Can We Estimate the LAP, RAP, PAP, AoP and CO from the Interventricular Pressure and Motor Current in a Moving-Actuator type Total Artificial Heart? Yes, We Can.

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Abstract

It is needless to say that the hemodynamic variables estimation is a very important study for the artificial heart. Even though its importance there have not been satisfactory results which can be applied to the real-world situations. This paper surveys and recommends how to cope with the problem of hemodynamic variable estimation for the moving-actuator type total artificial heart (MA-TAH).

- Glossary -

MA-TAH: Moving-Actuator type Total Artificial Heart
LAP: Left Atrial Pressure
RAP: Right Atrial Pressure
PAP: Pulmonary Artery Pressure
AoP: Aortic Pressure
CO: Cardiac Output
IVP: Interventricular Pressure
Vel_L: Left Velocity
Vel_R: Right Velocity
SL: Stroke Length
Br_L: Left Break Time
Br_R: Right Break Time
Imb_L: Left Imbalance
Imb_R: Right Imbalance
ISS: Inverse Static System
FSS: Forward Static system

I. Introduction

As stated in the previous Abstract, it is needless to say that the hemodynamic variables estimation is a very important study for the artificial heart, and even though its importance there have not been satisfactory results which can be applied to the real-world situations. Well-known pneumatic artificial heart has a subsidiary compliance chamber for preventing suction problem. But our developing moving-actuator type total artificial heart (MA-TAH) does not need compliance chamber, and the air located in the interventricular volume plays its role [1][2]. Nevertheless, when much higher load is applied, there is possibility that the suction will occur. Not only the suction problem the other hemodynamic variables, e.g., Left Atrial Pressure (LAP), Right Atrial Pressure (RAP), Pulmonary Artery Pressure (PAP), Aortic Pressure (AoP), Cardiac Output (CO), estimation is a very important for the physiological control. Especially, the temporary state of a high LAP is related with the sudden death, so the real time supervision of the LAP is required. Fig. 1. shows the locations and appropriate range of all of pressures [3].

Our MA-TAH has the potentials of the possibility of estimation of all pressure variables and CO. This paper surveys and recommends how to cope with the problem of hemodynamic variable estimation for the MA-TAH using the interventricular pressure (IVP) and motor current signals.

This paper is organized as follows. After this part of Introduction, the characteristics of the IVP and motor current signals will be studied exhaustively in section II. In section III, the methods of hemodynamic variables estimation using the results of section II is surveyed. In section IV, prerequisite studies are summarized. Finally, in section V, conclusions and recommendations are stated.

II. IVP and Motor Current Signals

The right and left atrial pressures are important parameters in automatic control of a MA-TAH. During operation of the MA-TAH, the interventricular space's volume is changed dynamically by the difference between the ejection volume of ventricule and the inflow volume of the other. Therefore, the changes in pressure of the interventricular space is related to the both atrial pressures. We can measure the IVP waveform using a pressure sensor and attempt to indirectly stimate the changes of atrial pressure [4]. Especially, Jo has studied the relations deeply [5]. The simple relation can be summarized as Eq. (1). Namely, IVP can attribute to the estimation of preload (atrial pressures: LAP, RAP)

With these results, we can estimate the AoP and PAP using the relations of Eq. (2) and (3). Namely, motor current have relations with afterload (AoP, PAP) like Eq. (4) Here, we can use the peak value or average one of motor current signals.

Finally, when we know the AoP and LAP, we can attempt to find the relation between CO and other variables like Eq. (5).

The detailed techniques can be divided into two classes. One is the approach of mathematical modeling [6][7][8], the other is the input-output data approach. And these will be reviewed in the continuous section.

III. Hemodynamic Variables Estimation

The mean value of estimated pressure signals rather than dynamic one is much favorable in the perspective of control, display, and data writing of an MA-TAH.

$$\text{LAP, RAP} \propto \frac{1}{\text{Negative Peak Value of IVP}} \tag{1}$$

$$\begin{aligned}\text{Power} &= IV \\ &\propto I \\ &(V=\text{Constant}, 24[V] \text{ DC Brushless Motor})\end{aligned} \tag{2}$$

$$\begin{aligned}\text{Power} &= (\text{Flow Rate}) \times (\text{Pressure}) \\ &\propto (\text{Effective Stroke Length}) \times (\text{Effective Pressure}) \\ &= \begin{cases} (SL + Imb\_L + Imb\_R) \times (AoP - RAP), & \text{for left stroke} \\ (SL + Imb\_L + Imb\_R) \times (PAP - LAP). & \text{for right stroke} \end{cases}\end{aligned} \tag{3}$$

$$I \propto \begin{cases} (AoP - RAP), & \text{for left stroke} \\ (PAP - LAP). & \text{for right stroke} \end{cases} \tag{4}$$

$$\begin{aligned}CO &= f((\text{Effective Left Stroke Length}), (\text{Effective Right Stroke Length}), \\ &\quad Vel\_L, Vel\_R, AoP, LAP) \\ &= f((SL/2 + Imb\_L), (SL/2 + Imb\_R), Vel\_L, Vel\_R, AoP, LAP)\end{aligned} \tag{5}$$

The relations of Eq. (1) and (4) is a multiple-input and single-output (MISO) system. The target is to estimate the unknown one input variable (LAP, RAP, AoP, PAP) given known other input variables (SL, Imb_L, Imb_R, Vel_L, Vel_R) and the output one (IVP, Current). We will call this *inverse static system* (ISS) problem from now.

Conversely, the CO estimation is the problem of finding the output value (CO) given known input variables (SL, Imb_L, Imb_R, Vel_L, Vel_R, AoP, LaP). We will call this *forward static system* (FSS) problem from now. Motor current solely can also play the control index [9].

First, FSS problem can be solved by the mathematical modeling or other approach. But, the higher nonlinearities prevent the solving the problem. For this considerations, there have been intelligent theory technique such as neural network, fuzzy logic, genetic algorithm and so on. Intelligent theory can be applied to not only the hemodynamic variables estimation but also the control of the MA-TAH [10][11] and ventricular assist device (VAD) [12]. Recently, Om *et al.* proved the highly correlated relations among the interpolation, fuzzy reasoning, and neural networks [13][14], and showed the multidimensional linear interpolation technique is a sufficient and satisfactory method for this problem [15].

Secondly, RSS problem is a much more hard than the FSS one. If the function (or relation) have not inverse form, it is an impossible problem. But, we have the insight that the function has the inverse form right now. We are now on the way of developing a new general method to cope with this problem [16].

IV. Prerequisite Studies

There remained prerequisite studies before hemodynamic variables estimation from the IVP and motor current signals. We summarized them as follows.

4.1. Reliable Passive Control Scheme

We can say that the reliable center position is an important factor because of its possibility of affecting other variables related with length. So reliable positioning is also important for setting a reliable hemodynamic variables estimation. And the range of the control input variables must be settled reasonablely.

4.2. Reliable IVP and Current Signal Acquisition

There are much to be done how to get reliable IVP signals. As hardware aspects, IVP base-line drift and deformable membrane problem must be solved. As software aspects, the noise problem which occur in both the IVP and motor current signals must be solved. Also, the transmission error overlaid this problem. We verified *in vitro* experiment that the characteristics of the noise is very nonlinear, so the nonlinear filter is required [17].

V. Conclusions and Recommendations

It is needless to say that the hemodynamic variables estimation is a very important study for the artificial heart. Even though its importance there have not been satisfactory results which can be applied to the real-world situations. In this paper, we have showed that our MA-TAH has the potentials of the possibility of estimation of all pressure variables and CO. This paper surveyed and recommended how to cope with the problem of hemodynamic variable estimation for the MATAH using the IVP and motor current signals. The approach of our team's study can be summarized by two groups: one is a mathematical modeling study, the other is the intelligent theory technique one. Proposed method introduced in this paper is belonged to the second one. Not only the proposed method but also the first one require much higher load for the considerations of real-time processing during the operation of the MA-TAH. So, the utilization of digital signal processor is required.

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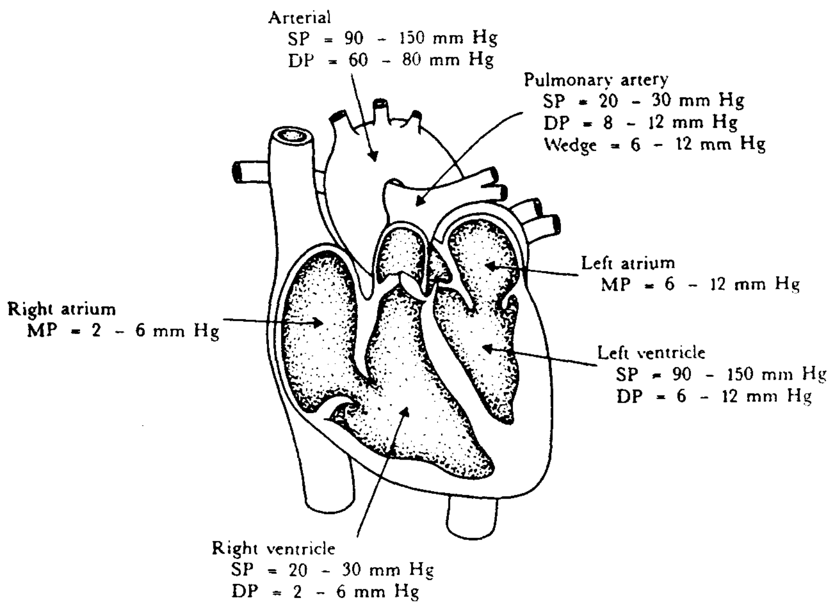

Fig. 1. Typical values of circulatory pressures.