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Measurement of the Angle of Attack of an Aerophysical Missile Complex in Flight Based on the Hall Effect Sensor and Electronic Measurement System

A.M. Pavliuchenko, O.M. Shyiko, T.I. Klochkova

Sumy National Agrarian University, 160, Herasym Kondratiev St., 40021 Sumy, Ukraine

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The method of direct continuous measurement of the angle of attack of an aerophysical missile complex, with the use of a Hall effect sensor, when in motion in its path for the numbers of Mach of the flow $M_\infty \leq 4.5$, Reynolds along the forebody length $Re_{L,\infty} \leq 10^8$, acceleration $a \leq 32$ g under the operation of a dual-thrust rocket engine (DTRE) is presented. The airborne electronic measurement system of the aerophysical missile complex, including the silicon Hall effect sensor as a sensor of the missile complex orientation in relation to the full vector of the Earth's magnetic field in this experiment, is described in detail. The Hall effect sensor has been installed between the two concentrators of magnetic flux from permalloy plates to amplify the Earth's magnetic field. The voltage in the magnetic field measurement channel has been determined by the dependence of $u = K \cdot H_\perp$, where K is the meter conversion coefficient, $H_\perp$ is the projection of the magnetic field intensity vector on the meter. A signal from the Hall effect sensor has arrived at the magnetic storage. Based on processing the path data on the angle of elevation, azimuth and range, it is found that the direction of a vector of free external stream velocity in flight of the missile complex with the operating DTRE has not changed, and the angle between the axis of this complex and the full vector of the Earth's magnetic field has been constant. This has enabled to conclude that the angle of attack in flight of the aerophysical missile complex is equal to zero with a precision of 0.3°. The result corresponds to the known theoretical data and is important for the calculation of thermal flows, surface friction resistance, bottom resistance in the presence of laminar-turbulent transition, turbulent regime of wall boundary flow and its relaminarization on streamlined surfaces. Based on flight data, a scheme of the aerophysical complex for measuring the angle of attack of an uncontrolled supersonic rocket with the aim of studying its oscillations and the problem of flight stability in the active and passive sections of the trajectory is proposed.

Keywords: Aerophysical missile complex, Angle of attack, Airborne electronic measurement system, Hall effect sensor, Earth's magnetic field, Magnetic field concentrators, Magnetic field intensity, Current density.

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1. INTRODUCTION

The flight path of supersonic rocket projectiles [1], supersonic aerophysical missile complexes [2], hypersonic space rockets [3, 4] is accompanied by complex aerodynamic, aerophysical processes, aerodynamic heating, vibrations, structural deformations, oscillatory processes, longitudinal and transverse overloads, aerodynamic loads in operating liquid-propellant rocket engines (LPRE) and solid propellant rocket engines (SPRE). In wall boundary flows under different flow regimes of super- and hypersonic vehicles in flight, there are effects of compressibility, non-isothermicity, laminar-turbulent transition, reverse transition from the turbulent flow regime to laminar (relaminarization), unsteadiness, aeroelasticity of the streamlined surface, longitudinal pressure gradient, vibration, separation of the wall turbulent flow with the formation of dangerous local peaks of heat flow and static pressure on the surface. In order to determine various characteristics of super- and hypersonic vehicles such as wave drag, surface-friction drag, and base drag, numerical calculation methods are used based on the Prandtl's wall boundary layer equations [4] and the most general Navier-Stokes nonlinear differential equations involving various turbulence models [5], experiments in super- and hypersonic wind tunnels [6] and missile complexes [2, 3].

In general, axisymmetric super- and hypersonic vehicles move in their path with the angle of attack, which is the angle between the direction of the external flow velocity vector and the tangent at a given point on the vehicle's surface. In the presence of the angle of attack, the flow of these vehicles is three-dimensional, and the theoretical solution to problems of aerodynamics and gas dynamics, aerophysics, heat transfer, taking into account all the above effects, is extremely difficult. The monitoring of the angle of attack of aircrafts and missiles plays an important role for controlling their flight, ensuring reliability at all its stages, during maneuvers.

2. PROBLEM STATEMENT IN GENERAL TERMS

When creating supersonic rocket projectiles, hypersonic missiles of various types in order to obtain reliable data on their various characteristics based on numerical methods of calculation, primarily using the Navier-Stokes nonlinear differential equations, it is important to use reliable quantitative information on the angle of attack in the flight path of these vehicles, especially after the cutoff of engines such as LPRE and SPRE. To stabilize the flight path of supersonic rockets and hypersonic missiles, they should be in rolling motion. With the angle of attack, the flow around these vehicles is three-dimensional that leads to their asymmetric flow about the longitudinal axis, the asymmetric transition from laminar flow regime to turbulent on the surface and the asymmetric reverse transition from turbulent to laminar regime, asymmetric heat flows to aerodynamic surfaces and asymmetric ablation of thermal protective coating, particularly of hypersonic space missiles [3, 4]. This affects the flight dynamics. In addition, the three-

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dimensional flow of such bodies raises the problem of applicability of turbulence models, which are mainly hold for two-dimensional flows.

Given the importance of quantitative data on the angle of attack when creating supersonic rocket projectiles, super- and hypersonic aircrafts and missiles, it is a problem point of making direct measurement of the angle of attack on the aerophysical missile complex at the numbers of Mach of the flow $M_\infty \le 4.5$, Reynolds along the forebody length $Re_{L,\infty} \le 10^8$, acceleration $a \le 32$ g under the operation of a dual-thrust rocket engine (DTRE).

3. GOAL OF THE ARTICLE

To solve the problem raised, it is essential to develop a new effective and implementable airborne electronic measurement system with sufficiently high speed and telemetry under the operation of a DTRE of the aerophysical missile complex with acceleration of up to $a \le 32\ g$, vibration, deformation, aerodynamic wall heating, various flow effects mentioned above at the Mach numbers of flight path of $M_\infty \le 4.5$. The Hall effect sensor, which enables to connect reasonably from physical standpoint the Earth's magnetic field and the processes of the missile complex forebody flow, is used as a sensitive element in determining the angle of attack.

The general goal of the article is to obtain reliable data on the angle of attack in flight path of the supersonic aerophysical missile complex under the operation of a DTRE.

4. RECENT RESEARCH AND PUBLICATION ANALYSIS

By now, there have been scientific research, articles and patents aimed at developing methods and systems for measuring aerodynamic angles of attack in flight of aircrafts for various purposes.

The work [7] has analyzed various methods and devices earlier developed for measurement of aerodynamic angles of attack and sideslip. A method for determining the angles of attack and sideslip has been implemented on the basis of a multifunctional air pressure head with special air pressure holes. This special multi-channel air pressure head enables to measure only the local angle of attack, which may differ significantly from the true angle of attack of an aircraft as a result of the air flow distortion at the place of pressure measurement. The local angle of attack varies greatly under the influence of vertical wind gusts in the perturbed atmosphere. To measure the true angle of attack of an aircraft, it is essential to measure several local angles of attack by placing air pressure heads in different parts of the aircraft wing or fuselage.

The scientific paper [7] provides for the analysis of a method for determining the angles of attack and sideslip for flight tests of a hypersonic aircraft with the use of air pressure probes on the spherical surface of the aircraft nose, located with specified steps in the longitudinal and lateral planes, a three-stage sensor of linear acceleration and angular velocity. The calculation of aerodynamic angles of attack has been carried out by processing the measured parameters from air pressure probes using the known kinematic relations.

In the work [7], static and dynamic pressure, air velocity pressure, and three-component linear acceleration are measured using accelerometers installed in body axes in the center of gravity of the aircraft. The aerodynamic angle of attack is calculated in the onboard digital computer using approximate model equations of normal and side forces affecting the aircraft, the analytical and experimental dependence of lift coefficient on the angle of attack taking into account data on the projection of the acceleration vector on the aircraft symmetry plane. The accuracy of determining the angle of attack is checked as well.

In the scientific paper [8], pressure measurements are made by means of air pressure probes, which are installed at discrete points in the drainage holes on the spherical nose of a hypersonic aircraft with specified steps in the longitudinal and lateral planes. Overloads and angular velocities are measured. Drainage holes on the aircraft nose are heat-resistant, and their number does not exceed four. Velocity pressure is measured. The algorithm for determining the angles of attack and sideslip of a hypersonic aircraft has been developed, statistical modeling is carried out, and the values of mathematical expectation and standard deviation are determined. The method for determining the angles of attack and sideslip is applicable for hypersonic aircrafts with the Mach numbers of up to $M_\infty = 10$.

In the work [9], the flight data on the angle of attack and sideslip have been obtained using an unmanned aerial vehicle (UAV) based on the measurement of pressure of free-stream flow on the nose cone of this UAV. A probe aerodynamic sensor of the angle of attack and sideslip has been used on the basis of the NASA's work on the creation of a system for measuring the parameters of air flow at certain points on the nose cone of the aircraft or on the wing leading edge (family of systems FADS – Flush Airdata Sensing). These systems have been tested on the F-18 aircraft and used in the X-33, X-34, and X-38 projects. The author [9] has developed a functional diagram of the angle of attack and sideslip meter. Freescale MPXV5004 integrated sensors with internal temperature drift correction have been used as pressure probes, a temperature sensor has been installed, and calibration tables for the values of signals from the pressure probes have been introduced. The work [9] refers to the measurement of the angle of attack and sideslip on UAVs, such as X47A developed in the United States.

The scientific paper [10] suggests an indirect method for determining the angles of attack and sideslip of aircrafts. In [10], it is noted that incidence vanes installed on many aircrafts have dynamic errors, and the systems of measuring angles of attack and sideslip using multifunctional air pressure tubes (MAPT) require the installation of several MAPTs with the need to heat them to prevent icing that reduces the actual reliability of the method due to an increase in the amount of electronic equipment. In the work [10], the proposed method for determining the angles of attack and sideslip of aircrafts is based on their calculation using such initial parameters of the aircraft movement as the speed head determined by the dynamic pressure, overload vector, data on the centrifugal force in curvilinear motion obtained using accelerometers, the aircraft weight, wing area. To determine the angle of attack, the known ratio is used: $C_{y\alpha} = Y_\alpha / qS$, where $Y_\alpha = n_{y\alpha} \cdot mg$ is the lift; C_{ya} is the lift coefficient; q is the velocity pressure; S is the wing area; n_{ya} is the lift-to-weight ratio; mg is the aircraft weight. This dependence is true for the entire aircraft (fuselage, engine nacelles, etc.) using the correction ΔY_α. The increment of the local angle of attack in the presence of angular velocity around the longitudinal axis of the aircraft is taken into account on the basis of calculations. The work [10] contains the calculation of random and systematic errors of in-flight measurements related to the accuracy of indirect determination of angles of attack. The method [10] may be used as a complement to the well-known schemes of measurement of the aerodynamic angle of attack.

Despite the variety of methods for measuring the angle of attack, the problem of measuring the angle of attack, especially on super- and hypersonic aircrafts, has not been addressed as yet. At the same time, there is a practical need to develop direct methods of measuring the angle of attack for rocket and space equipment, super- and hypersonic aircrafts [11]. In the above works, there are no direct measurements of the angle of attack and sideslip in flight of aircrafts. Methods of measuring the angle of attack are widely used on aircrafts for various purposes, as discussed above, in the atmospheric phase.

5. PRESENTATION OF THE RESEARCH BASIC MATERIAL

The angle of attack is one of the most important dynamic characteristics of sub-, super- and hypersonic aircrafts. It affects the characteristics of their flow, aerodynamic forces, flight dynamics, the aerodynamic heating of surfaces. The control of the angle of attack is required for the physically justified interpretation of various data of flight experiments, for control of aircraft flight. At the same time, reliable flight data on the angle of attack are important in the design of super- and hypersonic projectiles, missiles and aircrafts. Flight data on the angle of attack are of particular importance for the correct comparison of experimental results obtained in aerodynamic installations, aircrafts and on the basis of numerical calculations, primarily using the Navier-Stokes equations and effective difference schemes, when forming a flight data bank for automatic design systems (ADS).

It is known that for missiles with an SPRE well-stabilized in flight, the take-off of which is carried out with large overloads, the angle of attack is almost close to zero. This position was verified by the authors in the flight of the multi-purpose aerophysical missile complex. It was created on the basis of a supersonic meteor missile with a DTRE at the Mach numbers $M_\infty \leq 4.5$, the Reynolds numbers calculated along the forebody length $Re_{L,\infty} \leq 10^8$, acceleration $a \leq 32\,g$, and described in [2]. This work uses a direct method of measuring the angle of attack of the specified aerophysical missile complex under the operation of a DTRE with the Hall effect sensor, which in this case is the sensor of the aerophysical complex orientation towards the full vector of the Earth's magnetic field.

The continuous quantitative measurement of the angle of attack of the given aerophysical missile complex in flight in its path under the operation of first- and two-stage engines has been carried out on the basis of the Hall effect sensor, airborne electronic measurement system. The Hall effect consists in the appearance of the electric field with the intensity vector $\vec{E}_x$ perpendicular to $\vec{H}$ and $\vec{j}$ in a conductor with current density $\vec{j}$, placed in the magnetic field with intensity $\vec{H}$. The value of the electric field intensity $\vec{E}_x$ (the Hall field) is equal to $E_x = R \cdot H \cdot j \cdot \sin\alpha$, where R is the Hall coefficient, α is the angle between the vectors $\vec{H}$ and $\vec{j}$ ($\alpha < 180°$). If the vector $\vec{H}$ is perpendicular to the vector $\vec{j}$, then $E_x = R \cdot H \cdot j$. The Hall electromotive force (EMF) current changes its sign, when the direction of the magnetic field vector changes.

The silicon Hall sensor installed between two magnetic flux concentrators made of sheet permalloy and designed to strengthen the Earth's magnetic field was used in the flight experiment. The concentrators were located perpendicular to the axis of the aerophysical missile complex forebody. Voltage in the magnetic field measurement channel is determined by the dependence $U = K \cdot H_\perp$, where K is the meter conversion coefficient taken from the calibration, $H_\perp$ is the projection of the magnetic field intensity vector $\vec{H}$ on the meter. The signal from the Hall effect sensor arrived at the magnetic storage. The angle of elevation of the aerophysical missile complex in a takeoff position was 87°. The calculated initial angle between the Earth's magnetic field vector and the axis of the aerophysical missile complex forebody was 25.17°. The analysis of flight data has resulted in obtaining the following information.

Firstly, based on the processing of path data (angle of location, azimuth, range), it is found that the direction of the velocity vector of the free-stream flow in flight of the aerophysical missile complex with running first- and two-stage engines (solid propellant rocket engines) has not changed. Secondly, the angle between the axis of the aerophysical missile complex and the full vector of the Earth's magnetic field is constant in flight with the engines running. These two experimental facts have enabled to conclude that the angle of attack of the aerophysical missile complex is equal to zero. The error of measuring the angle of attack has not exceeded 0.3°. When processing the flight data obtained using the Hall effect sensor, the signal from the magnetic tape was sent to the input of the frequency-voltage converter and after subtraction of the pilot signal it was sent to the computer for processing.

Based on the results of measurements of the angle of attack of the aerophysical missile complex using a Hall effect sensor, it should be noted that this method of measuring the angle of attack may be used in the study of the parameters of paths and other aircrafts up to the Mach numbers of flight $M_\infty \leq 5.0$ and acceleration $a \leq 32\,g$, for example, rocket projectiles in the power-on flight. Initial disturbances in the power-on flight that receive the projectile as a result of separation shock lead to the appearance of the angles of attack of the projectile when interacting with the oncoming air flow.

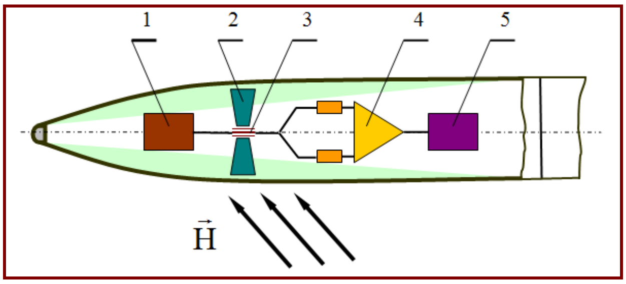

Fig. 1 – Schematic diagram of measuring the angle of attack using the Hall effect sensor: 1 – power supply; 2 – magnetic field concentrator; 3 – Hall effect sensor; 4 – amplifier; 5 – magnetic storage

The angle of attack is determined by the position of the projectile axis and velocity vector of the center of mass of the projectile. Due to the fact that the projectile axis makes precessional oscillatory motion with respect to the velocity vector of the center of mass, the plane and magnitude of the angle of attack change with the frequency of precession. Fig. 7 in [12] shows the calculated dependence of the angle of attack on time in the powered-flight phase for projectile. It can be seen that in a short period of time of $\tau \cong 0.15$ s the projectile axis changes its direction sharply and enters a precession movement with a circular frequency of $\nu \approx 150\ s^{-1}$ that leads to the angle of attack of $\alpha \cong 1.2°$. In the future, due to the stabilizing and damping moments, the precessional oscillatory movement fades over the course of $\tau \cong 1.0$ s, and the angle of attack becomes practically equal to zero.

It is impossible to trace such changes in the angle of attack accurately by means of ground measurement tools. In this regard, it is proposed to use airborne electronic measurement tools to measure the angle of attack. To do this, the prototype of a rocket projectile is converted through modernization into an aerophysical flight measurement system with a separable and parachuted forebody.

The forebody of the complex is equipped with the airborne electronic measurement system for measuring the magnetic field intensity based on a Hall effect sensor that enables to register changes in the position of the projectile axis in relation to the vector of the Earth's magnetic field intensity (Fig. 1). In this case, the direction of the velocity vector of the center of mass of the aerophysical flight measurement system is determined using three-component accelerometers and acceleration integrators.

The paper [13] presents the results of research on the development, manufacture and use of primary magnetic flux concentrators for measuring weak magnetic fields, including space instrumentation for use in small spacecrafts, for measuring variations in the Earth's magnetic field, and for detecting hypogeomagnetic zones. The use of the phenomenon of magnetic flux concentration by ferromagnetic devices enables to develop sensors for measuring weak magnetic fields that have high magnetic sensitivity exceeding the average value for a conventional Hall effect sensor by 2-3 orders of magnitude without degradation of noise characteristics and time stability [13]. The Hall microminiature element, created on the basis of the heteroepitaxial *n*-InSb-*i*-GaAs structure, contains the substrate of monocrystalline *i*-GaAs, film magneto-sensitive area of *n*-InSb, a measuring crosshair in the form of a square of 30 × 30 microns, and gold electrical leads from a microwire welded using micro-welding or thermal compression. The working surface of the Hall effect sensor is sealed with a layer of elastosyl compound on a smaller base of the cone, the diameter of which is equal to or slightly exceeds the length of the measuring crosshair, and the thickness does not exceed the value of the gap $d = 100$ microns. The magnetic sensitivity of the Hall effect sensor at a control current of 60 mA is 500 mV/TL [14].

6. CONCLUSIONS

1. For the first time, the method of controlling the angle of attack of an aerophysical missile complex in flight in a path at the Mach numbers of the free-stream flow $M_\infty \le 4.5$, the Reynolds numbers $Re_{L,\infty} \le 10^8$, acceleration $a \le 32\ g$ based on the Hall effect sensor and airborne electronic measurement system has been implemented.

2. The method of direct control of the angle of attack in flight of an aerophysical missile complex in the conditions of running engine (solid propellant rocket engine) with the use of the Hall effect sensor is physically justified and reliable.

3. The developed method of controlling the angle of attack of an aerophysical missile complex in flight has sufficiently high accuracy and may be used for super- and hypersonic vehicles for various purposes.

4. Based on the flight data in [2] for measuring the angle of attack of an aerophysical missile complex, calculated data on the dependence of the angle of attack on time for an unguided rocket [12], the development of a microminiature Hall effect sensor in [13], the authors have proposed a scheme of an aerophysical flight measurement system for measuring the angle of attack of an unguided hypersonic missile projectile in order to study its oscillations and the problem of stability in in the active and passive sections of the trajectory.

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Вимірювання кута атаки ракетного аерофізічного комплексу в польоті на основі датчика Холла і електронної вимірювальної системи

А.М. Павлюченко, О.М. Шийко, Т.І. Клочкова

Сумський національний аграрний університет, вул. Г. Кондратьєва 160, 40021, Суми, Україна

Представлений метод прямого безперервного вимірювання кута атаки ракетного аерофізічного комплексу з використанням датчика Холла при русі по траєкторії для чисел Маха потоку $M_\infty \le 4.5$, Рейнольдса по довжині головної частини $Re_{L,\infty} \le 10^8$, прискорення $a \le 32\ g$ в умовах роботи двоступеневого ракетного двигуна на твердому паливі (РДТП). Детально описана бортова електронно-вимірювальна система аерофізічного комплексу, що включає датчик Холла, який є в даному експерименті датчиком орієнтації ракетного комплексу щодо повного вектора магнітного поля Землі. Датчик Холла був встановлений між двома концентраторами магнітного потоку з листового пермалою для посилення магнітного поля Землі. Напруження в каналі вимірювання магнітного поля визначалося залежністю $u = K{\cdot}H_\perp$, де K – коефіцієнт перетворення вимірювача, $H_\perp$ – проекція вектора напруженості магнітного поля на вимірювач. Сигнал з датчика Холла надходив в магнітний накопичувач. На основі обробки траєкторних даних про вугол місця, азимут, дальність було встановлено, що напрямок вектора швидкості набігаючого зовнішнього потоку повітря в польоті ракетного комплексу з працюючим двоступінчастим двигуном РДТП не змінювався, а кут між віссю цього комплексу і повним вектором магнітного поля Землі був постійним. Це дозволило зробити висновок про рівність нулю кута атаки в польоті ракетного аерофізіческого комплексу з похибкою 0.3°. На основі льотних даних запропонована схема аерофізичного комплексу для вимірювання кута атаки некерованого надзвукового реактивного снаряда з метою вивчення його коливань і проблеми стійкості польоту на активній і пасивній ділянках траєкторії.

Ключові слова: Ракетний аерофізичний комплекс, Кут атаки, Бортова електронно-вимірювальна система, Датчик Холла, Магнітне поле Землі, Концентратори магнітного поля, Напруженість магнітного поля.