# Adaptive Mechanical Model of Cardiovascular System

## Regulatory Processes

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***Abstract* – This paper describes regulatory processes of the adaptive mechanical model of the cardiovascular system (CVS). The CVS model simulates the physiological circulatory system of blood in the mechanical way. This device allows demonstration and measurement of realistic haemodynamic parameters such as blood pressure, cardiac output, vascular resistance etc. The mechanical CVS model is designed for scientific and educational purposes mainly.**

***Keywords - cardiovascular system; biological model; mechanical modelling; regulation***

## I. INTRODUCTION

The cardiovascular system is a system of the heart and vascular network in the human body, which allows distribution of oxygen and other vital substances between all parts of the human organism. The failure of the cardiovascular system is fatal for vital functions. The laws of fluid dynamics (specifically called haemodynamics) describe blood flow in the CVS. The blood flow (cardiac output), the blood pressure and the vascular resistance are the main parameters of haemodynamics. The diagnostics of many cardiovascular diseases is based on monitoring of these haemodynamic parameters. Modelling of the CVS is one way for the obtaining better knowledge of the human circulatory system. [4, 7]

The adaptive mechanical model of the CVS with the telemetric unit was developed at the author's workplace. The model consists of mechanical pump, mechanical valve, flexible and rigid tubes and other hydrodynamic elements. This device simulates pulsatile flow of fluid in plastic vessels. The telemetric unit captures vital parameters of the human body and transmits them into the mechanical model. This design allows measuring (invasively) of basic haemodynamic parameters that are captured in the human body in the non-invasive way. The model is primarily intended for educational purposes. [1-3, 5]

This paper deals with regulatory mechanisms of the mechanical model. The control unit of the mechanical model governs electro-mechanical elements and thereby it allows simulation all kinds of blood pressure curves (ventricular, arterial and venous).

## II. HAEMODINAMIC PARAMETERS

### A. *Cardiac Output*

The Cardiac Output (*CO* or *Q*) is the technical term for fluid flow in the main aortic vessel. The CO is volume of blood, which is ejected into the body by the heart per one minute.

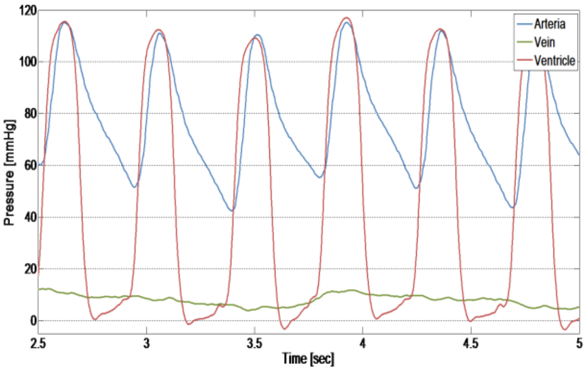
The CO may be measured by using indirectly methods. The most common methods are MRi, dilution or Fick method or Doppler sonography. Typical value of the CO for healthy and quiet body is 5.5 liters per minute. [6-8]

### B. *Blood Pressure*

The blood pressure (*p*) is a pressure which depends on vascular or heart walls. The pressure curve is pulsatile in the heart ventricle and arterial vessels. The flow in venous vessels is semi-continuous. The pulsatile blood pressure is described by the systolic, diastolic and mean pressure values (typical values are 120/80 (100) mmHg). The venous blood pressure is specified by the mean pressure value (typical value 6 - 12mmHg). [6-8]

The blood pressure might be measured by invasive method (catheterization method) or non-invasive methods (cuff methods). The real pressure curves are shown in fig. 1. Anonymized data were measured in University Hospital Motol in Prague.

Figure 1. The real pressure curves



### C. *Vascular Resistance*

The vascular resistance ($R_s$) is a force of vessels counteracting blood flow. The relation (1) between pressure and blood flow describes the resistance. Wood Unit (WU) is the most commonly used unit of the vascular resistance.

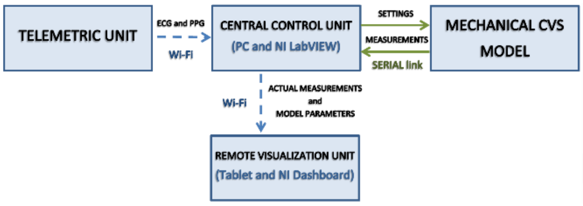
Typical value of systemic vascular resistance is 9 – 20 WU. [6-8]

$$R_s = \frac{p\ arteria - p\ atrium}{Q} \qquad [WU] \tag{1}$$

## III. ADAPTIVE MECHANICAL CVS MODEL

The description of the adaptive mechanical CVS model might by divided into three parts – the mechanical model with it's own control unit; vital function monitor with telemetric data transmission and central control and measurement unit. This paper is mainly focused on the mechanical model. [1-3]

Figure 2. The principle schema of the complete system



### A. *Model CVS construction*

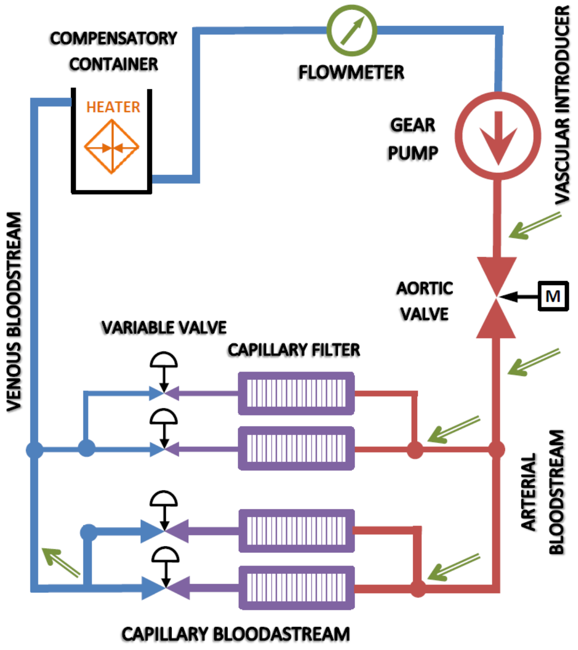
The adaptive model is realized by using hydraulic and electro-mechanical elements (fig. 3). The heart pump is imitated by the system of the mechanical gear pump and solenoid valve. The mechanical pump is chosen considering flow and pressure oversized limits and reverse mode possibility. The mechanical valve is used as the unidirectional aortic valve.

The vessel network consists of special tubes with different diameter and different elastic attributes. The vessel network is bifurcated into smaller vessels with capillary bloodstream that are afterwards re-converged to the main venous vessel.

The main vascular resistance is designed by using capillary filters (static resistance) and controllable valves (variable resistance). Controllable valves are designed by using servo-motors and tube-pressing mechanisms. The compensatory container is necessary for preservation of hydrodynamic stability and temperature regulation.

The accurate flow measurement is arranged by using the implemented instream flowmeter. Clinical vascular introducers with the hemostatic membrane represent the entrances for clinical catheters. The model's vessel network contains five vascular introducers at different places in whole vessel network. [1-3]

Figure 3. The fundamental schema of the CVS model

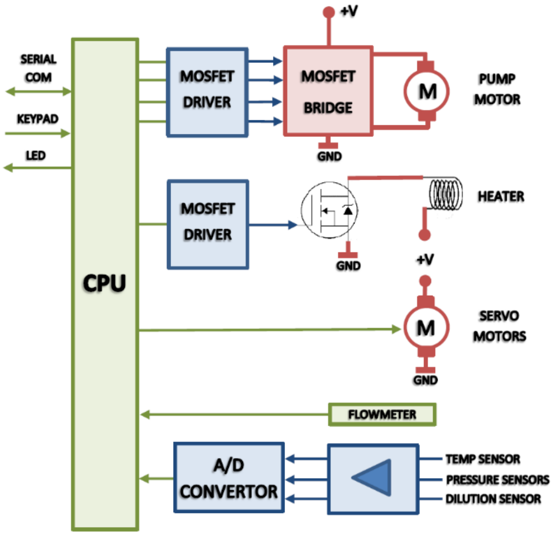


### B. *Control unit*

The mechanical CVS model consists of electromechanical elements that require control by using the microprocessor unit. The motor of the gear pump, the electromagnetic valve and the liquid heater are powered in pulse mode. The pulse power feed is arranged by MOSFET transistors with microprocessor controlling. The gear mechanical pump and the aortic valve work in the synchronous pulsatile mode with variable timing. The timing of the delay between pump and valve depends on the pressure's feedback system. It allows adjustment of intra-ventricular and aortic outlet pressure ratios. The temperature of the fluid is regulated by the system of the heating element, the temperature sensor and regulation mechanism. The variable vascular resistance system is actuated by servo-motors that are powered of the direct current supply. The angle orientation (compression rate) is determined by standard servo-signal, which is broadcasted by the microprocessor (see fig. 4).

The main control unit provides management of all measurements (pressure, flow and temperature). The model includes 6 clinical pressure sensors, liquid and termodilution temperature sensors and inline flow sensor. The sensor systems are designed by using operational amplifiers; subsequently output signals are digitalized by the AD convertor. The control unit communicates with the central control unit (PC, LabVIEW application) by using the serial link. The LabVIEW application provides analysis and displays measured signals. Model's haemodynamic parameters are controlled by the PC application as well. [1-3]

Figure 4. The fundamental schema of the main control unit



## IV. REGULATORY PROCESSES

The mechanical CVS model consists of several active elements. These elements require electrical controlling with the feedback or non-feedback regulation. The main control unit provides mainly liquid temperature regulation, ventricular/arterial pressure regulation and vascular resistance regulation.

### A. *Liquid Temperature Regulation*

Elastic attributes of plastic tubes depend on the temperature. Therefore, it is advantageous to maintain the physiological temperature of liquid (37 °C). Thermodilution method of the cardiac output determination requires the physiological liquid temperature as well.

The heater element and thermistor are placed in the compensatory container. It is possible to set target temperature in the range of 18 – 42 °C. The regulatory mechanism switches MOSFET transistor by using Pulse Wide Modulation (PWM) mode. The duty cycle of the PWM is determined by the temperature difference between actual and target temperature. This mechanism maintains the target temperature with the accuracy of 0.1 °C for all possible model settings.

### B. *Liquid Pressure Regulation*

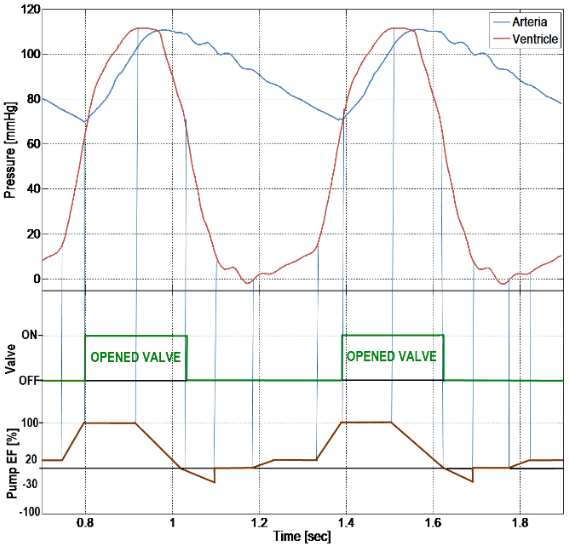
One of the aims of the cardiovascular modelling is to simulate the pulsatile pressure in different cavities of the system (ventricular, arterial and venous pressure). The ventricular behavior (contraction and relaxation of heart myofibers) might be described by ventricular pressure curve. The aortic valve opening and closing is observable on arterial pressure curve.

The contraction and relaxation of the ventricle are simulated by the gear pump that is able to pump in the outflow and backflow mode. The solenoid electromechanical valve simulates aortic valve function. The ejection fraction (EF) describes the pump motor power (consequently the cardiac output). The EF is proportional to the duty cycle of PWM. The outflow time is fixed to 250 ms with rising and falling character. The systolic ventricular pressure (and consequently also the systolic arterial pressure) is regulated by using the period-adaptive value of EF - according to the feedback arterial pressure measuring. The time of adaptation is about 10 heart cycles.

The backflow phase simulates relaxation of the ventricle with closed valve (partially the negative pressure). The empirical test revealed the optional motor power (30 % EF) for backflow phase (diastolic ventricular pressure). The backflow phase time delay is determined by the time-adaptive feedback ventricular pressure measuring.

The end-diastolic ventricular pressure is presented by outflow phase with closed valve. The regulation is based on the adaptive value of EF according to the feedback ventricular pressure measuring.

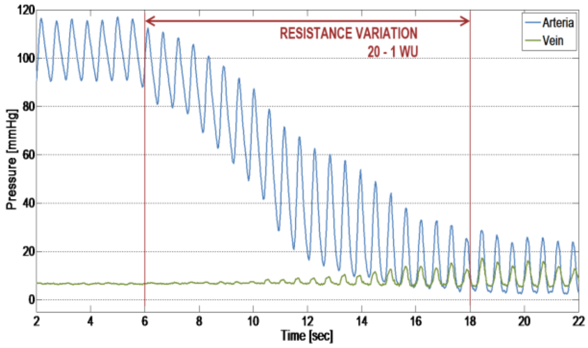
Figure 5. The principle of the ventricular pressure regulation



### C. *Vascular Resistance Regulation*

The vascular resistance is formed by using tube-pressing mechanisms that are actuated by servo-motors. The resistance determines the mean arterial pressure that is measured as feedback. The duty cycle of servo-signal is the time-adaptive value that is modified according to the pressure feedback measuring.

Figure 6. The resistance variation demonstration



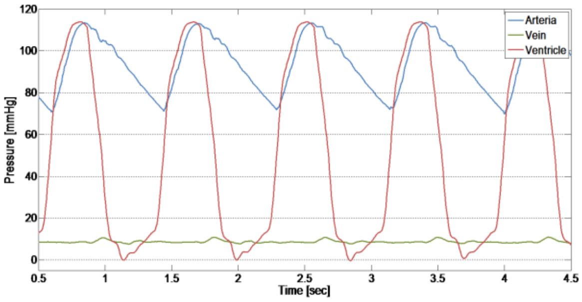
The resistance regulation (according to the arterial pressure) and the EF regulation (according to ventricular pressure as well) modify parameters in cooperation with by using the cardiac output and the pressure limits table.

## RESULTS

The mechanical model can simulate all kinds of physiological blood pressure curves – ventricular (with end-diastolic wave); arterial and venous pressure curves (see fig. 7). The maximal systolic pressure can be set up to 400 mmHg. The vascular resistance consists of the fixed components for the static filtering and variable components for pressure controlling. The cardiac output is determined by variable resistance setting (range 1 – 7 l/min). The simulated haemodynamic parameters and pressure curves are similar to physiological values.

The verification of results is based on comparison of simulated curves (see fig. 7) with physiological clinical haemodynamic measurements (see fig. 1). The comparison includes shape details, pressure values (systolic, diastolic, end-diastolic and mean) and character of waves. Simulated waves are very similar to physiological curves. This similarity is sufficient for the educational purposes.

Figure 7. Simulated pressure curves



## CONCLUSION

The adaptive mechanical model of the cardiovascular system allows simulation of haemodynamic parameters. This system contains telemetric device (with Wi-Fi communication interface) for the vital function acquisition of the human body; central control unit, that provides receiving of vital function’s parameters and controlling of the mechanical model according to real vital parameters.

The mechanical model contains the clinical vascular introducers that allow measuring haemodynamic parameters by using clinical devices as well.

This simulation system was mainly developed for educational purposes. The mechanical model allows demonstration haemodynamic measurements by using invasive methods.

## ACKNOWLEDGMENT

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