Detection of Characteristic Points of Ventricular Assist Device Driving Signal, Using Wavelet Decomposition.

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Abstract-**Pneumatic and hydraulic pressure and flow signals, measured on working ventricular assist device (VAD) during its test, describe its temporal hydrodynamic conditions. Signals registered as time samples series contain characteristic points or fragments, which reflect consecutive stages of VAD pulsate work. Because of nature of signals describing biological objects, they often can be time-varying, transient, non-stationary and affected by multi-sources noise. It makes in some situations characteristic points of pressure-flow curves unseen in time domain and automatic detection of these important instants is very difficult or even not possible. We proposed time-frequency (T-F) analysis approach, where signals are decomposed into adaptive, frequency sub-bands, using wavelet transform (WT), which is known as a suitable tool for biomedical non-stationary signal analysis. As a result of using WT, the multi-resolution T-F representation is obtained, which is sensitive and can detect both long-term trends and dynamic, sudden changes in input signal. Our research signal database was created as a result of VAD tests performed for different control parameters on mock circulatory system, designed and made in our Institute. Results of proposed automatic detection procedure were presented for three types of WT basis function. We work on application of our study effects in control algorithm of testing devices for the determination of the critical control parameters of VAD work conditions.**

Keywords: **characteristic points detection, wavelet transform, ventricular assist device.**

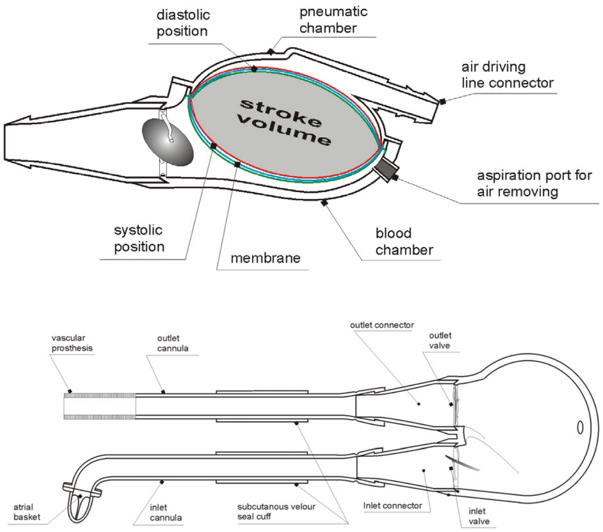

Fig. 1. Polish ventricular assist device (POL-VAD)

I. INTRODUCTION

One of the basic goals of digital signal processing methods is to extract important and specific information, which can not be directly obtained from accessible signals. Such a situation takes place in presented in this paper problem of using time-frequency signal analysis for detection of characteristic points from signals, measured on heart valve prostheses and Polish ventricular assist device (POL-VAD) during tests.

Presented in fig.1 POL-VAD is a pneumatically driven, membrane type (U-shaped) blood pump, which was developed in Institute of Heart Prostheses in Zabrze, Poland, to support the failure patient heart during recovery or as a bridge to transplantation. Mechanical, disc valves Sorin-Biomedica® were placed in inlet and outlet channels, which through special prepared caniulas can be connected to patient cardiovascular system during cardiac surgery operation. Both VAD walls and membrane are made of bio-compatible polyurethane. A driver unit creates a pulsate air wave, which through a elastic pipe is sent to pneumatic part of POL-VAD.

Generally, from the medical point of view, the VAD control optimization means the achievement of required by physician hemodynamical system conditions with minimization of harmful effects connected with external heart assist device usage. In clinical practice, realization of this goal is often done by setting control parameters in such a way to ensure the full filling and full ejection of VAD during its pulsate work cycle. This is not a trivial task because of both the features of device and changeable conditions of patients cardiovascular system, what determines the blood supply into organism.

Pump control parameters, which characterize the pneumatic drive wave, can be divided into two groups:

1) Time relations: frequency *(F)* and percent of systole *(%S)* (ratio of the ejection fraction to the whole cycle time)
2) Pressure relations: force (P_F) and suck pressure (P_S).

The most important for estimation of assisted patient hemo-dynamic conditions are following hydraulic signals connected with blood flow through POL-VAD:

1) P_{IN} – input pressure
2) P_{OUT} – output pressure
3) P_V – pressure measured inside the chamber
4) Q_{OUT} – output blood flow

From POL-VAD control point of view, only pressure P_D and flow Q_D of pneumatic driving wave is accessible. That's why the first step in approach of automatic detection of pressure and flow characteristic points, is to associate them

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Abstract

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with the pneumatic - control signals, what will be presented in the next section. As a next stage, time-frequency representation of analyzed signals is obtained. Because of nature of signals describing biological objects, processed signals are time-varying, transient and non-stationary. It makes, that in some situations characteristic points of pressure-flow curves can be unseen in time domain and automatic detection of these important instants is very difficult or even not possible. We proposed time-frequency (T-F) analysis approach, where signals is decomposed into adaptive, frequency sub-bands, using wavelet transform (WT), which is known as a suitable tool for biomedical non-stationary signal analysis [1], [2]. As a result of using WT, the multi-resolution T-F representation is obtained, which is sensitive and can detect both long-term trends and dynamic, sudden changes in input signal. These features, verified in many applications makes the WT more useful for analysis of described problems than the Short Term Fourier Transform with constant-width window [3]. Others commonly used T-F signal representation methods like Wigner Distribution (WD) and its modification Smoothed WD or Choi Williams Distribution (CWD) features, which make difficult to apply them for non-stationary signals.

II. EXPERIMENTAL PROCEDURE

To test presented detection procedure, data base of POL-VAD in vitro test were created. Mock circulatory investigation system, designed in our laboratory was used to collect described above signals characterizing the VAD work. 266 sets of signals were recorded for different values of driving parameters:

1) Frequency *(F)* - 30, 35, 40, … 115, 120 [bpm]
2) Percent of systole *(%S)* - 20, 30, ... 70, 80 [%]
3) After-load on VAD outlet, simulating arterial systemic resistance *(R_S)* – two values.

Signals were collected using data monitor and acquisition system, with sample frequency F_S=250 [Hz].

III. METHODOLOGY

In this section, consecutives steps of characteristic points detection procedure as well as the issues connected with choice of methods parameters are presented.

A. Determination of analyzed signals characteristic points.

Based on results of performed in our Institute research on the influence of control parameters on the hemodynamic conditions of POL-VAD work [4], the recorded signals characteristic points and fragments were determined.

Fig.2 a-d presents the drive pneumatic wave P_D in comparison with four described above signals, connected with VAD operation: hydraulic pressures: P_{IN}, P_V, P_{OUT}, and flow Q_{OUT}. The crucial peaks and phases, which reflect consecutives stages of VAD pulsate work, marked on fig.2 are shortly described below.

FE – state of chamber full ejection, at the end of systolic cycle phase. This is an effect of force continuation in the extreme membrane position.

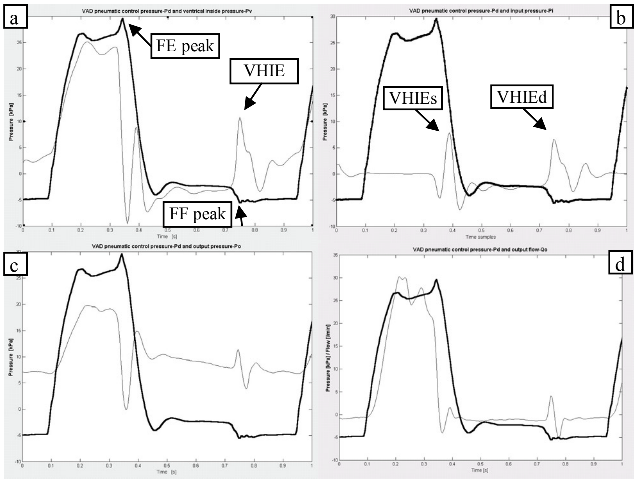

Fig. 2 The comparison of VAD pneumatic driven signal P_D (thick line) with pressure measured chamber inside (a), input pressure P_{IN} (b), output pressure P_{OUT} (c) and output flow signal Q_{OUT} (d). Characteristic points are marked (see text for description).

FF – state of chamber full fill, at the end of diastolic cycle phase. This is an effect of suction continuation in the extreme membrane position.

VHIE – ventricular hemodynamical inertial effect, which is also called as “hydraulic hammer” can be seen as a characteristic pressure and flow wave caused by sudden membrane stopping after systolic FE (VHIEs) or diastolic FF (VHIEd) phases.

B. Wavelet decomposition application.

The continuous wavelet transform (CWT) expressed by (1), can be interpreted as the correlation function between the signal *s(t)* and the wavelet $\psi_{a,b}(t)$, obtained by the scaling (*a*-parameter) and shifting (*b*-parameter) the basic function $\psi(t)$ [5].

$$CTW\{s(t)\}(a,b)=\left\langle s(t),\psi_{a,b}(t)\right\rangle=\frac{1}{\sqrt{a}}*\int_{-\infty}^{\infty}s(t)*\psi\left(\frac{t-b}{a}\right)dx \quad (1)$$

In frequency domain it corresponds to process of passing the signal s(t) through a filter, represented by wavelet $\psi_{a,b}(t)$ transfer function. So multi-resolution analysis of signal means its decomposition into frequency subbands, corresponding to different values of scale parameter *a*.

Discretization of CWT parameters *a* and *b* leads to discrete wavelet transform (DWT), which results can be less redundant than for CWT. In presented work, the effective way of DWT perform introduced in late 1980’s by Mallat was used [6]. In j^{th}-level of the Mallat algorithm, signal is decomposed into two complement function spaces of details s_{Dj} and approximations s_{Aj}. In practice, the approximation and detail associated with j^{th}-level are computed from the approximation coefficients at the next higher scale j+1, using a quadrature mirror filter pair.

The features both of filters and algorithm performance are determined by the type of basic wavelet and scaling function used for analysis. Taking into consideration the specific character of studied problem, wavelet properties list, including following items was created:

1) Ortogonality
2) Biortogonality
3) Compact support
4) Symmetry
5) Regularity and smoothness
6) Number of vanishing moments
7) Analytical formula of basic function
8) Interpolation
9) Rational coefficients

Base on these features, for further analysis we chose three types of basic functions, which usage in presented detection procedure was compared:

1) Daubechies : *Db4*
2) Symlets : *Sym5*
3) Biortogonal-Spline: *Bior 2.4*

C. Characteristic points detection procedure.

After determination of crucial points for optimal VAD control on described in section I pneumatic and hydraulic signals, main stages of proposed their automatic detection procedure are following:

1) Determination of signal characteristic fragment or peak to detect.
2) Finding the cycle start point for all synchronized pressure and flow signals.
3) The most appropriate WT decomposition level determination, according to Mallat algorithm, for analysis of specified characteristic signal part.
4) Definition of the detailed decision rules for each detected signal fragment.

III. RESULTS AND DISCUSSION

Results presented in this paper are devoted to automatic detection of characteristic pneumatic driving pressure peak - *FE* (fig.2a), which reflects the full ejection state of VAD pulsate work. According to described in previous section algorithm, for each of chosen basic wavelet function, Mallat multilevel decomposition of driving VAD pressure P_D was performed. Frequency subbands limits, corresponding to different level of Mallat decomposition, in frequency range specified as significant for pressure and flow signals [7] are following:

$b_2 : 31.25 \div 62.5$ [Hz] $b_3 : 15.63 \div 31.25$ [Hz]
$b_4 : 7.81 \div 15.63$ [Hz] $b_5 : 3.90 \div 7.81$ [Hz]
$b_6 : 1.95 \div 3.90$ [Hz] $b_7 : 0.98 \div 1.95$ [Hz].

Fig.3 presents the result of Mallat decomposition of pressure P_D into seven levels. Both for cycle start point and FE peak determination, we chose extracted from WT coefficient detail component S_{D1}.

The comparison of original pressure signal P_D with absolute values of component S_{D1} samples, is showed in fig.4 The local maximums of the WT modulus at chosen decomposition level - S_{D1} were used to locate interesting analyzed signal parts, according to following procedure:

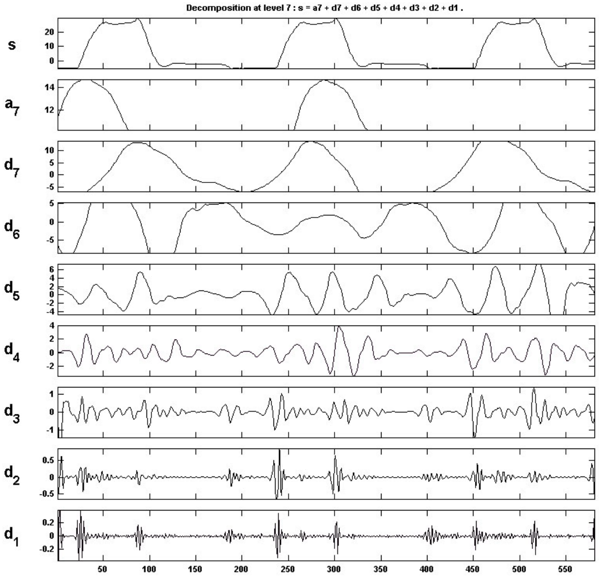

Fig. 3 Multilevel, wavelet decomposition of VAD driven signal P_D , according to Mallat algorithm.

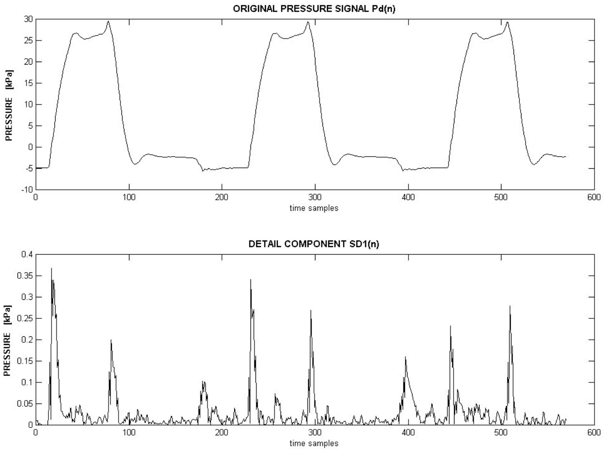

Fig.4 Original VAD driving signal P_D and its detail component on first level of Mallat decomposition.

1) Using threshold detection value - S_{TR} , the cycle starting point (CSP) can be set as the maximum value of $|S_{D1}|$ over given time period. This moment corresponds to the beginning of systolic (ejection) phase of pulsate VAD work.
2) After estimating the CSP, the next maximum detected by threshold value S_{TR} is assumed as characteristic peak *FE*.
3) Third $|S_{D1}|$ detected maximum corresponds to next important driving pressure P_D peak of VAD full fill *FF*.

To verify proposed procedure based on WT time-scale signal representation, we performed the automatic detection for all signals recorded during experiment for different VAD driving parameters (see section II). Tab. 1 presents the percent of correctly detected CSP and peaks *FE*, for three chosen types of WT basic function.

TABLE 1
The percent of correctly detected cycle start points (CSP) and full ejection peaks (FE).

	Db4	**Bior 2.4**	**Sym5**
CSP [%]	88.2	85.4	83.9
FE [%]	87.6	84.2	83.4

Obtained results show, that the type of applied WT basic function has a significant meaning for quality of detection procedure. False detection of CSP, caused the errors in FE peak place definition. As a next step in work on presented subject, the adaptive detection threshold level will be used and rules for remain characteristic point of VAD driving pressure P_D will be determined.

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