibre Mach-Zehnder interferometer (MZI) has been described in Ref. 13. Such a method operates over a wide range of target velocities; unfortunately it needs good shielding of MZI and is optically complicated. The second approach is presented in Ref. 14, where a frequency-modulated laser and FFT spectrum analyser have been used to simultaneous measurement of both distance and velocity of the target. However, simplicity of the optical part of this system is achieved at the expense of an electronic complexity. As opposite to these methods, the numerical processing of detected interferometric signal has been used. This method (see Fig. 2) is based on application of the unique algorithm of discrete fast Fourier transformation (DFFT) [15]. First, after application of a classic FFT procedure, a special spatial filter is applied. This filter, based on the Euler relation between trigonometric and complex exponential function representation, takes only half of the frequency spectrum (positive or negative components) for further calculation. Such ob-

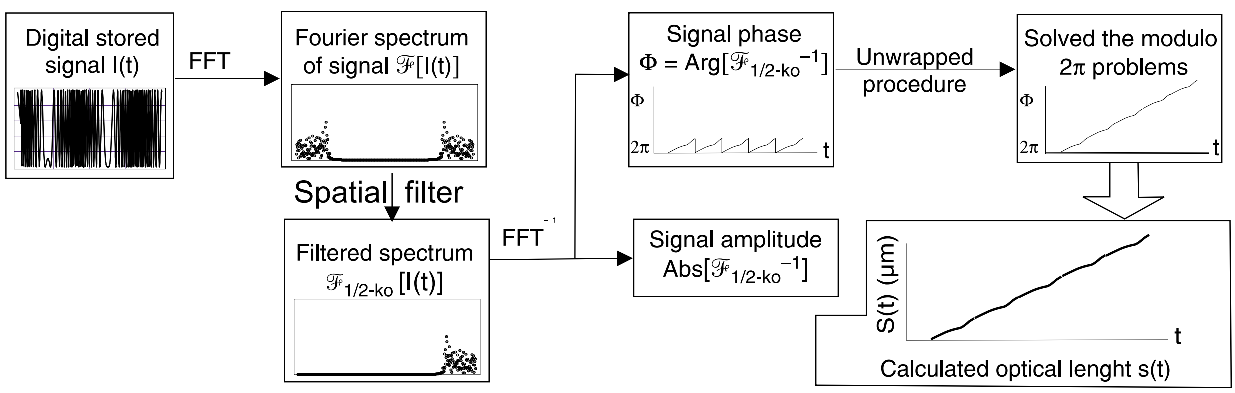

Fig. 2. Diagram of applied DFFT method.

tained data ($\mathcal{F}_{1/2\text{-ko}}$) are used for inverse Fourier transformation (FFT^{-1}). Next, only the phase component of FFT^{-1} ($\Phi = Arg[\mathcal{F}_{1/2\text{-}ko}{}^{-1}]$) is used. For it, the procedure named 'unwarapphase' from *Mathematica* programme (Wolfram Research) has been used. This solves modulo 2 problems existing in a classic interferometric system. Finally, the easy procedure of optical path calculation from phase is used. Such an approach gives a simple and cheap system which secures good measurement accuracy.

3. Theoretical analysis of SRFP fibre interferometer

Usually the Doppler effect is treated as frequency changes. However, in reality, this effect is connected with the changes of the space-time vector of moving wave, thus gives the changes of wavelength. Such approach needs to be analysed including the Lorentz transformation. The physical situation is schematically shown in Fig. 3.

The signal detected by the detector consists of the results of interference between the signal beam E_s (the wave reflected from the moving surface), and the reference beam E_r (the wave reflected from the end face of GRIN rod lens). Because the physical situation is connected with moving in one direction only, (parallel to the axis x and ζ see Fig. 3), therefore in the analysis one-dimensional model is used.

Hence the reference beam has the following waveform

$$E_r = A_r \exp[-i(\omega t + \pi)], \tag{2}$$

where A_r is the amplitude of reference beam, ω the light frequency, t is the time connected with reference beam, and π is the phase connected with reflection from GRIN output surface. The signal beam, reflected from the moving surface, that is initially located at the distance d from optical head and moving with the velocity v in the direction parallel to the signal beam, has the form

$$E_s = A_s \exp[-i(\omega \tau - k\zeta + \pi)], \tag{3}$$

where A_s is the amplitude of the signal beam returned to optical head, $k = 2\pi/\lambda$ λ is the wavelength, (τ, ζ) is the time and space in moving co-ordinate system.

On the basis of the Lorentz transformation, the variables (τ, ζ takes the form

$$\zeta = \frac{x + vt}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}; \quad \tau = \frac{t - \frac{vx}{c^2}}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}. \tag{4}$$

Finally, the signal beam of Eq. (3) has the following form

$$E_s = A_s \exp\left\{-i\left[\frac{2d\left(k + \frac{kv^2 + 2v\omega}{c^4}\right) + t\left(2kv + \omega\left(1 + \left(\frac{v}{c}\right)^2\right)\right)}{1 - \left(\frac{v}{c}\right)^2} + \pi\right]\right\}. \tag{5}$$

If the amplitudes of the above beam are equal to each other ($A_r = A_s = A$), then, the detection unit measures interference of those waves as intensity changes described by the following form

$$I = (E_r + E_s)(E_r + E_s)^* \sim 2A^2\left[1 + \cos\left(\frac{2d\left(k\left(1 + \left(\frac{v}{c}\right)^2\right) + \frac{2v\omega}{c^2}\right) + 2tv\left(k + \frac{v\omega}{c^2}\right)}{1 - \left(\frac{v}{c}\right)^2}\right)\right]. \tag{6}$$

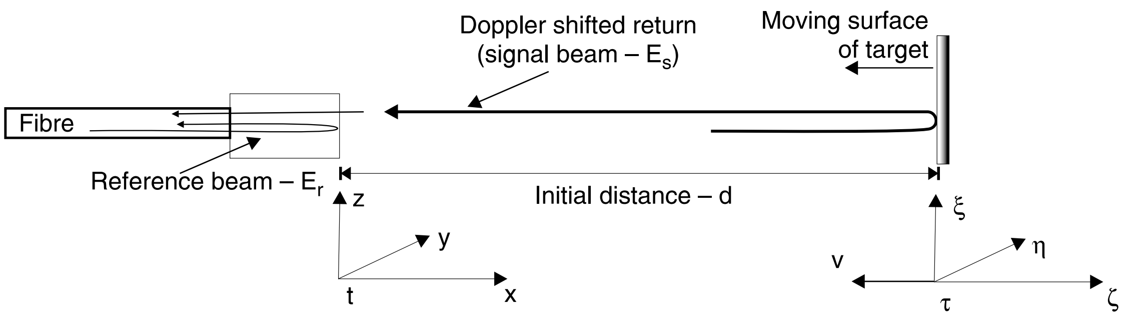

Fig. 3. Scheme of physical situation.

If the detected velocity is small, in comparison with the light speed (v<<c), the above relativistic relation is

$$I = 2A^2\left\{1+\cos\left[\frac{4\pi}{\lambda}(vt+d)\right]\right\}. \tag{7}$$

It can be seen from the last formulae that the constant velocity (v = const) gives classical Doppler frequency shift $f = 2v/\lambda$ [5] Then, a rotation frequency of the target can be simply measured by application of standard synchronic detection using external function generator, as shown in Fig. 1. On the other hand, for varying v, one can obtain from Eq. (7) the following relation

$$I = 2A^2\left[1+\cos\left(\frac{4\pi}{\lambda}\int_0^t v dt + \frac{4\pi d}{\lambda}\right)\right], \tag{8}$$

where integral value is equal to the path of the movement in the direction parallel to light propagation, so flatness variation of the surface at the target face can be measured.

This information is recognised from interferometric output signal by the DFFT processing technique. If, for instance, the flatness variation is caused by simple non-perpendicularity of rotating surface to the axis of rotation, the SRFP system sees it as the following movement path

$$s(t) = \int_0^t v dt = a\sin(2\pi ft). \tag{9}$$

where f is the frequency of target rotation and a is the maximum value of the surface moving in measuring point, with respect to the target face in rotation axis. The distance a can be treated as 'face run-out' for the given measuring point. Then, detected interferometric signal has periodic multi-components, see the example in Fig. 4(a).

The application of DFFT processing of the one registered period [Fig. 4(b)] gives a possibility of receiving the 'face run-out' distribution with theoretical method accuracy shown in Fig. 5. As one can see, the worst accuracy is obtained for vanishing v-moves, which is related to point of absolute value of 'face run-out' calculation. On the other hand, the relative minimal error exists for maximum v-moves, i.e., when the target surface is in perpendicular position to the rotation axis. In general, the theoretically calculated relative error of the applied method is in the range 0.5% to 0.1%, and depends on non-perpendicularity

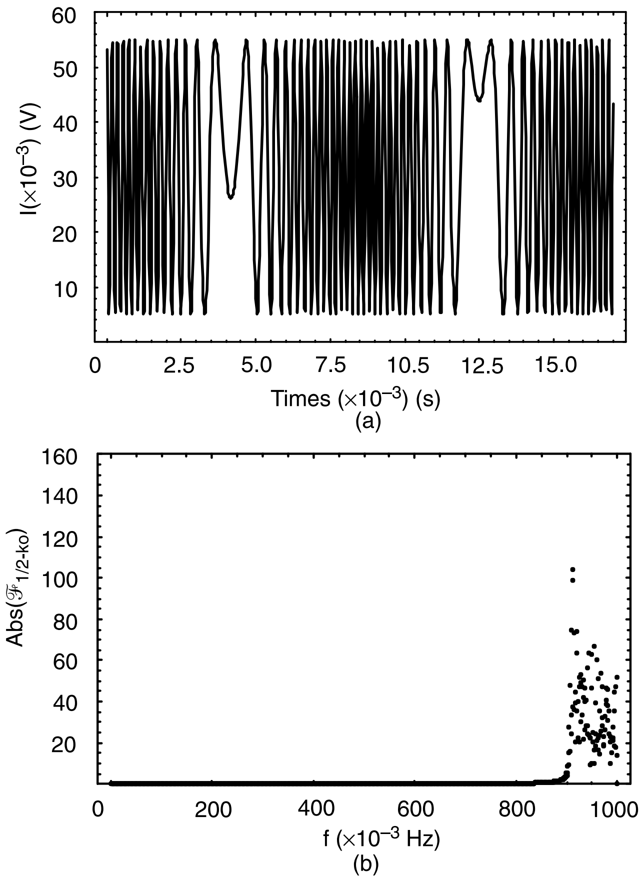

Fig. 4. Numerical simulation of detected signal for assumed simply non-perpendicularity of rotational disc with respect to the rotation axis (a) and its Fourier spectrum amplitude after applied filter (b).

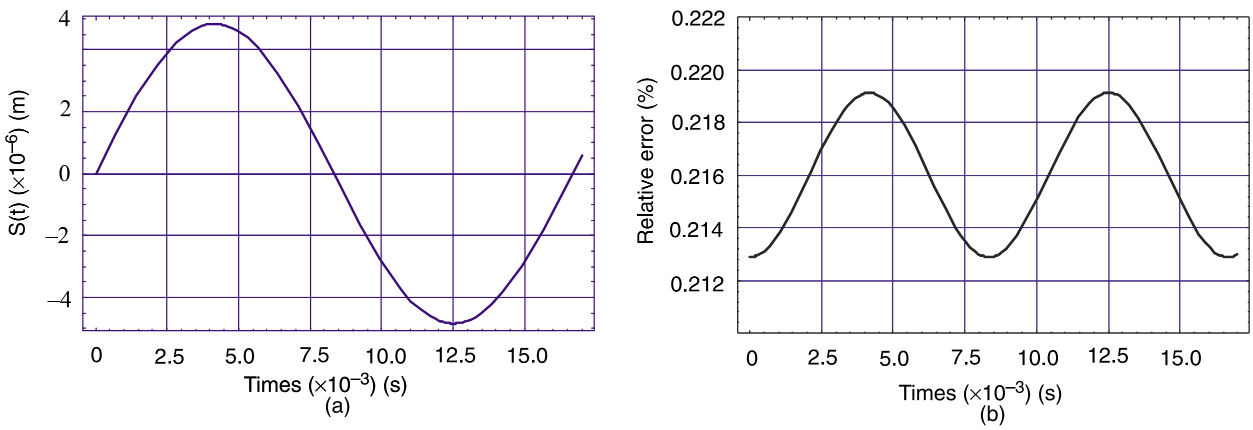

Fig. 5. Theoretically calculated 'face run-out' in dependence on time (a) and the method accuracy (the relative error changes in dependence on time) (b).

of disc with respect to the rotation axis. High accuracy of the presented method, different from well know accuracy of classic laser vibrometers [16], is due to high sensitivity of interferometric nature of measurement.

Moreover, the same numerical processing of measured signal for many periods makes it possible to calculate the precession angle of whirling mass as the changes of initial phase of consecutive periods because in such a situation the detected signal, Eq. (9), contains the time dependent amplitude a with a period significantly larger then a rotation one.

4. Experimental results

Experimental system employs the laser source operating at 0.68 µm with coherence length about 0.3 m and special 3 dB X-type fibre coupler made by single-mode fibre (UMCS-Lublin) with $\lambda_c = 0.62$ µm. The optical head used GRIN rod lens producing a collimated beam diameter of 0.5×10^{-3} m. This GRIN rod lens was connected with the fibre end with low (< –40 dB) back reflection using special glue and additionally prepared antireflection layer on a GRIN surface. Mainly, the optical head has produced the measured total system loss of 11.2 dB. The system was initially tested using a linearly moving mirror as the test object [see Fig. 6(a)]. This represented a well-defined system which is readily calibrated. The data points shown in Fig. 6(b) represent the calculated values of mirror move with a constant velocity of 0.08×10^{-3} ms^{-1}. Similar results have been obtained for different mirror speeds. Those results have shown good linearity of DFFT method used for calculation.

The SRFP optical fibre interferometric system has been used for testing rotation parameters of classical magnetic hard disc (see Fig. 7) and dynamically tuned electromechanical (DTEM) gyro (see Fig. 8). The latter device is used as artificial horizon in the air force training plane. The rotation speed equal to 3 600 and 17 650 turns/min has been obtained for the magnetic disc and DTEM gyro, respectively. These results have been obtained by applying the standard synchronic detection with external function generator HP-33120A, as shown in Fig. 1. Thus, using the SRFP fibre system gives simply non-contact method for measurement different rotation elements especially for high value of a rotation speed.

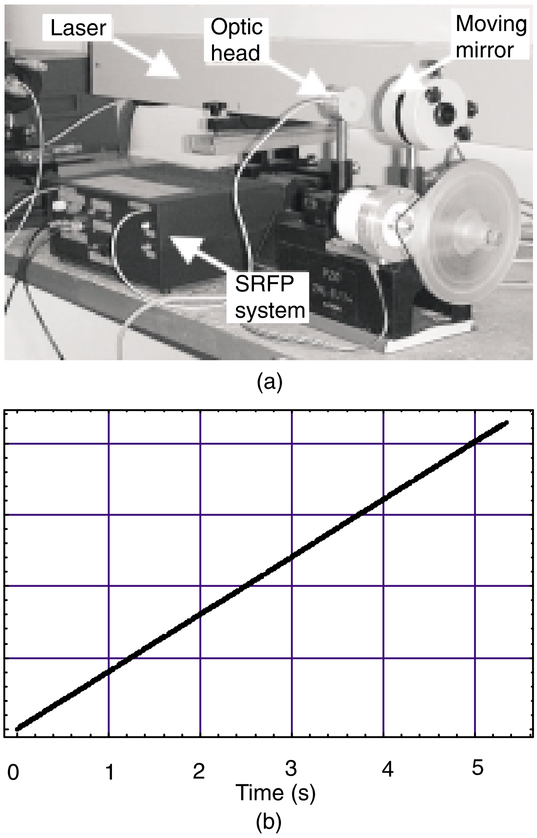

Fig. 6. General view of the SRFP system tested by controlled linear moving mirror (a) and obtained values of mirror move (b).

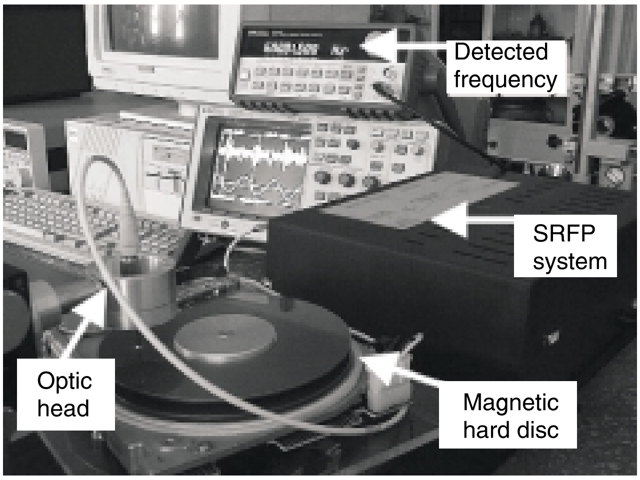

Fig. 7. View of SRFP system with measured magnetic hard disc (detected rotation speed 3600 turns/min).

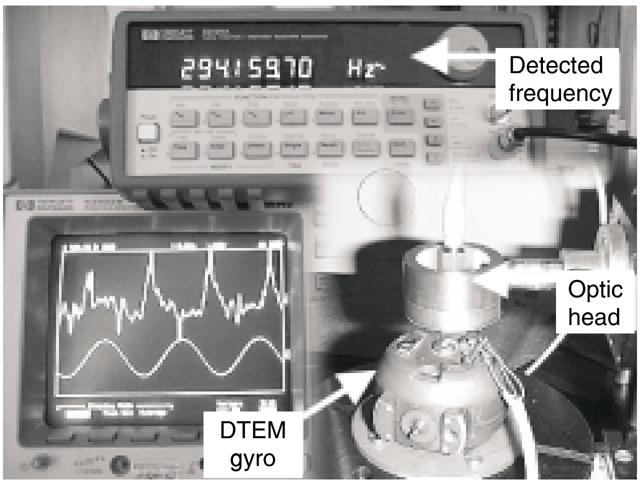

Fig. 8. View of SRFP system with measured DTEM gyro (detected rotation speed 17650 turns/min).

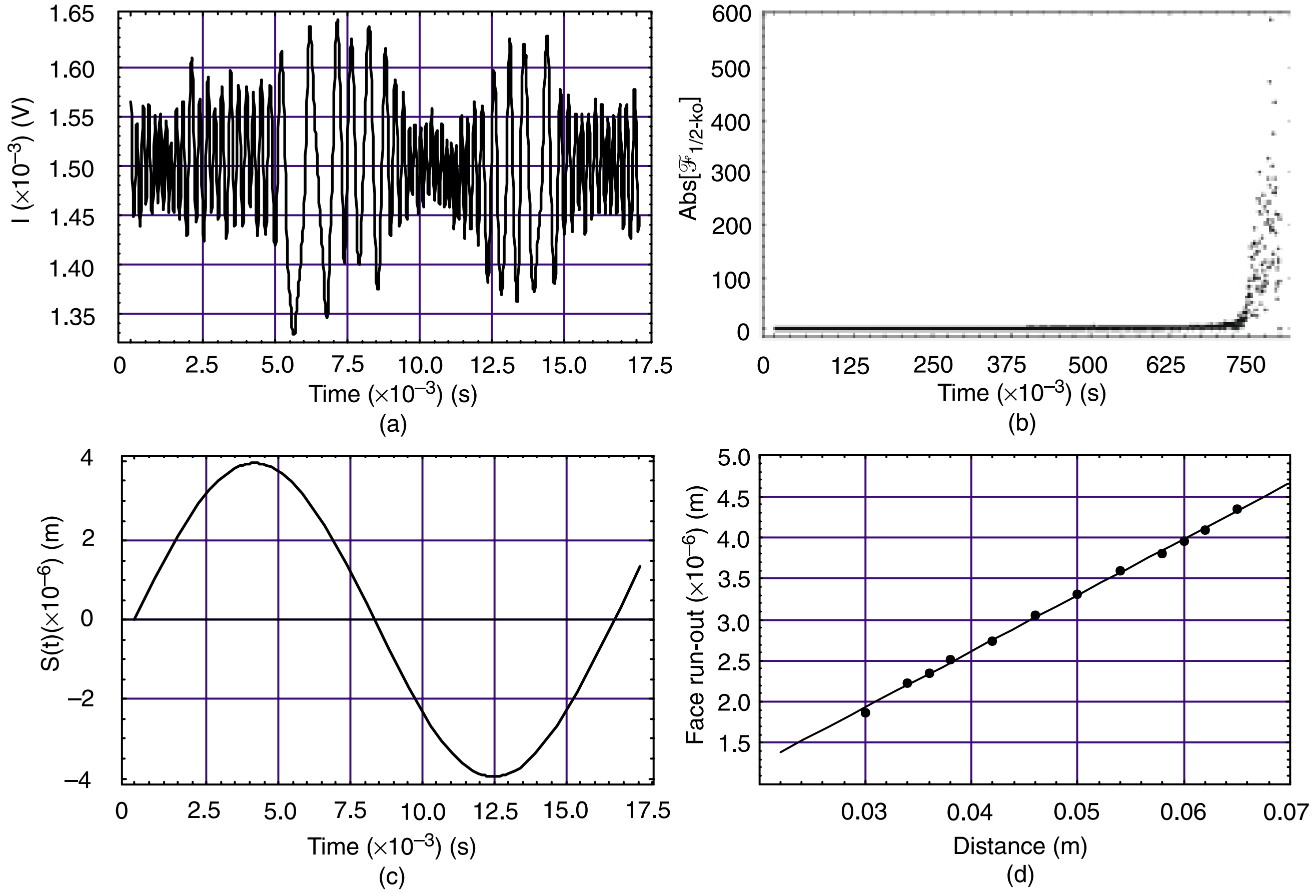

Fig. 9. Experimentally obtained signal for magnetic hard disc (a), its Fourier spectrum amplitude after filter applied (b), calculated value of 'face run-out' (for distance 0.06 m) (c), and calculated disc surface deviation (d).

The interferometric signal, presented in Fig. 9(a), has been used for calculation of non-perpendicularity of disk surface with respect to the rotation axis. The example of this calculation for the measured point placed near the outside border of the disk (equal to 0.06 m from a disk centre) is presented in Fig. 9(c). As one can see from the results presented in Fig. 9(d), the value of this parameter is 1.87 μm and 3.95 μm for the measured point placed at the distance 0.03 m and 0.06 m to the disc centre, respectively. For simplifying the assumption that there exists only deviation of disc surface from perpendicularity to rotation axis, this value gives the deviation angle of 4×10^{-3} degree [see solid line in Fig. 9(d)]. The calculation made with different registered periods of the detected signal gave the same results with relative error of 4.02%. The vibration of optical head during measurement has been identified as the main source of error increase.

The experimental investigation of dynamically tuned electromechanical gyro has shown that its rotation speed has similar fluctuations. Taking into consideration the phase relation between consecutive periods of the registered signal (see Fig. 10), the precession angle and frequency equal to 9.7×10^{-4} deg, and 0.6 Hz has been obtained, respectively. As a source of this effect, the clearance of bearings has been identified.

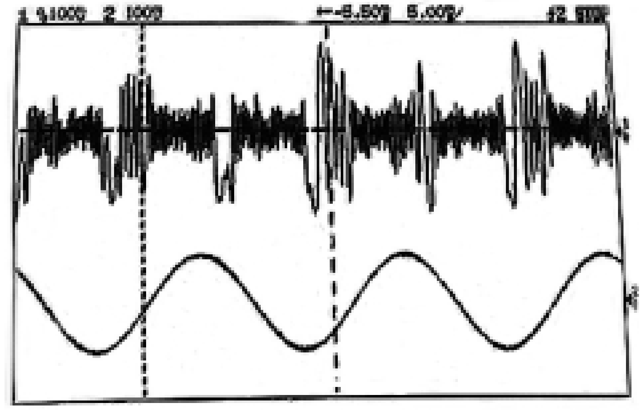

Fig. 10. The multi-period signal (upper) detected for the DTEM gyro used for precession angle calculation. Lower signal – signal used by synchronic detection (HP-33120A).

5. Conclusions

A different look on the possibility of Doppler effect measurement as an interference with time-changed optical path has been presented. The Doppler effect always exists in the interference phenomena where an optical path is time dependent, but many authors do not use it in this approach. The new design of fibre-optic interferometer in single-reflection Fabry--Perot configuration makes possible to test 'face run-out' and precession parameters of whirling mass and spinning disc with high accuracy. The special design of optical head has secured polarisation stability as well as good environmental shielding. Of course, the presented system can be used only for target of sufficient reflecting surface but no mirror surface is needed (in practice a few percent reflection is enough). To ensure the light is scattering back to the receiver optics, the scattering surface will be sufficiently diffused for a speckle pattern to be formed. This speckle pattern repeats with every rotation of the target and produces a pseudo-random instrument output, periodic at target rotation frequency. If the surface is rough, any Doppler effect would be lost in random fluctuations. The limitation for distance between optic head and target might be main disadvantage of the presented SRFP fibre interferometer system. Thus, the source with suitable coherence length should be used. A bigger cost of such a source is partially compensated by simplicity as well as low cost of other system elements. The application of this system for testing devices rotating at a very high speed such as disc-type, molecular and other centrifuges will be published.

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