Nonlinear SVD – filtration in hemodynamic parameters evaluation hydrocuff systems

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Abstract. The article illustrates the prospects of using the hydrocuff technology of oscillations formation for evaluating hemodynamic parameters. An approach to improving the parameters accuracy estimation by increasing the oscillations amplitude and subsequent nonlinear SVD – filtering of the obtained blood pressure compression waveform based on singular spectral analysis is presented.

1. Introduction

Modern computer systems allow to solve a number of tasks related to receiving and processing signals [1], however, the problem of obtaining and converting initial signals for evaluating hemodynamic parameters with non-invasive methods remains unsolved.

One of the methods for obtaining data at evaluating hemodynamic parameters is volumetric compression oscillometry. Nevertheless, the use of an air cuff significantly changes the shape of the oscillometric curve due to the compressibility of the air. In addition, significant uncertainty in finding characteristic points is caused by noise, mechanical vibrations, and various artifacts.

In the article, it is proposed to use an oscillometric curve obtained on the basis of hydro-cuff technology as the initial signals. This technology has not been used before to solve the tasks of evaluating hemodynamic parameters and, as shown by preliminary studies, it is unique.

The main advantages of hydro-cuff technology are associated with a significant increase in the amplitude and small distortion of the waveform. This creates prerequisites for a significant increase in the accuracy of hemodynamic parameters estimation for non-invasive estimation methods.

Hemodynamic processes are associated with blood circulation in the cardiovascular system. In medical terms, the task of evaluating hemodynamic parameters is to find the relationship between the estimating hemodynamic parameters and certain types of pathologies caused by the presence of cardiovascular system diseases. Generally, hemodynamic parameters characterize blood pressure (BP), cardiac activity, and the state of the vascular system.

Currently, many systems have been developed that can directly or indirectly evaluate hemodynamic parameters.

Increasing the blood pressure accuracy measurement is directly related to the need to increase the sensitivity of arterial blood pulsation transducers. The increase in sensitivity is due to the increased influence of various motion artifacts, the appearance of components caused by mechanical movement of organs (the process of breathing, heart contractions, muscle contraction, etc.), which are obtained for further processing. Its combined influence leads to distortion of the pulse waves amplitude-frequency characteristics, which ultimately affects the accuracy of the characteristic points representation of the
curve for hemodynamic parameters forming algorithms based on the pulse waves processing and its circumflex. The use of linear filters of various types [2] significantly distorts the pulse waves dynamic characteristics, which makes its inefficient use in signal processing algorithms.

In this regard, a nonlinear SVD filtering method based on singular spectral analysis, the use of which makes it possible to distinguish trend and periodic components quite effectively against the background of noise generated when registering pulse waves is proposed. [3].

2. Materials and methods
Considering the transfer of pressure arising in the cuff to the pressure sensor as a process of sound propagation in a segment of a finite length artery, the equations for calculating the force $F_0$ and the displacement $\varepsilon_0$ applied to the pressure sensor is written down. In [3] it is proposed to consider the model of such a process as a model of a symmetric four-pole. By entering the amplitudes of the total force $F_l$ acting on the area $S$, the equations for calculating the force $F_0$ and the displacement $\varepsilon_0$ are:

$$F_0 = C h(\gamma l) F_l + S \rho c S h(\gamma l) \dot{\varepsilon}_l,$$
$$\dot{\varepsilon}_0 = \frac{S h(\gamma l)}{S \rho c} F_l + C h(\gamma l) \dot{\varepsilon}_l,$$

(1)

where $F_0 = S p_0$, $F_l = S p_l$, $S$ is the artery cross-sectional area, $p_0$ and $p_l$ are the pressure at the artery input and output, $l$ is the artery length, $\gamma$ is the adiabatic index, $\rho$ is the density medium filling the artery, and $c$ is the sound speed in the medium filling the artery.

Since the four-pole model is linear, the amplitude of the pressure pulsations perceived by the sensor will be proportional to the acting force $F_0$, the quadrate of which is proportional to the acoustic impedance of the four-pole. It is known [4] that the values of the characteristic impedance for gaseous, liquid and solid states differ by several magnitude orders. In this regard, replacing air by a liquid makes its application promising because of the incompressibility properties. This allows to increase the oscillations amplitude, almost by a magnitude order, compared to the air cuff.

As an example, figure 1 shows a graph of the pressure change in the hydro-cuff placed on the forearm with an excess pressure of 82 mmHg.st.

![Figure 1. A blood pressure compression oscillogram.](image)

The oscillogram shows a physiological origin disturbance caused by the patient's breathing. Elimination of both physical and physiological nature interference using linear filters leads to distortions of filtered signals of arterial blood pulsation, which in turn increases the errors in determining the biosignal amplitude-time characteristics [1].
Greater selectivity in filtering and noise isolation can be achieved by using nonlinear filtering methods, in particular filtering based on a singular time series decomposition. Singular spectral analysis (SSA) is used in the study of time series for forecasting [5], highlighting trend and periodic components [6]. This method can also be used for nonlinear signal filtering [7].

For spectral SSA analysis:
1. From the time series \( X = [x_0, x_1, \ldots, x_{N-1}] \) form the trajectory matrix

\[
X = \begin{pmatrix}
    x_0 & x_1 & \cdots & x_{K-1} \\
    x_1 & x_2 & \cdots & x_K \\
    \vdots & \vdots & \ddots & \vdots \\
    x_{L-1} & x_L & \cdots & x_{N-1}
\end{pmatrix}
\]

size \( L \times K \), where \( L \) is the length of the window made up of segments of the time series containing \( N \) members, \( K = N - L + 1 \) is the number of vectors included in the trajectory matrix

2. Perform a singular decomposition (SVD – decomposition) of the resulting trajectory matrix \( X \). It needs to calculate eigenvalues \( (\lambda_1, \lambda_2, \ldots, \lambda_L) \) of \( S = XX^T \) matrix and two unitary matrix \( U \) and \( V \), consisting of left and right singular vectors of matrix \( S \) respectively.

Then \( X = \sum_{i=1}^{L} X_i \), where \( X_i = \sqrt{\lambda_i} U_i V_i^T \).

3. Perform diagonal averaging of the matrix \( X_i \) and obtain averaged time series \( Y_i \) such that the original series \( X = \sum_{i=1}^{K} Y_i \).

In accordance with the procedure above, the initial formulation of the SVD - filtering task consists of two difficult-to-formalize procedures: selecting the length of the window \( L \) and selecting a limited number of averaged time series \( Y_i \) for generating the filtered signal.

It is proposed to select the length of the \( L \) window using synchronous accumulation with a consistently changing accumulation interval and subsequent the standard deviation estimation of the filtered signal. The periodic signals presence in the original time series with a period multiple of the accumulation interval will increase the standard deviation. The maximum accumulation interval that maximizes the output of a synchronous storage device can be taken as the length of the \( L \) window.

3. Results

Figure 2 shows the procedure results for selecting the window length.

![Fig 2](image)

**Figure 2.** Selecting the window length.

The resulting waveform analysis will allow to select the window length equal to \( L = 4459 \), the number of the decomposition eigenvectors is equal to \( K = 9268 \). Figure 3 shows the pairwise sums of the first 12 decomposition eigenvectors.
Figure 3. Waveforms of pairwise sums of the 12 eigenvectors of time series decomposition blood pressure changes.

The oscillograms analysis of 12 eigenvectors shows that eigenvectors can be approximated by harmonic functions. Table 1 shows the approximating results the waveforms of pairwise sums of eigenvectors.

| Amplitude | Period s | Frequency Hz | Phase rad | Eigenvectors sum |
|-----------|----------|--------------|-----------|------------------|
| 3.0       | 0.0      | 0.0          | 0.0       | 1-2              |
| 2.9100    | 0.7920   | 1.2626       | 0.7700    | 2-3              |
| 2.1400    | 0.3959   | 2.5259       | 1.7600    | 5-4              |
| 1.3500    | 0.2639   | 3.7898       | 1.7000    | 5-6              |
| 0.6700    | 10.5508  | 0.0948       | 4.0600    | 7-10             |
| 0.6300    | 0.1980   | 5.0493       | 2.0200    | 8-9              |
| 0.4200    | 0.4115   | 2.4300       | 1.5000    | 11-12            |

Figure 4 shows the blood pressure waveform decomposition spectrum into harmonic functions.

Figure 4. The blood pressure waveform decomposition spectrum into harmonic functions.

The singular spectral analysis made it possible to identify the main harmonics of the decomposition of the original blood pressure compression oscillogram (figure 1). According to table 1, the main harmonic is present in the compression waveform, which is determined by the pulse rate ($f_1 = 1.2626$
Hz), the second, third and fourth harmonics, as well as the harmonic with the patient’s respiratory rate ($f_0 = 0.0948$ Hz).

Figure 5 shows an error waveform for approximating the original blood pressure waveform with 12 eigenvectors.

![Figure 5](image-url)  
*Figure 5 Approximation errors.*

The mean square errors (RMS) of the approximation are summarized in table 2.

| Table 2. RMS approximations. |
|-----------------------------|
| RMS approximations of the original blood pressure waveform by 12 eigenvectors mV. | 0.8556 |
| RMS approximations of the original blood pressure waveform by harmonic functions mV. | 0.9444 |
| RMS of harmonic analysis mV | 0.1988 |

Due to the orthogonality of the singular decomposition eigenvectors, it is possible to achieve the required approximation accuracy by including an additional number of eigenvectors in the harmonic analysis.

4. Conclusion

The results obtained show high efficiency of using SVD - filtering based on singular spectral analysis. As a result, a trajectory matrix $X$. A singular value decomposition (SVD – decomposition) of obtained trajectory matrix $X$ is conducted. The diagonal averaging of the $X_i$ matrix is performed and the averaged time series $Y_i$, are obtained. The main harmonic components of the blood pressure compression oscillogram are highlighted. The standard deviation of approximation errors does not exceed 1 mV.

The use of a hydro-cuff tonometer followed by nonlinear SVD filtering of the resulting blood pressure compression waveform based on a singular spectral analysis makes it possible to effectively isolate and eliminate physical and physiological interferences in tonometry, thereby increasing the accuracy of measuring hemodynamic parameters.

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