Kamil JAKUSZKIN
Wrocław University of Technology, Chair of Electronic and Photonic Metrology

Verification of properties of artificial ventilation device using ball screw drive transmission

***Abstract**. Author of the paper conducted a series of multiple test scenarios in order to verify properties of modified mechanical ventilation device with ball screw drive transmission. The apparatus was tested under various conditions including some popular respiratory system measurement methods, results showing its repeatability and stability of generated airflow patterns were presented. In conclusion, author indicated on direction of future work concerning tuning and corrections in drive setup.*

***Streszczenie.** Autor przeprowadził szereg eksperymentów mających na celu weryfikację własności modułu sztucznej wentylacji wykorzystującego śrubowe przeniesienie napędu. Moduł zbadano pod względem powtarzalności oraz stabilności generowanych wzorców przepływu oraz wskazano problemy i kierunek przyszłych korekt w pracy układu.(**Badanie właściwości modułu urządzenia do wentylacji mechanicznej ze śrubowym przeniesieniem napędu**).*

Keywords: artificial ventilation, respiratory system resistance
Słowa kluczowe: sztuczna wentylacja, opór układu oddechowego

Introduction

In order to understand the complexity of human respiratory system, one must realise its importance and function in maintaining organism's vital functions. Continuous and proper gas exchange determines the work of all organs and tissues, including neural system, which is particularly sensitive for homeostasis disturbances. The complex structure and mechanics of the respiratory system result from its superb effectiveness [1, 2]. Even severely damaged lung tissue is capable of supporting life. Proper function of the respiratory system may be compromised by pathological changes which must be identified and treated properly. There are several popular diseases which cause irreversible changes in lungs, although, accurately diagnosed, they are manageable. The most popular case is COPD (Chronic Obstructive Pulmonary Disease) commonly caused by chronic tobacco smoking [3, 4]. Respiratory system complexity produces the need of detailed analysis of its function in order to achieve a good estimation of changes in multiple compartments. Proper estimation grants a fair chance to create correct response for occurred conditions. Many measurement techniques have been developed in order to improve the knowledge. For the purpose of this paper author concentrated on those, which are utilized during mechanical ventilation. The suffering of the treated patient is minimized by incorporating procedures which mainly involve passive measurements of pressure and volumetric airflow in mouth area (proximal part of respiratory system). Produced results are used for evaluating various indexes [5], control feedbacks for mechanical ventilators and also real time data [6, 7].

Modern ventilators provide wide range of scenarios and modes [8]. There is a trend towards avoiding controlled ventilation modes (the whole breathing work is done by machine) and leaning to supported modes which are more natural and less risky from physiological point of view. Hardware realization of most positive pressure ventilators include using of flow patterns and feedbacks that shape gas portions according to current patient needs, programmed routines, and borderline conditions [9, 10].

The aim of the paper is to present designed and assembled drive which is capable of providing various flow patterns. The analysis of generated signals was made. Constructed ventilator unit is a part of the multi-method setup for measurements of respiratory system mechanics. Several test scenarios were conducted in order to depict capabilities and limitations of featured apparatus. Acquired data was processed and conclusions were shaped. All tests involved presence of test objects [10, 11] ranging from simple parabolic resistors through precise calibration elements to more complex lungs mechanical model (artificial lung: Dual Adult PNEUVIEW 5600i by Michigan Instruments). Test scenarios involved utilization of simple square and ramp flow patterns with modifications, some of which incorporated flow interruption [12, 13, 14] as well as Optimized Ventilator Waveform (OVW) [15, 16].

Methods: Hardware overview

Recently assembled drive transmission device is an evolution of previous ventilator, described in [17]. New construction includes several elements:

- ball screw with pitch of 20 mm and cap in order to shift rotation into linear motion of the piston
- a set of two linear guideways consisting of bearing block and rail applied for stabilizing the screw,
- precise piston with volume of 2 dm^3 as flow pump,
- SM 86-80 stepper motor with M542 microstepping driver and power supply,
- miscellaneous elements, i.e. connectors, couplings and bearings.

Stepper motor with 200 steps per revolution is capable of generating maximum torque of 4.5 Nm which is sufficient. Driver was adjusted to produce flow ranges up to 2 dm^3s^{-1}. The function of the system is actuated and governed by PCI data acquisition card programmed in LabView environment. Actual prototype is a part of multi-method setup for measurements of respiratory system mechanics and serves as flow patterns generator in mechanical ventilation routine as well as part of other researched measurement methods. The mechanism needs to meet requirements concerning the method and precision of drive transmission, oscillations reduction and precise volume application. Precise piston setup with maximum volume of 2.20 dm^3 and diameter of 15.00 cm is capable of generating volume portions of 1.77 cm^3 per motor step.

Methods: Flow pattern generation

In order to test function and repeatability of designed apparatus, several tests and routines have been prepared. The first step was generation of control signals for motor and valve [18]. Author used Matlab environment. Patterns were sampled with 1 kHz. Signal level was scaled to meet control application conditions and sets of various shapes were generated. Two basic groups of patterns included constant flow with linear volume rise (Fig. 1) and increasing flow (linear rise). For experimental needs, rise/fall times of flow Q varied from 1 ms (single sample step) to 750 ms (end-of-inspiration pause halftime). Interrupter pattern *Int* shows moment of flow occlusion for 100 ms and its synchronisation with the end of inspiration. *Int* signal was used only in particular test scenarios. Presence of flow interruption during breathing influences on volume levels provided into test object. Model volume V must be corrected by changes in expiration time in order to acquire zero volume *Vcorr* at the end of expiration.

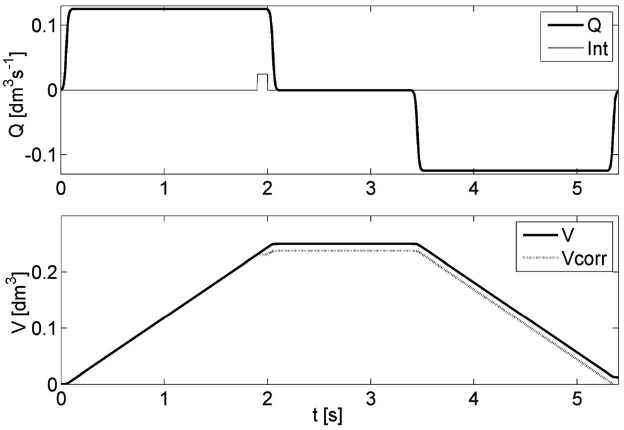

Fig.1. Flow and occlusion patterns and corresponding volume signals

In order to test system in dynamic conditions optimised ventilator waveform (OVW) [15] pattern was generated.

Results

Due to measurement conditions and apparatus function, all recorded signals were biased by noise originated from step work of the motor and slight vibrations of the transmission. Mechanical interferences were visible and particularly visible for low airflow values. In order to clear acquired data automatic de-noising algorithm was incorporated. Author performed wavelet decomposition using Daubechies 'db3' wavelet with soft thresholding [19] and signal reconstruction with modified detail coefficients. Data processed by described operation (Fig. 2) was further researched.

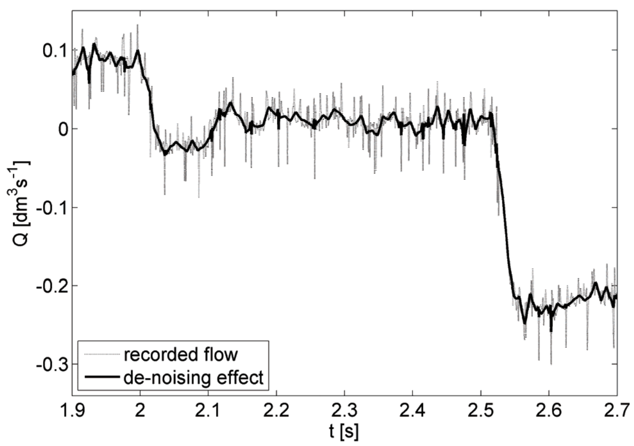

Fig.2. Effect of de-noising algorithm used on flow signal

Proper results conditioning provided base material for the following analysis.

In order to verify the accuracy and ranges of generated signals under specified conditions, several tests using passive resistive elements were conducted. As a test object, author used flow dependant resistor with parabolic characteristic. Resistor symbol *Rp20* achieves its nominal value of 20 cmH_2O/dm^3s^{-1} (1.96 kPa/dm^3s^{-1}) upon flow value of 1.08 dm^3s^{-1}. Researched resistor was tested under range of constant flow patterns generated according to previously described manner (Fig. 1). Resistance was calculated as the ratio of generated pressure change ΔP (in relation to atmospheric pressure) to flow value Q that induced that change.

$$R = \frac{\Delta P}{Q} \quad (1)$$

where: R – resistance, ΔP – static pressure drop, Q flow value [20].

Resistance calculation included averaging a set of 1500 samples representing static inspiration conditions. Results are presented in Table 1 and show its flow dependence.

Table 1. Recorded resistances of *Rp20* for corresponding flow values

Flow value Q [kPa/dm^3s^{-1}]	Mean resistance R [kPa/dm^3s^{-1}]
0.01	0.23
0.03	0.10
0.09	0.16
0.49	0.84
0.95	1.88

Analysis showed, that error of resistance estimation also depends on flow rate (Fig. 3). Relative error value was set as double SD calculated form each of recorded signals (pressure – circle marker, flow – triangle marker). Relative resistance error can be treated as sum of above mentioned errors. Figure 3 shows, that resistance error value for flow under 0.1 dm^3s^{-1} is greater than 100%. This state can be explained by the fact, that treated resistive element is unable to generate proper pressure drops for certain flows. Error value rapidly decreases and for flow values greater than 0.28 dm^3s^{-1} settles on less than 20%, which is satisfying from experimental point of view. During zero flow conditions (Fig. 2) step work of motor is clearly visible. Such state was necessary to keep positive pressure values during end-of-inspiration pause.

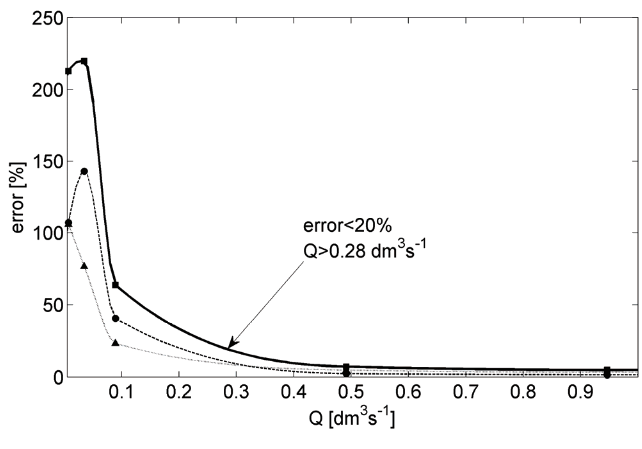

Fig.3. Relative error values for *Rp20* resistance in function of flow (pressure component – circle marker, flow component – triangle marker, resistance error – square marker)

Similar analysis was done for linear type calibration resistor. Resistor symbol *R5* has declared linearity within flow ranges up to 2 dm^3s^{-1} with 20% inaccuracy. In order to test the ventilator within wide flow ranges, a series with ramp flow patterns was conducted. The experiment included 10 measurement series with 5 full respiratory cycles, each. Every cycle was actuated by ramp pattern rising up to maximum flow value of 0.5 dm^3s^{-1}. In this case each resistance value was averaged upon respiratory cycles within one series to show repeatability of generated patterns. Table 2 presents resistance values evaluated from 1500 sets of samples of linearly rising inspiration fragment. Exponential fit was done in order to depict error trend. The mantissa of each exponent was treated as maximum error for each series.

Table 2. Resistances of *R5* for corresponding measurement series

Series number	Mean resistance R [kPa/dm^3s^{-1}]	Maximum relative error [%]
1	0.4807	17.94
2	0.4851	22.12
3	0.4882	19.32
4	0.4906	20.18
5	0.4863	18.55
6	0.4870	24.34
7	0.4830	19.83
8	0.4842	21.85
9	0.4817	28.12
10	0.4782	26.74

Resistance *R5* shows minor flow dependence what is presented on Figure number 4. The work of used test object *R5* enables testing for wide range of flow values, and in particular, for values lower than 0.2 dm^3s^{-1}. From experimental point of view it is very valuable ability which improved knowledge on system behaviour near desired borderline conditions. Recorded data suggest that even for very low airflow, evaluated resistance is valid, which indicates on correct and repeatable pattern generation in wide parameter range.

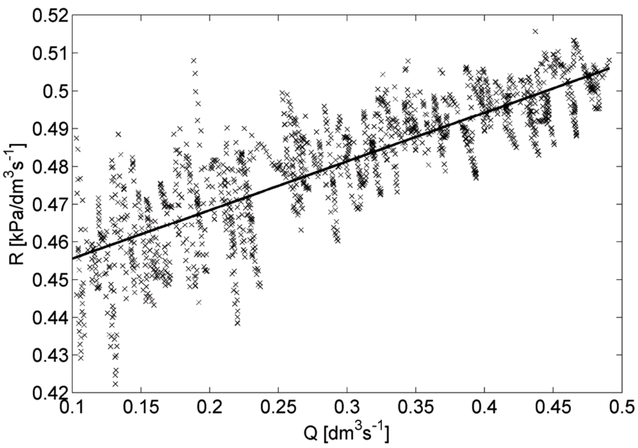

Fig.4. Changes of resistance of *R5* resistor in function of flow (solid line - linear fit, x markers – sample errors)

Relative error analysis showed, that standard deviation is not greater than 15% for wide range of flow values (Fig. 5). Even for low values of volumetric flow stable pressure drops were generated for each series. Maximum error for single samples never exceed the point of 30% which is consistent with device calibration certificate. The ability of providing precise portion of gas volume was observed. Theoretical error estimated for each measurement series upon exponential fit evaluation precisely describes trend towards lower values within wide flow ranges.

Flow values greater than 0.5 dm^3s^{-1} for constant flow patterns were generated with mean sample error lesser than 5%, which indicates on high repeatability. During flow changes an observation has been made showing that there are several regular oscillatory distortions for expiration phase. These oscillations can be described as an effect of resonance of the ball screw with the mounting plate. Similar effects were observed in later experiments.

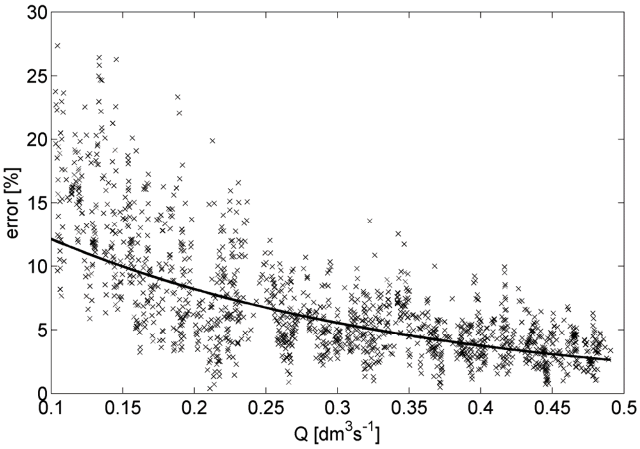

Fig.5. Relative error values for *R5* resistance in function of flow (solid line - exponential fit, x markers – sample errors)

Designed ventilator apparatus was tested under complex conditions. Author generated OVW flow pattern, which is an evolution of Forced Oscillation Technique. The OVW experiment included creation of dynamic flow pattern consisting of seven cosine functions that meet 'non-sum non-difference' (NSND) condition [15]. The executed experiment was to show repeatability and stability of airflow in case of floating amplitude. Five series of full OVW measurement cycles were recorded.

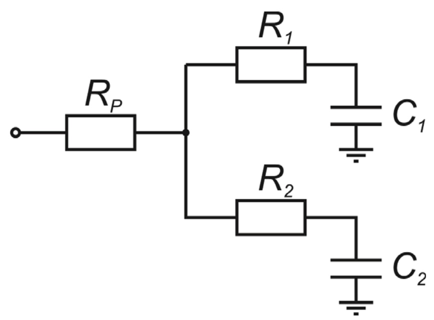

Fig.6. Electrical analogue of 'healthy' lung mechanical model (R_P=*Rp5*, R_1=R_2=*Rp20*, C_1=C_2=0.5 dm^3kPa^{-1})

Mechanical lung adjusted to 'healthy' condition [21] was used as test object which implicated utilization of parabolic resistors and springs (modelling lung compliances C_1 and C_2). Mechanical model can be modelled [22] as simple electrical analogue (Fig. 6) consisting of two parallel branches (lungs) and one proximal resistance (upper airways). Resistive elements *Rp5* and *Rp20* are parabolic resistors with nominal values of 5 cmH_2O/dm^3s^{-1} (0.49 kPa/dm^3s^{-1}) and 20 cmH_2O/dm^3s^{-1} (1.96 kPa/dm^3s^{-1}) respectively. Results show, that flow generator is repeatable (Fig. 7). Averaged signals were confronted with absolute error in form of envelopes. Detailed flow data shows that flow distortions are at level of 5% and less. Pressure signal error is not greater than 15% which indicates on interferences originated from tested object.

In order to estimate flow and pressure measurements accuracy, an experiment using constant flow patterns and 'healthy' mechanical lung was conducted. Author generated a respiratory pattern including rapid flow interruption realized by occlusion valve embedded with pressure sensor (Fig. 1). Two series of five respiratory cycles with different tidal volumes (0.5 dm^3 and 1.0 dm^3) were commenced.

Relative error, calculated as median of doubled SD, is presented in Table 3. Median function proved to be useful from numerical calculations point of view, because of near zero flow values during end-of-inspiration phase. During high flow scenario, pressure relative errors were greater, especially in the beginning and the end of each cycle. This issue is highly repeatable and can be explained by unwanted oscillations originated from test object recoil pressure response (which was not observed during simple resistor experiment).

Table 3. Measurement errors for different gains of flow pattern

Tidal volume *Vcorr* [dm^3]	Pressure relative error [%]	Flow relative error [%]
0.5	3.86	8.34
1.0	14.55	3.77

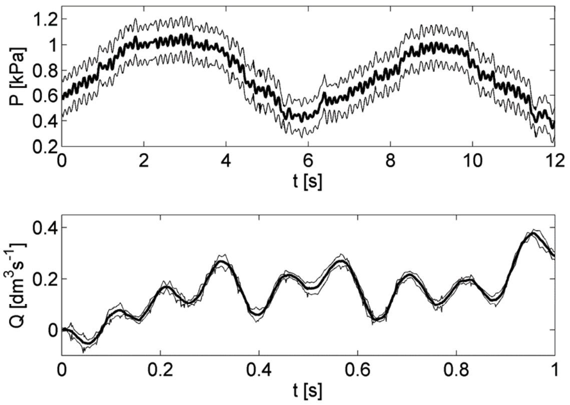

Fig.7. OVW pressure and flow signals within error envelopes

Dynamic changes of flow pattern require fast responses from the drive. The limiting factor on this field is used step motor and its way of function. Some measurement techniques are more sensitive to rapid flow changes. As an example author incorporated rapid flow interruption in the end of inspiration and the start of expiration. Post inspiratory flow interruption may be useful in evaluating respiratory system parameters using Interrupter Technique [17]. Simulation of valve closing/opening was realized by incorporating sigmoid function with various transition times t_{close} (1, 2, 5, 10, 20, 50, 100, 200, 500, 750 ms). The aim of the following experiment session was to asses knowledge of airflow and pressure behaviour during rapid pattern changes. A series consisting of 5 full respiratory cycles for each transition time was commenced (Fig. 8). Volumetric flow value was set to 0.25 dm^3s^{-1} in order to achieve overall tidal volume of 0.5 dm^3. In order to achieve steady conditions and eliminate external influences, author used previously described linear resistor *R5* as test object.

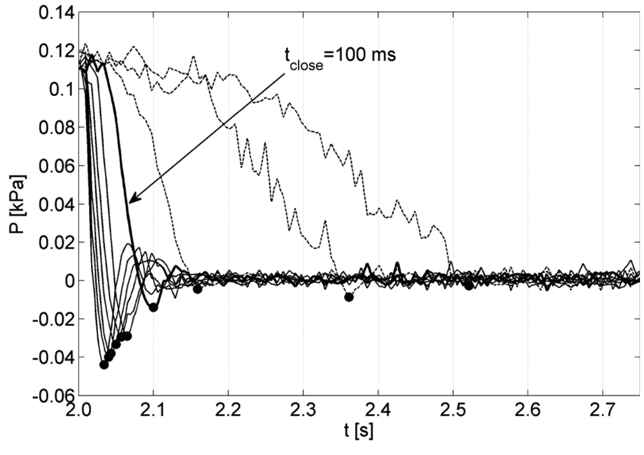

Fig.8. Pressure signal details for range of occlusion times (solid – t_{close}<100 ms; dashed – t_{close}>100 ms; circle marker – first oscillation minimum)

Pressure oscillations occurred during occlusions. In order to evaluate real transition times, author calculated the position of the first minimum of each signal and the time moment of their occurrences. Taking into account sensor parameters and measurement conditions, 10% of maximum pressure value was set as steady-state borderline (P_{steady}=0.012 kPa). Analysis showed (Fig. 9), that 100 ms closing time guarantees optimal position around steady-state pressure.

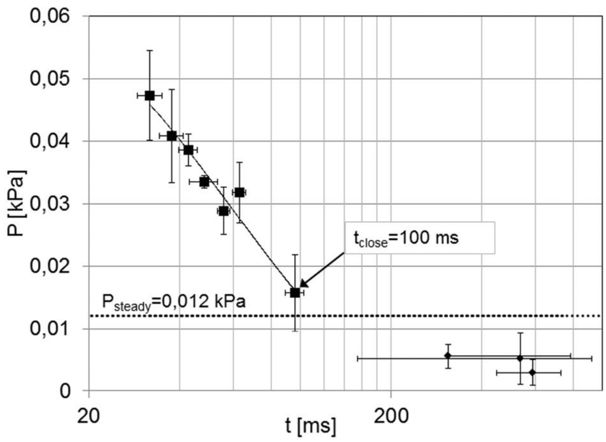

Fig.9. First oscillation minimum values and their spread across pressure and time (square marker - t_{close}=1 ms)

Experiment proved that for closing times greater than 100 ms oscillations can be neglected, thus produce the most stable transfer characteristics.

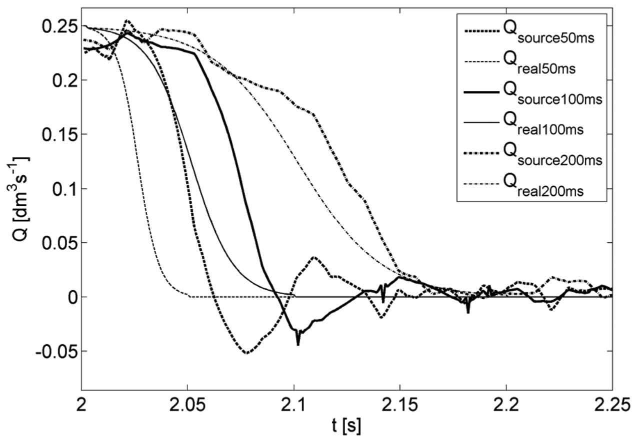

Fig.10. Motor reaction times in comparison with source signals

Due to its finite step, motor can only generate signals with limited transfer function. Analysis showed, that system reflects pattern behaviour only above specific reaction time. Figure 10 presents motor reaction times for chosen sigmoid function patterns. Solid lines (100 ms closing time) depict optimal transfer function in order to achieve full occlusion. This is the borderline time for actual construction.

Conclusions

Author of the paper conducted a series of multiple test scenarios in order to verify properties of modified mechanical ventilation device with ball screw drive transmission. The aim of the analysis was to indicate on issues that have influence on proper function of the apparatus. Modified construction was created in order to achieve better parameters of provided signals as well as to improve their ranges. Ventilator can cooperate with different test objects and may be utilized during various respiration scenarios. Analysis showed that generated signals are highly repeatable in wide range of parameters. Thanks to utilization of different test objects, it was possible to adequately conduct planned scenarios. Construction of the device includes supplying programmed volume portions into phantom of respiratory system. Minimum volume is limited by step work of the motor which can be overcame by incorporating microstepping control. Maximum volumetric airflow the apparatus can provide is not greater than 2 dm^3s^{-1} due to mechanical durability of the piston. In theory, larger flow-rates are possible to achieve.

Used flow patterns did not reflect actual artificial ventilation routines and were designed mainly for particular test routines. Constant and ramp-rising signals were conditioned in order to fit driver inputs. Test routine using parabolic resistor *Rp20* included resistance measurements in function of flow rate. Results presented in Table 1 are consistent with technical documentation of the test object. Generated flow values were repeatable above 0.28 dm^3s^{-1} (relative resistance error lesser than 20%). Figure number 3 shows decreasing error trend and significant difference between pressure and flow error components which indicates on higher accuracy of flow measurements within low values range. Similar analysis was made using linear resistor *R5*, a certified calibration tool sustaining its properties in various conditions. For test routine author used ramp flow pattern. Such operation enabled visualization of result spread (Fig. 4 and Fig. 5). Experiment showed, that the apparatus is capable of generating accurate signals for low airflow values as well. Maximum error from a series (Table 2), evaluated for near zero flow based on exponential fit back extrapolation, is 28.12%. High repeatability is reflected in relative error values for more comparable flow rates (Q>0.1 dm^3s^{-1}) which are lesser than 15% (Fig. 5). The OVW scenario preformed on artificial lung showed that generated alternating flow signal is accurate and repeatable (max distortions lower than 5%), however corresponding pressure signal was biased by lung feedback (visible between ventilator cycles as pressure drops) with mean error rate 15%. The constant flow scenario confirmed above results for 1.0 dm^3s^{-1} flow value (Table 3).

Tests of motor motion for short reaction times showed a vital issue – inability of the system to generate very rapid occlusions, shorter than 30 ms (Fig. 9). Experiment showed, that optimal closing time for current setup is 100 ms. Such time is needed to seize flow within several motor steps without significant signal distortions.

In future work author will concentrate on improving system ability to generating rapid flow interruptions and on utilization of such feature in Interrupter Technique measurements. LabView application used for control and data acquisition can work in infinite loop within single scenario pre-set. Current efforts include utilization of inductive linear position sensor in order to provide feedback data for precise piston position evaluation and for making real time corrections.

REFERENCES

[1] Rhoades R., Bell D. R., Medical physiology: principles for clinical medicine, *Lippincott Williams & Wilkins*, 3-rd edition, (2009), 329-390

[2] Frey U., Merkus P.J.F.M., Paediatric Lung Function, *European Respiratory Society*, Monograph (2010), 47, 1-34

[3] American Thoracic Society. Standards for the diagnosis and care of patients with chronic obstructive pulmonary disease, *Am J Respir Crit Care Med,* (1995), 152, 77–121

[4] Celli B.R., MacNee W., Standards for the diagnosis and treatment of patients with COPD: a summary of the ATS/ERS position paper, *European Respiratory Journal*, (2004), 26, 932-946

[5] Barbini P., Brighenti C., Cevenini G., Gnudi G. A dynamic model of the normal lung for studying expiratory flow limitation in mechanical ventilation, *Ann. Biomed. Eng.*, (2005), 33, 518-530

[6] Hess D., Kacmarek R. M., Essentials of mechanical ventilation, *McGraw-Hill Professional*, 2-nd edition, (2002), 1-136

[7] Guerin C., Richard J., Measurement of respiratory system resistance during mechanical ventilation, *Intensive Care Med*, (2007) 33, 1046–1049

[8] Mireles-Cabodevila E., Diaz-Guzman E., Heresi G. A., Chatburn R. L., Alternative modes of mechanical ventilation: A review for the hospitalist, *Cleveland Clinic Journal Of Medicine*, (2009), 76, 417-430

[9] Grianti F., Montecchia F., Di Bari L., Baldassarri M., A Versatile Mechanical Ventilator (DIGIT) with High Flow Stability and a Programmable Inspiratory Phase Flow Pattern, *IEEE Transactions On Biomedical Engineering*, (1996), 43, 1062-1072

[10] Stell I. M., Paul G., Lee K. C., Ponte J., Moxham J., Noninvasive Ventilator Triggering in Chronic Obstructive Pulmonary Disease A Test Lung Comparison, *Am J Respir Crit Care Med,* (2001), 164, 2092–2097

[11] Polak A. G., Mroczka J., Nonlinear model for mechanical ventilation of human lungs, *Computers in Biology and Medicine*, (2006), 36, 41–58

[12] Neergaard J. von, Wirz K., Die Messung der Strömungswiderstände in den Atemwegen des Menschen, insbesondere bei Astma und Emphysem. *Z. Klin. Med*. (1927), 105, 51-82.

[13] Jabłoński I., Mroczka J., Computer-aided Evaluation of a New Interrupter Algorithm in Respiratory Mechanics Measurement, *Biocybernetics and Biomedical Engineering*, (2006), 26, 33–47

[14] Jabłoński I., Mroczka J., A forward model of the respiratory system during airflow interruption, *Metrology and Measurement Systems*,16, (2009), 2

[15] Kaczka D. W., Ingenito E. P., Lutchen K. R., Technique to Determine Inspiratory Impedance during Mechanical Ventilation: Implications for Flow Limited Patients, *Annals of Biomedical Engineering*, (1999), 27, 340–355.

[16] Kaczka D. W., Lutchen K. R., Servo-Controlled Pneumatic Pressure Oscillator for Respiratory Impedance Measurements and High-Frequency Ventilation, *Annals of Biomedical Engineering*, (2004), 32, 596–608

[17] Jabłoński I., Mroczka J., Frequency-domain identification of the respiratory system model during the interrupter experiment, *Measurement*, 42, (2009), 3, 390-398

[18] Jabłoński I., Mroczka J.: A station for the respiratory mechanics measurement by occlusion techniques, *Metrol. Meas. Syst.*, 14, (2007), 2, 229–240.

[19] Donoho D. L., De-Noising by Soft-Thresholding*, IEEE Transactions on Information Theory*, 41, (1995), 3, 613-627

[20] Jabłoński I., Mroczka J., Frequency indexes of respiration during interrupter experiment, *Metrology and Measurement Systems*, 15, (2008), 2, 153-163

[21] Jakuszkin K., Analysis of Properties of a Lung Mechanical Model During Artificial Ventilation Using Measurement Station, *Metrol. Meas. Syst.*, 17 (2010), 3, 427-438

[22] Mroczka J., Szczuczyński D., Inverse problems formulated in terms of first-kind Fredholm integral equations in indirect measurements, *Metrol. Meas. Syst.*, 16, (2009), 3, 333-357

Authors*: mgr inż. Kamil Jakuszkin, Politechnika Wrocławska, KATEDRA METROLOGII ELEKTRONICZNEJ I FOTONICZNEJ POLITECHNIKI WROCŁAWSKIEJ ul. B. PRUSA 53/55 50-317 Wrocław, E-mail: kamil.jakuszkin@pwr.wroc.pl.*