Synthesis of the Structure of the Respiratory System in Forced Expiration

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Abstract. *In computational simulation (with MATLAB) RLC lung model was synthesised. The authors of this report presented how sensitive is model form of the conditions of modelling: start point and procedures that select the curve-parameters, according to minimum mean-square error criterion.*

Keywords: respiratory system, modeling

1 Introduction

Main part of the respiratory system - the lungs - is built of two types of elements: bronchial tree and alveolar bags. They are characterised by physical features: gas flow resistance *R* concerning the respiratory ducts, compliance *C* of alveolar wall and gas inertia *L* covered in both them.
The structure of the lungs is more complicated, independently of the region between trachea and the last alveolar bag. All these elements play important role during whole forced expiratory process.
Two elements: gas flow resistance *R* and compliance *C* of alveolar define lung time constant $\tau = RC$. Its value changes in different kinds of the respiratory system defects [1], [2].

2 Metter of the forced expiration

The respiration is the process in which the air flows between lungs and environment going through airways from/into alveolar bags. The forced expiration is a special kind of breathing. During it a patient inhales a great amount of gas into his lungs and then expires it immediately with a great force, generating maximal flow velocity. In this way he prepares on his respiratory center in the brain the impulse that creates pressure jump (a unit step function). The lungs are pressed and the gas flows outside [2]. Such lungs answer plays important role during the respiratory system diagnosis (Fig. 1).

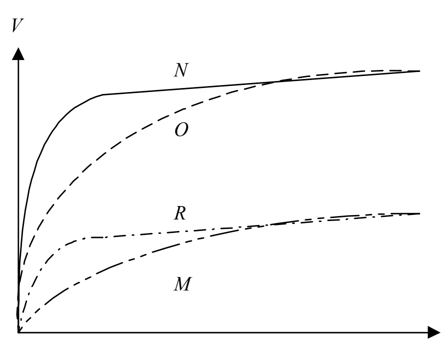


Fig. 1. The answer *V*(*t*) of the respiratory system during forced expiration: different states for healthy lungs and in pathology. *N* - normal, *O* - obstructive, *R* - restrictive, *M* - mixed (obstructive and restrictive)

Healthy patient quickly expires a great amount gas. In obstructive case the gas flows slowly and time constant τ grows, similarly like for a mixed respiratory system defect. In restrictive case the patient expires less gas volume.
The time constant τ is usually big when only the flow resistance of airways grows. The forced expiration can disclose it when only the exciting signal (in analogy to the electronic *RC* serial circuit), has form of jump (Heaviside's step function) [3]. When not, the conclusions about the respiratory system state can be unreal.
This is the reason that in forced expiration the exciting signal should be known precisely.

3 Synthesis of the respiratory system model

In analysis, presented here, the assumption was made that the exciting pulse $E_Q(t)$ is narrow, with time duration was less then 0.2 second. The general structure of modelled system is similar to low-pass filter with real poles [4], [5]. The structure of the system is presented on Fig. 2A.

In the circuit synthesis six different configurations of the serial forms of one-port boxes were used: **1** - three *RC*-parallel sections, **2** - three *RL*-parallel sections, **3** - two *RC*-parallel and one *RL*-parallel sections, **4** - two *RL*-parallel and one *RC*-parallel sections, **5** - one *RC*-parallel) and *RLC* (configuration presented on Fig. 2.B), **6** - one *RL*-parallel and *RLC* (configuration presented on Fig. 2.B.

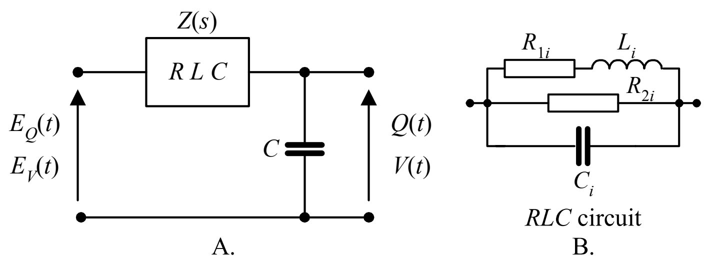


Fig. 2. A - The electrical model of the respiratory system. Remarks: $E_Q(t)$ i $E_V(t)$ – unknown excitation, generating flow and volume curves $Q(t)$ and $V(t)$ respectively; B - Elementary section *RLC* used during the respiratory system synthesis

The block *RLC*, depicted on Fig. 2.A had a special form. It was built of structures serially connected by the above **1 ÷ 6** configurations, always with the resistor R_0. At the beginning of simulation the excitation signal $E_Q(t)$ had a form of rectangular pulse. It changed its form in final stages (V, VI, see Table 1) of transmittance coefficients definition for model.

Table 1. The results of the respiratory system modelling; an example

The stage of synthesis	The characteristic of the circuit	Δ [%]
I	One pole	2.65
II	Two poles	1.68
III	Three poles	1.48
IV	Four poles	1.47
V	Four poles; the first corrections of the excitation signal and model parameters	0.23
VI	Four poles; the second corrections of the excitation signal and model parameters	0.23 (comparing with stage V - not visible differences)

The simulation started from the easiest form of the model (one-pole transmittance function). It was the basis for the next step of modelling. In this way the second-order circuit was found, with two-pole transmittance function. This model was the basis for the next step of synthesis. For finding V and VI solutions the form of excitation signal was changed.

During every calculation the "shake" method was used. It means that for each model, calculated values of parameters for the first model (with the use of MATLAB program) was changed a little and calculating procedure started at the beginning. For some repeated simulations this solution was accepted for which mean-square error defined like

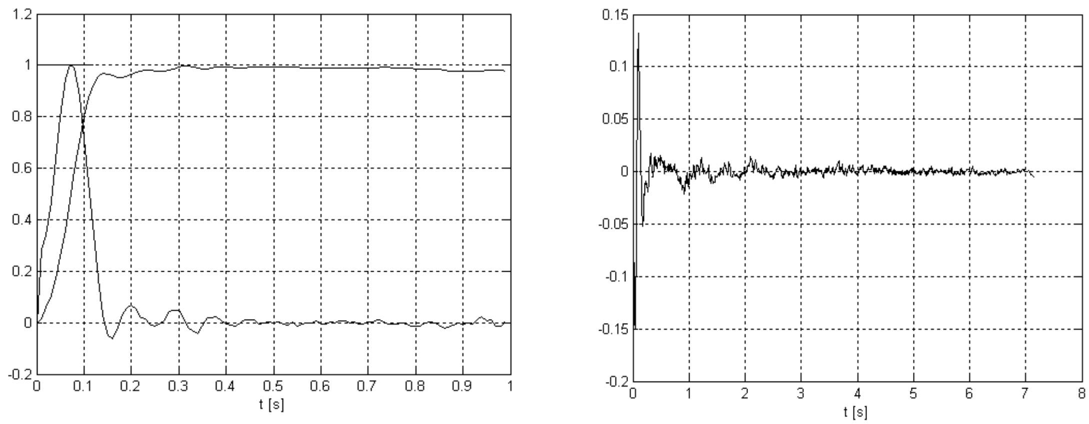
$$\Delta = \sqrt{\frac{\sum_{i+1}^{N} \left[Q(i\,T) - Q_i^m \right]^2}{N}} \tag{1}$$

where: N - number of samples, i - number of current sample, T - sampling period (here: $T = 0.01$ s), $Q(i\,T)$ - $i^{\text{-th}}$ sample of flow velocity value, Q_i^m - $i^{\text{-th}}$ sample of modelling flow velocity, had the minimum value.

The more complicated circuits could have different forms. For limitation of circuits' proposition the assumption was made, that synthesised *RLC* model should have positive values of elements and fulfil the conditions and residues, Re $z_i > 0$.

4 Synthesis results

All calculations were made with using of MATLAB program. The most interesting exciting signal had the form presented on Fig. 3, 4. Looking for it the minimisation Δ error (1) was taken into consideration.



A. B.

Fig. 3. A - The forms of the exciting signals (all normalised) used during a model synthesis: generating flow volume $Q(t)$ signal response and volume signal $V(t)$ for stage VI. $E_V(t) = \int_0^t E_Q(\tau)d\tau$, similarly like $V(t) = \int_0^t Q(\tau)d\tau$; B - The greatest differences $(Q(i\,T) - Q_i^m)$, concerning of the flow velocity $Q(t)$ modelling for four-pole function transmittance, for rectangular excitation pulse

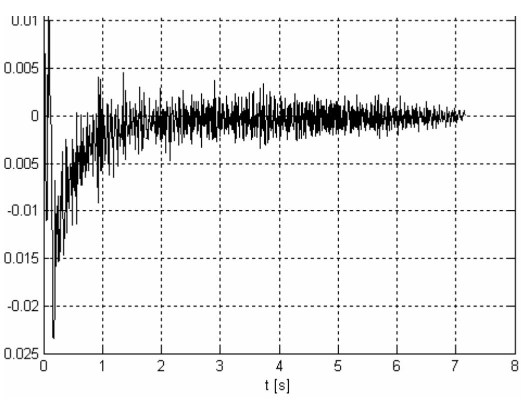


Fig. 4. The greatest differences $(Q(i\,T) - Q_i^m)$, concerning of the flow velocity $Q(t)$ modelling for four-pole function transmittance, for VI stage

5 Conclusions

During the respiratory system modelling in forced expiration the different structures should be taken into consideration. The important role in identification of *RLC* structure of the lungs plays the form of the excitation signal. Both: *RLC* circuit and excitation signal was chosen here.

The final results of synthesis are presented in Table 1 and on Fig. 5.

The biggest error 2.65 % is for the first form of synthesised circuit, built only of *RC* circuit (the most popular model and most frequently used). The important changes of error value have been obtained in second and fifth stage. In the first case the structure of the model was changed from the first to the second order circuit. In the second case the excitation signal had been changed as well.

The results confirm that the synthesis was carried out correctly, and starting point was well chosen for the higher degree models.

In the end of simulation it must be pointed that the obtained final form of exciting signal is similar to the natural, which was measured experimentally in a real object.

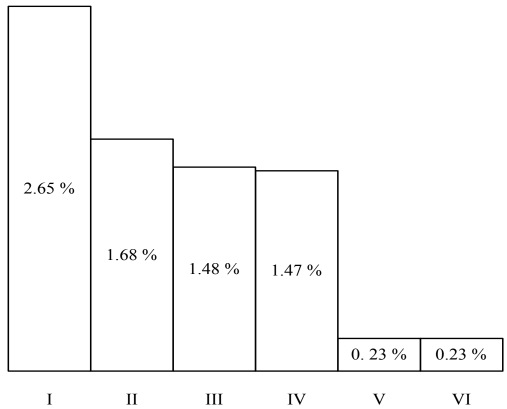


Fig. 5. The error concerning of six stages of the respiratory system synthesis

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