FUZZY Gain Tuning of PI Speed Controller Depending on Afterloads In Total Artificially Heart

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Abstract

In this paper, the control scheme is proposed that PI controller parameter used for TAH speed control is adapted by fuzzy logic method using only the motor current waveform. By scheduling PI parameters, minimization of the vibration and the energy consumption and overcoming AoP loads becomes possible.

In *in vitro* tests experimental results show our approach is a good scheme that is adapted to changing afterloads well.

Key words - Total artificial heart, Fuzzy control, Aortic pressure

Introduction

For use in patients with severe forms of heart disease for which no surgical repair is possible, artificial hearts have been under development for the past 30 years and human survival over a year has become possible with artificial heart as demonstrated in the United States and in Europe. Since 1984, we also have been developed an electromechanical total artificial heart (TAH) typified by the pendulous moving actuator mechanism and implanted in several animals for clinical application. Fig. 1 shows a perspective view of the TAH. A brushless DC motor as an energy converter is assembled in a moving actuator, which is intervened between a left and right artificial ventricular blood sac. Most research groups developing the motor-driven TAH use a brushless DC motor as an energy converter based on the property that the motor has a high reliablity and high output torque to weight ratio. The pendulous motion of this moving actuator pumps out the blood filled in

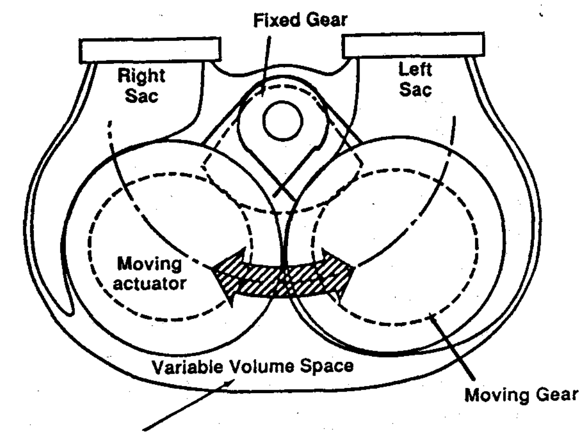

Fig. 1. A schematic diagram of the motor-driven total artificial heart

a right or left blood sac alternatively. The moving actuator and the blood sacs are enclosed by polyurethane housing. In this TAH a control system has been also developed. The requirement for the control system is as follows.

The primarily task of the TAH control system is the adaptation of cardiac output to organ perfusion demand. Usually TAH requires 4-5 [L/min] Cardiac Output(C.O). C.O can be controlled by cardiac volume and pump rate. If we can control these two parameters simultaneously, C.O can be adapted to the organ demand. So precise position and speed control is very important.

The second task of the TAH control system is to gurantee reliability and durability. To improve the reliability of the control, it is necessary to use fewer sensors. Instead of using other sensing parameters (current, IVP) , hemodynamic parameters should be estimated.

The third task of the TAH control system is to minimize the energy consumption. In a totally implantable TAH, a stroage battery with artificial heart and internal controller is implanted in the body. By transcutaneous energy transmission (TET) system located outside body, energy can be transmitted to internal battery. It is very important to minimize the energy in the perspective of reducing the size of internal battery and the total amount of transmitted energy.

The fourth task or the TAH control system is the robustness to several external disturbances and change of system parameters. Afterloads such as aortic pressure (AoP) which is closely related to cardiac output is very important hemodynamic parameter. TAH is required to overcome very large afterloads by increasing AoP. Usually the range of AoP is between 80 - 120 mmHg. But sometimes because of overflow of cardiac output and other hemodynamic demand, AoP can increase to 200 - 300mmHg. The speed and position control should consider these operation environments.

PI Controller

Proportional-integral-derivative (PID) controllers are used broadly in industrial control processes because of their simple structure and robust performance in a wide range of operating conditions. Because TAH is time-varying, nonlinear and is influenced by circulatory system, it is difficult to derive TAH model. The use of PID controller does not require an exact process model and hence, is effective on TAH. And TAH control require the reliable and simplied structure. So in this system, proportional-integral (PI) controllers is used.

The transfer function of a PI controller has the following form:

$G(s) = K_p + K_i /s$ (K_p: proportional gain, K_i: integral gain)

The discrete-time equivalent expression for PI control used in our TAH, has the following form:

$$u(k) = K_p e(k) + K_i T_s \sum_{i=1}^{n} e(k)$$

($u(k)$: control signal input, $e(k)$: error between reference velocity profile and actual response velocity, Ts : sampling periods)

PI control can be devided into two main categories. In the first category, the controller parameters are fixed during control. In the second one, the controller parameters are tuned during control. This controller requires frequent on-line retuning. In this paper using fuzzy gain scheduling, the self-adaption of the PI controller according to the change of afterloads such as AoP overcomes the loss of optimality of the controller parameters. Also by adaption of PI controller, it is possible to reduce the total energy consumption, and to reduce the vibration that can make damages to the surrounding organs in TAH designed for operating in a very long term,. By scheduling

PI parameters, minimization of such damages and overcoming AoP loads is the important goal of this control scheme.

Load dependent control by fuzzy inference engine.

1. Input parameter

The afterload is chosen as the control input parameter. This is the important control parameter that is relative to the distrubance of the circulatory system as mentioned above. In proportion to afterloads, motor torque changes. The general mathematical model of DC motor has the following form:

$$\frac{d\theta}{dt} = w \qquad - (1)$$

$$K_t i = J_m \frac{dw}{dt} + B_m w + T_L \qquad - (2)$$

$$E_m = L\frac{di}{dt} + Ri + K_e u \qquad - (3)$$

(θ: angle(rad), w: angular speed (rad/sec), i: motor input current (A), E_m: voltage(V), T_L: frictional torque (Nm), K_e: back emf constant(Vs/rad), K_t :torque constant(Nm/A), R: serial resistance(Ohm) L:inductance(H), J_m: angular momentum (Nmsec^2) B_m: Damping constant(Nmsec))

As shown in the above differential equations, current is proportional to the frictional torque. So by measuring the current signal, we can estimate the afterloads. In this paper the total summation of AD-converted current values during one stroke is used as input parameter of fuzzy inference engine (see Fig. 6.). In Fig. 2. the relations between AOP and the sum of current value are shown. Using the fact that the normal range of AOP is between 80-120mmHg, the quantitative values of input parameter is transformed into linguistic form (see Fig. 3.).

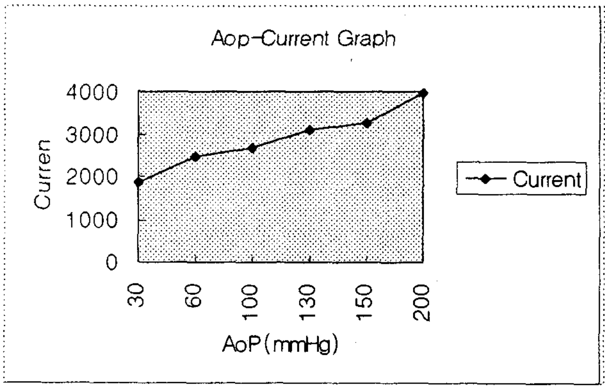

Fig. 2. The relation between AoP and the sum of AD-current signal during one stroke.

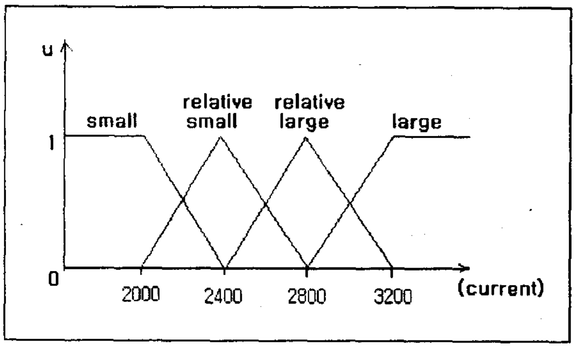

Fig. 3. Membership function of current

2. Fuzzy Inference Engine

Even if AOP is very high, motor must operate overcoming very large load. If in this event PI gain is low, the pump rate of TAH is lowered and motor eventually happens to stop.

In this event very large control signal is needed regardless of energy consumption and high vibration. So PI gain is required to rise. When AOP is low, relatively small control signal is enough to satisfy the demand of TAH. Instead, energy consumption and the vibration of TAH operation can be reduced. Low PI gain is required for advantages of low PI gain which was mentioned above.

In a first approach, optimal range of PI gain must be choosen. Fig. 4. and 5. show the relations between error and PI gain. In Fig. 4, I gain changes within broader scope than P gain. In Fig. 5, P gain changes within broader scope than I gain. Through this experiment, optimal PI gain range was evaluated. The possible range of P and I gain is between 1 - 1.75 and 0.1 - 0.25, respectively. PI gain membership functions are shown in Fig. 8.

In Fig. 7. the fuzzy inference rule-base is described. The basic inference rule is that if the sum of current AD signal is A, PI gain is A (A:small, relative small, relative large, large). In other word, PI gain have a tendency to increase or decrease according to the sum of current signal during one stroke. We defuzzificated the final values by center of area (COA) method.

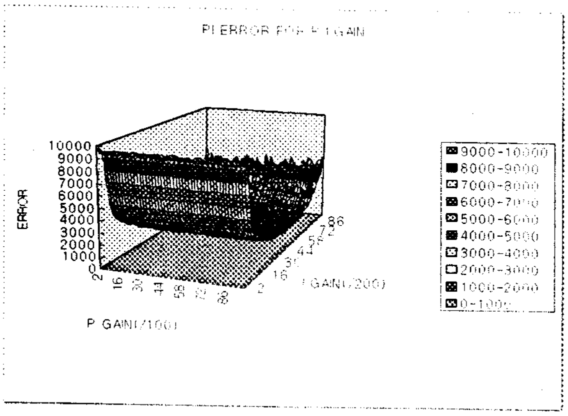

Fig. 4. Relation between Error and P,I gain

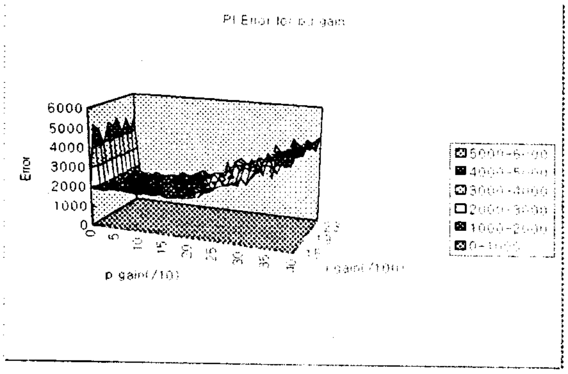

Fig. 5. Relation between Error and P,I gain

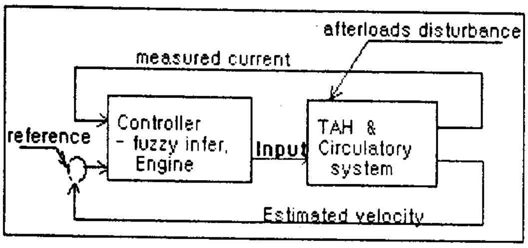

Fig. 6. Fuzzy inference engine & TAH speed controller

Current	PI gain
small	small
relative small	relative small
relative large	relative large
large	large

Fig. 7. Rule-based Tabel

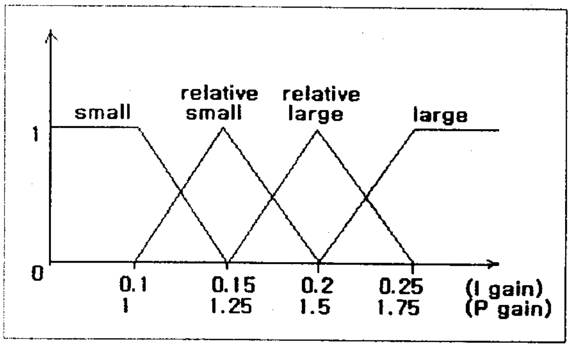

Fig. 8. Membership function of PI gain

Result - *In Vitro* Test

The proposed fuzzy method was tested in mock circulation system. Each pump chamber was coupled with a mock circulation loop to simulate pulmonary or systemic preload and afterload conditions, respectively. During tests, other hemodynamic variables were maintained in normal state whereas the left afterload was changed as disturbing parameter. In the test protocol, the simulated AoP was changed in the range of 30 mmHg - 220 mmHg. In Fig. 9. when using fuzzy method the relation between the change of PI gain and the sum of current AD-signal during one stroke is shown. When current is high, AoP is also high. PI gain follow the sum of current AD-signal in real time. That is, PI gain follow the waveform of AoP. In Fig. 10. and Fig. 11. the relation between the sum of current AD-signal and that of the absolute velocity error during one stroke is shown. When the sum of current AD-signal is small - AoP is low -, error sum in the proposed method is slightly higher than that in fixed PI gain. In this duration, although error sum is considered, energy consumption and the reduction of vibration are more considerable than increasing error. As AoP increases, this situation is reversed. Error sum in the proposed method becomes smaller than that in fixed PI gain. In this duration, in order to overcome the large afterloads motor velocity is needed to follow rapidly reference velocity profile. So given large PI gain becomes to response rapidly in spite of external disturbances. And the error sum becomes decreased.

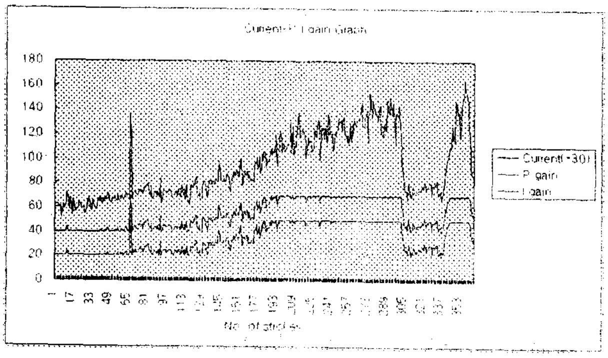

Fig. 9. Curves of the PI gain that follow changing current values under fuzzy control

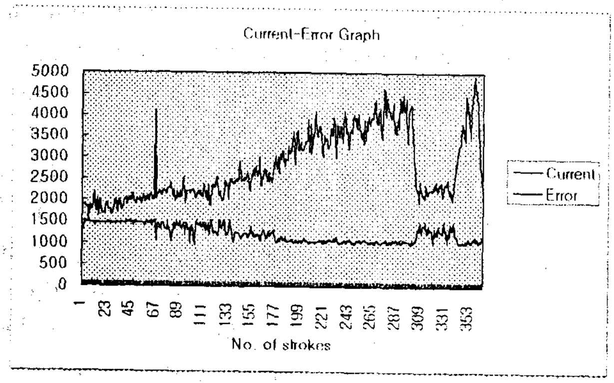

Fig. 10. Curves of the sum of current signal and the absolute error sum under fuzzy gain tuning

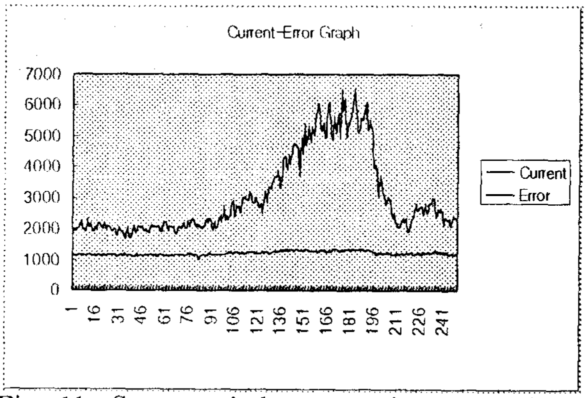

Fig. 11. Curves of the sum of current signal and the absolute error sum under fixed PI gain

Conclusion

In this paper, the fuzzy control method to schedule PI gain depending on the afterloads of TAH was proposed. Using the current value as an input parameter and fuzzy inference engine PI gain is adapted to the changing afterloads. In *in vitro* test, the efficiency and reproducibility of this method was testified.

The problem to be solved in the future is that this fuzzy controller must be insensitive to error. So the error which corresponds to the difference between reference velocity profile and estimated velocity one should be used as input parameter besides the current signal.

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