Synthesis of Spatially Periodic Multi-Harmonic Optical Field for Laser Doppler Blood Flow Meter

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Abstract - The application of a synthesized spatially periodic multi-harmonic optical field in a laser Doppler anemometer is considered. The present technique is aimed at increasing the velocity measurement range of the instrument. This is particularly important in blood flow measurement applications. The probe field is formed by the holographic technique employing the static periodic wavefront modulator and the field-forming hologram. By proper selection of the parameters of these components, the probe field with pronounced high-order spatial harmonic content is obtained. This results in the presence of several Doppler frequency harmonics in the output signal. One of the harmonics, which fits into the input span of the Doppler frequency processor is used for velocity determination. The results of mathematical and physical modeling of the multi-harmonic optical field are presented.

Key-Words: - Correlation synthesis of optical fields, Holography, Laser Doppler Anemometry, Fiber optic sensors.

1 Introduction

Laser Doppler anemometry measures velocity of objects through Doppler shift of laser light [1]. In the differential-type Laser Doppler Anemometers (LDA) [2], the stationary spatially periodic optical field of a quasi-sinusoidal intensity distribution is used as an instrument virtual probe. The stationary spatially periodic optical field in differential-type LDA is usually obtained by interferometric techniques. The spatial period of the probe field relates the Doppler frequency shift f_D to object velocity in accordance to the following expression

$$f_D = v/\Lambda,$$

v is the object velocity in the direction of field variation.

In many important applications the object velocity varies with time in a relatively wide range, this resulting in correspondingly large Doppler frecuency variations. This presents a serious problem in Doppler signal processing because of a limited input frequency span of any practical electronic Doppler signal processor. In addition, the signal amplitude and the signal to noise ratio in the LDA is inversely related to signal frequency. This results in the uneven accuracy over the LDA operational range. In particular, in reduced accuracy in the measurement of relatively large velocity.

The large ratio between the maximum and minimum velocity is frequently encountered in some biomedical applications of LDA, in particular in laser plethysmography [3], Doppler skin perfusion imaging [4], cell protoplasm velocity measurement, etc. In these applications, the maximum flow velocity $v_{\max}$ typically is not very large (1-30 cm/s). But the minimum flow velocity of interest is usually very small ($v_{\min} \rightarrow 0$). This results in a very large ratio $v_{\max}/v_{\min}$ and, consequently, in significant difficulties in Doppler signal processing.

As we show later in this paper, using the periodic optical field composed of several spatial harmonics in the LDA may reduce these difficulties. It is shown in our previous work [5] that the stationary spatially periodic optical field can be synthesized by the holographic technique employing the periodic wavefront modulator and the field-forming hologram. It is shown also in the same paper that the holographic technique permits to obtain the optical field with different spatial harmonic content. In such case the output signal contains s*everal* Doppler frequencies corresponding to a *single* object velocity. In [5], it is suggested that this signal property can be used for extending the input range of velocities of the LDA instrument.

In this work, we investigate the principal characteristics of the multi-harmonic optical field obtained through the holographic synthesis from the point of view of its application in the differential-type LDA. In particular, we investigate the case when the multimode optical fiber is used as a light source in the field-forming holographic arrangement.

2 Synthesis of optical field

We consider the stationary spatially periodic non-sinusoidal optical field. One particular example of such field is shown in Fig 1. This field has an enhanced spatial harmonic content (multi-harmonic field). We consider the field-forming holographic optical system shown schematically in Fig 2.

Fig 1. Spatially periodic multi-harmonic optical filed used in the LDA.

This is the two-component beam-forming system implementing preliminary spatial modulation of the beam wavefront. The laser light emitted by the multimode optical fibber 1 is directed to a lens 2, a static wavefront modulator 3 and then to the field-forming hologram 4. In the general case, the resultant field is described by the expression [5]:

$$u(x, y) \sim [\tau(x, y) \otimes \tau^*(x, y)] \times [q_{ij}(x, y) \otimes q_{ji}(x, y)], \quad (1)$$

where $\tau(x, y)$ is a complex transmission function of the modulator and $q_{ij}(x, y)$ is the field distribution at the optical fibber exit during hologram recording and reconstruction.

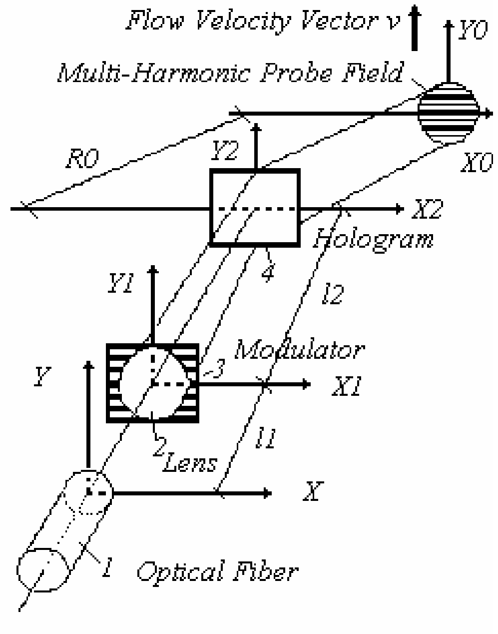

Fig 2. The principle of the holographic synthesis of the spatially periodic multi-harmonic optical field.

Let us find the analytical relation between the synthesized optical field intensity I, optical field complex amplitude at the emitting multimode fiber endface $e(x, y)$, and geometrical parameters of the optical arrangement shown in Fig 2.

3 Problem solution

To simplify the analysis we assume the paraxial case. We assume that in the arrangement shown in Fig 2 the lens (2) and static diffraction modulator (3) are in the same plane (x_1, y_1). Then the complex amplitude distribution in the hologram plane under Fresnel approximation

$$w\,(x_2, y_2) \sim \{[\,e(x, y)\,h_{l1}(x, y)]t(x_1, y_1)\}\,h_{l2}(x, y),$$

$$h_l = -\frac{i}{\lambda l}\exp\left\{ik\left(\frac{x^2+y^2}{2l}\right)\right\}$$ is the free space pulse characteristic,

$$t_L(x_1, y_1) = \exp\left\{\frac{-ik\left(x_1^2+y_1^2\right)}{2f}\right\}$$ is the lens phase transformation, $t(x_1, y_1)$ is the modulator transmission function.

Let us express the modulator transmission function $t(x_1, y_1)$ in terms of the spatial frequency spectrum $\tau(K_x, K_y)$:

$$t(x_1, y_1) = \\ = \int\int \tau(K_x, K_y)\exp\{i(x_1K_x + y_1K_y)\}dK_x dK_y.$$

In the case of the periodic modulator, its spectrum $\tau(K)$ is the sum of the δ-functions

$$\tau(K) = \sum_{n=-\infty}^{+\infty}\tau_n\delta(K_y - 2\pi n\nu)\delta(K_n),$$

$n\nu$ is modulator period number per unit length.

After a series of transformations, we get the optical field intensity distribution in the LDA measurement volume

$$I \approx \left(G_0^* \otimes G\right)\left(G_0^* \otimes G\right) * T(y_0), \tag{2}$$

$$T(y_0) = \sum_{n,m=-\infty}^{+\infty}\tau_n^2\,\tau_m^2\exp\left\{-\frac{2\pi i l_2 y_0 \nu}{R_0}(n-m)\right\} \tag{3}$$

is the modulation function.

The expression (2) permits to find the principal characteristics of the LDA probe field.

Spatial frequency spectrum of the function $T\,(y)$ consists of a series of harmonics

$$\Lambda_n = \frac{R_0}{\nu\, l_2\, n}.$$

Thereafter, in contrast to the harmonic field distribution function found in other LDA types the synthetic field in the present case has a complex multi-harmonic periodic structure.

In the particular case of the wavefront modulator with the rectangular phase profile producing a phase deviation of π, there is no zero diffraction order in the autocorrelation function. Considering the effect of –2nd, –1st, +1st, and +2nd diffraction orders, we get from (3):

$$T = 2\tau_1^4 + 2\tau_2^4 + 4\tau_1^2\tau_2^2\cos\left(2\pi y\frac{l_2}{R_{0\ 0}}\nu\right) +$$

$$2\tau_1^4\cos\left(4\pi\nu\, y_0\frac{l_2}{R_0}\right) + 2\tau_2^4\cos\left(5\pi\, y_0\nu\frac{l_2}{R_0}\right) +$$

$$4\tau_1^2\,\tau_2^2\cos\left(6\pi y_0\nu\frac{l_2}{R_0}\right).$$

In this case, the spatial frequency spectrum consists of four harmonics:

$$\Lambda_1 = \frac{R_0}{\nu l_2};\ \Lambda_2 = \frac{R_0}{2\nu l_2};\ \Lambda_3 = \frac{R_0}{3\nu l_2};\ \Lambda_4 = \frac{R_0}{4\nu l_2}.$$

These harmonics are produced by the interference of beams of different diffraction order. For example, the harmonic Λ_1 is produced by the interference of beams of the –2nd and –1st order. The harmonic Λ_2 is produced by the interference of beams of the –1st and +1st order etc. The amplitudes of the harmonics Λ_1 are determined by the quantity $\tau_{m.}$

Thus, the use of the periodic phase structure for the static wavefront modulator permits to obtain the LDV probe field with the spatial distribution described mainly by a periodic spatial autocorrelation function of the modulator $\tau \otimes \tau^*$, and having random amplitude modulation determined by the factor $q_i \otimes q_j^*$.

Rectangular phase profile of the wavefront modulator permits to obtain intense high diffraction orders and, hence, to modify the spatial probe field distribution, which is not sinusoidal in this case. The harmonic content of the probe field depends on the modulator phase profile and, thereafter, can be modified within some relatively large range.

4 Optical field study

The layout of the arrangement used for hologram reconstruction and velocity measurement is shown in Fig 3.

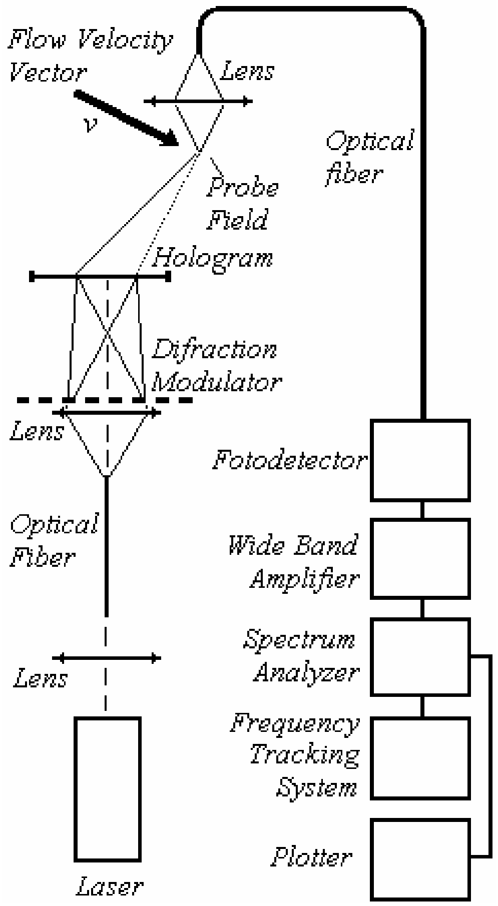

Fig 3. The arrangement for the hologram reconstruction and velocity measurement.

This is the LDA employing the multi-harmonic probe field obtained by the holographic synthesis technique. The operation of this device is similar to the differential-type LDV. However, in contrast to the traditional differential-type LDA, the spatially periodic probe field is obtained employing one single optical fiber, a modulator and a field-forming hologram. The optical system that produces the synthetic probe field is attached to the termination of the multimode optical fiber. The light of the remote laser source is guided via the optical fiber to field forming optical system. This provides for convenient use of the LDA in laboratory and field environment.

The spatial structure of the optical field obtained under various combinations of fiber, modulator and hologram parameters was studied experimentally.

The best results were obtained when the singlemode fiber was used for hologram recording and reconstruction (Fig 4). The distribution in Fig 4 a corresponds to the case when the singlemode fiber was used both for recording and reconstruction of the hologram.

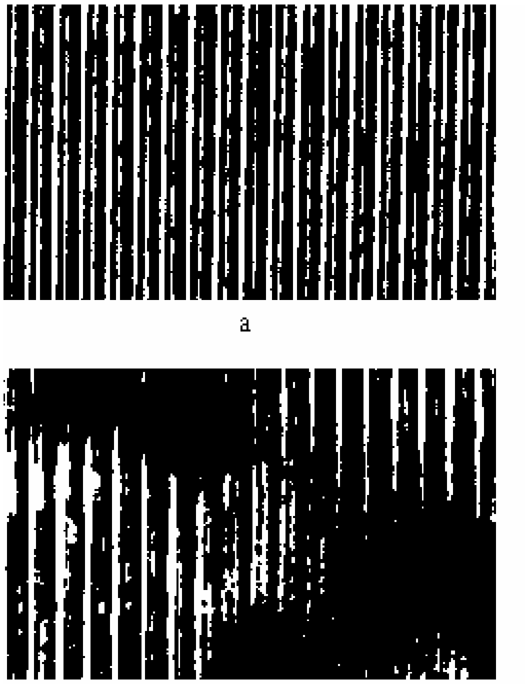

Fig 4. Photograph of the synthetic multi-harmonic optical field obtained with the singlemode optical fiber used for hologram recording. a – singlemode optical fiber used for hologram reconstruction; b - multimode optical fiber used for hologram reconstruction.

In the case of the field distributions shown in Fig 4 b, the single mode fiber was used for hologram recording and multimode one - for reconstruction. In both cases, the fringes are straight and their pattern is regular. The field has pronounced high-order harmonic content and, thereafter, is suitable for LDA applications.

Spectral composition of the multi-harmonic probe field was studied experimentally by optical filtering of some particular diffraction orders. The results of this study are shown in Fig 5.

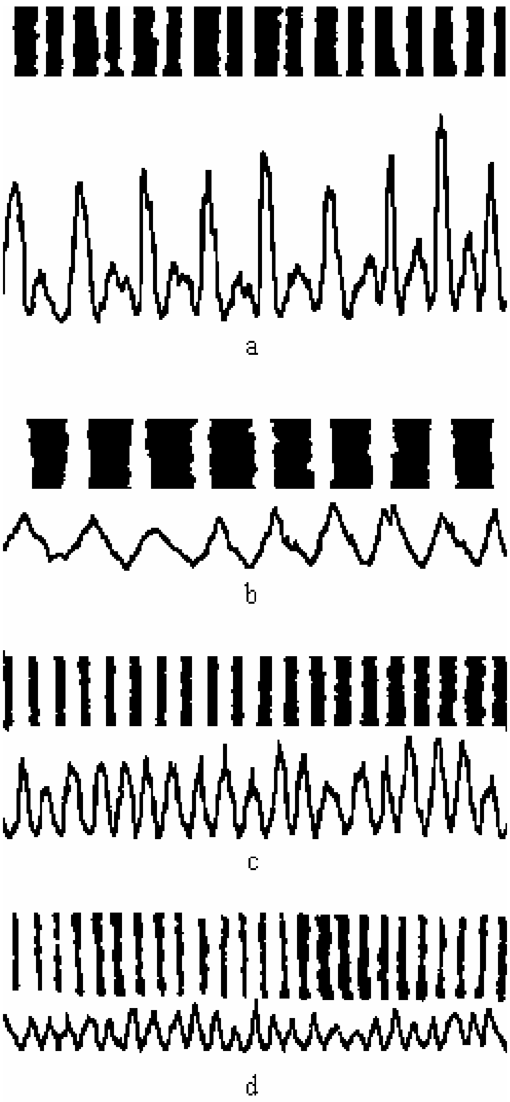

Fig 5. Photographs of field fragments and spatial distribution of field intensity of the LDA. a - the synthetic multi-harmonic probe field; b – the 1st spatial harmonic of the field; c- the 2nd spatial harmonic; c- the 3rd spatial harmonic.

The distribution shown in Fig 5 a corresponds to the obtained probe field with complex multi-harmonic composition. In Fig 5 b, the first spatial harmonic is presented. The second and the third spatial harmonics are plotted in Fig 5 c and Fig 5 d. These data show that in this particular case the amplitude of the second harmonic is the largest. Higher diffraction orders do not contribute significantly to the field spatial distribution.

5 LDA signal composition

The multi-harmonic probe field was employed in a prototype LDA system. In the output signal, several Doppler frequency harmonics associated with the object single velocity value were observed and used for velocity determination. The experiment permitted to investigate the effect of multi-harmonic spatial field structure on Doppler signal composition.

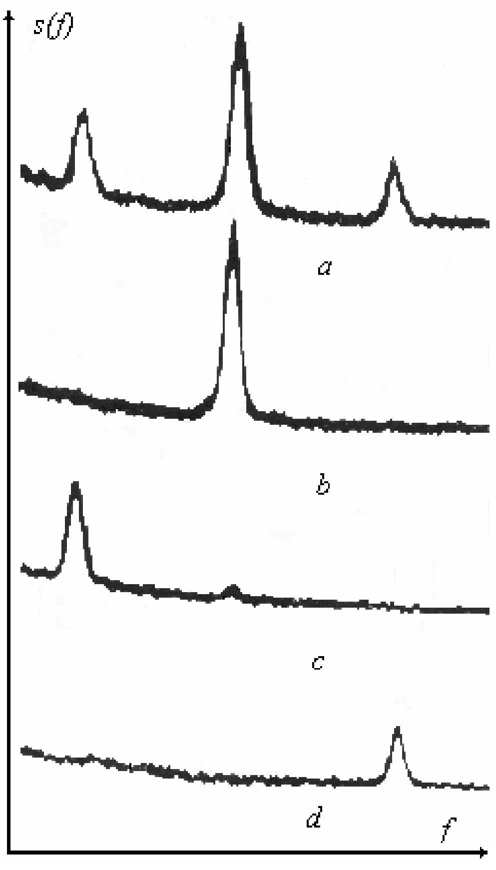

Fig 6. The frequency spectrum of the output electric signal of the LDA recorded by a plotter with a large integration time (a) and the harmonics of the Doppler signal (b, c, d).

Experimentally, several harmonics of Doppler frequency were observed in the output electrical signal (Fig 6) in the case of multi-harmonic probe field. For each of Doppler frequency components, the linear dependence of the frequency on object velocity was established.

By means of selective electric filtering it was possible to suppress some particular Doppler frequency components (Fig 6 b, c, d).

On the other hand, the existence of several Doppler frequency harmonics in the LDV output signal permits to perform the intelligent signal processing by automatic selection of a particular Doppler frequency harmonic present in the signal. Another option consists in simultaneous processing of several Doppler frequency harmonics. This can provide for increased velocity measurement range and improved accuracy.

6 Conclusions

The holographic synthesis as described in this work permitted us to obtain the spatially periodic multi-harmonic optical field with characteristics suitable for LDA applications. In particular, for blood flow velocity measurement. In this method, the static wavefront modulator employed determines relative amplitudes of spatial harmonics. By proper selection some modulator parameters during its fabrication, some necessary distribution of the harmonic amplitudes can be obtained.

The use of the multimode optical fiber together with holographic arrangement permits to reduce the effect of modal noise (modal composition variations) caused by fiber movement, vibrations, etc. on LDA performance. Simultaneously, the use of the multimode fiber permits to ease the specifications for the components of optical system and their adjustment, which simplifies the use and maintenance of the LDA.

Multiple Doppler frequency harmonics present in the LDA signal can be used for more accurate velocity determination and for increasing the operational span of the LDA.

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References:

1. N. E. Almond, D. P. Jones, and E. D. Cooke, “High quality photoplethysmograph signals from a laser Doppler flowmeter: preliminary studies of two simultaneous outputs from the finger,” *J. Biomed. Eng.,* Vol. 10, pp. 458-462 (1988).
2. S. Khotiaintsev and L. Yarovoi, “Differential Doppler velocimeter with fiber-optic lightguide and small-size optical probe head,” *Sov. J. Quantum Electronics*, Vol. 16, no. 6, pp. 1273-1278 (1989).
3. H. Shmidt-Shonbein, S. Ziege, W. Rutten, and H. Heidmann, “Active and passive modulation of cutaneous red cell flux as measured by laser Doppler Anemometry,” *VASA Suppl.*, Vol. 34, pp. 38-47 (1992).
4. K. Wardell, A. J. Jackobsson, and G. E. Nilsson, “Laser Doppler perfusion imaging by dynamic light scattering,”, *IEEE Trans. Biomed. Engin.*, Vol. 40, No. 4, pp. 309-316 (1993).
5. A. V. Gnatovsky, N. V. Medved, S. N. Khotiaintsev, and L. K. Yarovoi, “Correlation synthesis of probe field for laser-Doppler velocimeters with multimode fibre waveguides,” *Sov. J. Quantum Electron.*, Vol. 20, no. 2, pp. 132-134 (1990).