Control of Breath Simulator

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Abstract— The paper discusses the control of a specific LUNG simulator. This model was created for educational purposes and it is used for simulation of required respiration wave. The article describes the basic equations for simulation of the breath simulator that was used to verify of controller, and a program for controlling the simulator. These simulations are used on either rubber substitute lung or real lungs. The simulator can simulate breathing during various diseases or detect different lung properties (e.g., stiffness, puncture).

1. INTRODUCTION

Breath simulator described in this article can operate in different modes, either independently without using PC or as PC-controlled. The user can choose from several preset control modes. The most important mode is the control of breath curve with the controller (the feedback). In this mode the breath curve is preset, which represents the unusual breathing. This curve can be directly changed in the program code. The simulator is than able to model breathing problems for educational purposes. The LabVIEW and real-time platform CompactRio were used for programming and visualization of control. This platform controls a motor connected to the bellows and other components. The bellows are attached to the box/thoracic chamber, a mechanism that simulates (very roughly) the corresponding part of human and/or porcine body, the thorax. Although the thoracic chamber cannot fully substitute human body, it is capable of providing realistic simulation with related physiological conditions and pathological anomalies [1–3].

2. MATHEMATICAL MODEL OF THE THORACIC BOX

The simulator model has been converted into equations and subsequently modeled in Matlab Simulink. Key assumption that had to be met and that is used as a basis of creating equations, is the size of the volume.

$$V_t = V_{t0} + V_i - V_l \tag{1}$$

where V_t is the volume of the TB [dm^3], V_{t0} is the initial volume of the TB (when the P_b is in the zero position), V_i is the volume added by the movement of the piston P_b and V_l is the volume of the lung, S_p is the area of the piston, p_v is the vacuum inside the thoracic box [5].

And then also equation for linking of the relationship between pressure and volume

$$p_t = \frac{p_a V_{t0} + 24.35 \cdot n_0}{V_t} \tag{2}$$

where m represents the leakage of air into the TB, p_a is the atmospheric pressure, and n_0 is the initial amount of the air inside the TB.

The last phenomenon we needed to simulate was the leakage of the box as it creates unstable amount of substance in the box and turns the pump on.

$$\frac{dm}{dt} = C(p_a - p_t) = Cp_v \tag{3}$$

where $p_v = p_a - p_t$ is the vacuum in the TB, and C [mol s^{-1} bar^{-1}] is the leakage constant.

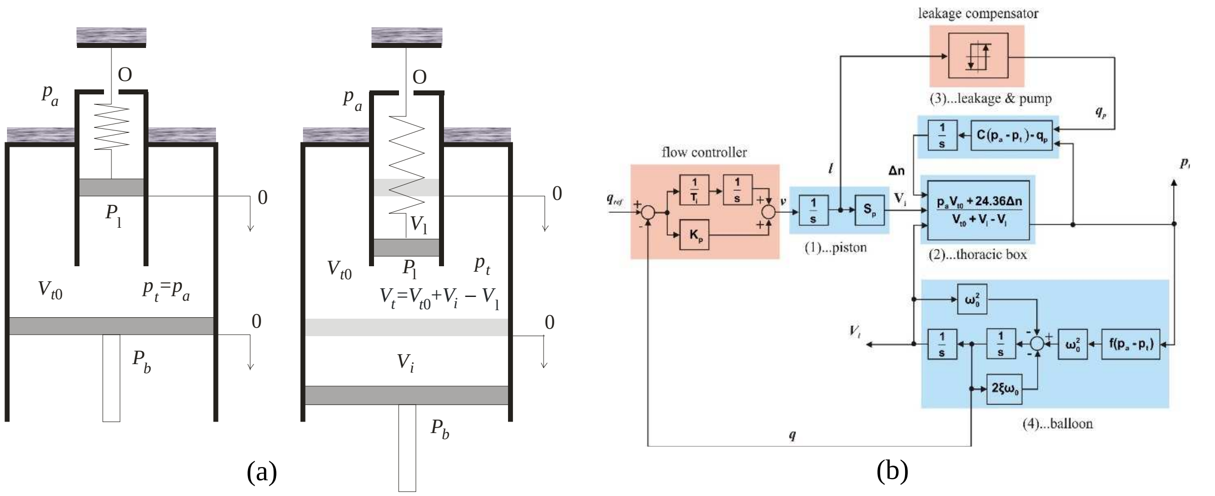


Figure 1: (a) An abstract approximation of the lung simulator. (b) Schema of simulator.

3. MATHEMATICAL MODEL OF THE LUNG EQUIVALENT

As providing a mathematical model of a lung tissue is an extremely complicated task, we chose a rubber balloon as the lung substitute. However, even a mathematical model of the balloon can be provided only with difficulty [4]; let us therefore start with the simplest linear model of the balloon in the form of the cylinder shown in Fig. 1(a). The following equation then represents its function in the lung simulator:

$$\ddot{x} + \frac{B}{m_p}\dot{x} + \frac{K}{m_p}x = \frac{F}{m_p} \tag{4}$$

where x is the position of the piston, B is the damping parameter, K is the stiffness of the spring, m_p is the mass of the piston, and F is the force acting on the piston.

Equation (4) can be written in the more abstract form

$$\ddot{V}_l + 2\varsigma\omega_0\dot{V}_l + \omega_0^2 V_l = \omega_0^2 f(p_v) \tag{5}$$

where V_l ... the volume of the balloon [dm^3], ω_0... the natural frequency [rad/sec], ξ... the damping coefficient $\varsigma > 0$, p_v... the vacuum [bar].

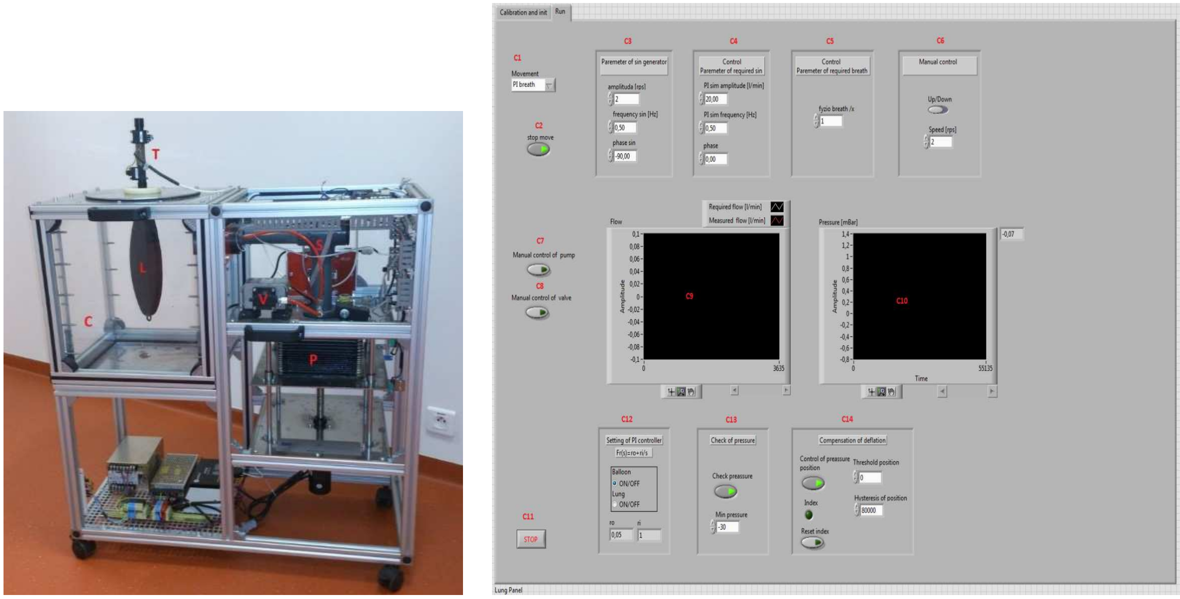
This model was simulated in Matlab Simulink (Fig. 1(b)) and was used for testing of controller, which was obtained from measurement data by identification toolbox in Matlab [6].

4. SIMULATOR

The simulator consists of several important parts that are seen on the picture Fig. 2(a). The first part is the thoracic chamber where the lung is located. Thoracic chamber is a plastic box with holes (C). These are used for connecting different sensors and bellows. The lung (L) is tightly attached to the object with two flow sensors, which is mounted on the top of box (T). The flow is created by the negative pressure in the box and it can be changed by bellows (P). The movement and volume of bellows are controlled by an engine which is located underneath. Another important part is the vacuum pump (V). That is used to compensate the leakage. The valve is placed on the top of bellows for the event of negative pressure reduction. It connects bellows with the outside atmosphere directly. The model is equipped with several sensors. These are flow sensors, a pressure sensor, reference and limit position sensors [7, 8].

5. REALIZATION AND RESULTS

The actual control is implemented in LabVIEW and applied to the platform CompactRio 9024 that contains one digital and one analog card. The main parts such as motors and pumps are controlled by PWM signal from the digital cards. The analog card is used only for reading data from the flow and pressure sensor. The program consists of three parts. The first one is the calibration part. As the environmental influences are not always the same, calibration of equations for calculation



(a) (b)

Figure 2: (a) The electromechanical structure of the LUNG simulator. (b) Run window.

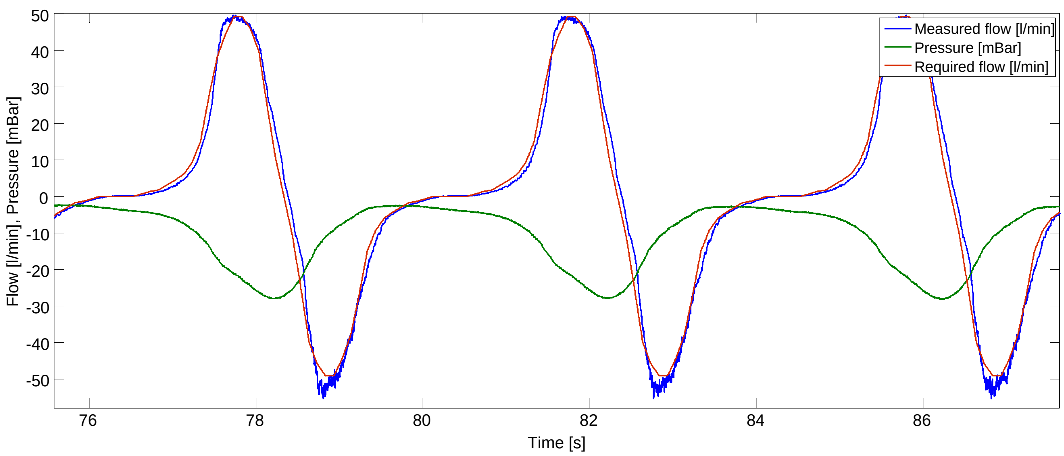


Figure 3: Test of the simulator with a real pig lung.

of pressure and flow should be done before each measurement. Another part is the initialization and setting the initial position of bellows and pressure in the box. Because the simulator does not contain an absolute incremental encoder, the start position must be set by the reference sensor and then the position is calculated by the software. The third part is the simulation of breathing curve. The control window is in Fig. 2(b).

The program offers four options for piston running.

These four different types are called *Gener sin*, *PI sin*, *PI breath*, *Manual*.

Gener sin: In this mode, only the required value of speed is set as the input and the program doesn't use any feedback. The resulting shape of the flow depends on the lung and model parameters. The controller is not used.

The shape of required speed value is sine waveform, which is generated from sin generator.

PI sin: In this mode, the controller uses feedback from the flow sensor and its required shape of flow is sine wave.

PI breath: This mode again uses the controller and the required shape of flow is a predefined breath pattern. The values of required flow are defined in the programme. The user can change only the gain of this signal in the box. The shape of the signal is in Fig. 3 as required flow. Its maximum amplitude is 50 l/min and the frequency is 4 Hz.

Manual: This mode is used for moving the piston manually.

The user can also change various parameters of running simulations. The most important of these parameters are the controller constants and the setting of the pump so that it compensates the leakage of the box.

The system was tested with a real pig lung and its results can be seen on the Fig. 3. As the controller was used the PI controller.

6. CONCLUSIONS

All the systems of the lung simulator have been converted into equations and the model has been created in Matlab Simulink. Also in this environment, the controller was designed and tested. Physical realization has been programmed in LabVIEW and implemented into real-time platform CompactRio. Several windows were created for an easy control of the simulator. During startup the windows for calibration and for setting the initial conditions are activated. After setting of all the important values the program is switched to the Run window where is the control panel. User can than choose from several modes: control, control with feedback or manual control of bellows. In the control mode with feedback a breath curve is predefined, this curve can be changed when required. The simulator was tested with real pig lungs and it has very good results as it is shown in Fig. 3. Inaccuracies appear only at the vertices of the curve.

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