8th IFAC Symposium on Biological and Medical Systems
The International Federation of Automatic Control
August 29-31, 2012. Budapest, Hungary

Concept study of a nonlinear mechanical lung simulator

Gabor Vanyi, Norbert Gut, Joern Kretschmer, Knut Moeller

Furtwangen University, Department of Biomedical Engineering
Germany (e-mail: moe@hs-furtwangen.de).

Abstract: The aim of this study is to design an anatomically-oriented simulator for lung dynamics and gas exchange in the lungs; to be used for ventilator tests and especially for automated prototypes. It has to demonstrate arbitrary reactions according to specified disease patterns that are realized via respiratory mechanics models, even including nonlinearity. The simulator is a combination of piston cylinders and controlled by an FPGA based real time controller platform. This controller has standard Ethernet interfaces to PC-s, where a graphically programmed interface allows the user to change parameters and even their individual Matlab code. This concept emphasizes on gas exchange as well; by generating some specific tidal expiratory CO_2 curves via a specified internal gas mixture into cylinder combinations. The architecture of an anatomically oriented lung simulator has been derived and the first components have been manufactured and tested. A control scheme has been discussed and is recently put under development. First steps towards a robust and accurate reproduction of nonlinear dynamic responses by a simulator interacting with a ventilator have been made.

Keywords: mechanical ventilation, simulator based test and training, dynamic respiratory system, respiratory signals, Real Time (RT), FPGA, computer (PC)

1. INTRODUCTION

Modelling medical processes is a dynamically growing area of science. The use of mathematical formulas to describe them is widely used. Nowadays, not just models, but also model families are used just to describe the human respiration process, from inhalation through the airways to chemical reactions within the blood cells. Medical researchers and therapists are utilizing these descriptions and today's models can serve different purposes, such as the diagnostic purpose of automated measures through newer generations of ventilators (AUTOPILOT [1]). For the development and test of automated therapy devices a realistic patient behaviour is required that provides a flexible and realistic test bed for e.g. the AUTOPILOT system. This active simulator has been designed to couple with the ventilator and react as realistic as the patient's own respiratory system. This system will have different purposes; one of which is to assist embedded training of medical staff in clinical settings.

Simulators can be classified to either pure mathematical software model or a systematically designed mechanical system that can be physically connected to a ventilator. Most software solutions may include more than just definitions of lung mechanics in addition to gas exchange or cardiovascular dynamics ([2]).

These mechanical simulator systems are divided into two groups: passive and active simulators. The simplest ones are passive representations of lung mechanics, of which lung compliance and elasticity are defined by a plastic bag and resistance can be altered by a pipeline with a clamp in front of the test lung. Figure 1 shows a general explanation of the passive lung model families.

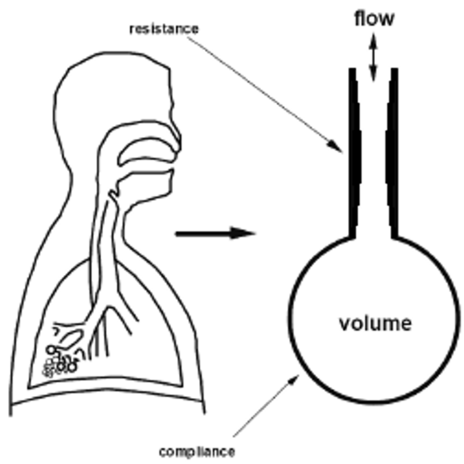

Figure 1: Passive lung model, in which resistance was replaced with a pipe and the compliance with a balloon.

More elaborate passive systems, like the Michigan Test Lung (Michigan Instruments Inc., Grand Rapids, MI) are still not able to adjust simulated lung mechanics dynamically, either if it is based on computer models or given nonlinear settings.

Active simulators (Figure 2) can simulate different lung diseases, such as Acute Respiratory Distress Syndrome (ARDS) or Chronic Obstructive Pulmonary Disease (COPD), as well as spontaneous breathing and pulmonary reflexes. They are available on the market and mainly contain a cylinder piston system with an integrated controlling system. Examples for these setups are the ALS 5000 breathing simulator (IngMar Medical Ltd. USA), or the 1101 Series (Hans Rudolph Inc. USA), or experimental systems [3]. However, a number of tests have shown that these simulators were unstable and had problems in reproducing high dynamical compliance changes, as found in ARDS patients [4]. Therefore, a new development is important for a realistic lung simulation [5].

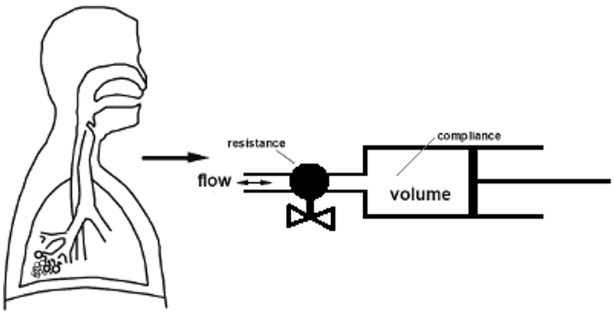

Figure 2: Active lung simulator model, which contains a valve (as resistance) and wave form generator (cylinder)

2. CONCEPT

2.1 Design of cylinder

In a first approach a single large cylinder with piston was tried. This solution was built with an O-ring gasket between the large tank and the piston's surface. Unfortunately it required a very high power linear motor to overcome friction. An Inventor 3D stress test was made to examine the reasons; the result is shown in Figure 2. As depicted in the figure, the piston's edge and inner surface of the cylinder requires a very high stress. The high friction shown could not be overcome by other sealing concepts, because either gas leakage occurred or control was hampered by adhesion. To overcome this problem, another solution has been chosen.

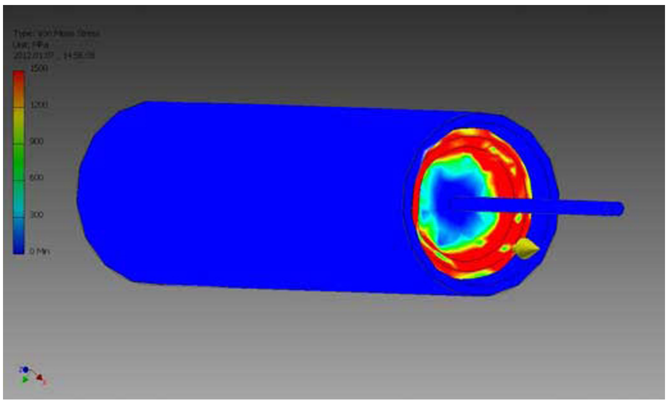

Figure 3: The O-ring based cylinder's stress test. As shown in the picture the friction between the wall and the piston is so high, it requires a high peak-power ($F_{peak\ max}$=580N) linear motor. That high power requirement in the friction was not enough to follow the estimated quick reactions and precise compliance changes.

The second setup is based on a double, roll membrane gasket. These membranes are placed between the piston and the end of the tank's housing. These two membrane's surfaces have been fully filled with air, in order to reduce the friction and prevent leakage. This setup also has been simulated in the Inventor 3D program. The stress test result is presented in Figure 4. As shown in the figure, this solution requires significantly less power to move the piston than the earlier solution.

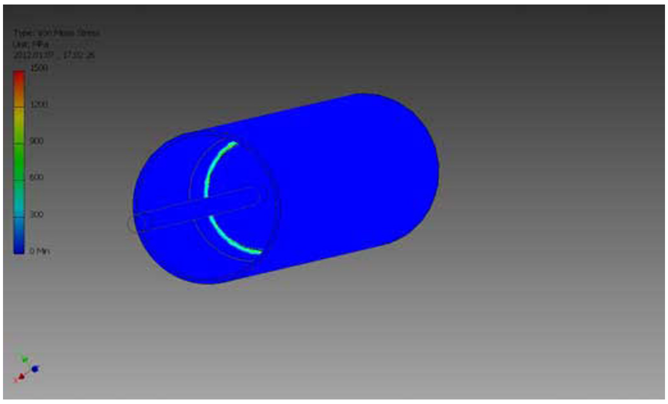

Figure 4: Solution of double membrane piston shows significantly less friction between the inner surface of tank and piston. Decrease of this leakage allows the use of lower peak-power linear motor ($F_{peak\ max}$=220N). As friction is not significant anymore, velocity can be increased and leakage can be stopped. The estimated gas control can be solved.

A prototype of this second setup has been produced and at the moment is ready to be applied for simulations. The cylinder's volume is 315mm^3, and multiple of those will later be coupled in parallel. Furthermore, this solution was revised and formed into an anatomically correct architecture.

2.2 The anatomically correct cylinder combination

The current concept comprises seven, synchronized pistons. Six pistons are based on the lung's volume parameters and one piston is used to reproduce high dynamic components such as cardiogenic oscillations (Fig. 8). Figure 5 illustrates the overall setup of the system.

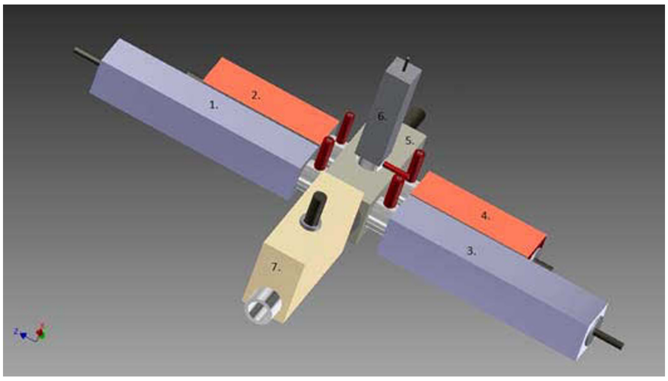

Figure 5: Combination of piston-cylinder systems to mimic different anatomical and dynamical components of the respiratory system.

The main concept is based on the lung capacity and volume diagram (Fig. 6):

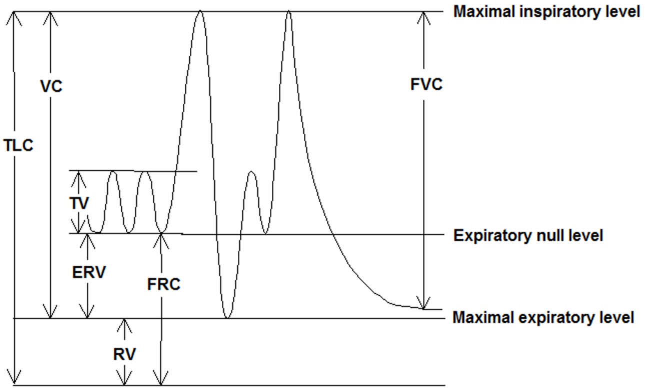

Figure 6: Lung volume diagram.

The main components are the blue and red cylinders working in parallel, which reproduce the airflow. During inhalation the left cylinder will be filled with air from the environment, while the right cylinder will be filled with the given mixture of CO_2 through the red pipe on the top. This process works vice-versa, thus producing the tidal volume and inspiratory reserve volume in the blue ones (number 1 and 3 in Fig. 5), and expiratory reserve volume in the red ones (number 2 and 4 in Fig. 5). These cylinders are connected to the expiratory reserve volume cylinder (number 5 in Fig. 5), where volume is mostly constant, although modifiable in cases of certain diseases. Therefore, this space is used mostly as a mixing place of the inhaled and exhaled gas. An anatomical dead space is placed in front (number 7 in Fig. 5). This cylinder's piston has the largest surface, because the minimal given volume is 150ml, and further expandable to 300ml. This space is also important to mimic realistic gas concentration curves, e.g.. play an important role in the typical form of a capnogram. The smallest cylinder is found on top of the expiratory reserve cylinder (number 6 in Fig. 5). It represents the cardiogenic generator. The volume of this cylinder is not very large; since it creates little peaks at a specified heart rate.

The specific symptom 'cardiogenic oscillation' (the rhythmical disturbances of the heart beat on airway pressure) i.e. a sample of a cardiogenic pattern overlaying an end-inspiratory pause (EIP), is shown in Figure 7.

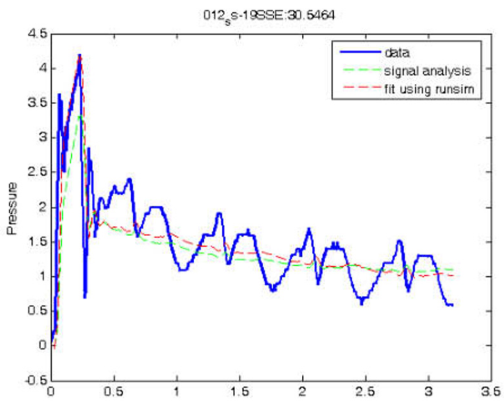

Figure 7: Cardiogenic oscillations (blue) recorded during an end inspiratory pause of an ARDS patient. Red and green line show different model fits of lung tissue relaxation extracted from the data.

Pressure dependent changes in the pattern of cardiogenic oscillations can best be reproduced in an independent fast piston system. The adaptable cylinder is set up as an independent cylinder, which simplifies the control of other cylinders.

2.3 Gas exchange

Capnography is an investigated monitoring technique that is available on the ICU at the patient's side. Thus, a lung simulator should provide a gas mixture that shows a realistic capnogram for the clinician or the Autopilot system. Typical phases of capnograms would have been reproduced through a flexible dead space by inflating a given CO_2 concentration into the lung cylinders. The airway is regulated through the edges of the cylinder's connections via butterfly valves.

Phase 1 of a capnogram is simply generated by removing the gas out of the dead space during the first phase of expiration. An increasing fraction of CO_2 would be produced by mixing the gas with a higher CO_2 fraction in the given cylinder (loaded through the separated red coloured pipes). Concentration would be constant at the end of expiration.

The anatomically oriented construction naturally reproduces realistic CO_2 curves that can be obtained using standard equipment provided by the manufactures of ventilators.

This phenomenon together with wave form generation is not solved. Gas exchange is usually modelled and solved with three-way valve or just calculated in Matlab models [8].

2.4 Controlling system setup

The overall system plan is depicted in Figure 8. It consists of a ventilator that is remotely manipulated by a Fuzzy based controller to optimize the ventilator's settings [1, 6]. This machine faces the mechanical lung simulator, which is controlled through a real time control system. The RT system is connected to a PC, which executes a patient's behaviour model and shows the current results of the simulation.

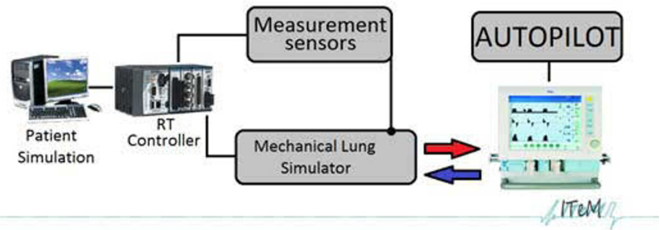

Figure 8: Test setup with the active lung simulator for the evaluation of the AUTOPILOT system. A Personal Computer running the simulation model and the RT Controller implements a suitable reaction to the ventilation regime. The AUTOPILOT system in the ventilation machine analyses the situation of the 'patient' and optimizes the ventilator settings.

Thus, this system makes it possible to run tests deterministically, while at the same time allowing flexible reactions to change in therapeutic measures by the Autopilot system or a clinician. The mechanical simulator consists of several anatomically modified cylinder systems that are able to mimic gas exchanges and flow-pressure reactions.

This two attributes could be solved first in this development. Blood composition will be solved on software side of the simulator in calculations [8] and demonstrated as extension of this hardware distribution.

2.5 Electronic equipment

The electronic equipment was assembled from different parts: the RT controller and measurement card with servo controller were taken from National Instrument (Austin, USA), linear motors and its servo drives have been ordered from LinMot (Spreitenbach, Switzerland). Signals are read into the PC through the RT system and shown graphically by a LabVIEW program. The set point trajectory, which the system has to follow, generates a given patient behaviour model derived from an individually specified Matlab script (Mathworks, Natick, USA).

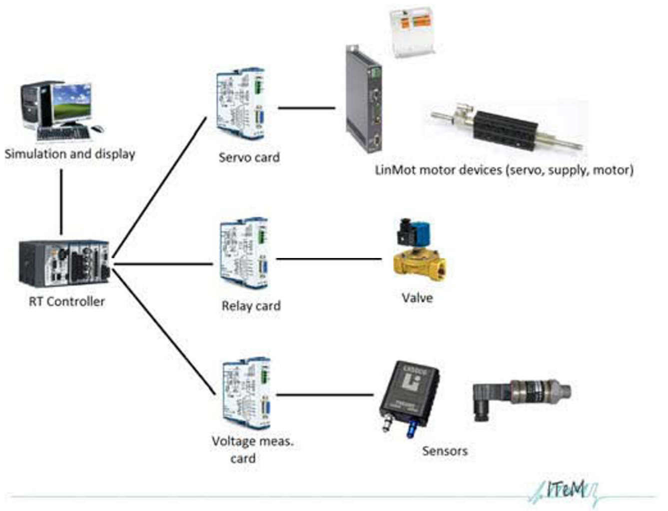

Figure 9: The electronic part required for the mechanical simulator setup. The real time controller (RT-controller) is programmed and updated via the PC, which implements the software patient simulation. The desired behaviour is achieved by addressing individual servo units of different motors (here only one shown, but in reality 5 other motors are used) through the NI servo cards. In addition, a number of valves are needed to control the airways and produce coughs and other reflexive reactions through the exchange model.

3. DISCUSSION

The presented simulator is a combination of different cylinder piston systems that enables a reproduction of several realistic gas exchange properties, in addition to the arbitrary mechanical properties of a patient's lung. After some attempts with a single cylinder piston system [7] were hampered by either sealing or friction problem, a new promising design is implemented. The dead space cylinder is working perfectly, but control regime of the interaction of another four components to reproduce a re-calculated response as in form of a PID or fuzzy extension model control still requires further developments and trials. The separation of tasks into different components as in a specialized cardiogenic oscillation module should simplify and stabilize the behaviour of the overall system.

The main limitation of the present study is its preliminary status, as it is mainly based on the concept and construction. Unfortunately real data are not yet available in mechanical experiments or in studies with simulated patient's pathologies. Further validation will use all five (number 7,1,2,5 and 6 cylinders in Fig. 5) modules operating in parallel still need to be conducted.

4. CONCLUSION

The proposed modularized setup offers a sophisticated way to simulate lung mechanics in mechanically ventilated or spontaneous breathing patients. Promising results in the construction show the potential of employing roll membranes as a sealing in cylinder piston systems that can be combined into anatomically oriented cylinder ensembles.

5. ACKNOWLEDGMENT

This study was partially supported by the National Ministry of Education and Research (WiM-Vent, Grant 01IB10002D. MOTiF-A Grant 1781x08), Draeger Medical, Lübeck and the German Foundation of Research (DFG, #MO 579/1-2).

REFERENCES

[1] S. Lozano, K. Moller, A. Brendle, D. Gottlieb, S. Schumann, C. A. Stahl, and J. Guttmann, "AUTOPILOT-BT: a system for knowledge and model based mechanical ventilation," *Technol Health Care,* vol. 16, pp. 1-11, 2008.

[2] J. Kretschmer, A. Wahl, and K. Moller, "Dynamically generated models for medical decision support systems," *Computers in biology and medicine,* vol. 41, pp. 899-907, Oct 2011.

[3] V. V. Meka and J. H. van Oostrom, "Bellows-less lung system for the human patient simulator," *Medical & biological engineering & computing,* vol. 42, pp. 413-8, May 2004.

[4] Z. Zhao, J. Guttmann, and K. Möller, "Adaptive SLICE method: an enhanced method to determine nonlinear dynamic respiratory system mechanics," *Physiological Measurement,* vol. 33, pp. 51-64, 2012.

[5] J. Arntz, D. Gottlieb, S. Lozano, J. Guttmann, and K. Möller, "Evaluation of an automated PEEP controller in mechanical ventilation support," in *ECIFMBE 2008, IFMBE Proceedings*, Antwerp, Belgium, 2008, pp. 1080-3.

[6] S. Lozano-Zahonero, D. Gottlieb, C. Haberthür, J. Guttmann, and K. Möller, "Automated mechanical ventilation: Adapting decision making to different disease states," *Med. Biol. Eng. Comput.,* vol. 49, pp. 349–358, 2010.

[7] J. Arntz, M. Schneider, J. Guttmann, and K. Möller, "Entwicklung eines aktiven Lungensimulators," *Biomed Tech*., vol. 55 (Suppl. 1), 2010.

[8] Kretschmer J, and Möller K., „A Hierarchical Model Family of Cardiovascular Dynamics" *5th European Conference of the International Federation for Medical and Biological Engineering 2011.*Budapest, Hungary