360. A method for air flow measurement using high frequency vibrations

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Abstract. Air flow measurements are very important in technological processes. A new air flow measurement method is proposed. The method is based on the interaction of air flow with the end of a fiber waveguide located in the flow. As the result of this interaction, random high frequency vibrations are generated in the fiber waveguide. The stochastic transducers are created for the realization of this method. The stochastic transducer consists of the fiber waveguide, the piezoceramic element and the preamplifier.

Keywords: Air flow measurement, gas flow measurement, stochastic processes, transducers.

Introduction

Air flow measurements are very important in the industry. Methods that are currently in use can be divided into two groups: aerodynamic and kinematic [1]. Aerodynamic methods are based on the interaction of the force with some artificial obstacle in the flow. The methods of differential pressure, vortex, turbine as well as variable area flow rate measurement are classified as aerodynamic methods [2-4]. The method of the differential pressure is based on the use of constrictive devices (such as diaphragms, nozzles, Venturi nozzles, etc.), which create the difference of pressures. Kinematic measurement methods are based on the measurement of air flow velocity. If average air flow velocity or its profile in the space is known then the flow rate can be calculated. Thermo-anemometric, electromagnetic, ultrasound, laser flow rate measurement methods are kinematic ones [5-7].

The above-mentioned air flow methods are not able to operate in high-pressure, high-temperature environments. The air flow measurement method proposed in this paper is based on the interaction of the air flow with the end of the fiber waveguide located in the flow [8]. As a result of this interaction, random high frequency vibrations are generated in the fiber waveguide. The intensity of high frequency vibrations depends on the air flow velocity. The stochastic transducers are created for the realization of this method.

The purpose of this work is to propose an air flow measurement method, to create a measurement transducer and to investigate its metrological characteristics.

The structure and working principle of the stochastic transducer

The stochastic transducer consists of the fiber waveguide, the piezoceramic element and the preamplifier. The fiber waveguide can be made from various materials. In our case the waveguide is composed of a set of thin copper wires. Several fiber waveguides of different length were produced and analyzed.

The working principle of the stochastic transducer is based on the fact that air whirls are generated when air flow moves past the end of the fiber waveguide. They cause high frequency vibrations (fluctuations of the pressure) and their propagation in the waveguide. Random high frequency vibrations $\xi(t)$ with power spectrum G_ξ are generated in the end of the waveguide. High frequency vibrations propagated along the waveguide are converted into voltage with the help of piezoceramic element. Then this voltage is amplified with a preamplifier. The block diagram of the stochastic transducer is shown in Fig. 1.

The power spectrum of the signal of the transducer output is:

$$G_T(\omega) = G_\xi(\omega, P_p, V, T) \cdot |K_O(\omega)|^2 \cdot |K_W(\omega)|^2 \times$$
$$\times |K_P(\omega)|^2 \cdot |K_A(\omega)|^2, \qquad (1)$$

where $G_\xi(\omega, P_p, V, T)$ is the power spectrum of high frequency vibrations; P_p is the pressure fluctuation; V is air flow velocity; T is the temperature; $\left|K_O(\omega)\right|$ is the modulus of the acoustical transfer function of the space between the end of the fiber waveguide and the inner surface of the pipe. It depends on the diameter of the pipe, the pressure of the air, the sound speed in the air, and the diameter of the end of the fiber waveguide; $\left|K_W(\omega)\right|$ is the modulus of the transfer function of the fiber waveguide; $\left|K_P(\omega)\right|$ is the modulus of the transfer function of the piezoceramic element; $\left|K_A(\omega)\right|$ is the modulus of the transfer function of the preamplifier.

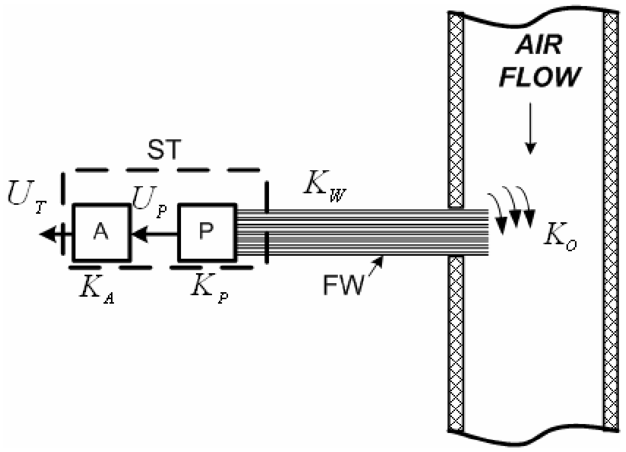


Fig. 1. Block diagram of the stochastic transducer: ST – stochastic transducer; A – preamplifier; P – piezoceramic element; FW – fiber waveguide; K_O – acoustical transfer function of the space between the end of the fiber waveguide and the inner surface of the pipe; K_W – transfer function of the fiber waveguide; K_P – transfer function of the piezoceramic element; K_A – transfer function of the preamplifier; U_P – voltage of the output of the piezoceramic element; U_T – voltage of the output of the stochastic transducer

Experimental results and discussion

It can be assumed that the resulting signal at the transducer output is random and has a Gaussian distribution because the elements of fiber waveguide interact with the flow and create elementary random signals at the transducer output. Propagation channel and air flow velocity will determine the power spectrum of this signal. A measurement system shown in Fig. 2 is formed in order to check this assumption.

A stable air flow is generated supplying air by the air compressor. This air flow is measured simultaneously using the stochastic transducer and the flow meter. A calibrated Venturi nozzle is used for flow measurement. The signals are amplified and visualized in the oscilloscope. Then the signals are measured using the Agilent Technologies digital oscilloscope 54622A with the sampling frequency 200 MHz and the 8-bit analog/digital converter. Afterwards the signals are fed to a computer. The Matlab software was used for data analysis.

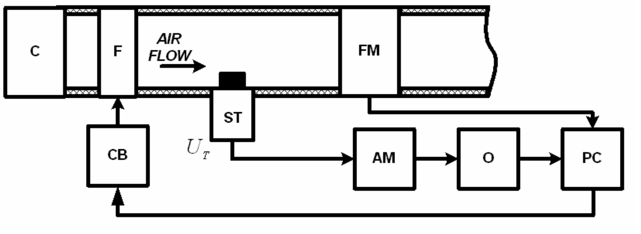


Fig. 2. The experimental measurement system: C – air compressor; ST – stochastic transducer; FM – flow meter; AM – amplifier; O – oscilloscope; PC – computer; F – air flap; CB – control block; U_T – voltage of the output of the stochastic transducer

To test whether a single distribution function obtained from an experiment is Gaussian, we run the Jarque-Bera test (Matlab, Statistics Toolbox) for goodness-of-fit at a significance level of 0.01 (99 % confidence level). The Jarque-Bera test evaluates the null hypothesis that the given sample data has the Gaussian distribution, against the alternative hypothesis that the same sample data does not have a Gaussian distribution. The distribution of the output signal of the stochastic transducer is presented in Fig. 3.

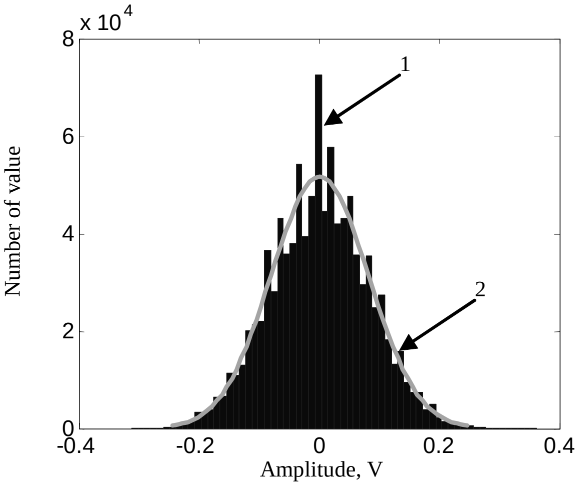


Fig. 3. The distribution of the output signal of the stochastic transducer – 1; the Gaussian distribution – 2. Results are obtained for the stable air flow velocity

The signal characteristics at the transducer output in the frequency domain as well as in the time domain are important. This paper presents the characteristics of the four created stochastic transducers. The calculated power spectrum densities for different stochastic transducers are given in Fig. 4 and Fig. 6. The signals of the stochastic transducers have resonance character and different shapes of the power spectrum densities as illustrated in Fig. 4 and Fig. 6. They depend upon the parameters of the stochastic transducers.

The relationship between the calculated power spectrum density and air flow velocity is presented in Fig. 4. It is demonstrated that the positions of the frequency band resonances do not depend upon the air flow velocity.

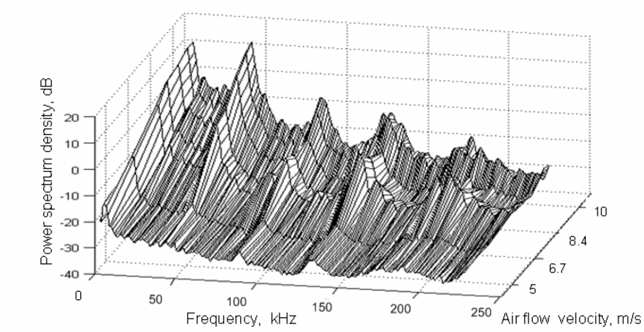


Fig. 4. The relationship between power spectrum density of the stochastic transducer signals and air flow velocity (the parameters of the stochastic transducer are presented in the Table 1 – 1)

Each stochastic transducer has analogous structure but different parameters. The structures of the stochastic transducers are presented in Fig. 6 (b,d,f) and Fig. 8. The values and the parameters of the stochastic transducers are presented in Table 1, Fig. 5 and Fig. 6.

Table 1. The parameters and values of the stochastic transducers

Notations	*d*, mm	Shape and *a*, mm	*m*, mm	*s*, mm	*l*, mm	Characteristics
1	4	□ 6	6	0.4	40	Figs. 4, 8,
2	1	○ 2.5	2.5	0.1	130	Figs. 6(a), 6(b)
3	4	○ 4	2.5	0.1	90	Figs. 6(c), 6(d)
4	4	□ 6	5	0.1	80	Figs. 6(e), 6(f)

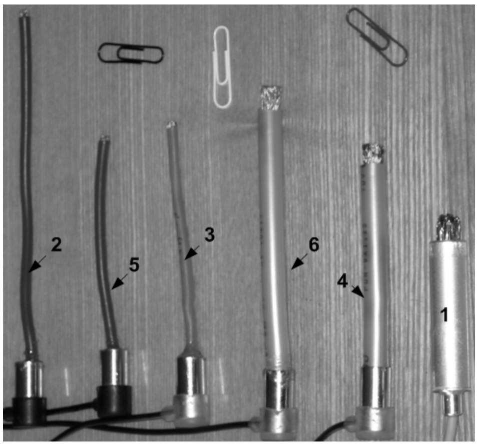


Fig. 5. Stochastic transducers

In order to evaluate the maximum speed of measurement it is necessary to establish the quadratic correlation interval. The measurement duration should be longer than the quadratic correlation interval [9]. For this reason the autocorrelation is calculated and it allows to estimate the necessary minimum measurement duration. The minimum measurement duration ensures statistically reliable and non-correlated measurement result.

The minimum measurement duration (the quadratic correlation interval) is evaluated according to the following equation:

$$\tau_{k.q} = \int_{0}^{\infty} \rho^2(\tau) d\tau , \qquad (2)$$

where $\tau_{k.q}$ is the quadratic correlation interval; $\rho\ (\tau) = \dfrac{R(\tau)}{R(0)}$ is the standard autocorrelation function. In our case $\tau_{k.q} \approx 0.5 \cdot 10^{-3}$ s. It can be noted that signals, obtained by dividing the measured signal into time intervals of a length $\tau_{k.q}$, do not correlate with each other [9-10]. The standard autocorrelation function of the stochastic transducer signal is presented in Fig. 7.

The measured output signal of the stochastic transducer is a noise type non-stationary signal. It can be described by the root mean square (RMS) value and the envelope [11]. RMS value of the stochastic transducer signal is calculated according to the following equation:

$$RMS = \sqrt{\frac{1}{N-1} \sum_{n=1}^{N} U_T^2(n)} , \qquad (3)$$

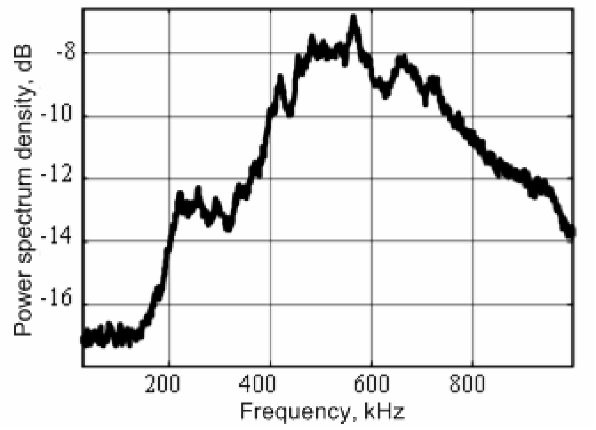
where $U_T(n)$ is the digitized time signal of the stochastic transducer; *N* is a number of points.

The signal envelope is a slowly varying function, which can be estimated by using various algorithms [11]. The signal envelope is calculated by dividing the output signal of the stochastic transducer into overlapping *M*-length segments and calculating their RMS:

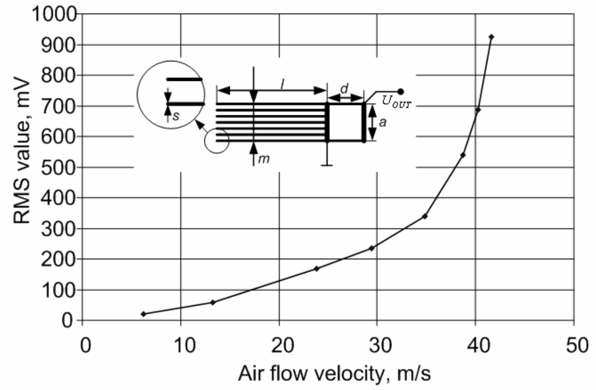
$$ENV(r) = \sqrt{\frac{1}{M-1} \sum_{n=r}^{r+M} U_T^2(n)},\ r = 1,2,...,(N-m-1), \qquad (4)$$

where *M* is the length of a segment; $U_T(n)$ is the digitized time signal of the stochastic transducer.

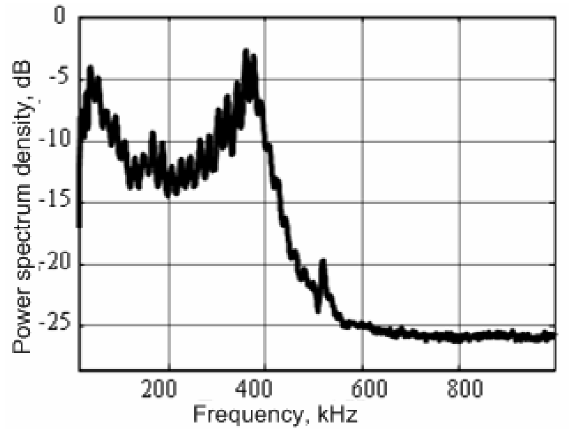
The calibration of the stochastic transducer showing the dependence of the output signal RMS of the stochastic transducer on the air flow velocity has been performed. The relationship between measured RMS values of the stochastic transducer signals and air flow velocity is presented in Fig. 8. The RMS values are measured 10 times at the each point of the calibration curve. The measurement duration for each RMS value is 5 ms. The averages of the RMS values (RMS_{AVE}) are used for the calibration curve (Fig. 8).



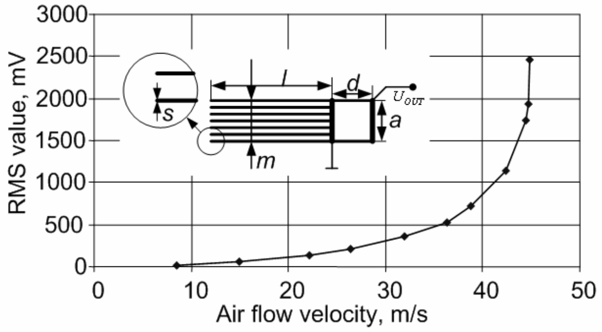
(a)



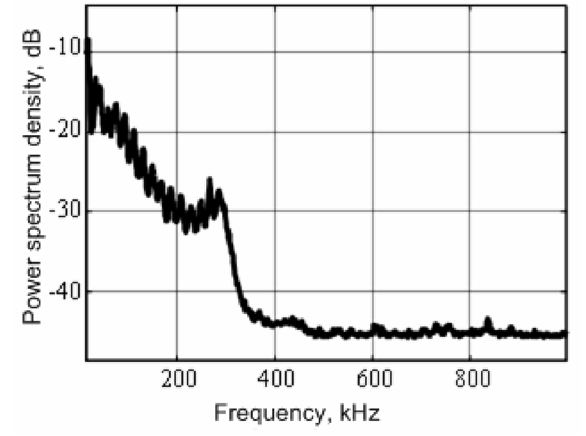
(b)



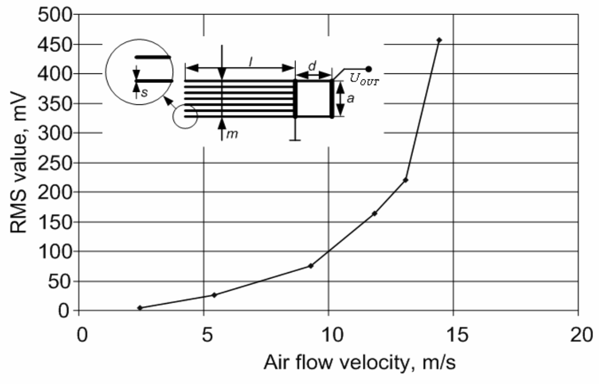
(c)



(d)



(e)



(f)

Fig. 6. (a), (c), (e) The power spectrum densities for different stochastic transducers; (b), (d), (f) the relationships between measured RMS values of the different stochastic transducers signals and air flow velocities; (a), (b) first stochastic transducer (Table 1 – 2); (c), (d) second stochastic transducer (Table 1 – 3); (e), (f) third stochastic transducer (Table 1 – 4)

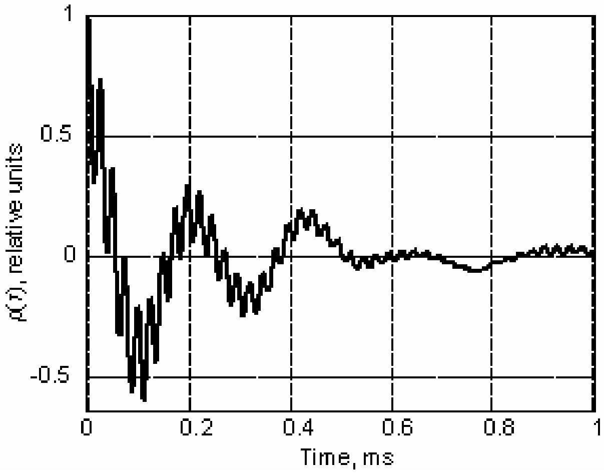


Fig. 7. The standard autocorrelation function of the stochastic transducer signal (the parameters of the stochastic transducer are presented in Table 1 – 1)

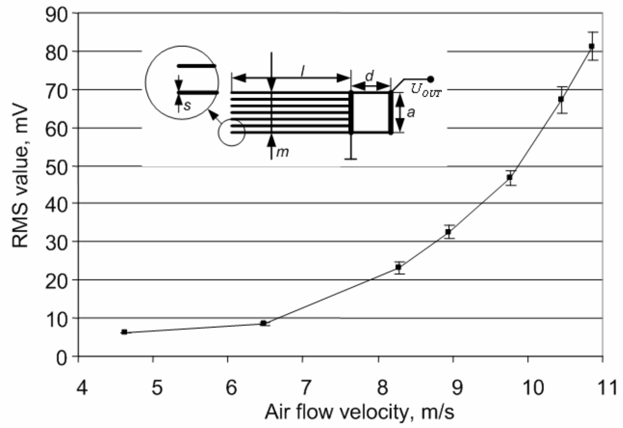


Fig. 8. The relationship between measured RMS values (with the uncertainties) of the output signals of the stochastic transducer and air flow velocity (the parameters of the stochastic transducer are presented in Table 1 – 1)

The uncertainties are estimated experimentally and calculated for each point of this curve. The RMS values at each point of the calibration curve are calculated according to:

$$RMS_{AVE} = \frac{1}{N}\sum_{n=1}^{N} RMS(n)\,, \tag{5}$$

where RMS_{AVE} is the average of the RMS values at each point; N is the number of the RMS values.

The standard uncertainty of the measured signal RMS values is calculated in the following way:

$$u_{RMS} = \sqrt{\frac{1}{N(N-1)}\sum_{n=1}^{N}(RMS(n) - RMS_{AVE})^2}\,. \tag{6}$$

The expanded uncertainty of the measured signal RMS values can be obtained:

$$u_{EXP} = k \cdot u_{RMS}\,, \tag{7}$$

where k is the coverage factor.

The coverage factor will be k =2, providing a level of confidence of approximately 95%. The results of the calculated uncertainties of the RMS values are presented in Table 2 and in Fig. 8.

One of the most important transducer properties is its dynamics. The measurement system shown in Fig. 2 is used in order to evaluate the transient response of the stochastic transducer. The air flap opens and closes the pipe (it is used to change the air flow). Fig. 9 shows the transient response of the stochastic transducer. This transient response enables to define a settling time t_s. The settling time is used to evaluate the transient response characteristic of the stochastic transducer. It is defined as the time for RMS value to vary from 0 – 90 % of steady-state value. For the present stochastic transducer t_s is approximately 20 ms as is indicated in Fig. 9. The transient change in the air flow velocity is shorter than the settling time of the stochastic transducer.

A filter that distinguishes a certain frequency band can be used in order to increase signal-to-noise ratio. In the case of the analyzed transducer (Fig. 4), the best signal-to-noise ratio is equal to 39 if the filter of 30 kHz – 60 kHz frequency band is used.

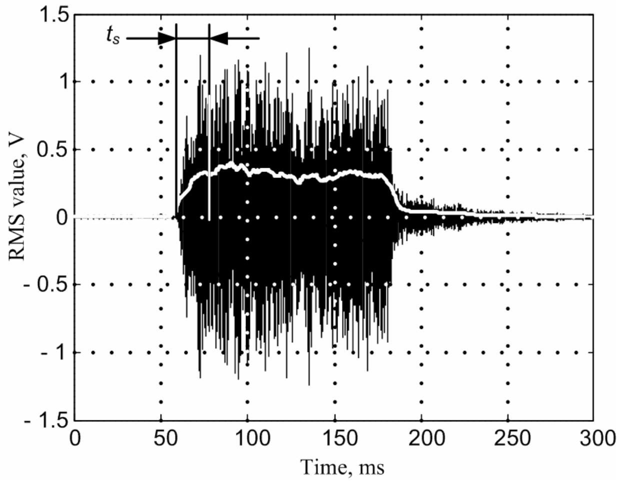


Fig. 9. Dynamic characteristic of the stochastic transducer (white line indicates the envelope of the measured signal; the parameters of the stochastic transducer are presented in Table 1 – 1).

Table 2. The results of the calculated uncertainties of the RMS values at each point of the calibration curve (Fig. 8)

Flow velocity, m/s	4.69	6.48	8.29	8.96	9.77	10.44	10.86
RMS_{AVE} , mV	6.10	8.61	23.25	32.52	46.81	67.14	81.26
u_{RMS} ,mV	0.0467	0.1961	0.78	0.87	1.02	1.70	1.86
Coverage factor	2	2	2	2	2	2	2
u_{EXP} , mV	0.0935	0.3922	1.56	1.74	2.05	3.40	3.73
u_{EXP} , %	1.53	4.55	6.71	5.35	4.38	5.06	4.59

Concluding remarks

A new air flow measurement method was proposed as well as stochastic transducers for air flow measurement were developed. Transducers are based on high-frequency vibrations measurement. It is demonstrated that these stochastic transducers have a simple construction and their working principle is based on the generation of high-frequency vibrations in the fiber waveguide. The stochastic transducers can be used for high-pressure, high temperature environments since fiber waveguide is made from copper. It is estimated that the settling time of stochastic transducer is approximately 20 ms and the accuracy of the measurement of air flow velocity is approximately 7 %.

Further work will be devoted to investigate the application of the stochastic transducer for the measurement of the different ranges of air flow velocity. Investigation of the application of the stochastic transducer under different environmental conditions is also in the scope of our future research.

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