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The Aortic Valve Dynamics Role in the Recovery Treatments of Patients with Left Ventricular Assist Devices

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Abstract— **This paper intends to define an optimal range for the pump speed of Rotary Left Ventricular Assist Devices (LVADs) that are used in bridge-to-recovery treatments. If the pump is operating within that optimal range, the aortic valve will be working properly (i.e. opening and closing) in each cardiac cycle. The proper operation of the aortic valve is a very important factor in helping the heart muscle recovers. The optimal range varies depending on the severity of the Heart Failure (HF) and the level of activity of the patient. A comparison is shown between the total flow produced as a result of operating the pump within the optimal range and the physiological demand of the patient. The comparison suggests that for cases of mild to moderate HF the flow produced is close to the physiological demand, but in severe cases the flow is significantly less than what the patient requires. Furthermore, our results suggest that data from the pump flow and the left ventricle volume signals can be used to test whether or not the aortic valve is experiencing permanent closure. Also an investigation of the aortic valve opening duration is presented for two cases: first, for mild HF case with varying Heart Rate (HR) and then for fixed HR and mild to severe HF cases. These Simulation results are obtained using a 6th order mathematical model of the cardiovascular-LVAD system.**

I. INTRODUCTION

THE LVAD is a mechanical pump that can assist the native heart of HF patient in providing the body with its needs of nutrients and oxygenated blood. This pump provides an alternative path for the blood to continuously flow with a higher rate between the ventricle and the aorta.

Rotary LVADs have been successfully used as bridge-to-transplant devices. In some cases, however, physicians may rule out transplant due to the condition or age of the patient. This type of LVAD treatment is called destination therapy and it has an objective of permanently providing support to the patient [1]. LVADs can also be used as bridge-to recovery. It was recently observed that some patients can be weaned from the LVADs as their hearts recover and are able to function in a manner similar to a healthy heart. . This treatment is now gaining more attention in the LVAD literature [2], [3]. In this paper, we consider the LVAD used as a bridge-to-recovery treatment.

When the LVAD is operated at a relatively low speed, the blood may regurgitate from the aorta to the left ventricle through the pump. If so, it will cause the volume of the ventricle to increase by 1 to 2 l/min [4]. This needs to be avoided since it reduces the pump flow rate [5]. Another situation that needs to be avoided is the permanent closure of the aortic valve. It happens when the pump speed is increased beyond a certain limit leading to an increase in the rate of ventricle unloading. It will then be difficult for the ventricle to create enough volume to build up pressure sufficiently high to open the aortic valve. The permanent closure of the valve causes problems such as: (1) significant change in the patient's hemodynamic conditions, (2) aortic valve fusion or stenosis which occurs to about 88% of LVAD patients [6], and (3) stagnation of flow and thrombosis formation [7]. The latter may cause coronary occlusion, which means the oxygenated blood intended to feed the heart muscle will be blocked by the thrombosis formed on the coronary.

These problems have no major impact in case the LVAD is used as a bridge-to-transplant or as destination therapy treatments. But it is important that they be avoided in bridge-to-recovery treatments. The opening and closing of the aortic valve will help prevent these problems by keeping the heart muscle active and doing part of the work. Also, flow through the aortic valve will help washout the thrombosis formed around the valve and blood will flow through the coronary to feed the heart muscle.

II. SYSTEM DESCRIPTION

Fig. 1 shows a 6th order circuit model of the combined cardiovascular-LVAD system. This model is adopted from previous work [8] where all the elements (resistances, inductances, capacitances and diodes) used are well explained and typical standard values are provided. There is a need to discuss in more details some elements in this circuit that are directly related to this paper. First, R_S represents the systemic vascular resistance and is used to simulate the level of activity of the patient. Second, $E_{\max}$ is a representation of the elastance of the left ventricle. It is represented in the circuit by the reciprocal of the capacitance $C(t)$. In simulation, its value can be varied to represent different levels of severity of the patient's heart failure. In the model, $E_{\max}$ can take a reference value of 2 mmHg/ml to represent a healthy heart. A sick heart will have $E_{\max}$ between 1 to 0.25 mmHg/ml to represent different levels of HF from mild to severe, respectively. Third, D_A and D_M are two diodes representing the aortic and mitral value, respectively. Diodes are in ON or OFF state

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based on the voltages across them, just like heart valves are closed or open based on the pressure across them. Hence, the diodes can simulate the four phases of the cardiac cycle as mentioned in TABLE I.

Finally, H_P is the pressure (head) across the pump. It is a function of the pump flow and the pump speed, and it can be determined using the following expression:

$$H = R^{*}Q_P + L^{*}\frac{dQ_P}{dt} + \beta\omega^2 \tag{1}$$

Where ω is the pump speed, Q_P is the pump flow, β is a constant, and R^{*} and L^{*} are the summation of resistances and inductances, respectively, in the pump and cannulae models.

TABLE I
PHASES OF THE CARDIAC CYCLE

Modes	Valves		Phases
	Mitral	Aortic	
1	closed	closed	Isovolumic relaxation
2	open	closed	Filling
1	closed	closed	Isovolumic contraction
3	closed	open	Ejection
-	open	open	Not feasible

TABLE II indicates the six state variables (the first five are for the left ventricle model and the last one represent the pump model) for this circuit model. The model maintains enough complexity to accurately describe the interaction between the cardiovascular system and the LVAD. It is validated in [8] and is shown to reproduce pressure and flow waveforms that are consistent with data in normal subjects.

TABLE II
STATE VARIABLES IN THE CARDIOVASCULAR MODEL

Variables	Name	Physiological meaning (units)
$x_1(t)$	LVP(t)	Left ventricle pressure (mmHg)
$x_2(t)$	LAP(t)	Left atrial pressure (mmHg)
$x_3(t)$	AP(t)	Arterial pressure (mmHg)
$x_4(t)$	AoP(t)	Aortic pressure (mmHg)
$x_5(t)$	Q_T(t)	Total flow (ml/s)
$x_6(t)$	Q_P(t)	Pump flow (ml/s)

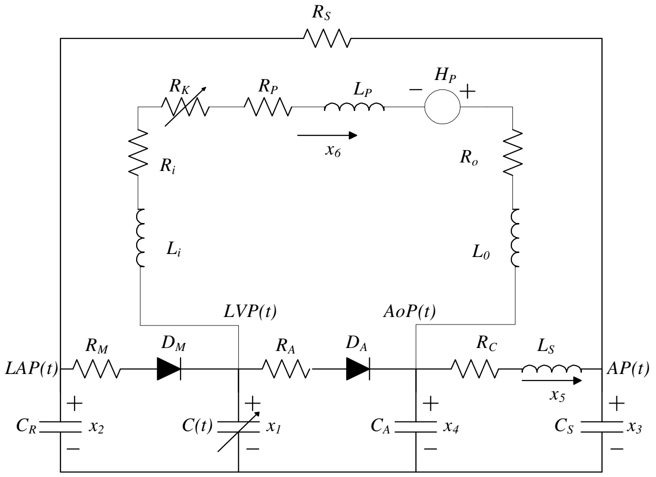

Fig. 1: Combined cardiovascular-LVAD model

III. METHODOLOGY

The objective here is to determine the optimal pump speed range which ensures that the aortic valve is functioning properly; that is opening and closing once every cardiac cycle. A comparison of the total flow produced to the physiological demand needs to be performed in order to determine whether or not operating within the optimal range can provide sufficient perfusion to the patient.

A. Identification of the Optimal Pump Speed Range

In this section, we will show results when the pump speed is linearly increased from 7,000 rpm to 12,000 rpm over a period of 60 seconds according to the following relation:

$$\omega(t) = 83.3t + 7000 \tag{2}$$

The aortic valve dynamics are observed (by following the state of D_A). Under normal operation the aortic valve opens and closes once every cardiac cycle, as seen in Fig. 2, up to the point when the speed reaches 9,500 rpm ($t = 30$ s) at which point the valve closes during the entire cardiac cycle (we can observe this in simulation through the diode D_A being open circuit for the entire cycle). The borderline between normal operation and permanent closure is defined to be the upper limit of the optimal range (9,500 rpm in Fig. 2).

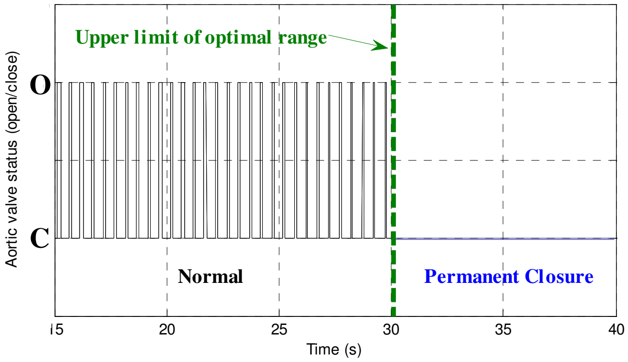

Fig. 2: Aortic valve status (O=open, C=close).

The lower limit of the optimal range is defined as the speed below which backflow occurs. This can be determined by observing the pump flow signal (see Fig. 3) when it reverses direction (i.e becomes negative). In Fig. 3 this occurs at 7,416 rpm (t = 5 s).

TABLE III shows the nine cases for which the simulation is performed. As seen we varied the level of HF from mild to severe and the activity level from "at rest" to "very active". It is worth mentioning that the heart rate (HR) was varied from 60 to 120bpm, while R_S is adjusted in every case to maintain the mean arterial pressure at the normal blood pressure range of 90 to 100 mmHg. [9].

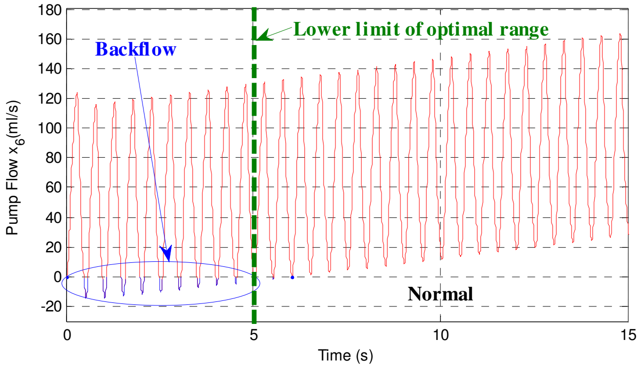

Fig. 3: The lower limit of the optimal range.

B. *Calculation of the Pump Flow at the Optimal Speed*

As mentioned in the previous section the optimal speed is the speed beyond which the aortic valve remains closed. It represents the highest value in the optimal range. The total flow, produced as a result of operating at the optimal speed, is calculated and will later be compared to the physiological demand of the patient. In this section the combined cardiovascular-LVAD model is used again but is driven by a constant pump speed (the optimal speed).

TABLE III
DIFFERENT CASES FOR THE SIMULATION

	E_{max} =1.0	E_{max} =0.75	E_{max} =0.25
HR = 120, R_S =0.5	mild HF very active	moderate HF very active	severe HF very active
HR = 80, R_S =1.0	mild HF active	moderate HF active	severe HF active
HR = 60, R_S =1.2	mild HF at rest	moderate HF at rest	severe HF at rest

C. *Determination of the Physiological demand*

TABLE IV shows the physiological demand in the three cases of different level of activity. These values are obtained from simulating the circuit model represented in Fig. 1 when the pump is not connected and the ventricle is assumed to be healthy (i.e. E_{max} =2 mmHg/ml) Note that the circuit model of the healthy ventricle without the pump is autonomuos.

TABLE IV
CARDIAC OUTPUT FOR UNASSISTED HEALTHY HEART

case	Cardiac output (l/m)
Very active, HR = 120, R_S =0.5	10.27
active, HR = 80, R_S =1.0	5.92
at rest, HR = 60, R_S =1.2	4.83

IV. SIMULATION RESULTS

Fig. 4 shows the pump flow signal for a simulation of mild heart failure and very active patient. The lower limit of the optimal range is set at $\omega(5) = 7,416$ rpm and the upper limit is at $\omega(30) = 9,500$ rpm. It is interesting to notice that the slope of the envelope of the maximum values of the pump flow signal becomes zero exactly at the upper limit of the optimal range (when the permanent closure of the valve happens).

Fig. 5 shows the Left Ventricle Volume (LVV) signal. Note that the envelope of the minimum values decreases at a higher rate after the permanent closure of the aortic valve.

Both Fig. 6 and Fig. 7 show plots of the opening durations of the aortic valve versus pump speed for different HR values and different level of HF, respectively. It is obvious that when the pump speed increases the duration of the aortic valve opening decreases.

Fig. 8 shows a comparison between the physiological demand and the total flow produced when operating within the optimal range. The comparison is made for the three cases described earlier: at rest, active and very active. Note that in the mild HF case the amount of support is between 80% and 82% of the physiological demand. But in the severe HF case, the total flow produced is only 31% to 33% of the physiological demand.

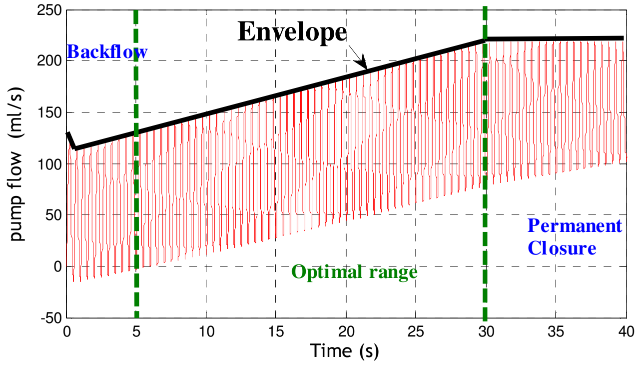

Fig. 4. Simulated Pump Flow waveform of mild HF and very active patient

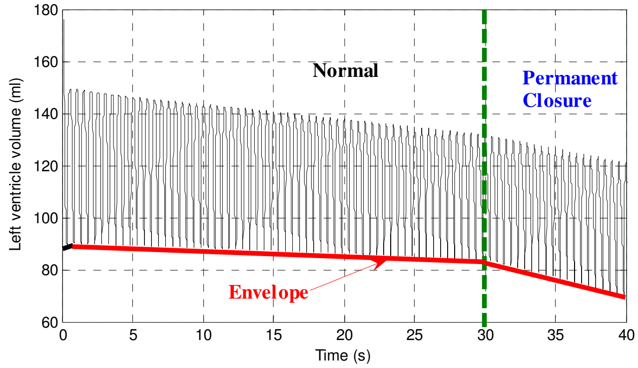

Fig. 5. Simulated Left Ventricle Volume waveform of mild HF and very active patient

V. DISCUSSION

When developing a feedback controller with the objective of maintaining the pump speed within the optimal range for recovery, we should note that the pump flow is the most useful candidate to be the feedback variable in the system. This signal can be used to recognize and establish both the upper and lower limit of the optimal range. The left ventricle volume (if available) can also serve as the feedback variable, but it can only be used to identify the upper limit.

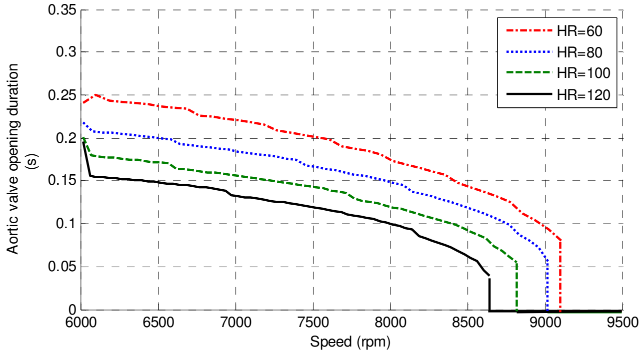

Fig. 6. Aortic valve opening duration in each cardiac cycle against pump speed (at different HR)

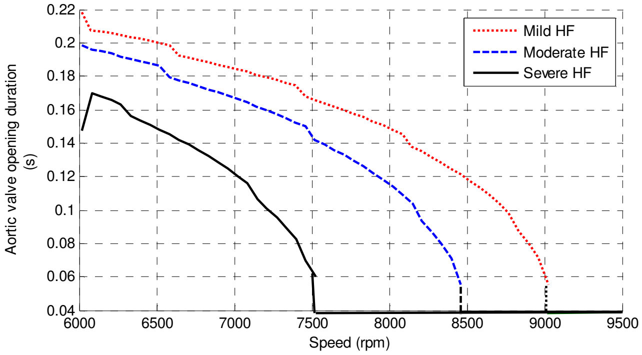

Fig. 7. Aortic valve opening duration in each cardiac cycle against pump speed (at different HF levels)

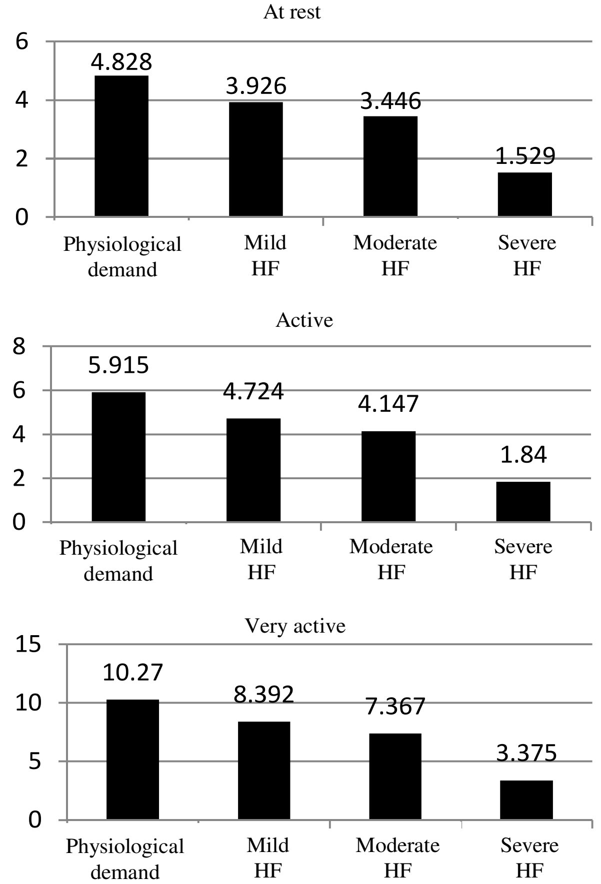

Fig. 8. Total blood flow (l/min) for three different cases of HF compared to the physiological demand of the patient.

We should mention that in case of severe HF, operating within the optimal range will be dangerous as the amount of support provided is far below the physiological demand of the patient.

Another obstacle in applying such controller to severe HF cases is the length of the optimal range. In the very active case, for example, the optimal pump speed range of a severe HF patient is only 120 rpm. Adjusting the pump speed within this narrow range is difficult and cannot be done with a high degree of accuracy. On the other hand, in cases of mild HF the optimal range is about 2100 rpm.

VI. CONCLUSION

In this paper, the role of the aortic valve in the bridge-to-recovery treatments of LVAD patients is explained and presented. An optimal pump speed range, where the aortic valve works properly in each cardiac cycle, is defined and established using a 6th order model of the left ventricular system and LVAD. Both the pump flow signal and left ventricle volume signal have been shown to be possible feedback variable for an automatic controller that can keep the speed within this optimal range. A comparison of the pump flow to the physiological demand of the patient suggest that in severe cases of HF operating within the optimal range will not provide the appropriate amount of support.

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