MODELING AND SIMULATION OF A BLOOD PUMP FOR CONTROLLER DEVELOPMENT

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Abstract - A mathematical model describing the pressure-volume relationship of the Novacor left ventricular assist system (LVAS) was developed. The model consisted of lumped resistance, capacitance, and inductance elements with one time-varying capacitor to simulate the cyclical pressure generation of the system. The ejection and filling portions of the pump cycle were modeled with two separate functions. The corresponding model parameters were estimated by least squares fit to experimental data obtained in the laboratory. The model performed well at simulating pump pressure of operation throughout the full cycle. Computer simulation of the pump with a cardiovascular model demonstrated the interaction between the LVAS and the cardiovascular system. This model can be used to incorporate on-line cardiovascular parameter estimation and to design a new controller for the LVAS.

1. Introduction

Heart disease is a major health problem in the United States and throughout the world [1]. 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 (LVAS) could provide a satisfactory alternative.

The control of existing devices depends on human operation, as shown in Fig. 1 (top). This manual approach is effective in a monitored environment but requires continuous engineering and clinical support limiting the patient's activities. A new controller under development, shown in Fig. 1 (bottom), will adjust the pump operation to changes in the patient's body demand based on estimates from a cardiovascular model. It has been previously shown that the aortic pressure (AoP) and aortic flow (Aof) measurements are necessary to estimate cardiovascular model parameters [2]. If these necessary signals can be derived or substituted using measurements from the LVAS itself, invasive sensors in the human body would not be needed.

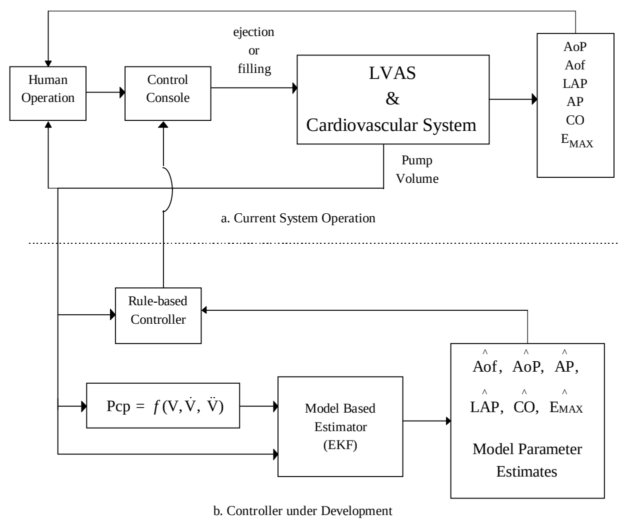

Fig. 1 LVAS Control (current system above dashed line)

This paper illustrates the use of a simple lumped parameter model to describe the pressure-volume relationship of the Novacor LVAS 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 counterpulsation operation, the pump volume measurement, supplied by the LVAS, can be used to estimate the aortic flow. If the pump pressure can also be derived from the pump volume information, an invasive measurement of the aortic pressure would be eliminated. Thus the cardiovascular system estimator can be used to identify the model parameters without any indwelling sensor in the human body. 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 and the systemic circulation was also constructed to show the interaction between the blood pump and the cardiovascular system.

2. System Description

The Novacor LVAS is a spring-decoupled dual pusher-plate sac-type blood pump driven by a pulsed-solenoid energy converter. Fig. 2 illustrates the principal components of the pump and their function during a typical operation cycle [3]. The cycle begins with the pump sac filled with blood and solenoid unlatched (Fig. 2a). At the start of pump ejection, shown in Fig. 2b, 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, shown in Fig. 2c, 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.

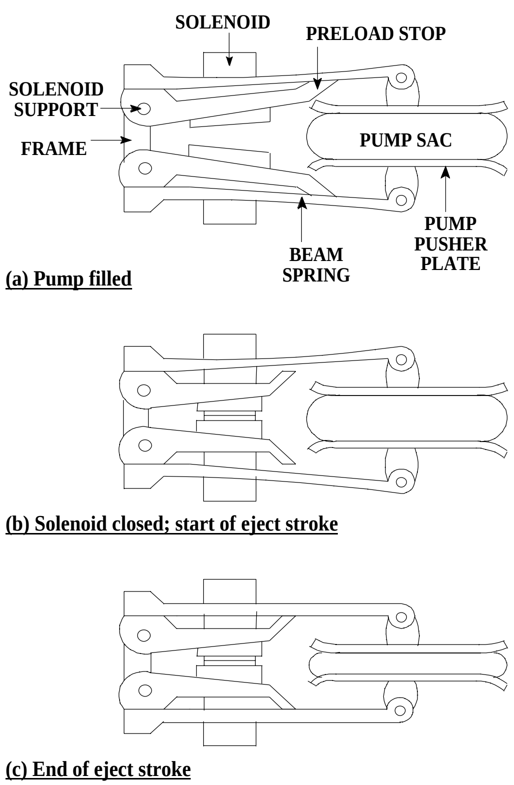

Fig. 2 Schematic LVAS operation [3]

An electric analog of the Novacor LVAS pump, shown in Fig. 3, 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

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

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

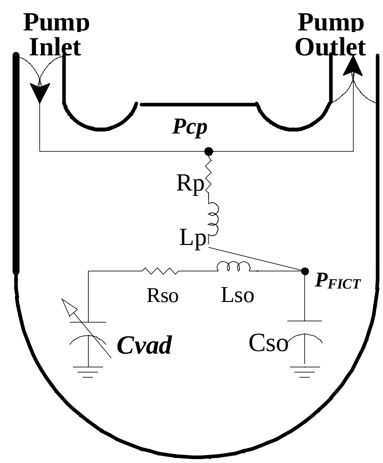

Fig. 3 LVAS pump chamber model

3. Experimental Method

Two experiments were conducted to determine the functions and the parameters of the pressure-volume relationship, P(V), and the fluid viscosity and inertance during pump ejection and filling.

a. Quasi-static experiment:

In the first experiment, the LVAS pump was operated in a mode in which the solenoid is held closed ("HALT EJECTION" mode [4]), allowing a quasi-static estimation of P(V) during pump ejection to be characterized. The schematic of the experiment is shown in Fig. 4. A Novacor LVAS 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.

At the start of this experiment, the LVAS 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 .

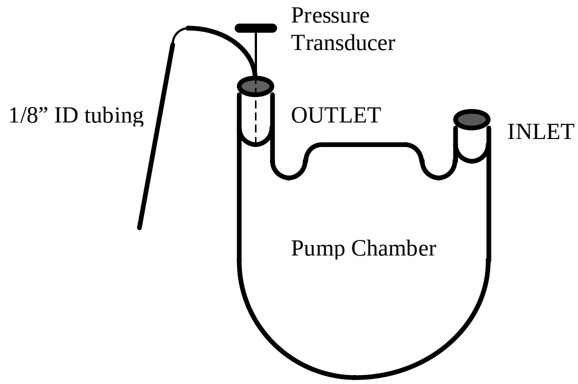

Fig. 4 Scheme of the "Halt Ejection" experiment

b. Dynamic experiment:

In the second experiment, the LVAS pump was attached to a passive "Penn State type" mock circulation loop [5] as shown in Fig. 5 which includes two compliance chamber and a fixed fluid resistor. The LVAS 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.

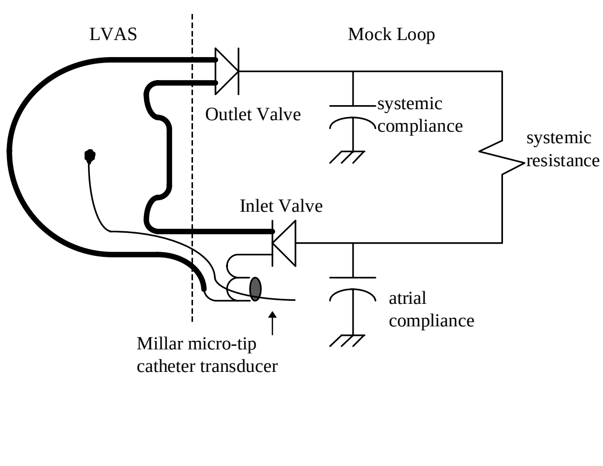

Fig. 5 Scheme of the mock loop experiment

4. 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 [6].

c. Pump chamber fluid mechanics parameters estimation:

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

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

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

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

where $W(t_k)=[\dot{V}(t_k) \quad \ddot{V}(t_k)]^T$, $\Delta P(t_k)=Pcp(t_k)-P_{FICT}(t_k)$, 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 [7],

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

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

$$\dot{X} = \begin{pmatrix} 0 & 1 \\ -\omega_n^2 & -2\zeta\omega_n \end{pmatrix} X + \begin{pmatrix} 0 \\ \omega_n^2 \end{pmatrix} P(V). \qquad (6)$$

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

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

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) to remove the high frequency noise that is amplified by the time derivative calculation. In order to avoid phase shift, a forward-backward filtering technique was used [8].

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, $\hat{P}cp$,

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

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

5. 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 [9]. The function

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

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. Fig. 6 (a) shows the fit of P(V) in (9) during pump ejection to the experimental data.

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

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

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. 6 (b) shows the fit of P(V) in (10) to the experimental data.

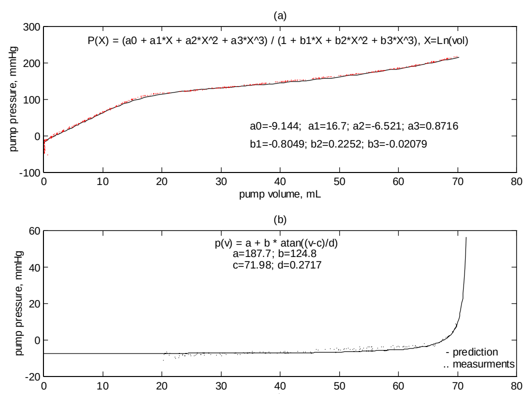

Fig. 6 Novacor pump P-V relationship
(a) ejection; (b) filling

b. Pump chamber fluid mechanics parameters:

Identification of the viscosity and inertance parameters in the LVAS 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 [10]. 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 in (5) 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 7(a) shows the pump pressure measurement and the model prediction versus time at 15 BPM.

c. <u>Model validation:</u>

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. 7(b). A small residual error index, E_I=11.93%, indicated that the model performed very well overall.

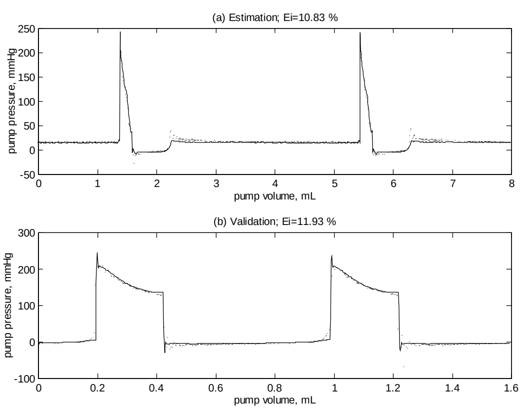

Fig. 7 Predicted (solid line) vs. measured (dashed line) pump pressure (a) estimation; (b) validation

6. Computer Simulation

In order to realize the interaction between the LVAS and the cardiovascular system, the LVAS model was connected with a cardiovascular model [11] for simulation. The electric analog of the model was shown in Fig. 8. Since the LVAS operation depends on the pump flow rate [4], the conduits should be modeled in detail so that the pump flow from simulation will be close to the actual pump flow. Also, this detailed model will predict the aortic pressure (AoP) more accurately and thus can be used as the input signal for the estimation of the cardiovascular model parameters [2]. The inflow and outflow cannulas were modeled by T-networks [12], while the model parameter values were determined by least squares fit to the experimental data. The state-space analysis with the Runge-Kutta fourth order method [10] was used and implemented in MATLAB to solve the dynamic equations simultaneously. The amplitude of $E_V(t)$ was decreased to 33%, the heart rate was increased to 100 BPM, and R_S was increased to 125% of the nominal values in [11] to simulate heart failure. Computer simulation was performed for 12 seconds. The LVAS was on for the first 6 seconds and was off for the last 6 seconds. The hemodynamic waveforms predicted from simulation are shown in Fig. 9. The predicted waveforms from simulation showed that the left ventricular pressure and volume were decreased and the aortic pressure was increased when the LVAS was on. These phenomena were consistent with experimental results obtained in a calf [13].

7. Conclusion

A lumped mathematical model of the Novacor LVAS 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). This model will be used for the estimation of the cardiovascular model parameters and for the design of the Novacor LVAS controller.

A computer simulation describing the coupling of the LVAS with the cardiovascular system has been developed. The changes of the hemodynamic variables while the LVAS was on and off in simulation were the same direction as changes obtained in animal experiments. The accuracy of this simulation needs to be further validated with clinical data. This simulation can be used for the test of the new controller under development before in-vivo experiment.

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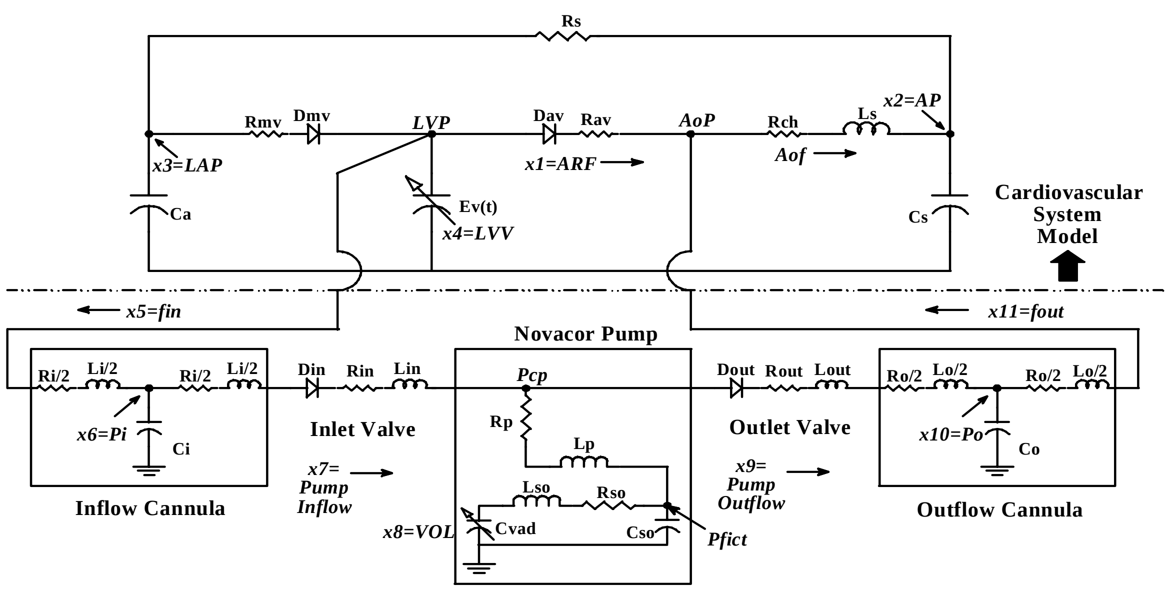

Fig. 8, Electric analog of the Novacor LVAS with a cardiovascular system model

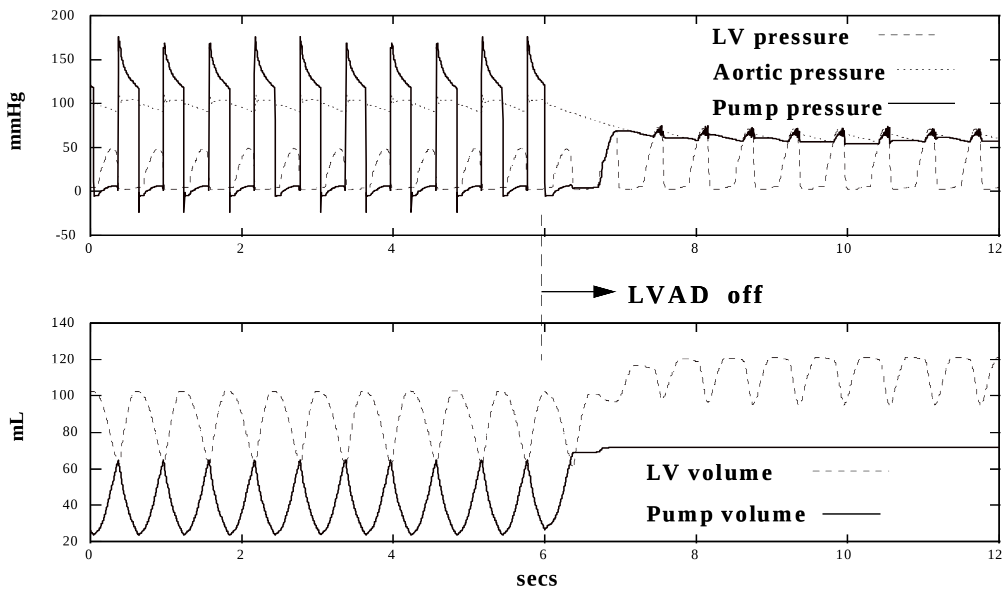

Fig. 9, Simulation result of the LVAS with the cardiovascular system