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Dynamic Error Correction Method in Tachometric Anemometers for Measurements of Wind Energy

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Abstract: Measurements of air flow velocity are essential at every stage of the design, construction and operation of wind turbines. One of the basic measurement tools in this area is the tachometric anemometer, which is based on the simple physical phenomenon of the air kinetic energy exchange with a rotating measuring element. Tachometric anemometers have favorable operational features and good static metrological parameters. However, in the case of fast-changing flows, the measurement is burdened with a significant dynamic error, and the measured average value of the velocity is overestimated. This article presents the concept and results of pilot studies of a dynamic error correction method of tachometric anemometers. The correction consists of the precise measurement of the rotor's rotational velocity and determination of the measured air velocity, taking into account the dynamics of the instrument. The developed method can be used in tachometric anemometers intended for laboratory, technical and industrial measurements in time-varying flows. One of the important application areas is the measurement of wind energy.

Keywords: wind energy; air velocity; tachometric anemometer; dynamic error; measurement correction

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1. Introduction

Measurements of the air flow velocity are of key importance at each stage of the implementation of wind energy projects [1]. Anemometric measurements are used in laboratory tests in the process of modeling and optimization of devices [2]. When selecting the location of turbines and wind farms, comprehensive measurements of the characteristics of local air flows are necessary [3]. This applies to daily and annual characteristics, flow stability, turbulence intensity, spatial profiles, wind shear and other parameters [4]. Anemometric measurements are also important for making long-term forecasts of the energy efficiency of wind farms [5]. At the stage of turbine operation, it is necessary to constantly monitor wind parameters, both in terms of optimizing energy efficiency and predicting threats and failures, and in the process of maintenance and repairs [6,7]. Measurements of the flow velocity are also extremely important in the field of ecology and research on the impact of wind turbines on the environment, animals and humans [8].

Instruments used in wind energy for anemometric measurements are based on the use of various physical phenomena. Depending on the metrological requirements, mechanical anemometers, pressure tubes, thermal anemometers, ultrasonic anemometers, and optical anemometers are used [9]. The basic type of anemometer used in technical and industrial measurements is the mechanical tachometric anemometer.

The name "tachometric anemometers" was introduced by the author to refer to the whole group of mechanical anemometers having a rotating measuring element. These anemometers have various structures, but the common element is the mechanical rotor rotating under the influence of air flow. An overview of the design of tachometric anemometers and their applications in the mining industry, which is interesting from the point of view of development, is presented in [10]. The flow velocity is measured indirectly by measuring the rotational speed of the rotor. Depending on the purpose, the rotors of tachometric anemometers have different shapes, and use different methods of reading the rotor rotational speed and different systems of signal processing, linearization, filtration and averaging.

In addition, regarding wind energy, tachometric anemometers are one of the basic types of measuring instruments. The work [11] analyzes the operation of the cup-anemometer group over long time intervals for the purpose of determining the operating conditions of wind energy. The signals of anemometers placed at different heights in one of the meteorological stations in Saudi Arabia were examined. The analysis of the signals from cup anemometers allowed for the formulation of conclusions concerning the influence of the height of the anemometers' placement on the tower on the measurement results. The influence of the shading of the measuring tower was investigated. Annual mean, median, and standard deviation values of the wind velocity were found to be substantially the same for sensors placed at the same location at all altitudes. Based on the analysis of the measurement results, specific, optimal types of wind turbines were selected for the tested location. The article [11] proves the thesis that metrological issues and the properties of measuring instruments constitute an important element of wind energy optimization.

Tachometric anemometers are based on the exchange of kinetic energy between the tested gas stream and a rotating measuring element. The most commonly used measuring elements are a vane, cup, turbine or propeller rotor. Other constructions of the measuring element can also be encountered. The angular velocity of rotation of this element is a measure of the flow velocity. Tachometric anemometers are often used due to their simple operating principle and good static parameters. The main advantages of these instruments are: simple and durable structure; linear dependence of rotor velocity on flow rate; low sensitivity to other flow parameters, such as temperature, pressure and humidity; their averaging properties; and low price of the devices.

One of the disadvantages of tachometric anemometers is that they do not allow the determination of the wind direction. Additional mechanical sensors or other measurement methods, such as ultrasonic anemometers [12], must then be used. However, this type of anemometer is currently less commonly used than mechanical tachometric anemometers in wind energy measurement. One of the relevant factors here is certainly the relatively high price of ultrasonic anemometers, which, however, due to studies such as those presented in [12], may soon change.

However, the main disadvantage of mechanical tachometric anemometers seems to be their poor dynamic properties. The dynamic properties of mechanical tachometric anemometers are an important issue analyzed in many scientific publications. The work [13] is dedicated to the issues of construction and dynamics of cup anemometers. The anemometer with three cups, which is the author's original design, is tested here. The construction of the equation of motion for the rotor of the vane anemometer and the study of the effect of overestimating the average velocity measurement is included in the article [14], and is the basis for considerations in subsequent publications. In article [15], the analysis covers the transient states of the turbine anemometer response to the test excitations. The article [16] is devoted to measurements in fast-changing and pulse flows with the use of an anemometer with a turbine. An overview of the applications of anemometers in research on turbulent flow issues is presented in [17]. In many articles analyzing dynamic processes, selected detailed metrological issues are considered. The work [18] presents the key issues related to the measurement of atmospheric turbulent flows. The use of mechanical anemometers for the measurement of time-varying flows in liquids is discussed in [19]. The work [20], by comparison, is devoted to the issue of measurements in pulsed fluid flows with the use of miniature turbines. The influence of air density on the calibration of the anemometer is the subject of the work [21], while in the article [22], using CFD techniques, the influence of the medium viscosity on the work of the anemometer is analyzed. In the work [23], an attempt was made to apply artificial neural networks to model static and dynamic phenomena for the cup anemometer. The analysis of the anemometer response to acoustic fluctuations is discussed in the article [24].

The relatively large inertia of the measuring element implies a significant dynamic error in the measurements of fast-changing flows. This error overestimates the measured average velocity and limits the applicability of these anemometers in velocity fluctuation studies [25]. A method of improving the dynamic properties of anemometers through the use of active control in a feedback loop was previously developed [26]. However, this method requires a significant expansion of the hardware structure of the instrument. The author of this article also developed a method of software correction of the output signal from the thermal anemometer [27]. However, this article presents a new method of dynamic error correction for tachometric anemometers. It should be emphasized that, in this article, we deal with only one element concerning the assessment and improvement of the parameters of tachometric anemometers. The aim of the article is to present the assumptions of the new method, the possibility of its technical application, and the preliminary, pilot results of the research verifying the method. Comprehensive tests of the prototype anemometer in a wide range of changes in flow parameters and other metrological parameters were not carried out. The aim of the article is to present the theoretical foundations of the method and an exemplary application to the constructors of apparatus and measuring instruments in order to enable its application in the developed instruments intended for measuring specific issues. Each device, depending on the shape and parameters of the rotor and the signal processing algorithm used, will have specific metrological parameters. The determination of these parameters and the associated measurement uncertainty are an important element of a correct measurement process [28].

2. The Method of Dynamic Measurement Error Correction of Tachometric Anemometers

In order to analyze the proposed method, let us consider a simplified tachometric anemometer model using the rotor kinetic energy balance [29]. The change in kinetic energy E of the rotor over time $\mathrm{d}t$ is related to the transfer of kinetic energy by the gas mass part $\mathrm{d}m$ acting on the rotor in this time:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{\mathrm{d}m(V^2 - v^2)}{2\mathrm{d}t} \tag{1}$$

Velocity V of the gas reaching the rotor is the flow velocity to be measured, and v is the velocity of the gas mass part $\mathrm{d}m$ leaving the rotor in the time $\mathrm{d}t$. In the presented model, it is assumed that the velocity v is a linear function of the angular velocity of the rotor ω, with the proportionality coefficient a depending on the rotor shape:

$$v = a\omega. \tag{2}$$

This assumption [29] results from the fact that the gas mass $\mathrm{d}m$ acting on the rotor is linearly controlled by the rotor angular velocity, similarly to the case of a fan. The mass of gas that exchanges kinetic energy with the rotor at time $\mathrm{d}t$ is given by the equation:

$$\mathrm{d}m = \rho s v \mathrm{d}t, \tag{3}$$

where:

ρ—gas density,
s—cross-section of the rotor in the plane perpendicular to the velocity V. Substituting (2) and (3) into (1), and denoting the moment of inertia of the rotor as I, we obtain the relationship:

$$I\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{\rho s a}{2}(V^2 - a^2\omega^2). \tag{4}$$

This equation is a simplified dynamic mathematical model of the rotor of a tachometric anemometer. It shows the dependence of the rotor angular velocity ω on the measured flow velocity V. The parameters of Equation (6) I, s, a, are the quantities characterizing the mechanical properties of the rotor, while the density ρ characterizes the tested gas.

A typical measurement with a standard tachometric anemometer consists in placing the anemometer rotor in the tested flow and measuring the mean angular velocity of the rotor during a given period. The value v_1 of the measured flow velocity is determined in accordance with Model (4), assuming that the measurement is performed in the steady state:

$$v_1 = a\omega. \tag{5}$$

The parameter a of Equation (5) is most often determined during instrument calibration in a wind tunnel. In many cases, the static relationship (5) additionally takes into account the intercept, higher powers of angular velocity or complex algebraic expressions [30]. This allows the static error to be minimized.

Such a measurement in fast-changing flows is always burdened with a dynamic error. This error is caused by not taking into account the dynamic states described by Equation (4). This phenomenon overestimates the measured average velocity and limits the possibility of using tachometric anemometers to measure velocity fluctuations. The proposed method of correction of the dynamic measurement error of tachometric anemometers consists in determining the v_2 value of the measured flow momentary velocity from the dynamic Model (4) in accordance with the relationship:

$$v_2 = \sqrt{a^2\omega^2 + b^2\frac{\mathrm{d}\omega}{\mathrm{d}t}}, \tag{6}$$

where:

$$b = \sqrt{\frac{2I}{\rho s a}}. \tag{7}$$

In the process of calibrating the anemometer, both the static parameter a and the dynamic process parameter b should be determined. Note that both parameters have a length dimension. The momentary angular velocity of the rotor in the presented method must be measured with high accuracy and time resolution. This makes it possible to determine the time derivative of the angular velocity of the rotor with sufficient approximation for the required accuracy of the measurement.

Standard, commercial tachometric anemometers measure the angular velocity or rotor rotation frequency with a low time resolution [31]. The maximum number of counted pulses during one revolution is usually several dozen, and is typically the number of pulses related to the number of rotor segments, or the number of marks of the coding disc placed on its axis [32]. Therefore, it is not possible to apply the proposed method directly to standard instruments. However, magnetic, precision angular position sensors are now easily accessible and cheap. Their advantages are a resolution of 12 to 14 bits per revolution and a very short conversion time. The use of such sensors enables the implementation of the proposed method in tachometric anemometers.

3. Experimental Verification of the Method

The block diagram of the test stand for the verification of the method of correcting the dynamic error of the anemometer is shown in Figure 1.

The tested tachometric anemometer was a vane anemometer type. The rotor radius is about 45 mm, with a shape comprising eight blades with an angle of inclination of 45°. On the rotor axis there is a magnet co-operating with the angular position sensor with a resolution of 14 bits, model AS5147 from AMS. The sensor through the SPI interface and the Controller block sends information about the rotor position to the Computer. A sampling time of 5 ms was used. The rotor parameters of Equation (6) were experimentally determined in a calibration wind tunnel stand [33] with results of a = 34 mm, b = 281 mm. In order to carry out dynamic tests, the anemometer is placed in a test stream of air. The test flow is generated by a wind tunnel equipped with a fan, a honeycomb stream straightening system and an outlet nozzle. It is not an easy task to create a reference flow for the dynamic testing of anemometers. It is practically impossible to build an experimental stand that produces a variable in time flow with preset shape, amplitude and frequency parameters. Various methods are used to evaluate the dynamic parameters of anemometers. One of these is to develop a good anemometer model and evaluate the dynamic properties on the basis of simulation tests. However, this is an approximate method. Various modulation methods are used to generate the actual test stream. Depending on the required parameters, it may provide appropriate control of the tunnel drive motor, swinging shutters, vibrating elements (membranes) on the walls of the tunnel, or elements causing vortexes of the stream. In our tests, the flow is modulated by a rotating shutter. The shutter is made in the form of a metal mesh semicircle. For half the period of spinning the shutter, the air stream is free, and for the second half of the period, it is dumped with a mesh. The mesh lowers the stream velocity by about 15%. In this way, a periodic, quasi-rectangular air flow is generated. The air velocity and shutter frequency are set from the Computer via the Controller block. Additionally, the system is equipped with a hot-wire Constant-Temperature Anemometer [34], which is used to control the test flow. This anemometer allows for observation of the shape of the generated flow, and measurement of its amplitude and frequency parameters. A hot-wire sensor made of thin tungsten wire having a diameter of 5 μm and resistance at a reference room temperature of 6 Ω was used here. The sensor cooperates with the Constant-Temperature Anemometer with a filament overheating ratio of 1.8. This allows a 20 kHz bandwidth in the tested velocity range to be obtained. This is at least one thousand times more than the frequencies of interest for tachometric anemometers. The Constant-Temperature Anemometer was calibrated in a reference tunnel in the range of 0.5 to 20 m/s. The uncertainty of calibration is 2%. The signal from the anemometer is converted into a digital signal, which was linearized and filtered in the computer.

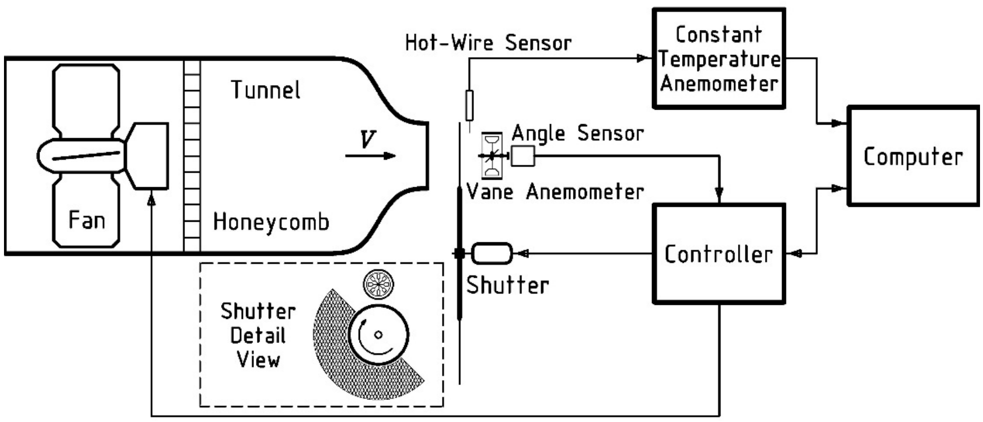

Figure 1. Diagram of the test stand.

Initial tests were carried out for two average velocity values: 2.5 and 12.5 m/s. Four shutter frequencies were used: 0.2, 1, 5 and 25 Hz. The change in the angular position of the anemometer rotor over time was recorded by the Controller and Computer. On this basis, the angular velocity of the rotor was calculated by dividing the difference in angular positions by the sampling time. Its derivative was calculated from two successive values of the rotor angular velocity. In order to minimize signal noise, the algorithm of inertial averaging of the derivative with a time constant of 10 ms was used. The measurements carried out in this way, together with the determined parameters, made it possible to calculate the measured flow velocity. The value of v_1 of the measured velocity was calculated for the standard method from the dependence in Equation (5). Using the proposed method of dynamic correction, the value of v_2 from Equation (6) was also calculated. The measurement results for the average flow velocity of 2.5 m/s are shown in Figure 2.

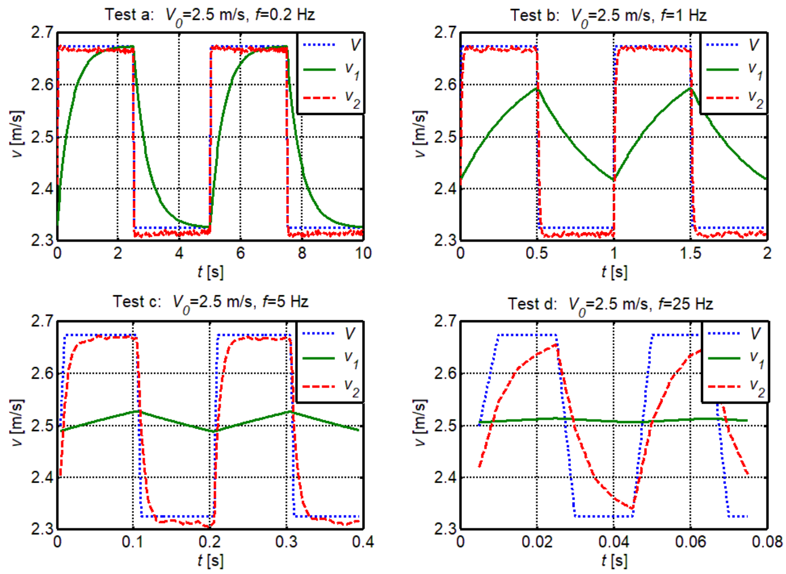

Figure 2. Measurement results for the average velocity of 2.5 m/s and the frequency of flow modulation: (**a**) 0.2 Hz, (**b**): 1 Hz, (**c**): 5 Hz, (**d**): 25 Hz.

For the standard measurement method, waveform v_1, a significant dynamic measurement error in relation to the shape of excitation V is visible. The error is caused by a relatively large rotor inertia. At 1 Hz, the waveform still roughly reaches the excitation value. For the frequency of 25 Hz, the variability of the waveform v_1 is practically invisible. In contrast, we observe an overestimation in the average velocity. Based on the response time to the rectangular excitation, the frequency bandwidth of the anemometer was estimated to be 0.07 Hz in this case.

It can be seen from the v_2 waveform that the application of the described correction method allows for a significant reduction in the dynamic error. The waveform for 1 Hz is practically in line with the excitation, and for 5 Hz the dynamic error is still small. The estimated frequency bandwidth here is around 2.75 Hz. It is therefore 40 times wider than that of the standard method. A small amount of noise is visible on waveforms calculated using the presented correction method. It is inseparably related to the principle of calculating the derivative from the discrete signal.

Similar tests were carried out for an average velocity of 12.5 m/s. The results are shown in Figure 3.

The dynamic error of the waveform v_1 for the standard measurement method is smaller than that previously found due to the rotor inertia. At 0.2 Hz, the waveform roughly reaches the excitation value. For the frequency of 25 Hz, the variability of the waveform is still well observable. Figure 3d clearly shows the overestimation of the average velocity above 12.5 m/s. Due to the small amplitude of the excitation changes, amounting to about 15%, the increase in the average velocity is not very large. Based on the response time to the rectangular excitation, the frequency bandwidth of the anemometer in this case was estimated to be 0.36 Hz.

The course of the measured velocity v_2 shows also a significant reduction in the dynamic error. However, the waveforms are similar to those obtained for the lower velocity. For frequencies up to 5 Hz, the waveform is practically compliant with the excitation. A slight overshoot is observed here. The estimated frequency bandwidth is approximately 3.1 Hz. Thus, it is almost 10 times greater than for the standard method. In the conducted tests, the change in the corrected anemometer bandwidth with the increase in f the flow velocity is rather low. This may be related to the applied method of inertial averaging of the derivative of the angular velocity of the rotor. Here, we deal with a necessary compromise between the bandwidth and the noise in the measured signal.

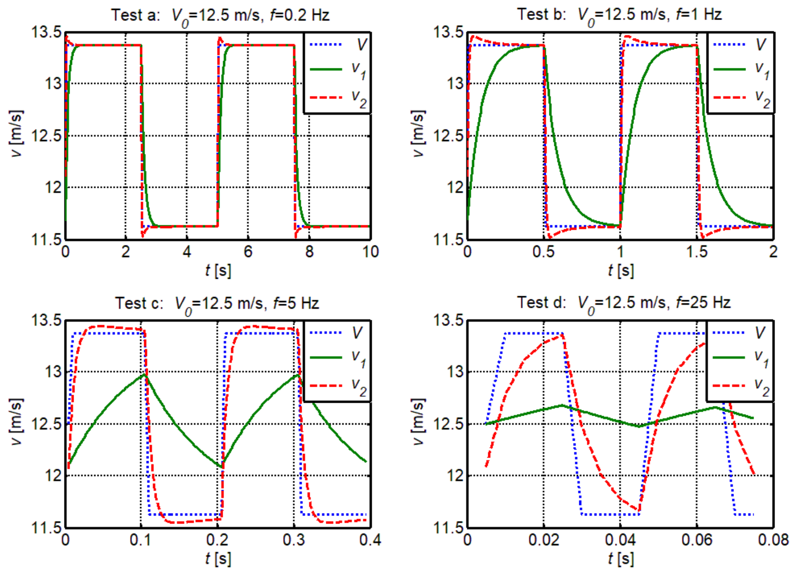

Figure 3. Measurement results for the average velocity of 12.5 m/s and the frequency of flow modulation: (**a**): 0.2 Hz, (**b**): 1 Hz, (**c**): 5 Hz, (**d**): 25 Hz.

This article presents the results of verification research for two velocity values and four flow pulsation frequencies. These results are representative of the whole conducted research and allow for the formulation of general, presented conclusions regarding the confirmation of the presented method. The values of velocities and frequencies were selected in the range that reflects the actual conditions of using tachometric anemometers in typical applications. It is necessary to emphasize once again the fundamental difficulties associated with testing the dynamic properties of anemometers. The author is aware that the presented experimental studies can be extended, both in terms of the range of parameters and the methodology of research and apparatus. However, according to the author, the results of the research are fully acceptable as confirmation of the effectiveness of the proposed method. Further research, if it is going to be conducted, should concern the application of the method in devices designed for, for example, serial production.

4. Conclusions

The article presents the concept of a method of correction of the dynamic measurement error of tachometric anemometers. The results of the pilot studies carried out for the vane anemometer confirmed the adopted assumptions and the effectiveness of the method.

Measurements of velocities fluctuations using tachometric anemometers are disturbed by a dynamic error, and the measured average velocity is overestimated. However, it is possible to correct these errors by processing the output signal. The correction algorithm based on the dynamic model of the anemometer enables the extension of the frequency bandwidth and reduction in the dynamic error. The algorithm requires measuring the angular velocity of the rotor with high accuracy and time resolution, and calculating the derivative of the angular velocity. The calculated derivative of the angular velocity of the rotor is used for the measurement correction. The quality of the estimation of this quantity affects the effectiveness of the method. It is important to optimize the derivative calculation algorithm to minimize the dynamic error, but also the noise of the measurement signal.

It is not a trivial issue to create a reference flow for testing the dynamic properties of anemometers. For the purposes of the research presented in this article, a rotating diaphragm modulating the air stream was used. To control the test flow, a Constant-Temperature Anemometer with a hot-wire sensor having a diameter of 5 µm was used. The tests showed a significant reduction in the dynamic error and the extension of the frequency bandwidth of the vane anemometer by about 40 times for the velocity of 2.5 m/s, and 10 times for the velocity of 12.5 m/s. The quantitative parameters of the improvement in the dynamic properties of the measurement are mainly related to the quality of the estimation of the derivative of the angular velocity of the rotor. The presented method and its possible variants can improve the dynamic parameters of tachometric anemometers used in the measurement of fast-changing flows. This requires the use of a high-performance angular velocity sensor and signal processing system in these anemometers.

The article concerns only one selected problem in the field of tachometric anemometers. It proposes an original method of minimizing the dynamic error in the measurement of flows that vary in time. The issues related to mechanical anemometers vary and cannot be discussed in detail in the case of the pilot verification tests presented here. Issues such as total measurement uncertainty, directional characteristics of the anemometer, influence of the medium parameters on the measurement, invasiveness of the sensor, and many others are considered in other articles on measurements with mechanical anemometers. The article is a preliminary conceptual work and presents pilot research confirming the assumptions of the method. The implementation of the presented method in actual, commercial measuring instruments intended for laboratory, technical and industrial tests [35] requires taking into account individual metrological requirements and parameters of the anemometer. These works should take into account the parameters of the tested flow, the required metrological properties, the type, structure and parameters of the rotor, and other individual features.

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