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FULLY AUTOMATED SYSTEM FOR AIR VELOCITY PROFILE MEASUREMENT

The paper presents the idea of a system for controlling the movement of a flowmeter for air velocity profile measurement. In such a system, due to massive amount of data and limitations of the Data Acquisition Equipment, it is necessary to use moveable sensors. The flowmeter sensor is moved with the use of a linear module with a stepper motor and a tooth-belt drive. The location and speed of the sensor are controlled by a program based on the idea of virtual instrument. The proposed structure allows the user to control operation of the stand and provides automatic measurement. A wide range of velocity and step increments of the stepper motor drive, and flexibility of the virtual instrument software, allow one to create effective measurement systems ensuring sufficiently precise location with optimal time duration of measurement. It is shown that the linear module with tooth-belt is an effective alternative for similar modules with micro-screw drives.

1. Introduction

A large number of physical phenomena, different quantities and properties lead to many measurement techniques [1, 2]. There is no universal procedure and measurement equipment that might be applied to specific problems. However, typical measurement equipment consists of sensing elements, data acquisition board and software. Measurement systems become more complex for the phenomena which require information from more than one point, i.e. linear or matrix data acquisition points are necessary. This assumption leads to an increase in the number of sensors, data acquisition channels – but usually this possibility is limited by data acquisition boards. Another idea is to use a moving sensor. In this case, for adequate measure-

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ment, it is necessary to control location and movement of the sensor. For that reason, a standard software, which is used for data acquisition, cannot be used effectively and custom modifications are usually impossible.

This paper presents an idea of a system for control of movement of a flowmeter for air velocity profile measurement.

2. Techniques for velocity profile measurement

A fluid stream measurements can be performed in different ways [3, 4]. In many cases, the axi-symmetrical velocity profile is required, and it is necessary to know its exact shape in the place where the flowmeter is mounted. Local resistant devices such as elbows, valves, throttles, diffuser, etc. generate velocity profile deformation. It is important to define the distance behind such components for which the velocity profile is re-formed to a stable form. It depends on the type of the local resistance device and the kind of flow (Reynolds number). The uncertainty of the measurement increases when measurement devices are installed in the areas with higher disturbances of the velocity profile [5].

However, often in metrological practice, we have to deal with the need of shortening the distance between the obstacle and the flowmeter due to specific characteristics of the installation. In the case when the application of a flow straightener is unjustified due to economic or metrological considerations, the measurements of velocity profiles can be undertaken in selected locations of the installation with the aim of assessing the effect of flow deformation due to the presence of a flowmeter [6, 7]. Due to an unexpected distribution of the fluid velocity, it is necessary to take measurements in considerably larger number of points than it is stipulated in the Norm [8]. Such measurements are possible on an automated, original laboratory stand.

Figure 1 presents the main idea for this measurement. Local velocity of the medium is measured using the differential pressure method. By moving the sensor along the measuring path, one can define velocity profile on this path. Determination of velocity profile in selected areas is possible with the use of the Prandtl tube (Fig. 1), whereas summary measurements for undisturbed (axi-symmetrical) velocity profiles can be performed manually for only several points.

At these points, the differential pressure $\Delta p = p^{+} - p^{-}$ is measured with the use of a manometer or pressure transducer. For the given density ρ of the fluid, the local velocity V can be calculated as

$$V = \sqrt{\frac{2\Delta p}{\rho}} \tag{1}$$

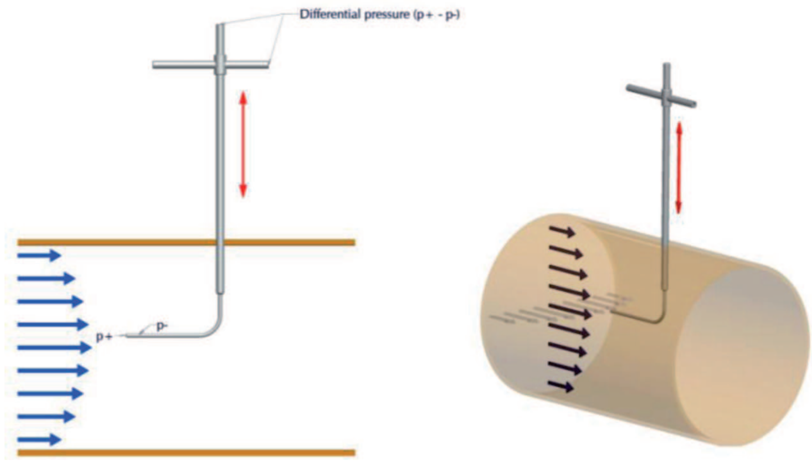

Fig. 1. The main idea for velocity profile measurement

In this method, one needs to control simultaneously a number of flow parameters, and because of that the method is inaccurate. Additionally, differential pressure Δp fluctuates during measurement and an averaging procedure must be applied. However, for a stable flux, where the velocity profile depends on Reynolds number only, it is enough to perform measurements in a few points, whose location is defined in the Norm [9].

The stream of air is strongly disturbed within some sections of the pipeline, e.g. directly behind the elbows. The measurement of the air flux velocity profile in this case becomes more complex. It is necessary to increase the number of measurement points. Some experiments show that the number of measurement points must be increased even tenfold. Velocity profile of deformed characteristics requires measurements of higher resolution (significantly smaller distances between points) in each series. An additional problem is how to define the exact location of a specific measurement point in relation to the pipeline axis. Traditional, manual measurement turns out ineffective and it is necessary to use an automated system in which linear displacement of the sensor is controlled by a computer program.

The aim of this paper is to present the automated system for air flux velocity profile determination. It is proposed to use the linear module with stepper motor drive. The control program is based on the idea of a virtual instrument and allows the user to control the location of the flowmeter and perform measurements automatically. One control program sets up the stand parameters and controls the flowmeter movement and data acquisition. The stand operation is described in the scheme in Fig. 2.

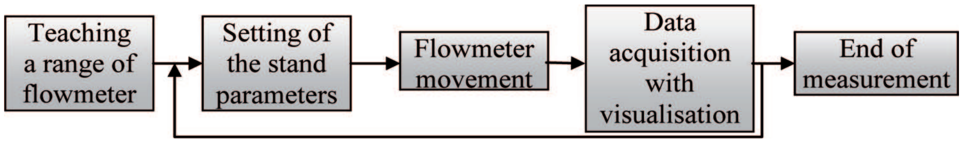

Fig. 2. Stand operation scheme

3. Components of the measurement system

The overall view of the test stand with essential parts of this installation is presented in Fig. 3a. The flow of air is realized with the use of a centrifugal blower with an electric motor drive. The average speed of the air flow is changed smoothly to the required value by a frequency converter (control of the electric motor rotational speed). The average speed of the flow is determined using a reference method with the use of high-class turbine flowmeter (Fig. 3b). In order to specify the velocity at the place where the flowmeter is mounted, one uses two absolute pressure transducers (Fig. 3c) and two thermometers Pt-100 (Fig. 3d).

This setup makes it possible to measure the change of air density caused by the drop of pressure between the impact flowmeter and the turbine flowmeter. The differential pressure in the Prandtl tube is measured with the use of impulse conduits and the integrated unit of differential pressure transducer with three-way block of valves (Fig. 3e).

The control of efficiency of the blower, data acquisition and storage are performed with the use of National Instruments data acquisition boards. The specialized data acquisition system CompactDAQ (Fig. 4) is equipped with the following components:

- NI 9217 Module for resistance measurement (temperature measurement),
- NI 9203 Module with analog current input channels (4-20mA) to measure the currents from the absolute pressure transducer, differential pressure transducer, and the barometer,
- NI 9265 Module with analog current output channels (4-20mA) to control the electric motor rotation (frequency converter),
- NI 9411 Module with counter input channels cooperating with the turbine flowmeter,
- NI 9403 Module with digital input/output channels to control the stepper motor and limit sensors.

4. Drive system for flowmeter movement

The main goal of the system is to control the flowmeter movement. In this case, the position of the flowmeter along the pipe diameter is important. The pipe diameter is measured automatically with the use of the so-called

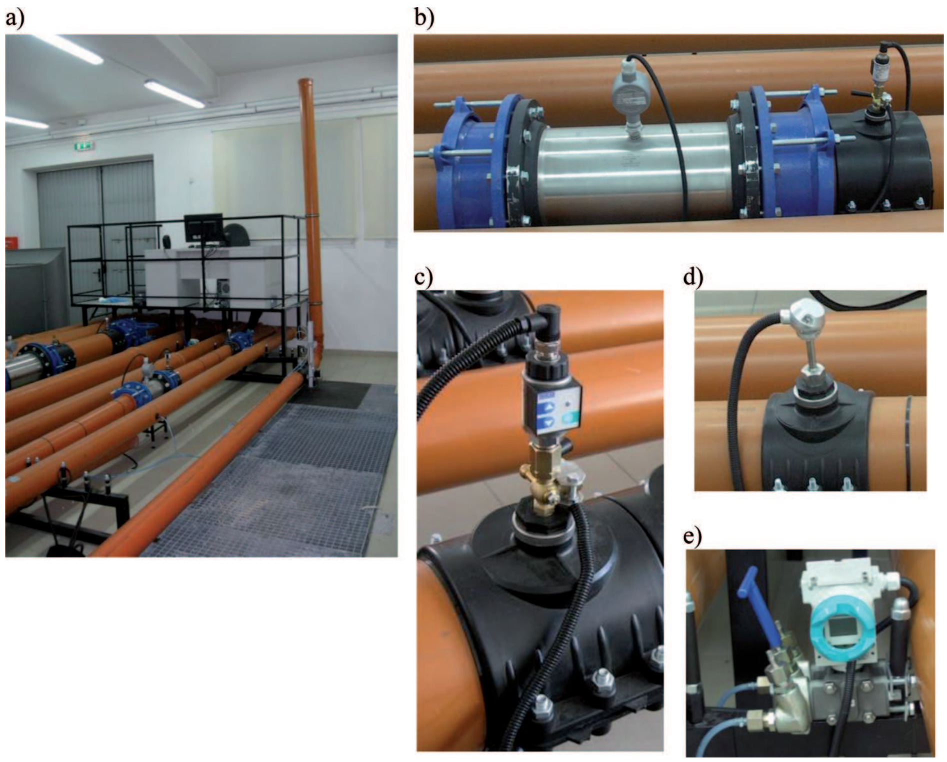

Fig. 3. Test stand for examining disturbances behind the segmented elbow: a) general view, b) turbine flowmeter, c) absolute pressure transducer, d) thermometer Pt-100, e) differential pressure transducer

Fig. 4. NI data acquisition boards integrated as CompactDAQ system

"teaching" procedure based on location of the limit sensors. Position of the limit sensor must be set by the operator. The "teaching" procedure makes it possible to detect the range L of the flowmeter movement: the flowmeter is moved between the limit sensors and the range of its movement is defined (Fig. 5). Than, the user can define the resolution dL of the measurement, and the step of movement is calculated in this module. Next, the stand can be started and measurement procedure is activated. The sensing element is moved to its starting position and data acquisition is performed. Then, the drive of the flowmeter moves the sensor by a previously calculated step. These operations are continued until the range of movement is reached.

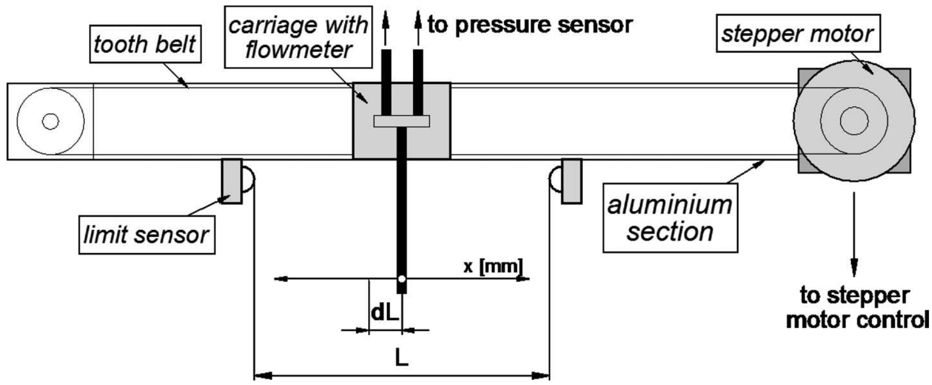

Fig. 5. Structure of the flowmeter movement system

The proposed system is based on a stepper motor drive that controls the flowmeter movement. Linear displacement of the sensor is performed with the use of the linear module WOBIT MLA0373-5HK3SKK (Fig. 6) [10], whose task is to convert the rotation of the shaft of the stepper motor into the linear displacement of the carriage. The stepper motor is controlled in an open loop system. An additional controller is applied in this module - three digital signals are used to control the stepper motor. The control program must generate standard TTL digital signals:

EN – enabling or disabling the supply of the coils of the stator,

DIR – changing the direction of rotor's rotation,

CLK – pulse signal controlling rotational speed of the rotor; frequency of this signal defines the rotational speed of the motor.

User can select one of the step method control: full step, half step and micro-step (1/4, 1/5, 1/8, 1/10 and 1/16). The nominal current of the stator coils can be set in the range of 1.2 to 3.6A and the supply voltage of 30V is applied. According to the step control method, the resolution of the rotation is from 200 steps up to 2000 steps per one rotation.

The base of the linear module is made of special shape aluminum section, which can be used to build complex two- or three-dimensional drive structures.

The overall view of the linear module, its application and the clamp on the carriage (the Prandtl tube handle) is presented in Fig. 6.

This mechanical structure ensures that the measurement is performed for the points defined in the "teaching" procedure with resolution up to *dL= 0.1* mm, and the user can change the resolution very easily. The application of such a device makes it possible to precisely measure the air flux velocity profile many times faster than in the manual case. Additionally, maximum resolution for manually-controlled movement of the flowmeter is equal to that on the scale placed on the Prandtl tube – usually 5 mm. During the movement of the flowmeter in the direction perpendicular to the pipeline axis, the flowmeter angular position relative to the axis of the tube remains unchanged.

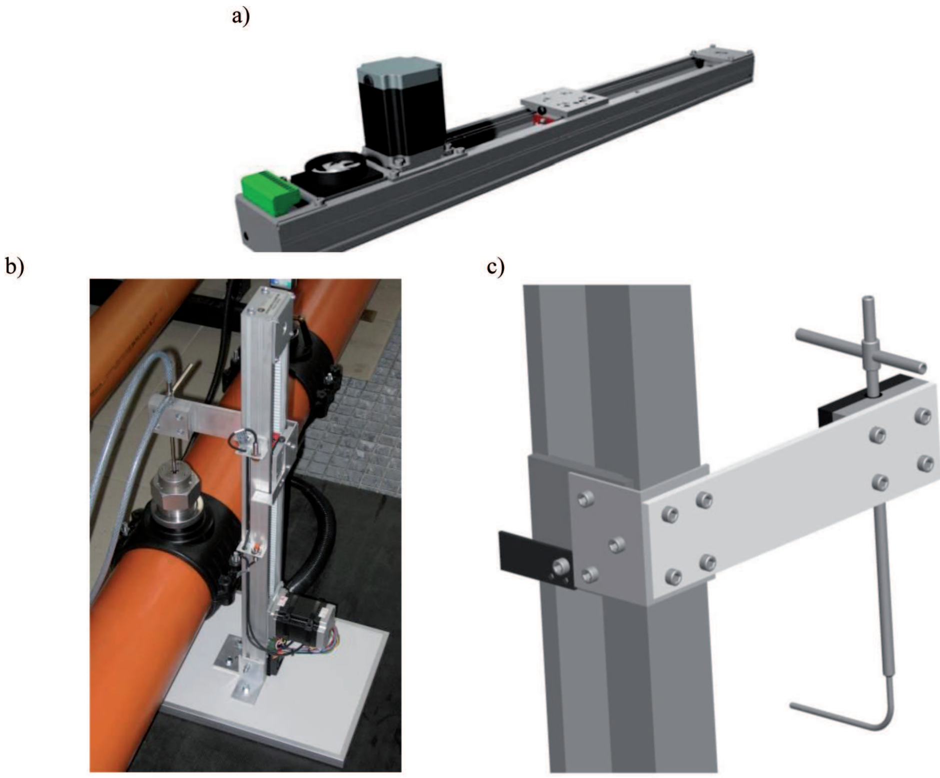

Fig. 6. Application of the WOBIT MLA0373-5HK3SKK linear module a) overall view of the module [10] b) pipe and the linear module, c) handle of the Prandtl tube

5. Control program

Modern, high level graphical programming languages make it possible to create software for measurement and control devices as virtual instruments. A virtual instrument consists of an industry-standard computer or workstation equipped with powerful application software, cost-effective hardware such as plug-in boards, and the driver software. Such an assembly performs the functions of traditional instruments – its appearance and operation imitates physical instruments, such as oscilloscopes or multimeters.

The Author's program for measurement and control of the flowmeter movement was created in the LabVIEW environment, which contains a comprehensive set of tools for acquiring, analyzing, displaying, and storing data. The applied program allows one to investigate velocity profiles, represent them graphically, analyse and store them in a file (Fig. 7).

The user has a complete information about measurement procedure: current position of the Prandtl tube along cross-section of the pipeline. Investigation of the velocity profile must be performed for some values of the average speed of the air flux in the range from 10 m/s up to 26 m/s. It is possible to select the average velocities for which the measurement is made – here 5 levels can be selected and a constant step of 4 m/s is set. When measurement for a selected level is finished, the status is changed to "OK", and the next measurement is automatically started. The RPM fields store rotation of the electric motor of the blower for which the average speed of the air flux has been reached. The RPM value is defined by means of an adaptive procedure, where rotation speed is automatically changed until the average speed of the air flux is reached. The tolerance of the air flux speed is equal to ±0.1m/s. Additionally, real value of the average speed is stored, too. Storage of the RPM helps us to save time during the following series of measurements.

It is important in the case when the environment conditions (pressure and temperature) fluctuate during the measurements. To reduce the level of disturbances of the air stream, a cloth filter with different permeability is placed at the inlet. Because of air pollution, this filter has some influence on the environment conditions, too. The actual state of the filter is controlled, and the corresponding information is displayed – the user is warned of possible irregularities.

The measurement begins with the "teaching" procedure, which defines actual distance between the limit sensors (Fig. 8). The internal diameter of the pipeline is known, and the distance between the inner wall of the pipeline and the first measuring point should be equal to 0.03D, where D is the internal diameter of the pipeline. According to that, the user can set the suitable location of the limit sensors (*L nominal* field in Fig. 8). Next, the stepper motor moves between the limit sensors and *L*, the measurement distance is measured. If this distance is within the specified tolerance (*Tolerance coef.* filed in Fig. 8), the electric motor of the blower is automatically activated and measurements are started according to the settings of the average speed of the air flux (Fig. 7). During the measurements, the user can read information on the conditions of environment, such as temperature and pressure, from the sensors (Fig. 9).

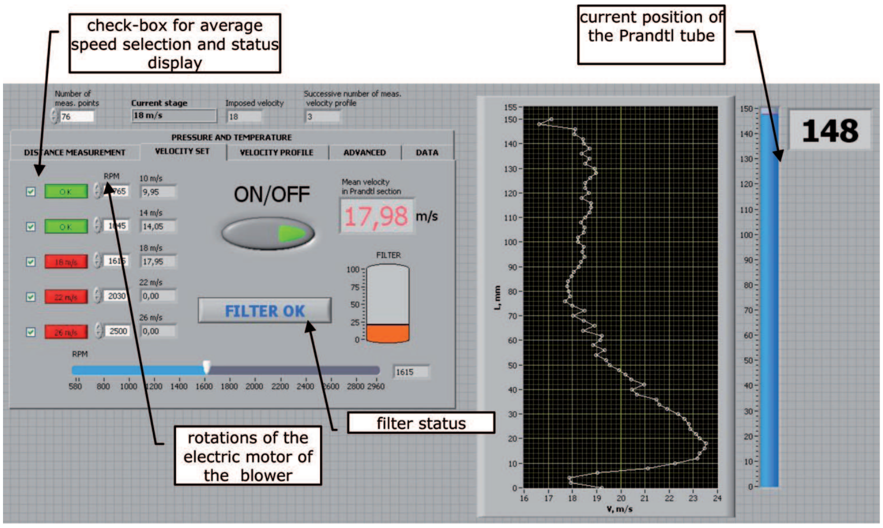

Fig. 7. Measurement of the velocity profile – selection of the average speed

Comparison of velocity profiles for manual and automatic control is presented in Fig. 10. Measurements were made for average velocity of 10 m/s and two cross-section locations were investigated. The Prandtl tube was located behind the elbow at distances 4D and 7D, where D is the inner diameter of the pipeline. The manual method is characterized by greater local disturbances, so that the user must take decision about how to interpret them. It must be taken into account that manual setting of the location of the flowmeter can strongly influence the final results. Higher resolution of the measurement makes it possible to reduce that error. Firm and rigid handling of the Prandtl tube ensures repeatability of measurements.

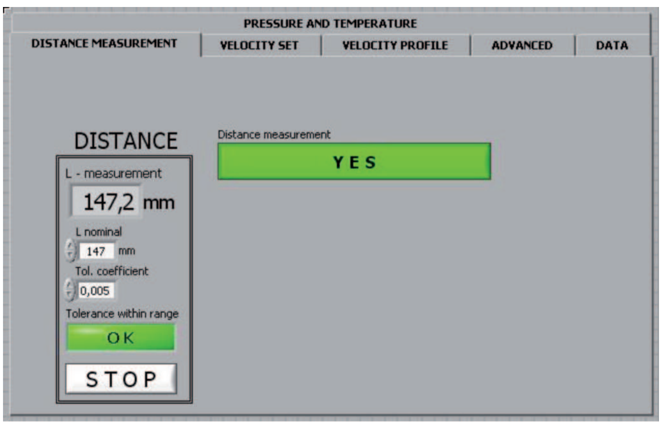

Fig. 8. Limit sensors distance measurement

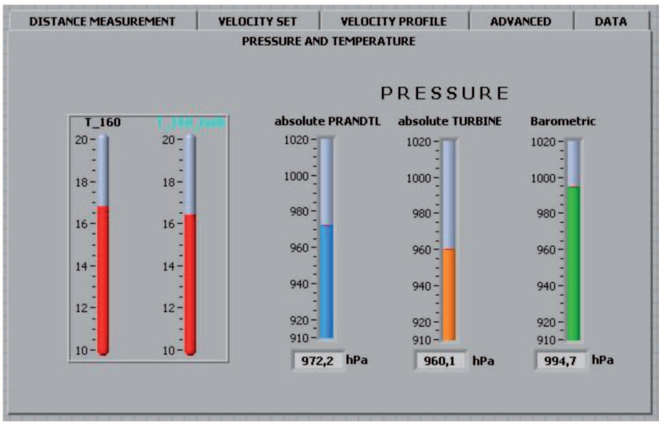

Fig. 9. Limit sensors distance measurement

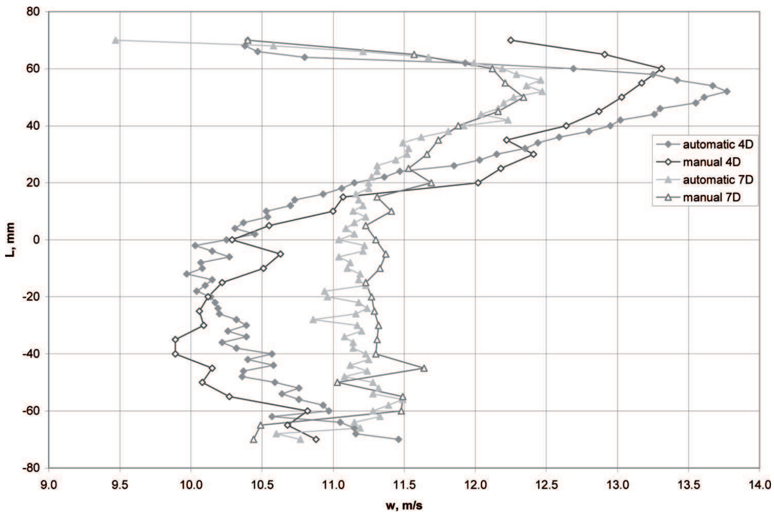

Fig. 10. Air flux velocity profile behind the elbow for manual and automatic measurement

6. Accuracy of measurements

To investigate accuracy of measurements, some tests were performed and signals from five sensors were analysed:

– *Local pressure* was used to define local velocity of the air stream for the velocity profile definition,
– *Reference pressure* was used to control of the average speed of the air flux in the tube system,
– *Electric motor speed* allowed for controlling the drive of the blower,
– *Absolute pressure* and *Temperature* was used to calculate actual density of the air.

The tests were performed for three levels of the average air flux velocity (10 m/s, 18 m/s and 26 m/s) and 10 series were registered at each level. A sampling frequency of 58 Hz was used during the test and 10 seconds time history of the measured signals was recorded. Each measured signal consisted of 580 samples.

Time history, probability density function and power spectral density function for series No.1 and average air flux velocity of 10 m/s are presented in Fig. 11, and Fig. 12 shows these quantities for average air flux velocity of 26 m/s.

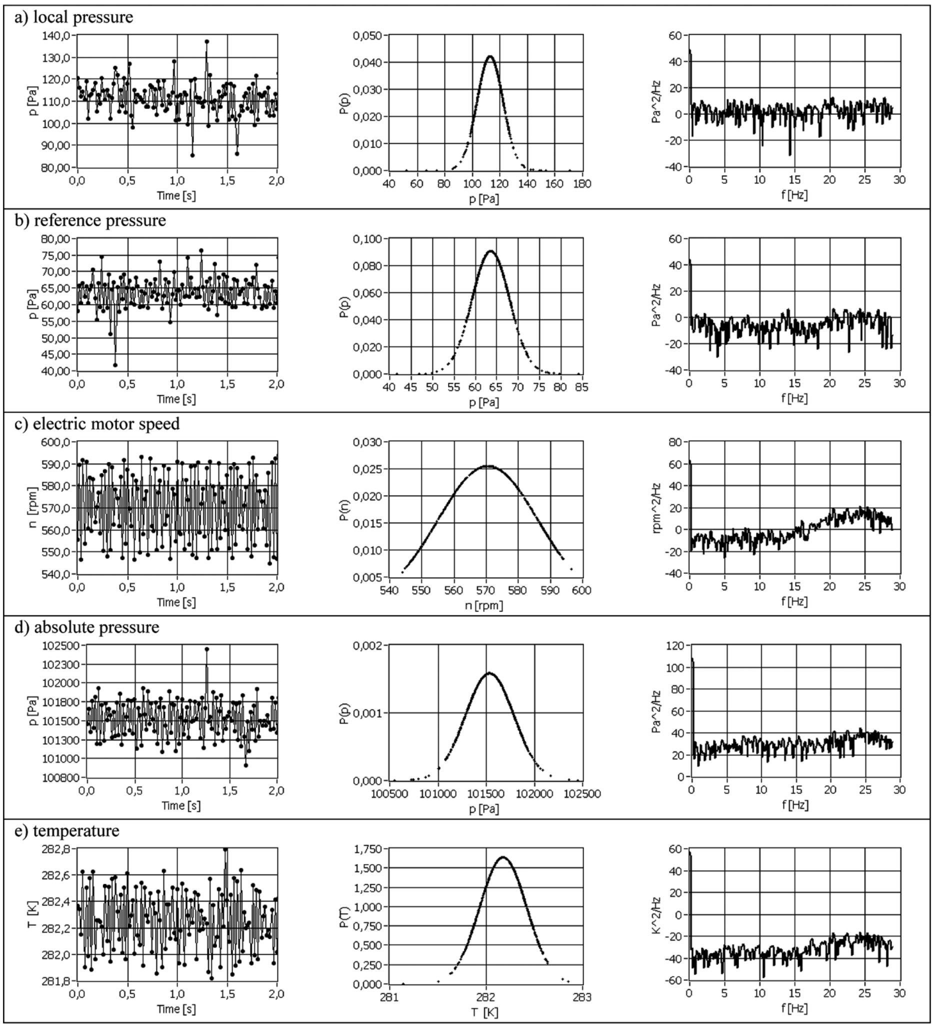

Fig. 11. Time history and characteristics for selected series with average air flux velocity 10 m/s

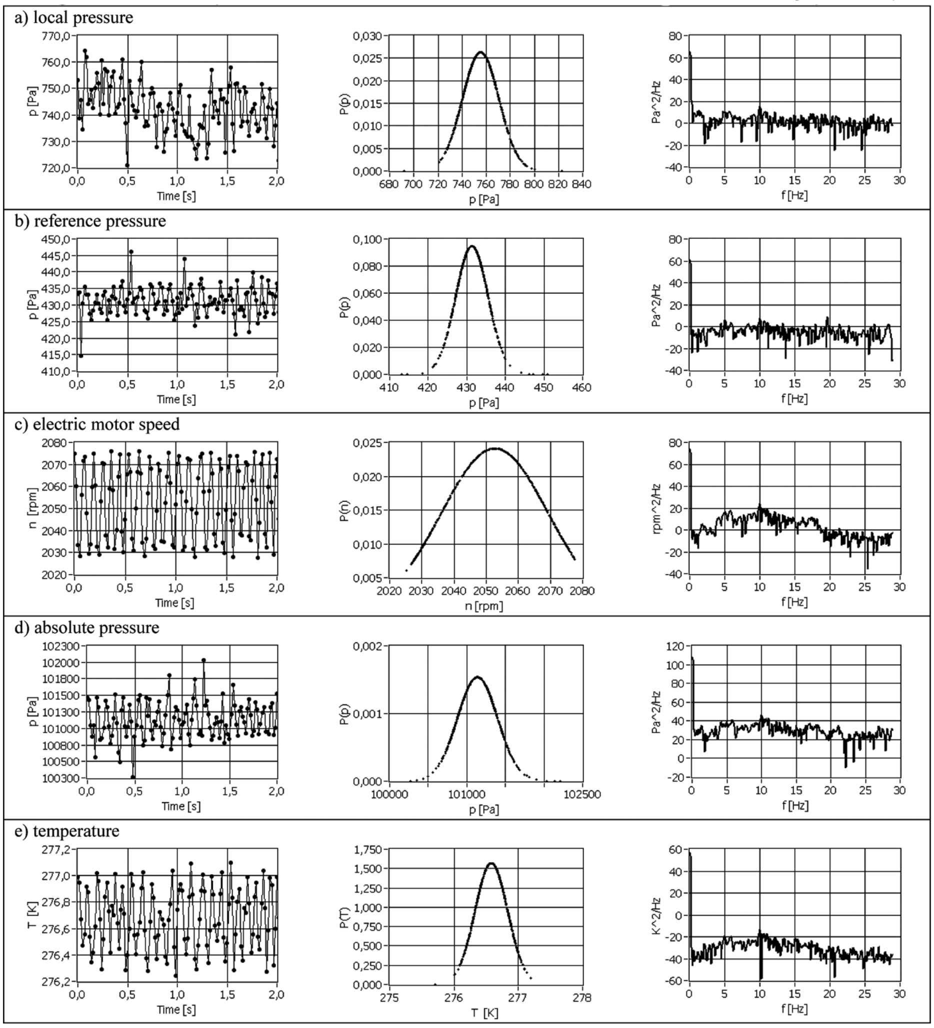

Fig. 12. Time history and characteristics for selected series with average air flux velocity 26 m/s

The analyzed signals can be characterized by normal probability density function. Its power spectrum density function is typical for random signals with a nonzero mean value. One cannot observe any dominating harmonic component in the power spectrum density diagrams. Similar characteristics were drawn for all measured signals.

Repeatability of the measurement can be described by mean value of the signals, and standard deviation can be used to investigate the scatter band of the measurements. The mean value $\bar{x}$ and the standard deviation σ for time series $x(t)=[x_1, x_2, x_{3,...,} x_n]$ can be written as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i; \sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}}, \tag{2}$$

where n is number of samples in time history x(t).

Taking into account that, for normal distributed sequences (with large number of samples), the level of confidence p=95% is reached for the scatter band Δx=2σ, the relative error δ can be defined as:

$$\delta = \frac{\Delta x}{\bar{x}} \cdot 100\% = \frac{2\sigma}{\bar{x}} \cdot 100\%. \tag{3}$$

Table 1 presents the results of analysis. It can be observed that the standard deviation is almost constant for signals from each sensor for all series – a stable noise occurs during measurement and the level of the measured quantity does not influence the scatter band of the signal. Maximum error is observed for local and reference pressure measurements and it varies from 18.7% to 3.0% for the local pressure, and from 14.2% to 1.8% for the reference pressure.

7. Summary

The presented system for automated control of the air flux measurements combines simple mechanical structures for sensor driving and flexible, high level programming environment. This system allows us to increase resolution of measurement, what can be very important for velocity profile determination for pipeline components where strong local disturbances of the air stream exist.

The system helps the user to define and control all necessary parameters and conditions: distance between limit sensors, necessary step distance between consecutive measurement points, average velocity of the air flux, temperature and pressures.

The applied linear module with stepper motor drive consists of simple and reliable mechanical structures and can be controlled without using additional sensors for detection of the actual flowmeter location. Easy and flexible control of the stepper motor's angular resolution makes it possible to increase the quality of velocity profile diagram.

The control program presents a modern idea of the virtual instrumentation. Information from sensors is used to start the stand, maintain constant conditions of the stand operation and to make decision on the time instants when the measurement should be performed. Graphical language of the LabVIEW allows for building a flexible control software. The user can

Table 1.

Mean value and standard deviation of the signals

Average air flux speed level	Series	Local pressure [Pa]			Reference pressure [Pa]			Electric motor speed [RPM]			Absolute pressure [Pa]			Temperature [K]		
		Mean	Std. Dev.	Error %	Mean	Std. Dev.	Error %	Mean	Std. Dev.	Error %	Mean	Std. Dev.	Error %	Mean	Std. Dev.	Error %
10 m/s	1	112,8	9,5	16,8	63,6	4,4	13,8	571	15,6	5,5	101536	252,0	0,5	282,2	0,24	0,2
	2	114,9	10,1	17,5	63,4	4,3	13,6	571	15,4	5,4	101528	244,3	0,5	283,4	0,24	0,2
	3	112,6	10,2	18,1	63,0	4,1	13,1	570	15,8	5,5	101523	246,0	0,5	283,5	0,24	0,2
	4	115,0	10,3	17,9	63,3	4,2	13,2	570	15,5	5,4	101517	230,4	0,5	283,4	0,23	0,2
	5	113,7	10,6	18,7	63,3	4,5	14,2	570	15,8	5,6	101533	237,7	0,5	283,4	0,24	0,2
	6	113,9	9,8	17,2	63,0	3,9	12,5	570	15,6	5,5	101521	234,6	0,5	283,3	0,24	0,2
	7	114,5	10,3	18,0	63,3	4,3	13,5	571	15,5	5,5	101527	238,9	0,5	283,1	0,24	0,2
	8	115,1	10,0	17,4	63,2	4,3	13,6	571	15,6	5,5	101535	251,4	0,5	282,9	0,25	0,2
	9	114,2	10,1	17,7	63,5	4,1	12,8	571	15,5	5,4	101524	249,1	0,5	282,6	0,25	0,2
	10	114,9	9,4	16,3	63,3	4,2	13,2	571	15,5	5,4	101532	239,2	0,5	282,4	0,24	0,2
18 m/s	1	357,5	9,5	5,3	203,3	3,8	3,7	1289	16,1	2,5	101387	230,7	0,5	279,6	0,24	0,2
	2	362,9	9,4	5,2	202,7	4,2	4,2	1289	16,0	2,5	101373	235,1	0,5	281,1	0,24	0,2
	3	360,8	9,2	5,1	202,7	4,2	4,1	1289	15,9	2,5	101375	241,2	0,5	280,9	0,25	0,2
	4	358,5	9,5	5,3	202,9	3,9	3,9	1289	16,0	2,5	101379	252,0	0,5	280,7	0,25	0,2
	5	361,0	9,0	5,0	202,8	3,7	3,7	1289	16,1	2,5	101381	232,3	0,5	280,5	0,24	0,2
	6	361,5	8,1	4,5	203,0	3,8	3,7	1289	16,1	2,5	101380	229,7	0,5	280,3	0,23	0,2
	7	362,8	8,4	4,6	203,2	4,0	3,9	1289	15,6	2,4	101368	250,1	0,5	280,3	0,24	0,2
	8	361,0	10,5	5,8	203,1	3,9	3,8	1289	15,1	2,3	101377	238,3	0,5	280,1	0,24	0,2
	9	359,9	9,8	5,5	203,4	3,9	3,8	1289	16,2	2,5	101382	250,0	0,5	280,0	0,26	0,2
	10	362,1	10,2	5,7	203,3	3,9	3,8	1289	16,1	2,5	101385	233,7	0,5	279,8	0,24	0,2

Table 1. c.d.

26 m/s	1	755,4	15,2	4,0	431,3	4,2	2,0	2053	16,5	1,6	101138	259,6	0,5	276,6	0,25	0,2
	2	746,8	12,3	3,3	429,0	4,0	1,9	2052	16,5	1,6	101135	251,3	0,5	277,8	0,26	0,2
	3	754,6	11,6	3,1	429,5	4,0	1,9	2052	16,6	1,6	101133	247,9	0,5	277,7	0,25	0,2
	4	750,6	13,6	3,6	429,2	4,2	1,9	2052	16,5	1,6	101125	258,5	0,5	277,8	0,25	0,2
	5	743,4	12,5	3,4	430,0	4,3	2,0	2053	16,5	1,6	101132	245,7	0,5	277,7	0,25	0,2
	6	748,3	11,6	3,1	430,1	4,0	1,8	2053	16,5	1,6	101135	245,7	0,5	277,5	0,25	0,2
	7	757,0	11,2	3,0	430,1	4,1	1,9	2053	16,6	1,6	101136	252,3	0,5	277,3	0,24	0,2
	8	753,1	11,2	3,0	430,2	4,0	1,9	2052	16,6	1,6	101127	253,5	0,5	277,2	0,25	0,2
	9	752,3	11,6	3,1	430,7	4,0	1,8	2053	16,6	1,6	101128	249,3	0,5	277,0	0,25	0,2
	10	749,4	12,8	3,4	431,2	4,2	2,0	2053	16,6	1,6	101119	249,2	0,5	276,8	0,25	0,2

introduce new sensors and drives into the system while functionality of the programming environment allows him to extend the existing program easily.

All of the analysed signals can be described as random signals with normal distribution. Statistical analysis shows that the system generates stable measurement signals with narrow scatter band of the measured quantities. For the investigated stand, the greatest inaccuracy appears in the case of average air flux velocity equal to 10m/s, but the error is lower than 20%.

Application of the new mechatronic concept of measurement environment significantly increased the final quality of the air flux velocity profile diagrams: measures could be performed faster, more precisely, with higher repeatability. In comparison with standard measurement systems, the proposed solution is more flexible, and allows for extension with new sensors and drives. It is possible to use specialized DAQ cards to connect different kind of components of measurement system in a single, compact system. Usually, the software is the main problem in such systems, because number of components, their operation and control are quite unique. It is necessary to use a number of dedicated software packages, in which the user can not make changes. Moreover, it is difficult to connect software for several components in one integrated system. The presented idea of "virtual instrumentation" makes it possible to overcome this problem. Moreover, this structure of control system can be easy applied for research of different physical phenomena.

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Automatyczny system do wyznaczania profilu prędkości dla strumienia powietrza

S t r e s z c z e n i e

W artykule zaprezentowano system kontroli przemieszczenia przyrządu do pomiaru profilu prędkości strumienia powietrza. W takich systemach z powodu dużej liczby punktów pomiarowych oraz ograniczeń wynikających z urządzeń do akwizycji danych konieczne jest przemieszczanie elementu pomiarowego. Czujnik przepływu jest przesuwany za pomocą modułu liniowego z napędem w postaci paska zębatego i silnika krokowego. Położenie i prędkość czujnika jest kontrolowane za pomocą autorskiego oprogramowania bazującego na idei tzw. „przyrządów wirtualnych”. Układ kontolno-pomiarowy pozwala operatorowi na obsługę stanowiska oraz automatyczne przeprowadzenie pomiarów. Szeroki zakres prędkości obrotowej i dużej rozdzielczości napędu w postaci silnika krokowego oraz elastyczność oprogramowania pozwala tworzyć efektywny system pomiarowy zapewniający dostatecznie dokładną lokalizację punktów pomiarowych przy optymalnym czasie pomiarów. Wykazano, że napęd liniowy z zastosowaniem paska zębatego i silnika krokowego może być efektywną alternatywą dla podobnych urządzeń z śrubą napędową.