UDC 629.7.058 **doi: 10.26906/SUNZ.2023.4.040**

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COMPARATIVE ANALYSIS OF THE AIR FLOW VELOCITY DETERMINATION METHODS

Abstract. Study subject. The article presents the comparative analysis results of air flow speed measuring methods by using various physical principles (methods) of obtaining primary information. **The task** is to perform a comparative analysis of air flow speed measuring methods that based on pressure drop, as well as mechanical, thermoelectric, ultrasonic, laser and vortex methods. **The goal** is to assess the considered methods prospects for aircraft use. **The obtained results:** A comparative analysis of the main methods for airspeed measuring has been performed, and the obtained results have allowed to evaluate advantages and disadvantages of the considered methods. **Conclusions:** The performed comparative analysis results provided the conclusion that search for an optimal method remains actual task. The search of optimal method that will enhance the accuracy of airspeed determination with minimal implementation costs requires further research in this direction.

Keywords: aircraft, air speed, air velocity, anemometer, pressure tube, Pitot tube.

Introduction

Accurate determination of the air flow velocity is a prerequisite both for the safe piloting of the aircraft and for the performance of various information and navigation calculations. Everybody knows, flying an aircraft at a speed below the minimum permissible speed can cause stability and controllability losses. And the speed increase above limits can lead to aircraft destroying. In aircraft control systems there are several speed measuring methods are used depending on the tasks: relative to the air flow (Air Speed) and relative to the earth's surface (Ground Speed). Air pressure measuring methods are implemented to measure Air Speed. Doppler and inertial methods are used and to measure Ground Speed.

Air speed (V) is an object speed, such as an aircraft, relative to the air. [1]. The results reliability term in the article is understood as a synonym for the concepts of authenticity, match to the true value.

It should also be noted that the "human factor" plays a significant role in the functioning of the automated aircraft control system, along with the flight Automatic Control System (ACS), as the most important condition affecting the level of aircraft flight safety. The "human factor" manifests itself in errors, omissions or miscalculations that the pilot makes during the flight. As analysis of commissions conclusions created to investigate air crashes causes shows that one of the reasons for the pilot's erroneous decisions was an incorrect aircraft airspeed measurements results receipt. It was associated with shortcomings in the design of the Pitot tube, which is subject to the environment influence [2].

The goal of this article is to perform a comparative analysis of methods for air flow velocity measurements based on pressure drop method, as well as mechanical, thermoelectric, ultrasonic, laser and vortex methods, and to evaluate the perspective of the considered methods to apply on various aircraft.

Air Velocity Measurement Methods Analysis

There are few methods of air flow measurement. These can be measured by using of direct (mechanical) method or indirect (electrical, sonic or pressure drops, etc.) method (Fig. 1).

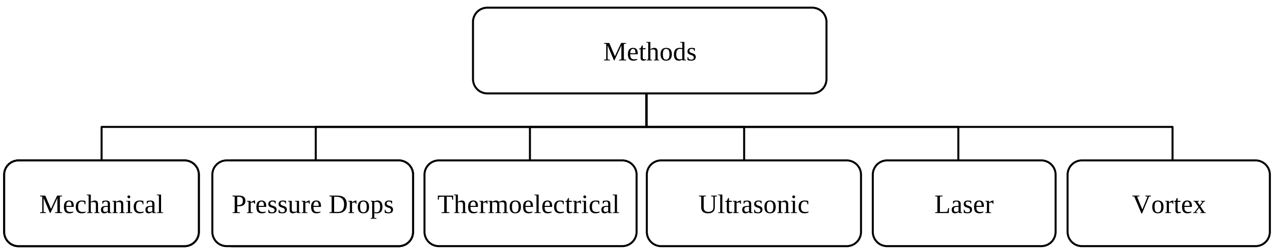

Fig. 1. Methods for Measuring Air Velocity

Induction (electromagnetic) methods based on the principle of measuring flow conductivity will not be considered in the article, as well as float and Coriolis flow meters because air does not have a necessary physical characteristic for measurement.

Mechanical Methods

A device build by this method measures the speed and direction of the airflow by Rotating Vane or Cap in the airflow.

The rotating velocity in this case is proportional to the air velocity and is calculated as [28]:

$$v = \omega * r,$$

where v - linear speed (m/s), ω - angular speed (radians/s), r - radius of the rotation (m).

Mechanical anemometers have a rather low accuracy, especially at low wind speeds. In order to analyze the real abilities of this method as a test device, Davis Vane Anemometer was chosen [24]. Fig. 2 shows the measured data scatter approximation.

The calculation of the values plotted on the graph was done with using of the well-known formula [23] for calculating the relative error:

$$K = |V_{True} - V_{Indicated}| / |V_{True},|,$$

where $V_{Indicated}$ – measured air flow velocity by the tested anemometer (m/s), V_{True} – true air flow velocity (m/s). The measuring instruments error used to calculate the true flow velocity was not considered, since their values are in all cases commensurate and can be neglected for comparative analysis.

The anemometer used for the experiment gives significant deviations from the true wind speed at speeds below 4 m/s.

There are also more accurate anemometers, such as the Vostas Cup, which allow to measure deviations in the range of values from 3 to 25 m/s with an error of ±1% (Fig. 3). This sample analysis showed that the average calibration error is 1.2% for the test velocity range from 4 to 26 m/s [25].

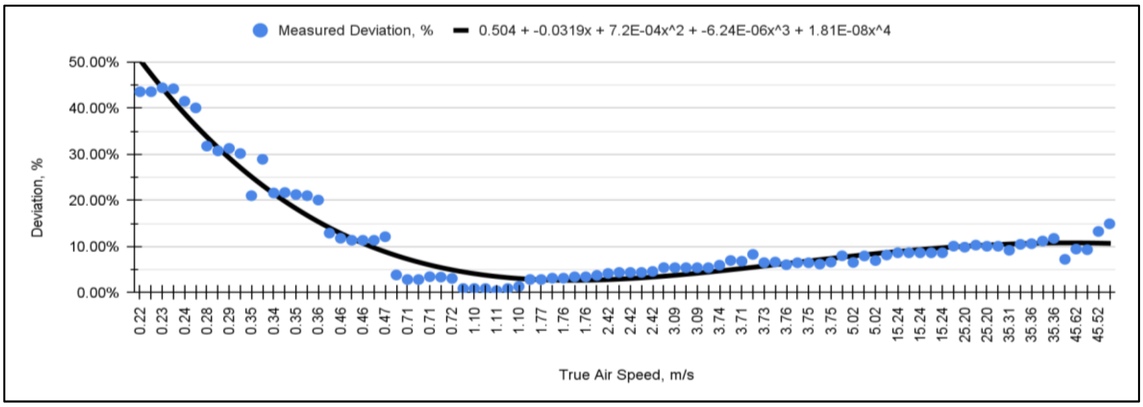

Fig. 2. Deviation graph of the measured from the true speed for Vane Anemometer

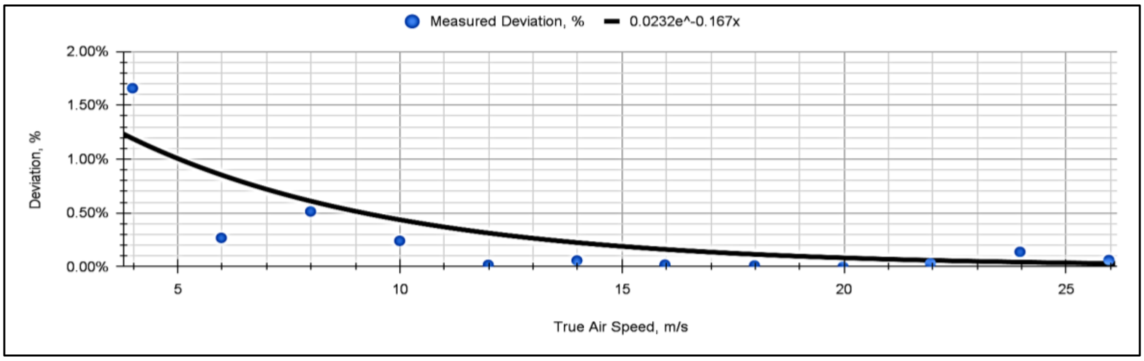

Fig. 3. Deviation graph of the measured from the true speed for Rotating Cup Anemometer

Methods Based on Pressure Drop Measurement

There are several foremost ways to implement this method for measuring the air flow velocity. However, the calculation of the measured value for all methods is based on Bernoulli's equation (Fig. 4) [3]:

$$v = c\, [2\, g\, \Delta h]^{1/2},$$

where c – coefficient that depends on reference liquid and units used or calculated, g – acceleration of gravity, $\Delta h = (h2 - h1)$ – height difference (fluid column).

The desired value is determined by measuring the pressure delta, at which the air flow velocity is calculated by measuring the pressure difference before and after the tapering through which the air passes. The differential pressure (Fig. 5) depends on the velocity, air density, and cross-sectional area of the channel at the measurement points [3].

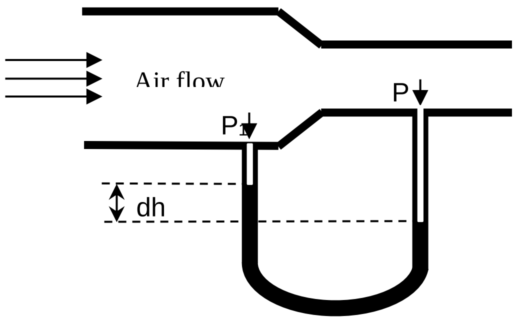

Fig. 4. Schematic of measurement based on pressure drop

The total external static pressure method estimates the air flow mass by measuring the pressure difference between air system inlet and return ducts. Particular methods of this method implementation are based on air pressure tube application, which uses a Pitot tube as a meter.

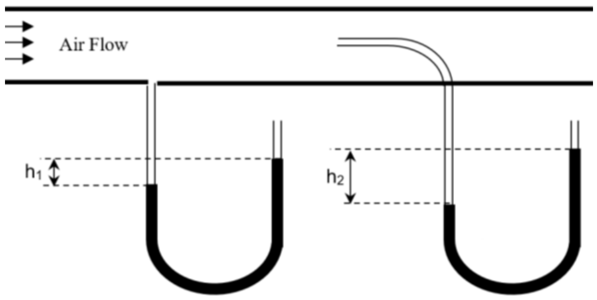

Fig. 5. Prandtl tube schematic

A combined air pressure tube is also used, which includes a static pressure tube and a dynamic pressure tube. Such air pressure tube is an aerodynamic probe in the pneumometric tube form, designed to measure the total and static pressure of the incoming air flow. The design is based on Prandtl tube (Fig. 5), a combination of a Pitot tube and a pressure tube to measure static flow pressure. Heating systems are added on aircraft to prevent icing [4].

A significant disadvantage of this air pressure tube design is the high probability of blocking the inlet, due to icing or external objects entering in the sensor, which can cause aircraft accidents [4]. The air pressure tube measurement accuracy is shown in Fig. 6.

Measurements of the parameters from the air pressure tube were performed in horizontal flight modes and results were averaged after six flights. The data were taken from three air pressure tube installed on the MI-171A2 as part of the KBO-17-1 complex [26] and were also displayed on graph (Fig. 6) as approximated curve.

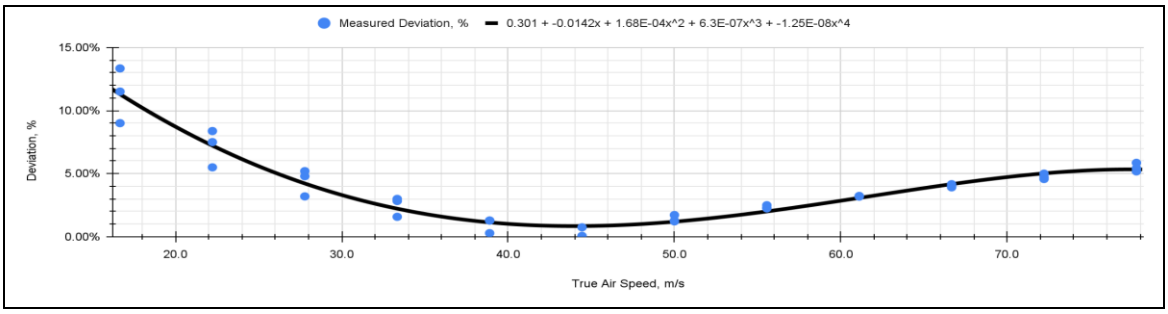

Fig. 6. Deviation graph of the measured from the true velocity for Air Pressure Tube

It can be concluded based on the test results, that the deviation does not exceed ±5% in the range 30 ...75 m/s (Fig. 6). As the velocity continues to increase, the difference from the true value of the airflow velocity is increasing.

At low speeds, below 25 m/s, the accuracy decreases and the deviation exponentially moves from the true value upwards.

If calibration factors are inputted into the measuring equipment to orient the curve as horizontally as possible, then it is possible to achieve acceptable error results (no more than ±10%) for speeds above 25 m/s for taken air pressure tube model.

Thermoelectric Method

The method implementation is using “hot-wire” anemometer, a device that measures air flow by heating a thin wire placed in an air stream. The wire cools as air passes through it, and the cooling rate is proportional to the air velocity. This method can measure air flow from very low to medium values.

There are also implementations where the heating and measuring elements are separate components of the anemometer, or where an additional "cold" resistor is used to measure ambient air and provides a reference for the "hot" resistor used to measure airflow [5].

Typically, calculations are performed in one of two device operation modes: in constant current mode or in constant temperature mode. Both modes calculations are based on the formula [6,7,40]:

$$v = [(E^2 - E_0^2) / A]^{1/n},$$

where E – the output voltage of the anemometer, E_0 – the voltage at zero flow, A, n – constants.

To research the accuracy of this method measurements, two tests were done. The first was at low speeds, which were below 0.3 m/s. The second was at medium speeds, which were higher than 8 m/s.

In the first experiment, three thermoelectric anemometers of the "hot wire" type were used in various designs. These were made from platinum coating tungsten wire with a length of 1.2 mm and a diameter of 5 μm. The tests were carried out using a closed wind tunnel with an operating speed range of 0 m/s to 2 m/s. Anemometers were tested at horizontal airflow (0^0), downward airflow (90^0) and upward airflow (-90^0) at a constant speed. The experiments were carried out at various average speeds ranging from 0.05 to 0.50 m/s [30]. The test results are shown in Fig. 7.

For the next experiment, an open-jet wind tunnel was used with a DANTEC Constant Temperature Anemometer (CTA) unit with a thermofilm probe manufactured by Thermo-Systems Inc. Such a wedge-shaped probe is usually used for both gases and liquids. This type is better when used in air or liquid at very high speeds, when a large load is placed on the sensor [31]. The test was carried out at speeds ranging from 8 ...33 m/s and the results are shown in Fig. 8.

It can be concluded based on the experiments results that thermoelectric methods are not very accurate for air flow speed measuring. Samples, which are assembled in the laboratory, require additional calibration and correction based on environmental conditions. Industrial sensors which are used in piping car systems, can measure air speed in range between 0.1 and 30 m/s with ±3% accuracy [20].

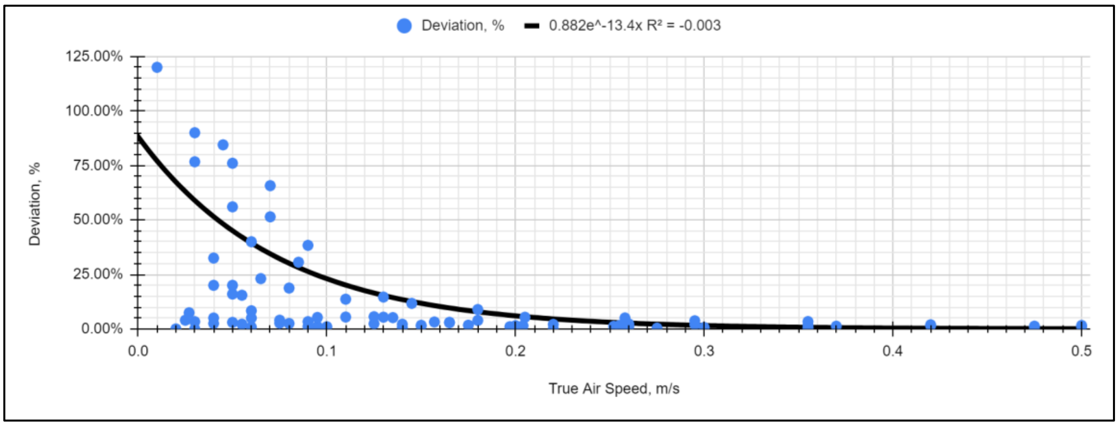

Fig. 7. Deviation graph of the measured from the true velocity (0.05 ... 0.50 m/s) for “Hot Wire” Anemometer

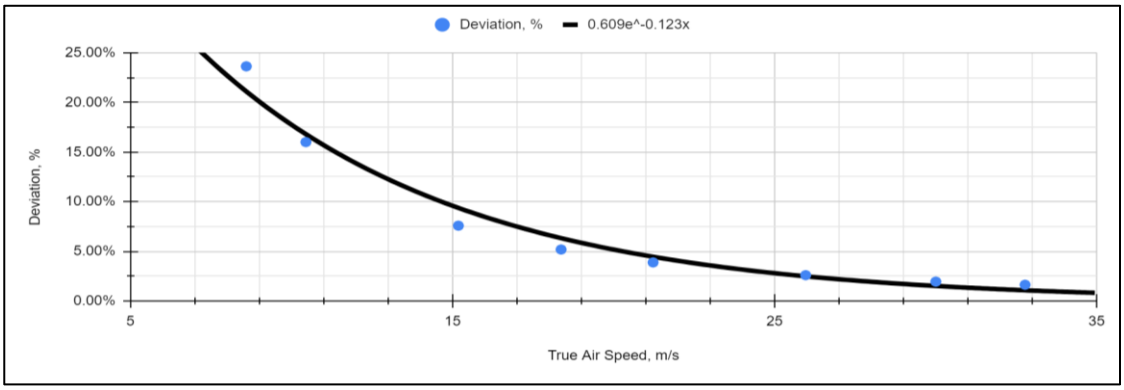

Fig. 8. Deviation graph of the measured from the true velocity (8 ... 33 m/s) for “Hot Wire” Anemometer

Ultrasonic methods

Transit-time Meters. Such methods are used to measure the difference in the ultrasonic pulses transit time moving in the same flow direction and reverse direction. The transit time difference is proportional to the average flow velocity in the sound waves path.

When air flow speed is zero, the signal transit time from T_1 to T_2 (Fig. 9) is equal to the transit time from T_2 to T_1. If air flow speed is not zero, the signal increases in the direction of downstream and decreases in the direction of upstream.

The speed of wind speed projection on the axis (V) connecting the two radiators can be determined by the following equation [8]:

$$V= a * (t_{21} - t_{12}) / (2*t_{12}*t_{21}),$$

where a – distance between T_1 and T_2 (m), t_{12} and t_{21} – ultrasonic signal transit time from transmitter 1 to 2 and vice versa, respectively.

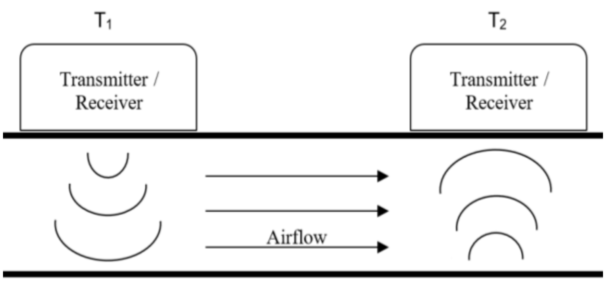

Fig. 9. Signal Transit Time Meter

Doppler shift flow meters. These measure the frequency shift of ultrasonic waves (Fig. 10) that reflect off particles or bubbles in the fluid.

The frequency shift is proportional to the relative velocity between the sound source and the reflectors. These flow meters are used for fluids with suspended solids or gas bubbles.

The flow speed (V) is calculated using the equation [8]:

$$V = (f_0 – f_1)*C_t / 2f_0\cos(a),$$

where C_t – velocity of sound inside the transducer, f_0 – transmission frequency, f_1 – reflected frequency, a – angle of the transmitter and receiver crystals axis.

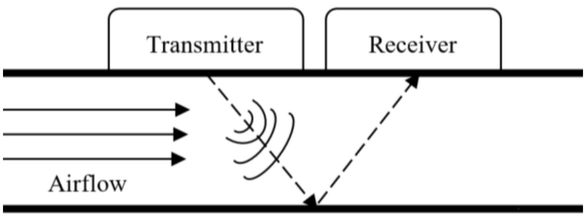

Fig. 10. Doppler shift flow meter

Open-channel flow meters. These measure the airflow in an open channel. These flow meters use ultrasonic waves to measure the signal transmission time in both directions from the transmitter to the receiver (Fig. 11) in open channel. The signal transmission time in the forward or in the opposite direction is inversely proportional to the wind speed.

And it can be calculated using the equation [8]:

$$t_{forward} = d/(c+V) \text{ или } t_{back} = d/(c-V),$$

where d – distance between transmitter and receiver (m), t – signal transmission time of downstream or upstream direction (s), c – sound speed (m/s), V – flow speed (m/s).

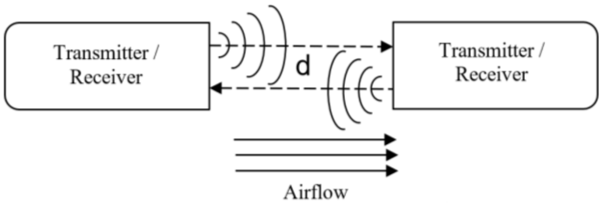

Fig. 11. Open-channel flow meters

Measurement Accuracy of Ultrasonic Anemometer

Measurement tests were carried out in several metrology laboratories of different countries. The following organizations participated in the testing process: PTB (Germany), LNE-CETIAT (France), VSL (Netherlands), E+E (Austria), NMIJ/AIST (Japan), NIM (China), CMS/ITRI (Chinese Taipei), NIST (USA), INRIM (Italy).

The ultrasonic anemometer is manufactured by SONIC CORPORATION.

The probe has three pairs of ultrasonic transducers and measures a three-dimensional velocity vector derived from the ultrasonic waves transit time between the pairs of transducers [27].

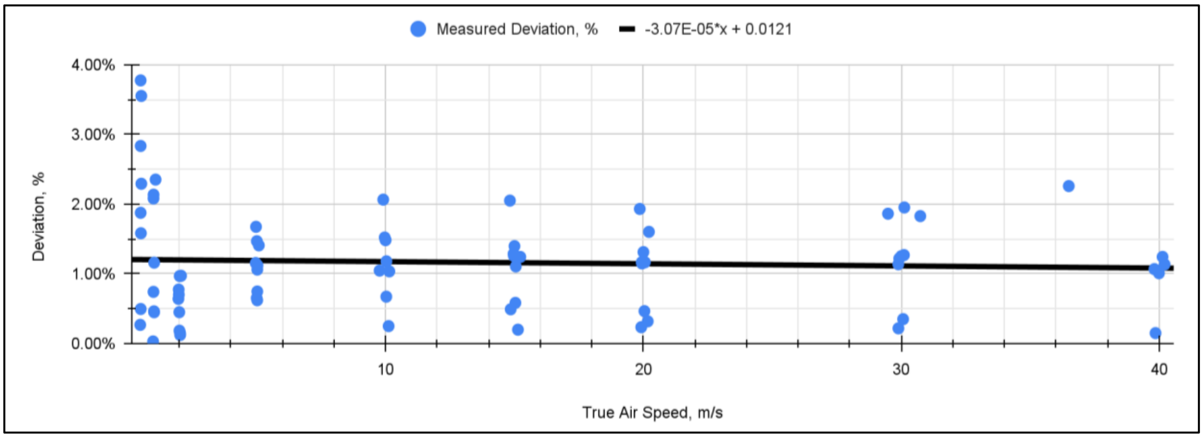

Fig. 12. Deviation graph of the measured from the true velocity for Ultrasonic Anemometer

Devices, which are based on the ultrasonic method, have more accurate characteristics as per test results. The deviation from the true value does not exceed ±2% (Fig. 12) over the entire measurement range of 0... 40 m/s. Significant advantages over previous measurement methods are acceptable accuracy at air velocities close to zero.

Laser method

Laser Doppler anemometer uses the Doppler shift in a laser beam to measure the flow velocity. It consists of a laser that splits into two beams (Fig. 13): direct and reflected. The direct flow is directed past the photodetector and moves away from the emitter to the AB direction. The particles in the second V stream reflect the light towards the receiver, where it is compared to the original beam. The frequency difference between the two beams is proportional to the speed of the particles.

So, the particles of the air flow move through the incident light wave of frequency f and scatters the light in all directions. The scattered light picked up by the receiver (photodetector) will be shifted for f_D.

The Doppler shift f_D depends on the speed V and direction of the particle motion, the light wavelength λ, and the orientation of the receiver. The orientation of the receiver is defined by the angle of α between the incident light wave and the photodetector. The direction of motion of the particle motion is defined by the β, the angle between the velocity vector and the bisector ABC [9] and can be calculated by the equation:

$$f_D = 2V/\lambda * \cos\beta * \sin(\alpha/2).$$

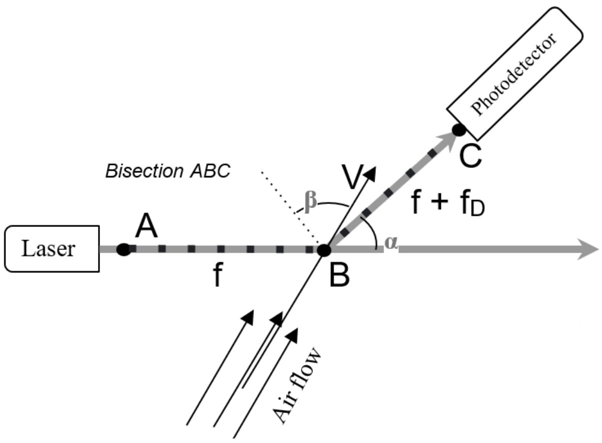

Fig. 13. Laser meter

The laser method has good measurement accuracy characteristics. The tests were carried out by nine different laboratories, as in the previous tests for the ultrasound anemometer. The laser Doppler anemometer system, which is used for the research, was carried out by ILA GmbH. Measurements were performed for the speed range from 0.5 m/s to 40 m/s [27].

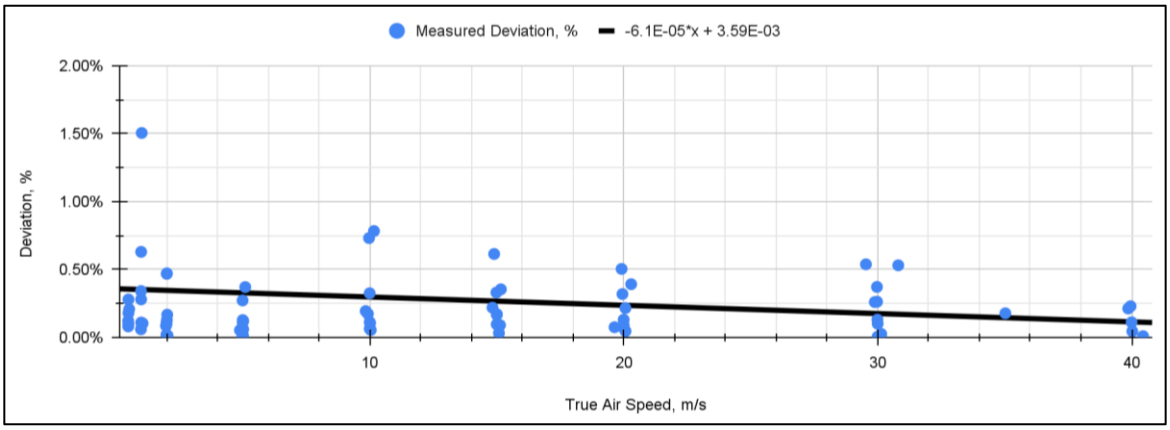

Fig. 14. Deviation graph of the measured from the true velocity for Laser Doppler Anemometer

The laser Doppler anemometer showed better characteristics with fewer results error. The error was ±1% (Fig. 14).

Vortex method

In the right flow conditions, the flow streamline around the researched body creates a regular pattern of alternating vortices, known as the Kármán vortex street (Fig. 15).

These vortices create a force acting on the body perpendicular to the flow [32, 33].

The vortex street generating velocity depends on the Reynolds number (Re). Reynolds proved that the flow becomes turbulent when the Re number is 2000-3000, and the flow becomes fully laminar when the Re is less than a few hundred. It can be calculated using the equation [34, 35]:

$$Re = (V*d)/\upsilon,$$

where V – incoming flow velocity, d – the characteristic size of the streamlined body (diameter for a round body), υ – kinematic viscosity.

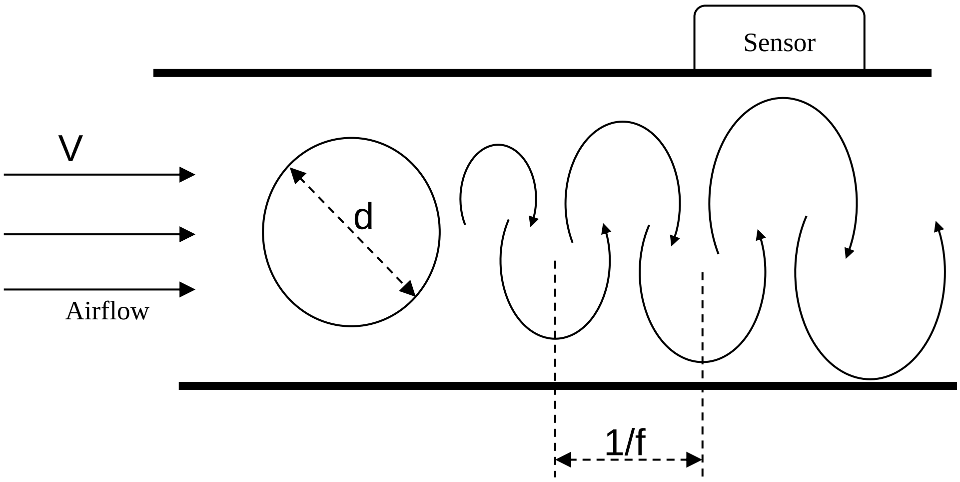

Fig. 15. Generating of Kármán vortices

The kinematic viscosity of air at a temperature of 15 °C is 1.82*10-5. [36]. Vortices will form within 10..100 m/s for 5 mm body diameter, and for 20 mm diameter – in range of 3..11 m/s.

A Kármán street is generating during the transition from laminar to turbulent flow in a limited range of speeds, and this range is highly dependent on the size of the streamlined body. Thus, this method has a narrow range of measurements with a fixed geometry of the streamlined body.

Comparative analysis of methods (Table 1)

Table 1 — **Advantages and disadvantages of air speed measuring methods**

Methods	Advantages	Disadvantages	Application specifics
Mechanical / Rota-ting Vane and Cap Anemo-meters	Simple and robust; Insensitive to flow direction;	A limited range of velocities; Can be affected by turbulence and vibration; Need regular calibration and maintenance; Can cause blockage and interference in the flow; Inert;	Rotating vane and cap anemometers are mostly used at airports, testing aerodynamic performance of aircrafts, monitoring air quality and ventilation systems.

Закінчення табл. 1

Pressure drop / Pitot Tube [29]	Simple and inexpensive; Have low pressure loss; Can also measure high velocities; Insensitive to flow direction;	Sensitive to foreign material (ice, dust, insects) that cause blocked pitot tube; Turbulence, vibration, and alignment errors; Low accuracy and rangeability; Need regular calibration and maintenance; Can cause blockage and interference in the flow if not properly installed; Low sensitivity at low speeds;	Are used on airplane, but has high risks with blocked Pitot tube (see Note #1)
Thermoelectric / Hot Wire [10]	Very small; Cause minimal disturbance to the fluid flow; Have high spatial resolution and frequency response, which means they can capture rapid changes in velocity and turbulence; Provide fast and accurate results;	Very delicate and can break easily if exposed to high temperatures or pressures. Need frequent calibration and correction for factors such as ambient temperature, humidity, wire contamination, etc.; Sensitive to electromagnetic interference and vibration; Hight current consumption;	Mainly used in modern household appliances; No application use on aircraft;
Ultrasonic	No moving parts, which reduces maintenance and wear and tear; Fast response time and high accuracy, which makes them suitable for turbulence measurements; Can operate in a wide range of environmental conditions, such as rain, snow, fog, dust, etc.;	Expensive and complex method; Sensitive to temperature variations and acoustic noise; Shadowing effects when the wind direction is aligned with one of the transducer pairs, which reduces the signal strength and accuracy; Require complex data processing;	Their accuracy and responsiveness make them suitable for turbulence measurements, as well as for measuring both horizontal and vertical wind components. They are used at weather stations located in difficult climatic conditions;
Laser [11]	Non-intrusive and do not disturb the flow during measurement; Not require a calibration; High accuracy; Can measure velocity in 3D; Can measure low and high speeds of semi-transparent substances; Can measure velocity and turbulence distribution in both free flows and internal flows;	Require transparent channels and particles in the fluid to scatter the laser light; Sensitive to optical alignment, vibration, and ambient light; Expensive and complex to operate compared to other types of anemometers;	Used in high-tech systems, such as jet engines or medical equipment, where high accuracy and reliability are required;
Vortex / Karman Street effect [38]	Easy installation maintenance and repair; No moving parts; Wide range of speed operation; Low power consumption; High accuracy;	High sensitivity to vibrations; Sensitivity to inhomogeneity of flow; High-speed shocks cause the vortex to oscillate; Does not work in turbulent flow; Influence on the measured flow dynamic; Narrow speed range without changing the body geometry and insensitivity at low flow speeds;	Used to measure the flow of air and liquids in closed systems (piping) for Mass Air Flow (MAF) measurement;

Note #1: All risks related to disadvantages can be mitigated by strict maintenance instructions. But the problems with blocked pitot tube effect is still huge, because:

- A blocked pitot tube can cause inaccurate or erroneous airspeed readings, which can lead to loss of control or stall of the aircraft [2, 12].
- A blocked pitot tube can be caused by insects, water, ice, tape, or other foreign objects [2, 12,13].
- A blocked pitot tube can be difficult to detect and diagnose during flight, especially in instrument meteorological conditions (IMC) [12].
- A blocked pitot tube can affect other instruments that rely on airspeed data, such as autopilot, flight management system (FMS), or stall warning system [2, 12,13].

Comparison of technical capabilities

By doing this task, anemometers on the market and their characteristics were analyzed. It was analyzed a possible measurement limits, measurement accuracy and resolution of the sensors, which are used in the devices. The summary table shows the parameters for each type of measuring instrument (Table 2).

Table 2 – **Technical capabilities comparison of air flow speed measures methods**

Type of anemometer	Measurement limits and accuracy
Mechanical / Rotating Vane	0.3 - 30 m/s ±1% [14]
Mechanical / Rotating Cup	0.5 - 30 m/s ±5% [15]
Pressure drop / Pitot Tube / Pressure tube	0 - 500 kPa ±0.3% [26] at 100 m/s speed, accuracy is ±3%; at 200 m/s speed, accuracy is ±10%
Thermoelectric / Hot Wire	0 - 230 m/s ±3% [20,38]
Ultrasonic / Doppler shift effect	0 - 65 m/s ±2% [17,18, 19]
Ultrasonic / Transit-time meters	0 - 10 m/s ±1% [21, 22]
Laser / Doppler shift effect	0 - 300 m/s ± 0.1% [16]
Vortex / Karman Street effect	± 1.5 %; measurement range 1:10

Summary

The mechanical method is completely unsuitable for aircraft use due to its capabilities and design features.

The fragile construction and the exactingness for setting up and calibrating of the thermoelectric method based on "hot wire" also causes doubts if using at aircraft. But it does not exclude the possibility of using this method to measure the air flow at high aircraft speeds.

As described above, the Pitot tube use can lead a certain hazard when operating an aircraft in adverse environmental conditions. Measuring devices based on this method are quite bulky and require high attention during operation, that makes them ineffective for a small aircraft on board use.

The laser method based on the Doppler effect is highly accurate. A feature of the laser meter is that it cannot be used in a transparent environment where the beam is not scattered by the flow.

Vortex sensors have a number of advantages for air flow speed measuring. But a significant disadvantage of this method is the fact that the Kármán effect occurs during transients in a narrow speed range, which is far from the wide aircraft operation range. An extension of the measurement range is potentially possible when multiple meters are used.

Taking into account the advantages, disadvantages and features of ultrasound methods based on the Doppler effect, it is possible to use them on board aircraft at low and ultra-low speeds. It is also possible to use the ultrasonic method at medium speeds. The main advantage of using this method is that there are no parts that affect the airflow. Therefore, it doesn’t cause icing of devices that implement these methods.

Thus, the research for the optimal method, which can increase the reliability of determining the air flow velocity, remains a crucial task that requires additional research in this area. For example, studies [27] have shown that the ultrasonic method use on board an aircraft can increase the measurement accuracy from ±10% to ±4% at speeds of 0.6 M m/s, in comparison with a pitot tube use.

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Received (Надійшла) 30.08.2023
Accepted for publication (Прийнята до друку) 08.11.2023

Порівняльний аналіз методів, що використовуються для визначення швидкості повітряного потоку

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Анотація. Об’єкт дослідження. У статті представлено результати порівняльного аналізу методів визначення швидкості повітряного потоку з використанням різних фізичних принципів отримання первинної інформації. Метою даної статті є проведення порівняльного аналізу методів визначення швидкості повітряного потоку на основі перепаду тиску, а також механічних, термоелектричних, ультразвукових, лазерних і вихрових методів, та оцінка перспективності розглянутих методів застосування на різних літальних апаратах. **Результати.** Проведено порівняльний аналіз основних методів, що використовуються для вимірювання швидкості повітряного потоку, отримані результати дозволили оцінити переваги та недоліки розглянутих методів. **Висновки.** Результати порівняльного аналізу дозволяють зробити висновок, що пошук оптимального методу, який підвищить достовірність визначення швидкості повітряного потоку при мінімальних витратах на його реалізацію, залишається актуальним завданням, що потребує додаткових досліджень у цьому напрямку.

Keywords: літак, швидкість повітря, анемометр, приймач тиску повітря, трубка Піто.