Model of the Cardiovascular System: Pump Control

Miroslav LOZEK

Dept. of Circuit Theory, Czech Technical University, Technicka 2, 166 27 Prague, Czech Republic

lozekmir@fel.cvut.cz

Abstract. *Model of the cardiovascular system is mechanical simulator of the haemodynamic parameters of the human bloodstream. It is a system of pipes, valves, pump and other additional elements. The system is designed to imitate the flow of blood in a healthy human body. In the final model there are measured basic haemodynamic parameters such as blood pressure, cardiac output, pulse wave velocity and more. The main important part of the final model is a mechanical pump. The pump imitates the outflow of blood as in the healthy human heart. This paper describes the construction and control method of the mechanical heart pump in the model attached below. The aim of the project is to create a faithful mechanical model of the human cardiovascular system where it will be possible to measure haemodynamic parameters in the usual way. The mechanical model is intended for educational and observational purposes.*

Keywords

Cardiovascular system, heart, model, mechanical pump, blood pressure, haemodynamics.

1. Introduction

The cardiovascular system (CVS) of the human body is a complex system consisting of various types of blood-vessels with a wide range of diameters, 4-chamber heart that serves as the initiator of blood flow, control system consisting of a hormonal and nervous system, which provides auto-regulation. The composition of the blood affects the parameters of blood circulation too [1].

Given the enormous complexity of the CVS it is not possible to create accurate model that take account of each individual vessel. Therefore it is necessary to focus only on certain properties in a particular location of the system, which will be the point of interest.

This project is mainly aimed at monitoring the haemodynamic parameters measured in large arteries. On that basis it is possible to simplify a large part of the model and replace it with simple elements, which brings together the characteristics of individual vessel into the separated units.

2. The cardiovascular system

The cardiovascular system is a complex of organs to ensure blood circulation. The blood circulation provided the oxygenation of the body, transport life-giving substances to the cells and maintenance the homeostasis of the whole body [1].

2.1 Description of the CVS

The circulatory system can be divided by oxygenation into the oxygenated blood section and deoxygenated blood section. Oxygenated blood flows toward to organs by arterial system and away from the lungs by pulmonary veins. The arterial bloodstream is very strong and elastic. The flow of blood in arteries is pulsatile. Venous bloodstream is a rigid with a thin face. The flow of blood in venous is a continuous. Deoxygenated blood flows away from organs by venous system and toward to lungs by arteria pulmonaris. The arterial system is connected to the venous system by the capillary net (arterioles, microvessels, venules). Capillaries are the smallest vessels of the human body and from the haemodynamic view they are adjustable resistive elements transforming the pulsatile blood flow in arteries to the continuous blood flow in veins [1, 2].

The circulatory system can be divided by function into the systemic and the pulmonary circulation, where the center of these systems is the heart. The systemic circulation provides the transport of oxygen to cells. The pulmonary circulation provides blood oxygenation (see Fig. 1) [1].

The center of the CVS is human heart, which is the main actuator of the blood flow (see Fig. 1). The heart is composed of 4 chambers (2 atriums and 2 ventricles). At the moment of systolic ventricular contraction the oxygenated blood is ejected to the body from the left ventricle and becomes deoxygenated again and is returned through the right atrium into the right ventricle. At the moment of next systolic ventricular contraction the deoxygenated blood is ejected to lungs from the right ventricle. The re-oxygenated blood is returned by lungs into the left atrium.

The electrical conduction system of the heart provides correct sequences of the myocardial contractions. The electrical conduction system consists of cells with pacemaker action potential. This cardiac action potential is a self-pulse generator in the heart.

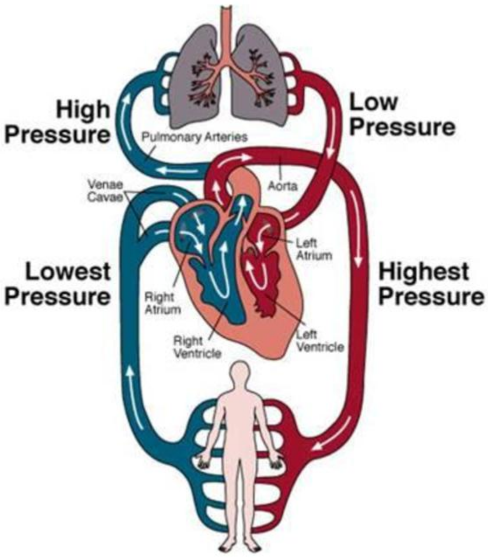

Fig. 1. Diagram of the cardiovascular system

2.2 Haemodynamic parameters

The haemodynamics of the cardiovascular system describes the physical behavior of fluid flow in the bloodstream. The haemodynamics is affected by mechanical parameters of blood vessels, cardiac pump output and blood composition [3].

One of the parameters describing the flow of blood vessels is called **P**ulse **W**ave **V**elocity [m/s]. This parameter is depended on the properties of blood vessels and fluid density ρ [kg/m^3] only. Properties of blood vessels are inner radius of the vessel r [m], face thickness of the vessel h [m] and modulus of elasticity E [Pa]. Pulse wave velocity can be used to diagnose vascular status. The relation describes Moens-Korteweg equation (1) [7].

$$PWV = \sqrt{\frac{E \cdot h}{2r \cdot \rho}} \tag{1}$$

Another important parameter is the cardiac output. Cardiac output is the quantity of the blood, which is ejected from the heart into the circulatory system. Cardiac output is usually related to the unit of the time or to a single cardiac cycle. The quantity of the blood ejected in one minute is called **C**ardiac **O**utput [l/m] and the quantity of the blood ejected in one cardiac cycle is called **S**troke **V**olume [l]. The relation of these variables is described by equation (2), where HR [1/min] means the heart rate [3, 6, 7].

$$CO = SV \cdot HR \tag{2}$$

Pressure, which the blood acts to the vessel's face is called the blood pressure. This pressure is invoked by the force of the myocardial contraction. The value of the blood pressure is affected by the vascular parameters. The blood pressure in each parts of the bloodstream is different. The blood pressure is usually measured on the large arteries, where the blood pressure curve is pulsatile. Usually, the blood pressure is described by local extremes of the curve. Local maximum of the curve is called systolic blood pressure and local minimum is called diastolic blood pressure [3, 6, 7].

2.3 Parameters of the bloodstream

The blood flow is significantly affected by the material properties of the bloodstream. Properties of the bloodstream can be enough described by parameters named resistance, compliance and inertance.

Bloodstream presents a resistance of the flow. This causes a decrease of the blood pressure. The organism is able to change resistance of the blood vessels using the vasoconstriction and vasodilation [6].

Blood vessels are more or less flexible. Increased pressure causes expansion of the vessels. It also means the increase of the vessels volume. The parameter called **C**ompliance [m^5/N] describes the elastic properties of the vessels. The relation between compliance, pressure gradient Δp [Pa] and volume of the vessel V [ml] describes equation (3), where V_0 [ml] means the volume of vessel without pressure gradient [6, 7].

$$V = V_0 + C \cdot \Delta p \tag{3}$$

The inertia of the blood flow of vascular system is described by a parameter inertance L [Ns^2/m^5]. The inertance depends on the length of vessel l [m], cross-section area of the vessel S [m^2] and fluid density of the blood ρ [kg/m^3]. (4) [6].

$$L = \frac{\rho \cdot l}{S} \tag{4}$$

3. Mechanical model of the CVS

The basic mechanical model of the CVS has based on the premise of a possibility to describe the parameters of the individual parts of the circulatory system. The final model is composed of 4 simple elements. The main part is a pump, which is an actuator. Other parts are 3 serial lines with different resistance, compliance and inertance. These lines presents arterial, venous and capillary bloodstream.

3.1 Analogy of the haemodynamic parameters

Biological haemodynamic parameters are very similar to the parameters of the electrical circuit, therefore it is possible to find analogies between the haemodynamic parameters and the electrical parameters (see Tab. 1) [8].

Physiological variable	Electrical variable
Liquid pressure (P)	Voltage (U)
Luquid flow (Q)	Current (I)
Resistance (R)	Electrical resistance (R)
Compliance (C)	Capacity (C)
Inertiance (L)	Inductance (L)

Tab. 1. Analogy of the haemodynamic parameters

3.2 Construction of the model

The basic mechanical model of the CVS is constructed by pipes, valves, compensatory containers and mechanical pumps.

In the basic model, for the first experiments, it is sufficient to use system of two pipes and controllable valve. A pipe with a high elasticity (low compliance) simulates arterial system. Very rigid pipe (high compliance) simulates venous system. Both pipes are connected by the controllable valve. This valve regulates resistance of the whole system (see Fig. 2) [7, 8].

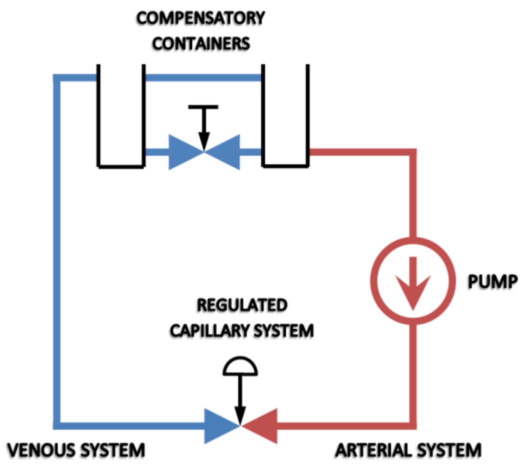

Fig. 2. Diagram of the mechanical CVS model

4. Pump of the model

In this project there is modeled the pressure wave only, it is not necessary to construct a complex 4-chambered pump. The pressure wave in the systemic circulation is important only, it musts imitate pressure output of the real human heart [7].

Common mechanical pump with enough dynamic flow can be used as a pump of the model. Gear pump (see Fig. 3) with sophisticated control is suitable for pumping fluid in the model.

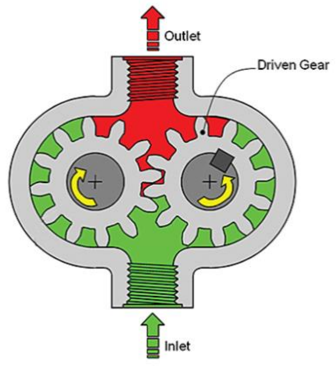

Fig. 3. Diagram of the gear pump [11]

4.1 Control of the pump

The aim of the sophisticated control is to model pressure wave pursuant to the real physiological curve of the blood pressure (see Fig. 4).

The nonlinear control of the motor of the pump enables very truthful modeling of the physiological blood pressure wave. The winding of the DC motor is an inductive element and acts as a low-pass filter. On that premise it is possible to control the motor by the pulse mode [9].

The **P**ulse-**W**ide **M**odulation is used to control the motor. The DC component of the output voltage is in proportion to the PWM duty cycle. To achieve good modeling results it is used high frequency of the PWM and a small step of the duty cycle [9].

The control of the voltage partially correlates with the generated pressure wave. The real shape of the generated pressure wave can be achieved by a sophisticated control algorithm.

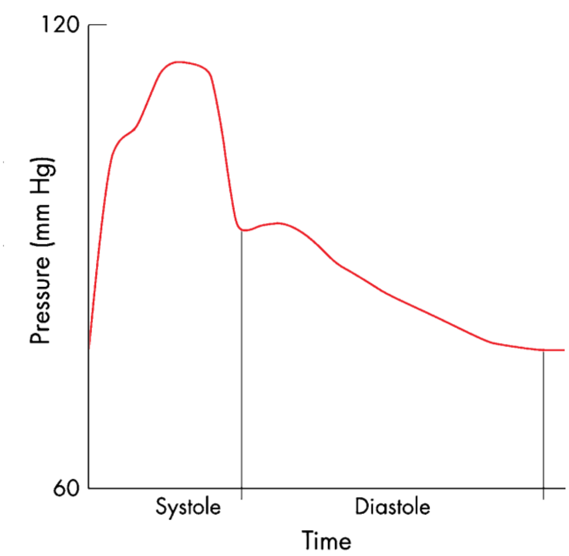

Fig. 4. Real blood pressure curve [10]

4.2 Pump control unit

The control unit is divided by the function into two sections (see Fig. 5). The signal section of the unit contains microprocessor, which generates the control signals. The power section of the unit contains the power switching devices.

Signal processor Parallax Propeller is able to process up to 8 parallel algorithms at once [12]. The processor generates the control signals to the switching devices according to an algorithm, developed by the process of each cardiac cycle and communicates with the control PC interface named ControlWeb [5].

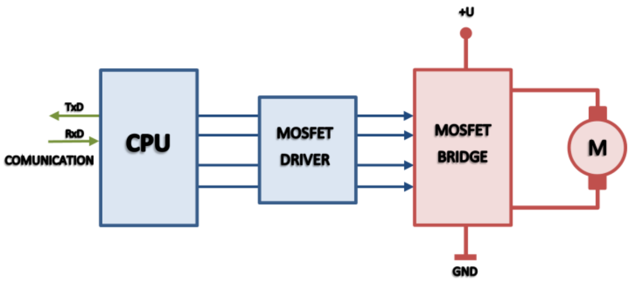

Fig. 5. Diagram of the control unit

The power section of the unit consists of 4 switching devices, which are arranged in two half-bridges (see Fig. 6) [9]. This allows to control in opposition phase, it increases the dynamic range of pumping.

The switching device is a MOSFet transistor with the channel N, which is characterized by the fast switching time, high power density and low ON-resistance [9].

Efficient switching is provided by the integrated drivers. The drivers deliver high electric charge in a very short time to the gates of the transistors. The drivers provide the protection against accidental switch of two transistors in one line at the same time [9].

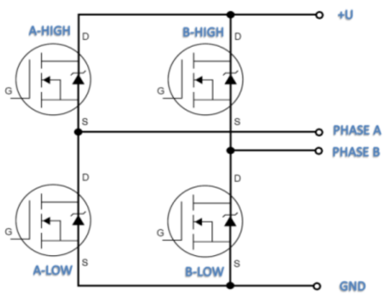

Fig. 6. Diagram of the power section of the control unit

5. Conclusion

The basic model of the cardiovascular system was created. The model is focused on the generating of the curve of the real blood pressure. The pressure gradient is generated by the gear pump with the sophistical control and by the mechanical valve.

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About Author

Miroslav LOZEK was born in Kadan, Czech Republic. He received Master degree in Biomedical Engineering at the Faculty of Electrical Engineering of the Czech Technical University in Prague in 2011. At the present time he is PhD student at the Department of Circuit Theory, FEE CTU in Prague. He is currently working on Modeling of Biological Systems, where he is now engaged in the hardware model of the cardiovascular system.