15th Triennial World Congress, Barcelona, Spain

NONINVASIVE FLOW ESTIMATION OF A ROTARY VENTRICULAR ASSIST DEVICE

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Abstract - An estimator identifying the flow rate through a rotary blood pump was developed. This estimation algorithm uses the pump current and speed signals to estimate the blood flow rate through the pump. The algorithm was derived based on the force balance between the electric torque generated by the motor and the load torque, including the mechanical losses. The corresponding estimator parameters were identified using experimental data in the laboratory. The estimator performed well in mock circulatory loop experiments simulating different physiologic conditions. This algorithm will be implemented in a single board computer to estimate the flow rate of the rotary pump in an implantable left ventricular assist device without invasive sensors.

Keywords: biomedical system, medical application, estimation algorithm

1. INTRODUCTION

Left ventricular assist devices (LVADs) are blood pumps used to augment the cardiac output of patients with left heart failure. These devices can be used as a therapy to allow the patient's heart to recover and as a temporary support to the patient until the heart transplant can be performed or as a long-term alternative to heart transplantation. Rotary blood pumps offer several advantages over the pusher-plate type pulsatile pumps due to their simplicity, low cost, small size, and high efficiency.

Control of the rotary blood pump is usually maintained by setting the pump at a fixed speed such that the pump can provide enough blood flow for the patient's organ perfusion (Schima, et al, 1992). However, determination of an appropriate pump speed setting to achieve a desired blood flow rate based on patient's body demand is difficult. A high pump speed with low right heart return can cause collapse of the left atrium or left ventricle, thereby damaging the blood and the heart tissue (Amin et al, 1997). On the other hand, a low pump speed at a high arterial pressure may cause retrograde flow into the heart (Tayama et al, 1997). Moreover, regardless of pump speed, an improperly fixed conduit can lead to blockage of the conduit causing a dangerous flow restriction through the device. For these reasons, it is important to monitor the pump flow to determine an appropriate pump speed setting as well as to detect conduit kinking. Direct flow measurement within the pump would require an implantable flow transducer. This is undesirable because of the risk of sensor failure and the need for additional wires passing into the patient's chest cavity.

The use of measurable signals from the LVADs to estimate the pump flow rate has been developed by several groups of researchers (Golding et al, 1998; Wakisaka et al, 1997; Choi et al, 1997). Golding et al, (1998) approximated the flow of a centrifugal blood pump as a polynomial function of normalized current. However, this model cannot estimate the reverse flow when the pump speed is not high enough against high pump outlet pressure because the current-flow curve is non-monotonic in that region. Wakisaka et al, (1997) estimated the flow rate of a centrifugal blood pump using pump power consumption, pump speed, and hematocrit (volume percent of formed elements in blood) as measurements. Although the flow estimates were close to the flow measurement in mock circulatory experiment using goat blood as test fluid, the physiologic condition in the experimental setup wasn't described, and therefore, the accuracy of the flow estimates due to cardiovascular physiology changes is not clear. Choi et al, (1997) used pump current and speed measurements to estimate the pump flow rate through an axial flow blood pump based on a motor dynamics. The estimator parameters were identified in a simple circulation loop experiment using water as test fluid. Since the circulation loop was not physiologically meaningful, the estimator parameters identified from the experiment may not accurately represent the pump characteristics in its actual operation conditions. Fluid viscosity and density are different in water and blood. The estimated flow using parameters identified in water might be inaccurate when the device is used in blood pumping.

In this paper, a flow estimator was developed for the AB-180 circulatory support system (AB-180 CSS, CardiacAssist, Inc., Pittsburgh, PA). The estimator uses the pump current and speed signals to estimate the pump flow rate based on balancing the torque between the motor and the load torque. Because the signals are obtained from a remote pump control unit, no invasive sensor is required. This estimator can predict the flow rate in the range of 1 to 6 liters per minute (LPM) within ±0.5 LPM. This estimation method will be implemented in a DSP based single board computer to provide the flow information necessary for proper pump speed adjustment and for detection of conduit kinking.

2. SYSTEM DESCRIPTION AND MODEL

The AB-180 CSS is a continuous flow LVAD, which consists of a rotary pump operated by a three phase permanent magnet brushless DC motor (BLDC), a continuous infusion system for lubrication, and an occluder system preventing retrograde flow into the heart in the event of device failure. The AB-180 CSS pumps blood from the left atrium to the ascending aorta. The pump is connected to the external control unit by a power cable that passes through the patient's skin.

Accounting for energy conservation, the electric torque generated by the motor equals the sum of the load torque and the mechanical losses as expressed by (Krause, 1989)

$$T_E = J\frac{d\omega}{dt} + B\omega + T_L\,, \tag{1}$$

where T_E is the electrical torque, J is the rotor's inertia, ω is the rotor angular velocity, B is the viscous friction coefficient, and T_L is the load torque of the motor. The electric torque can be further expressed as (Krause, 1989)

$$\begin{aligned} T_E = N_P \cdot K_T[&i_{as}\sin(\theta_r) + i_{bs}\sin(\theta_r - \frac{2\pi}{3}) \\ &+ i_{cs}\sin(\theta_r + \frac{2\pi}{3})], \end{aligned} \tag{2}$$

where K_T is the motor torque constant, θ_r=$N_P\theta$ is the electrical rotor angular displacement defined by the angle between the center of the north pole of the permanent magnet and the phase 'a' axis of the stator, N_P is the number of pole pairs of the rotor, and i_{as}, i_{bs}, and i_{cs} are stator currents. The stator currents are assumed to be sinusoidal signals: i_{as} = I sin(ω_rt-α), i_{bs} = I sin(ω_rt-2π/3-α), and i_{cs} = I sin(ω_rt+2π/3-α), where I is the current amplitude, ω_r=$N_P\omega$ is the electric rotor angular velocity, α is the angle between the center of the north pole of the rotor's permanent magnet and the north pole of the magnetic field due to the stator's currents. Substituting i_{as}, i_{bs}, and i_{cs} into (2) results in

$$T_E = 1.5\ N_P\ K_T\ I\cos(\alpha). \tag{3}$$

The controller chip, ML4411 (Micro Linear Corp., San Jose, CA), is used to control the motor operation in such a way that the angle α varies between ±15°. This results in a small variation of cos(α) between 0.966 and 1 so that (3) can be approximated by

$$T_E \cong 1.5\ N_P\ K_T\ I. \tag{4}$$

Combining (1) and (4) gives

$$1.5 \cdot N_P \cdot K_T \cdot I = J\frac{d\omega}{dt} + B\omega + T_L \tag{5}$$

Theoretically, the load torque on the pump motor, T_L, is related to the product of flow and pressure drop across the pump as (White, 1986)

$$T_L = k \cdot \Delta P \cdot Q/\omega, \tag{6}$$

where k is a constant coefficient, ΔP is the pressure drop across the pump, Q is pump flow rate, and ω is the motor speed. Measuring ΔP requires an invasive sensor. Due to the difficulty of measuring ΔP clinically, (6) cannot be used with (5) to estimate Q directly. An approximation of the load torque over the pump's operation range, providing a reasonable fit to the experimental data, is required to estimate the pump flow without pressure measurements. Therefore, a fundamentally new expression, given by

$$T_L \cong (K_1\sqrt{\omega} + K_2\omega^2)\,, \tag{7}$$

where $\hat{Q}$ is the estimated pump flow rate, K_1 and K_2 are constant coefficients, was developed empirically to approximate the load torque. Substituting (7) into (5) leads to

$$1.5K^{*}I = J\frac{d\omega}{dt} + B\omega + \hat{Q}\,(K_1\sqrt{\omega} + K_2\omega^2)\,, \tag{8}$$

where $K^{*}=N_PK_T$. Rearranging (8) yields the flow estimator equation given by

$$\hat{Q} = (1.5K^{*}I - J\frac{d\omega}{dt} - B\omega)\,/\,(K_1\sqrt{\omega} + K_2\omega^2)\,, \tag{9}$$

It is shown below that this novel approach can be used to estimate the flow rate accurately over the pump's range of normal operation using only motor current and speed signals.

3. PARAMETER IDENTIFICATION

In order to estimate the pump flow rate using (9), the first step is to identify the torque constant, K_T. Because of electromechanical energy conservation, the torque constant, K_T, (N·m/A) is equal to the back EMF constant, K_B, (V·sec/rad) in SI units. Therefore, K_T can be obtained by estimating K_B. The flux linkage, φ, in the stator windings due to the rotor magnet can be written as (Krause, 1989)

$$\boldsymbol{\varphi}=K_B\cdot[\sin(N_P\theta),\ \sin(N_P\theta-\frac{2\pi}{3}),\ \sin(N_P\theta+\frac{2\pi}{3})]^T, \tag{10}$$

The induced voltage, V, in the stator winding by the rotor's magnet can be written as

$$\begin{aligned}\mathbf{V} &= \frac{d}{dt}\boldsymbol{\varphi}\\ &= V_{MAX}\cdot[\cos(N_P\theta),\ \cos(N_P\theta-\frac{2\pi}{3}),\ \cos(N_P\theta+\frac{2\pi}{3})]^T,\end{aligned} \tag{11}$$

where V_{MAX} is the resultant maximum induced voltage which can be written as

$$V_{MAX} = \omega N_P K_B. \tag{12}$$

V_{MAX} and ω are measured experimentally so that K_B can be calculated by

$$K_B = V_{MAX} / (\omega\cdot N_P). \tag{13}$$

The parameters, J, B, K_1, and K_2 of (9) were identified by a least squares fit to the experimental data. To do so, (8) was rewritten in matrix form as

$$\mathbf{W}(t_k)\cdot\mathbf{K} = \mathbf{Y}(t_k), \tag{14}$$

where $\mathbf{K}=[J,\ B,\ K_1,\ K_2]^T$, $\mathbf{Y}(t_k)=1.5K_T\cdot I(t_k)$, $\mathbf{W}(t_k)=[\ \omega'(t_k),\ \omega(t_k),\ Q(t_k)\cdot\omega(t_k)^{1/2},\ Q(t_k)\cdot\omega(t_k)^2]^T$ and t_k is the k-th data point. The optimal parameter vector $\mathbf{K}^*$ for minimizing the least squares residual error between the measured $\mathbf{Y}$ and the predicted $\hat{\mathbf{Y}}$, is given by [4],

$$\mathbf{K^* = (W^TW)^{-1}W^T\cdot Y}, \tag{15}$$

where $\mathbf{W=[W(t_1),\ W(t_2),\ ...,\ W(t_n)]^T}$ and $\mathbf{Y=[Y(t_1)\ Y(t_2)\ ...\ Y(t_n)]^T}$, and n is the total number of data points used in the estimation. The time derivative of the motor speed was determined according to

$$\omega'(t_k)=[\omega(t_k) - \omega(t_{k-1})]\cdot f_S, \tag{16}$$

where $\omega(t_k)$ is the k-th motor speed measurement and f_S is the sampling frequency. A 3rd order digital Butterworth lowpass filter was used on the speed signal in (16) to remove any high frequency noise. In order to avoid a phase shift, a forward-backward filtering technique was used (Blauch, et al, 1993).

The accuracy of the model and the corresponding parameters was quantified by two error terms: the error index and the parametric error index. The error index,

$$E_I = \|\mathbf{Y} - \hat{\mathbf{Y}}\| / \|\mathbf{Y}\| \cdot 100\%, \tag{17}$$

where $\hat{Y} = W\cdot K^*$, represents the fitness of the data to the model. The parametric error index, PE, of the parameter estimate K_i^*, defined by

$$PE_i = \left\|\mathbf{Y} - \hat{\mathbf{Y}}\right\| / [K_i^* \cdot \sqrt{(\mathbf{W^T}\cdot\mathbf{W})_{ii}}\,]\,, \tag{18}$$

where $(\mathbf{W^T\cdot W})_{ii}$ is the *i*-th diagonal element of $(\mathbf{W^T\cdot W})$, is a reliability indicator that measures the relative error in the parameter estimate K_i^*. A small PE_i indicates that the residual error is very sensitive to K_i^*, thus more confidence can be placed on the value of K_i^* (Blauch, et al, 1993).

4. EXPERIMENTS

4.1 Torque constant identification experiment:

The experiment was conducted by spinning the rotor within the stator casing at a constant speed for three different speed settings spanning the entire operating range. The induced sinusoidal back-emf waveforms at each phase were then captured from the stator power cable using a digital storage oscilloscope. The amplitude, V_{MAX}, and the frequency, f, of the waveforms were measured from the oscilloscope. The rotor speed (rad/sec) was calculated by (ML 4428 Technical Note)

$$\omega = (2\pi f) / N_p. \quad (19)$$

For each speed, the values of ω and V_{MAX} were substituted into (13) to obtain an estimate of K_B. The values of K_B from each trial were averaged to obtain an estimate of the back-emf constant over the entire range of operating speeds.

4.2 Mock circulatory experiment:

The load torque of the motor in (7) is an empirical model. The model parameters, K_1 and K_2, must be identified under normal pump loading conditions so that the pump flow can be estimated using (9) under these conditions. A mock circulatory loop (Rosenberg, et al, 1981) experiment with an AB-180 CSS pump as shown in Fig. 1, simulating the patient's physiologic conditions, was conducted to identify the model parameters J, B, K_1, and K_2 in (9). The mock loop comprised a simulated atrium and ventricle, a preload chamber, a positive displacement pump as a native pumping heart, a systemic compliance chamber, and a variable resistance bed as the systemic resistance. The fluid in the mock loop consisted of a solution of 35% glycerol and 65% saline (by volume) at 21-23°C to simulate the viscosity of blood at 37°C (Sturn, et al, 1992).

In this experiment, the positive displacement pump was operated at the rate of 100 beats/min, with a stroke volume of 20 ml/stroke, to simulate a heart failure condition. The left atrial pressure (LAP) was set to 15 mmHg. When the AB-180 centrifugal pump was operating at 2200 RPM (lowest speed), the systemic resistance was adjusted such that the mean arterial pressure (MAP) reached 50 mmHg. The LAP setting was then changed from 5 mmHg to 20 mmHg in 5 mmHg increments. At each LAP setting, a function generator was used to provide a sinusoidal speed reference signal. Although normal use of the AB-180 pump is at a chosen constant speed, sinusoidal speed references are used to ensure a proper identification of the model parameters. The frequency of the speed reference signal was adjusted to 0.02 Hz, 0.04 Hz, 0.08 Hz, and 0.1 Hz. The peak to peak amplitude remained fixed such that the motor speed varied between 2200 RPM and 4700 RPM. The pump flow, motor speed, and motor current were acquired using a WinDaq™ data acquisition system (Dataq Instruments, Akron, OH) at the sampling rate of 200 Hz.

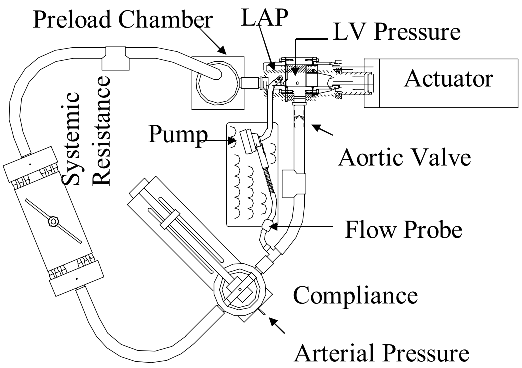

Fig. 1, Scheme of the mock loop experiment

4.3 Validation experiment:

The same mock loop configuration in Fig. 2 was used to generate data for evaluating the estimator performance at normal pump operation and at the event of outflow conduit kinking. In this experiment, the positive displacement pump was operated at the rate of 120 beats/min with the stroke volume of 20 ml/stroke. The LAP was set to 5 mmHg and 20 mmHg. At each of the LAP settings, the AB-180 was operated at 4500 RPM as the highest speed and at 3000 or 3500 RPM as the lowest speed such that a slightly retrograde flow occurs. At each speed, the systemic resistance was adjusted to obtain MAP values of 60 and 100 mmHg. These settings are related to the boundary conditions of the AB-180 patients. Validating the flow estimator using data from these settings would provide a useful evaluation of the estimator under different physiologic conditions. The pump flow rate, motor speed, and motor current signals were acquired with the sampling rate of 200 Hz/channel for 10 seconds. During data collection, the outflow conduit was clamped suddenly with a hemostat to simulate blockage of the outflow conduit.

5. RESULTS

The torque constant was obtained by averaging the estimated K_B from each stator phase at different rotor speeds. This resulted in $K_T = 3.6545\times10^{-3}$ (N·m/A).

Identification results for the remaining parameters are summarized in Table 1. The error indices are less then 1% with less then 10% deviations of the parameter estimates between data sets. The small values of PE_B, PE_{K1}, and PE_{K2} suggest that a high degree of confidence can be placed in these parameter estimates. Although PE_J is relatively large, the effect of inertia is insignificant when the motor is running at a constant speed. This implies that PE_J would have negligible impact on the accuracy of the model. The parameter estimates obtained from the data sets for the four LAP settings were consistent. The flow estimation result using data from a sinusoidal speed reference experiment with LAP of 5 mmHg is shown in Fig. 2. Note that the solid and dashed lines in Fig. 2 are barely distinguishable as a result of good matching between the measured and estimated flows. The mean values of the parameters, obtained by averaging the identified parameter values using data from each of the four LAP settings, were used as the model parameters for flow estimation.

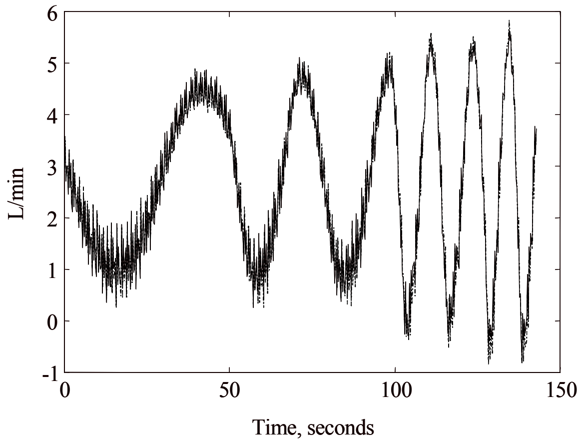

Fig. 2, Estimated (solid) vs. measured (dashed) pump flow

The performance of the estimator was validated using data from the mock loop experiment described above. The validation results are summarized in Table 2. The estimator was validated using 8 different experimental conditions. The estimator predicted the flow rate within ±0.5 LPM in all cases. When the outflow conduit was occluded, the flow estimate dropped immediately and remained near zero as shown in Fig. 3.

6. CONCLUSIONS

An estimator that uses motor current and speed signals to estimate the flow rate through the AB-180 rotary blood pump has been developed. The model parameters identified under different experimental conditions were consistent with small parametric error indices. Validation of the estimator showed that the estimator predicted the flow rate in all of the test conditions within ±0.5 LPM. This estimation algorithm will be implemented on a DSP based single board computer to provide real time flow estimation and tested in animal experiments for further validation.

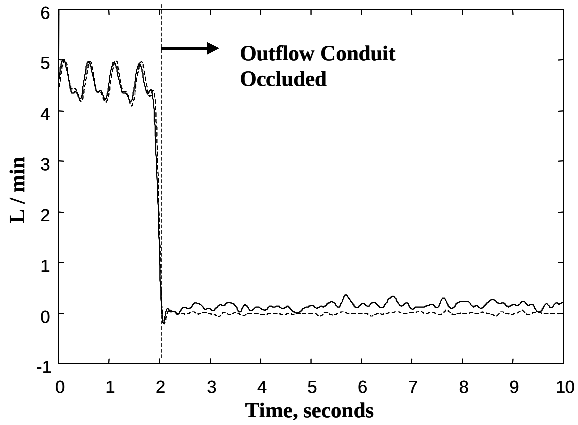

Fig. 3, Validation: estimated (solid) vs. measured (dashed) pump flow

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Table 1, Identification results

LAP (mmHg)	**J ($Kg \times m^2$)**	**PE_J**	**B ($N \times m \times sec/rad$)**	**PE_B**	**K_1**	**PE_{K1}**	**K_2**	**PE_{K2}**	**E_I (%)**
5	3.28E-06	0.49	1.07E-05	0.01	1.21E-05	0.07	1.90E-09	0.04	0.89
10	3.43E-06	0.51	1.08E-05	0.01	1.08E-05	0.08	2.01E-09	0.04	0.94
15	3.42E-06	0.51	1.08E-05	0.01	1.11E-05	0.08	1.98E-09	0.05	0.95
20	3.76E-06	0.46	1.12E-05	0.01	1.01E-05	0.09	1.98E-09	0.05	0.93
mean	3.47E-06		1.09E-05		1.10E-05		1.97E-09		
std. dev.	2.06E-07		2.28E-07		8.52E-07		4.53E-11		

Table 2, Summary of validation results

LAP (mmHg)	**MAP (mmHg)**	**Pump Speed (RPM)**	**Measured Flow (L/min)**	**Estimated Flow (L/min)**	**Mean Error (L/min)**
5	60	3000	2.4985	2.8652	-0.3667
5	60	4500	7.706	7.2685	0.4375
5	100	3500	0.6117	0.7274	-0.1157
5	100	4500	5.8504	5.6621	0.1883
20	60	3000	1.6829	1.5196	0.1633
20	60	4500	7.4455	7.0728	0.3727
20	100	3500	-0.4682	-0.1469	-0.3213
20	100	4500	5.4256	5.304	0.1216