ESTIMATION OF BLOOD PUMP PARAMETERS FOR CARDIOVASCULAR SYSTEM IDENTIFICATION

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Abstract - This paper describes the use of signal processing techniques to estimate the model parameters of a left ventricular assist device (LVAD). The model consisted of lumped resistance, capacitance, and inductance elements with one time-varying capacitor to estimate the cyclical pressure generation of the device using volume signal from the device. The model parameters were estimated by least squares fit to experimental data obtained in the laboratory. The purpose of this research is to estimate the pressure and flow signals, which are usually measured through invasive physiologic sensors, for an on-line estimator to identify cardiovascular parameters of patients who are under LVAD assist. The success of this development would provide a useful tool to monitor the cardiac function of LVAD patients without indwelling sensors. A computer simulation of the pump with a cardiovascular model was developed to demonstrate the interaction between the LVAD and the cardiovascular system. The simulation results showed agreement with those from an animal experiment and thus the simulation waveforms can be used for testing the cardiovascular estimator.

INTRODUCTION

Heart disease is a major health problem in the United States and throughout the world. Although heart transplantation is an accepted method to treat severe cases of the disease, the demand for heart transplants exceeds the supply. For many patients, a left ventricular assist system could provide a satisfactory alternative.

When LVADs are used to support the cardiovascular demand of patients while their are waiting for a suitable donor heart for transplantation, it is important to monitor cardiac function and hemodynamics of the patient. An on-line estimation procedure has been developed to estimate the parameters of a cardiovascular model, shown in Fig. 1 above dashed line, using aortic pressure (AoP) and aortic flow (Aof) measurements [1]. However, these signals are very difficult to measure under most of the clinical environments. If these signals can be derived or substituted using measurements from the LVAD itself, invasive sensors in the human body could be eliminated.

This paper illustrates the use of a simple lumped parameter model, shown in Fig. 1 below dashed line, to describe the pressure-volume relationship of the Novacor blood pump (Novacor Division, Baxter Healthcare Corp., Oakland, CA). This pulsatile pump accepts blood from the left ventricle at low pressure during natural cardiac systole and ejects into the descending thoracic aorta during cardiac diastole. In this counter-pulsation operation, most of the blood flow from left ventricle goes through the pump to the aorta, so the pump volume measurement, supplied by the LVAD, can be used to estimate the aortic flow. The pump pressure, derived from the pump volume information with the identified model parameters, will be used to substitute the invasive aortic pressure measurement. Thus the cardiovascular system estimator can be used to identify the model parameters without any indwelling sensor. This is the motivation for this research.

In this study, pump pressure and volume measurements were used to identify the model parameters and to quantify its accuracy. A computer simulation of the pump with the cardiovascular system model was also constructed to show the interaction between the blood pump and the cardiovascular system and compare to the animal experimental data for validation.

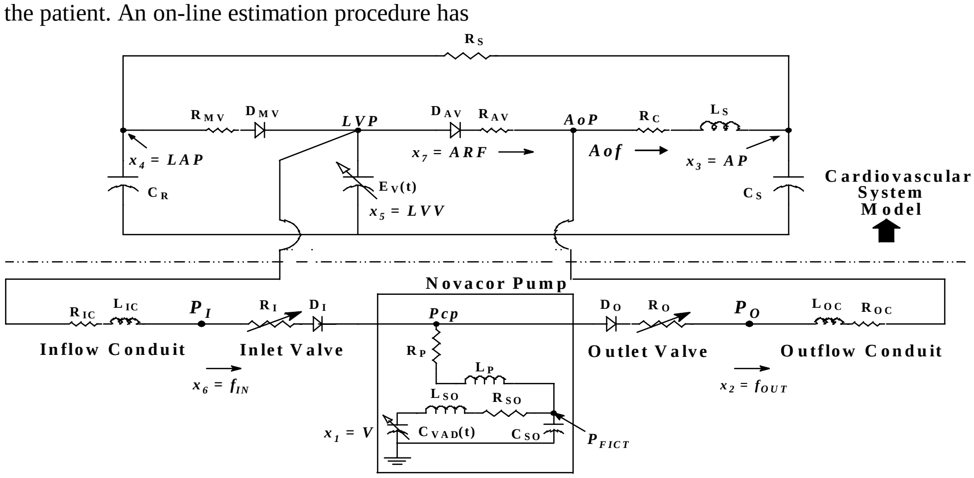

Fig. 1, The electric analog of the system model

SYSTEM DESCRIPTION

The Novacor LVAD is a spring-decoupled dual pusher-plate sac-type blood pump driven by a pulsed-solenoid energy converter. The cycle begins with the pump sac filled with blood and solenoid unlatched. At the start of pump ejection, the solenoid closes rapidly, deflecting the beam springs through the pump pusher plates and exerting a balanced force on the top and bottom surfaces of the blood in the pump sac. At the end of ejection, after the beam springs have released most of their stored energy and returned to their preload condition, the current to the solenoid is terminated, and the pump is free to fill for the next ejection cycle [2].

An electric analog of the Novacor LVAD pump, shown in Fig. 1 below the dashed line, has been formulated to facilitate analysis of the system. The purpose of this model is to predict the pump chamber pressure, Pcp, for a given instantaneous pump volume, V, based on the model parameters. The static pressure-volume relationship, P(V), representing the spring stiffness of the pump, was modeled by a time-varying capacitance, $C_{VAD}(t)$. A second order system, represented by R_{SO}, L_{SO}, and C_{SO}, was used to describe the dynamics of solenoid closure. The pressure response for a given P(V) was represented by the transfer function

$$P_{FICT}/P(V) = H(s) = \omega_n^2 / (s^2 + 2\zeta\omega_n s + \omega_n^2) \qquad (1)$$

where P_{FICT} is the pump pressure measurement in the absence of fluid mechanics effect in the pump chamber. The fluid resistance and inertance of blood in the pump chamber were represented by a resistance, R_P, and an inductance, L_P.

EXPERIMENTAL METHOD

Two experiments were conducted to determine the functions and the parameters of the function, P(V), and the fluid resistance and inertance during pump ejection and filling.

a. Quasi-static experiment:

In the first experiment, the LVAD pump was operated in a mode in which the solenoid is held closed ("HALT EJECTION" mode [3]), allowing a quasi-static estimation of P(V) during pump ejection to be characterized. The schematic of the experiment is shown in Fig. 2. A Novacor N100 pump was used with 1 inch diameter PVC tubing with rubber stoppers placed at the inlet and outlet ports. A 1/8 inch tubing was attached to the pump outlet tubing to introduce and remove fluid. A DTX pressure transducer (Viggo-Spectramed, Oxnard, CA) was placed on the outlet tubing near the pump to measure the pump chamber pressure, Pcp.

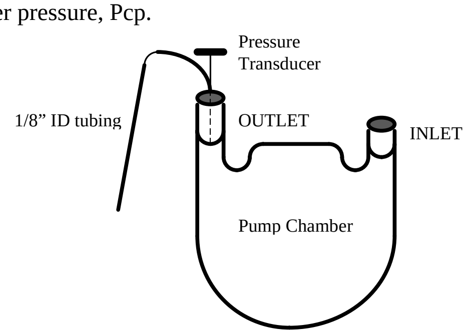

Fig. 2 Scheme of the "Halt Ejection" experiment

At the start of this experiment, the LVAD pump was filled with 72 mL water. The pump solenoid was then latched, and the fluid drained slowly at a controlled rate to minimize the effects of inertia and viscosity. The pump volume and pressure measurements were sampled at 50 Hz for a duration of 60 seconds and recorded digitally on an IBM 286 PC .

b. Dynamic experiment:

In the second experiment, the LVAD pump was attached to a passive "Penn State type" mock circulation loop [4] as shown in Fig. 3 which includes two compliance chamber and a fixed fluid resistor. The LVAD was operated at 15 beats per minute (BPM) and 75 BPM to generate dynamic pump pressure and volume data. The data obtained at 15 BPM were used to identify the fluid mechanics parameters, R_P and L_P, which could not be estimated during quasi-static conditions of experiment 1. This low pump rate was used because its filling portion is long enough to characterize P(V) throughout pump filling. The data for pump rate at 75 BPM were used to validate the accuracy of the model. The pump pressure and volume measurements in both pump rate were sampled at 1 kHz for two pumping cycles.

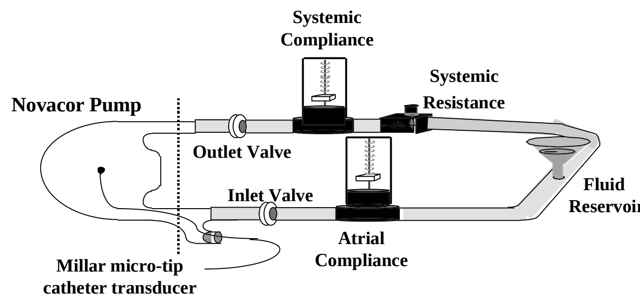

Fig. 3 Scheme of the mock loop experiment

MODEL PARAMETER IDENTIFICATION

a. Quasi-static pressure-volume relationship, P(V):

The static pressure-volume relationship consists of two parts: pump ejection ($\dot{V} < 0$) and pump filling ($\dot{V} > 0$). The "HALT EJECTION" experimental data were used to determine P(V) during pump ejection. The data were first smoothed by ensemble averaging over several successive trials. The smoothed data were then used to determine the function and its coefficients by a least squares fit algorithm (TABLE CURVE, Jandel Scientific, Corte Madera, CA).

The function P(V) during pump filling was determined by using the data obtained from the mock loop experiment with the pump rate at 15 BPM. In order to minimize the effects of the pressure transient at the start of filling, only the pump volume data between 20 mL and 70 mL were used for the P(V) function determination in TABLE CURVE.

b. The solenoid closure transient:

When the pump operation switched from filling to ejection and vice versa, the solenoid closure transient introduced a time delay and an overshoot in the pressure response. The second order system, as in equation (1), was used to describe this pressure transient. The time delay, defined as the difference between the maximum $\dot{P}cp$ and the maximum $\dot{P}(V)$, was 0.002 second. The maximum overshoot,

$$[Pcp(t_{MAX}) - P(V(t_{MAX}))] / P(V(t_{MAX})) * 100 \% \qquad (2)$$

was 16.5%, where t_{MAX} is the time that Pcp reached its maximum. These resulted in a natural frequency, ω_n, of 900 rad/sec, and a damping factor, ζ, of 0.5 [5].

c. Pump chamber fluid mechanics parameters estimation:

The pressure drop due to the fluid resistance and inertance, represented by R_P and L_P, can be written as

$$L_P \cdot \ddot{V} + R_P \cdot \dot{V} = Pcp - P_{FICT}, \quad (3)$$

where $\dot{V}$ and $\ddot{V}$ are the first and second time derivatives of the pump volume measurement. Equation (3) can be rewritten in matrix form as

$$W(t_k) \cdot K = \Delta P(t_k), \quad (4)$$

where $W(t_k)=[\ \ddot{V}(t_k)\ \ \dot{V}(t_k)]^T$, $\Delta P(t_k)=Pcp(t_k)-P_{FICT}(t_k)$, and t_k is the k-th data point. The optimal parameter vector K^* for minimizing the least squares residual error between the actual pressure drop, ΔP, and the predicted ΔP, given by [6],

$$K^* = (W^T W)^{-1} W^T \cdot \Delta P, \quad (5)$$

where $W=[W(t_1),\ W(t_2),\ \ldots\ W(t_n)]^T$ and $\Delta P=[\Delta P(t_1),\ \Delta P(t_2),\ \ldots\ \Delta P(t_n)]^T$. n is the total number of data points used for estimation.

The estimation algorithm requires calculation of P_{FICT} and the time derivatives of the pump volume measurement. Defining the state vector $X=[x_1\ x_2]^T=[P_{FICT}\ \ \dot{P}_{FICT}\ ]^T$, the second order system in (1) can be written in state space form

$$\dot{\mathbf{X}} = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 \zeta & -2\zeta\omega_n \end{bmatrix} \cdot \mathbf{X} + \begin{bmatrix} 0 \\ \omega_n^2 \end{bmatrix} \cdot P(V), \quad (6)$$

P_{FICT} can be obtained by integrating (6) from the initial state vector X(0), which in turn was determined by assuming that the pump has been completely filled in the filling phase so that the pump pressure has reached a steady state condition at the beginning of integration. The time derivative of the pump volume was calculated by

$$\dot{V}(t_k) = [V(t_{k+1}) - V(t_{k-1})] \cdot (f_S / 2), \quad (7)$$

where $V(t_k)$ is the k-th volume measurement and f_S is the sampling frequency. A 3rd order digital Butterworth lowpass filter was used following (7) with a forward-backward filtering technique to remove the high frequency noise that is amplified by the time derivative calculation without avoid phase shift [7].

d. Error analysis:

In any identification experiment, it is important to quantify the error of the model. For the static P(V) data, the coefficient of determination obtained from TABLE CURVE was used as the model accuracy index. A residual error index, defined by the percentage of mean normalized error between the measured Pcp and the model prediction, $\hat{P}cp$,

$$E_I = \|Pcp - \hat{P}cp\| / \|Pcp\| \cdot 100\% \quad (8)$$

where $\hat{P}cp = P_{FICT} + L_P^* \cdot \ddot{V} + R_P^* \cdot \dot{V}$, was used to quantify the pressure prediction error.

RESULTS

a. Quasi-static pressure-volume relationship, P(V):

The pressure and volume measurements collected from the “HALT EJECTION” experiment were used in TABLE CURVE to find an appropriate function P(V) and its parameters to represent the pressure-volume relationship during pump ejection. TABLE CURVE is a curve fitting program that can determine a function to approximate a data set by fitting the data to functions contained in the program. The program identifies the corresponding function parameters by minimizing the prediction error in least squares sense using the Levenburg-Marquardt algorithm [8]. The function

$$P(V) = (a_0+a_1X+a_2X^2+a_3X^3) / (1+b_1X+b_2X^2+b_3X^3) \quad (9)$$

where X=Ln(V), 0 mL<V≤71 mL, was found to fit the data (r^2=.999) as well as extrapolate well beyond the data set. The coefficients were a_0=-9.144, a_1=16.700, a_2=-6.520, a_3=0.872, b_1=-0.805, b_2=0.225, and b_3=-0.021. The data collected from the mock loop experiment with the pump rate at 15 BPM were used to determine the function P(V) during filling. The function

$$P(V) = a + b \cdot \tan^{-1}[(V-c)/d] \quad (10)$$

with the coefficients a=187.66, b=124.75, c=71.98, and d=0.27 was obtained from TABLE CURVE to describe P(V) during pump filling (r^2=0.962). Fig. 4 shows the fit of P(V) in (9) and (10) to the experimental data.

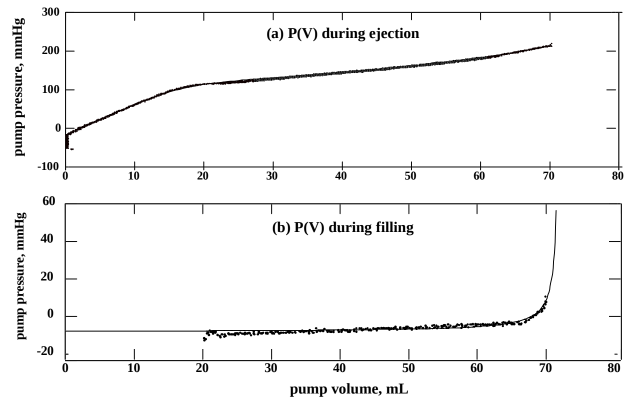

Fig. 4 Novacor pump P-V relationship

b. Pump chamber fluid mechanics parameters:

Identification of the viscosity and inertance parameters in the LVAD pump chamber as described in Section 4c was implemented in MATLAB (Mathworks Inc., Natick, MA) using the experimental data with the pump rate at 15 BPM. The static pressure-volume relationship P(V) was first calculated based on (9) and (10). P_{FICT} was computed by integrating (6) using the Runge-Kutta fourth order method [9]. Filtered volume data were then used to calculate the first and the second time derivatives. The same filters were applied to the time derivative signals to remove high frequency noise and the signals were used to estimate the parameter vector K in a least squares sense in (5). The parameter estimates were R_P^*=2.2946e-2 mmHg·sec/mL and L_P^*=5.8463e-4 mmHg·sec^2/mL. The error index as defined in (8) was E_I=10.83%. Figure 5(a) shows the pump pressure measurement and the model prediction versus time at 15 BPM.

c. Model validation:

The data collected from the mock loop experiment at 75 BPM were used to validate that the model can describe the hemodynamics under different operating conditions. The pump volume measurement was used with the model parameters obtained in Section 5b to estimate the pump pressure. This prediction was then compared with the experimentally measured pump pressure. The residual error index, defined by (8), was used as the overall assessment of the model performance. The predicted and measured pressure versus time are illustrated in Fig. 5(b). A small residual error index, E_I=11.93%, indicated that the model performed very well overall.

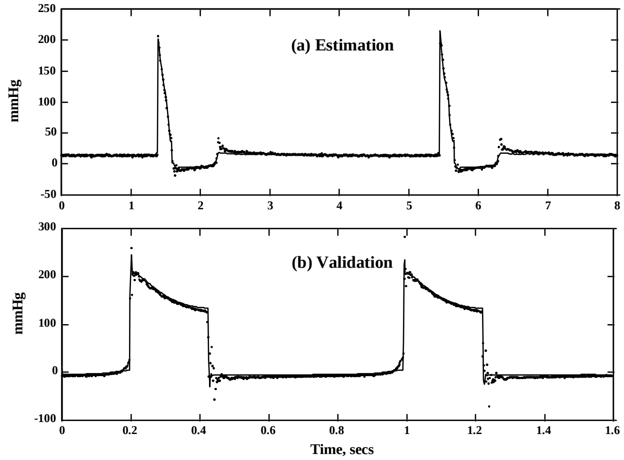

Fig. 5 Predicted (solid) vs. measured (dashed) pump pressure

COMPUTER SIMULATION

Since the pump model is used with the cardiovascular system model to identify cardiovascular parameters, a computer simulation incorporating the cardiovascular model with the pump model, shown in Fig. 1, was performed to demonstrate the effectiveness of the combined model. The models of the inflow and outflow conduits and the prosthetic valves were adopted from [10] while the model parameter values were obtained by least squares fit to the experimental data. The system dynamic equations of the model were described in a state-space form and solved using the Runge-Kutta fourth order integration method [9] in MATLAB. The amplitude of $E_V(t)$ was decreased to 33%, the heart rate was increased to 100 beats per minute, and R_S was increased to 110% of the nominal values in [1] to simulate heart failure. The LVAD was turned on and off in the simulation to show the pump effect to the cardiovascular system. AoP was increased and LVP decreased when the pump is on as shown in Fig. 6. Simulation also showed that AoP is always higher then LVP under LVAD support (aortic valve closed) so Aof can be estimated by the pump volume signal from the LVAD for on-line parameter estimation. The simulation waveforms were used to quantify the cardiac oxygen supply and consumption indices of the native heart [2]. These indices, in Table 1, showed the same directions of changes as the data from an animal experiment [2].

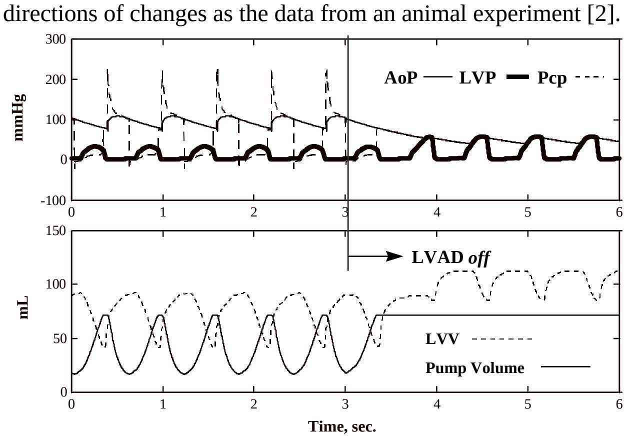

Fig. 6, Simulation of the LVAD with the cardiovascular system

CONCLUSION

A lumped mathematical model of the Novacor LVAD pump that can estimate the pump chamber pressure using only pump volume information has been developed. The accuracy of this model has been demonstrated by r^2 and the error index in (8). A computer simulation describing the effect of the LVAD to the cardiovascular system showed that the changes of the indices while the LVAD was on and off in simulation were the same direction as changes obtained from the animal experiment.

Since Aof can be derived by pump volume signal and AoP can be substituted by the pump chamber pressure estimate, the Kalman filter parameter estimation procedure can be used to obtain cardiovascular parameters without invasive flow and pressure measurements by incorporating this pump model into the cardiovascular system.

Table 1 Comparison of simulation results with the animal data

	Simulation		**Animal data [2]**	
LVAD	off	on	off	on
mean AoP (mmHg)	50	96	102	111
Max. LVP (mmHg)	58	34	105	35
C.O (L/min)	2.7	5.5	5.7	6.8
TTI (mmHg·s/min)	13	8	42	10
PTI (mmHg·s/min)	16	49	15	56
EVR	1.23	6.13	0.37	5.74
Max. $L\dot{V}P$ (mmHg/s)	701	567	1350	500

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