XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

THE HYBRID PNEUMATIC-NUMERICAL MODEL OF LUNGS – METROLOGICAL ASPECTS OF THE DESIGN

Kozarski M.[1], *Zieliński K*[1]*.*, *Pałko K.J.*[1], *Bożewicz D.*[2], *Darowski M.*[1]

[1] Institute of Biocybernetics and Biomedical Engineering PAN, Warsaw, Poland, mdarowski@ibib.waw.pl
[2] Institute of Precision and Biomedical Engineering Warsaw University of Technology, Warsaw, Poland

Abstract – The main purpose of this paper is presenting the new hybrid (pneumo-numerical) model of lungs as well as some results of its successful experimental examinations. This kind of models enables simulation of different lung properties including rheological and nonlinear features and may be also applied to develop different lungs mechanics measuring systems. The presented model design approach is based on the linear impedance transformation from the numerical to pneumatic signal environments.

Some metrological aspects of the model design and function are considered e.g. statical and dynamical accuracy of the impedance transformation.

The hybrid lungs model was experimentally verified in the typical respiration-model set-up evidencing its good dynamical and statical properties.

Keywords: Hybrid lungs model, impedance transformation, impedance transformation accuracy.

1. INTRODUCTION

Growing needs for better physical models of lungs mechanics are lately arising as a tool for development of new methods of lung assistance when the spontaneous patient respiration is supported. From this point of view the well known simple RC constant parameters analogue of the lungs mechanics are no longer sufficient. The lungs model should potentially enable introducing of different parameter nonlinearities, rheological properties of lungs and its surroundings. This kind of models may also be successfully applied to develop different measuring systems as far as identification of mechanical lungs parameters is concerned.

The main purpose of his paper is presenting of the new hybrid (pneumo-numerical) model of lungs, as well as results of experimental examinations. Also, some metrological aspects of the model design will be included e.g. accuracy of impedance transformation especially if problems of dynamic flow measurements are considered.

The presented model design approach is based on the linear impedance conversion [1] when an input "numerical impedance" of the electrical ladder network (existing as a computer program) is proportionally transformed into a pneumatic impedance found in the input pneumatic terminal of the model. The electrical network may contain any linear or nonlinear elements including electrical analogue of voltage and pressure sources simulating the spontaneous breathing of a patient.

The crucial element of the model is a voltage controlled flow source. In our design it is a pneumatic piston-cylinder system, where the piston is driven by an electromechanical gear-motor (MAXON RE75) combination. The flow produced by the moving piston is proportional to an input voltage of the motor controller.

2. MATERIAL AND METHODS

Electrical analogue of lungs mechanics presented in Fig. 1 are chosen from numerous now available models developed by many authors. The constant parameter RC model is widely used in clinical practice. The variable parameter RC and DuBois models (Fig. 1b) are not so popular mainly because of problems connected with model parameter measurements and identification in clinical situations [2,3,4]. Nevertheless the hybrid pneumatic-numerical model should allow to take into account this higher level of model complexity.

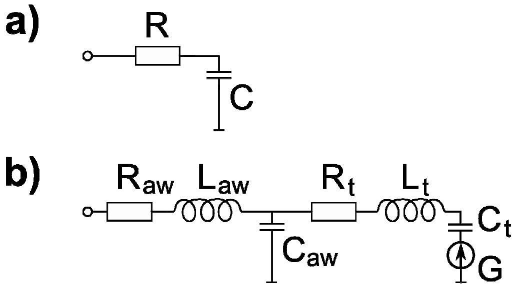
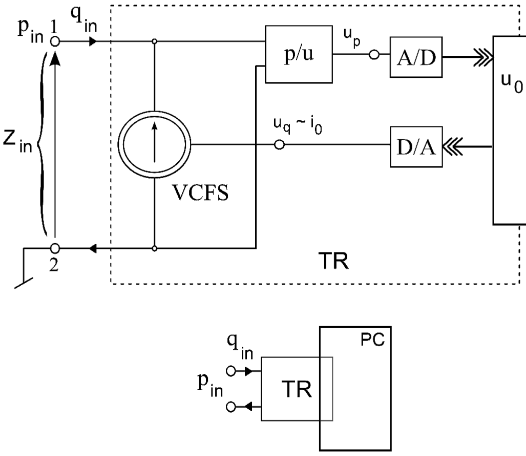


Fig. 1. Symbolic electrical representation of exemplary mathematical lungs models: a) RC model, b) DuBois model

Our design approach to this demand is presented in Fig. 2. It shows a general idea of the hybrid numerical-to-pneumatic impedance transformation. Input pressure p_{in} is proportionally transmitted ($u_p \sim p_{in}$) from the input pneumatic terminal (as input voltage u) to mathematical equations describing lungs behavior. Resultant current i_0 obtained as a numerical solution of these equations is sent as input voltage $u_q \sim i_0$ for voltage controlled flow source VCFS. So obtained input pneumatic impedance $Z_{in} = p_{in}/q_{in}$ is proportional (k_u, k_q coefficients) to impedance $Z_0 = u_0/i_0$

ISBN 978-963-88410-0-1 © 2009 IMEKO

representing static and dynamic properties of the mathematical lungs model.



$$q_{in} = k_q \cdot i_0$$

$$u_0 = -k_u \cdot p_{in}$$

$$Z_{in} = \frac{p_{in}}{q_{in}} = \frac{1}{k_q k_u} Z_0$$

Fig. 2. The hybrid pneumo-numerical transformer

VCFS may be realized in many ways. In our case this is the piston-type design presented in Fig. 3 as the physical part of the whole hybrid model of lungs. The numerical part of the lungs model is based on the DuBois model from Fig. 1b with distinguished the airway (R_{aw}, L_{aw}, C_{aw}) and tissue (R_t, L_t, C_t) sections along with a spontaneous breath generator p_{sb}. The numerical and physical parts are connected by A/D and D/A converters according to the hybrid transformation idea shown in Fig. 2.

The described VCFS has many advantages as compared to other designs (e.g. with analog electro-pneumatic diverting valves). First of all, it eliminates problem connected with dynamic flow measurements as the motor driven piston itself may be treated as an accurate flow standard. The accuracy of this flow generator mainly depends on accuracy of angular speed n measurement error. In the discussed case it is less than 0.5% of the actual *n* value. This is guarantied by the applied tacho-generator (Hübner GTL-5). Errors introduced by variations of cross-section area A of the piston-cylinder combination are negligible as compared to the tacho-error. The same touches the error introduced by lead variations of the ball-screw drive. So, the resultant error of VCFS is less than 0.5% what is acceptable for the discussed application. The next considerable source of a model error is pressure transducer p/u. For small temperature variations (25°C±10° characteristic for typical laboratory situation) the pressure transducer error is also smaller than 0.5% so the resultant error of the impedance transformation is assessed as following:

$$\frac{\delta Z_{in}}{Z_{in}} < \frac{\delta p_{in}}{p_{in}} + \frac{\delta q_{in}}{q_{in}} < 1\% \tag{1}$$

In the hybrid model there is also an opportunity of direct measuring of lungs volume variations. It is performed by the linear variable differential transformer (PELTRON PJZ150). The volume measurement error is also less than 0.3% in the whole range of volume variations.

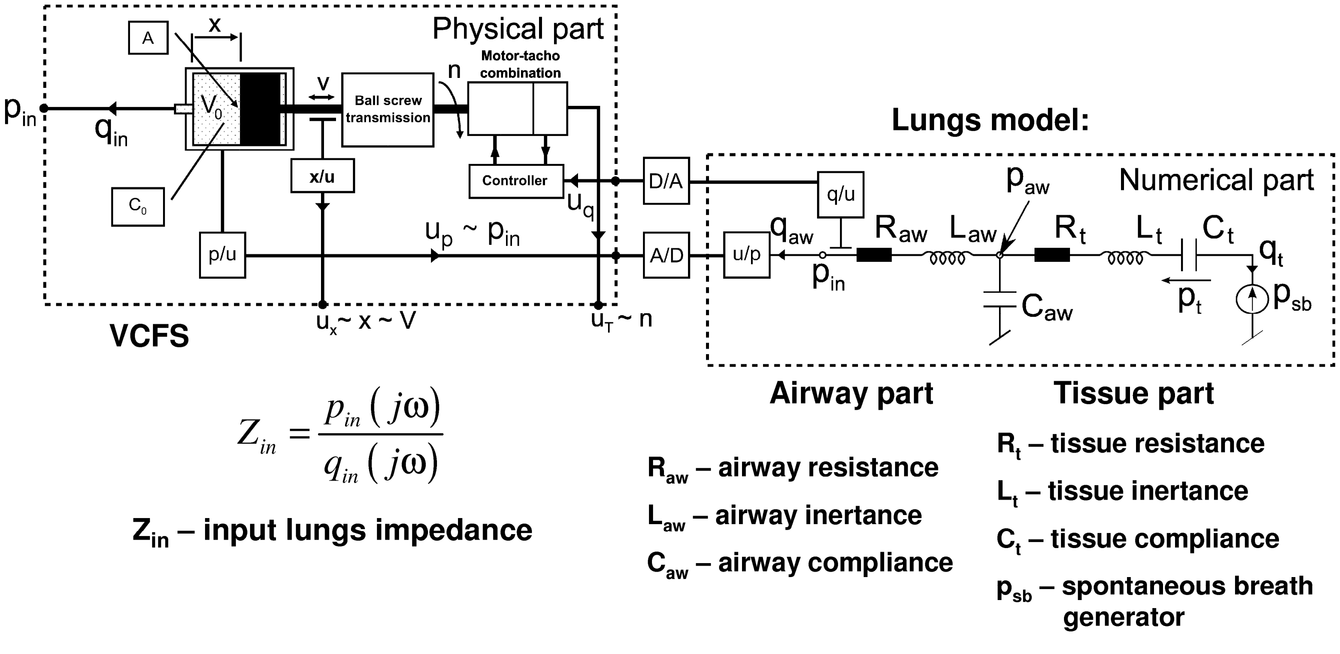


Fig. 3. The hybrid lungs model, $q_{aw} = q_{in}$

A dynamic properties of *VCFS* are remarkable. A time constant of the piston motor system response to the input step voltage is less than 1ms what is much better than is really needed in low frequency respiratory applications.

The low frequency lung ventilation , practically never exceeding 1Hz value is the predominant method of treatment in typical clinical situation. To represent perfectly flow and pressure traces found in the patient – respirator system it is enough to take into account higher harmonics up to 16th harmonic of the basic frequency. It means that the hybrid lung model reproducing dynamic flow phenomena in the 100Hz frequency range may be found as dynamically errorless for most of the respiratory applications.

The piston-based hybrid lungs model presented in Fig. 3 among many advantages has one functional limitation connected with volume V_0 of the cylinder chamber. This chamber is necessary to make possible bidirectional movements of the piston. On other hand it represents some time-variable pneumatic capacity C_0 actually existing in the system and may be expressed by the following equation

$$C_0 = \frac{V_0}{n_p \cdot p_a} \tag{2}$$

where

- n_p – politropic exponent,
- p_a – average absolute pressure in the cylinder.

The point is frequency dependence of the politropic exponents as the variability range is considerable (for air $1 \leq n_p \leq 1.4$). Volume variations cause pressure variations what brings about gas temperature changes. The pressure field is shifted in phase regarding the temperature field. These relations are mathematically complicated (expressed by Bessel functions) and can be analytically expressed only for simple chamber shapes. But there is one practical indication allowing to asses whether the real problem may by expected. It is based on the Womersley number α_W calculations:

$$\alpha_W = \frac{d}{2} \cdot \sqrt{\frac{\omega}{\nu}} \tag{3}$$

where

- d – characteristic dimension (the smallest linear diameter),
- ω – circular frequency of volume variations,
- ν – kinematic gas viscosity.

For $\alpha_W < 1$ the thermodynamic gas process may be treated as isothermal while $\alpha_W > 100$ the adiabatic process can be assumed. For $3 < \alpha_W < 20$ the strong frequency dependence of the n_p may be expected.

The capacitance variability itself does not presents the real problem because it well corresponds with natural lungs airway capacitance component C_{aw} variability and so may be easily taken into account.

3. LABORATORY EXAMINATIONS

The previously discussed hybrid model was tested in the typical respirator-model set-up presented in Fig. 4 where Nellcor Puritan Bennett 840 ventilator was applied working at the constant pressure mode of operation.

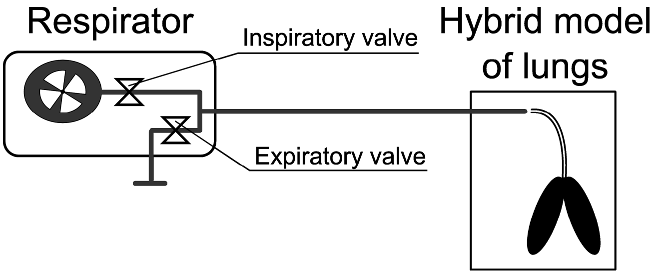


Fig. 4. The model-respirator experimental set-up

Exemplary flow and pressure traces in different points of the examined system are shown in Fig. 5. They evidence good dynamic and static properties of the lungs model observed as its flow response to small pressure noise generated by the ventilator. This effect is even better visible in equivalent spirometric loops presented in Fig. 6 where volume *V* is directly calculated from displacement *x* of the piston.

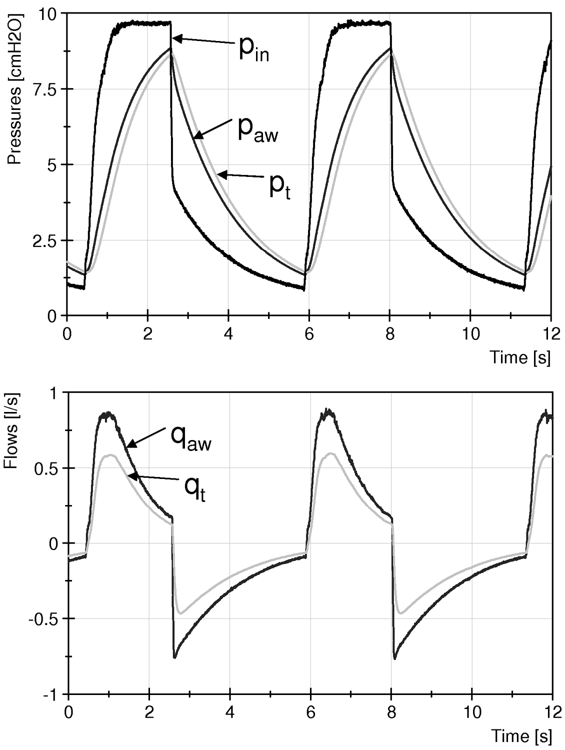


Fig. 5. Pressure and flow traces

Spirometric loops are of the first importance for physicians allowing many diagnostic conclusions but they make also possible to asses performance of the ventilator.

For example, the upper part of the volume-flow (V-q_{aw}) loop from Fig. 6a allow to say how fast is the expiratory valve of the ventilator. The horizontal line evidences good dynamic features of the valve. Next, the linearity of the left part of V-q_{aw} trace allow to asses the resultant expiratory resistance $R_{resultant}$ containing both the valve and model components.

Pressure-volume loop (Fig. 6b) gives basic information on energetic aspects of the lung ventilation as its area represents energy delivered to the lungs.

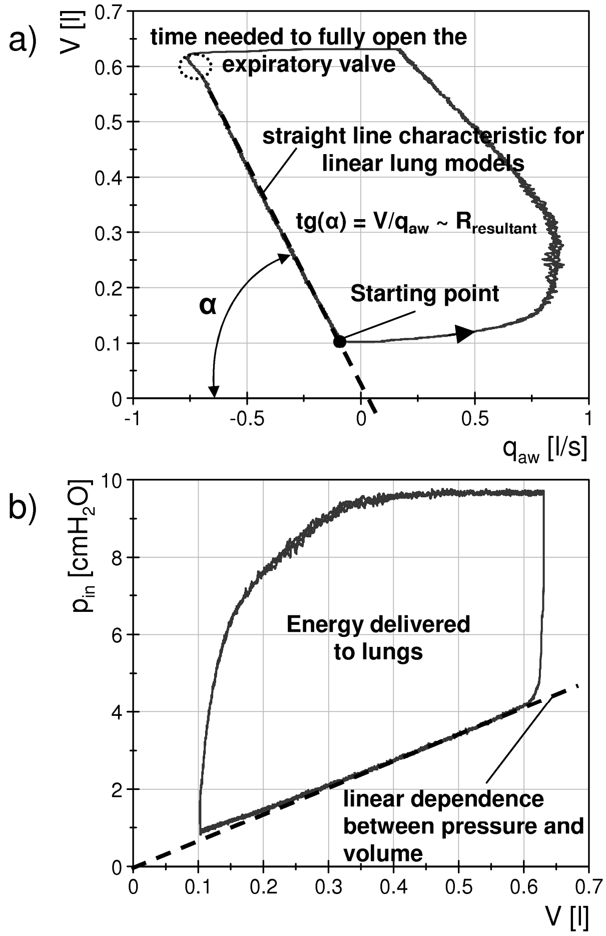


Fig. 6. Spirometric loops

The exemplary traces presented in Fig. 7 evidence the characteristic changes of input pressure p_{in} (Fig. 7a), input flow q_{aw} (Fig. 7b) and volume V (Fig. 7c) when airway resistance R_{aw} varies. The characteristic steep pressure decrease can be observed (Fig. 7a) as a function of the resistance value variations.

The flow courses from Fig. 7b confirm conclusions as far as very good dynamical properties of the hybrid model of lungs are concerned. The expiratory flow decreases to the maximum negative value immediately.

Volume traces from Fig. 7c are typical: what should be here pointed out is their high metrological quality thanks to direct volume measurements possible with the piston displacement transducer not influenced by noises generated in the respirator-model system.

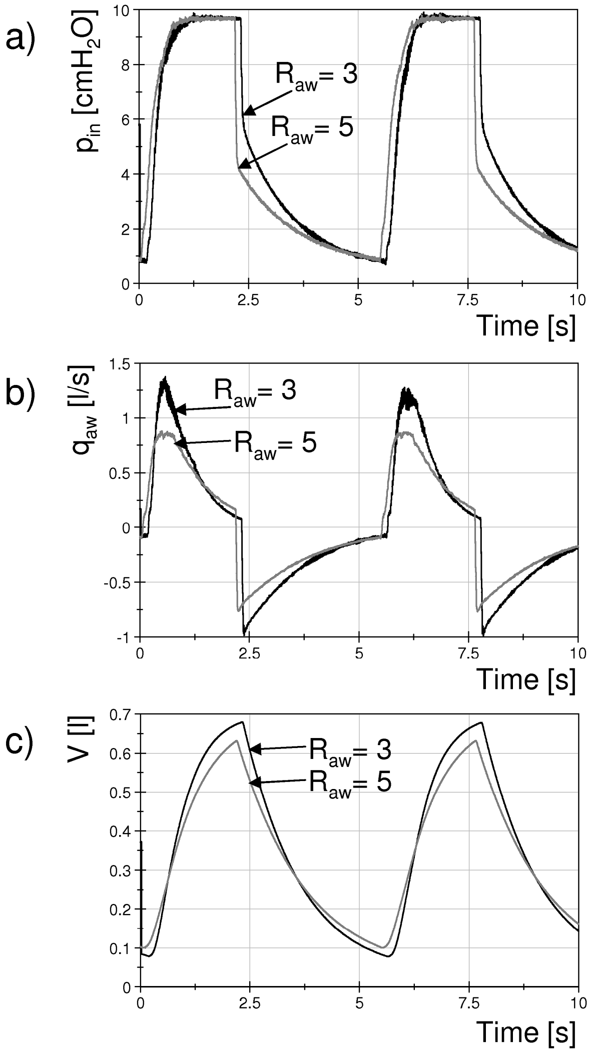


Fig. 7. Pressure (a), flow (b) and volume (c) traces for different airway resistances: R_{aw}=3 [cmH_2O*s*l^{-1}] and R_{aw}=5 [cmH_2O*s*l^{-1}]

The whole laboratory set-up is shown in Fig. 8. The respirator connected with the hybrid piston-cylinder model of lungs is clearly visible.

4. DISCUSSION AND CONCLUSIONS

Laboratory examinations proved very good statical and dynamical properties of the presented hybrid model of lungs.

The presented here design approach, consisting in extraction of a model section playing a role of the impedance converter, allows to transform signals from the numerical environments into the pneumatic one which makes possible direct connection of medical devices e.g. lungs ventilators.

Accuracy of the impedance transformation for large pressure and flow signal is better than 1% and is limited mainly by accuracy of motor rotational speed (0.5%) measurements. The motor-speed transducer applied in the hybrid model has been chosen as a compromise between requirements of acceptable accuracy of motor speed measurements and good dynamical properties. The tachometric transducer seems to be nearly perfect in this application. The resultant error including thermal drift in lab conditions never exceeded 0,5% of the current speed. It dynamical features are also considerable (passband > 16kHz). But what is especially important, there is practically no zero-voltage drift. Thanks to a low displacement drift can be reduced to value below of 1mm/hour.

Complexity of the applied mathematical model of lungs is constrained rather by physiological knowledge on lung function and possible identifying of its mechanical parameters than by technical limitations.

The hybrid models of lungs are flexible, accurate and enable modeling of complex mechanical lungs structure and function what is necessary to simulate different pathological pulmonary conditions and to check a new methods of lungs ventilation and new diagnostic tools.

The hybrid models seem to be sufficiently accurate to eliminate numerous “in vivo” experiments with lab animals.

Fig. 8. Laboratory set-up of the hybrid model of lungs

ACKNOWLEDGMENTS

This work was financed by the grant No. N R13 0032 04 in years (2008-2010) from the Ministry of Science and Higher Education of Poland.

REFERENCES

[1] M. Kozarski, K. Zieliński, K. J. Pałko, B. Stankiewicz, D. Bożewicz, M. Darowski, “The new hybryd pneumo-electrical piston model of lungs mechanics – preliminary tests”, *Biocybernetics and Biomedical Engineering,* (in print).

[2] A. G. Polak, J. Mroczka, “A simplified model for airflow in the bronchial tree”, *Proceedings of the 7th International IMEKO TC-13 Conference on Measurement in Clinical Medicine “Model Based Biomeasurements*”, pp. 3-6, Stara Lesna, Slovakia, Sept. 1995.

[3] D. W. Kaczka, G. M. Barnas, B. Suki, K. R. Lutchen, “Assessment of time-domain analyses for estimation of low-frequency respiratory mechanical properties and impedance spectra”, *Ann. Biomed. Eng*. vol. 23, pp. 135-151, 1995.

[4] K. R. Lutchen, K. D. Costa, “Physiological Interpretations Based on Lumped Element Models Fit to Respiratory Impedance Data: Use of Forward-Inverse Modeling”, *IEEE Interactions on Biomedical Engineering*, vol. 37, nº. 11, pp. 1076-1086, 1990.