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¹Mykola Dyvnych,
²Olha Sushchenko

ONBOARD LASER DOPPLER METER WITH IMPROVED STRUCTURE

Faculty of Air Navigation, Electronics and Telecommunications,
National University "Kyiv Aviation Institute," Kyiv, Ukraine
E-mails: ¹npdvn@gmail.com ORCID 0009-0000-6260-0069,
²sushoa@ukr.net ORCID 0000-0002-8837-1521

Abstract—A laser Doppler meter structure is proposed for measuring the three components of the airspeed vector during flight. The detailed diagram of the studied device is presented and described. The components of the structure are characterized. The principle of operation of the meter with a new structure is explained. The calculation of basic parameters of the meter has been done. The expressions for output signals are derived. The ratio signal/noise is estimated. The graphical representations of calculated parameters are shown. The meter enables direct, non-contact determination of key aerodynamic parameters, including airspeed, angle of attack, and sideslip. Compared to conventional pitot-static systems, the laser Doppler meter approach offers higher accuracy and reliability under varying flight conditions. The proposed structure can enhance flight control, stability, and navigation precision, forming the basis for further development of advanced optical air data systems.

Keywords—Doppler effect, laser meter, structure, angle of attack, sideslip.

I. INTRODUCTION

Unlike traditional methods, the laser Doppler method of measuring speed is non-contact, which allows obtaining more accurate information. A laser Doppler true airspeed meter was developed and experimentally investigated [1]. But this device used a powerful CO₂ laser, which required water cooling and had large dimensions. Currently, small-sized powerful laser diodes have been developed. The article proposes a laser Doppler angular velocity meter, which, unlike the one already developed, allows measuring three components of speed, angle of attack, and angle of slip and has small dimensions due to the use of laser diodes.

Airspeed data are essential for the flight control system, as they support both aircraft navigation and flight control functions. In addition to airspeed, the angles of attack and sideslip are critical flight parameters that must be continuously monitored and maintained within acceptable limits during operation. Exceeding the allowable angle of attack can result in an aerodynamic stall, significantly compromising aircraft performance and safety.

Similarly, sideslip negatively influences aerodynamic efficiency by reducing the lift-to-drag ratio. As a result, flight with excessive sideslip leads to increased drag and less efficient aircraft operation. Therefore, to ensure safe and efficient flight, the flight control system must receive accurate information not only on airspeed but also on the angles of attack and sideslip.

II. REVIEW OF PREVIOUS RESEARCH

The paper [1] describes the design of a laser Doppler meter capable of measuring two components of the airflow velocity vector. The proposed device can employ a compact, high-power laser diode as the radiation source, eliminating the need for a water-cooling system. However, measurements of only two components of the true airspeed vector are insufficient for determining the angles of attack and sideslip.

Airspeed is determined indirectly by measuring the dynamic pressure of the incoming airflow. The airspeed sensor is equipped with two ports that receive the total and static pressures. Additional measurement errors may arise due to airflow distortions around the sensor, which are caused by the aircraft fuselage or crosswind effects. Furthermore, the airspeed measurement is subject to methodological error due to variations in atmospheric pressure at Earth's surface [2].

The increased drag associated with sideslip reduces the aircraft's airspeed. At sufficiently low indicated airspeeds, the wing partially shielded by the fuselage may reach its critical angle of attack before the opposite wing. This can cause an asymmetric stall, potentially leading to the development of a spin [3].

Laser Doppler meters are widely employed to measure airflow velocity around aircraft models in wind tunnel experiments [4]. These instruments operate by directly measuring the velocity of microscopic tracer particles entrained in the airflow.

When the particle diameter is smaller than approximately 20 μm , the particles accurately follow the local flow velocity. The airflow velocity is then calculated from the Doppler frequency shift of the laser light scattered by these tracer particles.

Paper [5] presents an onboard laser Doppler meter designed to measure a single component of the true airspeed vector. The authors also report experimental results that demonstrate the feasibility of the proposed measurement approach. However, the system is limited to measuring only one component of the velocity vector. Furthermore, it relies on a high-power CO_2 laser that requires water cooling, leading to increased size and weight of the overall instrument.

The patent [6] presents the design of a laser meter capable of measuring all three components of the airspeed vector. Such a device enables the determination of not only the airspeed magnitude but also the angle of attack and sideslip angle.

The book [7] represents new solutions for various particle shapes and different kinds of illuminating beams. The specific light and mechanical effects necessary for creating new optical schemes and calculating procedures are represented here.

The improved technique of calculating parameters of Doppler sonar is represented in publication [8].

III. PROBLEM STATEMENT

The angle of attack is measured using an automatic angle-of-attack and overload sensing system, which forms part of the aircraft flight control system. The angle-of-attack sensor is a vane mounted on the side of the aircraft fuselage. Because it is positioned close to the fuselage surface, where the airflow is decelerated by the boundary layer, the measured values are affected by aerodynamic disturbances. These errors become particularly significant during sideslip conditions. Inaccurate angle-of-attack measurements can have serious safety consequences. If the flight control system receives erroneous angle-of-attack data, it may fail to prevent the aircraft from exceeding the critical angle of attack, resulting in an aerodynamic stall, rapid loss of airspeed, and potentially loss of control.

There is also a risk that water may enter the sensor shaft to which the wind vane is attached and subsequently freeze, causing the sensor to malfunction.

To improve the accuracy and reliability of angle-of-attack measurements, aircraft are typically equipped with two or three wind vane sensors. When two sensors are installed, the flight control system uses the average of their measured values. When

three sensors are employed, a majority-voting logic is applied to determine the valid angle-of-attack value.

A sideslip indicator is used to detect the presence of sideslip during flight. Rather than measuring the sideslip angle directly, it simply indicates whether the aircraft is experiencing sideslip.

The sideslip indicator consists of a metal ball enclosed within a curved glass tube filled with liquid. During coordinated flight, when no sideslip is present, the ball remains centered between two reference lines. If the aircraft experiences sideslip, the ball moves away from the center toward one side of the tube, indicating the direction of the slip.

During sideslip, the aircraft experiences a significant increase in aerodynamic drag, while the airflow over the wings becomes asymmetric. As a result, the fuselage partially shields one wing, reducing its lift. The uneven airflow may also produce different effective sweep angles for the wings, further contributing to a lift imbalance. This difference in lift generates a rolling moment that must be counteracted by aileron deflection to maintain level flight.

The increased drag associated with sideslip reduces the aircraft's airspeed. At sufficiently low indicated airspeeds, the wing partially shielded by the fuselage may reach its critical angle of attack before the opposite wing. This can cause an asymmetric stall, potentially leading to the development of a spin.

Therefore, direct measurement of key flight parameters, such as airspeed, angle of attack, and sideslip angle, is highly desirable.

Existing systems for measuring airspeed, angle of attack, and sideslip of an aircraft use separate measuring instruments, the functioning of which depends on the conditions of the flow around the aircraft. The use of total and static pressure receivers to determine airspeed, weather vane sensors to measure the angle of attack, and the glide indicator does not provide direct receipt of complete information about the spatial vector of the air flow velocity.

The main disadvantages of the existing scheme are the occurrence of additional errors due to distortion of the flow by the fuselage, the influence of crosswinds, and gliding flight. In addition, the failure or error of one of the sensors can lead to the formation of unreliable information about the flight parameters.

Therefore, the task arises of improving the technique for measuring aerobatic parameters by moving from separate and indirect measurement of

individual parameters to direct determination of the airspeed vector.

It is advisable to base the improved measuring scheme on the measurement of the three components of the airspeed vector in a coordinate system associated with the aircraft. According to the results of these measurements, the following should be determined: the three components of the airspeed vector V_x, V_y, V_z , as well as the angles of attack $\alpha = f(V_x, V_y, V_z)$ and sideslip $\beta = f(V_x, V_y, V_z)$.

Thus, **the analytical task** is to determine the structure and principle of operation and calculation of the parameters of an improved measurement system, which, based on the results of direct measurement of the three components of the airspeed vector, provides the determination of the airspeed, angle of attack and glide angle.

IV. THE STRUCTURE OF THE AIRBORNE LASER DOPPLER METER

The laser meter described in patent [6] is capable of measuring only the magnitudes of the velocity vector components, without determining their signs. This limitation introduces additional measurement errors and reduces the accuracy of the estimated flight parameters. In contrast, the proposed laser Doppler sensor measures both the magnitude and the sign of each component of the true airspeed vector. The operating principle of the proposed flight control system sensor is illustrated in Fig. 1.

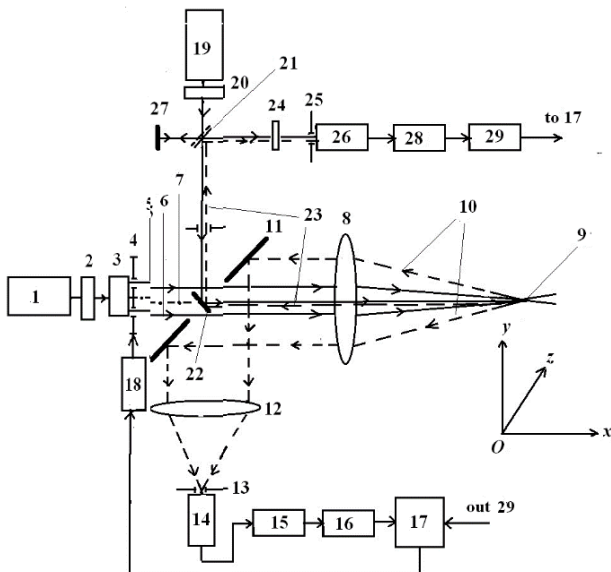


Fig. 1. Configuration of the laser sensor for measuring airflow velocity, angle of attack, and sideslip angle

The radiation emitted by laser diode 1, operating at a wavelength of λ_1 , is directed to the frequency shifter 2 and subsequently enters the collimator 3, where it is transformed into a parallel beam. A

diaphragm 4, containing two apertures, is positioned behind the collimator 3 (Fig. 2). As the beam passes through the diaphragm, it is divided into two separate rays, designated as rays 5 and 6. The apertures in diaphragm 4 (Fig. 2) are positioned at distances l_1 and l_2 from the optical axis 7 of the sensor (Fig. 1). Both apertures have identical diameters, such that $d = d_1 = d_2$.

Because the apertures are located at different distances l_1 and l_2 , laser beams 5 and 6 travel different optical path lengths before reaching the velocity measurement zone 9. To achieve interference between beams 5 and 6, the optical path difference $\Delta L = l_1 - l_2$ must satisfy the condition $\Delta L \geq \lambda_1$. Since the optical path difference $\Delta L = l_1 - l_2$ is small, the sensor can employ a laser source with a relatively low coherence length, such as a high-power laser diode.

The two beams are then focused into the velocity measurement zone 9 by lens 8.

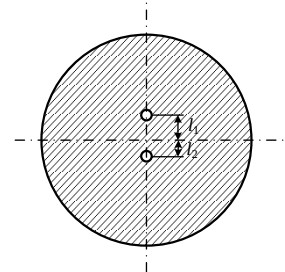


Fig. 2. The schematic representation of the diaphragm 4

The radiation 10 scattered by aerosol particles is collected by lens 8 (Fig. 3) and directed toward mirror 11. The scattered radiation has a wavelength of λ_1 . After reflection from mirror 11, the radiation is transmitted to lens 12. Mirror 11 is inclined at an angle of 45° with respect to the optical axis 7 of the sensor (Fig. 1).

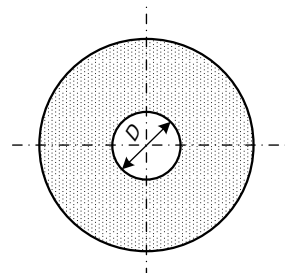


Fig. 3. The graphical representation of mirror 11

Mirror 11 contains a central aperture whose diameter must satisfy the condition $D > (l_1 + l_2)$.

The scattered radiation 10 is then collected by lens 12 and focused onto photodetector 14. A

diaphragm 13 is positioned in front of the photodetector to limit the received radiation.

The optical axis of the sensor is aligned with the longitudinal axis of the aircraft Ox .

The apertures in diaphragm 4 are arranged along the aircraft's lateral axis Oy , which is perpendicular to the Oxz plane (Fig. 1). With this aperture configuration, the Doppler signal frequency at the output of photodetector 14 is proportional to the corresponding component of the airspeed vector:

$$f_{dz} = \Omega_{m1} \pm \frac{2V_z}{\lambda_1} \sin \left[\arctg \frac{l_1}{f} + \arctg \frac{l_2}{f} \right], \quad (1)$$

where Ω_{m1} is the modulation frequency of the laser diode radiation 1; λ_1 is the wavelength of the laser diode; f is the focal length of lens 8; l_1 and l_2 are the distances of the axes of beams 5 and 6 from the optical axis 7 of the sensor.

The output signal from photodetector 14 is amplified by amplifier 15 and subsequently converted into digital form by the ADC 16.

The digitized signal, described by (1), is then processed by microprocessor 17, which determines the corresponding component V_z of the aircraft airspeed vector.

To measure the orthogonal velocity component V_y , the microprocessor 17 commands actuator 18 to rotate diaphragm 4 by 90° . After the rotation, laser beams 5 and 6 are aligned with the axis Oz . In this configuration, the output signal of photodetector 14 contains a Doppler component whose frequency is proportional to the corresponding component V_y of the aircraft airspeed vector:

$$f_{dy} = \Omega_{m1} \pm \frac{2V_y}{\lambda_1} \sin \left[\arctg \frac{l_1}{f} + \arctg \frac{l_2}{f} \right]. \quad (2)$$

In this operating mode, the sensor functions in a manner similar to that used for measuring the velocity vector component V_z . The measurements of the V_x and V_y components are performed sequentially with a certain time interval between them.

To determine the true airspeed vector component V_x , an additional laser diode 19 is employed (Fig. 1). The diode operates at a wavelength of λ_2 . Its radiation passes through frequency shifter 20 and translucent mirror 21, is reflected by mirror 22, and is subsequently directed by lens 8 into the velocity measurement zone 9.

The radiation 23 scattered by aerosol particles is reflected successively from mirror 22 and translucent mirror 21 before reaching photodetector 26. A selective optical filter 24 is placed in front of

the photodetector to suppress radiation at the wavelength λ_1 .

A diaphragm 25 is positioned in front of photodetector 26. To enable extraction of the Doppler frequency shift, a reference portion of the radiation emitted by laser diode 19 is directed to the photodetector. For this purpose, a translucent mirror 21 is placed in the optical path of the laser beam. A fraction of the incident radiation is reflected by translucent mirror 21, then redirected by mirror 27, transmitted through translucent mirror 21, and finally detected by photodetector 26.

The interference between the scattered radiation 23 and the reference radiation from laser diode 19 produces a Doppler signal. The frequency of this signal is proportional to the corresponding component of the air velocity vector V_x :

$$f_{dx} = \Omega_{m2} \pm \frac{2V_x}{\lambda_2}. \quad (3)$$

where Ω_{m2} is the modulation frequency of the radiation emitted by laser diode 19, λ_2 is operating wavelength.

The output signal from photodetector 26 is amplified by amplifier 28 and subsequently digitized by ADC 29. The digitized signal is then transmitted to microprocessor 17, which calculates the corresponding component V_x of the airspeed vector.

Using the measured velocity vector components V_x , V_y , and V_z , microprocessor 17 calculates the aircraft angle of attack and sideslip angle. Frequencies are determined by expressions (3), (4).

The angle of attack is determined from the V_y and V_x components of the velocity vector according to the following expression:

$$\alpha = \arctg \frac{V_y}{V_x}. \quad (4)$$

The sideslip angle is calculated as follows:

$$\beta = \arctg \frac{V_z}{V_x}. \quad (5)$$

Expressions (4), and (5) allow us to carry out navigation measurements.

V. CALCULATION OF LASER DOPPLER METER PARAMETERS

The signals measured at the outputs of photodetectors 14 and 26 are determined by the intensity of the laser radiation scattered by the microparticle [7]. Furthermore, these signals are influenced by the degree of coherence of the

scattered waves with respect to their intensity, polarization state, and phase [8].

The intensity of laser radiation scattered by water aerosol particles (with a refractive index $m = 1.33$) is governed by the aerosol particle diameter d and the wavelength λ of the laser diode emission.

Calculations were carried out to evaluate the characteristics of the Doppler signal. In particular, the relationships between the Doppler signal amplitude U_d , the signal-to-noise ratio S/N , and the aerosol particle diameter d were determined.

The Doppler signal amplitude was calculated using the following expression:

$$U_d = R k_a k_p k_f \left[\int_{\Delta\Omega} I_{s1i} r_i^2 d\Omega + \int_{\Delta\Omega} I_{s2i} r_i^2 d\Omega \right] \cos \omega_d t, \quad (6)$$

where R is a coefficient representing the electrical characteristics of the photodetector; k_a, k_p, k_f denote the matching coefficients of the scattered waves with respect to their intensity, polarization state, and phase [8]; I_{s1i}, I_{s2i} are the intensities of the scattered waves, calculated using the recurrent formulas presented in [7]; r_i is the distance between the micro-particle and the photodetector; and Ω is the angular aperture over which the scattered radiation is collected.

The signal-to-noise ratio was evaluated using the following expression:

$$S / N = \frac{R}{\Delta f} k_p^2 k_f^2 k_a \int_{\Delta\Omega} \sqrt{I_{s1i} I_{s2i}} r_i^2 d\Omega, \quad (7)$$

where Δf is the bandwidth of the photodetector.

Figure 4 presents the calculated dependences of the Doppler signal amplitude and the signal-to-noise ratio on the aerosol particle diameter calculated by formulas (6), and (7). Both the Doppler signal amplitude and the signal-to-noise ratio increase as the aerosol diameter becomes larger. However, for particles below a certain size, the signal-to-noise ratio decreases to approximately unity or lower. Under these conditions, the Doppler signal frequency cannot be measured with sufficient accuracy, resulting in unreliable velocity measurements.

Calculations were performed to evaluate the phase matching coefficient k_f and the signal modulation depth $V = k_a k_p k_f$. As illustrated in Fig. 5, the degradation of the Doppler signal characteristics is primarily caused by the phase mismatch between the scattered waves. This phase

mismatch reduces the modulation depth and, consequently, deteriorates the overall signal quality.

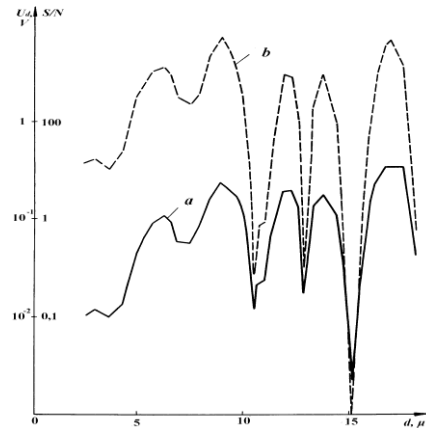


Fig. 4. Doppler signal $U_d = f_1(d)$ (a) and the ratio signal / noise $S / N = f_2(d)$ (b)

Calculations of the phase-matching coefficient k_f and the signal modulation depth $V = k_a k_p k_f$ were performed. From the graphs presented in Fig. 5, it is clear that the deterioration of the signal characteristics occurs due to the phase mismatch of the scattered radiation.

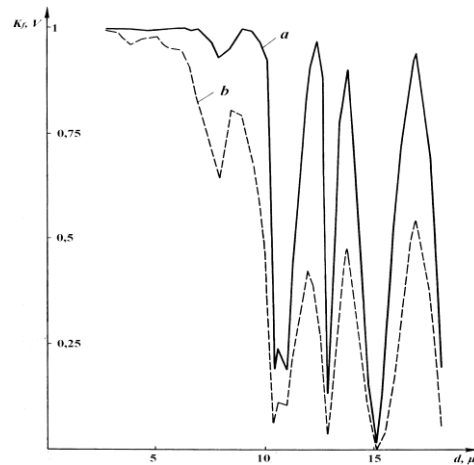


Fig. 5. Coefficient of phase matching $k_f = f_3(d)$ (a) and the coefficient of the modulation depth $V = f_4(d)$ (b)

To maintain measurement accuracy, Doppler signals exhibiting low modulation depth should be excluded through appropriate filtering.

The development of measuring instruments with enhanced performance characteristics plays a crucial role in improving the quality and reliability of flight control systems [9] – [11].

Further advancement of laser-based measuring instruments is closely associated with the development of efficient algorithms for the digital processing of navigation data.

VI. CONCLUSIONS

The developed laser Doppler meter enables direct and accurate measurement of essential flight parameters, including airspeed, angle of attack, and sideslip angle. By delivering real-time estimates of all three components of the airspeed vector, the system provides a comprehensive representation of the aircraft's aerodynamic state. This information can be incorporated into flight control systems to improve aircraft stability, control accuracy, and operational safety across a wide range of flight conditions.

Furthermore, the capability to directly determine these flight parameters without dependence on conventional pitot-static systems or indirect estimation methods enhances measurement reliability, particularly under conditions where traditional sensors exhibit reduced performance, such as at high angles of attack or in highly turbulent flow environments. The measurements provided by the laser Doppler meter can be utilized by advanced navigation algorithms to mitigate error accumulation and improve overall navigation accuracy.

The scientific novelty of the work is as follows. The method of laser Doppler anemometry for airborne aircraft systems has been further developed. An improved structural and functional architecture of a three-component meter has been scientifically substantiated and developed. Unlike known approaches that record only one or two velocity components without determining direction [1], [3], the proposed method for the first time allows simultaneous isolation of three spatial components of the airspeed vector together with their signs. This expands the theoretical basis of optoelectronic monitoring of aerodynamic parameters and provides full information content for direct determination of angles of attack and slip in real time.

Future developments may focus on integrating this technology into modern avionics and autonomous flight platforms, where it has the potential to significantly enhance flight control, optimize aircraft performance, and support the development of next-generation air data measurement systems.

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Dyvnych Mykola. ORCID 0009-0000-6260-0069. Candidate of Science (Engineering). Associate Professor. Faculty of Air Navigation, Electronics and Telecommunications, National University "Kyiv Aviation Institute", Kyiv, Ukraine.

Education: Kyiv Institute of Engineers of Civil Aviation, Kyiv, Ukraine, (1975).

Research area: inertial and laser measuring instruments, control systems.

Publications: 90.

E-mail: npdvn@gmail.com

Sushchenko Olha. ORCID 0000-0002-8837-1521. Doctor of Engineering Science. Professor.

Faculty of Air Navigation, Electronics and Telecommunications, National University "Kyiv Aviation Institute", Kyiv, Ukraine.

Education: Kyiv Polytechnic Institute, Kyiv, Ukraine (1980).

Research area: motion control and inertial navigation systems.

Publications: 351.

E-mail: sushoa@ukr.net

М. П. Дивнич, О. А. Сущенко. Бортовий лазерний доплерівський вимірювач із вдосконаленою структурою

Запропоновано структуру лазерного доплерівського вимірювача для вимірювання трьох компонентів вектора повітряної швидкості під час польоту. Представлено та описано детальну схему досліджуваного пристрою. Охарактеризовано компоненти структури. Пояснено принцип роботи вимірювача з новою структурою. Виконано розрахунок основних параметрів вимірювача. Отримано вирази для вихідних сигналів. Оцінено співвідношення сигнал / шум. Наведено графічні представлення розрахованих параметрів. Вимірювач дозволяє пряме, безконтактне визначення ключових аеродинамічних параметрів, включаючи повітряну швидкість, кут атаки та бічне ковзання. Порівняно з традиційними системами Піто-статичної діаграми, підхід на основі лазерного доплерівського вимірювача пропонує вищу точність та надійність за різних умов польоту. Запропонована структура може покращити керування польотом, стабільність та точність навігації, формуючи основу для подальшого розвитку передових оптичних систем аеродинамічних даних.

Ключові слова: ефект Доплера, лазерний вимірювач, структура, кут атаки, кут ковзання.

Дивнич Микола Полікарпович. ORCID 0009-0000-6260-0069. Кандидат технічних наук. Доцент.

Факультет аеронавігації, електроніки та телекомунікацій, Національний університет «Київський авіаційний інститут», Україна.

Освіта: Київський інститут інженерів цивільної авіації, Київ, Україна, (1975).

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Кількість публікацій: 90.

E-mail: npdvn@gmail.com

Сущенко Ольга Андріївна. ORCID 0000-0002-8837-1521. Доктор технічних наук. Професор.

Факультет аеронавігації, електроніки та телекомунікацій, Національний університет «Київський авіаційний інститут», Київ, Україна.

Освіта: Київський політехнічний інститут, Київ, Україна, (1980).

Напрямок наукової діяльності: системи стабілізації інформаційно-вимірювальних пристроїв.

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E-mail: sushoa@ukr.net