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Analysis of the pulse waveform in arterial vessels using the spectrum of the autodyne signal of a laser interferometer

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Abstract. **The results of measuring the derivative of the pulse wave using a laser autodyne based on the Fourier analysis of the low-frequency spectrum of the interference signal are presented. The features of using the windowed Fourier transform for window types and window widths are discussed. The correlation coefficient between the derivative obtained by direct differentiation of the sphygmographic signal and the frequency dependence of the windowed Fourier transform obtained from the analysis of the interference signal is calculated. It is shown that the amplitude of biovibration of the skin surface has the greatest influence on the correlation of the frequencies of the window spectrum of the autodyne signal with direct measurements of the pulse wave parameters by the sphygmographic method. Using a hardware-software system, we measured the sphygmogram of the pulse wave in the radial artery in a 19-year-old man who did not suffer from cardiovascular diseases. The derivative of the pulse wave obtained from the sphygmogram was compared with the dependence of the frequencies of the window spectrum of the autodyne signal. A comparative analysis of the dependences of the frequencies of the spectral harmonics of the window method with the derivative of the sphygmographic pulse showed a good correlation at the amplitudes of biovibration of the skin surface exceeding 10 μm.**

Keywords: *laser interferometry, autodyne, semiconductor laser, laser radiation modulation, distance measurement, self-mixing, pulse wave, pulse wave derivative, spectral signal analysis, windowed Fourier transform.*

1. Introduction

At present, portable non-invasive methods of recording the pulse waveform are increasingly used for the diagnosis of cardiovascular diseases [1]. These methods include photoplethysmography, sphygmography, rheography, laser Doppler flowmetry, etc. [2 – 5]. To improve the accuracy of pulse waveform measurements, it is proposed to use optical interferometry methods [6–9], among which autodyne systems are distinguished by high sensitivity to reflected radiation and compactness, since they do not imply splitting the laser beam into reference and measurement arms.

The term 'autodynes' implies open self-oscillating systems accessible to any external influences [10]. In Russian and foreign literature, the terms 'laser with delayed feedback' [11], 'self-mixing laser' [8, 9, 12], etc. are also accepted. Since the analysis of the dynamics of laser radiation was carried out in parallel with the analysis of the operation of microwave autodyne, then simultaneously with the term 'autodyne', the term 'laser with external feedback' began to be used [13].

The capabilities of laser autodyne interferometry ensure high accuracy of measuring microdispacements because the measuring signal is compared with a reference value, which is the wavelength of laser radiation [14].

The main methods for analysing an autodyne signal are methods for reconstructing the shape of a pulse wave from the maxima of the interference signal [15, 16], as well as from their frequency dependence on time [9]. A specific feature of homodyne interferometry methods is the difficulty in determining the direction of movement of the investigated surface of human skin. For this purpose, the reconstructed pulse waveform is compared with the results of its measurement by other non-invasive methods, which include ECG, PPG, sphygmography, and others [17]. An alternative to this approach is the reconstruction of the derivative of the pulse waveform, which is obtained by the methods of Fourier analysis of the interference signal [7, 8].

Determination of the derivative of the pulse waveform from the autodyne signal is the most promising method for diagnosing the state of the cardiovascular system, since it does not require additional non-invasive comparison methods and uniquely correlates with the modulus of the pulse wave derivative.

A specific feature of the technique for measuring the autodyne signal of the pulse wave is the different amplitude of oscillations of the skin surface in different parts of the human body, depending on age, as well as on weight and other anatomical features. Variation in the amplitude of oscillations of the skin surface strongly affects the shape and frequency of the autodyne signal. The aim of this work is to analyse the method for finding the derivative of the pulse wave from the spectrum of the autodyne signal using the windowed Fourier transform methods with determining the correlation of this method with direct measurements of the pulse waveform by the sphygmographic method.

2. Formation of the autodyne signal and its spectrum

When the external reflector moves, the variable normalised component of the autodyne signal is written in the form [18]

$$P = \cos[\omega(t)\tau(t)], \tag{1}$$

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where $\omega(t)$ is the semiconductor laser radiation frequency depending on the part of the laser radiation returned to the resonator; and $\tau(t)$ is the time the laser radiation passes the distance to the external reflector, which changes when the reflector moves.

The function $\omega(t)$ is found from the phase equation [19, 20]

$$\omega_0\tau(t) = \omega(t)\tau(t) + C\sin[\omega(t)\tau(t) + \psi], \quad (2)$$

where ω_0 is the radiation frequency of the semiconductor laser without feedback; C is a coefficient that determines the level of external optical feedback; $\psi = \arctan\alpha$; and α is the coefficient of the semiconductor laser emission line broadening.

The feedback level affects the autodyne signal shape and the laser diode emission frequency. When the feedback level is low ($C \ll 1$), the dependence of the phase of the laser diode radiation on the change in the phase of the wave in the external cavity of the laser with feedback becomes linear [21, 22], i.e., at $C \ll 1$, the change in the frequency of radiation of a semiconductor laser in time can be neglected ($\omega = \omega_0$). In this case, the normalised component of the autodyne signal coincides with the normalised component of the interference signal with isolation from the radiation source.

Assume that the object moves uniformly in a straight line with a constant velocity V during observation time t. In this case, the time of external cavity roundtrip by the laser radiation will take the form:

$$\tau(t) = (2/c)(L_0 + Vt) \quad (3)$$

(c is the velocity of light, and L_0 is the distance to the object). Then the variable normalised component of the autodyne signal can be represented as

$$P = \cos[(2\omega_0/c)(L_0 + Vt)]. \quad (4)$$

Comparing the obtained expression (4) of the variable normalised component of the autodyne signal with the cosine function

$$P = \cos(\Omega t + \varepsilon) \quad (5)$$

(where ε is the initial phase) and taking into account that $\omega_0 = 2\pi c/\lambda_0$, $\Omega = 2\pi\nu$, and ν is the frequency of the autodyne signal change under the translational motion of the reflector, we find the velocity of the object motion

$$V = \nu\lambda_0/2. \quad (6)$$

Thus, the velocity of the external reflector motion can be obtained by determining the frequency of the variable normalised component of the autodyne signal ν from Eqn (6).

3. Computer simulation of the pulse wave derivative and its determination from the autodyne signal spectrum using the window functions

The autodyne signal was simulated for the pulse wave of the radial artery, smoothed by the Gaussian function with a coefficient of 0.05. At the maximum, the displacement of the skin surface reached 30 μm (Fig. 1).

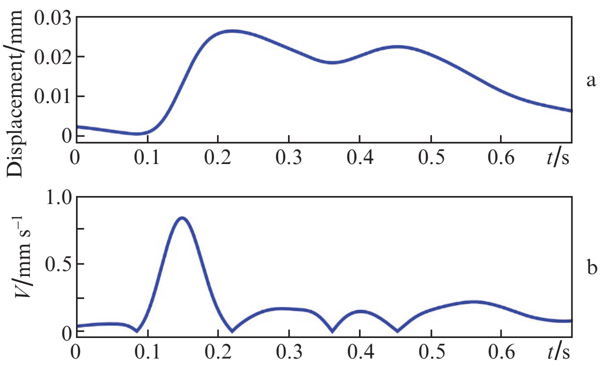

Figure 1. (a) Pulse waveform and (b) modulus of its derivative (at the maximum, the value of the shift is 30 μm).

The calculation of the variable normalised component of the autodyne signal was carried out in accordance with relation (4). The autodyne signal and its spectrum are shown in Fig. 2. The autodyne signal change step was set equal to 100 μs, and the sampling frequency was 7 kHz. As can be seen from Fig. 2b, the maximum frequency in the spectrum of the autodyne signal (~1200 Hz) is much less than the sampling rate of the autodyne signal shown in Fig. 2a.

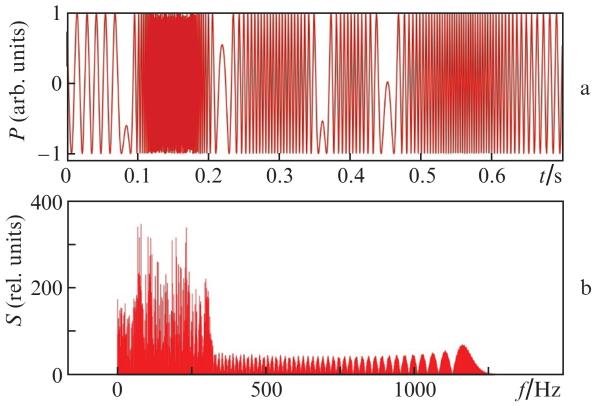

Figure 2. (a) Autodyne signal of a model pulse wave of skin surface displacements and (b) its spectrum, corresponding to Fig. 1.

To determine the velocity of the skin surface motion from the spectrum of the autodyne signal, the windowed Fourier transform was used. Since the rectangular window distorts the signal spectrum due to the ‘leakage’ of energy from the centre of the spectral window, the Hann, Hamming, and Blackman windows were analysed. Using temporal window functions decreases the level of sidelobes in the Fourier spectrum and reduces the displacement of adjacent spectral peaks.

When plotting the model pulse wave using window functions, it was noted that the Blackman window transform allows better amplitude resolution than the Hann and Hamming windows. This is essential when analysing the spectral characteristics of a signal. It was revealed that for the correct operation of the program with the Blackman window transformation, a smaller width of the Blackman window is required than for Hann and Hamming windows. Consequently, more windows with the same overlap will be processed and the accuracy of the resulting curve will increase.

A Blackman windowed transformation of the simulated signal was carried out with various window widths and degrees of overlap. In each window, the harmonic with the maximum amplitude was selected and its frequency was determined. The frequencies of these harmonics were entered into the data array, using which the time dependences of the frequencies of the harmonics with the maximum amplitudes for the period of the heart cycle were constructed.

We studies the influence of the Blackman window width on the correlation between the tine dependences of the frequencies of harmonics having maximum amplitudes (harmonic numbers n, Fig. 3) and the modulus of the derivative of the displacement pulse wave. The dots represent the frequencies from the calculated data set. For comparison, the same figure shows the modulus of the derivative of the displacement pulse wave shown in Fig. 1. For each time dependence of the frequency of the harmonic having the maximum amplitude, the Pearson coefficient of correlation (linear correlation coefficient) with the modulus of the derivative of the displacement pulse wave was calculated.

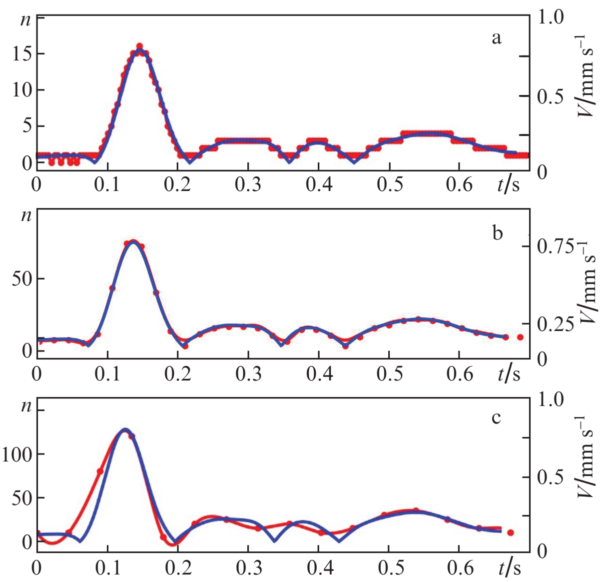

Figure 3. Dependence of the number n of the harmonic with the maximum amplitude (curves with dots of discrete values) on time over the period of a heart cycle for the widths of the Fourier transform window of (a) 0.93%, (b) 4.4%, and (c) 9.4%, as well as the moduli of the pulse wave derivative V (solid curves).

The use of the number of the harmonic rather than the frequency of the spectral component, allows a clear demonstration of the change in resolution at different widths of the Fourier transform window. With increasing window width, the number of harmonics plotted along the ordinate increases, which provides an increase in resolution. As can be seen from the results shown in Fig. 3, with a small width of the Fourier transform window (0.94%), due to the small number of discrete signal values in the spectrum, a small number of harmonics are observed in the window, which leads to the appearance of discrete signal levels (steps). The Pearson coefficient of correlation between the time dependence of the frequencies of harmonics with the maximum amplitudes and the derivative of the pulse wave was 0.9947 (Fig. 3a). With a window width of 9.4%, the resolution along the abscissa decreases, interpolation is performed using a limited number of points, and the Pearson correlation coefficient is 0.9956 (Fig. 3c). The optimal window width was 4.4%, for which the Pearson correlation coefficient was 0.9982 (Fig. 3b). Since the degree of window overlap did not significantly affect the Pearson correlation coefficient, a value of 30% was used in the calculations.

4. Influence of the skin surface biovibration amplitude

The amplitude of the skin surface biovibration significantly affects the shape and frequency of the autodyne signal. The change in the shape of the autodyne signal is determined by the phase change in the region of the extremum biovibration. The vibration amplitude has the greatest influence on the autodyne signal frequency and, in particular, on the resolution of the calculated signal and the Pearson correlation coefficient. We investigated the influence of the skin surface biovibration amplitudes on the correlation between the time dependences of the frequencies of harmonics having the maximum amplitudes and the modulus of the derivative of the pulse wave of displacement. The maximum skin surface biovibration amplitudes were 10, 60, and 100 μm. For comparison, the modulus of the pulse wave derivative is also presented. The calculations used a window width of 4.4%.

At small amplitudes of the skin surface displacement (Fig. 4a), the frequency of the interference signal decreases, particularly greatly in the diastolic region, which plays a major role in assessing the elasticity of arterial vessels. In this case, in the diastolic region the spectrum in the window has a minimum number of spectral components, which reduces the accuracy of determining the derivative of the pulse wave in the analysed region of the interference signal. The Pearson correlation coefficient between the time dependence of the

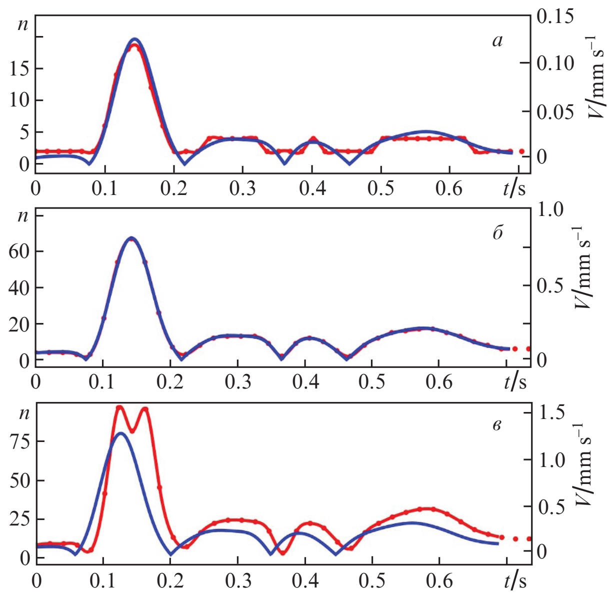

Figure 4. Dependence of the number n of the harmonic with the maximum amplitude (curves with dots of discrete values) on time over the period of a heart cycle for the maximum amplitudes of the skin surface biovibration (a) 10, (b) 60, and (c) 100 μm, as well as the moduli of the pulse wave derivative (solid curves).

frequencies of harmonics having maximum amplitudes and the derivative of the pulse wave was 0.9910 (Fig. 4a).

At large amplitudes of the skin surface displacement (Fig. 4c), the frequency of the harmonic with the maximum amplitude in the spectrum of the interference signal in the systole section significantly increases and reaches 4 kHz. Since the specified sampling rate of the autodyne signal is 7 kHz, the Kotelnikov condition is violated, and in Fig. 4c, a mismatch of the curves due to the high rate of autodyne signal change is observed. Therefore, to obtain correct results, hardware with a sufficient sampling rate of the measured signal is required. The Pearson correlation coefficient at a skin surface displacement amplitude of 100 μm was 0.8394 (Fig. 4c), and at a displacement amplitude of 60 μm, it was 0.9994 (Fig. 4b).

5. Experimental studies

Pulse wave measurements were carried out using a system of software and hardware [23], which includes the following units: an engineering station NI ELVIS (National Instruments, USA) for recording an analogue signal; a unit of an analogue-to-digital converter (ADC) based on the NI USB DAQmx-device; a system for compression and pressure recording (cuff, rubber bulb, pressure gauge, a MPX5050GP pressure sensor (Freescale Semiconductor, USA)); a personal computer; and LabView 8.5 software package for creating virtual instruments. Figure 5 shows a sphygmogram of a pulse wave measured in the area of the radial artery in a 19-year-old male volunteer having no cardiovascular diseases. The signal was preliminarily frequency filtered from noise.

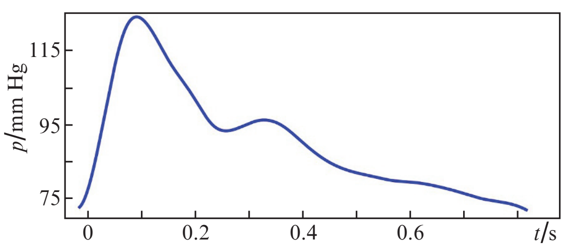

Figure 5. Pulse wave sphygmogram measured in the region of the radial artery.

Synchronously with the sphygmogram measurements, the displacement of the skin surface in the area of the radial artery below the measuring cuff was recorded. A schematic diagram of the laser autodyne experimental setup is shown in Fig. 6. In the measurements, we used an Arima ADL65052TL laser diode with a built-in photodetector having a radiation power of 5 mW and a radiation wavelength of 650 nm. The radiation of the semiconductor laser stabilised by a current source was directed to the skin surface in the area of the radial artery close to the skin surface. The radiation reflected from the skin surface was returned to the cavity of the semiconductor laser. The change in the radiation power was recorded by a photodetector built in the laser diode. The signal from the photodetector was fed to an ADC through an amplifier and a bandpass filter. The digital signal from the ADC was stored in the PC memory for subsequent signal analysis.

The results of measurements of the skin surface displacement using a laser autodyne, corresponding to one heart

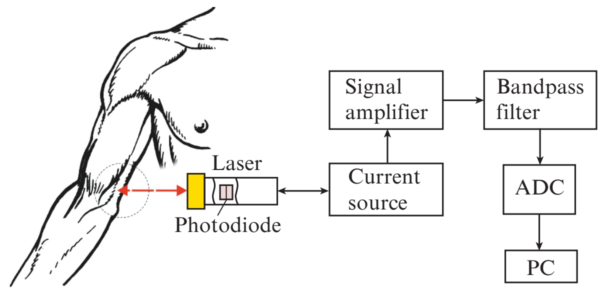

Figure 6. Schematic of the experimental setup.

cycle, are shown in Fig. 7a, the spectrum of the autodyne signal is shown in Fig. 7b. The sampling rate of the autodyne signal was 54 kHz. As can be seen from Fig. 7b, the maximum frequency in the spectrum of the autodyne signal (~2550 Hz) is much lower than the sampling frequency of the autodyne signal shown in Fig. 7a.

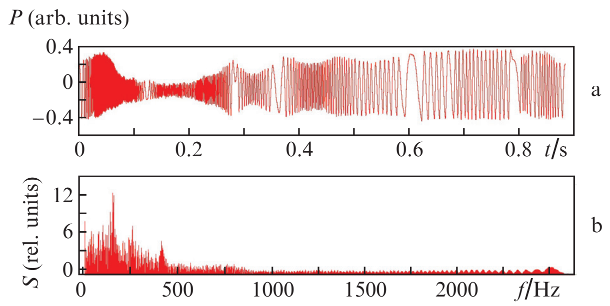

Figure 7. (a) Autodyne signal corresponding to one heart cycle and (b) its spectrum.

The measured autodyne signal was analysed using a Blackman window with a degree of overlap of 30% and a Fourier transform window width of 4.4%. The results of calculating the time dependence of the number of harmonics with the maximum amplitude of the windowed Fourier transform for the period of the heart cycle (points are discrete values for each window) are shown in Fig. 8. For comparison, the modulus of the derivative of the pulse wave of displacements, obtained by direct differentiation of the sphygmo-

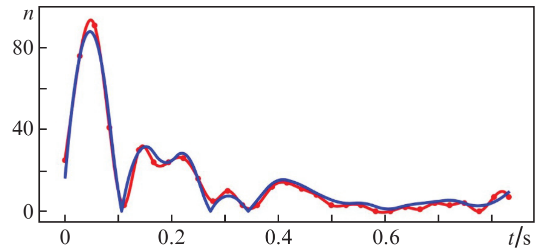

Figure 8. Dependences of the number n of the harmonic with the maximum amplitude (curve with points of discrete values) on time over the period of the cardiocycle, calculated from the interference signal, as well as the modulus of the derivative of the pulse wave of displacements, calculated from the sphygmographic dependence (solid curve).

graphic signal is also presented. The Pearson correlation coefficient was 0.9947.

6. Conclusions

Autodyne interferometry is one of the promising methods for diagnostics of pulse wave parameters, which is due to the possibility of creating compact mobile sensors for displacement of the skin surface with high resolution. A specific feature of the autodyne interference signal is the difficulty of obtaining the time dependence of the surface displacement amplitude, but the ability to determine the velocity of moving a skin area above the artery, which correlates with the derivative of the pulse wave, is relatively easy to implement. The most common method for recording the velocity of the skin surface movement is recording the frequencies of spectral harmonics in the Fourier transform window.

However, due to some features of the pulse wave, the correlation of this method with direct sphygmographic measurements of the pulse wave parameters does not always give a satisfactory result. For the analysis of the autodyne signal of the pulse wave, the most interesting is the diastolic region, the resolution of which determines the correlation coefficient and the accuracy of determining the pulse wave derivative.

We have found that the best correlation is achieved using the Blackman window transform. In this case, the width of the window for obtaining the greatest correlation is 3%–5% of the heart cycle period. The degree of window overlap does not significantly affect the Pearson correlation coefficient.

The greatest influence on the correlation of the frequencies of the window spectrum of the autodyne signal with direct measurements of the pulse wave parameters by the sphygmographic method is exerted by the amplitude of the biovibration of the skin surface. At small amplitudes of displacement of the skin surface in the diastolic region, the spectrum in the window contains a minimum number of spectral components, which reduces the accuracy of determining the derivative of the pulse wave. At large displacement amplitudes, the high frequency of the interference signal can become a source of distortion of the autodyne signal spectrum due to the uneven amplification properties of the detector in a wide frequency range and insufficient sampling frequency of the detected signal. In this regard, it becomes necessary to search for such a region of the skin surface biovibration above the artery, in which the signal provides good correlation for a given width of the Fourier transform window.

Measurements of pulse wave parameters in sphygmographic experiments and using a laser autodyne confirmed the possibility of obtaining a good correlation of their signals on the radial artery in a 19-year-old man without cardiovascular diseases.

Thus, we have shown the possibility of determining the derivative of the pulse wave from the autodyne signal of a semiconductor laser recorded in the area of the radial artery. A comparative analysis of the dependences of the frequencies of the spectral harmonics of the window method with the derivative of the sphygmographic pulse wave showed a good correlation at amplitudes of skin surface biovibration exceeding 10 μm.

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