Development of a Stroke Output Control Algorithm Using a Fuzzy Logic for a Left Ventricular Assist Device

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Abstracts A new stroke output control algorithm with a fuzzy logic for an electrohydraulic left ventricular assist device(EH-LVAD) was developed. The EH-LVAD pumps out blood from left atrium actively. Excessive suction of blood may cause fatal damage in left atrium. The LVAD has to provide a maximal stroke output without collapse of left atrium. In this study a new fuzzy algorithm for predicting and detecting suction and doing proper action on LVAD without using an extra pressure sensor but with bellows pressure signal and motor current signal is developed. The performance of the fuzzy control algorithm is demonstrated by the results from mock circulatory experiments.

Key Words : LVAD, suction, fuzzy, pressure waveform, current waveform

1 . INTRODUCTION

A left ventricular assist device(LVAD) helps patients with weakened or damaged heart, especially left ventricle. Those patients' hearts can not fully function as a 'pump' for circulating oxygenated blood from pulmonary into whole body including heart itself, because their muscle in left ventricle has been weakened or damaged by some causes such as coronary artery diseases. So the patients need secondary pumping device that can help the damaged heart. LVAD is a kind of such pump. LVAD is connected between left atrium and aorta. Generally, blood from pulmonary flows first into left atrium, then to left ventricle through atrioventricular valve, and finally out to body through aorta. In case with LVAD, LVAD bypasses blood from left atrium to aorta. Normal adult heart at rest usually pumps about 5 liters of blood per minute. However, damaged heart can pump at most 2 to 3 liters per minute. So LVAD, usually can pump up to 10 liters per minute, compensates for the lack of blood volume.

There are many types of LVAD. Each has different pumping mechanism. They are classified into two large groups. One group uses pneumatic type pumping mechanism and the other electrohydraulic type. Our LVAD is electrohydraulic type. Water is used as the medium that transfers pumping pressure of bellows to blood sac.

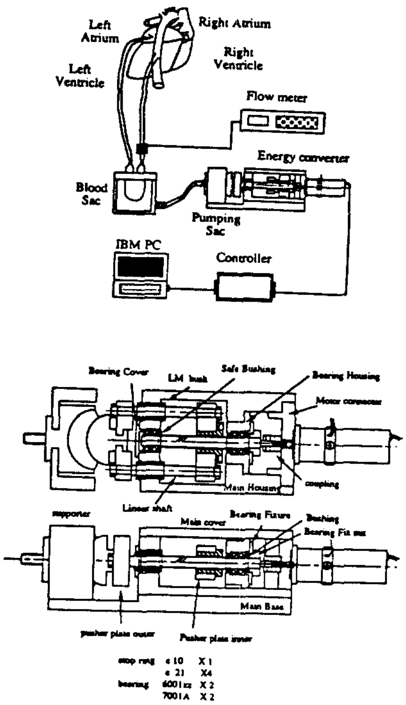

Fig. 1. LVAD schematic diagram

Water has much lower compliance than air. So the pressure generated by motor is not much different from the pressure experienced by blood sac. This property acts as both merit and demerit. The merit is that we can have more control on the blood flow than when using air as medium and we can synchronize pumping action of LVAD with that of natural heart more precisely. The demerit is that during diastolic period, the LVAD may suck up blood excessively from left atrium. Excessive suction may cause damage at left atrium or suction of external air into heart through the region of connection of left atrium and catheter, and result in thromboambolism. So the prevention of suction is critical issue with our electrohydraulic type LVAD. In case of natural heart, the volume of blood pumped out is as large as that came in left atrium and ventricle. So if LVAD could emulate this mechanism of natural heart, i.e., prevent excessive suction and moreover adjust their output volume spontaneously with respect to blood flow condition of heart, it would give out better result than in case the operator keeps control over the device and adjusts output manually.

In our LVAD, the only external sensor monitoring the condition of LVAD system is bellows pressure sensor. An absolute pressure sensor is attatched to bellows. The pressure signal is analog-to-digital converted and processed by the LVAD controller with 80C196KC as CPU, and the processed data are transmitted to PC using typical RS-232C serial communication protocol. A simple modeling of LVAD shows that bellows pressure has relation with left atrial pressure(LAP) and in-flow of blood from pulmonary vein to left atrium. So we have used bellows pressure in controlling the stroke velocity and stroke length of LVAD for detection and preventing of suction. Several usage of bellows pressure was developed and tested. However, the condition of heart and the characteristic of left atrium are non-linear and time-varying, and the modeling of heart and LVAD system which is practical as well as precise is very difficult. So precise estimation of condition of left atrium and blood flow using bellow pressure only is also very difficult.

With systems that can be controlled empirically by human expert but analytical modeling is impossible or very difficult, fuzzy control algorithm is widely used. In our case, it is observed in in-vivo test using mock circulation system that a rough indication of suction and LAP drop is presented in motor current and diastolic bellows pressure waveform. However, precise modeling is difficult and impractical to implement with usual micro-controllers. So we have developed a simple fuzzy controller and added it to present control program in motor controller unit and monitoring program in PC for detection and prevention of suction and regulating stroke output.

2 . MATERIALS AND METHODS

As described above, in mock ciculation experiment, some properties in motor current and bellows pressure waveform corresponding to the states of left atrium such as suction, low LAP, progress of suction are observed. According to the experiment results, early LAP drop(to 2-3mmHg ca.) is hardly reflected in the waveform. And from just beginning of suction, the waveforms are beginning to deform. In current wave form, early-rise and middle-fall of systolic maximum and progressive rise of diastolic maximum are appeared. In bellows pressure waveform, paint falling of diastolic minimum during early LAP drop, large falling of diastolic minimum during suction and secondary large-falling during each diastole under suction are appeared. We select 3 factors to represent the deformation of waveform, current systolic maximum- diastolic maximum ratio(CMR), diastolic bellows pressure minimum(DBPM), diastolic bellows pressure sum(DBPS). The CMR represents the beginning of suction and the progress of suction. When LVAD properly pumps, the ratio corresponds with the ratio of systolic velocity vs. diastolic velocity determined by human operator. But, with LAP drop, the ratio changes. So we can determine the state of left atrium by amount of the CMR change. The DBPM represents LAP drop and suction. The DBPS represents the progress of suction, because DBPS increases due to secondary large-falling under suction.

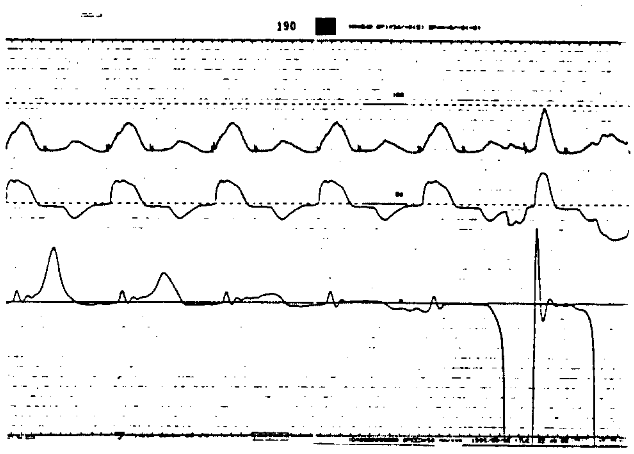

Fig. 2. The deformation of waveforms
(Top:Motor current, Middle:Bellows pressure, Bottom:LAP)

We developed simple fuzzy controller with CMR, DBPM, DBPS as inputs and systolic velocity, diastolic velocity, indicator of ovbious suction as outputs. CMR, DBPM and DBPS are classified into 4 categories.

The references that indicates the beginning of suction was determined from mock experiments. CMR, DBPS, DBPM are calculated at the end of diastole in PC. Then the values are transmitted to conrol routine in PC monitoring program.

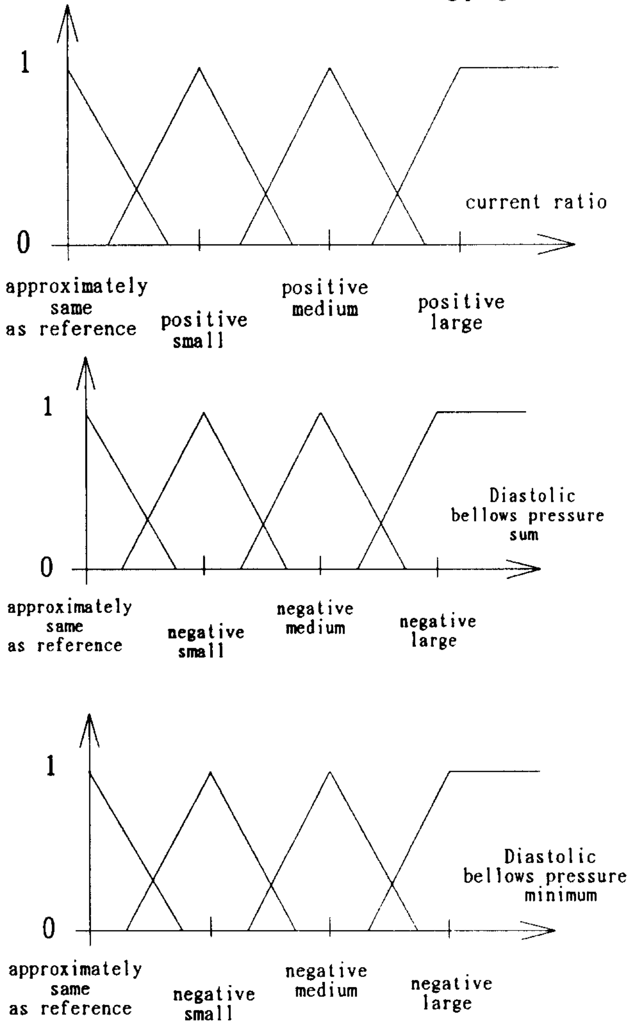

Fig. 3. The fuzzy partitions for controller

The control routine determines the control variable ouputs by a rule base. Since all possible combinations of inputs need not to be responded respectly, we made a simplified rule base. Each partition of input is corresponded to number 0,1,2,3 respctively, i.e. 'approximately same as reference' is 0, 'positive(or negative) small' is 1, 'medium' is 2, 'large' is 3. We assume the sum of the partition values is proportional to the degree of LAP drop. In case the sum is smaller than or equal to 6, the controller decreases velocities. In case the sum is larger than 6, at least one of the 3 factors indicates ovbious suction, so the controller stops pumping, waits a while, and starts again.

In this way, the controller prevents suction and regulates the output. We have tested this fuzzy controller in mock cicrculation test.

The mock circulation system we have used is consists of mock left atrium, conduits, catheter, two large water drums which simulate aortic pressure(AOP) and pulmonary venous pressure(PVP) respectively, AOP gauge, flow gage, and miscellaneous cocks.

LAP was measured by medical poligraph along with motor current and bellows pressure.

3 . RESULTS AND DISCUSSION

First we obtained the relationship between CMR, DBPS, DBPM and LAP.

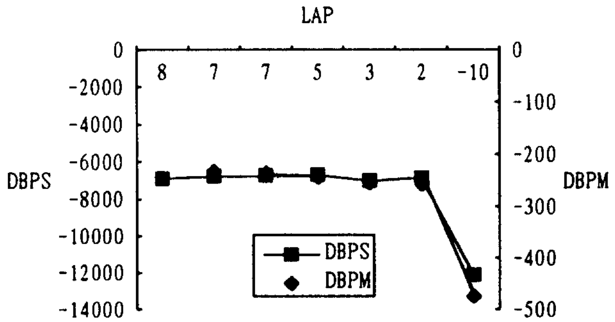

Fig. 4. The relationship between DBPS, DBPM and LAP

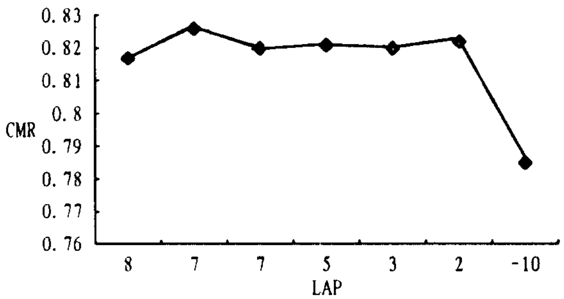

Fig. 5. The relationship between CMR and LAP

Then adjusted the shapes of membership functions and determines the references.Following is the results with fuzzy controller and without fuzzy controller.

Comparing two results, we see suction detection has been achieved. The controller determined suction and stoped motor.

It represented in current waveform as zero line.

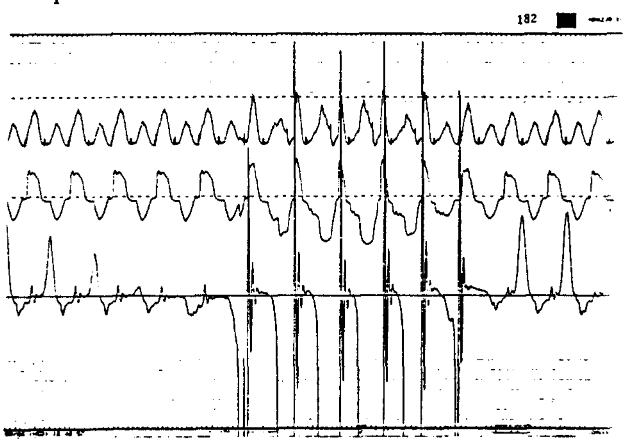

Fig. 6. Result without fuzzy controller
(Top:Motor current, Middle:Bellows pressure, Bottom:LAP)

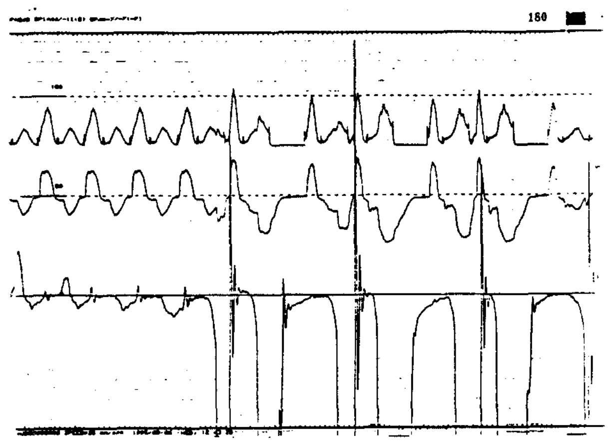

Fig. 7. Result with fuzzy controller
(Top:Motor current, Middle:Bellows pressure, Bottom:LAP)

Velocity decreasing which corresponds with LAP drop is not appeared remarkably. But, this can be adjusted by changing amount of velocity change in rule base. And suction detection is not achieved at every occurrence of suction but every other occurrence. This is because controller was implemented in PC (not in motor controller) and the transmission of changed velocity values to motor controller takes some delay. Moreover, immediate responce to suction during diastole is impossible, since this controller operates at every end diastolic point and affects next stroke.

4 . CONCLUSION

Suction detection and response have been achieved. But, this fuzzy controller working on PC could not respond instantaneously. For more immediate response to suction, development of fuzzy controller working on CPU in motor controller is required.

This test was done under very much restrictions such as fixed stroke length, aortic pressure etc. So the references and the shapes of fuzzy partitions can not applied well to conditions which is much different from that of this test. So more studies of waveforms under varying condtions is required.

Some experiments of this controller along with another control algorithm using bellows pressure data showed promising results. So more studies on the combination this fuzzy controller and another control algorithm is to be carried out.

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