# On-Line Identification of the Heart Hemodynamic Parameters via an Adaptive Estimator Using Invasive Noisy Blood Pressure Waveform Observations

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## Abstract

*In this study, an innovative least-squares adaptive estimator is developed for heart fault diagnosis. The reference model of this study is the one developed by Ursino in 1998. Mitral valve function is studied in this paper based on a new method which uses invasive noisy blood pressure waveform observations of left ventricle, left atrium, and left pulmonary vein. To meet this end, an adaptive algorithm is designed for estimation of discontinuous time-variant parameter values and then Ursino's model simulator is utilized for the evaluation of Mitral valve non-linear gain. The results obtained, indicate the high capability of the presented model in the estimation of different cardiovascular parameters and so fault diagnosis in heart valves.*

## 1. Introduction

When the cardiovascular system operates in healthy conditions, the hemodynamic parameters of the heart and vascular system have some nominal values representing normal function. However, in some cardiac abnormalities such as left or right ventricles hypertrophy, mitral valve stenosis or aorta aneurysms, hemodynamic parameters of the heart differ from the nominal values [1,2]. Recognition of the difference between the actual value of cardiovascular parameters and the nominal values for a specific subject, can lead to diagnosis of cardiac dysfunctions or vascular abnormalities.

Depending on the type of blood pressure measurements carried on the cardiovascular system, the information obtained on the mechanical function of heart can differ from each other. One approach in such observations is the non-invasive method, in which blood pressure waveforms are recorded using sensors in arms, hands, or parts of the legs. These types of measurements can be used for medical treatment in ICU or primary diagnosis [3,4]. However, they cannot be applied for more investigations of the mechanical function of heart and the vascular system due to the lack of accuracy.

Another approach for blood pressure measurements is the invasive method, in which more accurate waveforms can be recorded using tip sensors in ventricles, atria, and vessels. However, this method has its own specific risks [5,6].

Mathematical modeling of heart valves can lead to non-linear, discontinuous, time-variant functions, on which common detection algorithms cannot be applied due to their unique application for linear time-invairant systems. Recursive Pseudo Regression (RPR), Recursive Least Squares (RLS), Forgetting Factor (FF), and Kalman Filter (KF) are typical examples of such algorithms that can only be used for the estimation of parameters with moderate fluctuations in linear systems [7,8]. For the case of non-linear parameters, methods such as Non-linear Least Squares or Soft Computing approaches have been developed which have their own specific limitations [9,10].

In this study, we have developed an innovative adaptive estimation algorithm which is based on the adjustment of the parameters of a polynomial in a sliding window on the signal, using the least-squares method. The presented method is capable of estimating discontinuous time-variant parameter values based on invasive noisy blood pressure waveform observations.

## 2. Methods

*Selection of an Appropriate Model*: The reference model of this study is the one developed by Ursino in 1998 [11]. In his mathematical model, a comprehensive hydraulic analog consisting of different compartments is considered as the cardiovascular system model. Some of these compartments are used to reproduce the systemic circulation, and some other mimic the arterial, peripheral and venous pulmonary circulations. Each compartment includes a hydraulic resistance, a compliance, and an unstressed volume.

*Discretization of the Model:* The scheme of the discretization approach is depicted in Figure 1. This finally leads to the following recursive formula:

$$\dot{P} = f(P,u,t) \tag{1}$$

$$P_{n+1} = P_n + \frac{5T}{12} f_{n-2} - \frac{4T}{3} f_{n-1} + \frac{23T}{12} f_n \tag{2}$$

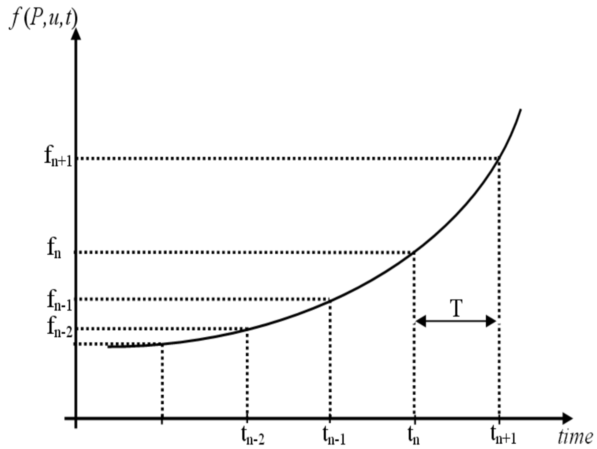

Figure 1. Schematic overview of the discretization algorithm

*Blood Pressure Observations:* In this study, invasive noisy blood pressure waveforms including left ventricle pressure (LVP), left atrium pressure (LAP), and left pulmonary vein pressure (LPVP) are used as the observations from the cardiovascular system for the online estimation of the heart hemodynamic parameters.

*Applying the Estimation Algorithm:* Consider a system with the following equation:

$$y(k) = g_1(k)x_1(k) + g_2(k)x_2(k) + n(k) \qquad (3)$$
$$k = 0,1,2,3,\ldots$$

Where $g_1, g_2$ are time-variant gains, $n$ is the noise in measurements, $y$ is the observation, and $x_1, x_2$ are regressor variables. Suppose that one of the observations of the system is as illustrated in Figure 2. Applying the estimation algorithm to the system, the outputs of the estimation model are obtained and represented in Figure 2, as to be compared with those of the actual observations. The true and the estimated values of time-variant parameters are depicted in Figure 3. As can be observed, the presented adaptive estimation algorithm has remarkable capabilities in the estimation of time-variant parameter values. The schematic overview of the Left Heart Model, derived from Ursino's model, is represented in Figure 4. As can be seen in this figure, Mitral valve is simulated as a non-linear element with time-variant parameters and equations of the Left Heart are as follows:

$$\begin{cases} F_{il} = \dfrac{f_{mitral}\left(P_{la} - P_{lv}\right)}{R_{la}} \\ F_{la} = \dfrac{P_{pv} - P_{la}}{R_{pv}} \\ \dot{P}_{la} = \dfrac{F_{la} - F_{il}}{C_{la}} \end{cases} \qquad (4)$$

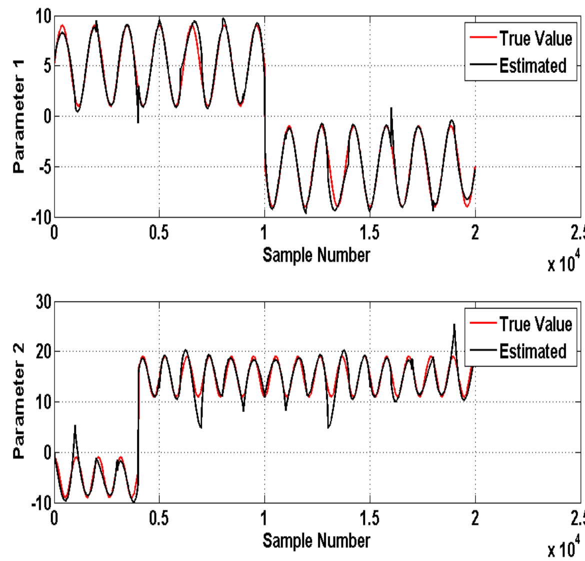

Figure 2. Estimation of two time-varying parameters (gains) with discontinuity using adaptive Least-squares procedure

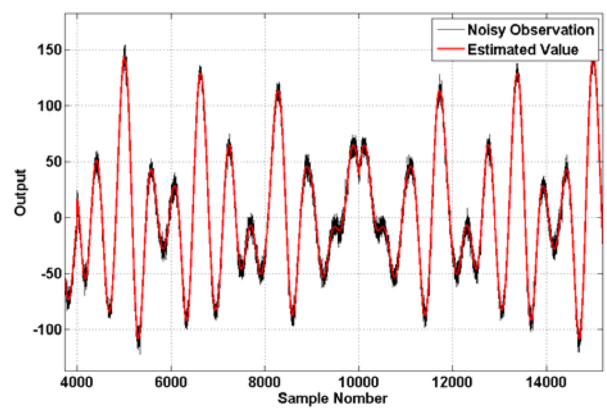

Figure 3. Tracking of the noisy observation using the adaptive parameter estimator

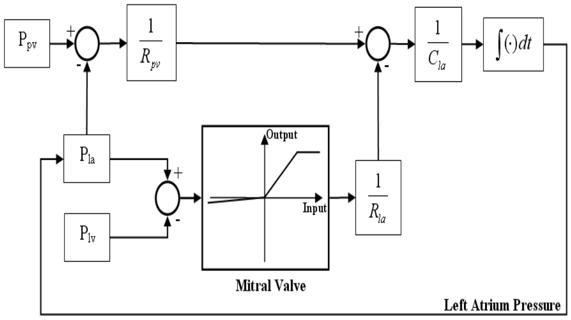


Figure 4. Schematic overview of the left heart based on Ursino (1998) model. The Mitral valve is modeled as a nonlinear gain

The pressure waveforms of Left Atrium, Left Pulmonary Vein and Left Ventricle are respectively illustrated in Figures 5 and 6 in two cases; mitral valve with normal function and mitral valve with dysfunction, i.e. bypass.

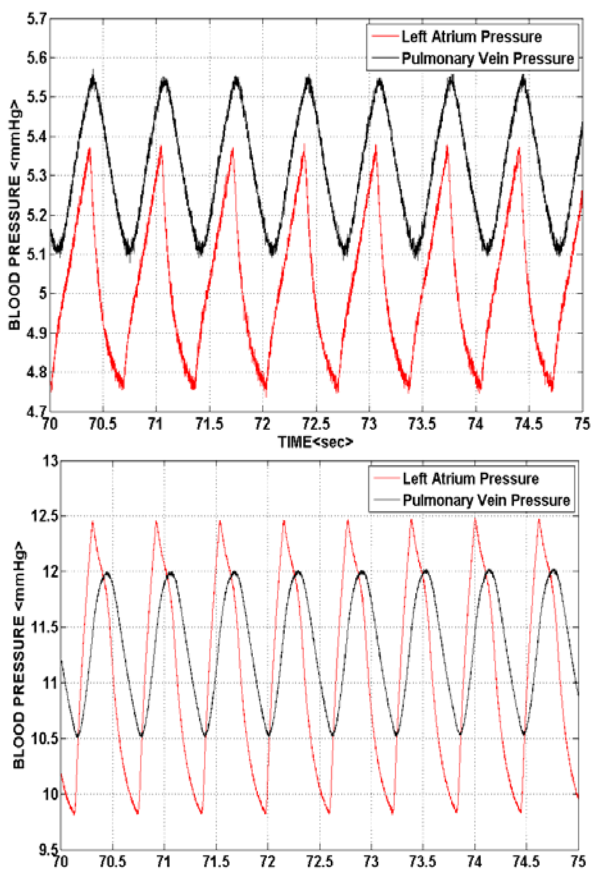


Figure 5. Left atrium and the pulmonary vein pressures obtained from Ursino model, Top: Normal Mitral, and bottom: Mitral valve with bypass dysfunction.

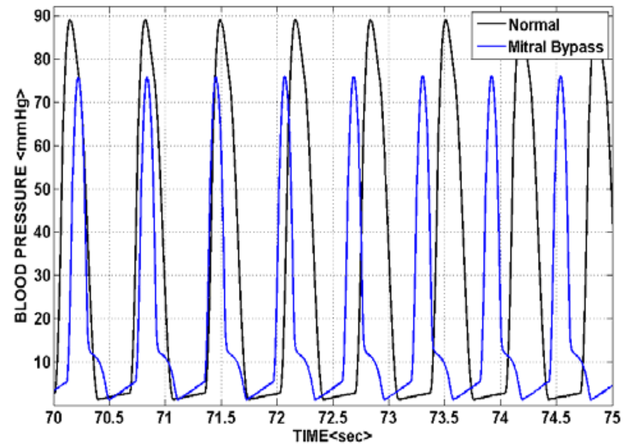


Figure 6. Left ventricle pressure with normal and abnormal Mitral valves.

## 3. Results

Applying the presented adaptive estimation algorithm to the corresponding model of equations 5, the parameters of the heart are estimated sequentially, parallel to the samplings of the aforementioned waveforms, and the corresponding variations, mean values, and variances of these parameters are analyzed. Finally, the resulted on-line parameter values are compared to the corresponding nominal (normal) values in order to diagnose cardiac abnormalities.
The results of this study are summarized in Table 1.

Table 1. The Results

| | Actual Mitral Leakage Percent (Simulation) | Estimated Value |
|---|---|---|
| Simulation # 1 | 10.0 | 11.2 |
| Simulation # 2 | 15.0 | 14.7 |
| Simulation # 3 | 20.0 | 19.8 |
| Simulation # 4 | 25.0 | 26.3 |

As can be observed in the table above, the presented adaptive estimation algorithm has remarkable capabilities in the estimation of time-variant parameter values for Mitral valve.

## 4. Discussion and conclusions

The reference model of this study is the one developed by Ursino in 1998. In his mathematical model, a comprehensive hydraulic analog consisting of different compartments is considered as the cardiovascular system model. Some of these compartments are used to reproduce the systemic circulation, and some other mimic the arterial, peripheral and venous pulmonary circulations.

An innovative adaptive estimation algorithm was developed in this study, which was based on the adjustment of the parameters of a polynomial in a sliding window on the signal, using the least-squares method. Invasive noisy blood pressure waveforms including left ventricle pressure, left atrium pressure, and left pulmonary vein pressure were used as the observations from the cardiovascular system for the online estimation of the heart hemodynamic parameters.

The presented method is capable of estimating discontinuous time-variant parameter values of the Mitral valve based on invasive noisy blood pressure waveform observations. Thus, the performance of different heart valves can be evaluated using this method under various physiological conditions.

The presented estimator, however, has significant error in the edges of the sliding window. Removing these edge effects and developing a more precise estimator can be the aim of future work.

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