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Interbeat Control of a Ventricular Assist Device for Variable Pump Performance

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***Abstract*—Pump performance is very important property in rotary blood pumps. Suitable pump performance often creates suitable blood flow regulation in long-term circulatory support. However, it is difficult to develop the blood pump with specific pump performance. In addition, optimal pump performance is still unknown. In this study, we have proposed a control method to implement variable pump performance in a single pump and evaluated the validity of the control method using computer simulation. The controller controls the dynamic change in the relationship between pump pressure head and flow rate by interbeat control. A repetitive control method was adopted in order to reduce cyclic error derived from the heartbeat. Simulation results indicate the possibility that the proposed controller can regulate so that the dynamic relationship between pressure head and pump flow is that of various type centrifugal pump.**

I. Introduction

Cardiovascular diseases are the leading cause of death in the world [1]. In the past decades, new devices for the diagnostic and treatment of such diseases were developed. Small implantable rotary pumps are now used as ventricular assist devices supporting the blood circulation of heart failure patients waiting for a heart transplant (bridge-to-transplant) and also to temporarily unload the ventricle during treatments such as cell therapy (bridge-to-recovery). Rotary blood pumps (RBPs) offer advantages for long-term total implantation because of their small size and high efficiency compared with pulsatile pumps.

Currently, RBPs used as left ventricular assist devices are mostly operated at a constant rotational speed in clinical use. However, it may be difficult to support enough cardiac output with constant rotational speed for dynamic change in physiological cardiac demand. Hence, several researchers have reported the physiological control method for ventricular assist devices. On the other hand, it has been reported that the blood flow of centrifugal pump at constant rotational speed can be regulated depending on the change in hemodynamics [2]-[4]. This is because the flow dynamics of centrifugal pumps at constant pump speed is very dependent on pump pressure head which depends on homodynamic change.

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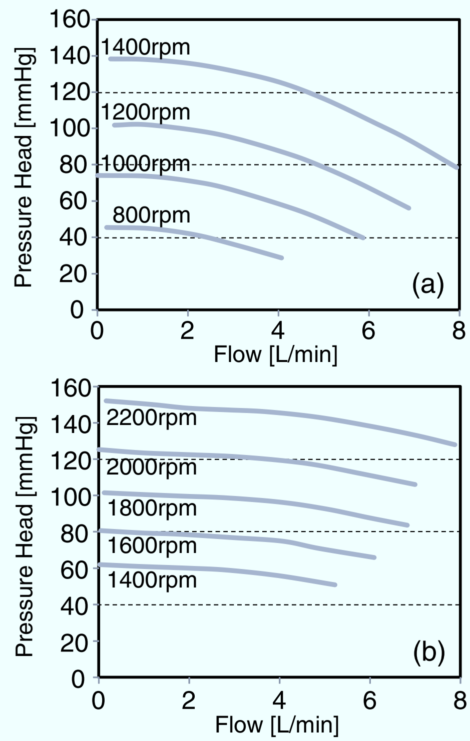

Figure 1. Pump performance of Gyro-pump (a) and EVAHERT (b)

The relationship between pump pressure head and pump flow is called pump performance which is static characteristic of a pump and is mainly determined by pump design. Fig. 1 (a) and (b) show the examples of the pump performance of Gyro-pump (Medtronic Inc) and EVAHERT (SunMedical Technology Research), respectively. Each pump has particular pump performance, and the different pump performance has a different effect on the assisted circulation [5]. Suitable pump performance is often contributes to suitable blood flow regulation in long-term circulatory support [6]. However, it is difficult to develop the blood pump with specific pump performance. In addition, optimal pump performance is still unknown.

Pump performance curve is changed by the pump rotational speed. Therefore, it may be possible to perform specific pump characteristic by dynamic control of pump rotational speed. The controller that can change pump performance of single pump contributes to know the desirable pump characteristics for patient's circulation. Besides, it may

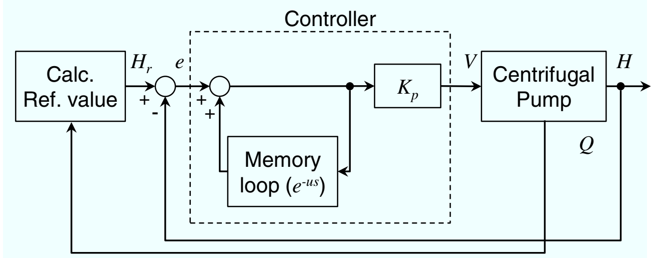

Figure 2. Block diagram of repetitive control system

be possible to change the pump performance depending on the cardiac condition during circulatory assistance.

In this study, we proposed the control method to implement variable pump performance and evaluated the control performance using computer simulation.

II. METHODS

A. Model of Centrifugal Pump and Dynamic Characteristic

In this study, Gyro-pump is used as controlled blood pump. Centrifugal pump is generally modeled as following differential equation.

$$L\frac{dQ}{dt} + H + c_1\omega Q + c_2 Q^2 - c_3\omega^2 = 0 \qquad (1)$$

where ω is the rotational speed, Q and H are flow and pressure head of pump, respectively, L is fluid inertance, and c_1, c_2 and c_3 are constant coefficients. (1) denotes that pump pressure head H is represented by quadratic polynomial in Q when Q and ω are constant. Hence, in this study, pump performance of actual pump is expressed as follows.

$$H = aQ^2 + bQ + \beta \qquad (2)$$

where a, b and β are parameters which are determined from actual pump performance.

Although the reference pump performance is static characteristics, the changes in H and Q have dynamic characteristics because of beating of native heart. Therefore, in this study, the controlled variable is pressure head which is determined by following equation.

$$H_r = f(Q) + L\frac{dQ}{dt} \qquad (3)$$

where H_r is instantaneous value of reference pressure head, $f(Q)$ represents reference pump performance. The innertance L was empirically determined as -0.2 in this simulation.

B. Control Algorithm

Proportional-integral-derivative (PID) feedback controller is often used for RBP controllers. However, it may be difficult to regulate pump speed so that pump pressure head equals to reference value within one beat because reference value changes quickly by beating of native heart. Therefore, a repetitive control method [7] is employed in this study. A repetitive controller adopts the internal model principle and consists of a periodic signal generator in order to reject periodic disturbances. Fig. 2 shows block diagram of control system including repetitive compensator which is expressed as time delay function in which delay u is equal to cardiac cycle.

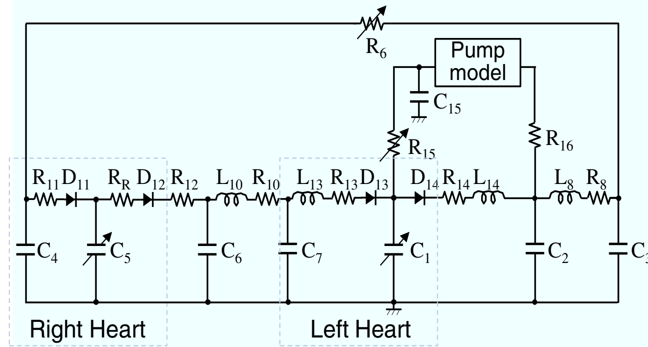

Figure 3. Electrical lamped circuit model

C. Computer Simulation

Fig. 3 shows the electrical lumped circuit model which represents circulatory system with a ventricular assist device. The general framework of the circulatory model is similar to that of Xu et al [8]. The pump model in the circulatory model was the deferential equation (1) in which coefficient parameters was determined using actual pump characteristics of Gyro-pump.

Two kinds of reference pump performance were introduced in simulations. One was a pump performance of different pump. The performance which was expressed as following equation was determined according to static characteristic of EVAHART.

$$f(Q) = -0.17Q^2 - 0.14Q + 105 \qquad (4)$$

The slope in H-Q characteristic of EVAHEAT is gentler than that of Gyro-pump.

Another was artificial pump performance which was expressed as linear expression with a various slope.

The control result in the simulation was evaluated by root mean square error which was defined as following equation.

$$E_D = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(H_r(k) - H(k)\right)^2} \qquad (5)$$

where k is denotes the discrete time, N is number of data point.

In addition, the realized static characteristic during control was estimated. If the change in pressure head during control closes to H_r, H-Q curve can be approximated by the polynomial like (3). Therefore, the estimated pump performance $f'(Q)$ was calculated and the difference between $f(Q)$ and $f'(Q)$ expressed by (6) was evaluated.

$$E_S = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left\{f(Q(k)) - f'(Q(k))\right\}^2} \qquad (6)$$

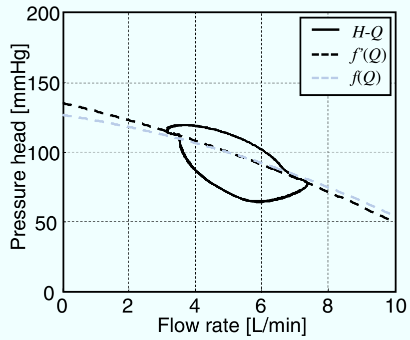

Figure 4. H-Q characteristic at constant rotational speed

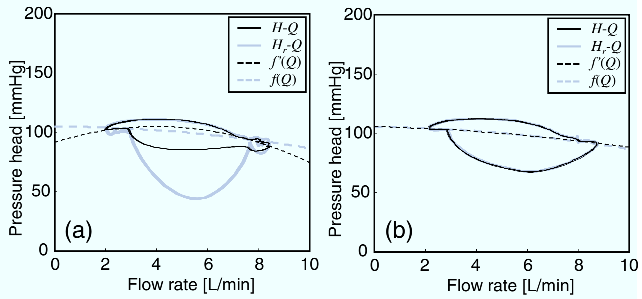

Figure 5. Result *H-Q* curves when the reference pump performance are like that of EVAHEART ((a): PID control, (b): repetitive control)

where $Q(k)$ is pump flow at kth sample during control.

In order to compare proposed control characteristics with that of other control method, the simulation using general PID controller was also executed. The PID parameter in PID controller was empirically determined.

III. Result and Discussion

A. Constant pump speed control

Fig. 4 shows the *H-Q* characteristic when the rotational speed is constant. The hysteresis locus of *H-Q* relationship (black solid line) is drawn on the pump performance of itself (black dashed line). The estimated static characteristic (gray dashed line) is close to pump performance. E_S between pump performance of Gyro-pump and $f'(Q)$ was 2.24mmHg. This result indicates the validity of approximation with (3).

B. Simulate different pump performance

Fig. 5(a) and (b) show the control result when the reference pump performance is set as (4) determined according to the characteristics of EVAHEART of which the slope is gentler than that of Gyro-pump. Both hysteresis loops (black solid lines) located on the reference pump performance (black dashed lines). E_S in PID control and repetitive control ware 1.72mmHg and 0.36mmHg, respectively. E_D of two results ware 4.99mmHg and 0.23mmHg, respectively. These results indicate the validity of repetitive control though there is still room for improvement in tuning PID parameters.

These results indicate that Gyro-pump can behave itself like EVAHEART by during-a-beat control. The control

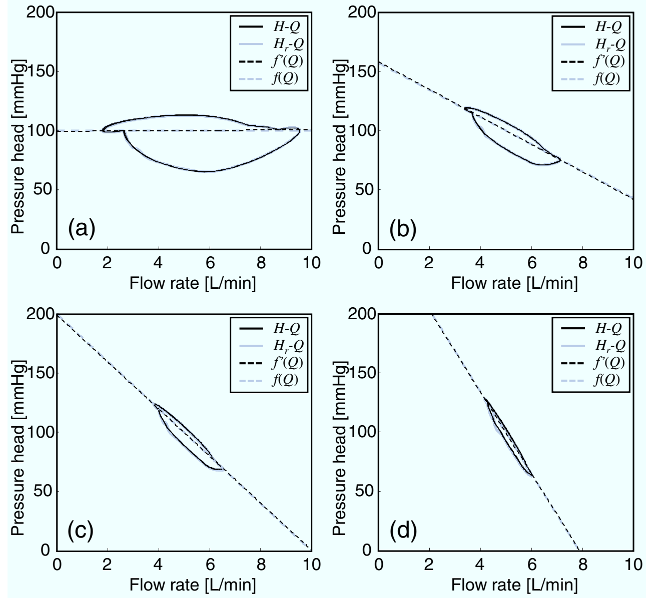

Figure 6. Result *H-Q* curves when the reference pump performance are linear expressions having various angle ((a): 0degree, (b): -30degrees, (c): -45degrees, (d): -60degrees)

TABLE I. Resuts of Residue at each angle

angle [degree]	0	-30	-45	-60
E_D	0.21	0.15	0.21	0.37
E_S	0.33	0.25	0.23	0.24

method may contribute to evaluate the effect of pump performance on assisted circulation and investigate optimal pump performance for blood pump.

C. Artificial pump performance

Figs. 6 (a) – (d) show the control results when the reference pump performance were artificial linear expressions which have various slope, and table I shows E_D and E_S of each control result. These results indicate that single pump can behave itself having artificial pump performance which have arbitrary slope. The slope of pump performance is one of important characteristics. For example, the pump which have gentle slope like EVAHEART have property that the pump is hard to disturb blood flow of native heart and transmit pulse pressure well. On the other hand having gentle slope also have disadvantage that a backflow occurs easily.

Fig. 7 (a) and (b) show the change in *H*, *Q* and pump rotational speed *N* when the slope of the reference pump performance are 0degree (Fig. 6(a)) and -60degrees (Fig. 6(d)), respectively. The rotational speed in Fig. 7(a) is regulated in a copulse mode (increased *N* in systole). On the other hand, in Fig. 7(b), the pump acts in counter pulsation mode (increased *N* in diastole). Pulse amplitude of pump flow in Fig. 7(a) is greater than that in Fig. 7(b). Therefore, it may be possible to develop the controller which can automatically change pump operating mode depending on circulatory condition by setting the suitable performance curve as a reference.

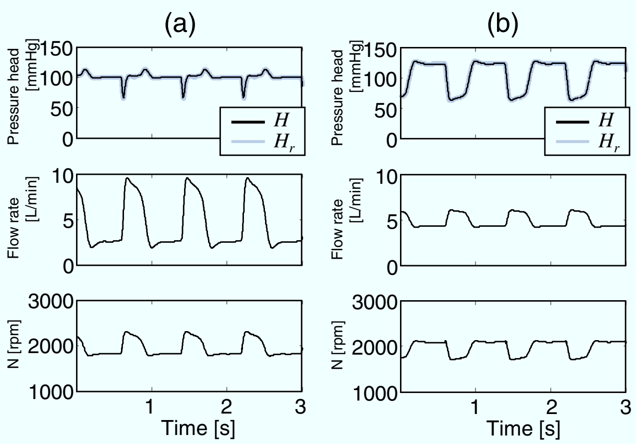

Figure 7. The change in H, Q and rotational speed N during control ((a); slope is 0degree, (b): slope is -60degrees)

IV. Conclusion

In this study, we proposed the control method to implement variable pump performance using repetitive control technique. Simulation results indicated that the controller can regulate the pump rotational speed so that the pump behave itself a different pump which have different pump performance from that of itself. This method may be useful to evaluate the effect of pump performance on assisted circulation and investigate optimal pump performance for centrifugal blood pump. In addition, it is possible to develop the controller which can change pump performance according to circulatory condition. In future works, it is necessary to investigate validity of the proposed method using mock circulatory system and animal studies.

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