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False spectra formation in the differential two-channel scheme of the laser Doppler flowmeter

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Abstract: Noise in the differential two-channel scheme of a classic laser Doppler flowmetry (LDF) instrument was studied. Formation of false spectral components in the output signal due to beating of electrical signals in the differential amplifier was found out. The improved block-diagram of the flowmeter was developed allowing to reduce the noise.

Keywords: false spectrum; laser Doppler flowmetry; sensitivity; signals beating; two-channel scheme.

Introduction

Laser Doppler flowmetry (LDF) is a noninvasive method to explore the blood microcirculation system [8]. It has appeared since the 1980s (approximately), but up to now having a broad application in medical research, this technique does not reach the practical medicine level yet. There is no one of practical-medicine problems for which LDF is a necessary and indispensable tool as the standard diagnostic approach. One of the reasons for this situation is frequently observed low reproducibility and a high dispersion of final medical diagnostic results, which makes impossible the personal diagnostic conclusion. In the majority of cases, significant differences in LDF results are only observed in groups of patients. Therefore, an audit of

the correct functioning of LDF diagnostic equipment for searching for random sources of noise is the relevant and actual problem.

LDF is based on illumination of tested tissue by laser light and detection of the backscattered radiation from the tissue by a photodiode [5, 6]. Total backscattered radiation from both moving red blood cells (RBCs) with the Doppler frequency shift and motionless (static) scatters with the initial radiation frequency is registered in the technique. Photocurrent generated on the photodiode is proportional to the optical power of a heterodyne mixture of these two light waves with changed and unchanged frequency, which produce low-frequency beatings due to the small Doppler frequency shift [2, 3]. Therefore, the photocurrent has low-frequency components within the acoustic frequency range, registration and processing of which allows to obtain important information about the blood microcirculation in skin or mucosa [9–11]. At present, in LDF the signal-processing algorithm is based on the classic model of Bonner and Nossal [2], in which the blood flow is calculated with the use of the first-order moment of the registered photocurrent power spectrum. Thus, the accuracy and reality of the frequency spectrum of all internal electrical signals in measuring instruments is very critical in LDF. Initial optical signals formation can be described using different models [1, 2, 12]. Several models among them, for example [12], allow to explore the influence of different levels of optical noise on the moments of the photocurrent power spectrum. However, the influence and the reduction of the electrical noise inside different electrical schemes of the LDF instruments is studied not so comprehensively.

The most widely used differential two-channel scheme for LDF instruments was developed by Nilsson et al. [6, 7]. It has several advantages. The differential scheme provides suppression of correlated signals (noise) in both channels, for example: motion artifacts, external light, etc, but output signals related to the blood flow are not suppressed in the scheme since the beating signals in each channel are uncorrelated due to the random nature of scattering and, so, can be considered as independent realizations of the same stochastic

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process [5]. That is why such a differential scheme has become popular among manufacturers of LDF instruments. However, the issue of a low-frequency electrical noise formation inside the scheme have not been completely studied yet. In this study, we tried to fill this gap. In our previous conference paper [4] we described the experimentally observed noise in the electrical circuit of the LDF instrument, as well as proposing the idea of how to improve the circuit. In this extended paper, the theoretical background of that and the simulation experiment (hereafter will be referred to as experiment) results are described in more detail.

Materials and methods

Noises in the differential two-channel setup of the typical LDF instrument “Lakk-02” (Lazma Ltd., Russia) were experimentally and theoretically studied. The electrical block-diagram of the instrument is similar to [7]. It is presented in Figure 1A, where: BO – biological object, PD – photodetector with a preamplifier, HPF – high pass filter, AMP – amplifier, DIV – divider, DA – differential amplifier, SPU – signal processing unit.

Special attention was paid to the differential amplifier DA and to its preceding units DIV, where, theoretically, the normalization of variable (*ac*) components of the photocurrent on the constant (*dc*) component of it should occur to eliminate the effect of the source’s light power [3]. But, as one can see in the Figure 1A, not only the constant, but all unfiltered *ac* components of signals can pass to DIV as the denominator. Therefore, in the theoretical part of the study, we decided to consider mathematically this part of the scheme in more detail (Figure 1B). Input *ac* signals X_1, X_2 forming the power spectrum and the total signals Y_1, Y_2 from photodetectors are fed to inputs of DIVs. We presented all these signals as the sum of discrete harmonic oscillations, frequencies of which in channels *I* and *II* are the same:

$$\begin{aligned} X_1 &= \sum_{k=1}^n A_{1,k}^* \cos(\omega_k t), \\ Y_1 &= A_{01} + \sum_{k=1}^n A_{1,k} \cos(\omega_k t), \\ X_2 &= \sum_{k=1}^n A_{2,k}^* \cos(\omega_k t), \\ Y_2 &= A_{02} + \sum_{k=1}^n A_{2,k} \cos(\omega_k t). \end{aligned} \quad (1)$$

where $A_{1,k}, A_{2,k}$ – amplitudes of k^{th} harmonic components of unprocessed *ac* signals in channels *I* and *II*; $A_{1,k}^*, A_{2,k}^*$ – amplitudes of k^{th} harmonic components of processed (filtered by HPF) *ac* signals; A_{01}, A_{02} – amplitudes of *dc* components of these signals; ω_k – frequencies of k^{th} harmonic components of the signals in both channels.

Then we tried to derive the output signal W for different cases of A_k and ω_k .

In the experimental part of the study, we connected simulated input signals X_i and Y_i from generators to the scheme and registered both the output signal W and its spectrum for different cases to find out the false spectra formation. In addition, we studied the W signal for the modified block-diagram of the instrument with additional low-frequency pass filters in both channels with the use of the graphical environment *Simulink*.

Results

According to (1) and Figure 1B, for outputs of DIVs we can write:

$$Z_1 = \frac{\sum_{k=1}^n A_{1,k}^* \cos(\omega_k t)}{A_{01} + \sum_{k=1}^n A_{1,k} \cos(\omega_k t)}, \quad Z_2 = \frac{\sum_{k=1}^n A_{2,k}^* \cos(\omega_k t)}{A_{02} + \sum_{k=1}^n A_{2,k} \cos(\omega_k t)}, \quad (2)$$

where Z_1, Z_2 – output normalized signals from DIVs in the channels *I* and *II*, respectively. In DA the subtraction

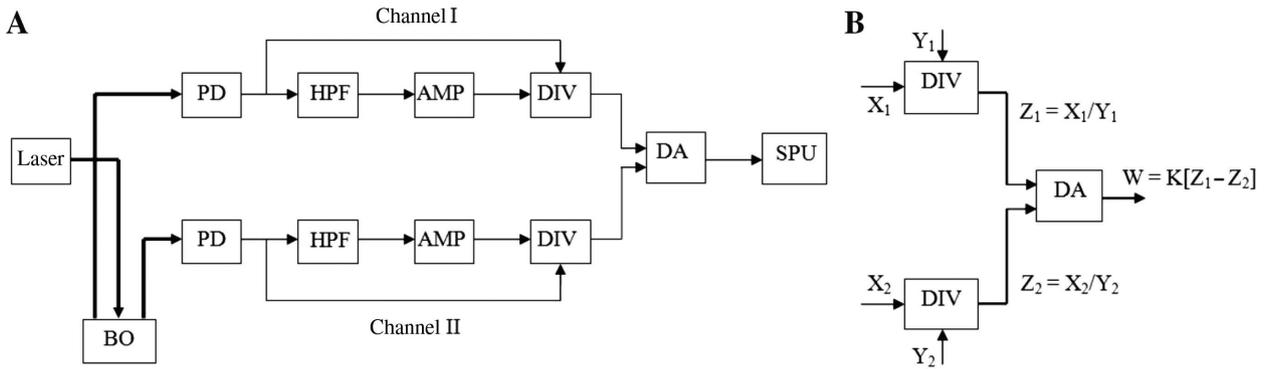


Figure 1: Block-diagram of the differential two-channel setup of “Lakk-02” instrument (A), Procedure of normalization and subtraction of signals in the circuit (B).

BO, biological object; PD, photodetector with a preamplifier; HPF, high pass filter; AMP, amplifier; DIV, divider; DA, differential amplifier; SPU, signal processing unit.

$(Z_1 - Z_2)$ and multiplication of the result on the amplification factor K yields:

$$W = K[Z_1 - Z_2] = K \frac{\left[\sum_{k=1}^n (A_{02}A_{1,k}^* - A_{01}A_{2,k}^*) \cos(\omega_k t) + \frac{1}{2} \sum_{k=1}^n (A_{1,k}^*A_{2,k} - A_{2,k}^*A_{1,k}) (1 + \cos(2\omega_k t)) \right. \\ \left. + \sum_{k=1}^n \sum_{m=1}^n (A_{1,k}^*A_{2,k+m} - A_{2,k}^*A_{1,k+m}) (\cos(\omega_k + \omega_{k+m})t + \cos(\omega_k - \omega_{k+m})t) \right]}{\left(A_{01} + \sum_{k=1}^n A_{1,k} \cos(\omega_k t) \right) \left(A_{02} + \sum_{k=1}^n A_{2,k} \cos(\omega_k t) \right)}, \quad (3)$$

where W – final output signal from DA.

As one can see from (3), the final output signal W contains, besides useful signal components, second harmonics of the useful signal and several beatings of them with frequencies $(\omega_k + \omega_{k+m})$ and $(\omega_k - \omega_{k+m})$. Frankly speaking, the result is quite evident, because a subtraction of two fractions with different $ac + dc$ denominators always leads to multiplication of signals and to appearance of their beating. This theoretical conclusion confirms exactly our previously published results that for input signals Z_1, Z_2 with the same frequencies and with different amplitudes A_{0i} of the dc components in their denominators, several false low- and high-frequency beatings can be seen in the DA output signal W [4].

At experiment in *Simulink*, the signal detected by the photodetector was simulated. In this simulation, we

assume that the mean speed v of RBCs has a Gaussian distribution. Therefore, the Doppler frequency shift related with the speed in the approximation of a single scattering has the Gaussian probability distribution, as well [12]. To get the most visible result in the false spectra formation, we considered a narrow spectral interval from 1.5 to 2.5 kHz with the maximum around 2 kHz, that approximately corresponds to $v_{max} = 0.6$ mm/s. These narrowband signals were simulated using the k -dimensional arrays of signal generators operating at certain frequencies in steps of 25 Hz. The signals were mixed in summation units SUM 1 and SUM 2, then the dc components were added to them in SUM 3 and SUM 4 respectively, and these total signals were connected to inputs of both channels (Figure 2).

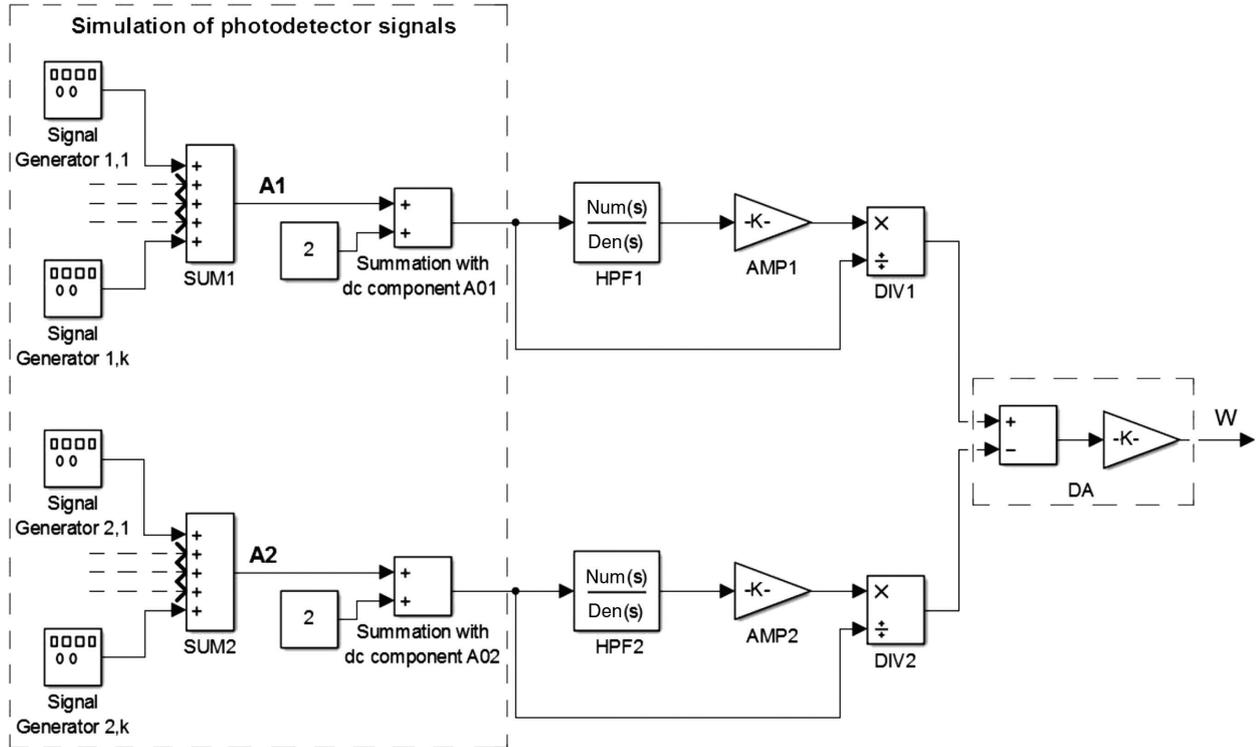


Figure 2: The differential two-channel setup of the LDF instrument in *Simulink*.

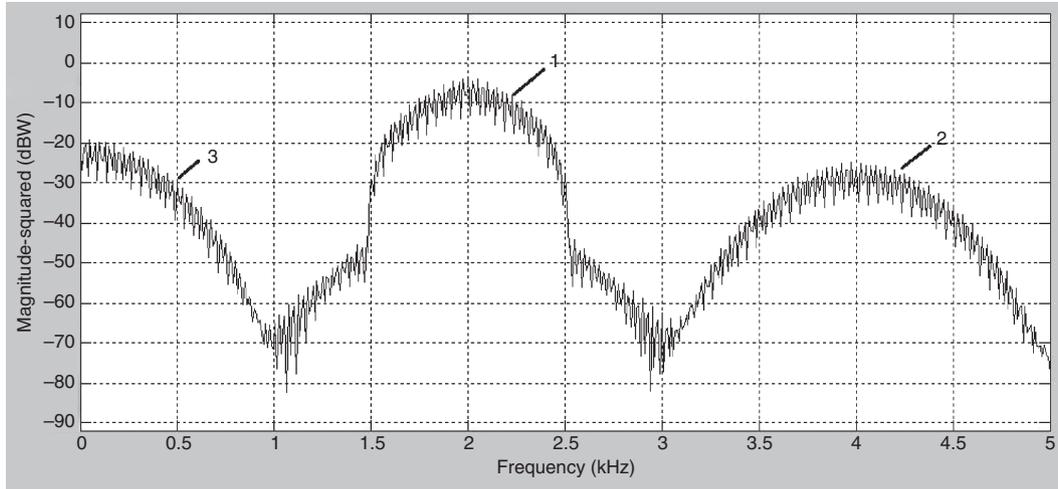


Figure 3: Spectrum of the W at input signals in the frequency range from 1.5 to 2.5 kHz (the level signal is defined as $P_{dbW} = 20 \lg(P_i/P_o)$, where P_i is signal power, $P_o = 1$ W).

Thus, the power spectrum of W was simulated (Figure 3). One can see, that the spectrum of W contains, besides the input useful signal 1, the second harmonics with high-frequency beatings 2 and the low-frequency beatings 3. This result also corresponds to (3) very well.

These beatings lead to the formation of false spectral components of the output signal W , which can be the cause of diagnostic errors and dispersion of results in LDF. The reason of these beatings is the presence of the residual ac components in normalizing signals Y_i , which after division and subtraction in DA produce a variety of harmonics. More precisely, the scheme does not provide the proper normalization of ac components by dc ones. Denominators in each channel contain both the dc and ac components, so the small difference in the denominators lead to their multiplication at subtraction [see Eqs. (2) and (3)] and to beatings of all spectral components.

To eliminate these drawbacks, the incorporation of two low pass filters (LPF) with cutoff frequency at 1–2 Hz into the scheme was proposed to minimize variables ac components in Y_i (Figure 4). LPFs do not transmit variable ac signals to DIVs, therefore the false beatings in W should not be formed. Power spectrum of W simulated for the improved scheme at the same condition of the input narrowband signals in the frequency range from 1.5 to 2.5 kHz is presented in Figure 5. The spectrum contains only input signals 1 without any beatings.

To evaluate the contribution of these spectral “noise” to the blood flow related output signal, the signal processing in SPU unit of the LDF instrument was simulated in *Simulink* as well (Figure 6). The output signal from SPU is defined as [6]:

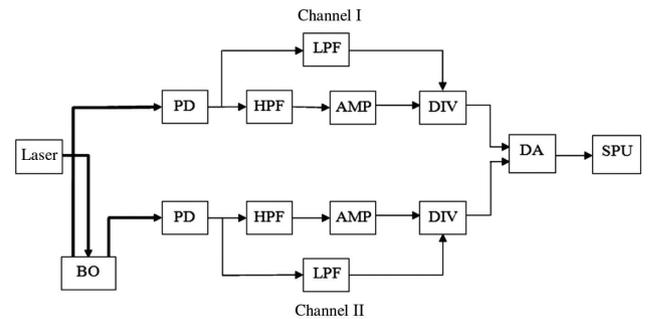


Figure 4: Improved two-channel scheme of the LDF instrument.

$$BF = \left\langle k_0 \int_0^{\omega_0} \omega P(\omega) d\omega \right\rangle, \quad (4)$$

where BF is the “blood flow”, k_0 is the proportionality coefficient, $P(\omega)$ is the power spectrum of the output signal W , ω_0 is the cutoff frequency of the LPF ($\omega_0 = 20$ kHz). The BF is proportional to the product of RBCs concentration and their average velocity. This parameter is usually expressed in perfusion units and is displayed on the screen in real time.

At the final stage of the experiment, the same narrowband signals mimicking the different RBCs velocities were connected to inputs of both channels of the classical and improved differential schemes, and the SPU response was simulated (Figure 7). The spectral ranges of these input signals were as follows: 1.5...2.5; 3.5...4.5; 5.5...6.5; 7.5...8.5; 9.5...10.5 kHz, that approximately corresponds to the following average RBCs velocities: 0.6; 1.2; 1.8; 2.4; 3 mm/s. As seen from the Figure 7, the false spectral

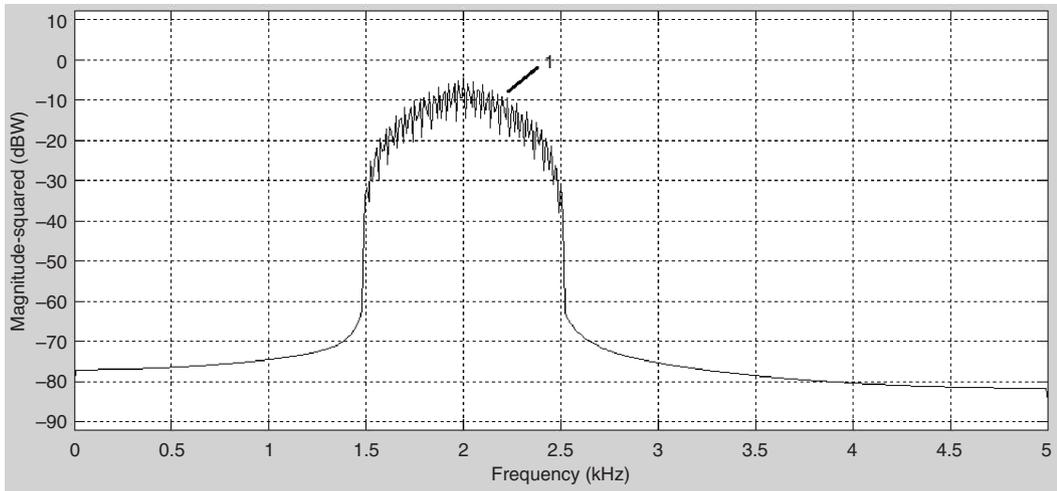


Figure 5: Power spectrum of W in the improved scheme of the LDF instrument.

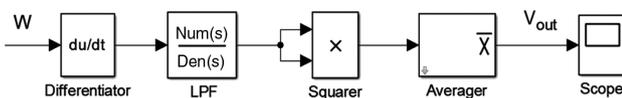


Figure 6: Block-diagram of the SPU of the LDF instrument in *Simulink*.

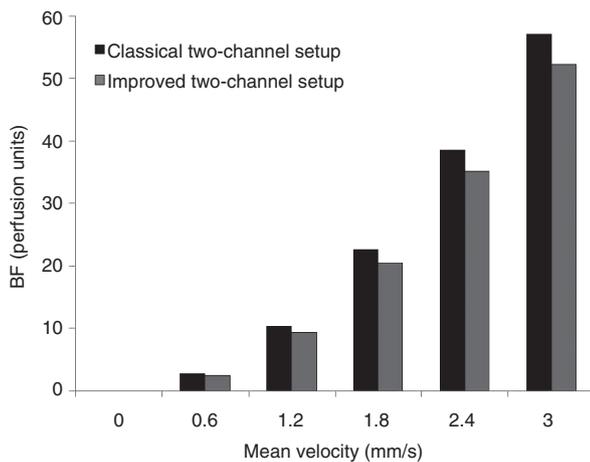


Figure 7: The flowmeter simulated output signal at different velocities for both the classical and improved two-channel setups.

components of W lead to the increase of the flowmeter output signal up to the level of 10%.

Discussion and conclusions

In the study, it was obtained that the most widely used differential two-channel setup [7] of LDF instruments has some drawbacks, which lead to formation of false spectral

components in the output signal. In particular, it is true for the “Lakk-02” instrument, which scheme was under our investigation, but probably is not true for instruments with another scheme. Other circuits should be checked in other studies. Nevertheless, for the scheme [7] it can have serious consequences in terms of impact on the final medical diagnostic result. False spectra can produce significant errors at diagnostics, because the blood flow in LDF and its spectral fluctuations are computed today with the use of the output spectrum. We saw the errors on the level of 10% in our experiments. Not so much, but nevertheless, in other conditions it can be different.

It may seem that the additional components in the spectrum, introduced by the lack of a low pass filter, have a systematic nature. Thus, since in LDF different provocation/stimulation tests are often used and the ratio of initial and final values of blood perfusion is evaluated, they will affect the signal before the provocation and after one equally, so on a final medical conclusion these additional frequencies might have no influence. But this is not quite true. In different states (at the rest, during the provocation test, etc.) there will be the different blood volume and the different speed of the blood cells in the tested tissue, therefore amplitudes of both the each ac spectral components and each dc components in the denominators of fractions Z_i will be different. The formation of W is not linear process in accordance with the eqs (2) and (3). Therefore, the additional frequencies will have influence on the result in all cases. Probably, this is the cause of the frequently observed low reproducibility and a high dispersion of final medical diagnostic results in LDF [10, 11]. Thus, the reduction of this noise is preferable anyway.

It was shown also, that additional low pass filters, if being incorporated in the scheme, allow to remove these

false spectral components. Therefore, we can propose, that the improved LDF instrument will have a higher diagnostic accuracy and reproducibility, which are not sufficient enough in LDF today.

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