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POLARIMETRIC UNMANNED AERIAL VEHICLE LANDING SYSTEM

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Abstract**—***The paper deals with questions of developing the advanced polarimetric landing system for unmanned aerial vehicle of plane type. The proposed polarimetric landing system can also be used for landing the unmanned aerial vehicle of other types. The article considered the existing landing systems for unmanned aerial vehicle as well as proposed the polarimetric landing system for unmanned aerial vehicle, which consists of two parts: the ground-based block (radiation unit) and the on-board block (measurement unit). The .methods for forming the glidepath with the use of polarized radiation and block diagrams of onboard and ground blocks channels are considered in the article. In these conditions, the ground-based block consists of three radiation channels, and the on-board block consists of five measurement channels. The proposed system, potentially, allows determining the attitude of unmanned aerial vehicle during landing, as well as, its deviation from glidepath with high accuracy and sensitivity. Polarimetric landing system for unmanned aerial vehicle allows providing landing on non-horizontal and moving plane of landing, as well as provide landing by complex trajectory. The formulas for recalculating the measured polarimetric parameters in the attitude parameters of unmanned aerial vehicle and parameters of its position relative to landing surface are given. In article were given result of the mathematical modeling of measurement channel. Based on the results of this modeling, it can be concluded that the dependence of the polarimetric parameters on the deviation of the unmanned aerial vehicle from the glidepath is primarily linear and depends on the attitude of the unmanned aerial vehicle.*

Index Terms—Block diagram; landing system; landing trajectory; measurement method; mathematical modeling; planar isotropic dielectric plate; polarimeter; unmanned aerial vehicle.

I. INTRODUCTION

The global trend towards widespread use of unmanned aerial vehicles (UAVs) in civil as well as in military areas observed in recent years. This is due to major technical and technological achievement of science and technology, the emergence of new lightweight and durable composite materials, the rapid development of microelectronic component base, the emergence and rapid development of highly efficient renewable power sources based on a lithium-polymer batteries, the development of satellite-based navigation systems, the development of computing technique and other [1]. One of the reason for the rapid UAVs development is that the use of UAVs in areas such as earth remote sensing, monitoring lines of communication and borders, retransmitting the signals, environmental monitoring, military intelligence and other areas can substantially reduce the cost in comparison with space or aviation systems.

The widespread use of UAV, especially in civil aviation, has led to the fact that, starting in 2005, the International Civil Aviation Organization (ICAO) has begun consultations on international application of UAVs in civil airspace. In accordance with the general concept of flight operations, UAVs should operate in accordance with ICAO standards that are intended for manned airplanes. Thus, systems of UAVs that perform flights beyond visual line of sight shall meet the requirements to the communication, navigation and surveillance systems offered for appropriate airspace [2]. In this case, landing approach and landing is the most complex and dangerous, in technical terms, the flight stages of both manned and unmanned aircraft. Statistical analysis of aviation fatal accidents and onboard fatalities by phase of flight (Fig. 1) shows that about 47% of accidents occur in the approach and landing phase [3].

Depending on a flight principle UAV divide on 5 groups: UAV of plane type (fixed-wing UAV), UAV with flexible wing, UAV of helicopter type (rotorcraft UAV, rotary-wing UAV), flapping-wing UAV, UAV of aerostatic type (blimps) [1]. The most widespread have UAVs of aircraft type and helicopter type. The major advantages of fixed-wing UAV are the big duration of flight, big maximum height and high speed of flight. The major advantages of rotorcraft UAV are the ability to hover in the air, high manoeuvrability and the ability to perform vertical take-off and landing.

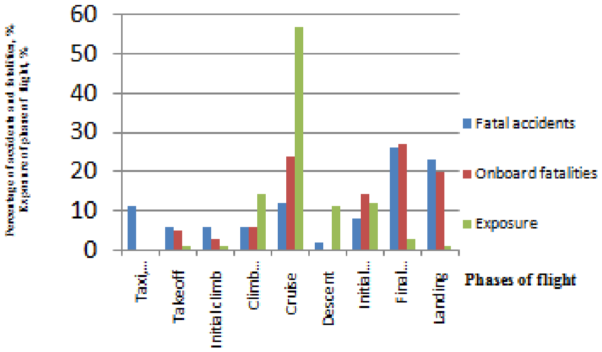

Fig. 1. Percentage distribution of aviation fatal accidents and onboard fatalities by phase of flight

Comparison of fixed-wing UAV and rotary-wing UAV (engine type, fuel load, disposable load) illustrate the advantages of fixed-wing UAV: long range, long duration of flight, better aerodynamic property, high useful load factor. However, rotorcraft UAV have another repudiatory advantage over fixed-wing UAV: the ability to land on a surface of limited size [4]. Therefore, in the future, we will focus on the landing system for fixed-wing UAV, as a more promising type of UAV.

A successful dealing with a problem of safe landing the fixed-wing UAV in a discrete airspace, in instrument meteorological conditions and without direct visibility, requires the development of a UAV landing system that will provide the required level of flight safety in accordance with the requirements and standards of ICAO. Since UAVs are used in different areas and have different purposes, so the UAV landing system in general should allow landing by complex trajectory, on a non-horizontal and on an unprepared for landing surface. Therefore, in order to ensure safe and efficient landing of UAVs, it is necessary to measure the UAV`s attitude relative to the landing plane and to measure the UAV`s deviation from a complex landing trajectory with high accuracy and sensitivity.

II. REVIEW

Depending on weight and duration of flight UAV are divided into [1]:

– mikro- and mini-UAV with near radius of action (take-off weight to 5 kg, range of action to 25…40 km);

– light UAV with small radius of action (take-off weight to 5…50 kg, range of action to 10…70 km);

– light UAV with average radius of action (take-off weight to 50…100 kg, range of action to 70…150 km);

– average UAV (take-off weight to 100…300 kg, range of action to 150…1000 km);

– average-heavy UAV (take-off weight to 300…500 kg, range of action to 70…300 km);

– heavy UAV with average radius of action (take-off weight more than 500 kg, range of action 70 … 300 km);

– heavy UAV with long duration of flight (take-off weight more than 1500 kg, range of action about 1500 km);

– unmanned warplanes (take-off weight more than 500 kg, range of action about 1500 km).

Following methods of landing are used for landing of fixed-wing UAV: the method of controlled falling, parachute method of landing, landing with used of catch wire, landing in the stop net, landing on the runway. Herewith, the method of controlled falling is used very rarely and mainly for mini- and micro-UAVs. Parachute method of landing, landing with used of catch wire, landing in the stop net are used for light UAVs with take-off weight up to 50 kg. For landing the medium and heavy UAVs with take-off mass more than 50 kg are used the runways.

Different systems and technologies are used for coordination the UAV`s landing and entering it into the landing area (into the starting point of landing): into the parachute deployment point, into the start point of controlled falling, into the point of engagement with the catch wire, into the point of location of stop net, into the point of glide-path capture. The main landing systems of manned airplanes, which are used for UAV landing are ILS (Instrument Landing System), GPS / GLONASS, MLS (Microwave Landing System), GCAS (Ground Controlled Approach System), VBLS (Visual Based Landing System) and others.

Instrumental landing system (ILS) is intended to provide the approach of the aircraft according to radio beacons signals of the international ILS system and landing system of the IL type. In it, the conditional planes of the set landing course and the glideslope are created by means of the electromagnetic fields of the course (CRB) and glideslope (GRB) beacons, the signals of which are accepted by on-board equipment. According to the information about deviation of the aircraft from the set landing trajectory, the process of control the aircraft in the manual or automatic control mode is carried out. The deviation measurement error of the course is ± 10 m, and the deviation of the glissade is ± 1.5 m. This landing system is most used for manned airplanes and is widely used for UAVs. Microwave landing system (MLS) has some advantages over ILS. But it didn`t find widespread use for both manned and unmanned civil aircraft. The use of satellite navigation systems (GPS / GLONASS) in combination with GBAS systems can provide approach of the aircraft according to I category of landing, but approach of the aircraft according to II and III categories of landing requires greater accuracy than GPS / GLONASS systems provide. But in spite of this, GPS / GLONASS systems are used to entering of the aircraft on the landing trajectory. The ground controlled approach system (GCAS) is used at military airfields. But this landing technology uses manual control, it is difficult to automate, and in addition, the GCAS have a low landing data refresh rate, which significantly reduces the ability to manage UAVs in critical situations. Visual landing systems (VBLS) are also used for landing UAVs. The principle of the VBLS is to analyze the image of the landing surface. This allows for automatic landing at an arbitrary unfitted aerodrome. Thus, the existing UAV landing systems do not provide fully automatic landing and landing with the required safety level in accordance with the requirements and standards of ICAO.

III. PROBLEM STATEMENT

Extension of scope the UAVs requires improvement of the effectiveness and safety of their flights. Landing is the most complex flight stage of UAVs as well as a manned aircraft.Providing automatic, safe and efficient landing of UAVs to an any equipped landing surface requires the development of new or improvement existing landing systems. In this case, the UAV landing system should provide measurement of the UAVs deviation from the complicated landing trajectory as well as determine the UAV attitude in relation to the landing surface with high accuracy and sensitivity and in real time. This will avoid the UAV collision with the landing surface by separate parts of the structure: a nose or a tail during landing with a pitch, a wing during landing with a roll. Also, the UAV landing system should be portable, have a simple structure, a small mass and small dimension, to ensure the operational preparation of any suitable for landing surface to UAV landing.

IV. PROBLEM SOLUTION

This paper is an extension of work originally presented in IEEE 4th International conference “Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD)” [9]. This article continues studying the issue of using polarimetry in aircraft landing systems and is aimed at a wider and more detailed examination of the polarimetric technology possibility to solve aircraft landing tasks. Polarimetric techniques are understood to mean the totality processes of collection, accumulation, processing, transmission, storage and display of information. They use polarimetric methods and devices to obtain basic information about the object. This article proposes the polarimetric landing method and system, which implements this method. The operation principle of the method is based on Fresnel's formulas. The proposed method and system are based on the use of physical properties of artificial electromagnetic waves in the optical band, which propagate in space.

Application scope of optical measurement methods in various fields of science and technology has expanded significantly in recent years. This is due to their advantages. Optical measurement methods have the following advantages: non-destructive testing, noncontact measurement, high measurement accuracy and sensitivity, high speed of measurements, and others. Polarimetric measurement method is one of the most sensitive optical measurement methods. Polarimetric measurement methods involve measuring the polarization properties of radiation after interaction of polarized radiation with the objects: the degree of polarization, azimuth plane of polarization, ellipticity and others. Polarimetric measurement methods allows measuring the azimuth plane polarization with accuracy 0,0005° [5]. And the use of the compensation principle in polarimetric measurements allows for high sensitivity. Polarimetric techniques are understood as totality of processes of collecting, accumulation, processing, transmission, storage and display of information about the object of study, which use polarimetric means and methods for obtaining primary information.

Polarimetric methods for determining the propagation direction of polarized radiation by measuring its angle of incidence are currently being developed. These developments allow determining the angle of rotation the moving object relative to a fixed starting point. Moreover, the polarized radiation source can be located both on a moving object and at a starting point. This is a possibility due to use the dielectric plane-parallel isotropic plate in the optical measuring channel, which rotates the polarization plane of the incident linearly, polarized radiation depending on its angle of incidence. In [6] has examined the application the method of determining the propagation direction of polarized radiation to determine the aircraft attitude during landing, and in [7] has examined the application the method of determining the propagation direction of polarized radiation in aviation navigation systems for determining the aircraft coordinates.

Rotating the polarization plane of polarized radiation after falling on isotropic planar dielectric plate with weakly absorbing material is explained by various transmittance and reflectance for p- and s-polarized beam components, which are described by Fresnel's formulas. Studies, presented in [10] and [11], confirm this statement and show that at falling of linearly polarized beam on the dielectric plate the reflected and refracted beams will also be linearly polarized, and the rotation angle of polarization plane will depend on the angle of incidence. The values of azimuth of polarization plane for the reflected and refracted beam that has passed through the two faces of the plate can be determined by the following formulas:

$$\varphi_r = \operatorname{arctg}\left(-\frac{\cos(i-r)}{\cos(i+r)}\operatorname{tg}\varphi_e\right),$$

$$\varphi_d = \operatorname{arctg}\left(\cos^2(i-r)\operatorname{tg}\varphi_e\right).$$

where φ_r is the azimuth of polarization plane of the reflected beam; φ_e is the azimuth of polarization plane of the incident beam; φ_d is the azimuth of polarization plane of the refracted beam; i is the angle of incidence; r is the angle of refraction.

The use of polarimetric technologies to improve the safety and efficiency of UAV landing is to develop a polarimetric landing system. The system includes a radiation block and a measurement block. The radiation block is placed on the surface of the landing and is intended to form a line of glidepath. The measurement block is placed on board the UAV and is intended to determine the UAV attitude relative to the plane of boarding and its deviation from the glidepath.

A. Polarimetric principle of forming the landing glideslope

The forming of landing glideslope by use of polarimetric means was considered by the authors in [8]. The scheme of forming the landing glideslope by means of polarized radiation is shown in Fig. 2 and consists in as following. The glissade line is formed as the intersection the plane of course and the plane of glissade. Plane of the glideslope is formed by scattering of plane-polarized radiation in a horizontal plane at the glideslope angle. However, the scattering angle of radiation in the vertical plane should be minimal. The plane of the course is formed by turning plane of the glideslope (scattering plane-polarized radiation in the horizontal plane) around the transverse axis (in the vertical plane) with simultaneous turning of radiation polarization plane.

Also, the glissade line can be formed as follows. The plane of the course is formed by scattering the plane-polarized radiation in a vertical plane. However, the scattering angle of radiation in the horizontal plane should be minimal. The plane of the glideslope is formed by turning plane of course (scattering plane-polarized radiation in the vertical plane) in a horizontal plane with simultaneous turning of radiation polarization plane.

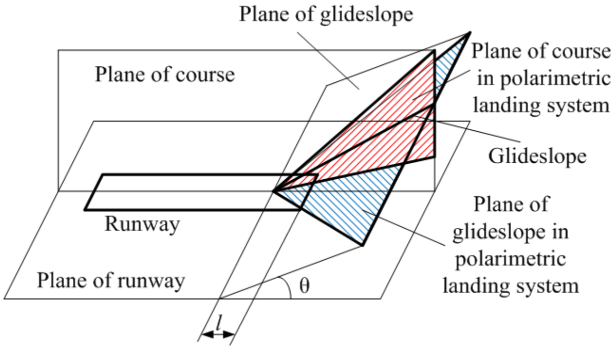

Fig. 2. Scheme of forming landing glideslope by using polarized radiation

Thus, plane of the course will be characterized by "zero" angle of incidence (or "zero" polarization azimuth plane of radiation strike upon dielectric plate) and the plane of the glideslope will be characterized by "zero" polarization azimuth plane of radiation strike upon dielectric plate (or "zero" angle of incidence). At the intersection of these planes will form a line of glideslope, which will be characterized by "zero" incidence angle and "zero" polarization azimuth plane of the incident beam.

B. Radiation block of a polarimetric UAV landing system

The radiation block of the polarimetric UAV landing system consists of two sub-blocks. The first sub-block consists of two channels and provides radiating of two scattered plane-polarized beams in the horizontal plane, which differ in wavelength and polarization azimuth plane. The dependence of the polarization azimuth plane on the direction of radiation in the first sub-block is shown in Fig. 3.

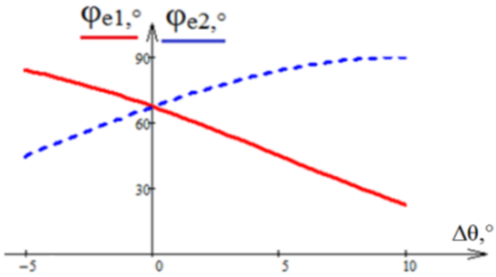

Fig. 3. Dependence polarization plane azimuth of radiation on the direction of radiation in the first sub-block of radiation block

The second sub-block consists of one channel and provides radiating scattered plane-polarized beam in the vertical plane. The dependence of the polarization azimuth plane on the direction of radiation in the second sub-block is shown in Fig. 4. The block diagram of one channel of the radiation block is shown in Fig. 5.

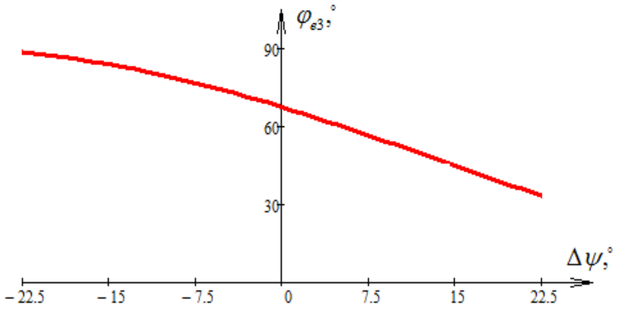

Fig. 4. Dependence polarization plane azimuth of radiation on the direction of radiation in the second sub-block of radiation block

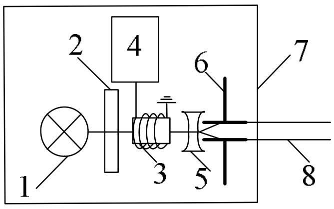

Fig. 5. Block diagram of one channel the radiation block

One channel of the radiation block includes radiation source 1; monochromator 2; Faraday cell 3; sound generator 4; scattering lens 5, slit diaphragm 6, which are placed on rotatable platform 7. Radiation source 1 is intended for radiation the plane-polarized radiation. Monochromator 2 is intended for transmission the wavelength on which the appropriate channel of measurement block is tuned. Faraday cell 3 is intended for rotating the beam polarization plane. Sound Generator 4 is intended to form control signals to the Faraday cell 3. Scattering lens 5 and a slit diaphragm 6 are intended for scattering plane-polarization radiation with a definite divergence angle in the vertical and horizontal planes. The platform 7 rotates around a vertical axis at constant frequency and provides changing the radiation direction of the beam 8. The beam polarization plane rotates simultaneously with platform. This ensures communication of polarization plane azimuth and the direction of radiation.

C. Measurement block of a polarimetric UAV landing system

The block diagram of one channel the measuring block is shown in Fig. 6.

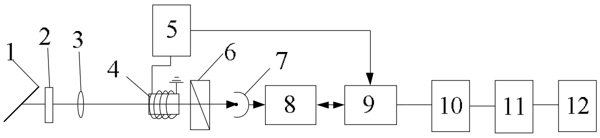

Fig. 6. Block diagram of one channel the measuring block

The measurement block consists of three sub-blocks, each of which is configured to measure the polarization plane azimuth of the beam of the corresponding radiation block channel. The first and second sub-blocks consist of two measurement channels, and the third sub-block has one measuring channel. Thus, the measurement block consists of five measuring channels.

The channel of measurement block consists of planar dielectric plate 1, which is intended to rotate the polarization plane depending on the angle of incidence and polarization plane azimuth of the incident beam, it provides getting primary information about incidence angle and polarization plane azimuth; optical filter 2, which is intended to transmission the wavelength on which the appropriate channel of radiation block is tuned; focusing lens 3, which is intended to focus the radiation on the Faraday cell 4; Faraday cell 4, which is intended to modulate polarized radiation in an alternating magnetic field; sound generator 5, which is intended to form control signals to the Faraday cell 4; analyzer 6, which is intended to determine the polarization plane azimuth; photodetector 7, which is intended to convert polarization plane azimuth into an electrical signal; narrow-band amplifier 8, which is intended for amplifying electrical signal; synchronous detector 9, which is intended to increase the measurement sensitivity and provide measurement "on zero signal"; microcontroller 10, which is intended for processing measurement results; storage unit 31, which is intended for collecting and storing measurement results; calculator 32, which is intended to perform mathematical calculations.

D. Operation of polarimetric UAV landing system

Polarimetric UAV landing system consists of five channels and provides measurement the five polarization azimuth plane of the transmitted beams φ_d, which are described by the following formulas:

$$\begin{aligned}
\varphi_{d1} &= \operatorname{arctg}\left(\cos^2\left(i_1 - \arcsin\left(\frac{\sin(i_1)}{n}\right)\right)\operatorname{tg}\left(\varphi_{e1}\right)\right),\\
\varphi_{d2} &= \operatorname{arctg}\left(\cos^2\left(i_2 - \arcsin\left(\frac{\sin(i_2)}{n}\right)\right)\operatorname{tg}\left(\varphi_{e1}\right)\right),\\
\varphi_{d3} &= \operatorname{arctg}\left(\cos^2\left(i_3 - \arcsin\left(\frac{\sin(i_3)}{n}\right)\right)\operatorname{tg}\left(\varphi_{e2}\right)\right), \quad (1)\\
\varphi_{d4} &= \operatorname{arctg}\left(\cos^2\left(i_4 - \arcsin\left(\frac{\sin(i_4)}{n}\right)\right)\operatorname{tg}\left(\varphi_{e2}\right)\right),\\
\varphi_{d5} &= \operatorname{arctg}\left(\cos^2\left(i_5 - \arcsin\left(\frac{\sin(i_5)}{n}\right)\right)\operatorname{tg}\left(\varphi_{e3}\right)\right),
\end{aligned}$$

where $\varphi_{d1}, \varphi_{d2}, \varphi_{d3}, \varphi_{d4}, \varphi_{d5}$ is the polarization plane azimuths of the transmitted beams in each measuring channels; $\varphi_{e1}, \varphi_{e2}, \varphi_{e3}$ is the polarization plane azimuth of the incident beams in each measuring channels; i_1, i_2, i_3, i_4, i_5 are angles of incidence in each measuring channels; n is the refraction index of dielectric plate material.

Dependence spatial incidence angle of radiation from the inclination angle of dielectric plates and planar incidence angles of radiation are determined by the following formulas:

$$\begin{aligned}
i_1 &= \operatorname{arctg}\sqrt{\operatorname{tg}^2\left(i_\psi + \varphi_{\text{pl}1}\right) + \operatorname{tg}^2\left(i_\theta + \theta_{\text{pl}1}\right)} \\
i_2 &= \operatorname{arctg}\sqrt{\operatorname{tg}^2\left(i_\psi + \varphi_{\text{pl}2}\right) + \operatorname{tg}^2\left(i_\theta + \theta_{\text{pl}2}\right)} \\
i_3 &= \operatorname{arctg}\sqrt{\operatorname{tg}^2\left(i_\psi + \varphi_{\text{pl}3}\right) + \operatorname{tg}^2\left(i_\theta + \theta_{\text{pl}3}\right)} \\
i_4 &= \operatorname{arctg}\sqrt{\operatorname{tg}^2\left(i_\psi + \varphi_{\text{pl}4}\right) + \operatorname{tg}^2\left(i_\theta + \theta_{\text{pl}4}\right)} \\
i_5 &= \operatorname{arctg}\sqrt{\operatorname{tg}^2\left(i_\psi + \varphi_{\text{pl}5}\right) + \operatorname{tg}^2\left(i_\theta + \theta_{\text{pl}5}\right)}
\end{aligned} \qquad (2)$$

where i_1, i_2, i_3, i_4, i_5 is the spatial incidence angle of radiation in each measuring channels; i_ψ is the planar incidence angle of radiation in horizontal plane; i_θ is the planar incidence angle of radiation in vertical plane; $\varphi_{\text{pl}\ n}$ is the horizontal inclination angle of dielectric plates in nth measuring channel; $\theta_{\text{pl}\ n}$ is the vertical inclination angle of dielectric plates in nth measuring channel.

Substituting equations (2) in the equations (1) and solving the formed system of equations we will find the planar incidence angle of radiation in horizontal and vertical planes (plane of course and plane of glissade) i_ψ, i_θ, and the polarization azimuth plane of the incident beams $\varphi_{e1}, \varphi_{e2}, \varphi_{e3}$.

The direction of beam radiation relative to plane of course ψ_φ and plane of glissade θ_φ, which are recorded on UAV board can be determined by the following formulas:

$$\theta_\varphi = \frac{\varphi_{e1} + \varphi_{e2}}{2}, \qquad \psi_\varphi = \frac{2\varphi_{e3} - \varphi_{e1} - \varphi_{e2}}{2}. \qquad (3)$$

The angles of deviation the UAV from the line of glissade can be found by the following formulas:

$$\begin{aligned}
\Delta\theta &= \theta_\varphi + i_\theta, \\
\Delta\psi &= \psi_\varphi + i_\psi.
\end{aligned} \qquad (4)$$

The attitude of the UAV can be found by the following formulas:

$$\begin{aligned}
\gamma &= \frac{\varphi_{e1} + \varphi_{e2} - 2\varphi_0}{2}, \\
\psi &= \Delta\psi + \psi_0, \\
\vartheta &= \Delta\theta + \theta_0.
\end{aligned} \qquad (5)$$

where φ_0 is the polarization azimuth plane of the radiation corresponding to the line of the glissade; ψ_0 is the runway heading; θ_0 is the inclination angle of the glissade.

V. RESULTS OF RESEARCH

The paper proposes the polarimetric landing system of fixed-wing UAV: the polarimetric principle of forming the landing glideslope, the radiation block and the measuring block of the polarimetric landing system, as well as the principle of its operation. The system consists of two blocks: the radiation block and the measuring block, which provides measuring in five channels: 4 glissade channels and 1 course channel. The system provides polarization plane azimuths measurements of the transmitted beams φd in five channels and provides calculation of the planar incidence angle of radiation in horizontal and vertical planes i_ψ, i_θ, as well as polarization plane azimuths of the incident beams $\varphi_{e1}, \varphi_{e2}, \varphi_{e3}$. The angles of deviation the UAV from the line of glissade and the attitude of the UAV are determined in the calculator by the formulas (4) and (5).

In the process of mathematical modeling was built plots a dependence graphs of polarization plane azimuths of the transmitted beams φd in five channels from angles of deviation the UAV from the line of glissade. Figure 7 shows the graph for the particular case: course angle, roll and pitch of UAV during landing is equal to zero ($\gamma = 0; \psi = 0; \vartheta = 0$).

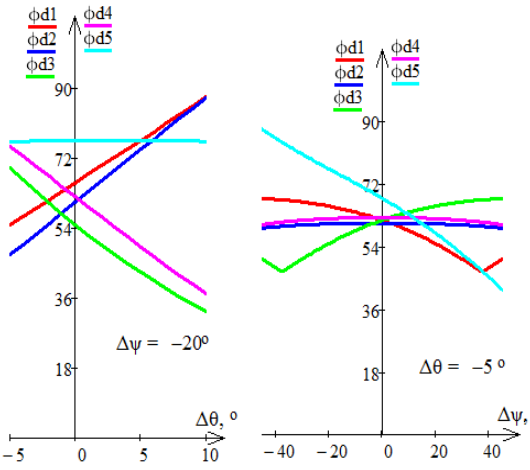

Fig. 7. Dependence graph polarization plane azimuths of the transmitted beams φd from angles of deviation the UAV from the line of glissade

After analyzing the graph, we conclude that the dependencies are mainly linear, and the sensitivity of the measurement depends on the UAV attitude.

VI. CONCLUSIONS

The article deals with the existing method and systems for UAV landing and proposed UAV landing system based on polarimetric technologies: proposed polarimetric method for forming the landing glideslope and polarimetric landing systems. Proposed system potentially, can provide landing on non-horizontal and moving plane of landing, as well as provide landing by complex trajectory due to high accuracy and sensitivity of determination the UAV attitude and its deviation from a landing trajectory. The article also shows the results of mathematical modeling of the measurement channel.

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А. Є. Клочан, А. Аль-Амморі, В. К. Суботіна, Хафед І. С. Абдулсалам. Поляриметрична система посадки безпілотних літальних апаратів

Статтю присвячено питанню розробки перспективної поляриметричної системи посадки безпілотних літальних апаратів літакового типу. Запропонована поляриметрична система посадки, також, може використовуватись для посадки безпілотних літальних апаратів інших типів. В статті розглянуто існуючі системи посадки безпілотних літальних апаратів, а також запропоновано поляриметричну систему посадки, яка складається з двох частин: наземного блоку (блоку випромінювання) та бортового блоку (блоку вимірювання). Розглянуто методи формування лінії глісади з використанням поляризованого випромінювання та блок-схеми каналів бортового та наземного блоків. При цьому наземний блок складається з трьох каналів випромінювання, а бортовий блок – з п'яти каналів вимірювання. Запропонована система потенційно дозволяє визначати просторове положення безпілотного літального апарату під час посадки, а також його відхилення від траєкторії посадки з високою точністю та чутливістю. Поляриметрична система посадки дозволяє проводити посадку на негоризонтальні та рухомі площини посадки, а також здійснювати посадку за складною траєкторією посадки. Наведено формули перерахунку поляриметричних параметрів, які вимірюються, в параметри просторового положення безпілотного літального апарату та його положення відносно лінії глісади. Показано результати математичного моделювання роботи каналу вимірювання, за результатами якого можна зробити висновок, що залежність поляриметричних параметрів від величини відхилення безпілотного літального апарату від лінії глісади має переважно лінійний характер та залежить від просторового положення безпілотного літального апарату.

Ключові слова: система посадки; траєкторія посадки; блок-схема; поляриметр; плоско-паралельна ізотропна діелектрична пластина; метод вимірювання; математичне моделювання; безпілотний літальний апарат.

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А. Е. Клочан, А. Аль-Аммори, В. К. Субботина, Хафед И. С. Абдулсалам. Поляриметрическая система посадки беспилотных летательных аппаратов

Статья посвящена вопросу разработки перспективной поляриметрической системы посадки беспилотных летательных аппаратов самолетного типа. Предложенная поляриметрическая система посадки, также может использоваться для посадки беспилотных летательных аппаратов других типов. Рассмотрены существующие системы посадки беспилотных летательных аппаратов, а также предложено поляриметрическую систему посадки, которая состоит из двух частей: наземного блока (блока излучения) и бортового блока (блока измерения). В статье рассмотрены методы формирования линии глиссады с использованием поляризованного излучения и блок-схемы каналов бортового и наземного блоков. При этом наземный блок состоит из трех каналов излучения, а бортовой блок – из пяти каналов измерения. Предложенная система потенциально позволяет определять пространственное положение беспилотного летательного аппарата при посадке, а также его отклонения от траектории посадки с высокой точностью и чувствительностью. Поляриметрическая система посадки позволяет проводить посадку на негоризонтальные и подвижные плоскости посадки, а также осуществлять посадку по сложной траектории посадки. Приведены формулы пересчета измеряемых поляриметрических параметров в параметры пространственного положения беспилотного летательного аппарата и его положения относительно линии глиссады. Показаны результаты математического моделирования работы канала измерения, по результатам которого можно сделать вывод, что зависимость поляриметрических параметров от величины отклонения беспилотного летательного аппарата от линии глиссады имеет преимущественно линейный характер и зависит от пространственного положения беспилотного летательного аппарата.

Ключевые слова: система посадки; траектория посадки; блок-схема; поляриметр; плоскопараллельная изотропная диэлектрическая пластина; метод измерения; математическое моделирование; беспилотный летательный аппарат.

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