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EVALUATING TRANSMITTERS FOR QUANTIFYING RESPIRATORY AIRFLOW IN THE BREATHING MECHANISM

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Abstract

Techniques for measuring fluid flow have been known since the 19th century. The first solutions based on the use of pressure only allowed relatively slow changes to be observed. It was not until measurement techniques based on the use of electronic components and the phenomenon of thermo-transfer, combined with a method enabling fast signal recording (A/C converters), that it became possible to analyse the flow of a medium (e.g. air) in detail. Although flow sensors based on measuring changes in resistance have been known for many years, new solutions are still being developed.

This paper presents the results of a study using three sensors. Their response to laminar airflow was investigated for different velocities (1.2 - 2.6 m/s). The flow forcing was implemented using an axial fan and the signals were measured simultaneously for all the sensors tested.

The results showed which sensors had the smallest dispersion of results (PAN and WA sensors) and confirmed that for the investigated velocity variations (0.14 m/s pitch) the results are unambiguously interpretable.. It should be noted that sensor research is related to the need to develop a device to measure flow as accurately as possible, while at the same time ensuring the comfort of the test person during the measurements. Therefore, the search was for a sensor that is small in size and at the same time resistant to damage and operation in a harsh humid environment.

Keywords: signal analysis, flow sensors, breathing, measurements

List of Symbols/Acronyms

ADC – Analog Digital Converter;
PWM – Pulse Width Modulation;
Vx – percentage coefficient of variation;
rms – root mean square.

1. INTRODUCTION

Continuously developed measurement techniques allow us to describe the reality around us in an increasingly more accurate way. Health is certainly one of the most important things. Therefore, we try to monitor every possible parameter related to it more and more carefully. This article presents tests carried out on three types of sensors that can potentially be used in medical systems supporting the diagnosis of the upper respiratory tract. The presented results are the first tests of two of the three tested sensors, so they mainly focused on:

- the stability of recorded signals with constant flow speed,
- check that for the tested flow rates the results are unambiguously interpretable (statistical tests).

Today, air sensors are commonly used in ventilators or other respiratory support devices. However, they are also increasingly found in devices that monitor the breathing process in athletes, used to determine physical fitness. This parameter, together with directly related muscle activity (electromyography),

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is an increasingly popular topic of research [1]. Ergospirometry is also well known test performed by professional athletes. Ergospirometry, also known as cardiopulmonary exercise testing (CPET), is a sophisticated diagnostic tool employed in the field of medicine to assess the integrated function of the cardiovascular and respiratory systems during physical exertion. This physiological examination provides valuable insights into the dynamic responses of the body to exercise, offering a comprehensive evaluation of cardiopulmonary performance. The test involves measuring multiple parameters, including oxygen consumption (VO_2), carbon dioxide production (VCO_2), minute ventilation (VE), heart rate, and other relevant variables, while the individual undergoes incremental exercise on a treadmill or stationary bicycle.

The earliest documented applications of flow measurements have been known since antiquity. The ancient Sumerian cities of Ur and Kish, near the Tigris and Euphrates (circa 5000 B.C.), used water flow measurement to manage water demands through canals and aqueducts to supply their cities. At that time, a simple obstacle placed in the water stream was used to measure flow. By measuring the level of the fluid flowing over the obstacle, it was possible to determine the amount of water flowing. In 1450, the Italian architect and member of the Florentine Academy, Leon Battista Alberti, invented the first mechanical anemometer. It consisted of a disk placed perpendicular to the wind direction, placed on a movable arm, and the force of the wind caused it to deflect from the vertical. The angle of the dial indicated the wind speed. It was the first recorded instrument for measuring wind speed.

Certain specific measurement techniques are used to measure human respiratory activity [1-3]. Breathing is a systemic process that distinguishes external and internal breathing. External breathing involves the supply of air to the lungs in the form of a gas mixture that contains about 20.8% oxygen. The concentration of oxygen, like other components of air, depends mainly on environmental conditions and altitude relative to sea level. The oxygen content also depends on the conditions under which the measurement is made, in a dry climate or in an environment with significant humidity. Air, or more precisely oxygen, which penetrates the alveoli through diffusion, enters the liquid environment – the blood. This process is known as indirect respiration. Then, oxygen is transported through the body's liquids to individual cells, or rather to its most important organs, the mitochondria [4, 5].

Oxygen from the air is used in energy production processes, and carbon dioxide, as the final product of intracellular metabolism, is excreted during each exhalation. The gas exchange in alveoli is its essential stage. Indirect methods for clinical assessment of patients include monitoring the breathing process continuous measurement of blood oxygen saturation (Saturation Level). The most difficult thing is the assessment of respiratory system parameters based on gas dynamics measurements in the respiratory tract - nasal cavity, throat and bronchial tree [6, 7, 8].

The primary test of respiratory activity, or rather the respiratory capacity of the lungs, is spirometry. The history of spirometry tests dates back to the 19th century, the first test measuring vital capacity was performed in 1846 by Hutchinson [**Błąd! Nie można odnaleźć źródła odwołania.**].

Over the years, the equipment for spirometry tests has been improved, it has become possible to measure the exhalation rate in one second, and the flow-volume curve has been determined.

There are many tests indicating various disease processes occurring in the upper respiratory tract (URT), such as the already mentioned spirometry, but also Plethysmography, Polysomnography, Interrupt Technique, Occlusion Technique [10 - 16, 26].

1.1. Characteristic of flow sensors

We can distinguish several categories of devices and divide liquids into several types. In general, liquids are divided into gases and liquids. Among these two generally accepted classes, there are several subclasses that should be dealt with particular care. Flammable liquids require special treatment, as well as measurements at extreme temperatures. When selecting an appropriate transducer (measurement method), the physical and chemical properties of the measuring substance and the conditions under which measurement will be carried out should be taken into account. Examples of such measurements include acids and food liquids [17, 18].

Flow meters can be divided according to the following classification [19]:

(i) Instruments using hydrodynamic methods,
(ii) Devices with a constantly moving element,
iii) Instruments using physical phenomena,
iv) Instruments using other methods.

The general division of flow measurement sensors can be divided into invasive and non-invasive measurement. The first group includes:

- measuring reducers,
- rotameters,
- turbine/vane anemometers,
- calorimeters.

Non-invasive sensors are as follows:

- ultrasonic anemometers,
- laser anemometry,
- a model using the doppler effect.

Non-invasive measurement methods have a very wide range of applications. In biology and medicine, it is used, among others, to measure the flow rate of blood and body fluids in in vivo studies.

Ultrasonic devices are widely used in medicine, mainly due to their non-invasiveness and high accuracy. An example of such a solution is an ultrasound examination.

1.2. Characteristic of breath airflow

Air humidity in rooms should be between 30 and 65% RH. At the same time, the air temperature in the human environment in the room should be around 20 ºC. The air exhaled by humans has a humidity of almost 95% and a temperature of about 34.8 ºC [**Błąd! Nie można odnaleźć źródła odwołania.-Błąd! Nie można odnaleźć źródła odwołania.**].

The relative humidity of exhaled air depends largely on temperature. The air in the lungs is saturated with water at 37 °C, that is, it has a vapor pressure of about 47 mmHg or a water content of about 44 mg/l. Most of this water vapor is provided by evaporation from the membranes lining the nose. As a result, these surfaces are slightly cooler. When you exhale, your breath passes through these cooled surfaces and loses some of its moisture, thus retaining at least some of the water in your body. This is illustrated in Fig. 1.

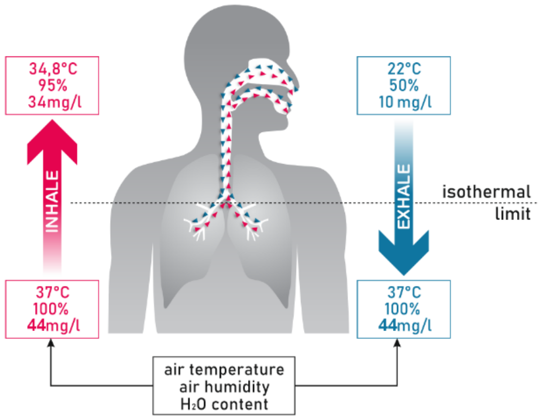

Fig. 1. Human breath

Differences in the physical properties of inhaled and exhaled air undoubtedly influence the air flow measurements measured during breathing measurements.

2. SENSORS

As previously described, various solutions based on thermoanemometric sensors (i.e. based on the use of heat transfer) are known. Their operating principle seems to be the best solution for the moment, taking into account both size, speed of response to flow changes and cost and ease of implementation.

Sensors were selected for testing whose operating principle was based on the use of the same phenomenon, i.e. a change in temperature under the influence of a medium flow. In our case, the medium was exclusively air flow.

Due to the uniqueness with each of the designs tested, the sensors worked with their own (dedicated to them) modules to condition the output signal as well as the power supply system of the heating element.

2.1. Flow sensor FS7

Of the transducers tested, the only commercially available solution on the market is the FS7 sensor. This is a solution from Innovative Sensor Technology. As previously mentioned, it is based on the principle of heat transfer, where both the heating element and the heated element are placed on a PCB (Fig. 2). The operation of the sensor is based on heat transfer through a medium. The heater, heats the flowing medium (air). This heat is transferred through the air to the temperature sensor. Depending on the air velocity, the amount of heat transferred varies (the higher the air velocity, the lower the amount of heat measured by the temperature sensor).

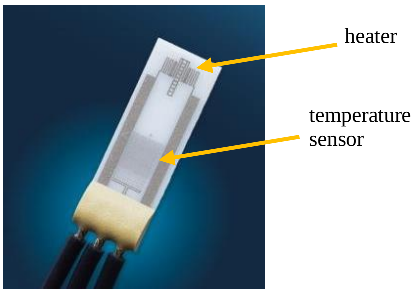

Fig. 2. Flow sensor FS7 [24]

The dimensions of the circuit board with traces applied are 6.9 mm x 2.4 mm x 0.2 mm. Thus, its small size should not introduce interference into the measurement process (noting that any measurement element can lead to airflow interference). According to the manufacturer, the FS7 (Fig. 3).is capable of measuring air flow in the 0 m/s to 100 m/s velocity range [24]. In this study, it was used together with a dedicated conditioning system called FS7 EvalKit by the manufacturer [25].

Fig. 3. EvalKit and sensor FS7 [25]

This circuit enables appropriate operation of the FS7 sensor heater as well as amplification of the signal with the sensor temperature. Thus, with the use of any measuring card operating in the voltage range of 0 - 10 V, it is possible to read a value proportional to the flow speed. After its appropriate conversion, the speed value expressed in m/s can be obtained.

2.2. Flow sensor PAN

This is a flow sensor developed by the Instytut Mechaniki Górotworu of the Polish Academy of Sciences in Krakow. The sensor also takes advantage of the fact that air flow of equal velocity will affect the heater differently. Its implementation is shown in Fig. 4, where on the left the sensor can be seen mounted in a transparent tube, while a close-up is shown on the right to show how thin and yet delicate the measuring element is. In this case, there is only one element, the heater. An illustrative drawing of it is shown in (Fig. 5).

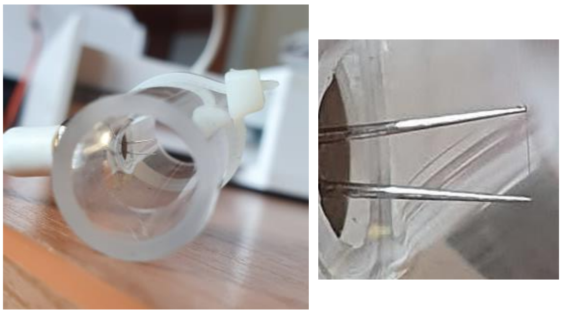

Fig. 4. Flow sensor PAN

The sensor has been made in a constant-temperature configuration, i.e. the power circuit has been designed to achieve a constant temperature value on the heater element (as opposed to systems that try to maintain a constant current value). The flow of air cools the heater, which causes its resistance to change. This in turn affects the current flowing through the heater. This is detected by the circuit amplifying the supply signal and consequently changing the voltage applied to the heater element, which has the effect of increasing the temperature until a pre-set value is reached (and so the resistance of the heater element returns to its initial value).

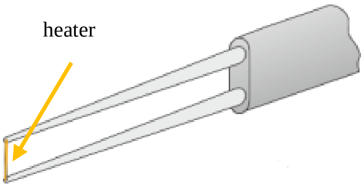

Fig. 5. Sensor construction [26]

The main advantage of this type of solution is the very fast response to changes in flow velocity. It can also be assumed that a measuring element (fibre) of such a small size does not interfere with the airflow. This is all the more important as, when measuring airflow during breathing, the patient should feel comfortable and, despite the discomfort of breathing into the measuring device, breathing should not be impeded.

As with the FS7 sensor, this solution also lacks the ability to measure flow direction, which previous work has shown to be a limitation.

In the rest of the article, this sensor will be called PAN.

2.3. Flow sensor WA

The last sensor tested was one designed by Weles Acoustics Ltd, a company specialising in designing, creating and manufacturing particle velocity sensors dedicated to precise vibro-acoustic measurements. Special thanks to Sieć Badawcza Łukasiewicz - Instytut Mikroelektroniki i Fotoniki for fabrication of the Weles sensor.

Their sensor is also based on the use of the thermal transfer phenomenon. However, unlike the PAN sensor, more than one fibre is used. As a result, in addition to being able to measure the velocity of the flow, the sensor also offers the possibility to measure its direction. This is important because, in patients with respiratory disorders, inspiration and expiration are often not cyclic (e.g. inspiration may be intermittent and may consist of several short breaths).

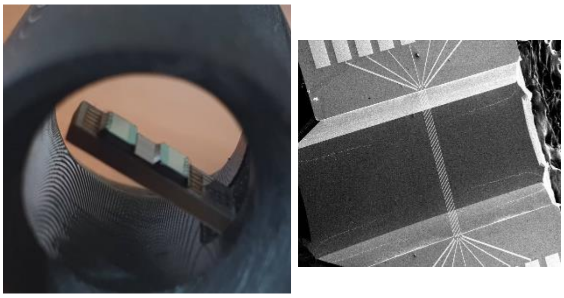

Fig. 6. Flow sensor WA

Figure 6 shows a photograph of the sensor (left) and its magnification using a microscope (right). Despite this small size (9.6 mm x 4.5 mm x 1.0 mm), the sensor technology used makes its resistance to mechanical damage extremely high.

In the rest of the article, this sensor will be called WA.

3. TESTS

In order to carry out comparative tests, a system was used to allow the air flow to be forced at several preset air speeds.

All measurements were performed using the LabVIEW environment. Statistical tests and analyses were performed in Matlab 2022b.

3.1. Measurement system

The measurement system was based on the system designed and tested during the realisation of the work [27]. The schematic diagram of the measuring system is presented in Fig. 7.

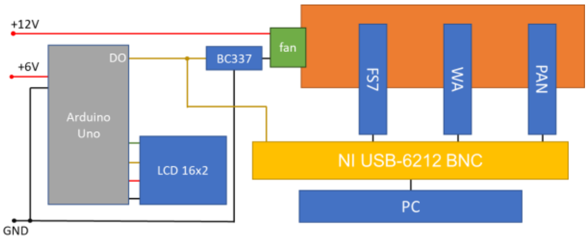

Fig. 7. Measure scheme

The circuit used a axian fan to force air flow (Fig. 7, green element), controlled using an Arduino UNO microcontroller (Fig. 7, grey element). In our system, the microcontroller was only a control element, but in many cases it allows for measurements using a 10-bit ADC converter [**Błąd! Nie można odnaleźć źródła odwołania.**8]. A variable logic signal from a digital output (DO) of either 0 V or 5 V being the fill of the PWN signal feeding the fan was used as the control signal. As the fan was designed to be powered by 12V, it was necessary to use an intermediate element in the form of a BC337 transistor. The fan speed was divided into eleven discrete levels that ranged from 50% to 100% of the maximum fan speed with a step of 5%. The lower limit of 50% was due, to the fact that below this value the fan operated erratically (the resultant voltage supplying the fan was too low). The sequence of each speed tested is shown in Fig. 8, where it can be seen that the measurement procedure was designed to include all possible combinations of speed variations. In this way, an attempt was made to avoid a situation where the measurement result could be influenced by the order of the airflow forcing velocity. Each of the tested filling values lasted 30 seconds and occurred 10 times during the entire measurement cycle (the entire measurement procedure lasted 55 minutes). In our opinion duration of 30 seconds was long enough for the flow to stabilise. Also, the 5% jump was considered small enough to be able to check the distribution of results for different airflow velocities. To avoid introducing additional air turbulence, no person was present in the room during the measurements.

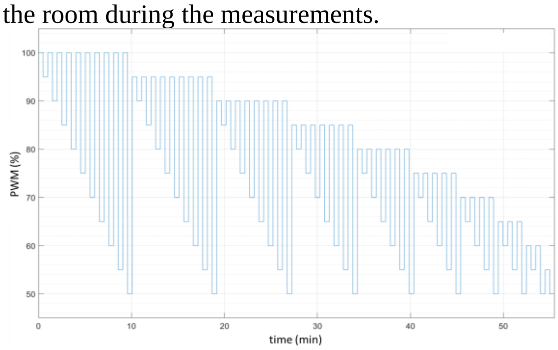

Fig. 8. Flow procedure (PWM order)

The signals of all three sensors tested were recorded using a 16-bit NI USB-6212 BNC measurement card at a sampling rate of 10 kHz, voltage range ±10 V. The actual PWM signal was also measured to be able to confirm or exclude its potential influence on the analysis results obtained at the analysis stage. It should be mentioned that, from the point of view of the rate of change of the airflow during the tests, a sampling rate of 100 Hz should be sufficient in our opinion, but increasing it will always have a positive effect on the quality of the recorded signal.

In order to ensure the same operating conditions, each transducer was mounted in a duct with the same diameter.

3.2. Measurements results

As previously mentioned, the duration for a single PWM value was 30 seconds. Afterwards, the PWM value was changed and measurements were again carried out at a constant airflow value. Due to the fact that it took a certain amount of time to achieve a stable speed and thus a stable airflow (fan run-up and stabilisation of speed), all analyses and presented results were carried out using a 20-second time interval (cutting off the first 10 seconds for the operating conditions to stabilise). The signals prepared in this way were subjected to further analyses.

For easier graphical interpretation, the results obtained are presented in ascending order, i.e. in such a way that all results for one PWM value (e.g. 80%) are placed adjacent to each other. Fig. 9 shows the ranked values as averages of 20 second intervals of the recorded PWM signal controlling the fan (Fig. 7 shows the signal controlling the Digital Output of the Arduino UNO microcontroller applied to the BC337 transistor). It can already be seen from Fig. 9 that the stability of the fan control signal was not ideal, but fluctuated slightly.

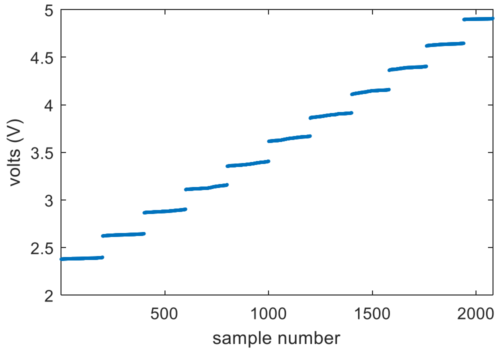

Fig. 9. PWN signal (real data from 20 s analyse window)

An analysis of the stability of the PWM signal was performed. For this purpose, the percentage coefficient of variation (Vx) was calculated. This is a universal measure that determines the percentage change in the analysed data set based on relation (1).

$$Vx = \frac{\sigma}{\mu} \cdot 100\% \qquad (1)$$

where: Vx – coefficient of variation
σ – standard deviation
μ – mean

To calculate it, values representing the averages of measurements with a 1 second window were used (obtaining 200 averages: 10 measurements times 20 results for each PWM value). The maximum calculated value of Vx was 0.46 %. It can therefore be concluded that the fan control voltage was stable varying by no more than 0.46 % of the nominal value on average.

To determine the flow velocity expressed in m/s, BENETECH GM 8903 was used (professional hot wire anemometer with a measurement range of 0 - 30 m/s and an error of ±3% ±0.1m/s). The average values of the measured velocities for the tested PWM fillings of the feed signal are shown in Fig. 10. It also includes the range of probable measurement error calculated from the manufacturer's data.

It should be mentioned that, from an electrical point of view, when using a PWM signal for control, it should be borne in mind that it produces an energy effect corresponding to the root mean square (rms) value of the PWM signal (for example, 50% PWM for a control voltage varying between 0 and 5 V will produce an effect like the application of 3.54 V).

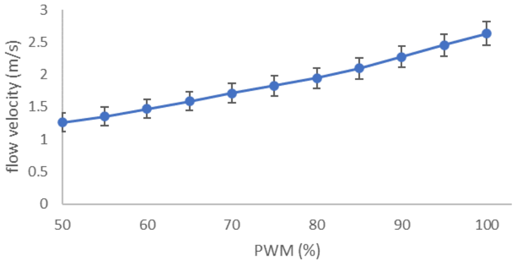

Fig. 10. Flow velocity

The above data enable the determination of the transition function between the voltage recorded by the sensors and the speed. However, this solution was not chosen for further analyses, as it would introduce additional error due to the quality of the linear regression model fit. Therefore, further analyses were carried out for voltage signals and not for speed.

The sensors tested had different sensitivities and conditioning circuit gains. As a result, the range of measured voltages for each sensor was radically different, which would make a direct comparison pointless. In Fig. 11, a boxplot shows the dispersion of the voltages for the entire range of flow velocities tested. It can be seen that both the dispersion and the range of values are completely different.

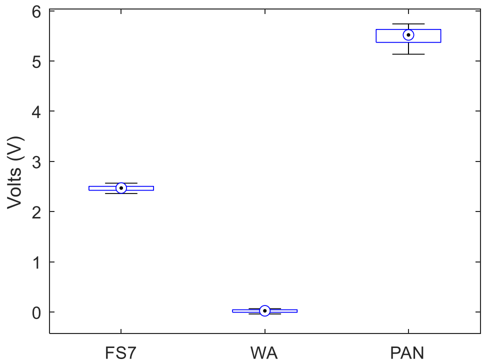

Fig. 11. Volts range for tested sensors

As mentioned earlier, the range of values measured with individual sensors depended on the conditioning circuit used, i.e. the analogue circuit supplied with the sensor responsible for amplification or possible filtering. As the conditioning circuits can be adapted to a specific ADC by setting the variation voltages at the sensor output, in our opinion, the influence of amplification should therefore not be considered in further analyses. In addition, the focus of the presented study was to investigate the stability of the obtained measurement results of the tested sensors as well as to check whether the difference between the tested flow rates would be unambiguous in interpretation (statistical tests were used for this purpose). Therefore, it was decided to scale the obtained values so that the maximum recorded value for each sensor was 1. Fig. 12 shows the values to be analysed (i.e. the average voltage values calculated for 1 second sections).

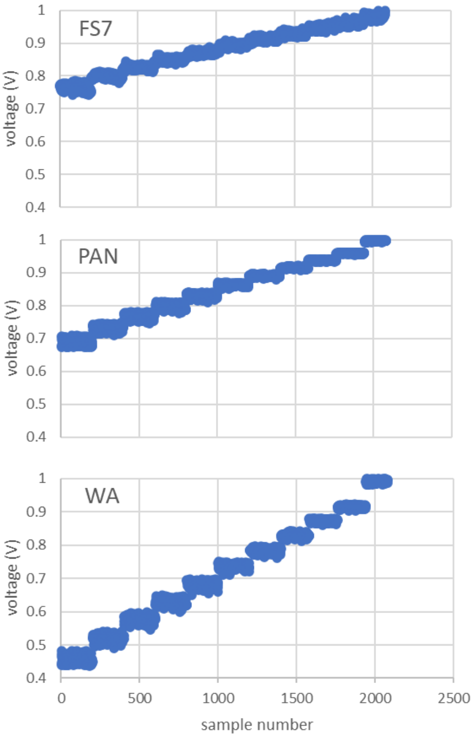

Fig. 12. Flow sensors 20 s window measured values

A visual analysis of the presented results allows the differences between the sensors to be observed, but a number of statistical tests were performed. A comparison of the results for all tested sensors and all tested PWM values is also shown in Fig. 12.

Fig. 13, in turn, summarises the measurement results of the tested sensors.

Firstly, signal stability analyses were performed for each of the measured PWM. For this purpose, the percentage coefficient of variation Vx was determined. The Vx coefficient was also determined for the fan control signal, denoting it as control signal (c.s.) . The results are shown in Fig. 14.

Figure 14 shows that, the largest dispersion of results occurred for low flow velocity values, for all the sensors tested. This is interesting in that the value of Vx for the control signal (c.s.) was not the largest in this area (see c.s. on Fig. 14). It can therefore be concluded that the measurement dispersion is not due the instability of the of control signal, but to the measurement properties of the sensors tested.

In the next step, it was tested whether there was a statistically significant difference between the results of adjacent PWM values (flow speeds). It was assumed that the data sets collected for each sensor and each flow velocity (corresponding to the fan control value in the PWM from 50 % to 100 %) should differ in a statistically significant way.

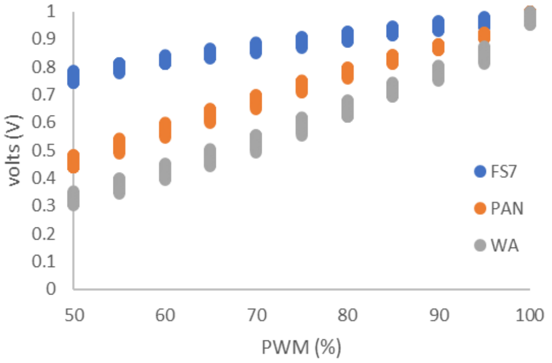

Fig. 13 Flow sensors results comparision

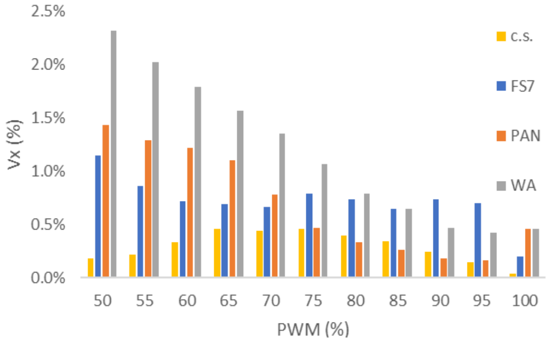

Fig. 14 Coefficient of variation for tested sensors

The Lilliefors test showed that, in a large proportion of cases, there were grounds for rejecting the H0 hypothesis (the distribution of the dataset under study follows a normal distribution). Therefore, in the absence of a normal distribution for both neighbouring groups (e.g. for the WA sensor and PWM supply 65 % - 70 %), the Wilcoxon test (the non-parametric equivalent of the Student's t-test) was used.

In Table 1, red indicates the rejection of H0 assuming a normal distribution of the data (Lilliefors test). In this case, the Wilcoxon test was used (the h and p results presented in the table are from the Wilcoxon test). The results marked in black indicate that there were no grounds for rejecting H0, that the study groups are characterised by a normal distribution. In this case, the variation between groups was tested with the Student's t-test (h and p results presented in the table are from the Student's t-test).

Table1 Statistical tests

PWM pair	FS7		WA		PAN	
	h	p	h	p	h	p
50-55	1	1.224E-160	1	1.255E-170	1	4.977E-67
55-60	1	9.876E-146	1	4.526E-160	1	5.285E-67
60-65	1	2.389E-137	1	5.613E-67	1	7.133E-67
65-70	1	5.863E-130	1	6.521E-67	1	6.569E-67
70-75	1	1.338E-123	1	4.831E-67	1	4.830E-67
75-80	1	1.126E-94	1	1.410E-178	1	4.829E-67
80-85	1	1.065E-88	1	3.321E-197	1	1.330E-63
85-90	1	3.221E-85	1	1.252E-198	1	1.665E-60
90-95	1	2.810E-56	1	3.289E-194	1	1.664E-60
95-100	1	3.840E-93	1	4.194E-252	1	3.772E-53

In Table 1, it can be seen that for all pairs tested, the tests performed at the 0.05 significance level rejected H0 that the groups tested were not statistically significantly different. Thus, the difference between the tested speeds was statistically confirmed.

4. DISSCUSSION

In the presented research, the results of airflow measurements using the three prototype flow sensors PAN, WA and the sensor FS7 were collated for the first time. While catalogue notes were available for the FS7 sensor, the other two sensors could only be based on our own measurements. The PAN sensor had already been tested few times and the measurement results had been presented in our earlier publications [8, 26]. In the case of the WA sensor, these were its first tests. Thats why we first decided to measure it in laminar air flow. Checking the suitability of the sensor for stable operating conditions would appear to be a natural first step in the research. Due to the measurement frequency of 1 Hz when measuring air velocity using the commercial BENETECH GM 8903, it was decided to analyse the results from the sensors tested with this time resolution.

The sensors were tested in two ways. In the first step, the dispersion of the measurement results was checked when the air velocity was kept constant. The percentage coefficient of variation Vx was used as a parameter characterising the stability of the measurements. The results are presented in Fig. 14. It also shows the stability of the fan power control signal (c.s. signal). It can be seen on it that, for most PWM signals, the Vx value for the c.s. signal is smaller than the Vx value of the sensors tested. However, it is interesting to note that in the case of the PAN sensor, for PWM in the range 75% - 95%, the coefficient of variation Vx of the PAN recorded signal is smaller than the Vx of the c.s. signal. This seems counterintuitive. However, it should be noted that the variability of the c.s. control signal should not quite be interpreted as variability of the flow velocity. The movement of the fan blades, due to their mass, will react more slowly to a change in the measured feed signal. Therefore, small changes in the supply signal will not necessarily realistically affect changes in flow velocity. In order to investigate this phenomenon in more detail, the flow velocity should be measured directly at a higher frequency sampling. Unfortunately, we did not have this possibility at this stage of the research. However, our experience shows that a variation in the control signal of no more than 0.46 % can be considered negligible on the results of further analyses.

By analysing the variation of the Vx parameter with increasing PWM (increase air velocity), it can be seen that the Vx value decreases for the PAN and WA sensors. The FS7 sensor behaves differently, for which the value of Vx remains more or less at a similar level for the entire range of measured velocities. This behaviour may be due to the design of the sensor. It should be reminded that the PAN and WA sensors are based on the use of an airflow-cooled fibre. In the case of the FS7 sensor, instead of a fibre we have a conductive material sputtered onto a PCB plate. It is therefore an element with a larger cross-section. Such an arrangement has greater inertia due to the much larger element responding to temperature change. This assumption was confirmed by a test involving a sudden stop of the air flow. This is shown in Fig. 15, where it can be observed that the falling time of the curve for the FS7 sensor was longer than for the other sensors, indicating that the heater element took longer to cool down.

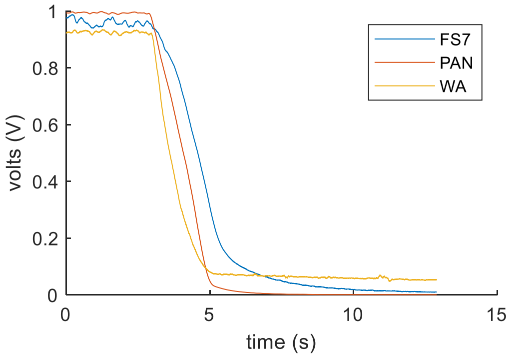

Fig. 15. Impulse change of flow velocity

Analysis of Fig. 14 also makes it possible to observe that the PAN sensor was characterised by a smaller dispersion of recorded values than the WA sensor. This was particularly evident for lower PWM values (lower flow speeds) for which the difference between the coefficients of variation Vx calculated as WA - PAN was close to 0.9 %. As the velocity increased, the difference decreased, but averaged about 0.4 % over the range of flow velocities investigated.

It can therefore be concluded that the PAN sensor was characterised by a smaller dispersion of the coefficient of variation Vx than the WA sensor.

However, it should be noted that the range of recorded signal variation from the WA sensor was very small (Fig. 9) which may have projected additional noise in the form of data aquisition card . In future, however, there is nothing to prevent the gain of the conditioning system from being adjusted to suit the range of the measuring card.

Next, it was examined whether the recorded changes in flow velocity were unambiguously interpretable. Statistical tests were carried out on whether the differences between the results for adjacent airflow velocities (represented by the PWM signal) are statistically significantly different. The results of the tests presented in Table 1. confirmed that for each of the sensors tested and for each of the measurement cases tested, a difference between the tested velocities can be found at the 0.05 significance level.

Two elements can certainly be considered as a limitation of the above tests. The first is that the step change of the PWM control signal was too high. In the case presented here, it was 5%, which in practice translated into a change in flow velocity between successive PWM values ranging from 0.1 m/s (low PWM values) to 0.19 m/s (highest PWM values). The velocity measuring device (BENETECH GM 8903) allowed us to display the results with an accuracy of 0.001 m/s, but note that the measurement error declared by the manufacturer for the velocities we tested was 0.14 m/s to 0.18 m/s. Thus, it was close to the measurement resolution of the sensors we tested. In order to carry out more accurate tests, a different control device than the BENETECH GM 8903 would have had to be used - with a higher accuracy.

The second limitation of the tests carried out was the range of velocities tested. In the presented tests, the limitation of the measurement system was to obtain stable low flow velocities. The lowest velocity value for a PWM of 50 % was near 1.2 m/s. If sensors are to be used to measure airflow during breathing, it will certainly be necessary to use sensors that allow correct measurements at low flow velocities, i.e. in the range up to close to 0 m/s. Therefore, an extension of the measuring system is also necessary in this respect.

5. CONCLUSIONS

This publication presents the results of a study of the measurement stability of airflow sensors. Of the sensors tested, only the FS7 is commercially available. The other two are prototypes. While all sensors are based on the same operating principle (thermo-transfer), the WA and PAN sensors have a similar manufacturing technology (use of fibre). This is confirmed by the behaviour of the percentage coefficient of variation Vx. While the PAN sensor has lower Vx values than the WA sensor (at the current stage of the WA sensor prototype), WA sensor has several additional features that make it more interesting. The WA sensor, due to the use of several fibres, has the ability to identify the direction of airflow (measurements not presented in this publication). This is a crucial feature especially for measurements in the breathing process. In addition, experience with PAN sensors indicates that they are quite sensitive to mechanical damage. According to the manufacturer's declaration, WA sensors are subjected to endurance impact tests during the production process, so despite their short experience in use, it should be assumed that they will maintain their measurement properties for longer time.

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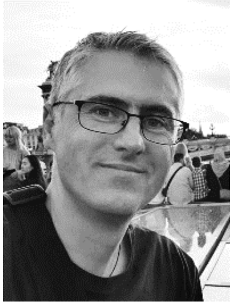

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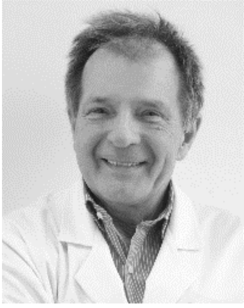

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