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"Georgi Benkovski"

Bulgarian Air Force Academy

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"Georgi Benkovski" Bulgarian Air Force Academy

Address

AERONAUTICAL RESEARCH AND DEVELOPMENT

Dolna Mitropolia, 5855

"St. St. Cyril and Methodius" №1, St.

asen_aerodynamics@abv.bg

Language Editor

Yavor Varbanov

"Georgi Benkovski"

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Contents

Comparative analysis of BLDC electric motor performance under different coupling configuration for motor-propeller system applications

Georgi Georgiev

Bulgarian Air Force Academy, Faculty of Aviation, goro78@gmail.com

Abstract: An experimental study was made of parts of the electro-mechanical characteristics of a brushless (BLDC) electric motor with different connection configurations (star, delta) when it is used in a propeller group engine. The thrust was measured against the current consumption under the same conditions.

Keywords *BLDC motor, Connection configuration, Propeller propulsion. Experimental comparison, Thrust performance, Efficiency analysis*.

1. Introduction

With the development of technology in recent decades, unmanned aerial vehicles are gaining more and more popularity and are widely used in various activities of human life. Nowadays, their application has become increasingly large in the occurrence of a number of crises [1], [2]. According to the research done on the trends and prospects of aviation storage batteries [3] and the general analysis of their energy storage technology [4], the need appears to investigate the possibilities of extending the flight time, generating additional energy by incorporating an additional engine -generator group in the construction of the UAV.

BLDC motors are widely used in (UAV) propulsion systems due to their efficiency, reliability and controllability. However, the optimal connection configuration of BLDC motors for propeller applications remains an area of active research [5].

In this study, two different connection configurations – star and delta – are presented and evaluated through experimental testing. The efficiency indicators studied include traction and current consumption under the same operating conditions. The experimental results provide valuable insight into the effects of different coupling configurations on the performance of BLDC motors in their propeller operation, aiding in the selection of coupling configurations for specific UAV propulsion system requirements.tolerance.

2. Trial staging

In order to ensure an unbiased assessment in the experimental approach, an electric motor model "EMAX CF 28-22" Brushless Outrunner 1200kv with a factory coil that has not been changed except for configuring its connection, as well as the same experimental setup [6], [7].

Uniformity was maintained under precisely replicated conditions throughout the experiments. The same propellers, the same power supply, and the same speed controller (ESC) were used.

3. Theoretical study

The torque of a BLDC electric motor can differ depending on the way of coupling the phases of the electric motor - star or delta configuration [8].

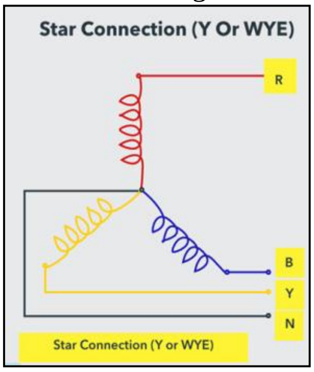

Fig. 1. Star Connection

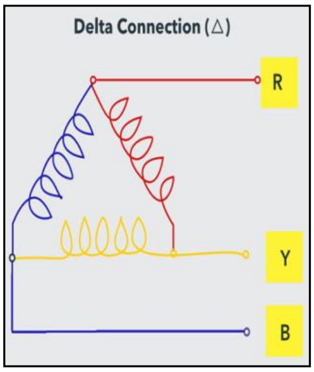

Fig.2 Delta Connection

In a star connection Fig. 1, all ends of the three windings are connected in one node, the neutral point. This configuration is preferred in applications that require more torque at lower RPM. For a delta connection Fig.2, the phases of the electric motor are connected in series to each other. This configuration always provides a higher top speed but with lower torque compared to a star connection.

Table 1. Comparison between star and delta configuration

Star Connection (Y)	**Delta Connection (Δ)**
A Star Connection is a 4 – wire connection (4th wire is optional in some cases)	A Delta Connection is a 3 – wire connection.
Two types of star connection systems are possible: 4-wire 3-phase system and 3-wire 3-phase system.	With Delta connection, only a 3-wire 3-phase system is possible.
Out of the 4 wires, 3 wires are the phases and 1 wire is the neutral (which is the common point of the 3 wires).	All 3 wires are phases in Delta connection.
In a star connection, one end of all three wires is connected to a common point in the shape of a (Y), so that all three open ends of the three wires form the three phases and the common point forms the neutral.	In a Delta connection, each wire is connected to two adjacent wires in the form of a triangle (Δ) and all three common points of the connection form the three phases.
The common point of the star connection is called the neutral or star point .	With Delta there is no neutral point .
Line voltage (the voltage between any two phases) and phase voltage (the voltage between either phase and neutral) are different.	Line voltage and phase voltage are the same.
Line Voltage is root three times phase voltage i.e. $VL = \sqrt{3}\ VP$. Here, VL is Line Voltage and VP is Phase Voltage.	Line Voltage is equal to Phase Voltage i.e. $VL = VP$.
With a star connection, two different voltages can be used because VL and VP are different.	In delta connection we get only one magnitude of the voltage
Line current and phase current are the same. $IL = IP$. IL is line current and IP is phase current .	The line current is the root of three times the phase current. $IL = \sqrt{3}\ IP$
The total three-phase power in a star connection can be calculated using the following formulas. $P = 3 \times VP \times IP \times \cos(\Phi)$ or $P = \sqrt{3} \times VL \times IL \times \cos(\Phi)$	The total three-phase power in a delta connection can be calculated using the following formulas. $P = 3 \times VP \times IP \times \cos(\Phi)$ or $P = \sqrt{3} \times VL \times IL \times \cos(\Phi)$

The table from [9] is used in the comparison of the two connections.

These comparisons are intended to contribute to a deeper understanding of BLDC motor behavior under the two connection configurations. This, in turn, will facilitate the choice of propulsion configuration for the (UAV), which will lead to an extension of its flight time.

In Fig. 3 and Fig. 4 a comparison is made between thrust and current consumption under equal conditions of the same electric motor in different connection configuration and propeller size 8 x 3.8.

These graphs show the relationship between the measured thrust in grams (on the ordinate) and the current values (on the abscissa). Tests were conducted with an 8x6 propeller and the results are shown in Fig.5 and Fig.6. A comparison between the two graphs shows some differences and similarities, such as:

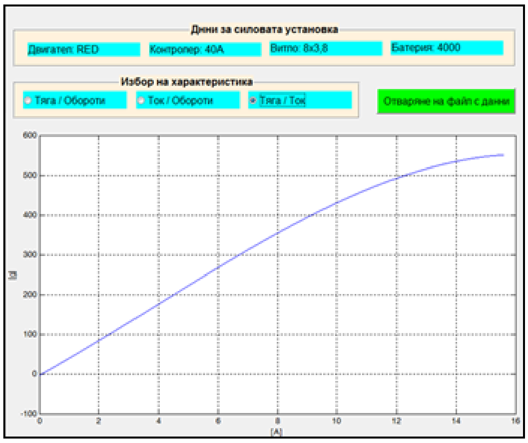

Fig.3 Delta configuration, propeller 8x3.8

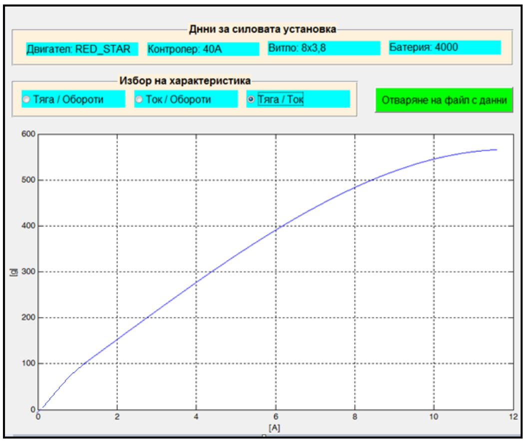

Fig.4 Star configuration, propeller 8x3.8

- Initial value of thrust: It is clear from the graphs that the initial value of thrust in star configuration (Fig.4) is higher compared to the initial value in delta configuration (Fig.3). This can be important in determining the appropriate configuration depending on the initial thrust requirements.
- Relationship between current and thrust: In both graphs it is clear that there is a clear positive relationship between current and thrust - higher current leads to greater thrust
- Rate of Rise: There are some differences in the rate of rise of thrust versus current between the two data sets. In the star configuration of Fig.4, the thrust increases faster at the beginning, then its increase slows down at higher current values, while in the first data set of Fig.3, the thrust increases more evenly throughout the current range .
- Thrust lag: Both data sets show thrust lag at the higher current values, although this lag may be more noticeable in star configuration.
- With the star configuration: from Fig.4 it can be seen that a greater thrust of 570g is achieved. with a lower current than 12A. Compared with delta configuration Fig.3. Here the thrust is lower - 550g, but a higher current of 16A is needed to achieve the thrust value than that of the delta connection.
- Configuration Efficiency: The star configuration demonstrates greater thrust efficiency over the delta configuration. Although lower current values are required, the thrust in the star configuration is found to be higher compared to the delta configuration under similar conditions.

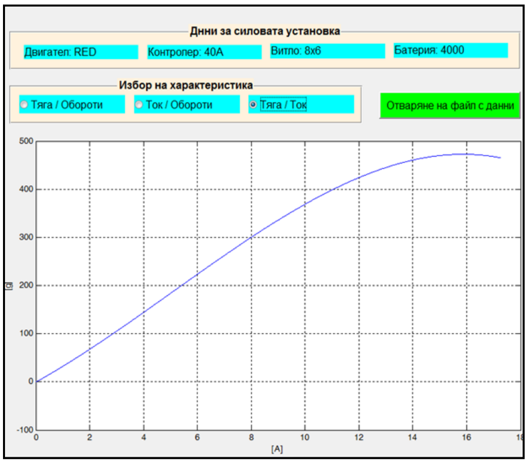

Fig.5 Delta configuration, propeller 8x6

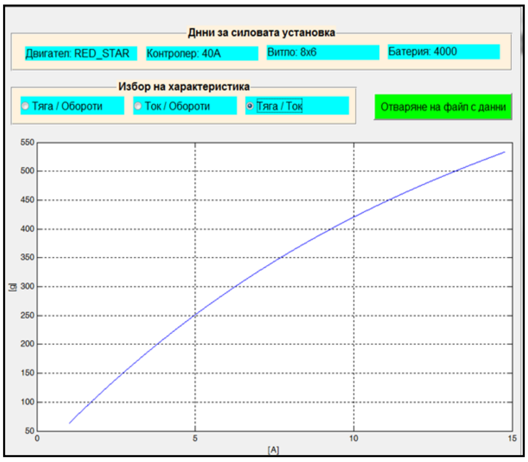

Fig.6 Star configuration, propeller 8x6

Both graphs show a non-linear growth of the thrust with respect to the current, its growth slows down at higher values of the current.

It is important to note that in the Delta configuration a maximum thrust of 470g was achieved. with a consumption of 16A, and with a star configuration 540g. with consumption 15A.

In Fig.7 and Fig.8, tests were carried out with a 10x4.7 propeller in star and delta configuration, the results show:

- Rate of Rise: There are some differences in the rate of rise of thrust versus current between the two data sets. In Delta Fig.7 configuration the thrust is 260g. with a consumption of 5A, while with the Star with a consumption of 5A, the thrust is 300g. With a consumption of 10A, when connected in Delta, the thrust is 420g, while with a star with 10A, 510g is achieved. Accordingly, consumption 20A and thrust 660g. with Delta configuration and 680g .with a consumption of 16A when connected Star.
- With the star configuration: Fig.8, a greater thrust of 680g is achieved. with a lower current than 16A. Compared to the Fig.7 delta configuration, the thrust is lower at about 660g, but a higher current of 20A is required to achieve a close thrust value.

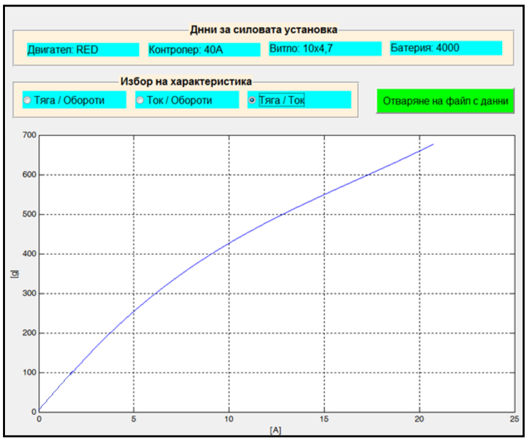

Fig.7 Delta configuration, propeller 10x4.7

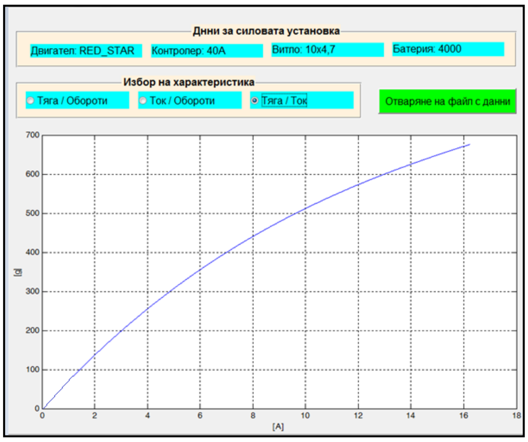

Fig.8 Star configuration, propeller 10x4.7

In summary, the graphs present important information on the relationship between current consumption and generated thrust of electric propeller motors, providing a basis for further studies of their performance [10].

This, in turn, will facilitate the selection of the (UAV) propulsion configuration, which will lead to an extension of the flight time.

4. Conclusion

- The graphs that have been obtained show the relationship between the current consumption and the generated thrust of two different configurations of the same electric motor with a propeller. They show an increasing trend, with current consumption increasing as thrust increases.
- Although the graphs are not perfectly straight lines, they appear to be linear in their general appearance, meaning that the relationship between current consumption and thrust generated is close to linear.
- The comparison between the two configurations shows differences in their characteristics. Star configuration produces higher generated thrust with less current consumption compared to Delta.
- The relationship between current consumption and generated thrust is essential to the operation of electric propeller motors. Graph analysis can be used to predict the results of various electric motor settings and improvements.

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Сравнителен анализ на производителността на BLDC електродвигател при различна конфигурация на свързване за приложения в система двигател-витло

Georgi Georgiev

Pleven, Bulgaria, goro78@gmail.com Air Force Academy, Aviation Faculty, Dolna Mitropolia, Bulgaria

Abstract:Направено е експериментално изследване на части от електро-механичната характеристики на безчетков (BLDC) електродвигател с различни конфигурации на свързване (звезда, триъгълник) при използването му в двигател - витлова група. Измерена е тягата спрямо консумацията на тока при еднакви условия.

Block Diagram Simulation of Aircraft Longitudinal Flight Dynamics

Konstantin Metodiev

Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria
komet@space.bas.bg

Abstract: Current study objective is to bring forth a block diagram and a signal flow graph in order to work out numerical solution of a system non-linear ordinary differential equations describing aircraft longitudinal motion. Kinematic parameters of an aircraft flying within plane of symmetry are determined by means of xCos, a block diagram editor available in SciLab environment. Developed diagrams have been validated by means of corresponding SimuLink counterparts. After carrying out several test cases, the obtained results are depicted and discussed thoroughly.

Keywords: *SciLab, xCos, Pilatus PC-9M, Flight Dynamics*

1. Introduction

Longitudinal flight dynamics, also known as longitudinal stability and control, refers to analyzing and understanding the motion of an aircraft within the symmetry plane during flight. It primarily focuses on stability and control characteristics related to the aircraft pitch motion, [1].

Pitch motion involves rotation of the aircraft around its lateral axis, causing changes in the angle of attack, pitch rate, and pitch attitude. Longitudinal flight dynamics aims to investigate the effects of these changes on the aircraft's stability and control.

Stability in longitudinal flight dynamics is concerned with ability of the aircraft to maintain a steady and balanced pitch attitude during different flight conditions. Linearized equations of longitudinal motion involve numerous stability derivatives. For example, derivative $\partial Cm/\partial C_L(\alpha)$ relates change in pitching moment to change in angle of attack and depends on aerodynamic center location along longitudinal axis (in relation to the mass center). Negative value ensures that the aircraft recovers from disturbance by restoring its original pitch attitude.

Control, on the other hand, refers to the pilot's ability to maneuver the aircraft within plane of symmetry. This involves control surfaces such as the elevator, which is meant to adjusts the aircraft's pitch. The elevator control effectiveness is crucial for maintaining control and achieving desired pitch changes during flight. There is a trade-off between aircraft stability and control properties.

Longitudinal flight dynamics also distinguishes the difference between static and dynamic stability. Static stability determines whether the aircraft will automatically return to its original pitch attitude after a disturbance, while dynamic stability assesses the aircraft's response to external disturbances over time.

The software package used to implement the project is xCos. It is a freely distributed software package for symbolical and numerical computations. It is part of the open-source software suite called SciLab, [2] which is designed for numerical computations and simulations. xCos provides tools for modeling, simulation, and analysis of dynamic systems using block diagrams and signal flow graphs. It is widely used in various fields such as control engineering, robotics, and mechatronics for system design and simulation. In addition, xCos is widely recognized as a free alternative to SimuLink, [3].

The proposed project makes use of a super block replicating the 3DOF (wind axes) block accessible in SimuLink Aerospace block set. Pilatus PC-9M turbo propeller has been chosen as a test plant. Its mass and geometrical quantities are used as initial conditions. Limited scientific data is publicly available with regard to flight dynamics properties of PC-9M. While detailed technical information may be proprietary, there are some general specifications and performance data that still can be found, for example, Snowden et al., [4], Savov, Marinov, [5]. In addition, a generic research on longitudinal flight dynamics of joined-wing aircraft is reported by Panayotov in [6].

2. Materials and Methods

The project has been implemented by means of SciLab, [2] and accompanying module xCos, an alternative to SimuLink. No additional toolboxes are required in advance to perform the simulation.

2.1. Formulae

To reveal the aircraft longitudinal motion, following system of Ordinary Differential Equations is solved numerically. The system has been suggested by MathWorks and published in [7], p.5-69.

$$
\begin{aligned}
&A_{xb} = A_{xe} - qV\sin\alpha \\
&A_{zb} = A_{ze} + qV\cos\alpha \\
&A_{xe} = \left(\frac{F_x}{m} - g\sin\gamma\right)\cos\alpha - \left(\frac{F_z}{m} + g\cos\gamma\right)\sin\alpha \\
&A_{ze} = \left(\frac{F_x}{m} - g\sin\gamma\right)\sin\alpha + \left(\frac{F_z}{m} + g\cos\gamma\right)\cos\alpha \\
&\dot{V} = \frac{F_x}{m} - g\sin\gamma \\
&\dot{X}_e = V\cos\gamma \quad \dot{Z}_e = -V\sin\gamma \\
&\dot{q} = \frac{M_y}{I_{yy}} \\
&\dot{\gamma} = q - \dot{\alpha} \quad \dot{\alpha} = \frac{F_z}{mV} + \frac{g}{V}\cos\gamma + q
\end{aligned}
\tag{1}
$$

The applied forces presumably act at the body center of gravity. Input variables are forces Fx, Fz, N, and body moment My, N.m, acting along the aircraft wind axes, moment of inertia Iyy, kg.m^2, constant mass m, kg. Gravity acceleration g, m/sec^2, is an optional input variable. Output variables are flight path angle γ, rad, pitch angular rate q, sec^{-1}, pitch angular acceleration dq/dt, sec^{-2}, aircraft location Xe, Ze, m, velocity in wind fixed frame, Vw, m/s, angle of attack α, rad. A relationship between body, wind, and Earth fixed reference frames is shown in Fig. 1.

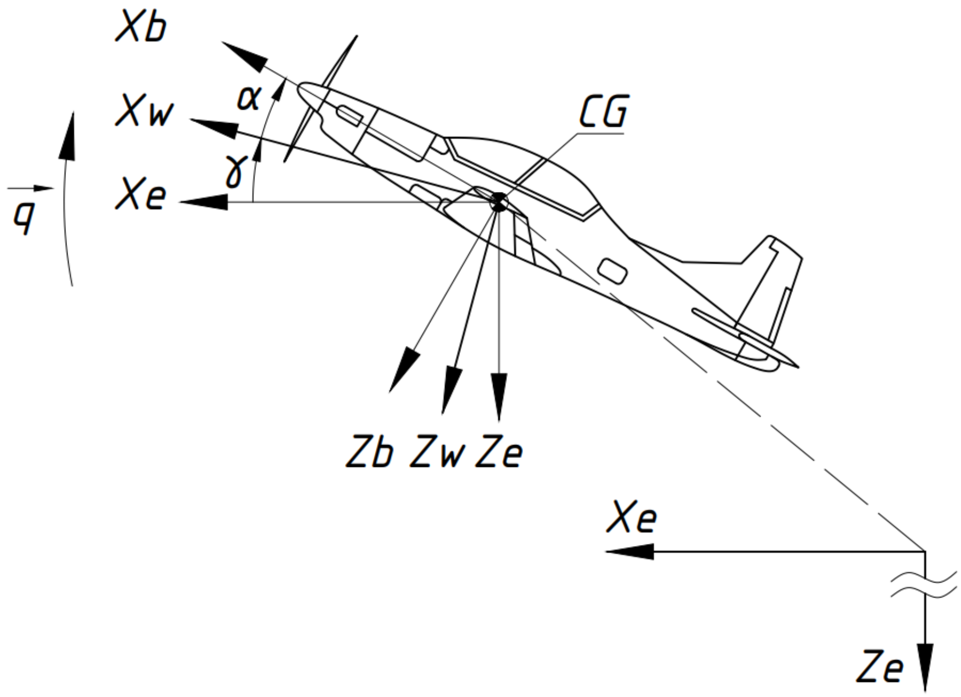

Fig. 1. Reference frames associated with presented model

2.2. Block diagrams

Contribution of the present study is implementing a longitudinal dynamics model in xCos by replicating the 3DOF (wind axes) and ISA blocks available in SimuLink Aerospace block set. Main block diagram is a closed loop in terms of aircraft angle of attack, linear velocity, pitch rate, and vertical displacement. It consists of force computation blocks, i.e. Aerodynamic coefficients, C2FM, and Thrust, International Standard Atmosphere (ISA) block, Dynamic Pressure block, and a 3DOF (wind axes) block, Fig. 2. The force blocks compute thrust, aerodynamic, and control forces whilst the 3DOF block computes dynamic and kinematic parameters of longitudinal motion (aircraft wind axes). Each block will be examined in succession.

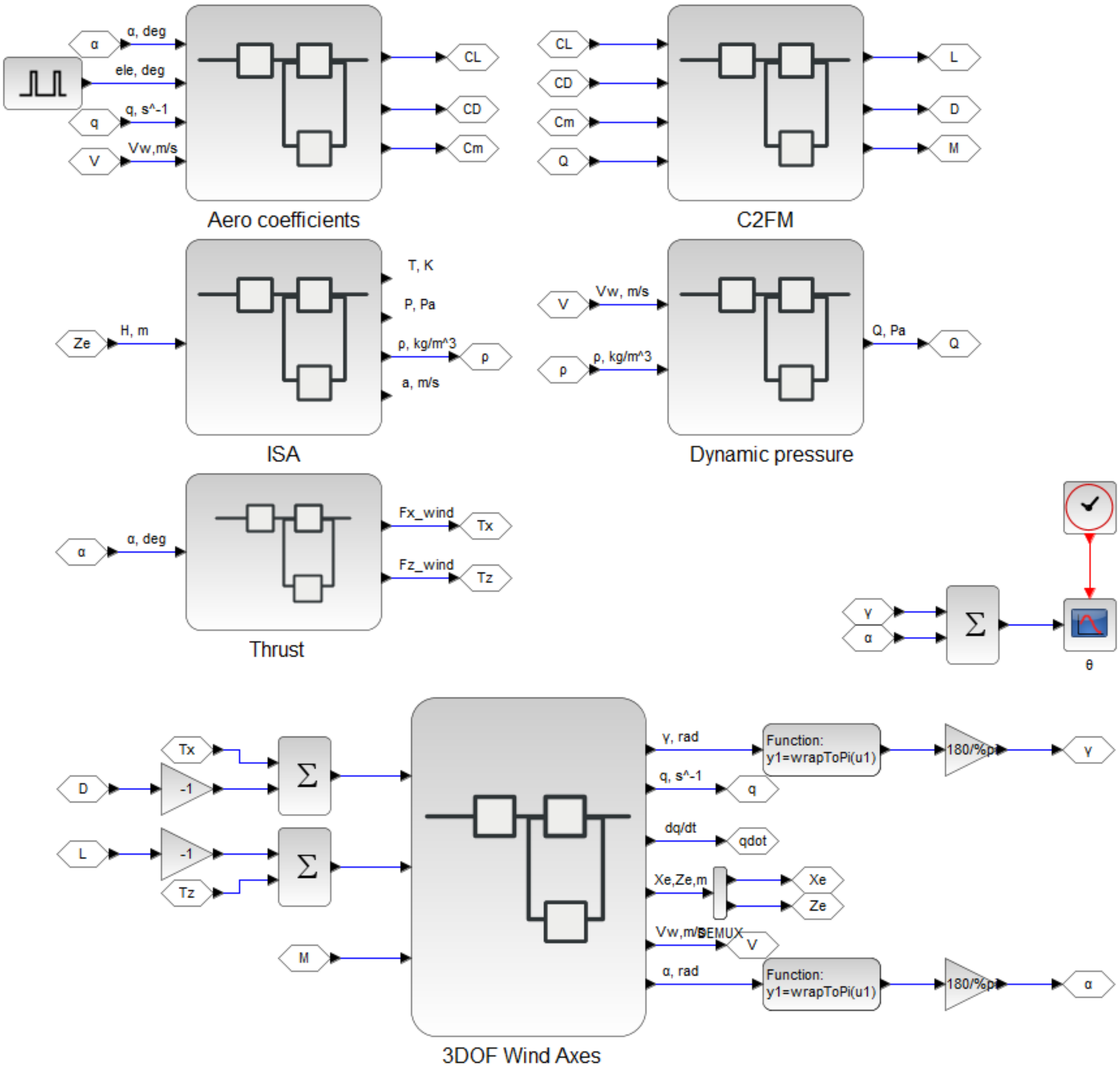

Fig. 2. Main block diagram of proposed model

In order to implement the model, following mass properties and stability derivatives were borrowed from paper [5] and FlightGear model of Pilatus PC-9M distributed for free by FGUK, [8]

- Moment curve slope: $\partial Cm/\partial\alpha = -1.023$, [5]
- $\partial Cm/\partial\dot{\alpha} = -7$, [8]
- Pitch damping due to pitch rate: $\partial Cm/\partial q = -15$, [8]
- Airplane neutral point location (percentage of mean aerodynamic chord): xAC = 18.2 %, [5]
- Airplane mass center location (percentage of mean aerodynamic chord): xCG = 15 %
- Empty weight 1616.6 kg; Max. take-off weight 2350 kg; Moment of inertia: Iyy = 5686.3 kg.m^2
- Altitude: 1000 m; Stall speed: 40 m/s; Max. speed: 154 m/s
- Distances: $l_{TAIL} = 6.1082$ m, MAC = 1.5911 m; Areas: $S_{TAIL} = 2.7639$ m^2, $S_{WING} = 16.258$ m^2

Thrust block contents is shown in Fig. 3. The interpolation block inputs are set after double clicking on the "Interp" block. These inputs are time-dependent user-defined values of the thrust vector stored in a *.csv file in advance.

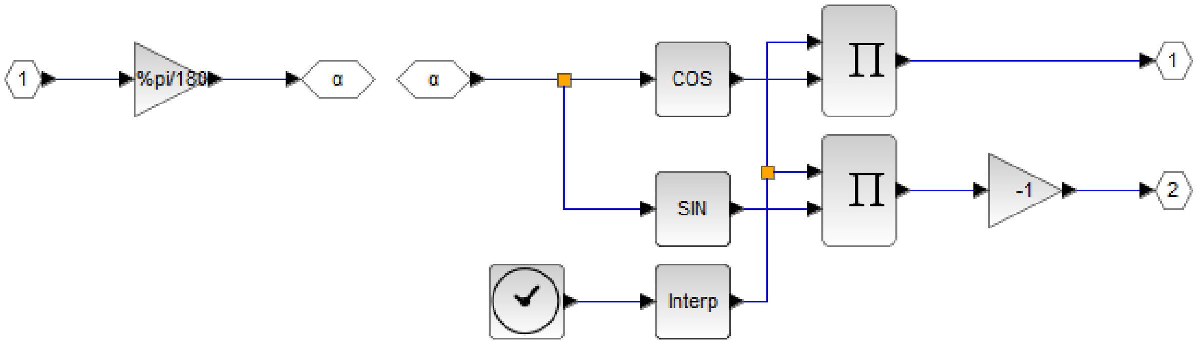

Fig. 3. Thrust block structure

ISA block provides information on pressure and density changes with altitude in addition to temperature and local sonic speed. The pressure decreases exponentially with increasing altitude, following the so-called barometric formula, [9] based on average sea-level pressure. Similarly, density decreases with increasing altitude due to the lower atmospheric pressure, resulting in a thinner atmosphere at higher altitudes. The barometric formula is not an exact representation of atmospheric pressure changes, as various factors like humidity, air composition, and local weather conditions can influence pressure readings. However, it provides a good approximation for standard atmospheric conditions.

In Fig. 4, the ISA block internal structure is shown. The user-defined functions p(u1), ρ(u1) implement the barometric formula according to what is written in [9]. The rest of the block diagram is self-explanatory. The presented ISA block has been put to the test with the SimuLink counterpart, [7] yielding identical results. The only block parameter used in current study in order to compute dynamic pressure Q is density of air (output 3).

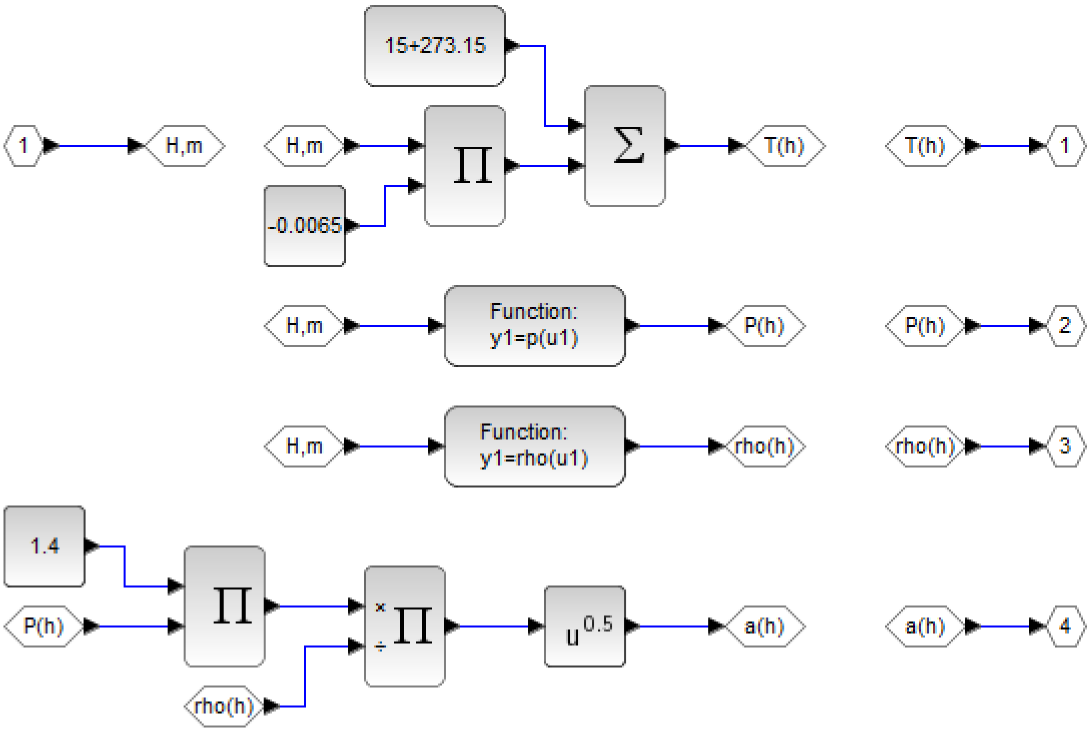

Fig. 4. ISA block structure

The C2FM block, Fig. 5, takes aerodynamic coefficients and converts them into forces (lift, drag) and longitudinal moment according to widely known formulae $L,D = C_{L,D}(\alpha)*0.5\rho V^2*S$ and $M = Cm(\alpha)*0.5\rho V^2*S*c\_bar$. The user defined function C2FM contains data about mean aerodynamic chord and wing planform area. The 4th input is dynamic pressure ($Q = 0.5\rho V^2$) which in turn is computed within corresponding block, Fig. 6.

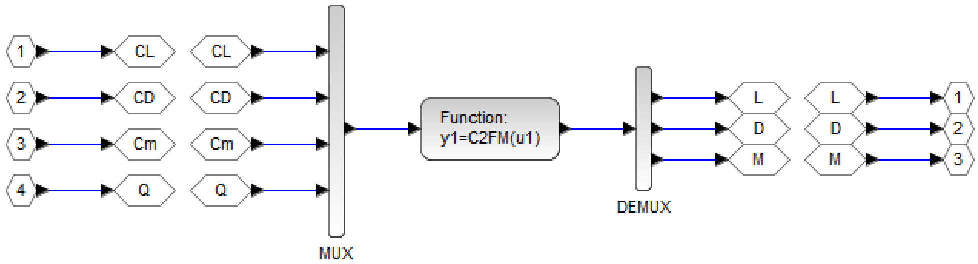

Fig. 5. C2FM block internal structure

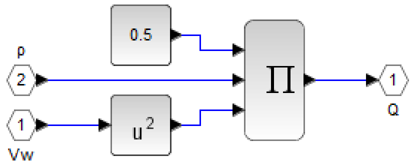

Fig. 6. Dynamic pressure block structure

In Fig. 7, the 3DOF (wind axes) superblock structure is shown. The block uses “goto” and “from” tags extensively in order to reduce number of tracks and achieve design clarity. The initial conditions are set after double clicking on “INTEGRAL_f” (1/s) block located in “System 1st order ODEs” region. Respectful reader is advised to get acquainted with following article [10] on how to solve system ODEs by means of a block diagram.

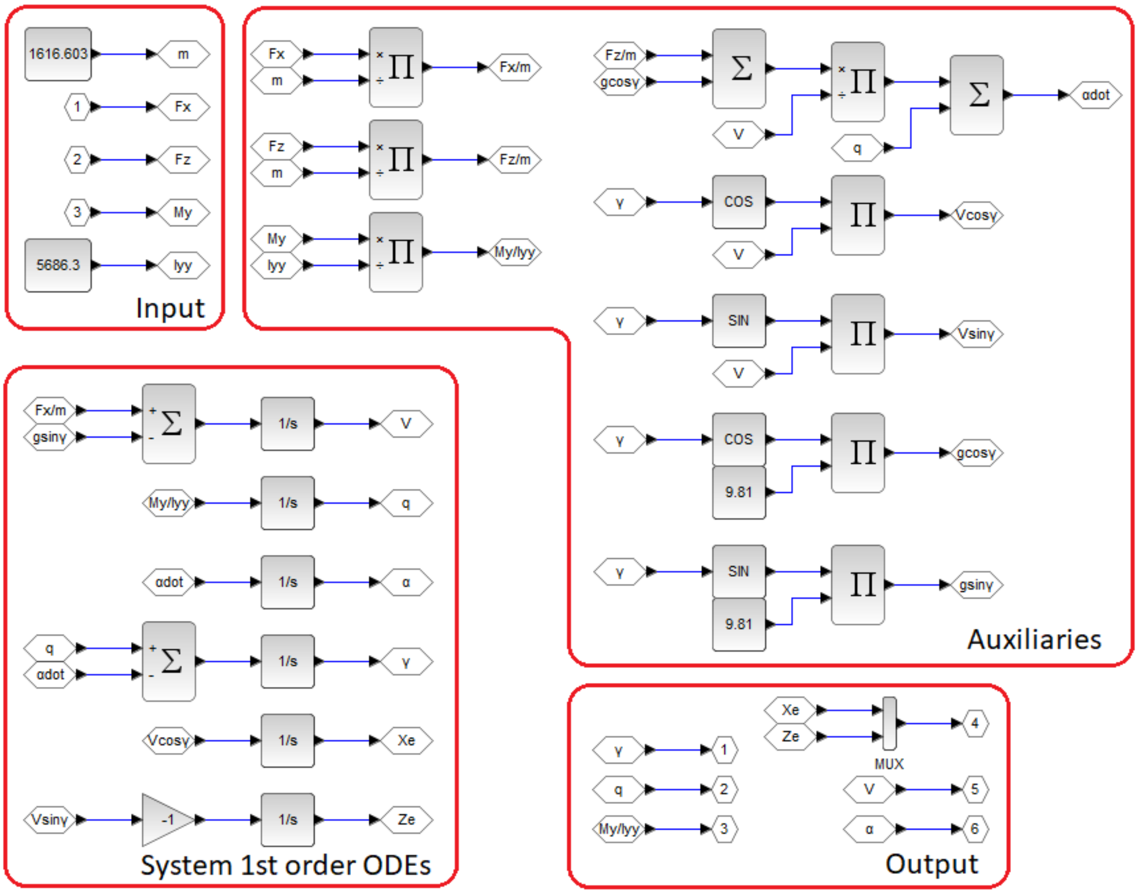

Fig. 7. 3DOF (wind axes) superblock structure

The most sophisticated and accountable block is "Aero coefficients." As its name may suggest, the block extracts aerodynamic coefficients from empirical data by means of interpolation. The only exception is longitudinal moment coefficient which is calculated according to equation, [11]:

$$(2) \quad C_{m,cg} = C_{m0} - \left(h_{ac} - h_{cg}\right)C_L - \frac{S_T}{S}\frac{l_T}{\bar{c}}C_{LT} + \frac{q\bar{c}}{2V}\frac{\partial C_m}{\partial q}$$

where hac and hcg are dimensionless distances between some datum (for instance mean aerodynamic chord origin) and neutral point and center of gravity respectively. The subscript "T" stands for "Tail." The quantity $\bar{V} = \frac{S_T}{S}\frac{l_T}{\bar{c}}$ refers to tail volume coefficient. Its value is of utmost importance to achieve stable trimmed flight. In addition, the pitch moment coefficient is augmented with ∂Cm/∂q derivative defining pitch damping property due to pitch rate q, s^{-1}. The derivative solely affects short-mode oscillatory motion. Its value is always negative. The contents of Aerodynamic coefficients block is depicted in Fig. 8.

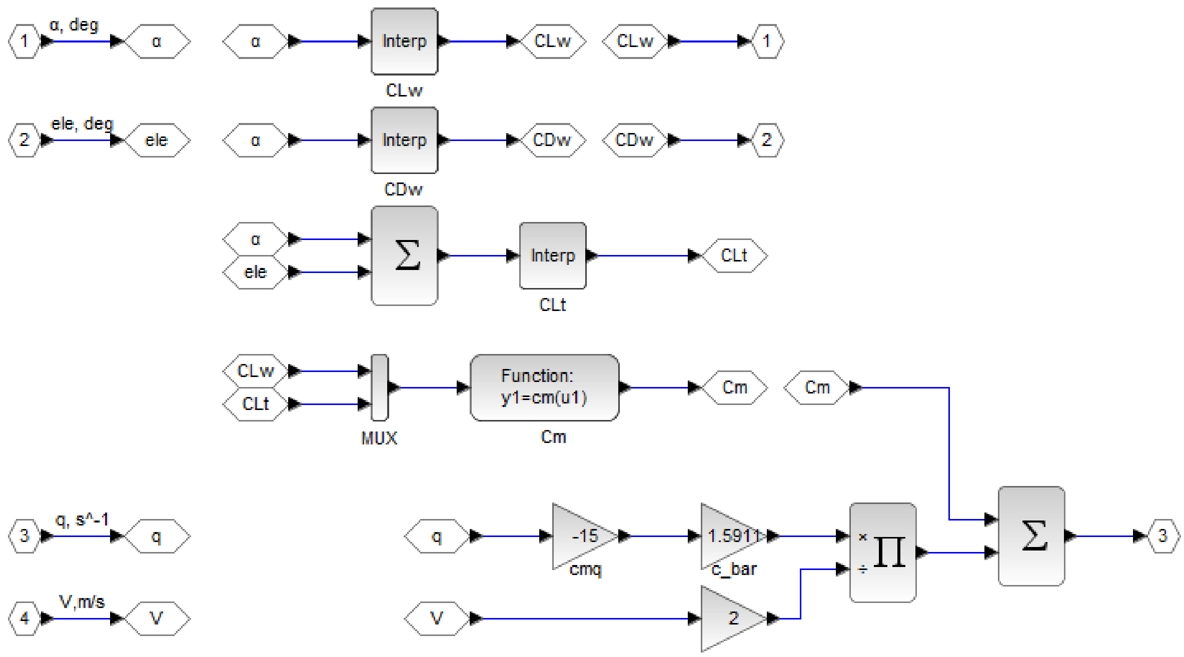

Fig. 8. Aero coefficients superblock structure

The user-defined function cm(u1) computes Cm coefficient in accordance with the aforementioned equation. Within the superblock structure, the elevator input is added to horizontal stabilizer angle of attack. The wing downwash hasn't been taken into account. Since data is insufficient, value assigned to tail lift curve slope is $\partial C_{LT}/\partial\alpha$ = 6.28 rad^{-1}. This value is recommended to either a flat plate or a symmetrical airfoil.

2.3. 3DOF (wind axes) superblock validation

Broadly speaking, validation of scientific results refers to a process of ensuring that the findings of a scientific study or experiment are accurate, reliable, and unbiased. It involves a rigorous evaluation of research methods, data analysis, and interpretation to determine if the results are valid and can be trusted. By undergoing a validation process, scientific results gain credibility and contribute to knowledge accumulation. That is why, the 3DOF (wind axes) block available in SimuLink, Aerospace Blockset, [7] has been used to put the proposed xCos super block to the test. The input values are chosen in arbitrary way with sole purpose of verifying the xCos super block credibility. Some results are shown in Fig. 9, i.e. pitch, angle of attack, linear velocity. There is a strong agreement between results obtained by either software bundle.

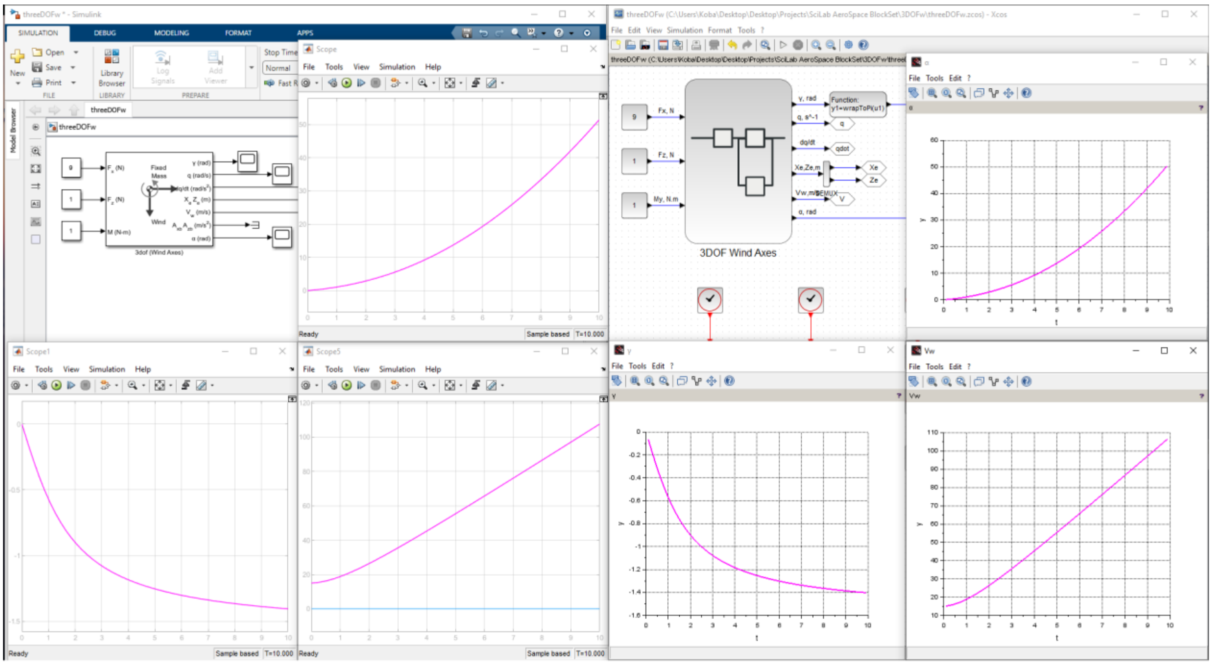

Fig. 9. A comparison between 3DOF (wind axes) superblock and SimuLink counterpart

3. Results

In following figures numerical results obtained after conducting a few serial computations are presented. Initial conditions are all set to zero unless otherwise stated. For each test case, specific initial conditions are described in figure caption.

Steady flight at (stall) speed of 40 m/s

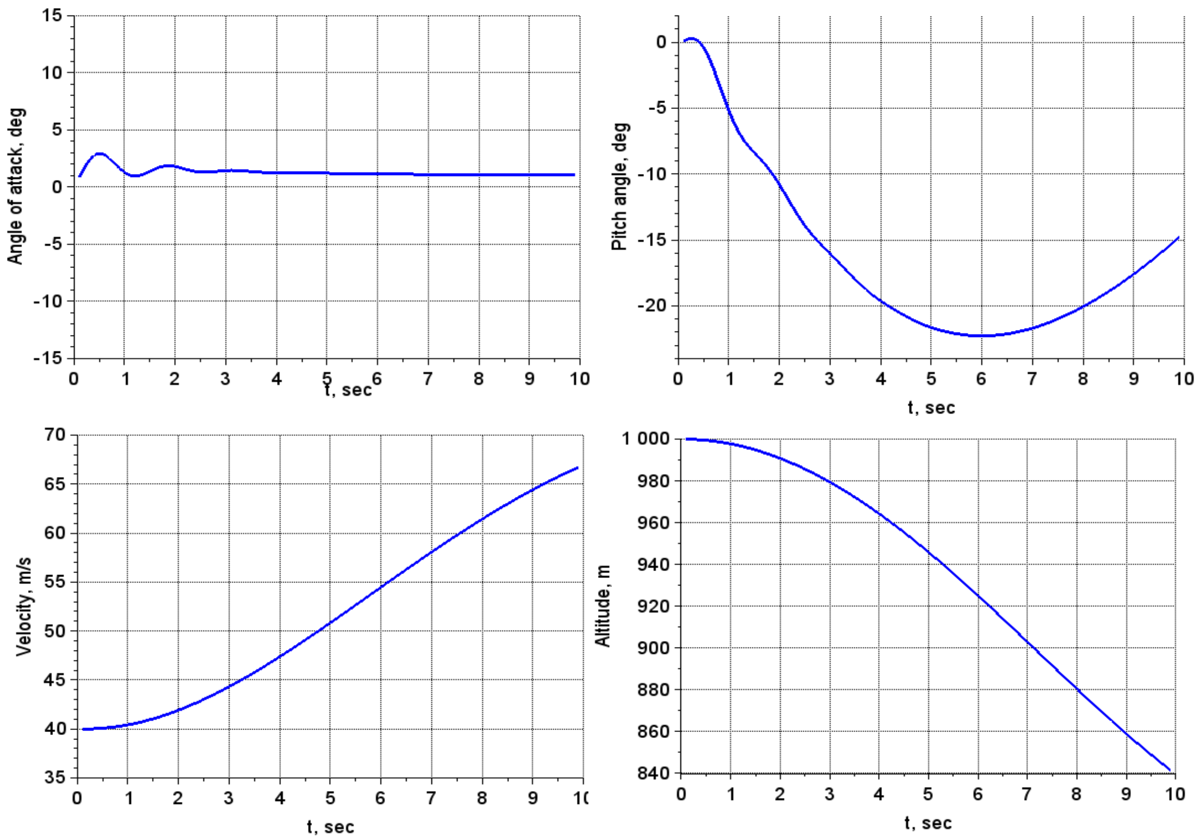

Fig. 10. V = 40 m/s, H = 1000 m, elevator δe = 0 deg, no thrust

Steady flight at speed of 80 m/s

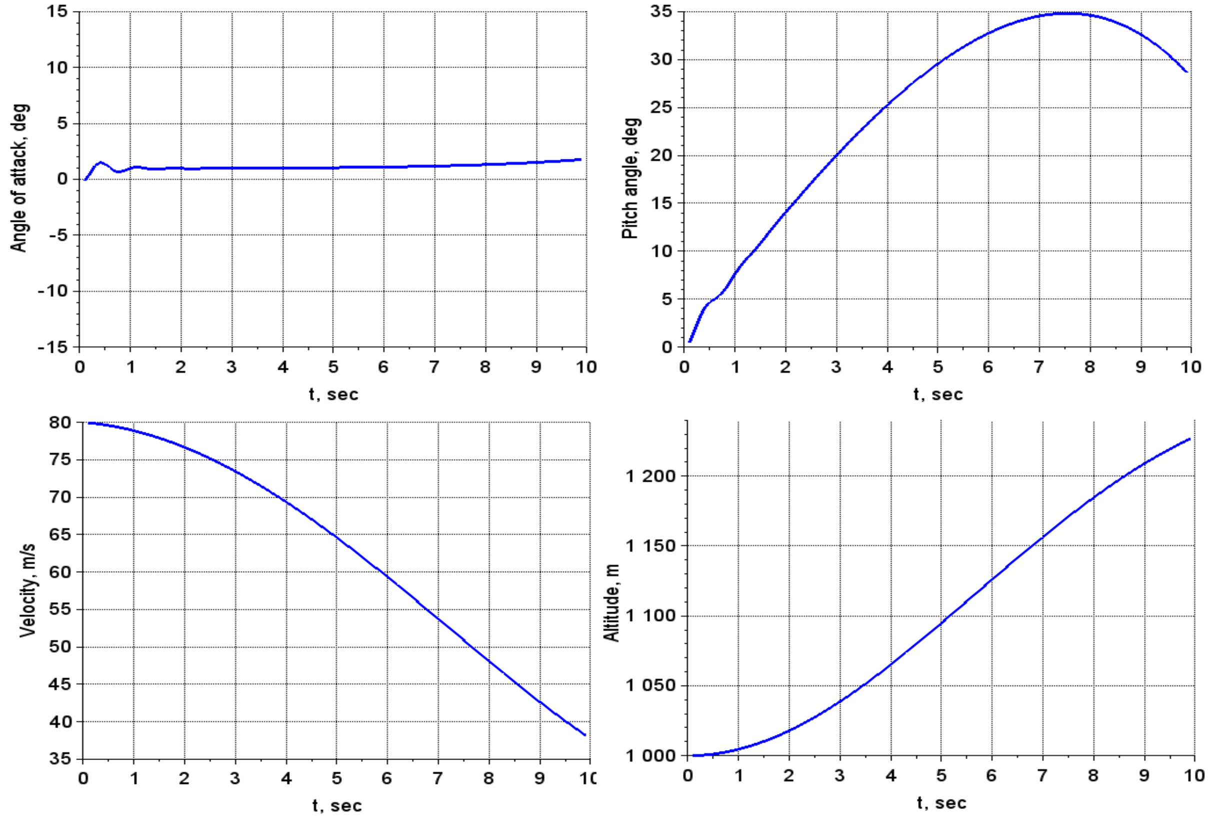

Fig. 11. V = 80 m/s, H = 1000 m, elevator δe = 0 deg, no thrust

Steady flight at speed of 80 m/s. Elevator is applied after third second at +8 deg (nose down)

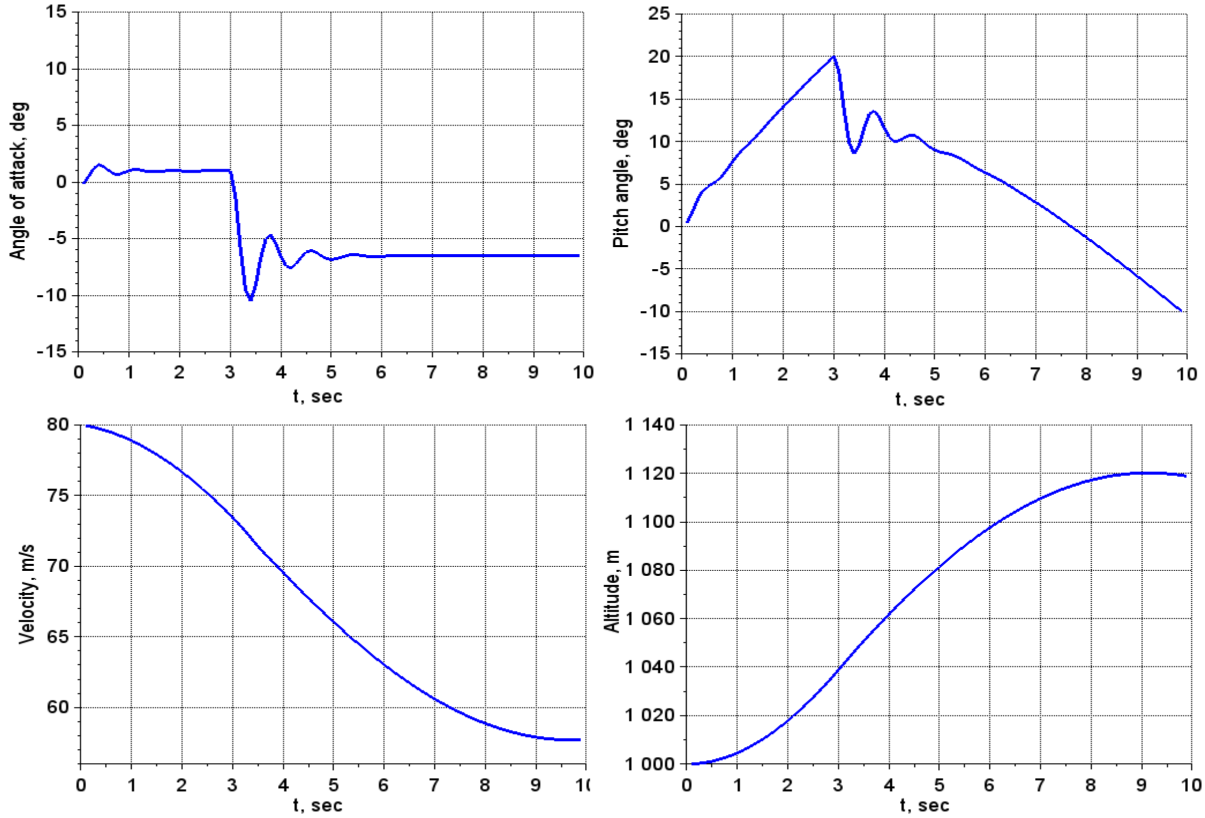

Fig. 12. V = 80 m/s, H = 1000 m, δe = (t < 3 s) ? 0° : +8°, no thrust

Steady flight at 80 m/s. Elevator is applied after third second at –8 deg (nose up). Thrust of 5 kN is applied within interval [2; 15] s. The aircraft is performing a loop maneuver.

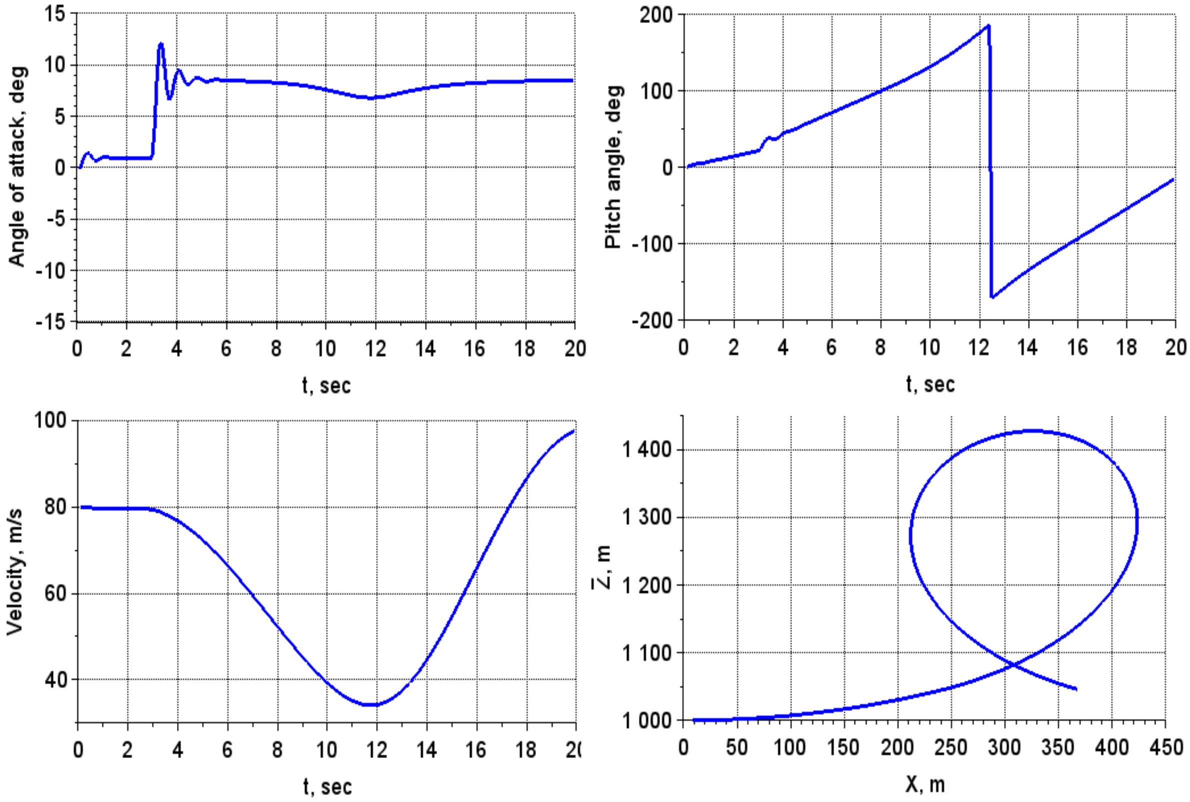

Fig. 13. V = 80 m/s, H = 1000 m, δe = (t < 3 s) ? 0° : –8°, thrust 5 kN

4. Conclusion

In presented study, a set of non-linear equations describing aircraft longitudinal motion have been solved numerically. Main study objective is to replicate the 3DOF (wind axes) superblock (available in Aerospace block set, SimuLink) in xCos environment. After validation, the superblock has been used to carry out simulations of various flight cases.

Generally speaking, decrease in speed without applying elevator (stick fixed) will cause the aircraft nose to fall. Increase in speed without applying elevator will cause the nose to rise. At low speeds, the aircraft is nose-heavy. If flight speed increases, the lifting force increases too; hence an unbalanced force excess appears, the flight trajectory is bent upwards and vice versa, see Fig. 10, Fig. 11.

Pilatus PC-9M is designed to be stable and predictable in flight, making it suitable for both basic and advanced training. It has a fully aerobatic design and is capable of performing a wide range of maneuvers, including loops, rolls, spins, and inverted flight. The flight control system of the PC-9M includes a combination of mechanical and hydraulic systems to ensure precise control and handling qualities, [1].

While PC-9M is primarily used as a trainer aircraft by various air forces around the world, it can also be adapted for combat roles, such as providing close air support, reconnaissance, and surveillance missions. Its capabilities include carrying a variety of weapons, including air-to-ground missiles, rockets, and machine guns, making it suitable for certain combat scenarios. However, it is important to note that the PC-9M is not designed or intended for high-intensity combat operations like a dedicated fighter aircraft.

Further project development might be as follows: taking into account wing downwash $\varepsilon = \frac{d\varepsilon}{d\alpha} + \varepsilon_0$ influence on horizontal stabilizer angle of attack, horizontal stabilizer lift curve $C_{LT}(\alpha)$ shift due to elevator, wing lift curve $C_W(\alpha)$ shift due to deployed flaps. Last but not the least, airplane coordinates should be converted from flat Earth to geodetic latitude, longitude, and height.

The current project might be acquired from link [12].

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Appendix. Function wrapToPi converts angle from [0; 2π] to [–π; π] range; results visible in Fig. 13

```
function y1 = wrapToPi(u1)

    t = u1 - 2.*%pi*floor((u1+%pi)/(2*%pi));
    y1 = t;

endfunction
```

Method for determining the influence of helicopter flight parameters and external fire-extinguishing device on the device's balance in flight

Nikolay Zagorski

Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria, nzagorski@space.bas.bg

Abstract: A study of the possibility of developing theoretical methods for ensuring flight safety of a helicopter with an external fire-extinguishing device if the conditions of their equilibrium has been carried out. The methods for determining the parameters of the flight and the external fire-extinguishing device of the equilibrium of the helicopter and of the device with full or empty external device in the conditions of their equilibrium are also investigated.

Keywords: *helicopter, external fire extinguisher, flight safety*

1. Introduction

To determine the safe flight modes of an AS532AL Cougar helicopter with an external fire extinguishing device “Bambi Bucket BB4453” (full of water or empty) for extinguishing fires, it is necessary to study and know the relative position of the helicopter and the external device in established flight at condition of their equilibrium. This will allow, with a first approximation, to determine the possibility of contact of the cable of the device with elements of the helicopter structure. In addition, the static loads of the “Helicopter-External Fire Extinguisher” system in flight and the required control margin must be evaluated.

In the present material, a study of the possibility of developing theoretical methods for ensuring flight safety of a helicopter with an external fire-extinguishing device in the conditions of their equilibrium was carried out. The methods for determining the parameters of the flight and the external fire-extinguishing device of the equilibrium of the helicopter and of the device with full or empty external device in the conditions of their equilibrium are also investigated.

The objectives thus set were achieved by determining the analytical dependences of the balance characteristics of the helicopter and the balance characteristics of the external device on the flight parameters of the helicopter and the parameters of the device. These analytical dependencies reduce the complexity of the analysis of the influence of the flight parameters and the external device on its balance and on the balance of the helicopter.

In order to make it possible to carry out an analytical description of the above-mentioned dependencies in the mathematical models of the helicopter and the external fire-extinguishing device, some additional assumptions have been introduced.

2. Initial states of the studied objects

It is known that the equilibrium of the aircraft represents such a state in which the sum of all forces and the sum of all moments acting on the aircraft (Fig. 1) are equal to zero [1].

Thus, for example, the conditions for equilibrium are fulfilled in established horizontal straight-line flight. Balancing is usually understood only when the condition is met that the sum of the moments acting on the helicopter is equal to zero [1–2].

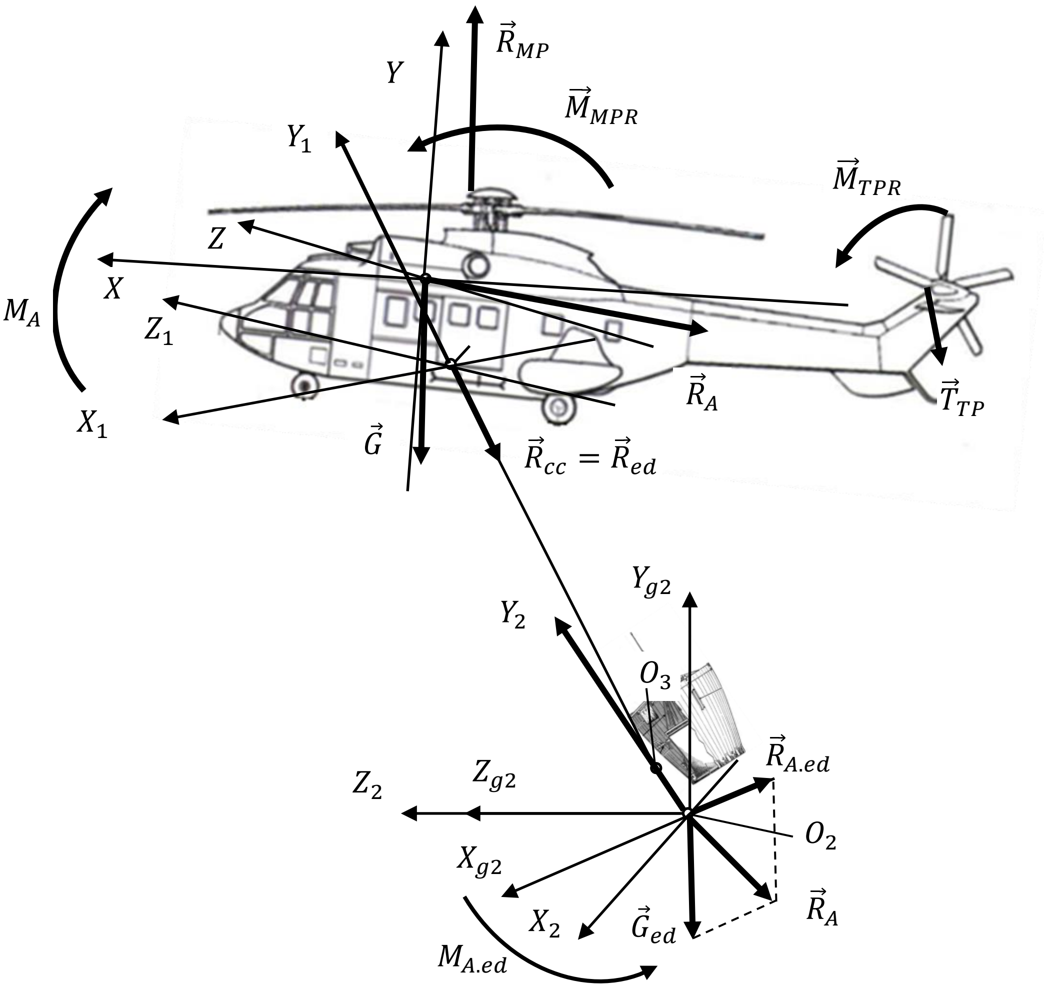

Figure 1. Equilibrium diagram of the system "Helicopter-external fire extinguishing device"

Mathematical model of behavior dynamics of external fire extinguishing device "BB4453" during helicopter flight

2.1. Basic limitations and assumptions made when compiling the mathematical model

In order to apply the method described above to determine the motion of the helicopter and the external device as two absolutely rigid bodies, it is necessary to introduce some restrictions and make some assumptions:

- angular displacements of the central cable (the soft connection for hooking the external unit to the helicopter) relative to the external unit itself are negligible. In this sense, the cable and the external device can be considered as one common body "Cable-external device";
- the helicopter and the external device are connected to each other with an ideal spherical joint located at the point of attachment of the cable to the helicopter;
- the aerodynamic characteristics of the external device are considered known and constant, i.e. non-stationary aerodynamic effects are not taken into account;
- the influence of the inductive flow from the main propeller on the external device is not taken into account, because the horizontal flight of the helicopter with an external fire-extinguishing device of the "Bambi Bucket" type is primarily considered;
- the influence of constant atmospheric turbulence on the helicopter and the external device is not taken into account;
- the central cable is assumed to be elastic in tension, but is assumed to be absolutely rigid in bending, always keeping the cable straight.

2.2. Equilibrium conditions in flight of the helicopter with an external fire-extinguishing device

There are different approaches to describe the condition of the helicopter and the external fire-extinguishing device and to study their mutual influence in flight. The task of compiling the helicopter motion equations has been solved by numerous researchers [3–12]. One of the more rational approaches used in the works cited above is used here. In it, the body of the helicopter is considered as an absolutely rigid body, and the impact on it of the air flow from the main and tail propellers is described by a system of forces and moments. In such an approach, the movement of the helicopter is described by a system of non-linear differential equations of the second order. Such equations can be successfully solved using numerical integration methods. They describe the dynamics of the helicopter's flight adequately enough, while at the same time they are sufficiently understandable.

The equations of motion of an absolutely rigid body are compiled as a consequence of the foundations of theoretical mechanics [13]. For this reason, the motion of the helicopter is described by the equations of the forces applied at the center of mass and the moments acting about the center of mass of the helicopter. In the most general form, in vector form, these equations are written as follows [14]:

- force equation:

(1) $m\frac{d\vec{V}}{dt} = \vec{F}$,

where: m is the mass of the helicopter;

$\vec{V}$ is the vector of the center of mass of the helicopter relative to the starting coordinate system;

$\vec{F}$ is the equivalent of all external forces acting on the helicopter;

- equation of moments:

(2) $\frac{d\vec{K}}{dt} = \vec{M}$,

where: $\vec{K}$ is the kinetic moment (or principal moment of momentum) relative to the helicopter's center of mass;

$\vec{M}$ is the main moment of the external forces (vector sum of the moments of the external forces acting on the helicopter relative to the center of mass of the helicopter.

Let's take a closer look and expand the right-hand sides of the equations of motion (1) and (2). In flight, the helicopter moves in a field in which the Earth's gravity (forces of attraction) acts, while at the same time acting on it are forces and moments created by the main and tail propellers and by the counter flow of air. In accordance with the above, the vector of the equivalent $\vec{F}$ of all external forces acting on the helicopter can be represented as the following vector sum:

(3) $\vec{F} = \vec{R}_{MP} + \vec{T}_{TP} + \vec{R}_A + \vec{G}$,

where: $\vec{R}_{MP}$ is the equivalent force of the main propeller;

$\vec{T}_{TP}$ is the thrust of the tail propeller;

$\vec{R}_A$ is the equivalent of the aerodynamic forces acting on the helicopter body;

$\vec{G}$ is the force of the helicopter's gravity.

In turn, the main moment $\vec{M}$ from the external forces represents the following vector sum:

(4) $\vec{M} = \vec{M}_{MP} + \vec{M}_{TP} + \vec{M}_A$,

where: $\vec{M}_{MP}$ is the moment that created by the main propeller;

$\vec{M}_{TP}$ is the moment that created by the tail rotor;

$\vec{M}_A$ is the aerodynamic moment of the helicopter body.

In this regard, the equation of forces (3) and moments (4) acting on the helicopter in flight must be supplemented, respectively, with the tension force in the cable $\vec{R}_{cc}$ and the moment from it $\vec{M}_{cc}$:

(5) $\vec{F} = \vec{R}_{MP} + \vec{T}_{TP} + \vec{R}_A + \vec{G} + \vec{R}_{cc}$,

(6) $\vec{M} = \vec{M}_{MP} + \vec{M}_{TP} + \vec{M}_A + \vec{M}_{cc}$.

In order to determine the value of the tensile force in the central cable $\vec{R}_{cc}$, it is necessary to determine the projection of the equivalent force $\vec{R}_{ed}$ of all the forces acting on the external device along the axis of the cable.

The equivalent force $\vec{R}_{ed}$ represents the following vector sum:

(7) $\vec{R}_{ed} = \vec{G}_{ed} + \vec{R}_{A.ed} + \vec{J}_{ap} + \vec{J}_{cf}$,

where: $\vec{G}_{ed}$ is the force of gravity of the external device;

$\vec{R}_{A.ed}$ is the equivalent of all aerodynamic forces acting on the external device;

$\vec{J}_{ap}$ is the inertial force arising during the accelerated movement of the attachment point of the external device to the helicopter;

$\vec{J}_{cf}$ is the inertial centrifugal force arising from the rocking of the external device.

Similarly, the movement of the helicopter itself relative to its center of mass will be caused by the impact of the moment $\vec{M}_{ed}$, which is the sum of the moments of the forces acting on the external device relative to the attachment point:

(8) $\vec{M}_{ed} = \vec{M}_{G.ed} + \vec{M}_{A.ed} + \vec{M}_{ap}$,

where: $\vec{M}_{G.ed}$ is the moment of the force of gravity of the external device;

$\vec{M}_{A.ed}$ is the moment of the aerodynamic force of the external device;

$\vec{M}_{ap}$ is the moment of the forces arising from the accelerated displacement of the attachment point of the cable to the helicopter.

The equilibrium condition of the helicopter with an external fire-extinguishing device derives from the equations of motion (7) and (8), taking into account the fact that this motion is carried out without acceleration:

(9) $\vec{R}_{MP} + \vec{T}_{TP} + \vec{R}_A + \vec{G} + \vec{R}_{cc} = 0$,

(10) $\vec{M}_{MP} + \vec{M}_{TP} + \vec{M}_A + \vec{M}_{cc} = 0$.

To ensure equilibrium of the “Helicopter-external fire extinguishing device” system, it is necessary to additionally fulfill the condition for equilibrium of the external device.

3. Method for determining the influence of the flight parameters of the helicopter and "BB 4453" on the balance of the device in flight

If the external fire-extinguishing device in flight is considered as two independent elements - cable and “BB4453”, connected to each other with a spherical joint in p. O_3 (Fig. 1), it is necessary to consider the conditions for the equilibrium of the cable separately.

Let's consider the balance of “BB4453” in relation to p. O_3. The equations describing the equilibrium of “BB4453” are derived from the equations of motion of "BB4453" described above (7) and (8):

(11) $\vec{G}_{ed} + \vec{R}_{A.ed} - \vec{R}_{ed} = 0$,

(12) $\vec{M}_{G.ed} + \vec{M}_{A.ed} = 0$.

In scalar form, taking into account the accepted sign rule, the following result will be obtained:

$$(13)\ \begin{cases} -G_{ed}\sin\vartheta_2 + X_{ed} - R_{ed.x2} = 0; \\ -G_{ed}\cos\vartheta_2\cos\gamma_2 + Y_{ed} - R_{ed.y2} = 0; \\ G_{ed}\cos\vartheta_2\sin\gamma_2 + Z_{ed} - R_{ed.z2} = 0; \end{cases}$$

$$(14)\ \begin{cases} G_{ed}r_{ed}\cos\vartheta_2\sin\gamma_2 + m_{x.ed}\frac{\rho V_{hf}^2}{2}S_{ed}l_{ed} + Z_{ed}r_{ed} = 0; \\ m_{y.ed}\frac{\rho V_{hf}^2}{2}S_{ed}l_{ed} = 0; \\ G_{ed}r_{ed}\sin\vartheta_2 + m_{z.ed}\frac{\rho V_{hf}^2}{2}S_{ed}l_{ed} - X_{ed}r_{ed} = 0, \end{cases}$$

where: r_{ed} is the distance from p. O_3 for fastening the bundle of ropes from the “cobweb” to the cable to the center of mass of “BB4453” (p. O_3), $r_{ed} < 0$;

$V_{hf} = V_{a.hf}$ is speed of established horizontal straight flight.

In order to simplify reasoning and calculations, as a first approximation, we will assume that the “BB4453” is a truncated cone that is slightly convex about 60% from the base of the device. The center of mass of “BB4453” is located in the vertical plane of symmetry$O_2X_2Y_2$. “BB4453” is attached to the central cable O_1O_3, with 24 short ropes (which together form the so-called “cobweb”), which will be considered as absolutely rigid bars. The ropes of the “spider web” come together at one point - O_3, where they are connected to the central cable by means of a ball joint.

Now an additional coordinate system $O_2X_{g2}Y_{g2}Z_{g2}$ (Fig. 1) can be introduced with the origin at the center of mass of the external fire extinguishing device "BB4453" (p. O_2). The direction of the axes of this coordinate system always coincides with the axes of the normal coordinate system $OX_gY_gZ_g$. Now the angular position of "BB4453" relative to the ground surface can be described using the roll angle γ_2, the pitch angle ϑ_2 and the roll angle ψ_2 of the external fire-extinguishing device.

With the established horizontal flight of the helicopter, the deviation of "BB4453" from the position that the device occupies in the "hover" mode takes place mainly in the plane coinciding with the plane $O_2X_2Y_2$ (Fig. 2). In this sense, the longitudinal equilibrium of the external fire-extinguishing device should be examined.

In the given case, the angular position of the external fire-extinguishing device relative to the Earth is described only by the pitch angle of the device ϑ_2. The presence of an angle $\Delta\vartheta_2$ between the axis of the central cable and the axis O_2Y_2 is related to the action of the aerodynamic moment of the external fire-extinguishing device:

(15) $M^*_{A.ed.z2} = m_{z.ed}\frac{\rho V_{hf}^2}{2}S_{ed}l_{ed}$.

To determine the value of the equilibrium angle of pitch ϑ_2 of the external device "BB4453" (Fig. 2) the equation of moments (14) about the axis parallel to the axis O_2Z_2:

(16) $G_{ed}r_{ed}\sin\vartheta_2 + m_{z.ed}\frac{\rho V_{hf}^2}{2}S_{ed}l_{ed} - X_{ed}r_{ed} = 0$.

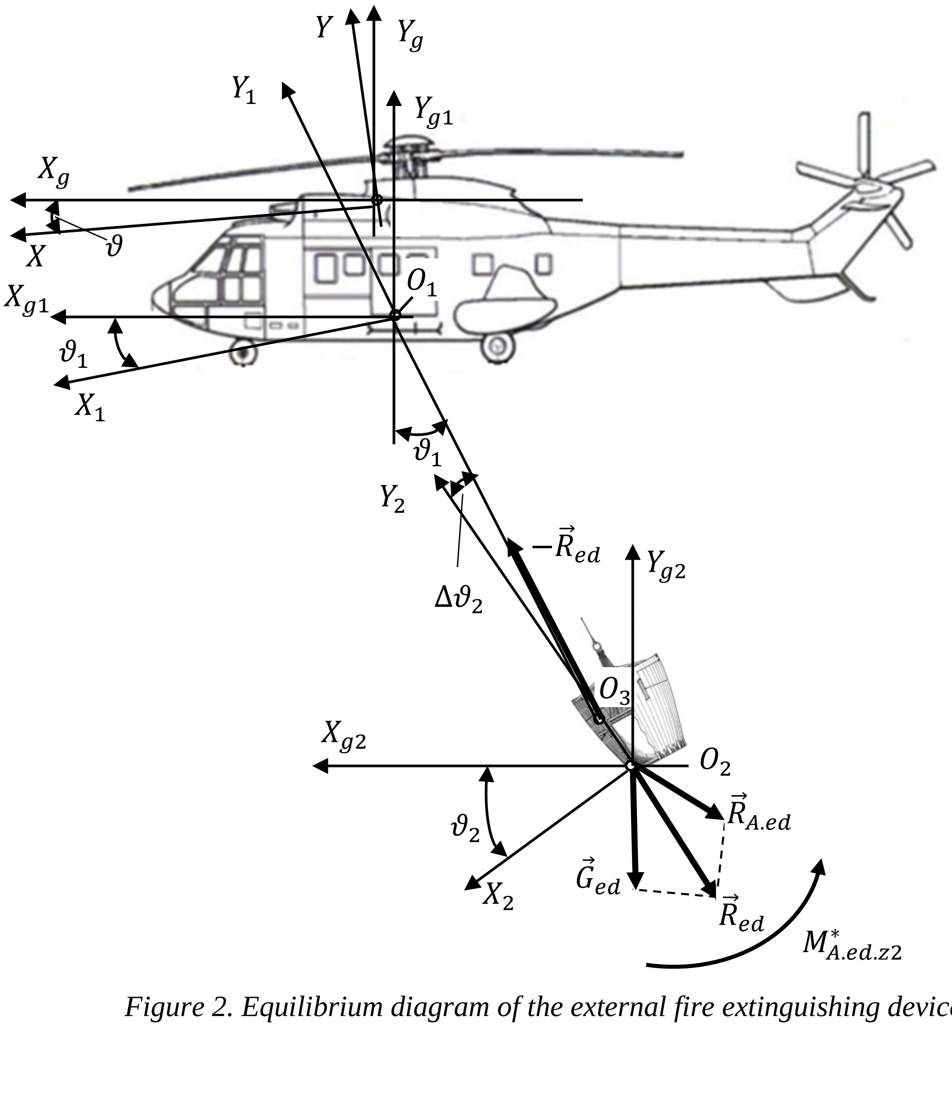

Figure 2. Equilibrium diagram of the external fire extinguishing device

Thus, the equilibrium pitch angle of the external fire-extinguishing device "BB4453" can be determined as:

(17) $\vartheta_2 = \sin^{-1}\left(\frac{X_{ed}r_{ed} - m_{z.ed}\frac{\rho V_{hf}^2}{2}S_{ed}l_{ed}}{G_{ed}r_{ed}}\right)$,

or, if the expressions for the aerodynamic longitudinal force and for the gravity force are used, the following expression will be obtained:

(18) $\vartheta_2 = sin^{-1}\left[\left(\frac{-c_{x.ed}S_{ed}r_{ed} - m_{z.ed}S_{ed}l_{ed}}{m_{ed}r_{ed}}\right)\left(\frac{\rho V_{hf}^2}{2g}\right)\right]$.

The analysis of (18) shows that the expression in the first small brackets consists of the parameters of the external fire extinguishing device "BB4453", and the expression in the second brackets consists of the flight parameters. Formula (18) clearly shows which parameters of the external device and in what way influence the value of the pitch angle ϑ_2.

If it is considered that the coefficient of aerodynamic pitch moment of the external device "BB4453" is negligibly small, i.e. $m_{z.ed} \approx 0$, then formula (18) will take the following form:

(19) $\vartheta_2 = sin^{-1}\left[\left(-\frac{c_{x.ed}S_{ed}}{m_{ed}}\right)\left(\frac{\rho V_{hf}^2}{2g}\right)\right]$.

In this way and under the accepted assumptions, the following parameters of the device play a major role in the value of the equilibrium angle of pitch of the external fire-extinguishing device "BB4453" in established horizontal straight flight:

- coefficient of longitudinal aerodynamic force of "BB4453" - $c_{x.ed}$;
- the characteristic area of "BB4453" - S_{ed};
- the mass of "BB4453" - m_{ed}.

If the following notation is entered:

(20) $c_{ed} = \frac{c_{x.ed}S_{ed}}{m_{ed}}$,

then we get the expression:

(21) $\vartheta_2 = \sin^{-1}\left(-c_{ed}\frac{\rho V_{hf}^2}{2g}\right)$.

According to its structure, the coefficient c_{ed} corresponds to the ballistic coefficient known in aerodynamics [15–16], which includes the parameters of the external device - $c_{x.ed}$, S_{ed} and m_{ed}. Therefore, c_{ed} can be taken as the ballistic coefficient of the external fire-extinguishing device "BB4453".

The analysis of (21) shows that the pitch angle of the external fire extinguishing device depends on the ballistic coefficient of the device, as well as on the flight parameters of the helicopter - speed and flight height, according to formula (19).

Using the diagram in Fig. 2, the equilibrium conditions of the central cable for attaching the external device to the helicopter can be analyzed. Since there is a ball joint in p. O_3, and we assumed that the cable itself will be considered absolutely rigid in bending (inelastic), it follows that no moments are transmitted from the external device "BB4453" to the central cable. Furthermore, we will assume that the cable has no mass of its own and no aerodynamic forces and moments act on it. Under such conditions, the equilibrium pitch angle of the central cable ϑ_1 is determined only by the direction of the vector of the reaction force in the hinge at p. O_3, equal in value and opposite in direction to the vector of the equivalent force of the external fire extinguishing device "BB4453" - $\vec{R}_{ed}$. The pitch angle of the central cable ϑ_1 will differ from the pitch angle of the external device ϑ_2 by some angle $\Delta\vartheta_2$, which is the result of the action of the aerodynamic moment of the device:

(22) $M_{A.ed.z2}^{*} = m_{z.ed}\frac{\rho V_{hf}^2}{2}S_{ed}l_{ed}$.

We can write that:

(23) $\vartheta_1 = \vartheta_2 - \Delta\vartheta_2$.

But since the assumption that $m_{z.ed} \approx 0$ was already accepted, it can be considered that $\Delta\vartheta_2 \approx 0$. This means that the axis O_2Y_2 of the connected coordinate system of the external fire-extinguishing device "BB4453" will coincide with the axis of the central cable, i.e. the axis of the cable will pass through the center of mass of the external device "BB4453". In this case, the pitch angle of "BB4453" will approximately coincide with the pitch angle of the central cable, i.e. $\vartheta_1 \approx \vartheta_2$. This means that, under the accepted assumptions, the central cable and the external fire-extinguishing device "BB4453" with a bundle of ropes (type "cobweb") can be considered as a single system. Thus, the balance of this system must be considered relative to the point of attachment of the central cable to the helicopter (at p. O_1 in Fig. 1 and Fig. 2).

With established horizontal straight flight, the pitch angle of the cable ϑ_1 coincides with the angle of deviation of the cable from the vertical position of the "BB4453" external device. Thus, for example, if the pitch angle of the helicopter ϑ (Fig. 2) is known, the angle(s) of the central cable relative to the axes of the associated helicopter coordinate system can be determined, as well as the distance between the cable and the elements of the body structure of the helicopter.

At the same time, it is not possible to directly determine the angle of deviation of the central cable from the vertical position (or the pitch angle ϑ_1) at the given height and flight speed of the helicopter, even with the assumptions made above. This is due to the fact that the coefficient of longitudinal aerodynamic force of the external device "BB4453" - $c_{x.ed}$ depends on the angle of attack α_2 of "BB4453", which is, however, unknown. It is only known that under the accepted assumptions, this angle is equal to the required pitch angle ϑ_1.

In the general case, such a task can be analytically solved only for such external devices that have a shape for which the coefficient of aerodynamic forces in the velocity coordinate system do not depend on the angle of attack.

As an example, an external device with a spherical shape can be considered. Formula (19) will be used to determine the pitch angle of the sphere. It should be taken into account that the equality holds for the sphere:

(24) $X_{ed} = X_{a.ed} \cos\vartheta_2$,

where $X_{a.ed}$ is the drag force in the velocity coordinate system.

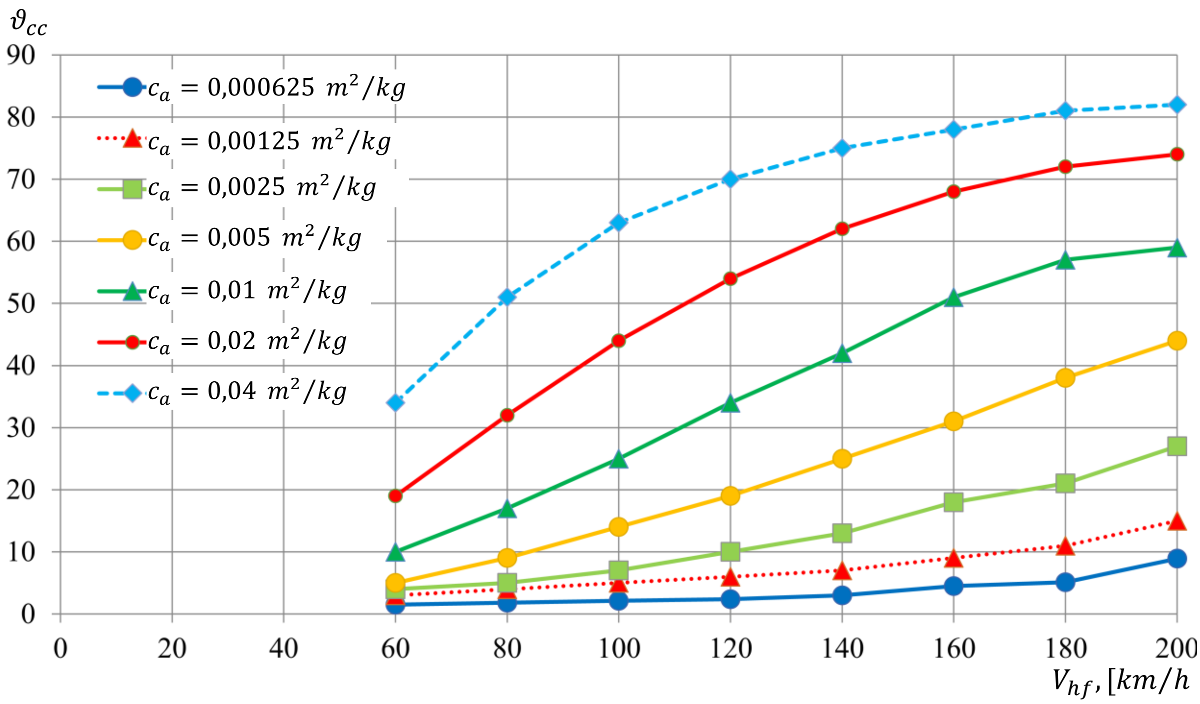

Figure 3. Value of the pitch angle of the central cable of an external device of spherical shape, depending on the speed of established horizontal straight flight and on its ballistic coefficient

Therefore:

(25) $\vartheta_2 = sin^{-1}\left[\left(-\frac{c_{x.ed}S_{ed}}{m_{ed}}\right)\left(\frac{\rho V_{hf}^2}{2g}\right)\right] = sin^{-1}\left[\left(-\frac{c_{xa.ed}S_{ed}}{m_{ed}}\right)\left(\frac{\rho V_{hf}^2}{2g}\right)\right].$

The final result is:

(26) $\vartheta_2 = tan^{-1}\left[\left(-\frac{c_{xa.ed}S_{ed}}{m_{ed}}\right)\left(\frac{\rho V_{hf}^2}{2g}\right)\right].$

Using the ballistic coefficient of the external device (in the form of a sphere), the formula will be written in the form:

(27) $\vartheta_2 = tan^{-1}\left(-c_{a.ed}\frac{\rho V_{hf}^2}{2g}\right).$

where $c_{a.ed} = \frac{c_{xa.ed}S_{ed}}{m_{ed}}$ is the ballistic coefficient of the spherical external device in the velocity coordinate system.

For an external device with the shape of a sphere, it is known that $\vartheta_1 = \vartheta_2$, using formula (27) the dependence of the pitch angle of the central cable $|\vartheta_1|$ at established horizontal rectilinear flight at a height $h = 0\ m$ as a function of the helicopter's flight speed - V_{hf} at different values of the ballistic coefficient $c_{a.ed}$. A wide enough range of external device ballistic coefficient values can be selected for the analysis to cover the ballistic coefficients of virtually all types of devices by mass, geometry, aerodynamic and inertial characteristics. It should also be noted that in aviation practice the flight speed of a helicopter with an external device usually does not exceed $(180 \div 200)\ km/h$. These dependencies are shown in Fig. 3.

The obtained dependences show that the deviation of the central cable from the vertical position increases with the increase in the speed of the horizontal flight and with the increase in the value of the ballistic coefficient of the external load. Practically, the dependences in Fig. 3 are applicable only for indicative calculations - in a first approximation, for loads that have a shape close to spherical.

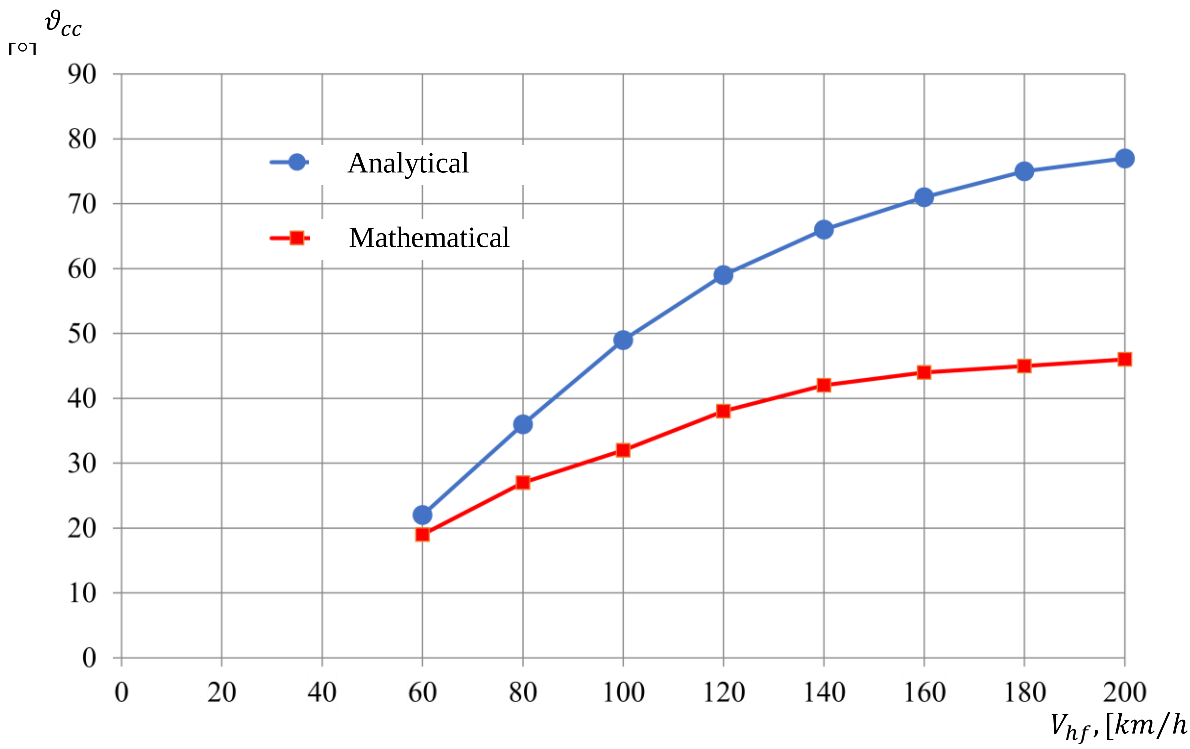

Figure 4. Value of the angle of deviation of the central cable of "BB 4453", depending on the speed of established horizontal straight flight

The aerodynamic characteristics of the external fire extinguishing device "BB4453" [17], as well as the following geometric and mass characteristics of this device, were used during the theoretical studies and calculations:

- characteristic area - $S_{ed} = 1{,}67\ m^2$;
- mass - $m_{ed} = 97{,}5\ kg$ (together with the central cable).

To carry out the analytical calculations, an average value of the ballistic coefficient of an empty external fire extinguishing device "BB4453" was determined - $c_{a.ed} = 0{,}0189\ m^2/kg$, as well as the coefficient of the device filled with water - $c_{a.ed} = 0{,}0009\ m^2/kg$.

In Fig. 4 shows the experimental and theoretical dependences of the pitch angle of the central cable of the external fire-extinguishing device as a function of the speed of an established horizontal straight flight. It is noticed that there is a significant discrepancy between the results obtained in the calculations according to formula (27) and from the mathematical model. This can be explained by the relationship between the ballistic coefficient of the external fire-extinguishing device - $c_{a.ed}$ from the angle of attack of "BB4453", as well as the presence of a negative lifting force of the device.

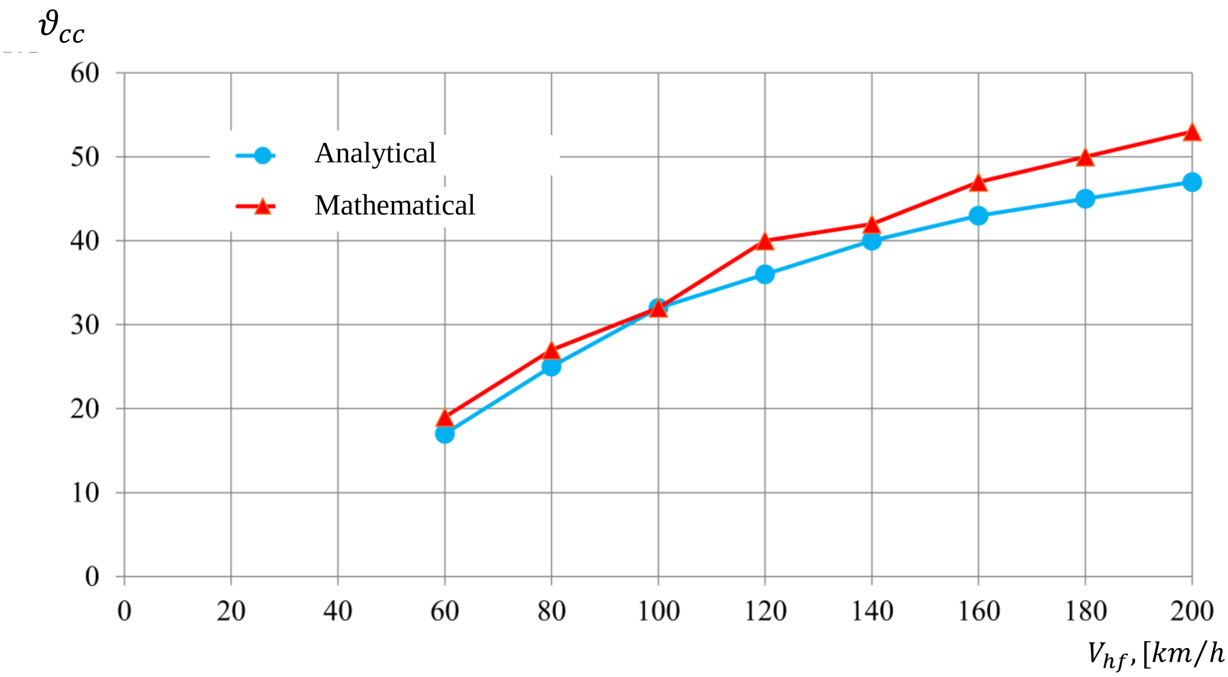

Figure 5. Value of the angle of deviation of the central cable of "BB 4453", depending on the speed of established horizontal straight flight at $K_{ed} = -0{,}7$

In this case, it should be taken into account that the ballistic coefficient $c_{a.ed}$ is calculated as a function of the frontal resistance force of the external fire-extinguishing device $X_{a.ed}$, i.e. in the velocity coordinate system of the external device. At the same time, the ballistic coefficient c is calculated by the longitudinal coordinate of the external fire-extinguishing device X_{ed} in the connected coordinate system of the device. It is necessary to take into account that in the flight of a helicopter with an external fire-extinguishing device, when the counter flow air flows around the device, a lifting force $Y_{a.ed}$ can be formed, which can have a positive or negative sign in the velocity coordinate system of the device. In this case, the coefficient $c_{a.ed}$ can be used. The value of the equilibrium pitch angle of the external fire-extinguishing device will depend on the lifting force $Y_{a.ed}$. Then, to determine the equilibrium angle of pitch (and of the central cable, if $\vartheta_1 = \vartheta_2$) it is necessary to know the dependence of the coefficient of lifting force of the device $c_{y_{a.ed}}$ or its aerodynamic quality $K_{ed} = c_{y_{a.ed}} / c_{x_{a.ed}}$ from the angle of attack. Therefore, the angle of attack can be defined as:

(28) $\vartheta_2 = tan^{-1}\left(\frac{1}{\frac{2g}{c_{a.ed}\rho V_{hf}^2} - K_{ed}}\right)$.

In Fig. 5 is shown a diagram of the dependencies of the pitch angle of the central cable of the external device as a function of the speed of an established horizontal rectilinear flight according to data from analytical calculations and from the results obtained with the mathematical model. An average value for the aerodynamic quality $K_{ed} = -0{,}7$ was used for the calculations. As can be seen from the resulting graphs in Fig. 5, when using formula (28) the data from the analytical expressions and from the mathematical model are very close.

If the ballistic coefficient c_{ed} is used, it is sufficient to know the dependence $c_{ed} = c_{ed}(\alpha)$. This means that it is sufficient to know the dependence of the longitudinal aerodynamic force of "BB4453" - X_{ed} on the angle of attack, since the normal aerodynamic force of the external device - Y_{ed} does not affect its balancing.

However, if the ballistic coefficient $c_{a.ed}$ is used, the aerodynamic quality of "BB 4453" - K_{ed} should be taken into account in the calculations, if $K_{ed} \neq 0$.

Aviation practice shows that in established straight-line horizontal flight of a helicopter with an external fire-extinguishing device, the values of the roll angle and the yaw angle of the external device tend to be close to zero if the external device itself has lateral and normal stability.

4. Conclusions

During the conducted research, it was established that with set and constant flight parameters - speed and height - the pitch angle mainly depends on the ballistic coefficient $c_{a.ed}$. A dependence was obtained for the increase in modulus of the pitch angle when increasing the ballistic coefficient of the external device. Also, the pitch angle of the external fire extinguishing device depends on the aerodynamic pitch moment $m_{z.ed}$ and on the aerodynamic quality K_{ed} of the device.

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Метод за определяне на влиянието на параметрите на полета на хеликоптера и на външното пожарогасително устройство за равновесието на устройството в полет

Николай Загорски

Резюме: Извършено е проучване на възможността за разработване на теоретични методи за осигуряване на безопасността на полета на хеликоптер с външно пожарогасително устройство в условията на тяхното равновесие. Изследвани са и методите за определяне параметрите на полета и външното пожарогасително устройство на равновесието на вертолета и на устройството с пълно или празно външно устройство в условията на тяхното равновесие.

Influence of the flight parameters of the helicopter and the external fire-extinguishing device on the balance of forces acting on the device

Nikolay Zagorski

Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria, nzagorski@space.bas.bg

Abstract: To determine the safe flight modes of a helicopter with an external fire-extinguishing device for extinguishing fires, it is necessary to study and know the mutual position of the helicopter and the external device in established flight under the condition of their equilibrium. The aerodynamic quality of the device significantly affects the value of the relative tension force of the central cable.

Keywords: *helicopter, external fire extinguisher, flight safety*

1. Introduction

To determine the safe flight modes of an AS532AL Cougar helicopter with an external fire extinguishing device "Bambi Bucket BB4453" (full of water or empty) for extinguishing fires, it is necessary to study and know the relative position of the helicopter and the external device in established flight at condition of their equilibrium. This will allow, with a first approximation, to determine the possibility of contact of the cable of the device with elements of the helicopter structure. In addition, the static loads of the "Helicopter-External Fire Extinguisher" system in flight and the required control margin must be evaluated.

Analytical dependencies are derived from commonly known helicopter flight dynamics equations. In order to make it possible to carry out an analytical description of the above-mentioned dependencies in the mathematical models of the helicopter and the external fire-extinguishing device, some additional assumptions have been introduced.

2. Initial states of the studied objects

It is known that the equilibrium of the aircraft represents such a state in which the sum of all forces and the sum of all moments acting on the aircraft (Fig. 1) are equal to zero [1].

Thus, for example, the conditions for equilibrium are fulfilled in established horizontal straight-line flight. Balancing is usually understood only when the condition is met that the sum of the moments acting on the helicopter is equal to zero [1–2].

In this regard, the equation of the forces and moments acting on the helicopter in flight must be written down and, accordingly, supplemented with the tensile force in the cable $\vec{R}_{cc}$ and the moment from it $\vec{M}_{cc}$:

(1) $\vec{F} = \vec{R}_{MP} + \vec{T}_{TP} + \vec{R}_A + \vec{G} + \vec{R}_{cc}$,

(2) $\vec{M} = \vec{M}_{MP} + \vec{M}_{TP} + \vec{M}_A + \vec{M}_{cc}$.

In order to determine the value of the tensile force in the central cable $\vec{R}_{cc}$, it is necessary to determine the projection of the equivalent force $\vec{R}_{ed}$ of all the forces acting on the external device along the axis of the cable.

The equivalent force $\vec{R}_{ed}$ represents the following vector sum:

(3) $\vec{R}_{ed} = \vec{G}_{ed} + \vec{R}_{A.ed} + \vec{J}_{ap} + \vec{J}_{cf}$,

where: $\vec{G}_{ed}$ is the force of gravity of the external device;

$\vec{R}_{A.ed}$ is the equivalent of all aerodynamic forces acting on the external device;

$\vec{J}_{ap}$ is the inertial force arising during the accelerated movement of the attachment point of the external device to the helicopter;

$\vec{J}_{cf}$ is the inertial centrifugal force arising from the rocking of the external device.

Similarly, the movement of the helicopter itself relative to its center of mass will be caused by the impact of the moment $\vec{M}_{ed}$, which is the sum of the moments of the forces acting on the external device relative to the attachment point:

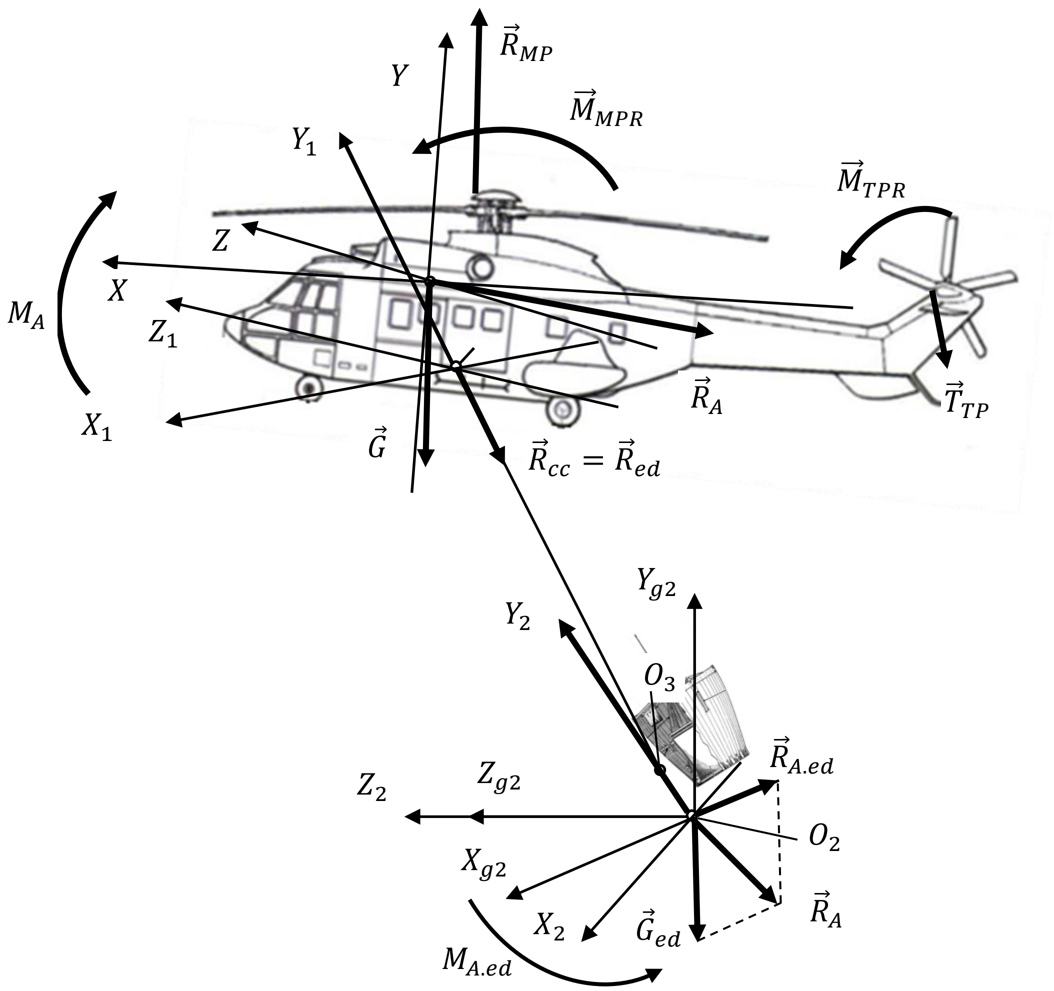

Figure 1. Equilibrium diagram of the system "Helicopter-external fire extinguishing device"

(4) $\vec{M}_{ed} = \vec{M}_{G.ed} + \vec{M}_{A.ed} + \vec{M}_{ap}$,

where: $\vec{M}_{G.ed}$ is the moment of the force of gravity of the external device;

$\vec{M}_{A.ed}$ is the moment of the aerodynamic force of the external device;

$\vec{M}_{ap}$ is the moment of the forces arising from the accelerated displacement of the attachment point of the cable to the helicopter.

From this equation it follows that the tension force of the central cable $\vec{R}_{cc}$ depends on the weight (mass) of the external fire extinguishing device - $\vec{G}_{ed}$ and on the aerodynamic force acting on the device in flight - $\vec{R}_{A.ed}$, which refers not only to the value but also to its direction. For example, if the lifting force of the external fire-extinguishing device is a positive value (Fig. 2), then it will reduce the tension force of the central cable. However, if the lifting force of the device has a negative value, the tension force of the central cable will increase.

(9) $R_{cc} = -\sqrt{(Y_{a.ed} - m_{ed}g)^2 + X_{a.ed}^2}$.

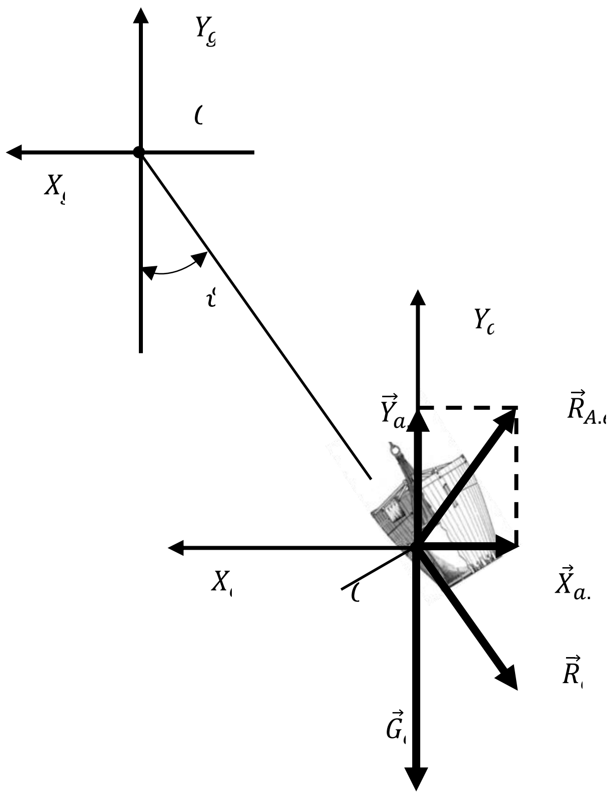

Figure 2. Scheme for determining the tension of the central cable of external device "BB 4453" in flight of the helicopter

If the tension force of the central cable is expressed in terms of the helicopter flight parameters and the parameters of the external fire-extinguishing device, using the modules of the values of all these parameters, the following expression will be obtained:

(10) $|R_{cc}| = \sqrt{\left(\frac{K_{el}c_{a.ed}m_{ed}\rho V_{hf}^2}{2} - m_{ed}g\right)^2 + \left(\frac{c_{a.ed}m_{ed}\rho V_{hf}^2}{2}\right)^2}$.

The analysis of formula (10) shows that the tension force of the central cable depends on the following parameters of the external fire-extinguishing device “BB4453”:

- mass of “BB4453” - m_{ed};
- aerodynamic quality of “BB4453” - K_{ed}.

If some transformations are made in equation (10), for example, to divide both sides by the weight of the external fire-extinguishing device [6], a mathematical expression for the relative dimensionless tension force of the central cable will be obtained:

(11) $|\bar{R}_{cc}| = \frac{|\bar{R}_{cc}|}{m_{ed}g} = \sqrt{\left(\frac{K_{ed}c_{a.ed}\rho V_{hf}^2}{2g} - 1\right)^2 + \left(\frac{c_{a.ed}\rho V_{hf}^2}{2g}\right)^2}$.

In Fig. 3 shows a graph of the dependence of the relative value of the tension force of the central cable $|\bar{R}_{cc}|$ as a function of the helicopter flight speed obtained in the calculations with the mathematical model and the calculations according to formula (11). This formula uses the average value of the ballistic coefficient for “BB4453” $c_{a.ed} = 0{,}0189\ m^2/kg$, as well as an average value of aerodynamic quality $K_{ed} = -0{,}7$.

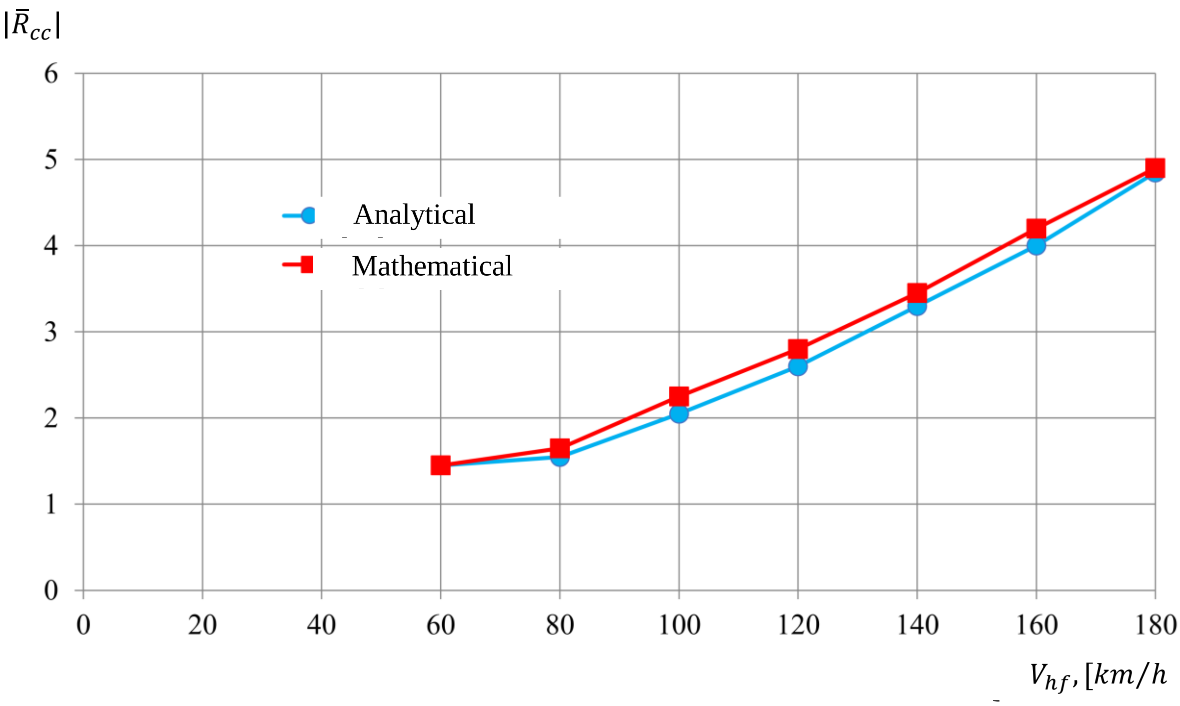

Figure 3. Schematic of the relative tension force of the central cable of an empty external device "BB 4453" as a function of the speed of the helicopter's established horizontal straight flight obtained by analytical calculations and with the mathematical model

The analysis of the graphs in Fig. 3 shows that there is a good agreement between the results of calculations by formula (11) and the results obtained with the model [7, 8].

Using the method described above for determining the influence of the helicopter flight parameters and the parameters of the external fire-extinguishing device on their equilibrium, a graph of the value of the relative tension force of the central cable $|\bar{R}_{cc}|$ in the conditions of established horizontal straight flight as a function of the helicopter flight speed V_{hf} at different values of the ballistic coefficient $c_{a.ed}$ and the aerodynamic quality of the external device K_{ed}.

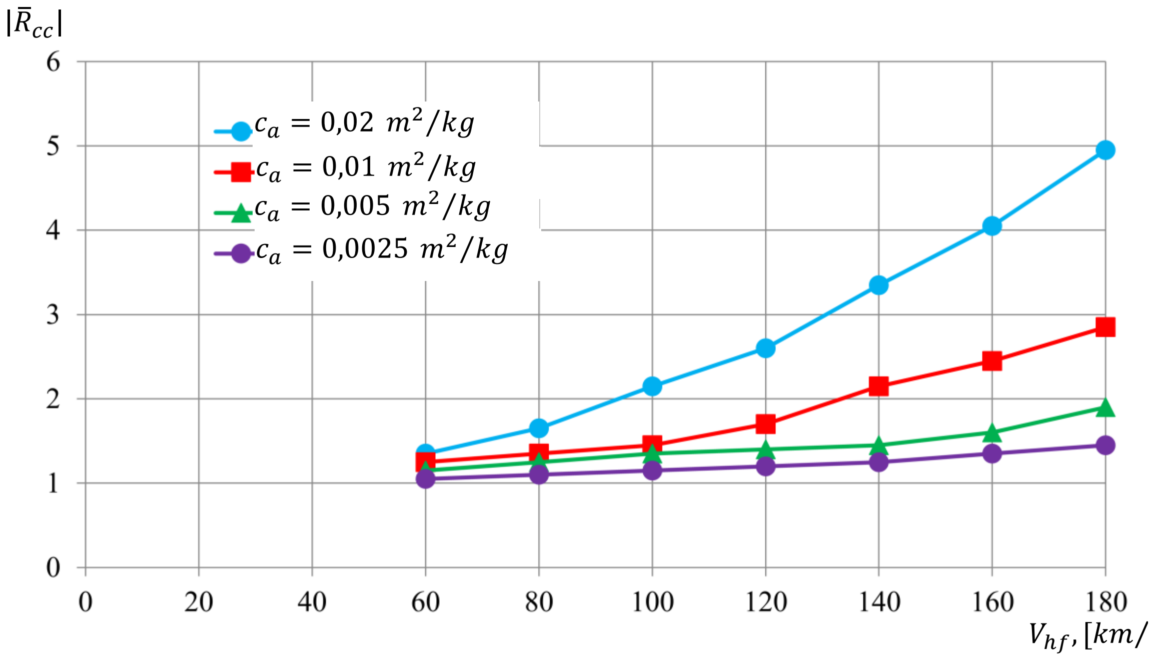

Figure 4. Relative tension force of the central cable of "BB 4453" as a function of the speed of the established horizontal straight flight of the helicopter at the aerodynamic quality of the external device $K_{ed} = -0{,}7$

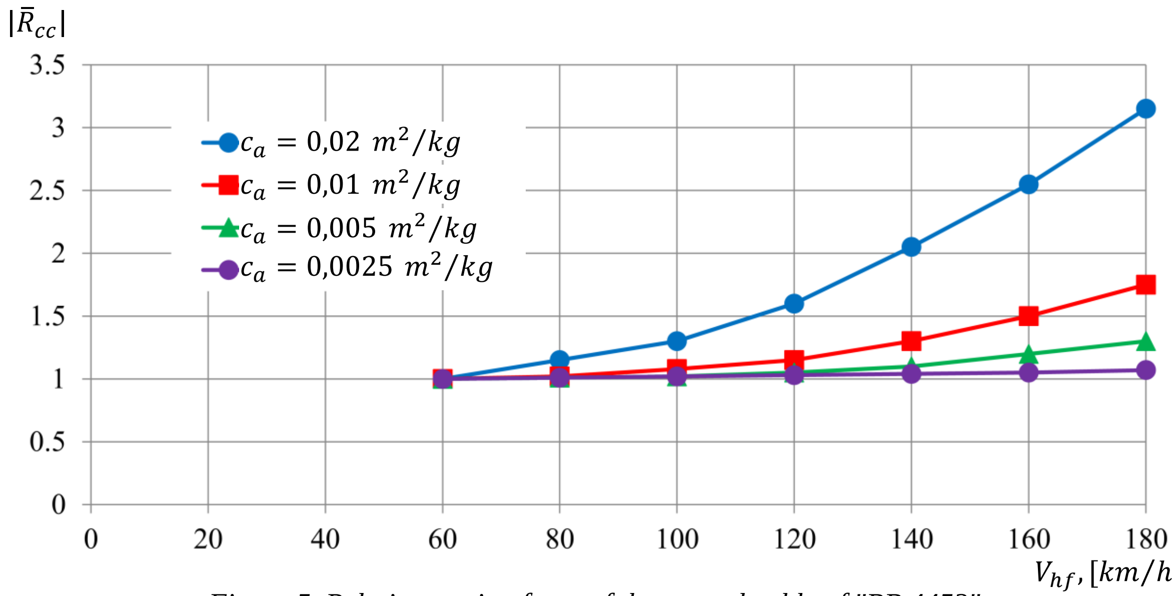

Figure 5. Relative tension force of the central cable of "BB 4453"
as a function of the speed of the established $K_{ed} = 0{,}0$

In Fig. 4, Fig. 5 and Fig. 6 are shown graphs of dependences of the value of the relative tension force of the central cable $|\bar{R}_{cc}|$ from the flight speed V_{hf} when changing the ballistic coefficient of the external device $c_{a.ed}$ in the range of values $c_{a.ed} = (0{,}02 \div 0{,}0025)\, m^2/kg$ for three values of the aerodynamic coefficient on the external device- $K_{ed} = -0{,}7$; $K_{ed} = 0{,}0$ and $K_{ed} = +0{,}7$.

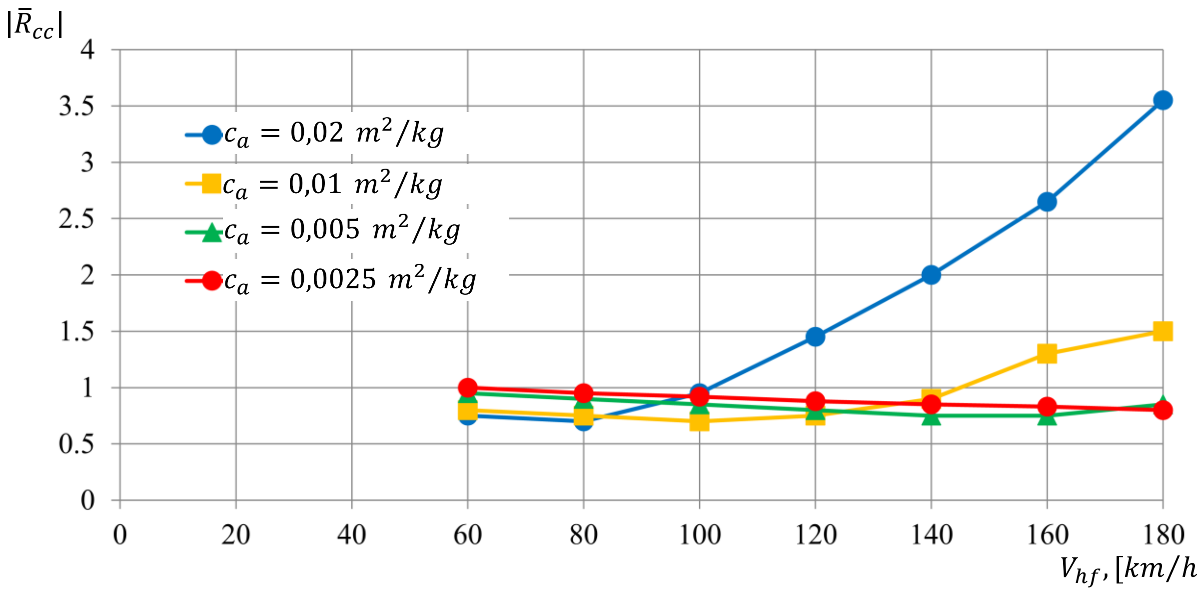

Figure 6. Relative tension force of the central cable of the "BB 4453"
as a function of the speed of the established horizontal straight flight of the helicopter
at the aerodynamic quality of the device $K_{ed} = +0{,}7$

The analysis of the graphs presented in Fig. 4, Fig. 5 and Fig. 6, shows that as the ballistic coefficient $c_{a.ed}$ increases, so does the value of the relative tension force of the central cable $|\bar{R}_{cc}|$. This trend is explained by an increase in the aerodynamic component of the force.

4. Conclusions

The aerodynamic quality of the external device K_{ed} significantly affects the value of the relative tension force of the central cable. It should be noted that with large values of the ballistic coefficient of the device, positive values of the aerodynamic quality $K_{ed} > 0$ can lead to situations where the module of the pitch angle of the central cable $|\vartheta_1|$ (i.e., the angle of deviation of the central cable of „BB4453“ from the vertical position) will become greater than 90^0. This explains the increase in the values of the relative tension force of the central cable as a function of the flight speed at values of the ballistic coefficient $c_{a.ed} = 0{,}01\ m^2/kg$ and $c_{a.ed} = 0{,}02\ m^2/kg$. However, this fact has only a theoretical aspect, since from the point of view of flight safety, an established horizontal straight flight should not be performed at such an angle of deviation of the central cable from the vertical position.

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Влияние на параметрите на полета на хеликоптера и на външното пожарогасително устройство на равновесието на силите, които действат на устройството

Николай Загорски

Резюме: За определяне на безопасните режими на полет на хеликоптер с външно пожарогасително устройство за гасене на пожари е необходимо да се изследва и познава взаимното положение на хеликоптера и на външното устройство в установен полет при условие на тяхното равновесие. Аеродинамичното качество на устройството влияе съществено на стойността на относителната сила на натегнатост на централния кабел.

Determining the influence of helicopter flight parameters and external fire-extinguishing device on the equilibrium of the helicopter-external device system in flight

Nikolay Zagorski

Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria, nzagorski@space.bas.bg

Abstract: Fighting fires with a helicopter and external fire extinguisher is a high risk activity. To determine the safe flight modes of an AS532AL Cougar helicopter with an external fire extinguishing device "Bambi Bucket BB4453", it is necessary to study and know the mutual position of the helicopter and the device in a steady flight under the condition of their equilibrium, as well as when the conditions change dynamically of flight and environment.

Keywords: *helicopter, external fire extinguisher, flight safety*

1. Introduction

To determine the safe flight modes of an AS532AL Cougar helicopter with an external fire extinguishing device "Bambi Bucket BB4453" (full of water or empty) for extinguishing fires, it is necessary to study and know the relative position of the helicopter and the external device in established flight at condition of their equilibrium. This will allow, with a first approximation, to determine the possibility of contact of the cable of the device with elements of the helicopter structure. In addition, the static loads of the "Helicopter-External Fire Extinguisher" system in flight and the required control margin must be evaluated.

In order to make it possible to carry out an analytical description of the above-mentioned dependencies in the mathematical models of the helicopter and the external fire extinguishing device, some additional assumptions have been introduced.

2. Initial states of the studied objects

It is known that the equilibrium of the aircraft represents such a state in which the sum of all forces and the sum of all moments acting on the aircraft (Fig. 1) are equal to zero [1].

In flight, the helicopter moves in a field in which the Earth's gravity (forces of attraction) acts, while at the same time acting on it are forces and moments created by the main and tail propellers and by the counter flow of air. In accordance with the above, the vector of the equivalent $\vec{F}$ of all external forces acting on the helicopter can be represented as the following vector sum:

(1) $\vec{F} = \vec{R}_{MP} + \vec{T}_{TP} + \vec{R}_A + \vec{G}$,

where: $\vec{R}_{MP}$ is the equivalent force of the main propeller;

$\vec{T}_{TP}$ is the thrust of the tail propeller;

$\vec{R}_A$ is the equivalent of the aerodynamic forces acting on the helicopter body;

$\vec{G}$ is the force of the helicopter's gravity.

In turn, the main moment $\vec{M}$ from the external forces represents the following vector sum:

(2) $\vec{M} = \vec{M}_{MP} + \vec{M}_{TP} + \vec{M}_A$,

where: $\vec{M}_{MP}$ is the moment that is created by the main propeller;

$\vec{M}_{TP}$ is the moment that creates the tail rotor;
$\vec{M}_A$ is the aerodynamic moment of the helicopter body.

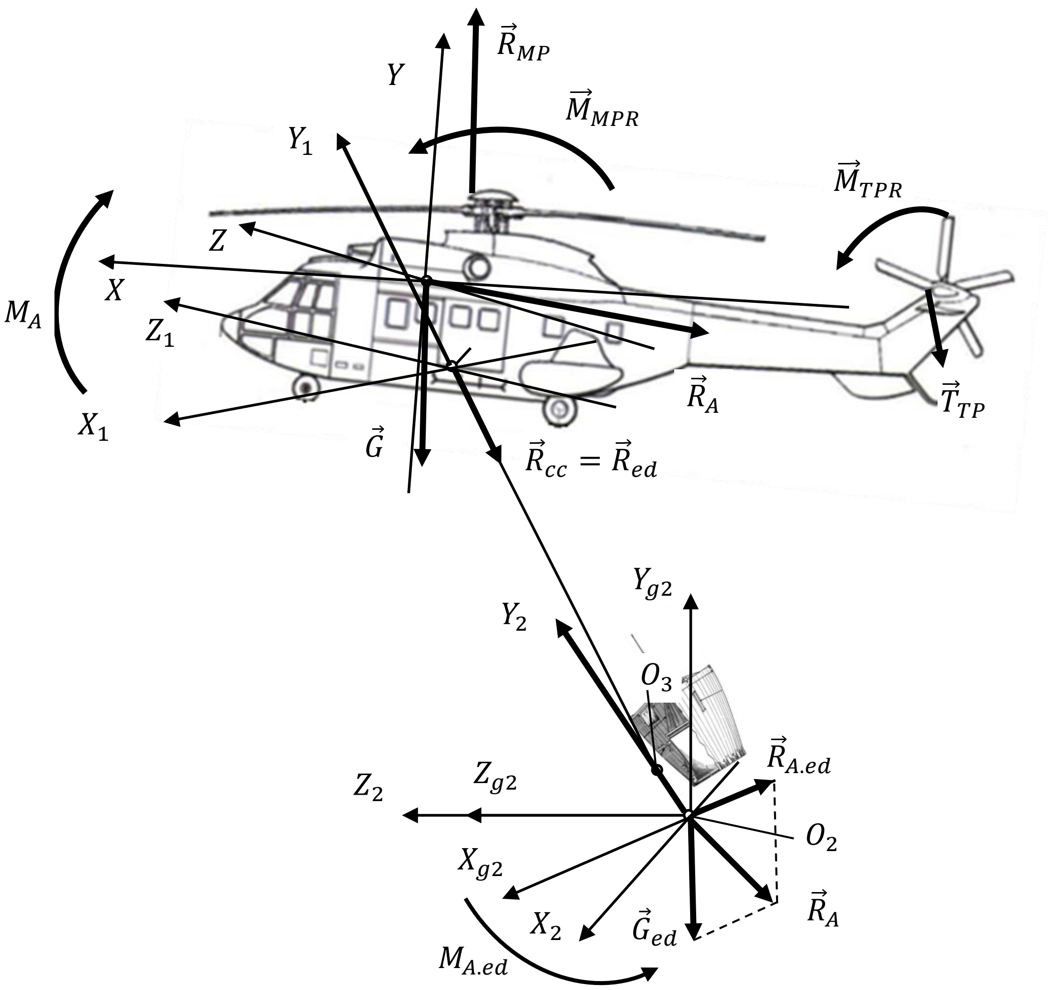

Figure 1. Equilibrium diagram of the system "Helicopter-external fire extinguishing device"

Thus, for example, the conditions for equilibrium are fulfilled in established horizontal straight-line flight. Balancing is usually understood only when the condition is met that the sum of the moments acting on the helicopter is equal to zero [1–2].

In this regard, the equation of forces (1) and moments (2) acting on the helicopter in flight must be supplemented, respectively, with the tension force in the cable $\vec{R}_{cc}$ and the moment from it $\vec{M}_{cc}$:

(3) $\vec{F} = \vec{R}_{MP} + \vec{T}_{TP} + \vec{R}_A + \vec{G} + \vec{R}_{cc}$,

(4) $\vec{M} = \vec{M}_{MP} + \vec{M}_{TP} + \vec{M}_A + \vec{M}_{cc}$.

In order to determine the value of the tensile force in the central cable $\vec{R}_{cc}$, it is necessary to determine the projection of the equivalent force $\vec{R}_{ed}$ of all the forces acting on the external device along the axis of the cable.

The equivalent force $\vec{R}_{ed}$ represents the following vector sum:

(5) $\vec{R}_{ed} = \vec{G}_{ed} + \vec{R}_{A.ed} + \vec{J}_{ap} + \vec{J}_{cf}$,

where: $\vec{G}_{ed}$ is the force of gravity of the external device;

$\vec{R}_{A.ed}$ m is the equivalent of all aerodynamic forces acting on the external device;

$\vec{J}_{ap}$ is the inertial force arising during the accelerated movement of the attachment point of the external device to the helicopter;

$\vec{J}_{cf}$ is the inertial centrifugal force arising from the rocking of the external device.

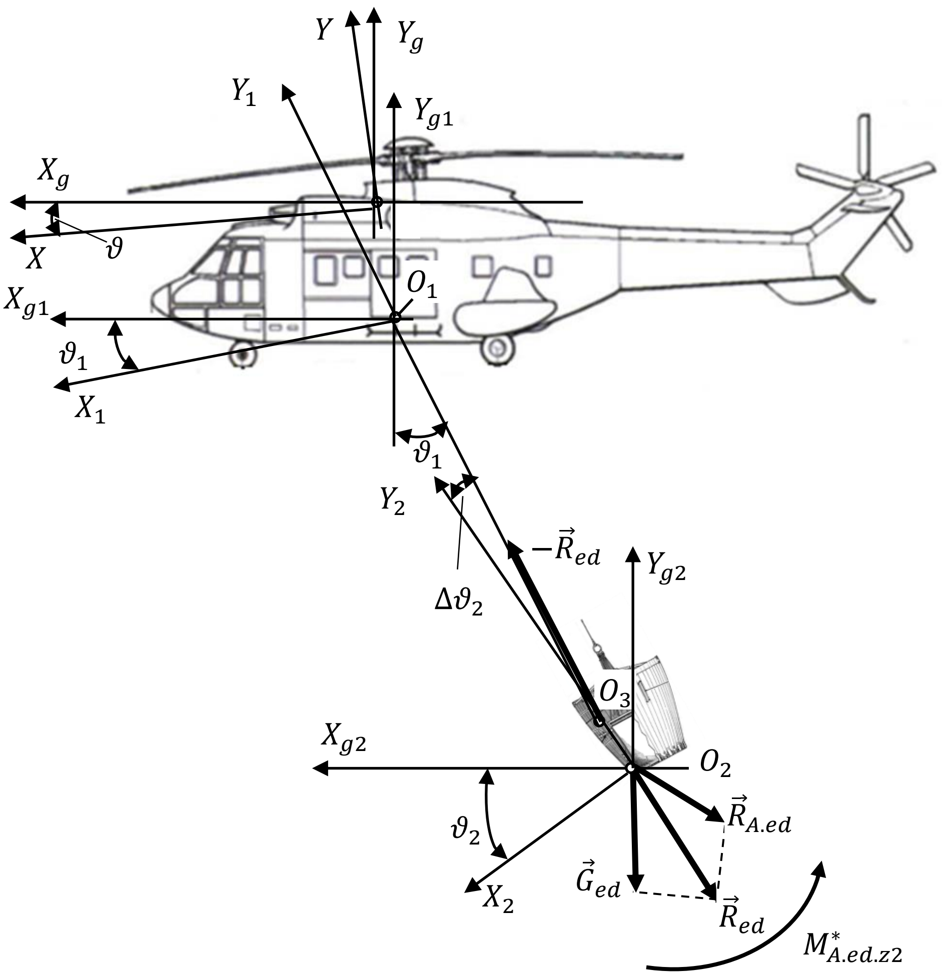

Figure 2. Equilibrium diagram of the external fire extinguishing device

Similarly, the movement of the helicopter itself relative to its center of mass will be caused by the impact of the moment $\vec{M}_{ed}$, which is the sum of the moments of the forces acting on the external device relative to the attachment point:

(6) $\vec{M}_{ed} = \vec{M}_{G.ed} + \vec{M}_{A.ed} + \vec{M}_{ap}$,

where: $\vec{M}_{G.ed}$ is the moment of the force of gravity of the external device;

$\vec{M}_{A.ed}$ is the moment of the aerodynamic force of the external device;

$\vec{M}_{ap}$ is the moment of the forces arising from the accelerated displacement of the attachment point of the cable to the helicopter.

The equilibrium condition of the helicopter with an external fire-extinguishing device derives from the equations of motion (5) and (6), taking into account the fact that this motion is carried out without acceleration:

(7) $\vec{R}_{MP} + \vec{T}_{TP} + \vec{R}_{A} + \vec{G} + \vec{R}_{cc} = 0$,

(8) $\vec{M}_{MP} + \vec{M}_{TP} + \vec{M}_{A} + \vec{M}_{cc} = 0$.

To ensure equilibrium of the “Helicopter-external fire extinguishing device” system, it is necessary to additionally fulfill the condition for equilibrium of the external device. With the established horizontal flight of the helicopter, the deviation of “BB4453” from the position that the device occupies in the “hover” mode takes place mainly in the plane coinciding with the plane $O_2X_2Y_2$ (Fig. 2). In this sense, the longitudinal equilibrium of the external fire-extinguishing device should be examined.

3. Determination of the effect of flight parameters and the external fire-extinguishing device on the equilibrium of the system in flight

The equilibrium of a helicopter with an external fire-extinguishing device in the conditions of established horizontal flight is described by equation (7) and equation (8).

Quite naturally, the external fire-extinguishing device, like any external load, has a significant effect on the forces acting on the helicopter in flight. This is because the external load can be of high mass, resulting in significant aerodynamic forces at high flight speeds. This in turn will result in a large increase in the tension force on the center cable, which is transmitted to the helicopter as a force applied at the point of attachment of the cable to the helicopter.

On the other hand, the external fire-extinguishing device has a significant impact on the balancing of the helicopter, i.e. of moment equilibrium. This is due to the fact that, as a rule, the point of attachment of the central cable does not coincide with the center of mass of the helicopter, therefore there is always an arm of the tension force of the central cable. This force creates a moment that affects the balance of the helicopter.

In order to perform an analysis of the influence of the force $\vec{R}_{cc}$ on the equilibrium of the helicopter, comparability conditions must be ensured, and several assumptions must be made for this purpose. First, the mass of the helicopter-external fire-extinguishing system is assumed to be equal to the mass of the helicopter without external load. In this case, the fire extinguisher is considered to be located in the cargo cabin of the helicopter.

When studying the longitudinal equilibrium of the helicopter, it can be assumed that the angle of roll of the helicopter $\gamma \approx 0$ and the air flow from the main propeller does not flow around the body of the helicopter. This is actually perfectly acceptable for the range of horizontal flight speeds under consideration. In this case, taking into account the above-accepted comparability condition in the analysis, and taking into account the sign rule, the force equilibrium condition (7) can be written in scalar form in the coupled helicopter coordinate system as follows:

$$(9)\ \begin{cases} H + X_f - (m_0 - m_{ed})g\sin\vartheta + R_{cc.x} = 0; \\ T + Y_f - (m_0 -)g\cos\vartheta + R_{cc.y} = 0, \end{cases}$$

where: m_0 is the mass of the helicopter (without external fire extinguishing device);

m_{ed} is the mass of the external device and the mass of the central cable, i.e. on the table of the “cable-external fire extinguishing device” system.

In the conditions of established horizontal straight-line flight, the projections of the tension forces of the central cable on the axes of the connected coordinate system can be determined by the following formulas:

$$(10)\ \begin{cases} R_{cc.x} = -R_{cc}\sin\vartheta_1\cos\vartheta + R_{cc}\cos\vartheta_1\sin\vartheta; \\ R_{cc.y} = R_{cc}\sin\vartheta_1\sin\vartheta + R_{cc}\cos\vartheta_1\cos\vartheta. \end{cases}$$

$$(11)\ \begin{cases} R_{cc.x} = R_{cc}\sin(\vartheta - \vartheta_1); \\ R_{cc.y} = R_{cc}\cos(\vartheta - \vartheta_1). \end{cases}$$

Determining the values of the projections $R_{cc.x}$ and $R_{cc.y}$ leads to changing all members of the equations in the system (9) to ensure the equilibrium conditions. In this case, the helicopter will balance at a new pitch angle, causing the helicopter's gravity force projections to change. On the other hand, in conditions of established horizontal straight flight, the angles of attack of the main propeller blades and other parts of the helicopter that are swept by the oncoming air flow will change.

Since there is a negligible increase in the helicopter's angle of attack, the increase in aerodynamic forces can be neglected by writing down the following system of equations:

$$(12)\ \begin{cases} H_0 + \Delta H + X_f(m_0 - m_{ed})g\sin(\vartheta_0 + \Delta\vartheta) + R_{cc.x} = 0; \\ T_0 + \Delta T + Y_{hst} - (m_0 - m_{ed})g\cos(\vartheta_0 + \Delta\vartheta) + R_{cc.y} = 0, \end{cases}$$

where: H_0, T_0 and ϑ_0 are, respectively, the longitudinal force, main propeller thrust and pitch angle of the helicopter without external fire-extinguishing device;

ΔH, ΔT and $\Delta\vartheta$ are, respectively, the increase in longitudinal thrust, main propeller thrust and pitch angle of the helicopter caused by the presence of an external fire-extinguishing device.

The longitudinal balance of forces acting on a helicopter without an external device can be expressed by the following system of equations:

(13) $\begin{cases} H_0 + X_f - m_0 g \sin\vartheta_0 = 0; \\ T_0 + Y_f + Y_{hst} - m_0 g \cos\vartheta_0 = 0. \end{cases}$

Assuming that the pitch angle of the helicopter without an external device is negligible, i.e. $\vartheta_0 \approx 0$ (which is confirmed by established aviation practice), then the following system of equations can be written:

(14) $\begin{cases} H_0 + X_f = 0; \\ T_0 + Y_f + Y_{hst} - m_0 g = 0. \end{cases}$

In this case, taking into account that $T_0 \approx m_0 g$, and $Y_f + Y_{hst} \approx 0$, and transforming the system (12) we will get the following system of equations:

(15) $\begin{cases} \Delta H + (m_0 - m_{ed}) g \sin\Delta\vartheta + R_{cc.x} = 0; \\ m_0 g + \Delta T - (m_0 - m_{ed}) g \cos\Delta\vartheta + R_{cc.y} = 0, \end{cases}$

In flight, the pitch angle of the helicopter is increased due to the presence of an external fire-extinguishing device. The value of this increase can be obtained from [3–5]. In this case, the rule will be taken into account that the trigonometric function “sine” of a small angle is approximately equal to the angle itself, i.e. $\sin\Delta\vartheta \approx \Delta\vartheta$.

(16) $\Delta\vartheta = \frac{\Delta H + R_{cc.x}}{(m_0 - m_{ed}) g}$.

From the second equation of the system (15), the value of increasing the thrust of the main propeller can be determined:

(17) $\Delta T = (m_0 - m_{ed}) g \cos\Delta\vartheta - m_0 g - R_{cc.y}$.

The relative thrust increase of the main propeller (vs. the weight force of the outboard) can be written as:

(18) $\Delta\bar{T} = \frac{\Delta T}{m_{ed} g} = \left(\frac{1}{\bar{m}_{ed}} - 1\right) \cos\Delta\vartheta - \frac{1}{\bar{m}_{ed}} - \frac{R_{cc.y}}{m_{ed} g}$,

where $\bar{m}_{ed} = \frac{m_{ed}}{m_0}$ is the relative mass of the external device.

Taking into account the rule that the trigonometric function cosine of a small angle is approximately equal to unity, i.e. $\cos\Delta\vartheta \approx 1$, then the thrust increase of the main propeller will be determined by the following expression:

(19) $\Delta\bar{T} = -m_{ed} g - R_{cc.y}$.

In such a case, for the relative increase in thrust of the main propeller we will get the following value:

(20) $\Delta\bar{T} = -1 - \frac{R_{cc.y}}{m_{ed} g}$.

To determine the increase in longitudinal force ΔH, which is necessary to calculate the value of the pitch angle of the helicopter $\Delta\vartheta$ by formula (16), it is necessary to determine the balance of the helicopter around the axis $\overrightarrow{OZ}$ of the connected coordinate system of the helicopter.

The force $\vec{R}_{cc}$ can create both a camber and a pitching moment, which depends on the helicopter's centering, flight parameters (mode) and external device parameters. In order to compensate the moment from the force $\vec{R}_{cc}$, it is necessary to increase the longitudinal force $\Delta\vec{H}$ which is directed backwards (to compensate for the pitching moment), as shown in Fig. 3. The balance of forces along the longitudinal axis of the helicopter $\overrightarrow{OX}$ is achieved by adequately varying the pitch angle of the helicopter to create a projection of the gravity force along this axis of value $(m_0 - m_{ed}) g \sin\vartheta$.

From the vector moment equation (8), the following scalar equation for balance of moments about the axis $\overrightarrow{OZ}$ can be written, noting that usually the point of suspension of the external device to the helicopter is structurally located on a line that coincides with the line of rotation of the main propeller:

(21) $(H_0 + \Delta H) y_h - (T_0 + \Delta T) x_h - M_{TPR} + m_{f.z} \frac{\rho V_a^2}{2} S_f l + Y_{hst}(r_{st.xh} - x_{cc}) - R_{cc.x}(r_{yh} - y_h) -$
$- R_{cc.y} x_h = 0.$

Taking into account the assumptions made above concerning the insignificant values of the differences in aerodynamic forces and moments that act on a helicopter without an external fire-extinguishing device and, when the helicopter has an external device, as well as for the insignificant change in the value of the reactive moment of the tail propeller - M_{TPR}, equation (21) can be written as follows:

(22) $\Delta H y_h - \Delta T x_{cc} - R_{cc.x}(r_{yh} - y_h) - R_{cc.y} x_h = 0$.

If in equation (22) we put the expression for increasing the thrust ΔT obtained in (22), and after several successive transformations are performed, the formula for increasing the longitudinal force of from the main propeller can be derived:

(23) $\Delta H = \frac{R_{cc.h}(r_{yh} - y_h + y_{ef}) - m_{ed} g x_h}{y_{ef}}$.

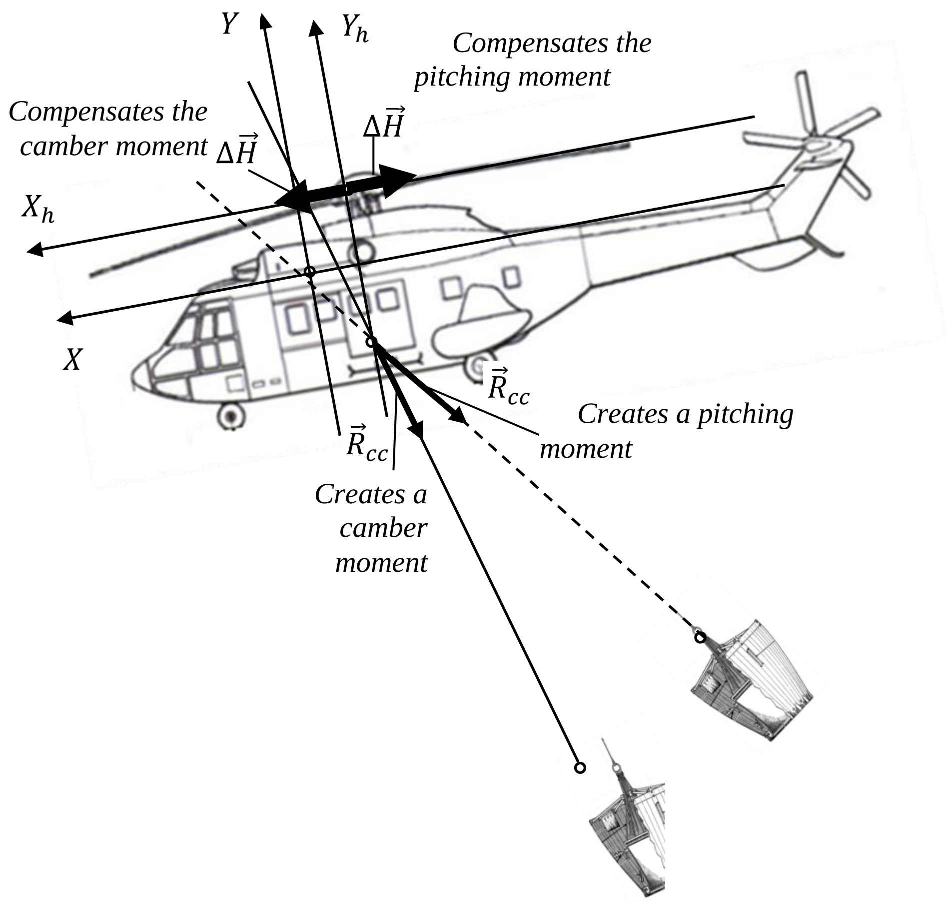

Figure 3. Scheme of increasing the pitching moment of the helicopter due to the presence of an external fire-extinguishing device

If the resulting expression in (23) is inserted into formula (16), the following expression for increasing the pitch angle will be obtained:

(24) $\Delta\vartheta = \frac{R_{cc.x}(r_{yh} - y_h + y_{ef}) - m_{ed} g x_h}{(m_0 - m_{ed}) g y_{ef}}$.

If the numerator and denominator of (24) are divided by the weight of the external fire extinguisher - $(m_{ed} g)$, the following expression will be obtained:

(25) $\Delta\vartheta = \frac{\frac{R_{cc.x}}{m_{ed} g}(r_{yh} - y_h + y_{ef}) - x_h}{\left(\frac{1}{\overline{m}_{ed}} - 1\right) y_{ef}}$.

In formula (23) the load of the longitudinal force from the main propeller - ΔH was determined. Next, it is necessary to determine the value of the increase in the angle of longitudinal deviation $\Delta\chi$ of the automatic tilter, which provides the necessary increase ΔH for the balancing of the helicopter.

It is known that the longitudinal force from the main propeller of the helicopter in established horizontal flight depends on the airflow over the main propeller, as well as on the angle of longitudinal deflection of the auto-tilt [6]:

(26) $H_0 = -T_0 k_{sm} - T_0 D_{MP} \chi_0$,

where: k_{sm} is the yaw coefficient - the angle of the longitudinal deviation of the aerodynamic axis of the cone of the blades of the main propeller from the structural axis of rotation of the main propeller of the helicopter when blown by the air flow in flight without an external fire extinguishing device;

χ_0 is the angle of longitudinal deflection of the auto tilter of the helicopter in flight without an external device.

When flying a helicopter with an external fire-extinguishing device, we can write the following expression:

(27) $H_0 + \Delta H = -(T_0 + \Delta T) k_{sm+} - (T_0 + \Delta T) D_{MP} (\chi_0 + \Delta \chi)$,

where: k_{sm+} is the angle of the longitudinal deviation of the aerodynamic axis of the blade cone of the main propeller from the design axis of rotation of the main propeller of the helicopter in the airflow in flight without an external fire-extinguishing device.

From this, the formula for determining the values of the increase in the angle of longitudinal deviation of the auto-tilt to achieve the longitudinal balancing of a helicopter with an external device can be obtained:

(28) $\Delta \chi = -\frac{\mathrm{H}_0 + \Delta \mathrm{H}}{(\mathrm{T}_0 + \Delta \mathrm{T}) D_{MP}} - \frac{k_{sm+}}{D_{MP}} - \chi_0$.

The angle k_{sm+} can be determined by the well-known formula from flight dynamics [7]:

(29) $k_{sm+} = 2\left(\lambda + \frac{4}{3} B \varphi_{01}\right) \frac{1}{B^2 - \frac{1}{2}\mu^2}$,

where: $\mu = \frac{V_{hf} \cos \alpha_{MP}}{\omega_{MP} R_{MP}}$ is the characteristic of the main propeller;

$\lambda = \frac{V_{hf} \sin \alpha_{MP} - v_i}{\omega_{MP} R_{MP}}$ is coefficient of air flow around the main propeller;

B is the coefficient of pressure losses at the ends of the main propeller. In a first approximation, it can be assumed that $B \approx 1$;

φ_{01} is the pitch of the main propeller in flight of the helicopter with an external fire-extinguishing device;

α_{MP} is the angle of attack of the main propeller;

ω_{MP} is the angular speed of rotation of the main propeller;

$v_i = \frac{T_0 + \Delta T}{2\rho F_{MP} V_{hf}} \approx \frac{m_0 g + \Delta T}{2\rho F_{MP} V_{hf}}$ is the inductive speed;

R_{MP} is the radius of the main propeller;

F_{MP} is the area described by the main propeller blades in flight;

ρ is the air density.

4. Effect of helicopter flight parameters and external fire-extinguishing device on helicopter pitch angle

Initially, the influence of the flight parameters on the pitch angle ϑ of the helicopter at different values of the mass of the external fire-extinguishing device should be investigated. In Fig. 4 are shown graphs with the results of the calculations using the mathematical model of the dependencies of the pitch angle of the helicopter as a function of the speed of an established horizontal straight-line flight of a helicopter without an external device and with an empty external fire-extinguishing device "Bambi Bucket BB4453". The pitch angle is measured relative to the building horizontal of the helicopter body.

The analytical expression for the increase in the pitch angle of the helicopter due to the presence of an external fire-extinguishing device, which reflects the dependence of the pitch angle as a function of the parameters of the external device and of the flight parameters, can be obtained from equations (9), (11) and (25):

$$(30)\ \Delta\vartheta = \frac{\sin(\vartheta_0+\Delta\vartheta+\vartheta_1)(r_{yh}-y_h+y_{ef})\sqrt{\left(\frac{K_{ed}c_{a.ed}\rho V_{hf}^2}{2g}-1\right)^2+\left(\frac{c_{a.ed}\rho V_{hf}^2}{2g}\right)^2}+x_h}{\left(\frac{1}{\overline{m}_{ed}}-1\right)y_{ef}}.$$

However, in this expression, the increase in pitch angle $\Delta\vartheta$ is present in both the left and right sides of the equation. Nevertheless, if it is taken into account that the angles of pitch and of the external fire-extinguishing device are small, and making the assumption that $\vartheta_0 = 0$, then the expression in (30) can be converted to:

$$(31)\ \Delta\vartheta = \frac{-\tan^{-1}\left(\frac{1}{\frac{2g}{c_{a.ed}\rho V_{hf}^2}-K_{ed}}\right)(r_{yh}-y_h+y_{ef})\sqrt{\left(\frac{K_{ed}c_{a.ed}\rho V_{hf}^2}{2g}-1\right)^2+\left(\frac{c_{a.ed}\rho V_{hf}^2}{2g}\right)^2}-x_h}{\left(\frac{1}{\overline{m}_{ed}}-1\right)y_{ef}+(r_{yh}-y_h+y_{ef})\sqrt{\left(\frac{K_{ed}c_{a.ed}\rho V_{hf}^2}{2g}-1\right)^2+\left(\frac{c_{a.ed}\rho V_{hf}^2}{2g}\right)^2}}.$$

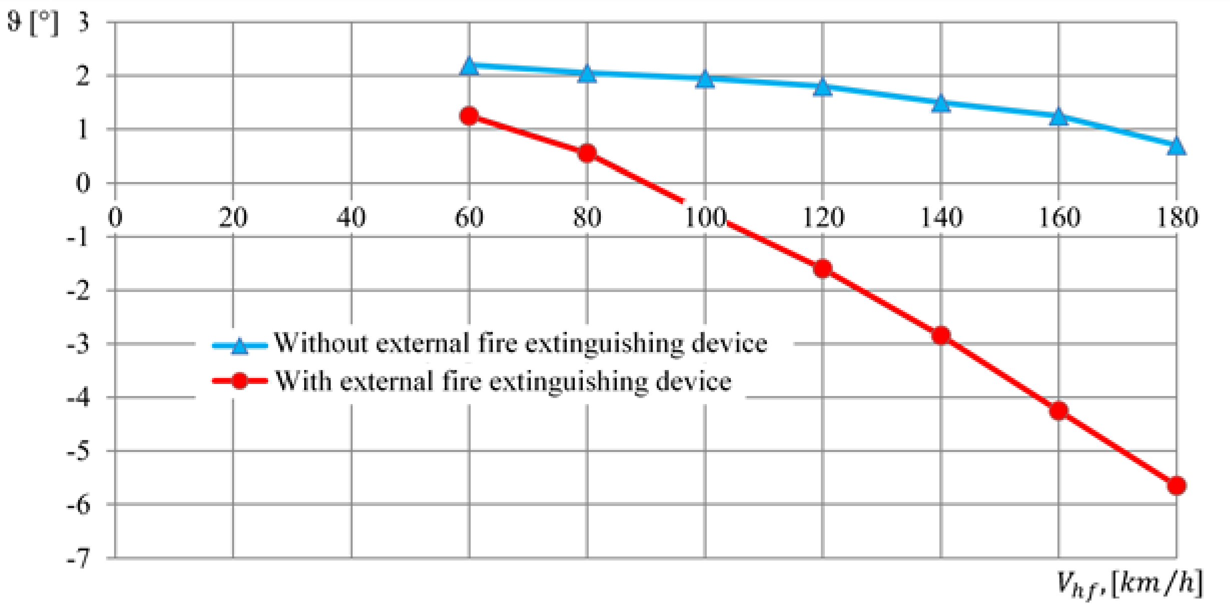

Figure 4. Plots of the pitch angle of the helicopter as a function of the speed of established horizontal straight flight, with and without an external fire-extinguishing device

In the case of a helicopter flight with an empty external fire-extinguishing device, graphs of the dependence of the increase in the pitch angle $\Delta\vartheta$ of the helicopter as a function of the flight speed obtained by the mathematical model and by calculations with formula (31), are shown in Fig. 5.

The analysis of the graphs in Fig. 5 shows that the results of calculations by formula (31) agree well with the results of the mathematical model, especially in the range $(60 \div 120)\ km/h$. As the flight speed increases, the discrepancy between the results of the analytical calculations and the mathematical model increases. This can be explained by the accepted assumptions in determining formula (31), as well as the accepted assumption in the analytical calculations for the constancy of the aerodynamic quality of the external fire extinguishing device - K_{ed} and the ballistic coefficient $c_{a.ed}$.

The analysis must be performed separately on the effect of each parameter of the external fire-extinguishing device on the increase in the pitch angle of the helicopter in established horizontal straight-line flight. First of all, the influence of the ballistic coefficient c_a at a constant value of the other parameters of the external fire extinguishing device, of the central cable and of the helicopter should be investigated:

- $K_{ed} = 0$;
- $\overline{m}_{ed} = 0{,}02$;
- $(r_{yh} - y_h) = -1{,}285\ m$;

- $x_h = 0{,}21\ m.$

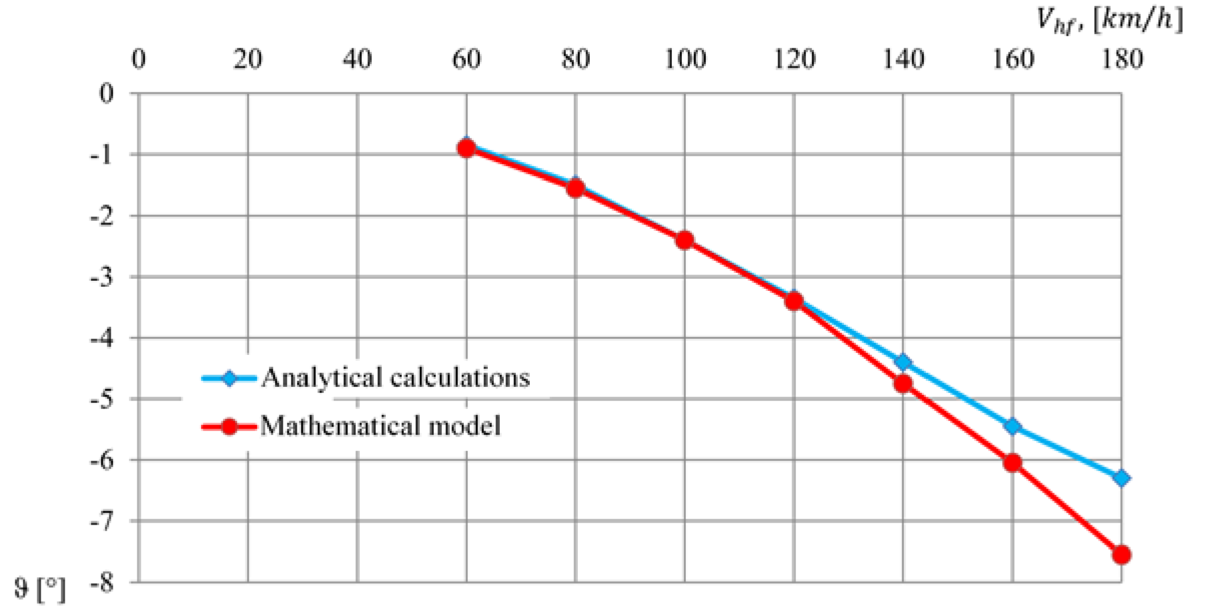

Figure 5. Plots of the dependence of the pitch angle of the helicopter with an empty external fire-extinguishing device "BB 4453 as a function of the speed of established horizontal straight flight, obtained in the mathematical modeling and in the analytical calculations

In Fig. 6 are shown the graphs of the increase in the pitch angle of the helicopter as a function of the speed of established horizontal flight and the ballistic coefficient of the external fire-extinguishing device under the assumed conditions.

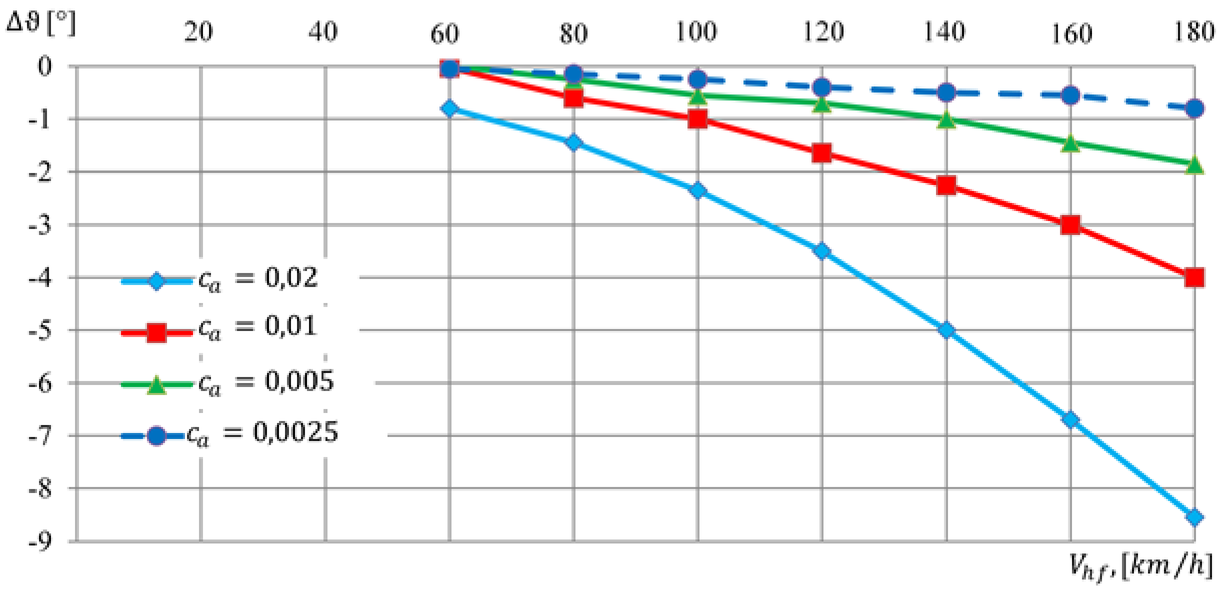

Figure 6. Graphs of the dependence of the change in the pitch angle of the helicopter as a function of the speed of established horizontal straight flight and the ballistic coefficient of the external device

The analysis of the presented in Fig. 6 dependences shows that with an increase in the helicopter's flight speed and the value of the ballistic coefficient of the external fire extinguishing device, the pitch angle of the helicopter also increases.

Let's determine the nature of the influence of the aerodynamic quality of the external fire-extinguishing device at constant values of the other parameters of the external device and of the helicopter:

- $c_{ed} = 0{,}02\ m^2/kg$;
- $\overline{m}_{ed} = 0{,}02$;
- $(r_{yh} - y_h) = -1{,}285\ m$;
- $x_h = 0{,}21\ m$.

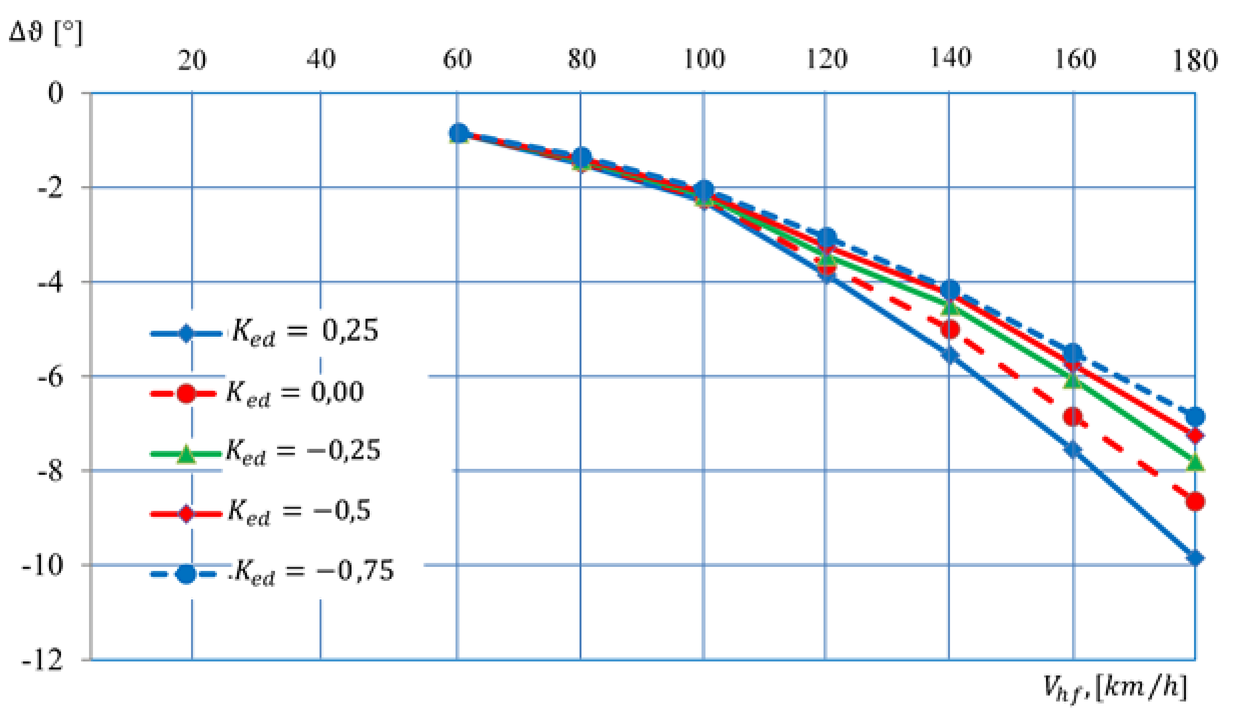

Figure 7. Dependence graphs for the variation of the helicopter pitch angle as a function of the speed of established horizontal straight flight and the aerodynamic quality of the external device

Fig. 7 presents dependence graphs for the change in the pitch angle of the helicopter as a function of the speed of an established horizontal straight flight and the aerodynamic quality of the external fire-extinguishing device at the already accepted values of the other parameters. The analysis of the dependences presented in this way shows that with an increase in the helicopter flight speed and the aerodynamic quality of the external device (taking into account its sign), the negative pitch angle of the helicopter also increases (modulo).

This circumstance can be explained by several reasons. First of all, aviation practice shows that the pitch angle of a helicopter with an external load always has a negative value. Secondly, with an increase in aerodynamic quality, the angle of deviation of the cable from the vertical position increases, which in turn leads to an increase in the value of the projection of the tension force of the cable along the central axis of the helicopter $R_{cc.x}$. In order to compensate this force, it is necessary to increase the negative pitch angle of the helicopter.

Consider the influence of the relative mass of the external fire-extinguishing device $\overline{m}_{ed}$ at constant values of the helicopter and the external fire-extinguishing device:

- $c_{ed} = 0{,}02\ m^2/kg$;
- $K_{ed} = 0$;
- $(r_{yh} - y_h) = -1{,}285\ m$;
- $x_h = 0{,}21\ m$.

Fig. 8 presents graphs of the dependences of the change in the pitch angle of the helicopter on the speed of established horizontal straight flight and the relative mass of the external fire-extinguishing device at the already accepted values of the other parameters of the helicopter and the external device. The nature of change of the dependences presented in this way shows that with the increase in the relative mass of the external device, the negative increase in the pitch angle of the helicopter increases by a module.

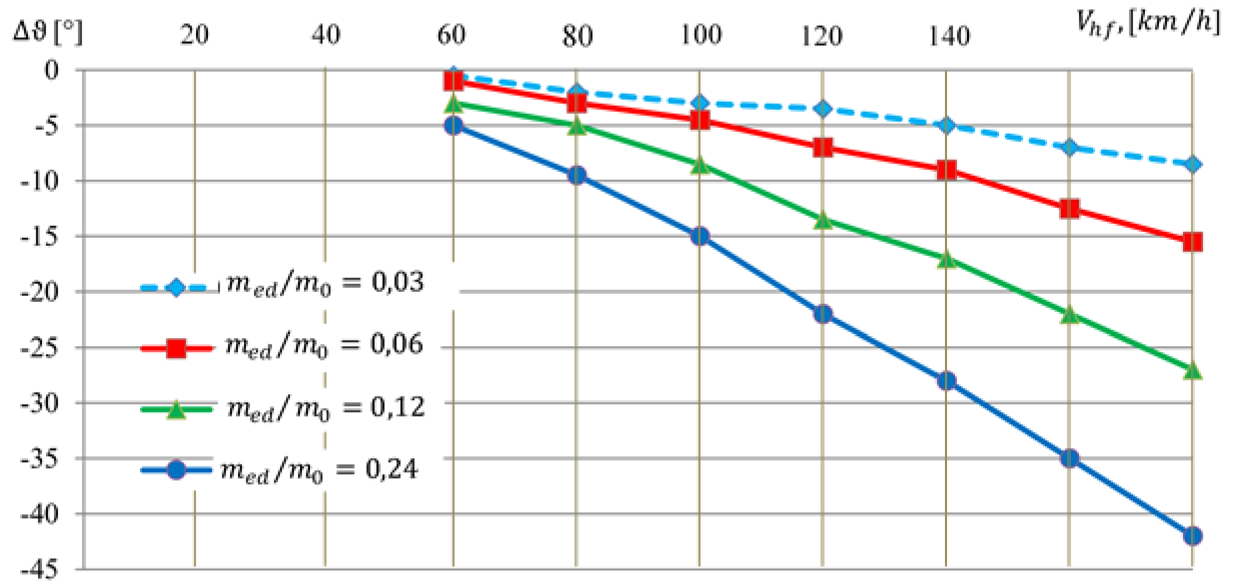

Figure 8. Plots of dependence of the change in the pitch angle of the helicopter as a function of the speed of established horizontal straight flight and the relative mass of the external device

This circumstance can be explained by several reasons. First of all, aviation practice shows that the pitch angle of a helicopter with an external load always has a negative value. Secondly, with an increase in aerodynamic quality, the angle of deviation of the cable from the vertical position increases, which in turn leads to an increase in the value of the projection of the tension force of the cable along the central axis of the helicopter $R_{cc.x}$. In order to compensate this force, it is necessary to increase the negative pitch angle of the helicopter.

Consider the influence of the relative mass of the external fire-extinguishing device $\overline{m}_{ed}$ at constant values of the helicopter and the external fire-extinguishing device:

- $c_{ed} = 0{,}02\ m^2/kg$;
- $K_{ed} = 0$;
- $(r_{yh} - y_h) = -1{,}285\ m$;
- $x_h = 0{,}21\ m$.

The significant increase in modulus of the negative pitch angle of the helicopter is explained by the fact that if the mass of the external device increases, and the ballistic coefficient remains constant, then this means that the product of the frontal resistance coefficient of the external fire-extinguishing device and the characteristic area of the external device $(c_{x.a}.S_{ed})$, which basically determines the value of the projection of the tension force of the cable on the longitudinal axis of the connected coordinate system of the helicopter - $R_{cc.x}$, which is compensated using the change of the angle of helicopter pitch.

Consider the influence of the helicopter's longitudinal alignment - x_h on the increase in the helicopter's pitch angle under constant conditions:

- $c_{ed} = 0{,}02\ m^2/kg$;
- $K_{ed} = 0$;
- $\overline{m}_{ed} = 0{,}02$;
- $(r_{yh} - y_h) = -1{,}285\ m$.

In Fig. 9 are shown graphs of the variation of the pitch angle of the helicopter as a function of the speed of established horizontal straight flight and the longitudinal alignment of the helicopter. From the presented dependences, it can be seen that the increase in the pitch angle of the helicopter depends very weakly on the longitudinal alignment of the helicopter.

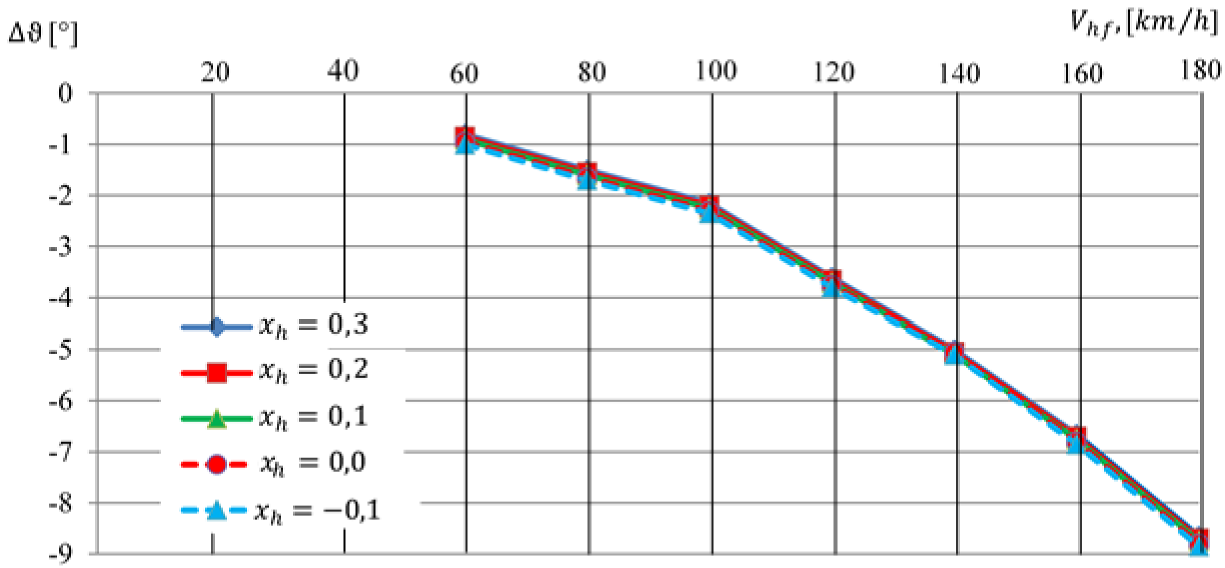

Figure 9. Plots of helicopter pitch angle variation as a function of established horizontal straight-line flight speed and helicopter longitudinal alignment

Analysis of these graphs shows that the results practically merge into a single line, indicating that when using formula (31) the summable x_h (which is located at the end of the numerator) can be excluded.

4. Conclusions

The general analysis of the obtained results shows that the ballistic coefficient of the external fire extinguishing device and its relative mass have the greatest influence on the increase in the pitch angle of the helicopter. It is reported that as both as the ballistic coefficient and as the relative mass of the external device increase, the negative pitch angle of the helicopter increases modulo. When the values are varied within reasonable limits, the aerodynamic quality of the external device has little effect on the increase in the pitch angle of the helicopter. The position of the point of attachment of the central cable of the external fire-extinguishing device to the helicopter along the normal axis of the base coordinate system of the helicopter is slightly more important. Longitudinal alignment has practically no effect on increasing the pitch angle of the helicopter. It should be emphasized that even when the point of attachment of the central cable of the external device to the helicopter coincides with its center of mass, the pitch angle of the helicopter will increase, which is explained by the need to compensate for the resulting force R ⃗_cc, which is directed backward.

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Определяне на влиянието на параметрите на полета на хеликоптера и на външното пожарогасително устройство за равновесието на системата „Хеликоптер–външно устройство“ в полет

Николай Загорски

Резюме: Гасенето на пожари с хеликоптер и външно пожарогасително устройство е дейност с висока степен на риск. За определяне на безопасните режими на полет на хеликоптер AS532AL Cougar с външно пожарогасително устройство „Bambi Bucket BB4453“ е необходимо да се изследва и познава взаимното положение на хеликоптера и на устройството в установен полет при условие на тяхното равновесие, както и при динамична промяна на условията на полета и околната среда.

Validation and verification in scientific computer simulation

Yoto Georgiev Georgiev

"UniPOS", Pleven, Bulgaria, y_g_g@abv.bg

Abstract: In the paper are discussed validation and verification of scientific computing. Validation and verification of scientific computer simulation are discussed as important aspect of scientific researches together with choice of computer language for coding of physical models. Validation and verification are concepts that are related to the very general field of modeling and simulation of physical systems.

Keywords: *validation, verification, scientific research, computational fluid dynamics*

1. Introduction

The term scientific computer simulation can be considered in both a narrow and a broad sense. In the narrowest sense, a computer simulation is a program that runs on a computing machine and uses step-by-step methods to study the approximate behavior of a mathematical model. In a wider sense, it can be considered a comprehensive method for studying real physical systems. In this broader sense of the term, it refers to the study of the entire process. This process involves choosing a model, finding a way to implement that model in a form that can be run on a computer, the so-called computer programming, calculating the output of the algorithm, and visualizing and studying the resulting data. Most programs for deterministic analyses are implemented in the computer language Fortran, and recently C++ has been widely used, especially in biology and medicine. In 2012, a new computer language designed for scientific computer simulations "Julia" was introduced [1].

Development of computational tools gives possibility for virtual engineering. Modeling of complex and sophisticated physical systems requires approximations and simplifying assumptions. Regarding computer programs and models, it must be demonstrated that the models and numerical methods used will provide a sufficiently accurate solution for the results obtained to be trusted. This is achieved through verification and validation of the models. The accuracy of the simulations can be affected by errors and uncertainties in the numerical calculations. These errors and uncertainties are generated in both conceptual modeling and programming and must be limited as much as possible. In the computer modeling of physical processes, there are three categories of errors, which at this stage of the development of science and technology are irremediable. These are errors from the mathematical formulation of the problem, errors from the discretization of the problem, and rounding errors in the arithmetic operations caused by the fact that calculations with computers are not carried out with complete accuracy. The reduction of errors and uncertainty leads to a better representation of real physical systems and thus increases confidence in the use of computer simulation. The pragmatic approach to reducing errors and uncertainty is the application of verification and validation of computer models. In case of validation, it is difficult to determine acceptability between measured data and results calculated by computer models. Performing validation and verification of computer programs and models requires more than a collection of data, it requires plan for the review. For some fields of science and engineering as aviation and power engineering it is necessary to be proved that computer models and simulation are validated and verified in accordance with accreditation rules [2, 3, 4]. In 2015 Kaizer extended the term validation and verification proposing the maturity assessment theory [5].

2. Validation in scientific computer simulation

Speaking about computer simulation we, first, need to define the meaning of the term. Irish scientist Francis Neelamkavil determines a term *simulation* as "the process of imitating important aspects of the system's behavior" [6]. Founders of the present-day concepts of validation are scientists Karl Popper and Rudolf Carnap. Computer codes for deterministic scientific analyses are developed by a large number of people, and development takes place over a long period of time. This often results in errors in the compiled program. The testing of the programs aims at reducing their defects by recognizing and subsequently removing them. A complex program never works right from the first time. The main purpose of validation and verification is to prove the correctness of the program or, if errors are found, to correct them. This allows evaluating and improving the quality of the given code. In most cases, it is very difficult to prove that there are no bugs in a program. This requires an extraordinary volume of work with high complexity and a need for infinite resources. Regardless of the size and specificity of the test deck introduced, it cannot be guaranteed that it will detect all errors in the code used. One can prove that every simple function and procedure in the code is correct, and then prove that they work together as they should. Today, however, there is no prospect of proving correctness in such a way that the specification and the theoretical proof are trusted more than the program itself. Code verification, which is defined as a comparison of the program's source code with the description and documentation, is not performed for most of them. Since the line-by-line verification of huge programs requires a lot of time and money, globally, this process is very limited and hardly implemented. It is usually verified that the investigated code has analogous behavior to that of other similar codes under identical simulated processes and with data obtained from the operation of the respective system. To indicate the degree of complexity, it is suggested referring to quantitative validation as ‘‘validation science’’[7].

Conducting the analyses themselves includes generally two stages: 1. reaching a steady state of the model; 2 calculation of the development of the transition process.

As a result of the first stage, stable model parameters should be obtained. At the second stage, the calculation of the transient processes is carried out according to a pre-compiled scenario depending on the goals of the analysis.

Although the primary purpose of code validation is to determine its correctness, this determination is qualitative rather than quantitative. The results obtained using the computer codes are intended to represent the processes with a certain level of credibility. An important clarification is that model validation and "input deck" validation is not the same thing. Model validation refers to the study of how the created model predicts given physical processes. In the validation of the "input deck" it is checked whether the created deck is adequately composed or not. The confusion comes from the fact that to validate the model one must build an "input deck" against which to test the model's behavior. A model and an "input deck" are organically linked, and consideration of the validation of one cannot be done without the other.

The methods used in computer codes for calculation must be fit for the purpose and the physical and logical equations must be implemented correctly. Regarding computer codes, it must be confirmed that:

- The physical models used to describe the processes are proven together with the associated simplifying assumptions;
- Correlations used to represent physical processes are proven and their limits of application established;
- The limits of applicability of the given code are defined;
- The numerical methods used will guarantee a sufficiently accurate solution.

Model validation means confirmation of the adequacy of the model of the real system with respect to the actual performance of the simulated installation. The goal is to demonstrate that the constructed model simulates well the system under consideration. Validating a computer code means evaluating the accuracy of the calculated values from the code against other results. What is checked is which processes and phenomena can be correctly modeled by the code and which cannot. The literature on the verification and validation of methods and models for engineering and scientific simulations is vast, but there are still open questions on this topic. The first step in validating large and complex systems is to calculate the steady state of the computer model.

Validation of computer models and programs suffer of in-principle shortcomings. Generally, available data from experiments covers a fraction of the parameter range expected in applications of a given computer models, the physical properties of materials are known to some extent as well as variations in values of quantities are expected and occurrence of complex situations are the reasons to consider that validation of computer models is not as trivial as it seems. The accuracy of most of the models for complex and sophisticated systems and processes cannot be validated in any meaningful way. An attempt to deal with those issues is the idea of adding a component to the validation process – „consistency with reality". In scientific literature dealing with the problems of validation and verification of computer simulations it may be encountered as the abbreviation V&V&C – acronyms for **V**alidation **V**erification and **C**onsistency.

3. Verification in scientific computer simulation

The purpose of verification is the identification and quantification of errors in the computational model and its solution. The Institute of Electrical and Electronics Engineers (IEEE) defined verification in 1991 as [8]: *the process of evaluating the products of a software development phase to provide assurance that they meet the requirements defined for them by the previous phase*. American Institute of Aeronautics and Astronautics defined verification as [9]: *the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model*. Regarding computer simulation, verification can be divided into three groups: solution verification, code verification and input deck verification. The first checks whether the output of the algorithm used approximates the exact solutions of the differential equations of the original model. The second verifies that the code, as written, performs the intended algorithm. The third verifies the input deck for the physical system.

The third step in scientific simulation modeling is discretization and algorithm formulation. In this step, the mathematical equations are defined in a way that they can be solved using a computer. A large part of the applied problems is modeled with complex differential equations or system of equations, the solutions of which cannot be found with the known analytical methods. Therefore, it is necessary to use approximate methods for solving differential equations. These methods include numerical methods. When choosing a numerical integration approach, one should take into account the capabilities of the method, the accuracy of the computer and the specific features of the phenomena being analyzed. The accuracy of a computational results are measured relative to two types of highly accurate solutions: analytical exact solutions and highly accurate numerical solutions.

Verifying that the source code, as written, performs the intended algorithms is the most difficult part – in other words that the computer code is free from errors. It is very difficult to prove the quality of hundreds of thousand programming lines of source code.

The third group of verification is concerning the input deck. The goal is to check the quality of nodalization of a given physical system. With proper spatial discretization, the calculated results are expected to approach the exact solution of the modeled equations as the number of control volumes of the simulated system increases. However, the results are strongly influenced by the mesh density and the nodal distribution of the control volumes. When conducting simulation modeling, a nodalization mesh must be built for the computer coding of the studied system. It is the responsibility of the scientist preparing the input deck to develop adequate nodalization. The two problem areas are spatial convergence and setting the multidimensional effects correctly.

4. Verification and validation in computational fluid dynamics

The foundations of fluid dynamics research were laid centuries ago. In modern days there are different methods for computer simulation of fluid dynamics as control volumes or finite volume method, finite element method, lattice Boltzmann method, direct numerical simulation and new methods as deep reinforcement learning applying artificial intelligence. In aerospace engineering structural analysis [10, 11]and computational fluid dynamics are the two main areas of aviation engineering determining the development in the following years.

As it is stated in [7] computer scientists, in the sense of dealing with computer simulations, and experimental scientists in the field of fluid dynamics had been pioneers in the development of methodology and procedures in validation. It is argued in [7] that validation experiments are indeed different from traditional experiments, i.e., validation experiments are designed and conducted for the purpose of model validation. It is determined that validation for computational fluid dynamics will require the incorporation of nondeterministic simulations, i.e., multiple deterministic simulations that reflect uncertainty in experimental parameters, initial conditions in empirical experiment, and boundary conditions that exist in the experiments that are used to validate the computational programs and models.

5. Comparison of C++ and Fortran for scientific programming

The fourth step in scientific simulation modeling is the computer programming of the modeled physical system. The description of each algorithm consists of separate steps (commands). Commands specify the execution of certain actions or determine the next command to be executed. Each algorithm consists of two types of parameters - data and rules for their processing. The choice of computer language is strongly connected with verification of the computer models and programs. The structural hierarchy of the components that make up scientific computer simulations is the structure that arranges the various components of scientific computer simulation in a vertical structure consisting of six levels: terms, assignment statements, coded physical function, coded group (subroutine/module), computer code and set of codes. This hierarchy organizes scientific computer simulations.

Modern programming languages can be grouped into five generations. The first generation formed the machine languages. Machine language is the elementary programming language that can be executed by the processor without any further conversions. In machine languages, instructions (commands) are specified by 0 and 1, and are executed directly in the hardware of the given processor. This means feeding the computer with columns of binary numbers. This method of programming is slow and complicated, leading to many errors. The solution to this problem is assembly languages. The long columns of numbers (0 and 1) are replaced by symbolic abbreviations. A disadvantage of the assembly languages is that they are applicable only on one type of hardware. Assembly programs cannot be directly ported. For this reason, high-level programming languages were born in the 1950s, one of the first being the Fortran language. High-level programming languages are independent of the underlying hardware. These are the third to fifth generation languages.

In 1954, work began on the creation of the FORTRAN language (FORmula TRANslation). In 1957, it was completed and realized as a means of creating programs for solving scientific and engineering tasks, and since then it has been the dominant programming language in scientific computing. It is used in computationally intensive fields such as numerical weather prediction, finite element analysis, computational fluid dynamics, geophysics, computational physics, computational chemistry, and many other areas of science. It is used as the language in which programs are coded to run benchmarks between the world's fastest supercomputers.

The reason for using such an old language lies in the fact that when the first process modeling codes were developed in various fields of science and technology, Fortran was the most used language for scientific calculations. Over time, more modern languages such as C++ appeared, but due to the need to translate ready-made source codes from one programming language to another and the inevitable errors, Fortran remained the main language in which programs for scientific analysis were coded. After Fortran, more specialized computer languages for scientific simulations were created, each designed for specific purposes, but none could displace Fortran as the primary computer tool for simulations in science and engineering. Fortran was the first high-level algorithmic language. The name - formula translator - suggests its purpose for programming computational processes. Over time, the language improved and became universal. Then the basic programming techniques were introduced, which remain unchanged even to this day. The first compiler was created for it. It is a procedural, and in its latest version, an object-oriented programming language - Fortran 2008. The main tool that Fortran and other high-level languages use to facilitate the modular principle of programming are subroutines. These subroutines are independent program units. A program unit is a part of a Fortran program compiled separately from other parts. Fortran supports two types of external subroutines: function subroutines and procedure subroutines.

Unlike languages such as COBOL, BASIC, and FORTRAN, C++ has no built-in I/O operators, resulting in a smaller executable program after compilation. Instead, input and output are done through C++ classes in the standard class libraries. In fact, many capabilities that are essential parts of other languages are implemented by C++ classes instead. Data conversion, string manipulation, and output data formatting are three examples of operations that C++ supports with classes and functions taken from the standard libraries, rather than with the language's internal capabilities. C++ is a small language, capable only of declaring and defining variables, assigning expressions to variables, and calling functions - only one of which, main(), is defined as part of the language itself. Standard C++ defines the form and behavior of a standard set of classes and functions in a standard set of class and function libraries. Programmer-defined classes and functions further extend the language to support specific problem areas. The advantage of C++ having operations as library functions is to improve flexibility.

Because C++ is in the gap between assembly and high-level languages, it can be defined as an intermediate-level programming language. It combines the structure of a high-level language with the power and efficiency of assembly language. This is one of its biggest advantages over other high-level computer languages. It is also one of the reasons why in the last two decades the C++ language has gradually replaced the Fortran language in scientific software.

C++ and Fortran are the main computer language for use in scientific computing. There is currently a debate in the scientific community which of the two languages should be used for implementation of scientific computer simulations. The choice of programming language for simulation modeling cannot be unambiguously defined. Each of the languages C++ and Fortran is applied and can be used in the program implementation of given physical models. Both C++ and Fortran are good enough and work fine.

Fortran is entirely intended as a computer language for programming numerical methods. Simulation modeling deals with large amounts of floating point numbers arranged in arrays, in the programming sense, and Fortran is the best computer language when it comes to processing large arrays of data - it can optimize much more aggressively than other computer languages. So Fortran is better for numerical scientific computing, for algorithms that can be expressed using arrays and don't need other complex data structures, so areas like finite differences/elements and solving differential equations are its area. For scientists who are not from the field of computer programing it is easier to code optimal programs in Fortran than in C++. C++ is a general-purpose language, so any algorithms can be programmed in it, and it is definitely better for algorithms that cannot be expressed using arrays, such as graphics, symbol manipulation, etc. It is possible to write array algorithms in C++, but it requires a lot more computer science knowledge and generally more work because you have to create array manipulation classes and manage memory by hand. In short, non-computer programming experts can write very good Fortran programs, but not good C++ programs.

Regarding the speed of calculations, it should be noted that most of the international benchmarks that are made between the different supercomputers are with programs written in Fortran. It is enough to mention the LINPACK library written in the Fortran language, on the basis of which the LINPACK performance test (LINPACK benchmarks) was compiled.

A critical feature missing from Fortran are templates, which allow C++ programmers to create portable, reusable code and improve the performance of complex expressions, including user-defined data types.

6. Conclusion

The ideas to use experiments to provide evidence of the accuracy or inaccuracy of a computer simulation are not always achievable as experimental testing is very expensive and not even sometimes possible. It is open issue to find a way to determine if the computer models are trustworthy or not. In the last decade addition was made adding „consistency with reality". One of the main issues with validation is to determine acceptability between measured data from empirical experiments and calculated by computer simulation results.

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AERODYNAMIC PROFILE OPTIMIZATION FOR A SMALL AIRCRAFT USING A GENETIC ALGORITHM

Georgi Yordanov Gvozdeikov

Bulgarian Air Force Academy, Faculty of Aviation, g.gvozdeykov@gmail.com

Abstract: The optimization of aerodynamic profiles plays an increasingly important role in the aviation industry. In airfoil optimization, design and parameterization is the key technique because it defines the design space. A suitable method is the combination of parameterization and genetic algorithms.

Keywords*: airfoil, optimization, genetic algorithm*.

1. Introduction

Even small improvements in aerodynamics can significantly affect the aerodynamic performance of an aircraft. This makes it necessary to actively seek and apply different methods for optimizing the aerodynamic profiles of the wing. For this purpose, various parameterization methods are developed and applied to complement the traditional methods.

"Parameterization" means representing the specifications of a model as a set of data and information. In aerodynamic optimization, parameterization is usually applied to represent the geometry of the model or shape. These geometric parameters are then used, as design variables for the designer or as input to optimization, to find a desired effective geometry that satisfies the required performance.

A well-accepted parameterization method most often has the following properties [2]:

• to provide high flexibility to cover the potential optimal solution in the design space;

• have as few design variables as possible;

• to achieve smoothness and realization of forms;

• to provide intuitive design parameters for geometric and physical understanding by design engineers when exploring the design space and setting optimization constraints;

• provide derivatives of the grid sensitivity with respect to the design variable, which is important for gradient-based optimization.

In real applications, a parameterization balance must be achieved, as it is unlikely that all requirements will be met. For example, parameterization methods with a large number of design variables can usually provide an extremely flexible design space.

The large number of design variables, however, increases the complexity of the design space and requires the optimizer to make additional efforts to find the most optimal solution possible. In general, the cost of optimization based on high-precision CFD calculations is even higher, which will lead to prohibitive computational costs.

On the other hand, for example, for some airfoils developed by NACA, only three parameters (maximum curvature, position of maximum curvature and maximum thickness) are used to represent the airfoil, which are unable to provide sufficient design space and satisfy the desired aerodynamic performance. Samareh (2001) reviews and compares some of these methods, classifying shape parameterization methods into the following eight categories: Basis vector, element field, partial differential equation, discrete (grid point), polynomial, spline, analytical based on CAD and Free Form Deformation (FFD) methods. Among these methods, discretized, analytic, polynomial, spline, CAD, and free-form deformation FFD are the most common [2].

Another method is the parameterized airfoil (PARSEC). This approach provides opportunities to address multimodal problems by dividing the airfoil into three sections: central, leading edge, and trailing edge. This ensures continuity between adjacent sections [3].

2. Genetic Algorithm optimization

Numerical optimization can reach a large overlap between calculated and empirical lift coefficient values. Different optimization approaches can provide the combined use to provide the appropriate method depending on the problem being solved.

In this regard, multi-parameter tuning contributes to achieving optimal results. The research presented in the article aims to present an optimization of the lift coefficient.

In genetic algorithms, chromosomes are selected based on their fitness vector, with those with a higher rank passing to the next generation. This process of evolution ensures the reproduction of the strongest of the previous generation, while also introducing new elements. It is necessary to introduce combinations, crossover or mutation to develop the newly selected chromosomes. Thus, the process is repeated over generations until an appropriate level of convergence is achieved [1].

The genetic algorithm provides selection of PARSEC parameter values with a certain accuracy. This necessitates setting an acceptable range or limits for each parameter, defining the step and defining the lengths of the domains to ensure that the optimization selects those parameter values in space that meet the required accuracy criteria [1].

In order to achieve rapid convergence of the results, a good selection of representatives of the initial population is necessary. Selection maintains variability by not excluding categorically and worse performing individuals, in these cases mutation is key in refining the process.

In order to carry out the optimization task, it is necessary to estimate the objective function for each set of parameters.

PARSEC parameters [3]:

p=[p1, p2, p3, p4, p5, p6, p7, p8, p9, p10, p11].

To these parameters, a randomizer must be created for a given range in order for the GA to generate random individuals.

The genetic algorithm for airfoil at different angles of attack generally follows the following algorithm.

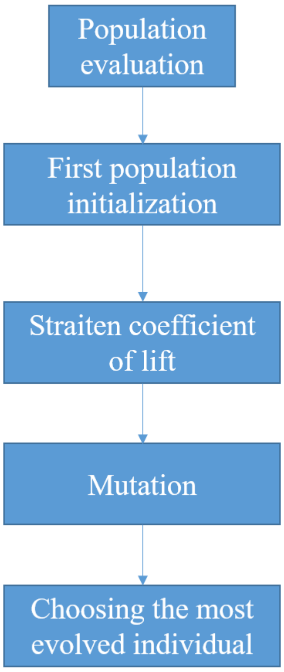

Fig.1. Airfoil Genetic Algorithm

As is known, the genetic algorithm is a stochastic search in which new states are created by combining pairs of parent states instead of modifying the current state [1].

This necessitates the introduction of an evaluation function to determine how suitable the current state is. To arrive at the evaluation function, the algorithm needs to have a population of randomly generated states (generation 0) [1].

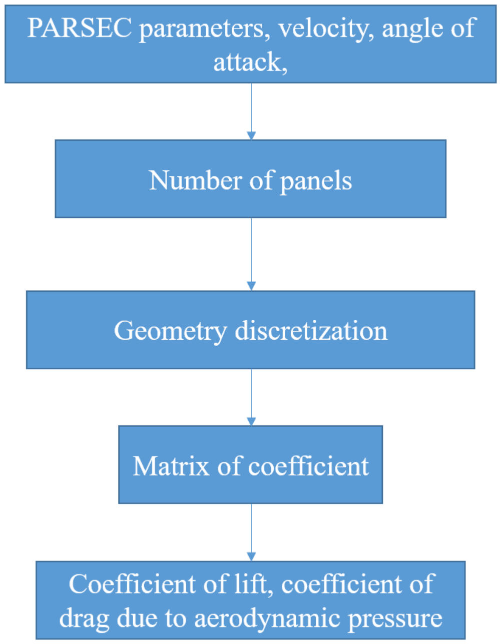

Fig. 2. Algorithm for the coeffecient of lift of an airfoil

The states of subsequent generations will depend on selection, crossover and mutation.

In the selection it is necessary to take part representatives of the best of the current generation (according to the evaluation function). These representatives are chosen at random.

Crossover, in turn, depends on the choice of the parent states to define the crossover point.

Mutation provides random changes in a small part of the new population in order to avoid the danger of falling into a local extremum.

3. Results

The genetic algorithm was applied to the NACA MS (1)-0313 airfoil, and the results are presented in Fig. 3 and 4 [4].

Initial: C_L= 0.707210

GA: C_L= 0.857964

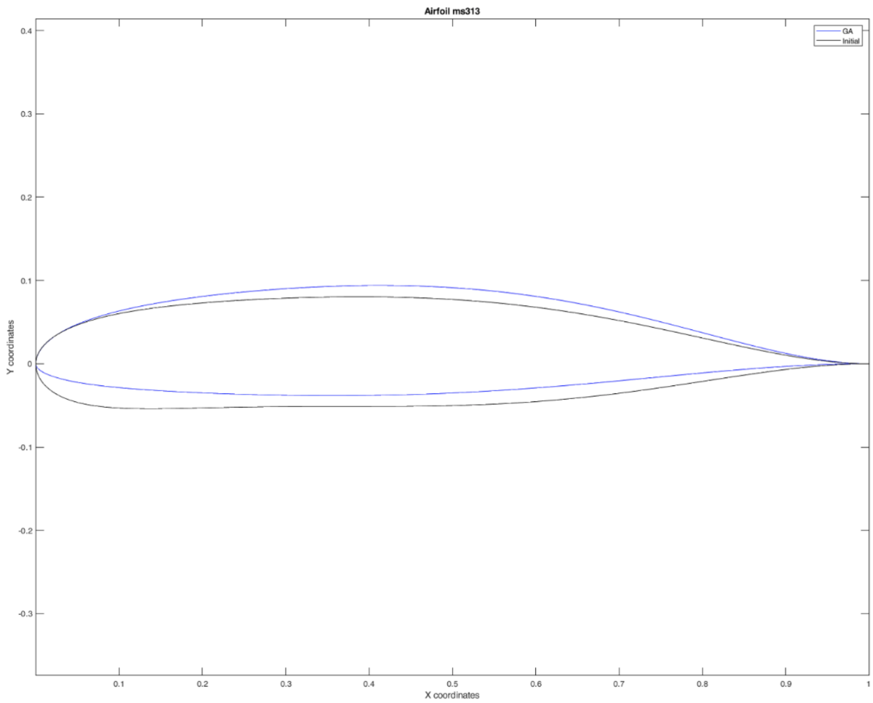

Fig. 3. Optimized shape of the aerodynamic profile NACA MS (1)-0313

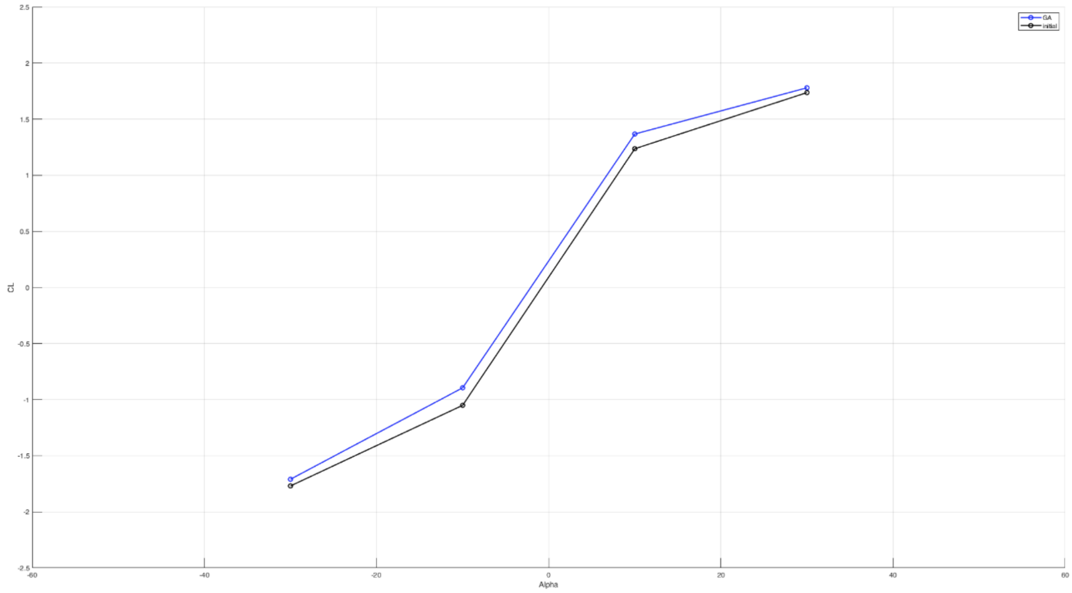

Fig. 4. C_L *(α)*

2. Conclusion

The study of the aerodynamic characteristics and more specifically the lift coefficient of the NACA MS (1)-0313 airfoil using PARSEC parameterization and genetic algorithm optimization show the significant increase in the lift coefficient. These algorithms show good potential for improving the airfoil characteristics of aircraft that can be operated at subsonic flight speeds. The study highlights the value of incorporating modern methods, and optimization marks a breakthrough in the design of modern aircraft.

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ОПТИМИЗИИРАНЕ НА АЕРОДИНАМИЧЕН ПРОФИЛ ЗА МАЛЪК САМОЛЕТ ЧРЕЗ ИЗПОЛЗВАНЕ НА ГЕНЕТИЧЕН АЛГОРИТЪМ

Георги Йорданов Гвоздейков
Висше военновъздушно училище, факултет „Авиационен“,
g.gvozdeykov@gmail.com

Абстракт: Оптимизацията на аеродинамичните профили, оказва все по-важна роля в авиационната индустрия. При оптимизацията на аеродинамичната форма, проектирането и задаването на параметрите е ключовата техника, защото чрез нея се определя пространството на проектиране. Подходящ метод е съчетаването на параметризация и генетични алгоритми.

Quantum simulation and Computational fluid dynamics

Yoto Georgiev Georgiev

"UniPOS", Pleven, Bulgaria, y_g_g@abv.bg

Abstract: The article presents progress in last years of computational fluid dynamics and the new possibility of using quantum computers. Technical progress in recent years has led to first demonstration of quantum computers. Remaining challenges and future research directions are summarized. Validation and verification of scientific computer simulation are discussed as important aspect of scientific researches.

Keywords: *quantum computing, scientific research, computational fluid dynamics*

1. Introduction

Recent years there is an overwhelming interest in quantum technologies. One of it, is quantum computing. One of the central challenges here is decoherence. Engineering researches can be divided into two main groups - empirical (experimental) and theoretical. Scientific computer simulations can be grouped into two: advancement of scientific knowledge and advancement of technical knowledge. As it was written times ago by theoretical computer scientist Donald E. Knuth in A = B "*Science is what we understand well enough to explain to a computer*"[1]. Term quantum supremacy was first used by John Preskill in 2012 [2]. Quantum computing is new paradigm of computing manipulating information in the form of quantum bits called qubits. It is new way to study fluid dynamics with great potential of a huge impact. Achieving quantum advantage in computational fluid dynamics simulations can lead to improvements in industries and applications such as automotive, aerospace and power engineering by providing more accurate simulations than ever before. Using quantum computers can make fluid mechanical simulations become more realistic especially in flows with very high Reynolds number, which is a very active area of research. Quantum computer will have effect on science comparable with inventions of microscopes, telescopes and thermometers. Quantum computing together with artificial intelligence will make revolution in next decade in computational fluid dynamics. At the time of writing the article most powerful quantum computer is IBM *Condo*r with 1121 superconducting qubits.

2. Scientific computer simulation

Simulation of physical systems has at least more than 2000 years history, starting with the Antikythera mechanism, the oldest known to science example of an analogue computer, from the second century BC. In science over the last six decades we have been in a process of transformation changing language of Mathematics with language of computations. Methods for computer modeling of various processes are considered with the very appearance of electronic computing machines and have a big history and numerous developments. The development of computer modeling of various complex dynamic systems since the middle of the twentieth century has been very rapid and has been accompanied by an increase in the capabilities of computing technology. Modeling of complex physical processes is one of the promising directions in computer informatics, in which there is scope for further development and research activity in the coming decades. The advantages of simulation modeling over experiments are relatively low cost, high speed, completeness of information and the possibility of mathematical modeling of real conditions. Low cost is the biggest advantage of computer simulations over field experiments, which require the use of expensive stands, consumables and complex measuring equipment. This advantage increases significantly as the scale of the experiment increases. The revolution in computing solved the problems of computational difficulty to achieve the desired accuracy and speed. With the current technological base of computer technology, a large number of options can be calculated in a short time. If these studies were done experimentally, they would take a lot of time and money.

The computer study gives detailed information about the entire course of the processes. Unlike a natural experiment, in mathematical modeling the variables are known at every moment of the process and at every point in the model. In experimental research, it is not possible to measure all variables in the entire study area. Some of the quantities are measured at given points, after which the whole field is reconstructed. The recording sensors themselves have certain measurement accuracy (uncertainty of the results) and also introduce disturbances into the data. To some extent, it can be said that computer modeling makes it possible to model processes that are closer to the real conditions than the experiment. In this way, very high temperatures and pressures can be modeled. In experimental studies it would be very difficult and even impossible to reach such conditions.

Computer modeling plays a very important role in training as well as flight simulators and not only.

The six steps of a scientific computer simulation are conceptual modeling, mathematical modeling, discretization and algorithm selection, computer programming, numerical solution and finally solution representation calculating the quantities of interest from the numerical results.

In the computer programming phase the discretized equations are coded into a computer program. *Fortran* "mother tongue of scientific computing", released in 1957, is considered as the main programming languages for scientific computing, due to its ability to handle large-scale numerical computations and its optimization for high-performance computing architectures. That is the reason why *Fortran* is used for benchmarking the world's fastest supercomputers. *C++* is a general-purpose language that is increasingly used in scientific simulations but it is not as efficient as Fortran in terms of performance and speed. On 14 February 2012 new computer language *Julia* was released. *Julia* was designed for high-performance scientific computing [3]. The main goal of computer language *Julia* is to fulfill the *Fortran* dream – automatic translation of formulas into efficient executable code. Choosing computer language is important as for programming phase but also for numerical solution phase.

Quantum computing requires development of domain-specific programming languages and compilation techniques totally different from conventional computer languages. Some of the quantum computer languages are *QMASM*, *cQASM*, *Q#, Scaffold, Qiskit, Cirq* and *Quipper*.

3. Verification and validation in scientific computing

Regarding computer simulation, it must be demonstrated that the models and numerical methods used will provide a sufficiently accurate solution for the results obtained to be trusted. General truth is that „*all scientific computer simulations are wrong, but some are useful*" [4].

There are three types of errors concerning scientific computer simulation – computational errors also called round-off errors [5, 6], nodalization (spatial) errors [5, 7] and time discretization errors. The machine epsilon is defined as the smallest positive number which, when added to one, yields a result other than one (it gives the difference between 1.0 and the next-nearest number representable as a machine-precision number) [6]. This value characterizes computer arithmetic and is used to study the effects of the rounding error – it measures the limitations of exact arithmetic using computers. Machine epsilon varies from machine to machine: higher precision computers will have a smaller epsilon. The correctness of the results depends on the machine epsilon value.

Verification and validation are the main means of assessing accuracy and reliability in computing simulations [8]. Validation is the comparison between experimental data and calculated results. Verification is check that the translation of mathematical formulas into computer software was made without errors. Issues with validation are that it is difficult to determine the thresholds of acceptability when measured and calculated data are compared. Issues with verification are that it is difficult to detect errors in thousands computer programming lines of code. Verification and validation are still open problems in scientific computer simulations, although they have been at the center of the attention of scientists for several years. Proposed solution in that direction is to introduce a new element in the process – consistency. Uncertainty analysis is very important to assure accuracy of simulation. Currently uncertainty estimations are based on macroscale approaches, where some error sources at the microscale are not considered.

4. Fluid dynamics

The beginning of fluid dynamics research can be traced back to Archimedes with his treatise „On Floating Bodies“ ca. 250 BCE. The bases of fluid dynamics are three types of conservation laws: conservation of mass, conservation of linear momentum and conservation of energy. They are expressed using the Reynolds transport theorem.

In recent years computational fluid dynamics have received considerable attention in the scientific community. A new branch of fluid mechanics called Non-Ideal Compressible Fluid Dynamics was developed, studying the dynamic behavior of fluids not obeying ideal-gas thermodynamics. The growing interest in numerical methods applied to science and engineering fields, and in particular to fluid dynamics problems, is related to the increase power of the computers in last years. Currently there are several technics for simulation of fluid dynamics all based on space discretization. In method of control volumes or finite volume method spatial discretization is performed on the basis of a finite-volume approach. The mass and energy equations are solved within control volumes/ finite volumes and the momentum equations are solved over flow paths or junctions connecting the centers of the control volumes. Finite-volume approach uses 6-equation system – 3 for liquid phase and 3 for gas phase. Additional mass conservation equations can be included for the description of transport of additional components dissolved within the fluids. Given system can be simulated by connecting basic fluid dynamic control volumes elements. It is excellent general purpose tool. Main advantage is that it is fast compare to other methods. Computer codes Ansys CFX and Ansys Fluent are one of the famous commercial computational fluid dynamics software based on a finite volume method approach. Other widely used codes based on finite volume method are RELAP5, French CATHARE, Russian Dinamika and German code ATHLET developed by research center in Garching.

The finite element method is used mainly for structural analysis of solids but is also applicable to fluid dynamics. Compare to finite volume method it is more accurate but with higher computational cost.

Forty years ago, the lattice Boltzmann method has been developed. The main idea is the shift from the continuum model to the discrete model. The lattice Boltzmann method is a novel numerical tool for multi-phase flows simulation that is based on streaming and collision processes of probability density functions on a lattice. Instead of directly solving the Navier–Stokes equations, this method solves the Boltzmann equation by a discretization procedure and using an approximation for the collision operator [9]. It is alternative to computational fluid dynamics Navier–Stokes based techniques. Since the pioneering work of Shan and Chen [10] in 1993, Lattice Boltzmann method has become a predictive mathematical model and numerical tool for the hydrodynamic regime of non-ideal fluids. After that a lot of non-ideal fluid dynamics models have been developed and used for a wide variety of applications in science and engineering. Important advantage is possibility for multiphysics simulations with that method. Comparison between lattice Boltzmann and finite-volume Navier–Stokes methods made by scientist in Nuclear research center in Saclay, France can be found in [11]. A hybrid numerical method coupling the lattice Boltzmann method and finite-volume Navier-Stokes method is proposed for aerodynamic simulations [12].

Direct numerical simulation is the most accurate and detailed approach for simulating turbulent flows. However the computational cost of direct numerical simulation is very high. For that reason at the moment there is no commercial application for that method.

Applying artificial intelligence has been a long-lasting goal of engineers and scientists. In last decade deep reinforcement learning has been used in a wide range of physics and engineering fields and particularly in fluid dynamics [13, 14].

5. Quantum computing – a new paradigm for computational fluid dynamics

The purpose of this section is to provide overview of how quantum computing can solved problems in fluid dynamics. The theoretical concept of quantum computer was proposed by iconic Richard Feynman more than 40 years ago [15]. In 2023 paper for quantum engine was publish in *Nature* paving way for totally new type of machines [16]. Quantum computers are machines based on quantum physics which deals with nature at the quantum level. Quantum computer manipulate information in the form of quantum bits using appropriate quantum algorithms. Quantum bits are objects that hold information describing given quantum physical systems being manipulated to perform a computational task. These quantum bits represent the state of given quantum physical system governed by laws of quantum physics. Mathematically it is determine by the wavefunction Greek letter-Ψ, which encodes the state of a quantum object in the form of probability amplitudes. The wavefunction is a function of the degrees of freedom for observed quantum object. Quantum computing has the potential to reach the higher levels of accuracy with a much faster speedup. Those accuracy and speed are done in a completely different way than classical computers. Several different approaches have been proposed for building a quantum computer and scientists and engineers are exploring multiple technologies for quantum computing hardware: superconducting quantum computing, trapped ion quantum computer and photonic quantum computer [17]. A quantum processor with “X” qubits can theoretically perform 2^X calculations simultaneously as each additional qubit doubles processing power of the machine. Quantum supremacy was declared by Google in October 23 2019 with programmable superconducting 53 qubits quantum processor called *Sycamore*, corresponding to a computational space of dimension 2^{53} (about 10^{16}), beyond the reach of the fastest classical supercomputers existing today [18]. According authors of the publication *Sycamore* can perform a series of operations in 200 seconds which on most powerful supercomputers would take approximately 10,000 years to complete [18]. In 2020 Chinese scientist using photonic quantum computer *Jiuzhang* reached quantum supremacy claiming that their quantum computer solves tasks in 200 seconds for which a classical supercomputer would require 2.5 billion years of computation [19]. One of most important application of quantum computers will probably be the simulation of physical systems [20].

To solve problems by quantum computer are needed two things: quantum computers (hardware) and quantum programs (software). Quantum programming is process of converting given algorithms in set of instructions understandable by quantum computer. It is connection between high-level mathematical algorithm expressions and low-level physical implementations. Different quantum programing languages are being developed by different research institutes and companies: QCL, Q#, Qiskit, Cirq, Quipper, PyQuil and Scaffold [21]. Quantum algorithms consist of variety of classical and quantum variables and routines which are to be defined using different coding techniques.

A promising alternative to traditional computational fluid dynamics approaches is quantum computing. Capable of processing large amount of data faster quantum computers can perform advanced simulation in fluid dynamics. Nowadays the simulation of fluid dynamics are made by classical computers based on the classical computing theory and the von Neumann architecture. However, with Moore’s law getting closer and closer to the physical limit as further shrinking the size below 1 nm will impose severe challenges, the importance of quantum computing has become increasingly prominent.

The discovery that quantum computers are gaining computational power at a doubly exponential rate is called "Neven's law". Scientist Hartmut Neven proposed in 2018 a law that the power of a quantum computer is expected to grow by the powers of powers of 2 compared to normal computers.

Using quantum computers for fluid dynamics can be done with lattice Boltzmann methods or one can use quantum based mathematical tools such as ordinary differential equation solvers for integrating and solving classical governing equations such as the Navier–Stokes equations. It has to be made translation from classical dynamics into the quantum language.

The lattice Boltzmann method is well suited for implementation on quantum computers. The primary reason is that the dynamical variables in both systems are based on some form of probability. The time evolution of the probabilities in the lattice Boltzmann method can be applied to the discrete quantum system used in quantum computing so that the simulation process can be performed entirely on quantum computer.

In continuum simulations governing differential equations are solved by quantum mechanics. Several of quantum algorithms for solving differential equations can be found in [21, 22, 23, 24]. One of the recent work on that topic is presented in [25] for study of the Navier-Stokes channel flow. In summer of 2023 was developed new quantum algorithms to compute the solution of nonlinear ordinary differential equations [26]. It is based on Koopman-von Neumann method. Interesting approach is proposed in [27] a hybrid quantum-classical algorithm called Variational Quantum Linear Solver for solving linear systems on current technology quantum computers.

With new technology raises the problem with validation and verification of the models and the calculated results. The issue with validation and verifications of the results is even more complex compared to classical simulations of fluid dynamics. Using quantum computers raises the question of how one can check whether quantum computers are producing correct results [28, 29]. It is a significant challenge on the road to scalable quantum computing technology. Application of quantum computing will only be realized if a level of precision can be reached. The main obstacle is that the nature of the computational task is such that it cannot be reproduced classically, and therefore traditional means of verifying a calculation is not possible. Several protocols for verification of the results are presented in [28, 29]. In classical computational fluid dynamics results from different models can be compared and validate each other as for example shown in [30, 31], which is not the case with quantum computation. Decoherence is the main problem at the moment with quantum computers and the reason still not having working quantum computer. Errors in quantum computation are due to decoherence and other quantum noise. Today quantum computers have error rates around 1 in 1000 compared with classical computers with error rates around 1 in 1 billion billion. Further progress is needed in error correction technology to reach at least an error rate of about one in a million. Many algorithms have been proposed [32, 33], but none solved the problem.

4. Conclusion

The ideas for quantum computing of fluid dynamics have been addressed in this article. Quantum computers will be applied to various fields of science and technology. Unfortunately, quantum computing is still at stage of research and development. It has to solve existing challenges before it becomes widely adopted. Quantum computing together with artificial intelligence will make revolution in next decade in computational fluid dynamics. The lattice Boltzmann method probably has biggest potential for performing multiphysics simulations on quantum computers, including fluid dynamics. Simulation of aircraft features Reynolds number about 108, supposing 1024 floating point operations per simulation, while it can be simulated by 80 qubits quantum computer [34]. On 04 December 2023 in scientific journal Nature is presented first-ever 1000-qubit quantum processor Condor designed by IBM with 1121 superconducting qubits [35]. To put it into perspective a quantum computer with 1121 qubits can process 21121 calculations simultaneously.

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Квантови симулации и Изчислителна динамика на флиудите

Йото Георгиев Георгиев

“УниПОС”, Плевен, България, y_g_g@abv.bg

Резюме: В статията е представен прогреса през последните години в областта на изчислителната динамика на флуидите, както и новите възможности, които предоставят квантовите компютри. Техническия прогрес в последните години доведе до първите демострации на квантови компютри. Обобщени са предизвикателства и бъдещите насоки на изследване. Валидирането и верифицирането на научните компютърни симулации са разгледани като важен аспект на научните изследвания.

MILITARY SPACE ASSETS

Asen Angelov Marinov
Bulgarian Air Force Academy, Faculty of Aviation, asen_aerodynamics@abv.bg

Abstract: Space assets allow the armed forces to gather information about adversaries, monitor activities in remote or restricted areas, and maintain operational superiority in asymmetric warfare scenarios.
Keywords*: space assets, armed forces, war.*

1. Introduction

Military satellites use different orbits based on their mission requirements. These include geostationary orbit for communications satellites, low-Earth orbit for reconnaissance and surveillance satellites, polar orbit for imaging and mapping satellites, and highly elliptical orbit for early warning and communication satellites.

Armed forces use space-based assets to gather intelligence in critical areas, using their capabilities to monitor activities, collect data, and gather intelligence without direct physical presence. Satellites equipped with advanced sensors and imaging systems allow the armed forces to monitor critical areas from space, providing valuable information for intelligence analysis and decision making [1].

The satellites, equipped with advanced sensors and imaging systems, allow the armed forces to monitor compliance, detect potential violations and gather evidence of arms control agreements and treaties. It ensures the resilience of its space-based assets against cyber-attacks through measures such as robust cyber security protocols, encryption of communication channels, continuous monitoring for intrusions or anomalies, penetration testing and regular software and hardware updates. They also create redundant systems and backup capabilities to mitigate the impact of cyber attacks. Space-based assets are used for border surveillance and security by monitoring border areas, detecting unauthorized crossings, tracking border activities, identifying smuggling or illegal activities, and providing intelligence for border patrol and security operations. Space-based assets improve the armed forces' situational awareness and border surveillance capabilities [2].

Military space assets provide critical communications capabilities on the battlefield by offering secure, resilient and global communications links. They enable seamless communication between military units, commanders and staffs, facilitating command and control functions, coordination and the dissemination of orders and information on the battlefield. They also play a vital role in national missile defense by providing early warning of missile launches, tracking missile trajectories, collecting data on missile defense systems, and facilitating command and control functions. They contribute to the detection, tracking and interception of ballistic missiles to protect national territories and assets.

The Armed Forces ensure the secure transmission of data from space assets through encryption algorithms, secure protocols and anti-jamming technologies. They establish secure ground stations, implement authentication and access control mechanisms, and regularly update security measures to protect data integrity and privacy during transmission. They also support aerial reconnaissance by providing high-resolution imagery, surveillance data and intelligence support to operations. They enable the collection of information on the positions of opposing forces, terrain features and potential threats, increasing the effectiveness of aerial reconnaissance missions [3].

2. Armed forces and satellites

The project has been implemented by means of SciLab, [1]. Both Celestlab, [2] and CelestlabX toolboxes are required in advance. An official permission to use the toolboxes is given by CeCILL free software license agreement, [3].

Military space assets are of great importance to strategic deterrence as they provide global surveillance, intelligence gathering, command and control and early warning capabilities. They enhance the military's ability to deter potential adversaries, monitor their activities, and respond effectively to threats around the world. They also support humanitarian and disaster response operations by providing real-time situational awareness, mapping and imagery data, communications links and coordination capabilities. They support damage assessment, search and rescue operations, delivery of aid and supplies, and coordination among response forces to facilitate effective disaster response.

The military protects its satellites from space-based electronic attacks through measures such as shielding satellites against electromagnetic interference, using advanced anti-jamming techniques, and developing countermeasures against directed-energy weapons or powerful microwave attacks. They also monitor and analyze space-based electronic signals to detect any intrusion attempts or attacks, provide intelligence support to ground forces by offering real-time situational awareness, surveillance data and target information. They assist ground forces in mission planning, target identification, threat detection, and improved overall understanding of the battlefield situation.

The military protects its satellites from the effects of space weather by designing satellites to withstand and mitigate the effects of solar flares, geomagnetic storms, and other space weather phenomena. Shielding, redundancy, and fault-tolerant systems are implemented to ensure operational continuity and minimize satellites' vulnerability to space weather-related disturbances. Ensure the survivability of their space-based assets during conflicts through a combination of measures, including dispersed satellite constellations, anti-jamming capabilities, rapid response capabilities, redundancy of systems and ground infrastructure, and the ability to restore or replace damaged or destroyed satellites. Counterspace capabilities are also being developed to deter or counter potential attacks against space assets [4].

Military space assets are used to gather electronic intelligence by intercepting, collecting and analyzing enemy electronic signals and emissions from space. They provide valuable intelligence on enemy communications, radar systems, electronic warfare capabilities, contributing to situational understanding and intelligence analysis. They also play a critical role in providing geospatial intelligence support by capturing high-resolution imagery, monitoring terrain or infrastructure changes, performing mapping and geospatial analysis, and providing accurate geolocation data [4].

Since the earth rotates to the east, it follows that each successive orbit will pass further and further west. At the same time, the orbital plane is stationary in inertial space and the satellite remains in the same orbit.

Since the Earth rotates at a constant rate of about 15° per hour, making 360° in 24 hours or 0.25° per minute, this can be used to determine the period. From where the nodal displacement (ΔN) to the west for each subsequent orbit can be calculated. The west nodal displacement during one orbit is the difference between 360° and ΔN.

Since the orbital displacement of the Earth's track ΔN depends on the speed of rotation of the Earth multiplied by the period of the orbit, it follows that the orbital displacement can also be used to determine the orbital period. If the orbital period is three hours, it follows that the Earth will rotate approximately 45° during one orbit, so the nodal displacement will be 315° (360° – 45°) (Fig. 2.1).

The period within 24 hours can be determined by the following formula [5]:

$$T\,[h] = \frac{360^o - \Delta N}{\frac{15^o}{h}}. \quad (2.1)$$

When the period is known, the semimajor axis of the orbit can be determined:

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}, \quad (2.2)$$

where: μ-gravitational parameter, for Earth - $3.986 \times 10^5\ km^3/s^2$.

The larger the semi-major axis, the smaller ΔN will be, therefore the projection of the orbit on the Earth's surface will appear more contracted, and in a geosynchronous orbit ΔN is 0°. Since the orbit is geosynchronous, it follows that the period of the satellite coincides with the rotation period of the Earth. Therefore, the projection of the orbit will appear as if the satellite is going back and forming a trajectory resembling the figure 2.1.

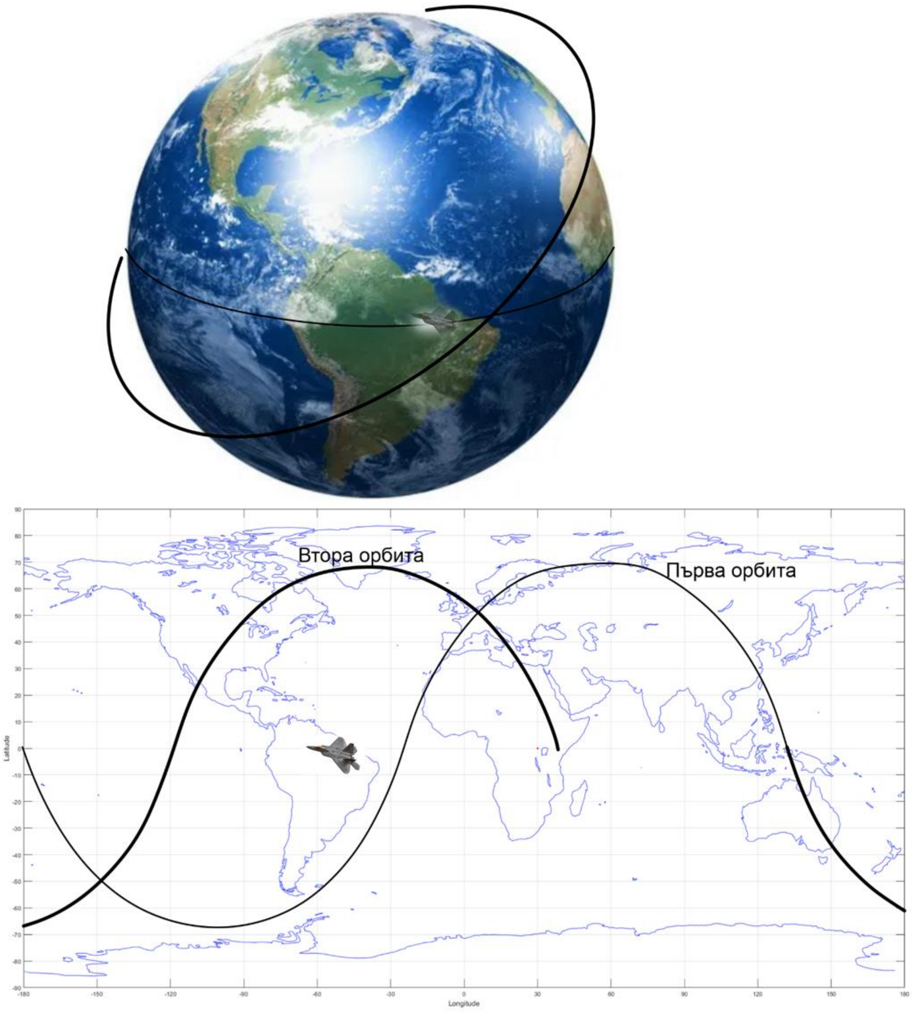


Fig. 2.1. Orbit trajectory

When the orbit has an inclination angle of 0°, the projection will be a point on the equator.

The eccentricity and location of the perigee also have a great influence on the projection of the orbit on the earth's surface. When the orbit has zero eccentricity, i.e. circular, its terrestrial trajectory is symmetrical (Fig. 2.2). When elliptical, it will differ above and below the equator.

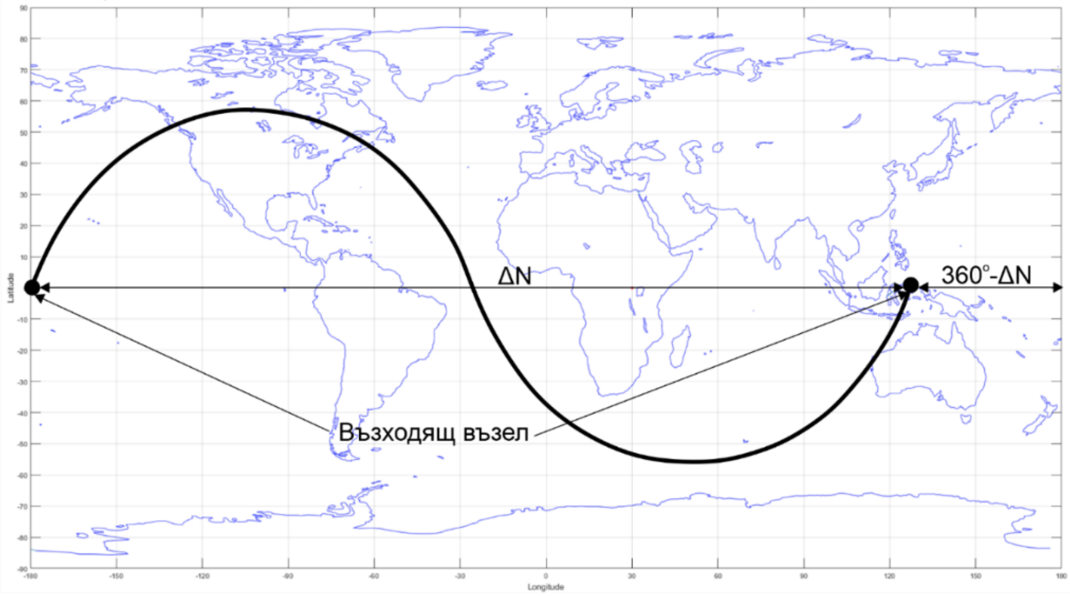


Fig. 2.2. Displacement of the ground track

In Figure 2.3, orbit A has perigee in the Northern Hemisphere because the trajectory is more extended and the satellite is moving at a higher speed, i.e. travels a greater distance, while orbit B has perigee in the southern hemisphere, for the same reason.

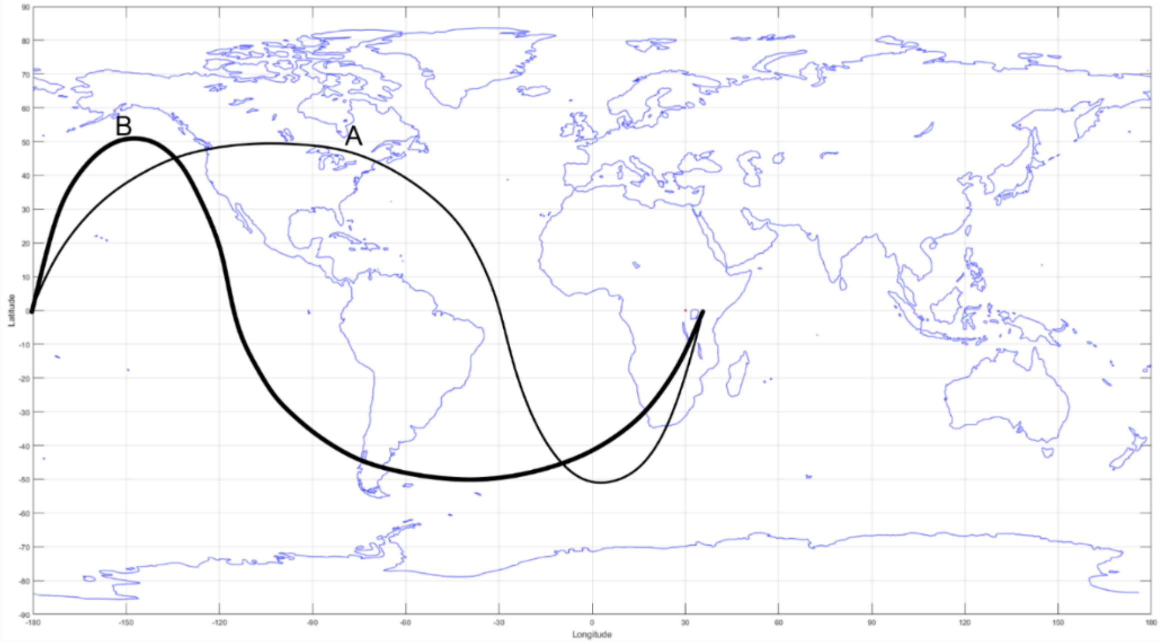


Fig. 2.3. Influence of perigee location on the projection of the orbit onto the Earth's surface

The projection of the satellite on the Earth's surface is a set of points over which the satellite passes, depends on the orbital elements of the satellite's orbit, and is very important for delivering the necessary information to the troops. This requires that the trajectory of each satellite can be designed in a way that ensures the effective conduct of military operations.

3. Numerical Solution

1.1. USA 327 [6]

North American Aerospace Defense NORAD ID: 52259
Int'l Code: 2022-040A
Perigee: 1,046.5 km
Apogee: 1,179.6 km
Inclination: 63.4 °
Period: 107.4 minutes
Semi major axis: 7484 km
RCS: Unknown
Launch date: April 17, 2022
Country: USA
Launch site: Air Force Western Test Range.
In orbit – 12 April 2024 .
Coordinated Universal Time (UTC) – 19:34:00 h.
Eccentricity - 0.00889223.
$e = 0.00889223$.
Perigee argument - 0º
Right ascension of the ascending node - 0º
True anomaly 0º

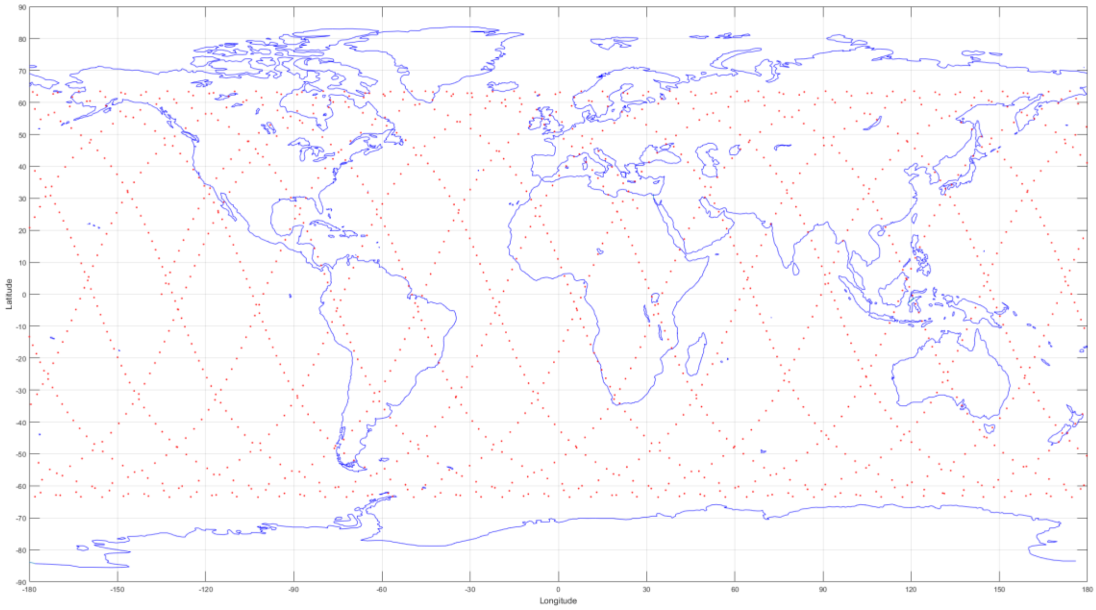
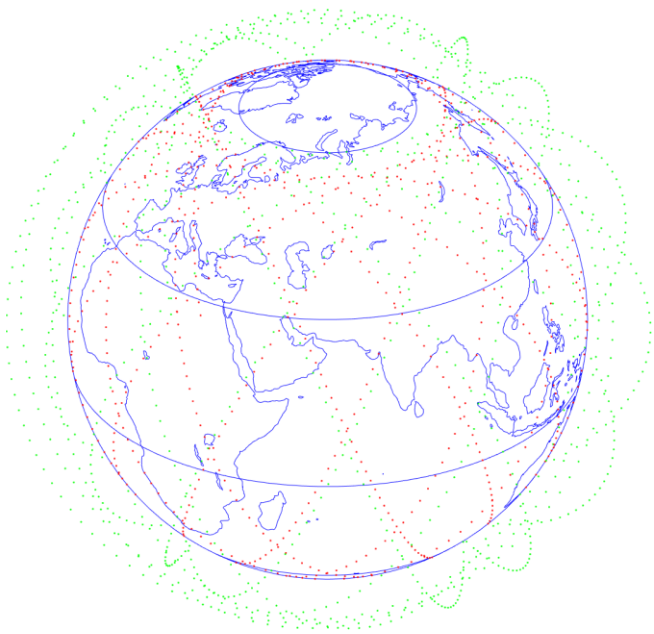


Fig. 3.1. Track satellite - USA 327

3D view:
Latitude – 30º;
Longitude – 60º.



Фиг. 3.2. 3D - USA 327

4.1. YAOGAN-34-02 [6]

North American Aerospace Defense NORAD ID : 52084.

Int'l Code: 2022-027A.

Perigee: 1059.2 km.

Apogee: 1134.5 km.

Inclination: 63.4°.

Period: 107 min.

Semi major axis: 7467 km.

RCS: Unknown.

In orbit: 17 март, 2022.

Country: People's Republic of China.

Launch site: Xichang Satellite Launch Center.

Date – April 12, 2024 г.

Coordinated Universal Time (UTC) – 19:34:00 h.

Eccentricity - 0.00504160.

$e = 0.00504160.$

Perigee argument - 0º.

Right ascension of the ascending node - 0º.

True anomaly - 0º.

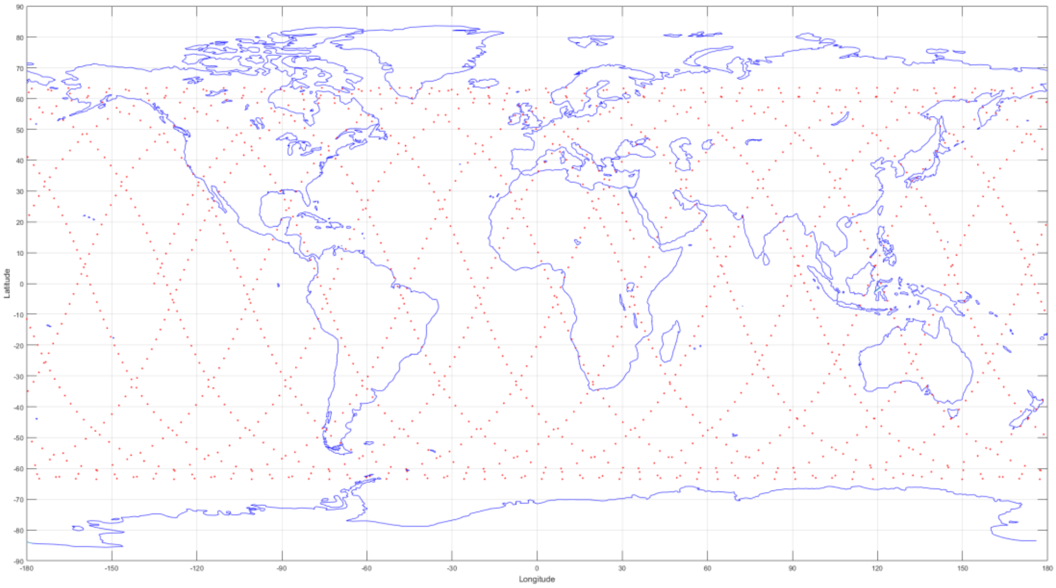


Fig. 3.3. Track satellite - YAOGAN-31 B

Fig. 3.4. 3D - YAOGAN-34-02

3D view:
Latitude – 30°;
Longitude – 60°.

4.2. TURKSAT 5B [6]

NORAD ID (North American Aerospace Defense) : 50212.

Int'l Code: 2021-126A.

Perigee: 35778 km.

Apogee: 35809.3 km.

Inclination: 0.1°.

Period: 1436.1 min.

Semi major axis: 42164 km.

RCS: Unknown.

Launch date: December 17, 2021.

Country: Turkey.

Launch site: Eastern air force range.

Date – April, 2024

Coordinated Universal Time (UTC) – 19:34:00 h.

Eccentricity - 0.000437228.

$e = 0.000437228.$

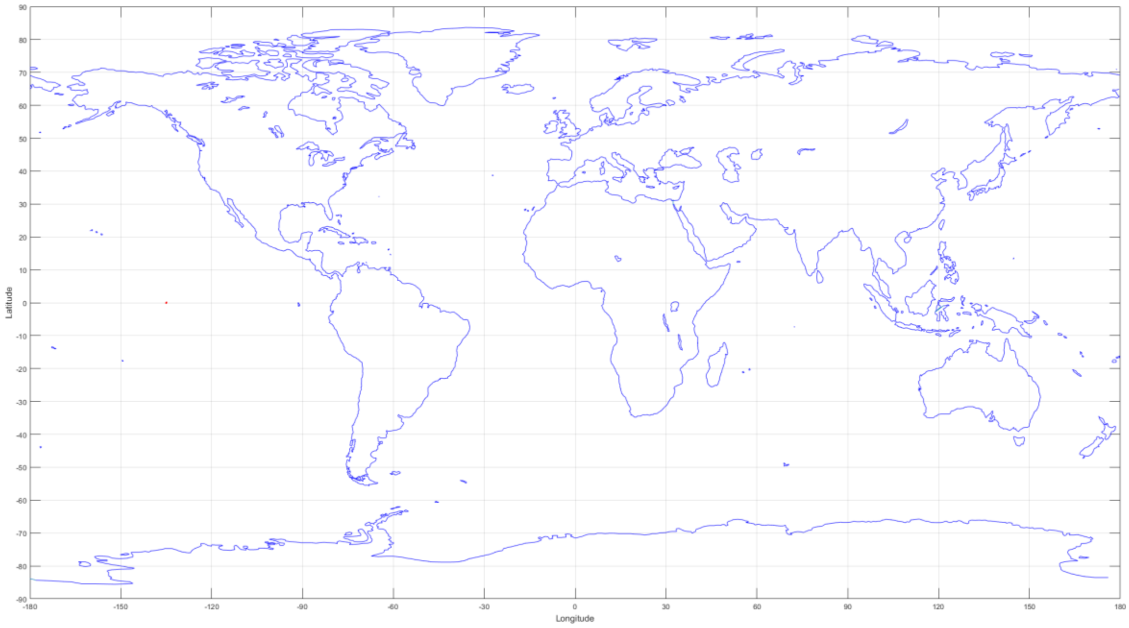


Fig. 3.5. Track satellite - TURKSAT 5B, Perigee argument -0°, Right ascension of the ascending node - 0°, True anomaly - 0°

Perigee argument - 0°/120°.

Right ascension of the ascending node - 0º/45º.

True anomaly - 0º.

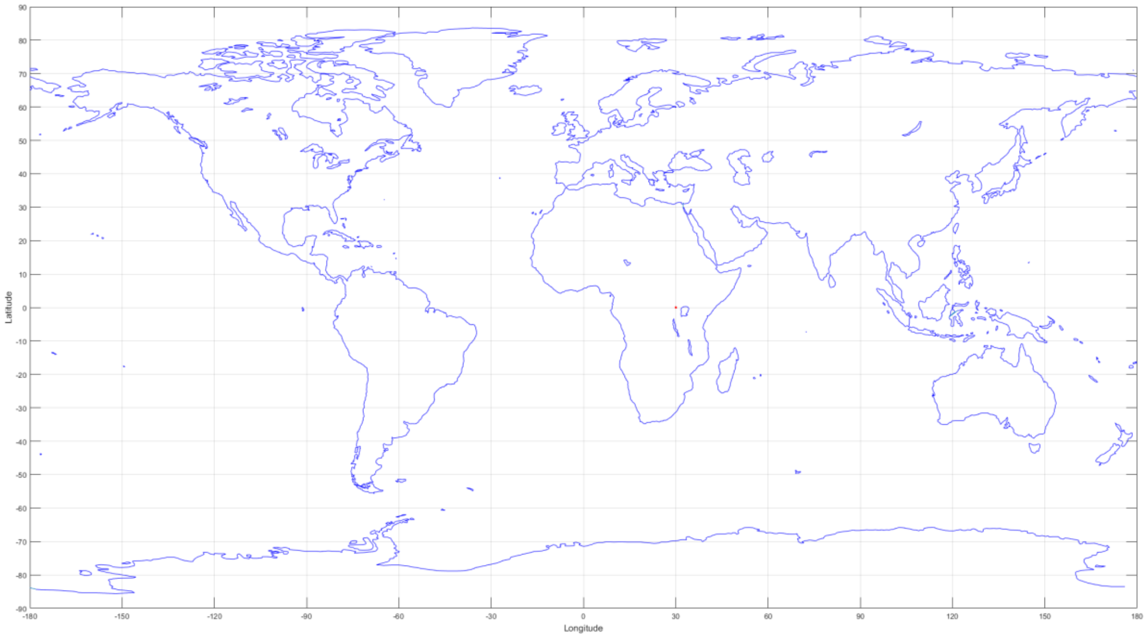


Fig. 3.6. Track satellite - TURKSAT 5B, Perigee argument -120º, Right ascension of the ascending node - 45º, True anomaly - 0º

3D view:
Latitude – 30º;
Longitude – 60º.

Фиг. 3.7. 3D - TURKSAT 5B, Perigee argument -120º, Right ascension of the ascending node - 45º, True anomaly - 0º

2. **Conclusion**

Military space assets support air defense operations by providing early warning of enemy air threats, tracking aircraft movements, relaying information to ground-based air defense systems, and supporting air defense command and control functions. They enhance the military's ability to detect and respond to air threats promptly and effectively, and in asymmetric warfare, provide advantages such as real-time situational awareness, intelligence gathering, surveillance capabilities, and secure communications channels. They enable the armed forces to gather information about adversaries, monitor activities in remote or restricted areas, and maintain operational superiority in asymmetric warfare scenarios.

To visualize orbits in outer space, the six classical orbital elements are used. In order to reliably rely on the data received from space, especially when preparing and conducting military operations, it is necessary to know the time in which the respective satellite passes over the area of interest in order to achieve the necessary coverage, bearing in mind that the satellite orbits tens of miles kilometers.

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ВОЕННИ КОСМИЧЕСКИ АКТИВИ

Асен Ангелов Маринов
Висше военновъздушно училище „Георги Бенковски“,
asen_aerodynamics@abv.bg

Резюме: Космическите активи позволяват на въоръжените сили да събират информация за противниците, да наблюдават дейности в отдалечени или забранени райони и да поддържат оперативно превъзходство в сценарии на асиметрична война.

SPACE OPERATIONS IN CLAUSEWITZ FUNCTION AND BI-ELLIPTIC TRANSFER

Asen Angelov Marinov
Bulgarian Air Force Academy, Faculty of Aviation, asen_aerodynamics@abv.bg

Abstract: The vulnerability of military satellites to strikes and jamming may necessitate a substantial change in their orbits, using different transfers. One of the possible transfers is bi-elliptic.

Keywords: *bi-elliptic transfer, satellites, armed forces, war*.

1. Introduction

In 2022, the EU identified space as a strategic area, on the basis of which an EU Space Strategy for Security and Defense was drawn up.

The strategy outlines countermeasures and the main threats in space and their ground infrastructure. The High Representative prepares a classified annual analysis of space threats at the level of the European Union, using the intelligence data of the Member States.

According to the adopted strategy, the space domain includes all elements relevant to the operation of space systems and the provision of space services, including the physical space environment, the various orbits and spacecraft, their ground and launch infrastructure, radio frequency links, user terminals, information, associated with and delivered by these space assets, the associated cyber environment and the core industrial space sector [6].

Threats posed by counterspace capabilities are directed against space systems, their supporting ground infrastructure, and data links between space systems and ground infrastructure.

Space Force countermeasures include direct attack and co-orbital anti-satellite systems, cyber attacks, electronic warfare, and directed energy. They can disturb, damage or destroy with reversible or irreversible effect. Also, the space sector and its supply chains are vulnerable to adversary interference [6].

An EU Outer Space Act is being considered to provide a common framework for security, safety and sustainability in outer space.

Space exercises are envisaged, including with partners, to develop the European Union's response to space threats and to explore solidarity mechanisms.

One of the priorities of the European Union's Space Policy, officially published by the European Council, is to stimulate and facilitate policies in such areas as security and defence, industry and digital technologies [6].

In Chapter VIII ("On War") Clausewitz predicts that "wars in which the whole of the popular forces of both belligerent parties are involved will not be conducted as hitherto, where everything is foreseen and calculated on the principle of regular armies facing against each other, but on completely different principles" [5].

2. Armed forces and satellites

The protection of the national interests of each country, regardless of the alliances in which it is a member, requires the development of capabilities that provide a complex response to military threats on a regional, local and global scale. This includes developing capabilities in peacetime to defend against air-space attacks, deter opposing forces, while at the same time ensuring the implementation of peacekeeping activities both independently and as part of international organizations.

A local war means a war that is fought in a geographically localized space, within a strategic direction (area) by groups of combat units in peacetime and, if necessary, with partial strategic deployment. Strategic goals in local wars are most often of a limited nature, when the complete defeat of the enemy's armed forces, the final undermining of its economic and military potential, the capture and annexation of strategically important areas or the entire territory are not foreseen [1].

The operational deployment of the troops is most often carried out on the eve of the war, and in case of a sudden attack by the enemy - with its beginning. It includes, in addition to the deployment of all forces and means of anti-aircraft and anti-missile defense to reflect an air-space attack of the enemy and the construction of orbital constellations of space systems.

The experience of conducting local wars shows that among the most important characteristics of modern offensive operations (combat operations) is the conduct of aerospace operations, including orbital transfers of artificial satellites for the information superiority of the types of armed forces and in joint ones, in advance in the eve and during the offensive.

This imposes a requirement on communications during armed conflict to overcome the emerging contradiction between the potential capabilities of deployed space communications systems and the incomparably smaller capabilities of tactical communications equipment and providing military intelligence to obtain information from space intelligence systems of interest of the use of precision weapons, [1].

In modern conditions, unmanned air attack vehicles have some significant advantages over both land and sea forces, as well as manned aviation, their role in warfare is constantly increasing, and their results depend directly on the results in the space domain.

When the conflict is maintained externally, information about opposing forces may come from allied nations that are not directly involved in combat or other operations but provide their intelligence capabilities for space and air reconnaissance. The advantage of using one's own forces in war is the priority opportunity to consistently deploy the entire intelligence system in the interest of one's own forces and assets. The implications of recent conflicts show the growing role of all types of intelligence, including space intelligence. Multinational Force Command receives most of its information using a pre-deployed orbital group of satellites that demonstrate reliability and effectiveness of intelligence and are used in real time. There is a need both to increase the share of guided munitions in the total amount of ammunition of multinational forces, which has fallen dramatically compared to the nineties of the twentieth century, when their share was 70-80%, and for a full integration of capabilities and actions of space, air, sea, land and special forces. Not allowing all types of armed forces to be heavily dependent on space communications alone, as they can be neutralized by jamming and kinetic strikes. The technologically leading countries in the world invest serious resources in their space programs related to the acquisition of new knowledge for all the objects listed above. This leads to competition in the field of science, which is needed, since the Cosmos at this stage is much more unknown than known to science. This competition, however, also formed a race in space science for military purposes, [1].

This line is described in Chapter I point 28 by Clausewitz in his iconic work "On War" - "war is like a chameleon, because it changes its color not only somewhat in each particular case, but also in general - in relation to the prevailing tendencies inherent in for her", [5].

The vulnerability of military satellites to strikes and jamming may necessitate a substantial change in their orbits, using different transfers. One of the possible transfers is bi-elliptic.

3. Numerical Solution

Clausewitz, On War, Book II, Chapter V, Critique “Knowledge of antecedent and contemporaneous events is based not only on certain information, but also on a number of assumptions and preconceptions; of course, there is scarcely any information about things that are not entirely accidental, that are not preceded by assumptions and expectations designed to take the place of information in case it should never be secured' [5].

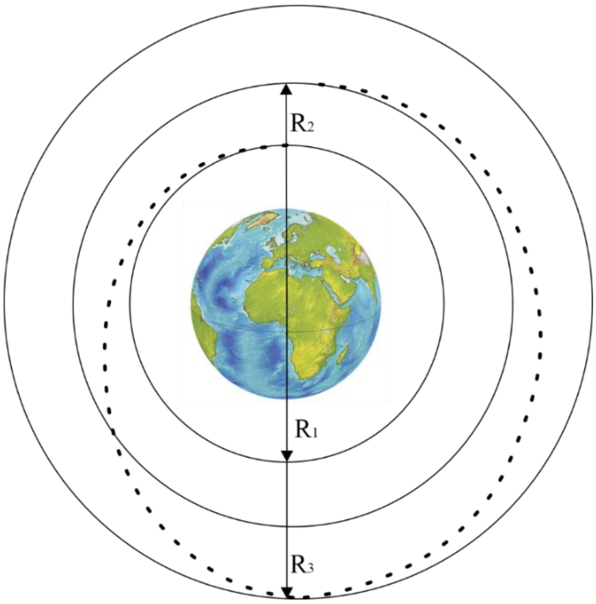

Fig. 1. Scheme of bi-elliptic transfer

To calculate the necessary velocities for bi-elliptic transfer, the mathematical apparatus described below can be used.

$$V_{p\,f.t.e.} = \sqrt{\frac{2\mu}{R_1} - \frac{2\mu}{R_1 + R_3}}. (1)$$

$$V_{01} = \sqrt{\frac{\mu}{R_1}}.$$

$$\Delta V_1 = V_{p\,f.t.e.} - V_{01} = \sqrt{\frac{2\mu}{R_1} - \frac{2\mu}{R_1 + R_3}} - \sqrt{\frac{\mu}{R_1}}, (2)$$

$$V_{a\,f.t.e.} = \sqrt{\frac{2\mu}{R_3} - \frac{2\mu}{R_1 + R_3}}. (3)$$

$$V_{a\,s.t.e.} = \sqrt{\frac{2\mu}{R_3} - \frac{2\mu}{R_2 + R_3}}. \quad (4)$$

$$\Delta V_2 = V_{a\,s.t.e.} - V_{a\,f.t.e.} = \sqrt{\frac{2\mu}{R_3} - \frac{2\mu}{R_2 + R_3}} - \sqrt{\frac{2\mu}{R_3} - \frac{2\mu}{R_1 + R_3}}. \quad (5)$$

$$V_{p\,s.t.e.} = \sqrt{\frac{2\mu}{R_2} - \frac{2\mu}{R_2 + R_3}}. \quad (6)$$

$$V_{02} = \sqrt{\frac{\mu}{R_2}}. \quad (7)$$

$$\Delta V_3 = V_{p\,f.t.e.} - V_{01} = \sqrt{\frac{2\mu}{R_2} - \frac{2\mu}{R_2 + R_3}} - \sqrt{\frac{\mu}{R_2}}. \quad (8)$$

$$\Delta \boldsymbol{V} = \Delta V_1 + \Delta V_2 + \Delta V_3 = \left(\sqrt{\frac{2\mu}{R_1} - \frac{2\mu}{R_1 + R_3}} - \sqrt{\frac{\mu}{R_1}}\right) + \left(\sqrt{\frac{2\mu}{R_3} - \frac{2\mu}{R_2 + R_3}} - \sqrt{\frac{2\mu}{R_3} - \frac{2\mu}{R_1 + R_3}}\right) + \left(\sqrt{\frac{2\mu}{R_2} - \frac{2\mu}{R_2 + R_3}} - \sqrt{\frac{\mu}{R_2}}\right). \quad (9)$$

Output quantities:

1) output height - 300 km;
2) target orbit - 35786 km;

Results

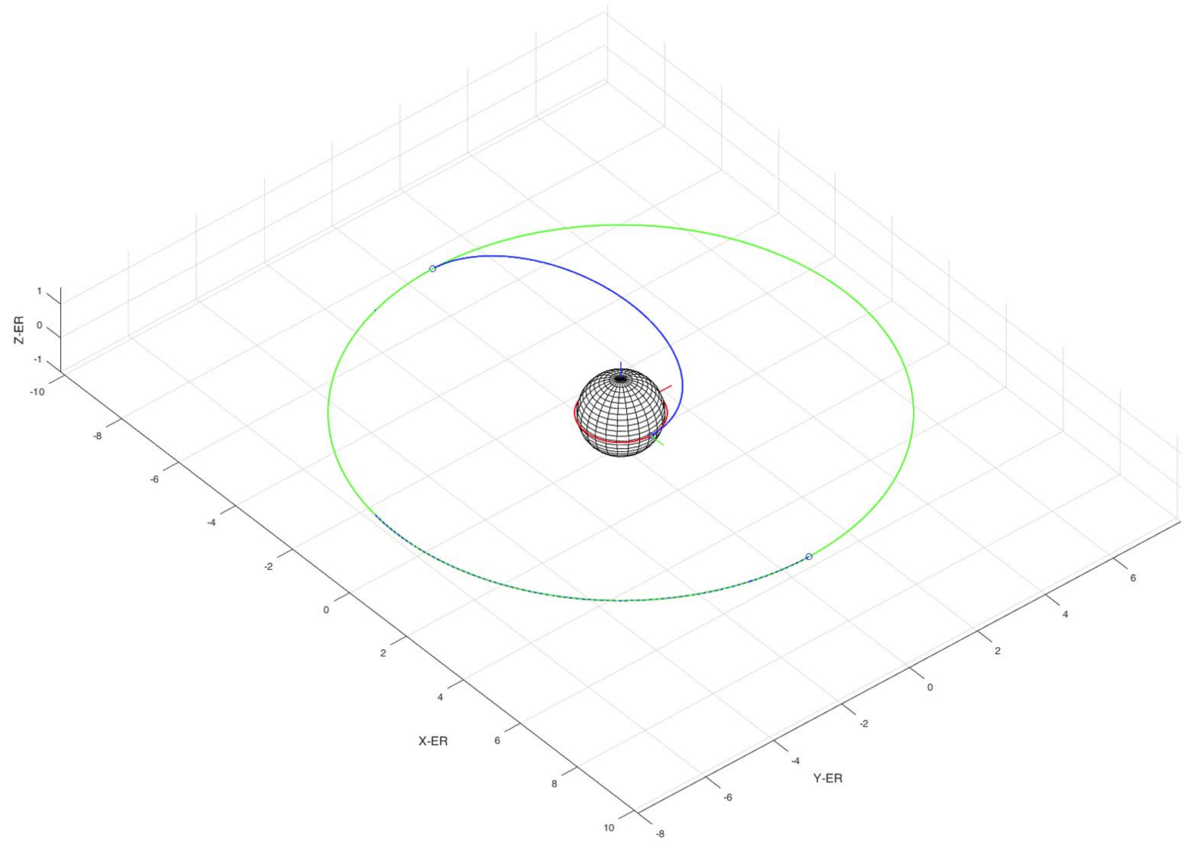

Fig. 2. Trajectory of bi-elliptic transfer under the specified conditions

$$V_1 = 7725.76\frac{\text{m}}{\text{s}} - \ initial\ orbit\ velocity;$$

$$V_{p\,f.t.e.} = 10151.49\frac{\text{m}}{\text{s}} - \ perigee's\ first\ transfer\ ellipse\ \ velocity;$$

$$V_{a\,f.t.e.} = 1607.84\frac{\text{m}}{\text{s}} - \ apogee's\ first\ transfer\ ellipse\ \ velocity;$$

$$V_{p\,s.t.e.} = 3074.6613\frac{\text{m}}{\text{s}} - \ perigee's\ second\ transfer\ ellipse\ \ velocity;$$

$$V_{a\,s.t.e.} = 3074.6612\frac{\mathrm{m}}{\mathrm{s}} - \ apogee's\ second\ transfer\ ellipse\ \ velocity;$$

$$V_2 = 3074.6613\frac{\mathrm{m}}{\mathrm{s}} - \ target\ orbit\ velocity;$$

$$\Delta V_1 = 2425.73\frac{m}{s};$$

$$\Delta V_2 = 1466.82\frac{m}{s};$$

$$\Delta V_3 = 0.00\frac{m}{s};$$

$$\Delta V = 3892.55\frac{m}{s};$$

$$t_{transfer} = 17.2423\ h - \ transfer\ time.$$

4. Conclusion

Threats posed by counterspace capabilities are directed against space systems, their supporting ground infrastructure, and the data links between space systems and ground infrastructure. Space countermeasures include direct attack, co-orbital anti-satellite systems, cyber attacks, electronic warfare, directed energy, and require building capabilities to rapidly transfer space assets. However, the condition of the impossibility of stationary superiority and control exacerbates the need to develop opportunities to avoid the impact on satellites from the enemy, ensuring the sustainable functioning of one's own space capabilities.

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КОСМИЧЕСКИ ОПЕРАЦИИ ВЪВ ФУНКЦИЯ ОТ КЛАУЗЕВИЦ И БИЕЛИПТИЧЕН ТРАНСФЕР

Асен Ангелов Маринов

Висше военновъздушно училище „Георги Бенковски“, asen_aerodynamics@abv.bg

Резюме: Уязвимостта на военните спътници към удари и заглушаване може да наложи съществена промяна в техните орбити, като се използват различни трансфери. Един от възможните трансфери е биелиптичен.

Innovative technologies in the maintenance of the L-39ZA aircraft – possibilities and solutions

Danail Damyanov, d.damyanov67@abv.bg

Abstract: Aircraft maintenance technology has advanced rapidly in recent years, with an emphasis on increasing safety, reducing costs, and increasing efficiency. Maintenance of aging aircraft is one of the serious problems facing the aviation industry. The use of new technologies speed up and improve the efficiency of maintenance procedures while increasing the reliability of aircraft.

Keywords : technology, maintenance, aircraft.

Introduction

Maintenance of old aircraft is one of the serious problems facing the aviation industry. It is related to the complex requirements from ensuring the safety of passengers to maintaining the operational efficiency of aviation operators. Aircraft maintenance technology has advanced rapidly in recent years, with an emphasis on increasing safety, reducing costs and increasing efficiency. The industry continues to push the boundaries of what is possible with the use of artificial intelligence, predictive maintenance, more sophisticated materials and new inspection procedures.

This article explores what opportunities exist for the continued operation of the L-39ZA aircraft and how new technologies contribute to addressing these challenges.

1. Maintenance of old aircraft and component wear

Today, the Bulgarian Air Force has 10 jet training aircraft in service L-39ZA, but only half of them have extended life and undergone major overhaul to maintain airworthiness. Bulgaria purchased a total of 36 aircraft from the former Czechoslovakia. The first batch of 18 L-39ZAs was ordered back in 1985 – 12 were delivered in 1986 and six in 1987. The second batch, also of 18 machines, arrived in our country in 1990. After the expiration of the originally assigned technical resource, the majority of the aircraft have been sold (including all of the first batch), and six of the remaining ones have had their service life extended in stages as they undergo overhaul by the manufacturing company.

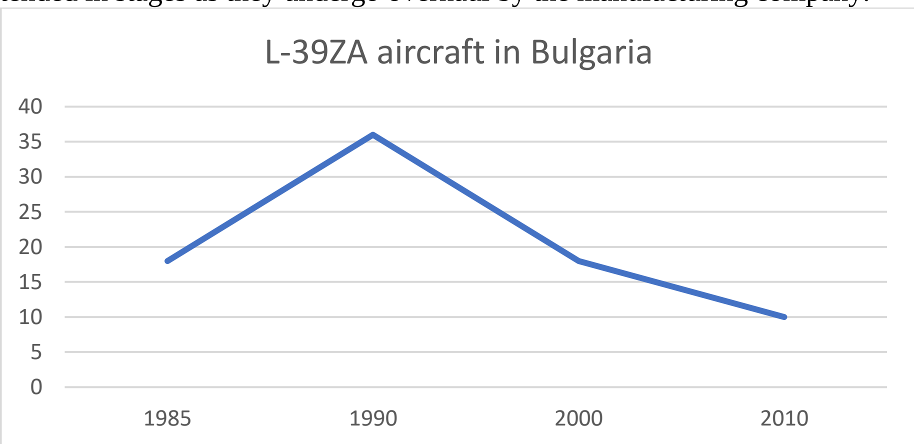

Fig.1 Number of L-39ZA aircraft

After the overhaul from 2013-2016, the machines received an extended total technical resource to 32 years and an inter-repair resource of 7.5 years and 1500 hours, whichever happened first. The extension of the resource is certified by issuing a special bulletin from Aervodohody aircraft (AVA) for the aircrafts that have undergone capital-restorative repair (in accordance with the SLEP program developed by the company). This bulletin specifically states that the life extension remains valid provided that the aircraft are operated in accordance with the manufacturer's instructions. This means that the limitations laid down in the operating documentation are followed and only new and/or refurbished spare parts approved by the manufacturer to maintain airworthiness are used when repairing the machines. [1]

According to the original manufacturer, the maintenance of aircraft that have been in service for 25 years or more requires completely new approaches and repair methods designed and developed to ensure trouble-free operation of the aircraft up to the age of 40 years. Applying the original old repair methods poses a significant risk to both the aircraft and its crew. [5]

To date and the current state of the aircraft, these initial methods do not satisfy the requirements and conditions defined by the design office of the L-39ZA aircraft in order to ensure airworthiness and safe operation.

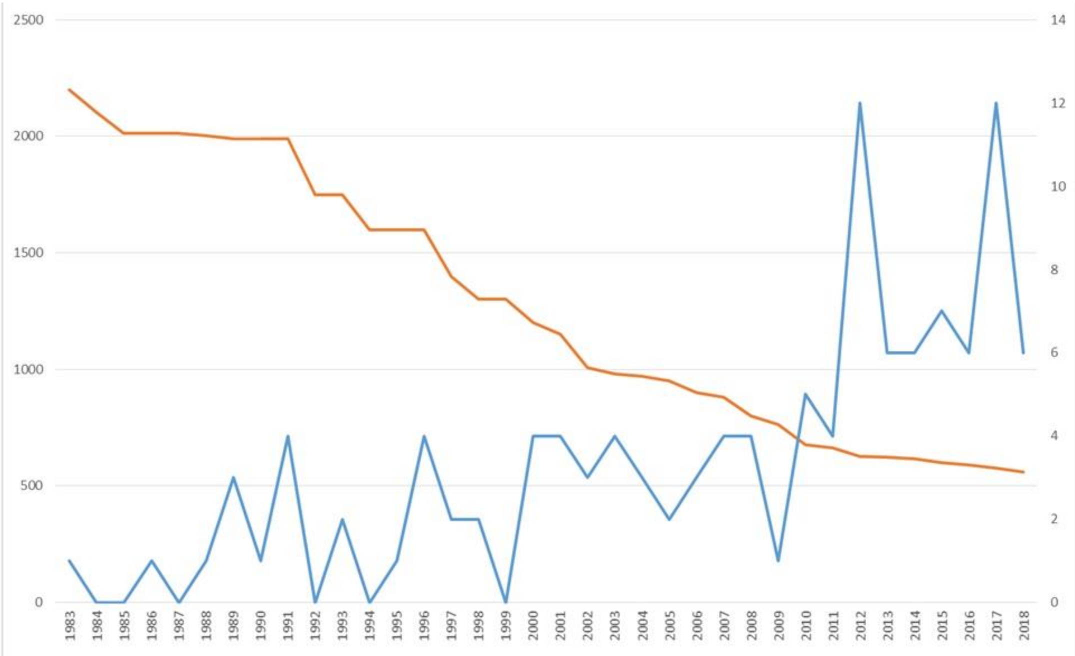

Fig.2 Number of aircraft L-39ZA in service and number of accidents

According to AVA, the fact that the number of accidents has increased significantly in recent years is also due to the fact that aircraft and their components over 25 years old require a maintenance system that is fundamentally different from that of aircraft up to 25 years. At the same time, unauthorized companies are not able to repair units that have been in operation for more than 25 years in a high-quality and complete manner. Their repairs are so shoddy, the manufacturer claims, that they often end in serious accidents. [6]

In 2018 alone, according to AVA data, six L-39 aircraft were lost in accidents, and in 2017 – 12.

Part of the modernization of the L-39ZA proposed by AVA is dictated mostly by considerations of replacing obsolete equipment that is no longer manufactured and maintained - this mainly concerns the aircraft's navigation and communication equipment. The navigation equipment is replaced by an American-made Garmin GTN 650 receiver with GPS/VOR/ILS navigation receivers, a separate DME receiver, a new transponder and a video camera recording the sight information. Also added is a new UHF/VHF radio station LUN 3520 Czech production to replace the old P-832H.

A deeper upgrade, which will make sense when using the L-39ZA to train pilots destined to transition to a new multirole fighter with advanced instrumentation , now includes avionics borrowed from the L-39NG program. The list of new equipment included two 6x8-inch color displays in each cockpit, a forward cockpit windshield indicator and an aft cockpit information repeater, plus a combined duplicating instrument, a new communications radio and flight data recording equipment.

One of the significant problems in maintaining the L-39ZA aircraft is the aging of the aircraft and components. As aircraft age, they become increasingly susceptible to wear and tear problems, ranging from metal fatigue and corrosion to mechanical parts and deterioration of electrical systems.

According to international standards for maintenance and repair on aircraft, these problems are costly and pose serious safety risks if not managed properly.

The complexity of maintaining older aircraft is further compounded by the need for specialized parts, often scarce for older models, and the expertise required to service older technology. Aviation maintenance of aging aircraft therefore requires meticulous inspection regimes, comprehensive maintenance schedules and proactive replacement of worn components to ensure airworthiness and safety.

This ongoing challenge highlights the delicate balance between extending the life of existing L-39 aircraft and the need to gradually modernize them .

Addressing the challenge of aircraft aging and component wear in L-39ZA aircraft maintenance involves a combination of technology solutions, strategies and best practices such as :

- Advanced surveillance systems

Condition monitoring systems can significantly improve the maintenance of aging aircraft. These systems use sensors and data analysis to monitor the health of various aircraft components in real time, identifying potential problems before they become critical. This predictive maintenance approach enables timely interventions, reducing the risk of unexpected breakdowns.

- 3D printing for spare parts

3D printing, or additive manufacturing, offers a solution to more efficiently produce spare parts, especially for older aircraft where parts may have gone out of production. This technology enables the rapid production of parts on demand, reducing the amount of time the aircraft is grounded for maintenance.

- Upgrading systems and components

Retrofitting older aircraft with newer AR technology can solve problems associated with aging systems. This may include upgrading avionics , control systems or other critical components to improve reliability and performance.

- Improved training and experience

Investing in specialized training of maintenance personnel through AR ensures that they have the knowledge and skills to handle the unique challenges of maintaining older aircraft. This includes understanding older technologies and the latest advances in aircraft maintenance.

2. Rising maintenance costs of old aircraft

The rising maintenance costs of L-39ZA aircraft are a serious problem that increasingly burden operators and maintenance facilities with financial difficulties. This problem stems from a variety of factors, including escalating spare parts prices, advanced technology components and specialized tools required for modern aircraft maintenance. [4]

Refining the aircraft's design requires highly skilled technicians, whose training and wages are another cost driver. Additionally, compliance with strict and ever-evolving regulatory standards often requires additional investment in training, equipment and system upgrades.

Obsolete aircraft, while cheaper to acquire, can be more expensive to maintain due to increased frequency of repairs, the need for rare parts for older models, and the potential for unexpected breakdowns. These factors collectively escalate the operational cost of aircraft maintenance and drive the need for effective, cost-effective maintenance strategies and solutions.

To mitigate the rising maintenance costs in aviation, a range of technological solutions can be used to optimize efficiency and reduce costs:

➢ Predictive maintenance technologies

Advanced analytics algorithms can analyze data from aircraft sensors to predict potential maintenance issues before they become serious. This predictive maintenance approach reduces the need for frequent inspections and repairs, thereby saving costs associated with unplanned downtime and extensive maintenance.

➢ Automation and AR in maintenance

Using automated systems and augmented reality (AR) for routine maintenance tasks can reduce the time and labor costs associated with these activities. AR can provide inspection and overhaul data more quickly and efficiently than traditional methods, reducing labor costs and faster turnaround times.

- Systems for remote diagnostics and monitoring

Advanced remote diagnostic tools enable real-time monitoring of aircraft systems and components, enabling maintenance teams to identify and address issues remotely. This can reduce the need for physical inspections and repairs, reducing maintenance costs.

- Advanced learning technologies

Augmented reality (AR) tools for training technicians can improve the efficiency and effectiveness of maintenance operations. Well-trained technicians are less likely to make costly mistakes, resulting in lower maintenance costs over time.

- Blockchain for supply chain management

Blockchain technology can streamline supply chain management in aviation maintenance. It increases transparency, reduces the risk of counterfeit parts and improves the efficiency of procurement processes, contributing to cost reduction.

3. Lack of skilled labor

The shortage of skilled manpower in L-39ZA aircraft maintenance is a significant challenge that affects efficiency and safety. This shortage is mainly due to an aging workforce and the retirement of experienced technicians, compounded by the increasing complexity of modern aircraft systems that require advanced technical skills.

Rapid advances in aviation technology require continuous training and retraining, creating a gap between the available workforce and the specialized skills required. This gap is exacerbated by a declining interest among younger generations in pursuing careers in aviation maintenance, often due to a need for more awareness about the profession or misconceptions about its prospects. [4]

Skilled labor shortages also pose a risk to maintaining the high standards of safety and reliability that are critical in aviation, requiring effective recruitment, training and retention strategies.

Addressing the skilled labor shortage in aviation maintenance requires a multi-pronged approach where technology plays a key role in attracting new talent and increasing the efficiency and capabilities of the existing workforce. Here are some technological solutions:

- Automation and Robotics

The implementation of automation and robotics in routine and repetitive maintenance tasks can compensate for the shortage of skilled labor. These technologies can perform specific tasks more quickly and accurately, allowing technicians to focus on more complex and critical aspects of maintenance.

- Augmented Reality (AR) for Learning

AR technologies can revolutionize the training and education of aviation maintenance personnel. These tools provide immersive, hands-on training without actual aircraft, allowing trainees to practice skills in a safe, controlled environment. This can make training more accessible and attractive to new participants.

- Artificial intelligence and machine learning

AI and machine learning can help with diagnostic processes, identify potential problems and recommend solutions. This technology can enhance the capabilities of existing technicians, allowing them to solve problems more effectively and efficiently.

- Online and distance learning management systems

Expanding access to learning through online and distance learning platforms can attract more people to the field. These platforms can provide flexible, scalable learning options that are more aligned with today's learning preferences.

- Advanced data analytics for predictive maintenance

Using data analytics for predictive maintenance can optimize the maintenance schedule and reduce maintenance staff workload. By predicting when maintenance is needed, resources can be allocated more efficiently, reducing the strain on limited staff.

Conclusion

L-39ZA maintenance challenges are multifaceted and evolving, requiring a dynamic and innovative response . The integration of new technologies such as advanced surveillance systems, 3D printing, augmented reality, predictive maintenance and automation are new solutions for aviation maintenance.

A focus on continuous learning, adaptation and technology integration will be fundamental to addressing the complexity of legacy aircraft maintenance . The aviation industry 's commitment to embrace these innovations reflects its role in maintaining the highest standards of safety, reliability and environmental protection.

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Иновативните технологии в поддръжката на самолет L-39ZA – възможности и решения

инж. Данаил Дамянов, d.damyanov67@abv

Резюме: Технологията за поддръжка на въздухоплавателните средства напредна бързо през последните години, с акцент върху повишаване на безопасността, намаляване на разходите и повишаване на ефективността. Поддръжката на остарели въздухоплавателни средства е един от сериозните проблеми, пред които е изправена авиационната индустрия. Използването на нови технологии ускоряват и подобряват ефективността на процедурите за поддръжка, като същевременно увеличават надеждността на самолетите.

Application of fused deposition modeling approach for 3D printing in the design and manufacturing of small unmanned aerial vehicles

Nikolay Kanchev

Bulgarian Air Force Academy, Aviation Faculty, Dolna Mitropolia, Bulgaria, nikolaikanchev@yahoo.com

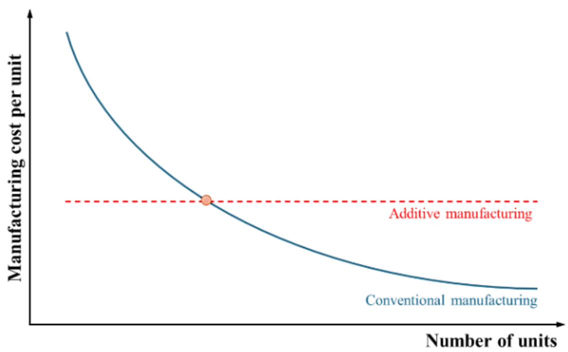
Abstract: 3D printing has improved manufacturing by providing new capabilities for product design, development, and production. The planar nature of fused deposition modelling technology for 3D printing imposes several limitations, particularly when it comes to production of complex geometries and achieving optimal part performance. An innovative approach that overcomes some of these limitations is non-planar 3D printing. In the aerospace industry where weight reduction and performance optimization are important the non-planar 3D printing offers significant advantages. It enables direct, on-demand manufacturing of structural and lifting components for small unmanned aerial vehicles (SUAV), significantly reducing the production time and cost. The paper provides a brief overview of the application of fused deposition modeling technology in the design and manufacture of SUAV structural components with an emphasis on the potential application of the non-planar printing method.

Keywords: *additive manufacturing, FDM, non-planar 3d printing, SUAV structural design*.

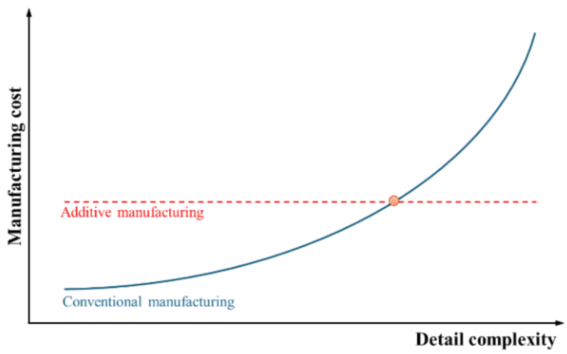
1. Introduction

Additive manufacturing allows the production of complex geometry without the manufacturing constraints of the conventional process thus significantly increasing design freedom. Rapid prototyping capabilities provide quick iteration and testing of designs as well as improving the product development cycle. This way it also enables easy customization of the printed items to meet specific requirements and improves the material efficiency of the process by reducing the waste compared to subtractive technologies. 3D printing allows on-demand and decentralized production which leads to a reduction in the logistics costs.

Additive manufacturing, unlike traditional subtracting methods, is a production process that is cost-effective no matter if there is one item to be printed or many. This advantage is particularly obvious when producing small-scale or custom items. Also, due to the layer-by-layer nature of the process, complex geometries can be manufactured without significant impact on the production cost. In result, 3D printing provides a consistent manufacturing cost that is unaffected by the scale of production and the complexity of individual items (Figure 1).



a)



b)

Figure 1. Comparison of additive and conventional subtractive manufacturing methods: a) unit cost vs. number of produced units; b) unit cost vs. unit detail complexity [11].

Currently, there are various methods for additive manufacturing, as each of those methods has its own advantages and limitations making it suitable for specific applications. When choosing the most appropriate technology, several factors should be considered: printing material, part complexity, surface quality, production volume and cost. A brief overview of the most common additive manufacturing technologies is presented in Table 1.

Table 1. Most common additive manufacturing technologies

Fused deposition modeling (FDM)	**Description:**	Building objects layer by layer using a thermoplastic filament heated to its melting point and extruded through a nozzle onto a build platform.
	Application:	Prototyping, tooling, low-volume production.
	Materials:	Thermoplastics such as ABS, PLA, PETG.
	Challenges:	Limited material selection, surface finish, dimensional accuracy.
	Advantages:	Low cost, simple process, wide range of materials, easy to use.
	Disadvantages:	Limited resolution, anisotropic mechanical properties, support structure requirement.
Stereolithography (SLA)	**Description:**	Using a UV laser to solidify liquid photo-polymer resin layer by layer on a build platform, creating highly detailed parts with smooth surfaces.
	Application:	Prototyping, concept models, dental applications.
	Materials:	Photopolymer resins.
	Challenges:	Post-processing for resin removal, material properties, limited build volume.
	Advantages:	High resolution, smooth surface finish, wide range of resins available.
	Disadvantages:	Limited build volume, material properties, post-processing requirement.
Selective Laser Sintering (SLS)	**Description:**	Sintering of powdered material (*nylon or other thermoplastics*) using a laser to selectively fuse the powder into layers, forming solid objects.
	Application:	Prototyping, functional parts, production parts.
	Materials:	Nylon, TPU, PA12 (*Nylon 12*).
	Challenges:	Powder handling, surface finish, post-processing for powder removal.
	Advantages:	No support structures required, wide range of materials, complex geometries.
	Disadvantages:	Limited resolution, poor surface finish, material properties.
Direct Metal Laser Sintering (DMLS)	**Description:**	Using a laser to selectively fuse metal powder into layers, building up metal parts with high strength and complex geometries.
	Application:	Aerospace, automotive, medical implants, tooling.
	Materials:	Titanium, stainless steel, aluminium alloys.
	Challenges:	Material properties, surface finish, post-processing: support removal
	Advantages:	High strength, complex geometry, accurate parts (*near-net shape*).
	Disadvantages:	High cost (*equipment and material*), limited build volume, surface roughness.
Electron Beam Melting (EBM)	**Description:**	Using an electron beam to melt metal powder layer by layer in a vacuum environ-ment, producing dense, fully melted metal parts.

	Application:	Aerospace, medical implants, automotive, tooling.
	Materials:	Titanium, cobalt-chrome, steel.
	Challenges:	Vacuum chamber requirement, build size limitations, surface finish.
	Advantages:	High density, good mechanical properties, reduced material waste.
	Disadvantages:	High equipment and operating costs, limited build volume, surface roughness.
Binder Jetting	**Description:**	Deposition of liquid binding agent onto powdered material, layer by layer, and solidifying the binder to create a solid part.
	Application:	Prototyping, sand casting molds, tooling.
	Materials:	Sand, metal and ceramic powders.
	Challenges:	Material properties, surface finish, post-processing: binding agent removal.
	Advantages:	High speed, low cost, large build volume, wide range of materials.
	Disadvantages:	Limited resolution, weak mechanical properties, post-processing.
Digital Light Processing (DLP)	**Description:**	Using a digital light projector to selectively cure liquid photopolymer resin layer by layer, producing detailed and accurate parts.
	Application:	Prototyping, dental applications, consumer products.
	Materials:	Photopolymer resins.
	Challenges:	Limited material selection, post-curing for resin hardening, layer adhesion issues.
	Advantages:	High resolution, fast printing speed, smooth surface finish, high details.
	Disadvantages:	Limited material selection, layer adhesion issues, post-curing requirement.
Continuous Liquid Interface Production (CLIP)	**Description:**	Using a UV light source and oxygen-permeable membrane to selectively cure liquid resin into solid parts continuously, enabling “rapid printing”.
	Application:	Prototyping, automotive, consumer products, medical devices.
	Materials:	Photopolymer resins.
	Challenges:	Material properties, oxygen inhibition, limited build size.
	Advantages:	High printing speed, smooth surface finish, low waste, wide range of materials available.
	Disadvantages:	Limited build size, oxygen inhibition, material properties.
Metal Binder Jetting	**Description:**	Deposition of metal powder layer by layer and selectively binding the powder together using a binding agent, followed by sintering.
	Application:	Prototyping, tooling, aerospace, automotive.
	Materials:	Stainless steel, bronze, inconel

	Challenges:	Material properties, post-processing for sintering, surface finish.
	Advantages:	High speed, low cost, complex geometries, no support structures.
	Disadvantages:	Limited material selection, sintering requirement, surface finish.
Carbon Fiber Reinforced Polymer (CFRP) 3D Printing	**Description:**	Using a combination of thermoplastic or thermoset resin and carbon fiber reinforcement to create lightweight, high-strength parts.
	Application:	Aerospace, automotive, sporting goods, marine.
	Materials:	Carbon fiber, thermoplastic or thermoset resin.
	Challenges:	Material properties, post-processing for resin removal, layer adhesion issues.
	Advantages:	High strength-to-weight ratio, lightweight, stiffness, corrosion resistance.
	Disadvantages:	Material cost, limited build size, complexity of printing process, nozzle wearing.

2. Fused deposition modeling technology

Fused deposition modeling (FDM) is one of the most common methods for 3D printing. It is a manufacturing technology for creating three-dimensional objects layer by layer from a digital model or design file (CAD). The general process involves four basic steps: design, pre-processing, printing, and post-processing (Figure 2). Using a specially developed slicing algorithm, the digital model is sliced into thin horizontal layers. During the printing process a thermoplastic filament, typically in the form of a spool, is fed into an extrusion nozzle mounted on a movable print head. The print head can move along the X, Y, and Z axes and by doing so it deposits melted filament onto the build platform according to the G-code instructions from the sliced model. The nozzle heats the filament to its melting point, allowing it to flow and adhere to the previous layer. As each layer is deposited and cools, it solidifies, bonding to the layer below. This layer-by-layer process continues until the entire object is printed. Depending on the detail complexity and printing parameters support structures may be added for stabilization of overhanging features if any. These overhangs should not exceed 45° of inclination with respect to the horizontal plane. This limitation describes the so-called overhang constraint in FDM 3D printing.

Fused deposition modeling offers several advantages including ease of use, accessibility, and support for a wide range of thermoplastic materials including ABS, PLA, PETG, and nylon. FDM printers are available in various sizes and price ranges which makes them suitable for both hobbyists and professional users. The main components of a typical FDM 3D printer are presented in Figure 3.

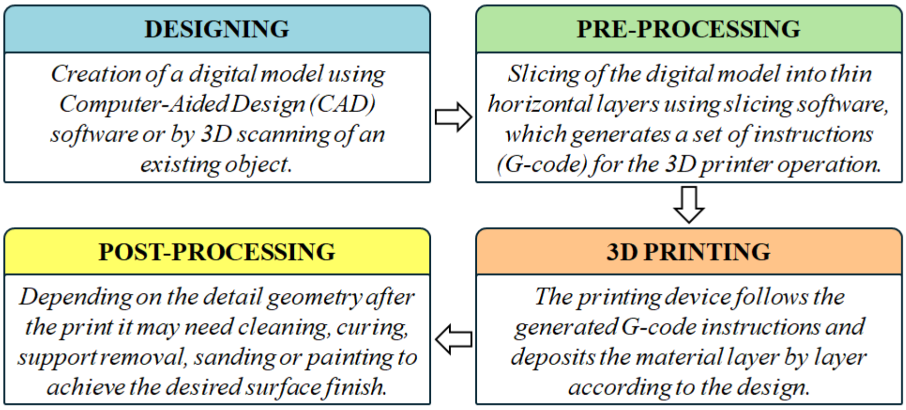


Figure 2. Basic steps of the general 3d printing process

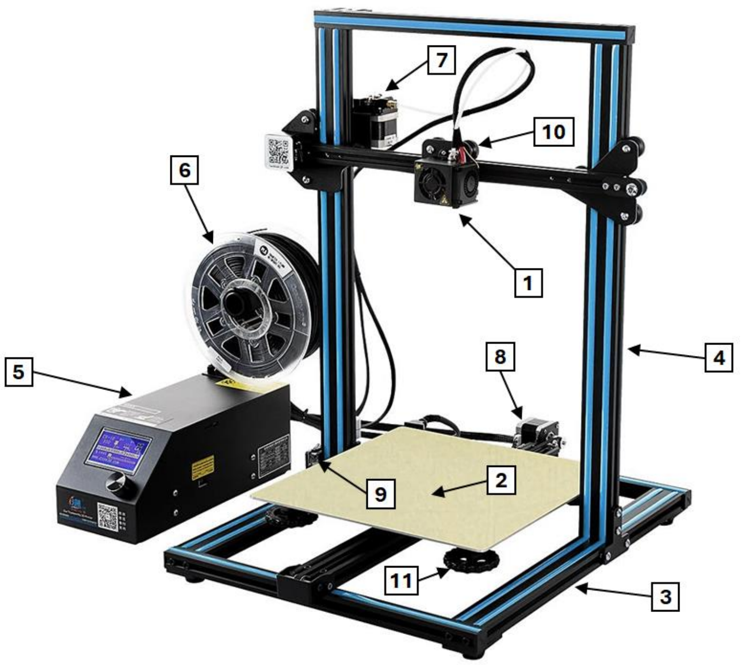


Figure 3. Typical FDM printer components (CR-10):
1. Nozzle kit: single extruder (0.4 mm; ≤ 250°C); 2. Hot bed support platform (≤ 100°C); 3. Base frame; 4. Vertical support frame; 5. Electronic control box; 6. Filament holder (1.75 mm); 7. X-axis stepper; 8. Y-axis stepper; 9. Z-axis stepper; 10. Extruder stepper; 11. Bed leveling adjustment.

On the other hand, layer-by-layer deposition can result in visible layer lines on the finished part, which inevitably affects the surface quality (*stair-stepping*). Additionally, FDM parts may exhibit anisotropic mechanical properties, which means that their strength and stiffness can vary significantly depending on the direction of printing. Furthermore, complex geometries and fine details may be challenging to print due to the nozzle diameter and layer height constraints (*low resolution*) [12]. In traditional planar FDM printing several parameters has major influence over the quality and accuracy of the final items. Those parameters are presented in Table 2.

Table 2. Basic FDM parameters

Parameter	Description	Effect
Layer Height	The thickness of the individual printed layer.	Smaller layer heights result in finer details and smoother surfaces but may increase printing time.
Extrusion Temperature	The temperature at which the filament is melted and extruded through the nozzle.	It affects material flow and adhesion between layers.
Bed Temperature	The temperature of the print bed.	It influences adhesion between the first layer and the build platform, preventing warping and ensuring part stability.
Printing Speed	The speed at which the extruder moves while depositing material.	Faster speeds reduce printing time but may worsen the print quality, especially on complex parts.
Infill Density	The percentage of the internal volume of the printed object that is filled with material.	Higher infill density increases strength and durability but also increases the amount of used material and print time.

Support Structures	The generation and printing of support structures which are necessary for the overhanging features (>*45°*).	Proper support settings prevent print failures and improve surface finish.
Cooling Fan Settings	The speed and activation temperature of the cooling fan.	Used to solidify the material and prevent overheating, especially for small features and overhangs.
Print Environment	Influence of the ambient air parameters over the printing process.	The print quality and material behavior is affected by the ambient temperature, humidity and airflow around the printer. Maintaining a stable print environment is essential for consistent results.

Optimizing these parameters based on the specific requirements of the print task and the characteristics of the used filament can significantly improve the quality of the planar FDM printing. Other procedures in this aspect are the regular calibration and maintenance of the printer, using only high-quality filaments, choosing optimal temperatures for the nozzle and the bed, and placing the detail in a way that minimizes the number of required support structures.

An effective approach is also to follow the Design for Additive Manufacturing (DfAM) principles [4], for example, to impose overhang constraints in the structural optimization procedure, to design a multiscale structure with an outer layered shell and an inner lattice of unit cells [14]. The ultimate goal is to improve the dimensional accuracy as well as the surface finish and mechanical properties of the printed items.

3. Non-planar FDM 3D printing

The FDM printing is inherently planar and achieving high quality surface finishes requires additional post-processing steps which increase the production time and cost. Support structures are often required during planar printing which adds extra material and printing time to the process. In addition, parts produced via planar 3D printing may have weak mechanical properties when the direction of the printed filament is not collinear with the applied force. The volume of the FDM printer also imposes build size constraints, requiring the larger parts to be assembled from multiple sections. An efficient way to overcome these issues is to produce the items through non-planar FDM printing process [3, 6, 8].

One of the key advantages of non-planar 3D printing is its ability to produce parts with complex geometry which otherwise could be difficult if not impossible to print using the traditional planar approach. This type of FDM printing allows manufacturing of details with intricate internal structures, overhangs, and interlocked features without generating supporting structures [1]. This is achieved by deposition of material with simultaneous movement of the extruder in X, Y and Z direction. The additional degree of freedom allows for printing of outer surfaces which are smoother compared to the planar FDM. The overall effect is improvement of the precision and efficiency of the process. The lack of generated support structures decreases both the printing time and the waste of filament material. Also, the possibility for utilizing high-performance materials like the continuous fiber reinforced polymers (*CFRP*) allows production of parts with higher strength and stiffness, particularly suitable for application in aerospace and automotive industries.

Several key challenges need to be addressed in order to perform non-planar 3D printing:
- development of advanced software and design tools for slicing of the highly complex geometry;
- precise control over printing parameters as well as optimization of the production process;
- minimization of the post-processing activities;
- scaling of the process to allow production of large details;
- certification of the printed parts.

As far as the non-planar slicing software is concerned a current trend is to transform or also “to bend” the planar G-code. Converting a regular 3D printer into a non-planar printing device involves hardware, firmware, and software modifications as well as calibration, testing and certification. The hardware and firmware modifications, for example, may include upgrading of the printer’s motion system by adding a tilting bed, rotating mechanisms, and others to allow the non-planar movement of the nozzle. The slicing software is responsible for generation of non-planar G-code with optimized print paths and minimum support structures. Also, the non-planar slicing procedure implementation should calculate an offset distance and limit angle to ensure that the nozzle does not collide with the already printed structure. One of the most important precautions in non-planar printing is to avoid the self-collisions of the printhead. That is why it is important to measure in advance the maximum allowable non-planar angle θ_{np} and the maximum non-planar vertical height h_{np} (Figure 4) for the used 3D printer [1]. Inclusion of the entire printhead width into the non-planar angle calculation allows printing of large surfaces with small curvature angles. On the other hand, if we only account for the extruder nozzle diameter (Figure 4) small surfaces with large angles (up to 45^o) could be printed.

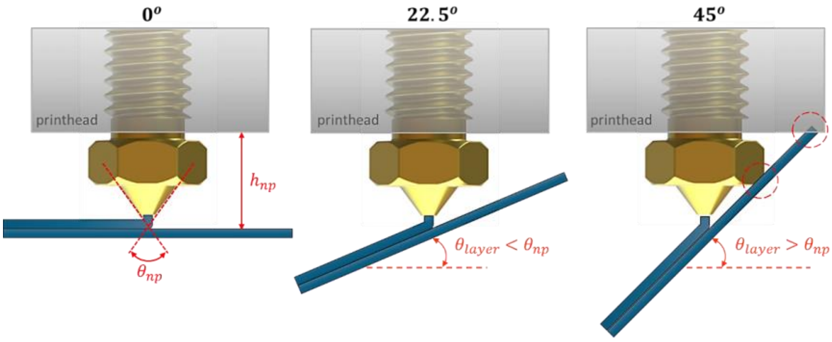


Figure 4. Printhead self-collision constraints for the non-planar toolpath generation algorithm: maximum allowable non-planar angle θ_{np} and maximum allowable non-planar height h_{np}.

4. Applications in aerospace engineering

The research in the field of aerospace applications of additive manufacturing methods is continuously growing [9, 10, 13]. The inherent benefits of 3D printing result in numerous designs of aviation and space components manufactured, certified, and installed on active aircrafts and satellites (Figure 5, 6, 7).

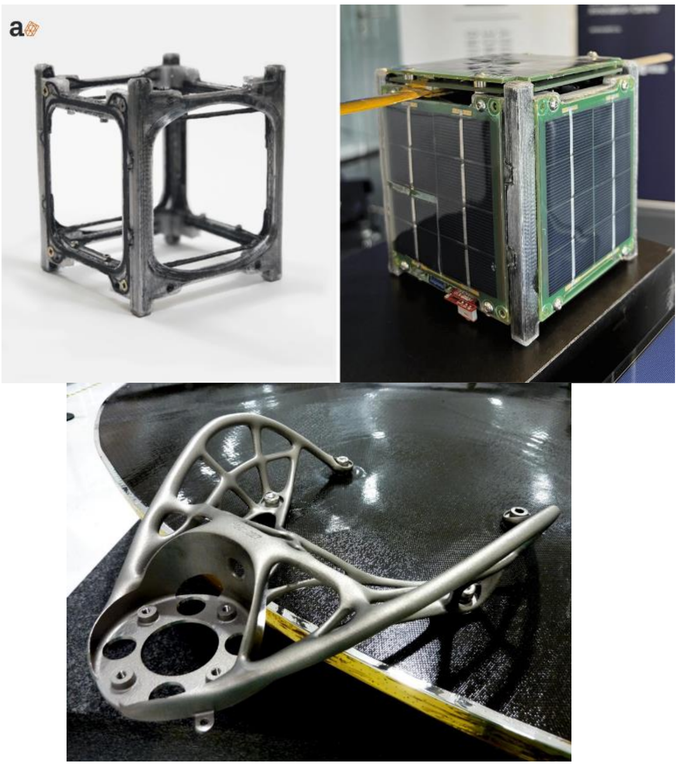
a) b)

Figure 5. Additively manufactured brackets for Airbus A350 XWB:

a) Cabin bracket: 1. Original and topology optimized [19,25]; 2. 3D printed bracket mounted on the structure [7]; 3. Bracket with printed supports for taking into account of the overhang constraints [26]; b) Vertical tail plane bracket built with EOS Aluminum AlSi10Mg [18]

a) *b)*

Figure 6. Additively manufactured components for jet engines:
a) Fuel nozzle tips for the GE CFM LEAP engine: 25% weight reduction, 30% cost efficiency increase, 15% better fuel efficiency, over 180 000 3D printed nozzle tips up to 2023 [24]; b) Topology optimized jet engine metal bracket [23].



a) *b)*

Figure 7. Additively manufactured components for aerospace industry:
a) Topology optimized 3D printed composite frame for CubeSat [15]; b) 3D-printed aluminum antenna bracket for communication satellite [17].

As we can see from these examples the sintering and binder jetting technologies provide high quality surface finish and excellent mechanical properties but at the cost of very expensive consumables and overall maintenance of the printer. On the other hand, traditional FDM printing process is cheap and efficient but generates surfaces with poor quality and stair-stepping (Figure 8).

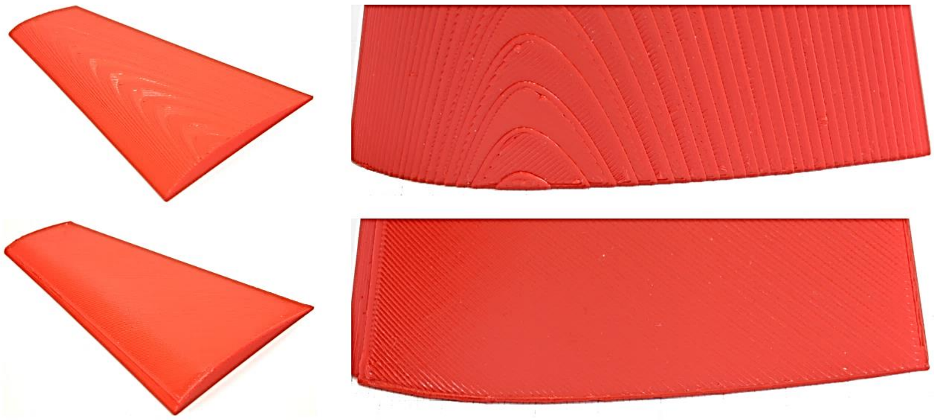


Figure 8. Comparison of a wing with NACA 4310 airfoil profile printed with planar layers (top) and a nonplanar surface (bottom) [1]

In the context of FDM printing only the non-planar approach allows production of parts with improved aerodynamic surface quality and mechanical characteristics (Figure 9). The improved surface finish leads to minimization of the post-processing procedures. Additional reduction in the weight of the printed component can be achieved by incorporating lattice infill structures under the non-planar shell.

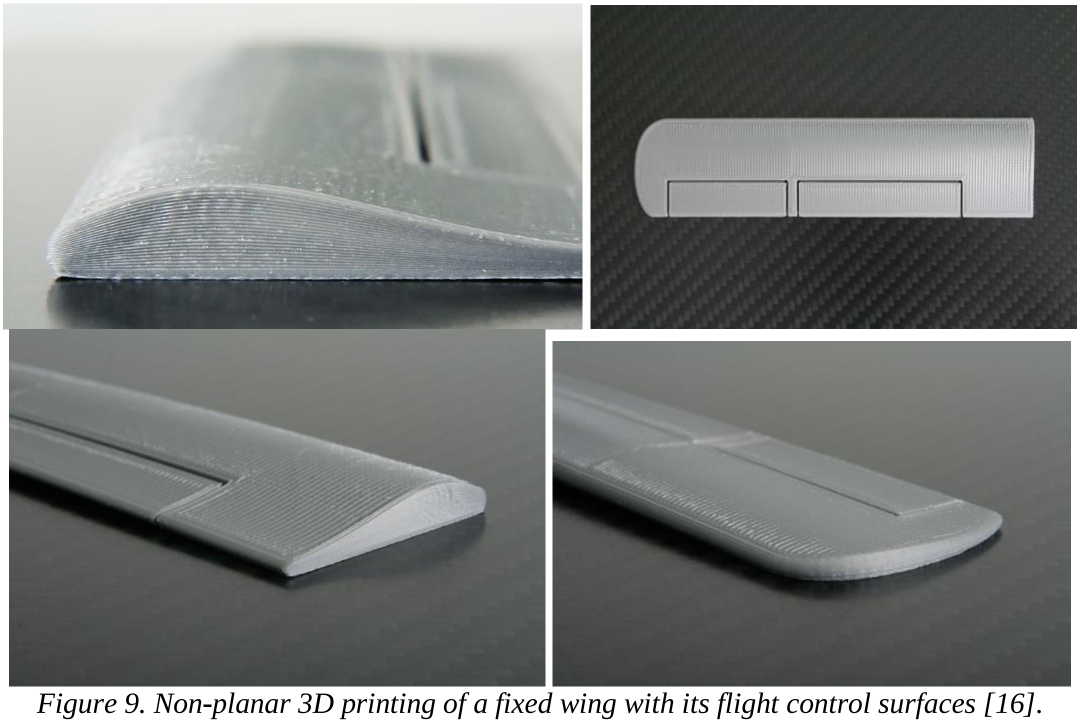


Figure 9. Non-planar 3D printing of a fixed wing with its flight control surfaces [16].

Additive manufacturing of components with aerodynamic surfaces by the non-planar method allows not only customization and rapid prototyping but also the production of the complete flying components. It also provides abilities for on-demand production of both rotary-wing and fixed-wing designs which have to meet certain mission requirements and performance criteria [5]. An example in this aspect is the US Army's ODSUAS concept for 3D printing of On-Demand Small Unmanned Aircraft System for deployment at the lower command echelon to perform particular reconnaissance task [21].

Despite its potential and advantages one of the greatest gaps in the literature regarding aerospace additive manufacturing is the lack of enough research on certification of both the materials used in the process as well as the final aerospace component. The equipment for 3D printing and the general additive manufacturing process are standardized in multiple international standards [20] most of which accepted and approved from the Bulgarian Institute for Standardization [22]. On the other hand, very few 3D printing materials have been successfully certified for aerospace applications with the majority of them being metal alloys and ceramics [2] not suitable for FDM printing. For the time being the utilization of polymer and CFRP filaments remains the only option for non-planar FDM printing of final structural components for small unmanned aerial vehicles with significant potential for reducing the production cost and time.

5. Conclusion

Advancements in additive manufacturing technologies, materials and pre-processing software allow application of 3D printing in the aerospace structural components design. Despite being one of the most efficient and economical among the 3D printing methods, fused deposition modeling requires additional surface treatment due to the stair-stepping nature of the printed part. Non-planar 3D printing offers significant potential for resolving those issues including the ability to produce lightweight, complex geometries with improved surface quality and minimal post-processing. To perform this type of printing a special slicing algorithm is needed to generate the non-planar toolpath accounting for the maximum allowable nozzle angle and vertical distance to avoid collision of the printhead.

On the other hand, applications of additive manufacturing in the aerospace industry are limited to sintering and binder jetting technologies with utilization of metal alloys and ceramic powders. The current state of research in the field of 3D printing technology is concentrated on the materials and production process certification and standardization.

As a result from the review, it can be concluded that when comparing with the rest of 3D printing methods the non-planar FDM approach has potential not only for rapid prototyping and customization but also for direct on-demand manufacturing of ready-to-fly lifting surface components for small UAVs with significant reduction in production time and cost.

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Приложение на технологията за 3D принтиране чрез отлагане на разтопен материал при проектиране и производство на малки безпилотни въздухоплавателни средства

Николай Кънчев

Резюме: 3D принтирането предоставя нови възможности за проектиране, разработка и производство на детайли. Равнинният характер на процеса на печат по технологията чрез отлагане на разтопен материал налага ограничения по отношение на крайното качество на повърхностите на компоненти със сложна геометрия. Иновативен подход за преодоляване на този недостатък е прилагането на неравнинен метод за 3D печат. В аерокосмическата индустрия, където ниското тегло и оптималният производствен процес са от съществено значение, технологията за неравнинно принтиране предоставя значителни предимства. Позволявайки директно тримерно отпечатване на предварително заявени носещи и аеродинамични компоненти за малки БВС, този подход способства за понижаване на времето и разходите за производство. В статията е направен кратък обзор на приложението на технологията за 3D принтиране чрез отлагане на разтопен материал при проектирането и производството на детайли от конструкцията на малки безпилотни въздухоплавателни средства с акцент върху потенциалното приложение на неравнинния метод за печат.

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Analysis of the structural composition of common aviation terms: a corpus-based study

Valya Tsvetanova

Bulgarian Air Force Academy 'Georgi Benkovski', valtsvetanova@gmail.com

Abstract: This article aims to present the basic characteristics of the structural composition of 60 aviation terms which are often used by aviation professionals, and people interested in flying. We discuss the morphological composition of the terms, categorizing them into groups according to their specific features. Attention is paid to the essential role some of these terms have had in the expansion of the aviation terminological field.

Keywords: *aviation terminology, morphology, word formation, corpus linguistics*

1. Introduction

Technology and science have been developing rapidly during the 20th and 21st centuries, introducing new concepts and terms, thus enriching specialized languages. The aviation terminological field is not an exception. Man has always been enchanted by the idea of flying. That dream has led people to the development, and the invention of technologies used in their attempt to conquer the unknown. As a result, the aviation terminological field has been expanding. Nowadays, it comprises of terms that originate from Latin, Greek and Old French to terms which came into existence in the 20th century. There is no doubt that the field is still expanding since aviation language is developing, together with aviation itself.

The present research is based on a small corpus: 60 terms have been extracted from two chapters in the Pilot's Handbook of Aeronautical Knowledge, (Aircraft Construction and Aerodynamics of Flight), issued by the Federal Aviation Administration. Although these terms are randomly chosen, they all have something in common - they are often used among aviation professionals and we consider them to be among the key terms in the aviation terminological field. We are interested in finding out what the prevalent structural patterns among these terms are, analyzing the morphological processes such as affixation, compounding, and conversion. The topic of the word formation processes related to aviation English has been researched by Azis, Rosa, Kovtun and others.

2. Data and Methods

The terminology used in the two chapters is crucial for the understanding of the operation and performance of aircraft. The corpus consists of 60 essential aviation terms, and it is considered as preliminary data for future research work.

The methods used for the analysis are descriptive and quantitative. A descriptive method of research is used for the analysis of each term and categorizing it in terms of its morphological structure. The method is also utilized by the author to research the ability of some of the most used terms to participate in word formation processes in the aviation terminological field. Quantitative analysis is performed to show the most numerous types of nouns. Also, the software tool Sketch Engine is used for frequency counts and studying the modifiers and modified words.

3. Research

Terms can be examined from three perspectives: formal structure (pronunciation and morphology), semantic content (terms refer to objects in real world and the meanings they have is a set of descriptive features), and their functional point of view (grammatical category and distribution). The formal side of a terminological unit is called a designation or term. Terms are base-level phonological presentations which have a phonetic form. .. Morphologically, terms are structures of constituent morphemes which form the basis of meaning [1]. A term is a linguistic unit that can be analyzed into smaller, meaningful components, called morphemes. A morpheme is the smallest unit of language which has formal and semantic significance. Lexical units can be simple (they contain only one morpheme), or complex (they have more than one morpheme). The basic morphological structure of terms is the same with that of words. If the morpheme is simple, it coincides with the root. The term is called simple.

Morphology plays an important role in term formation. Various morphological processes can be applied to create a new term. We can talk about affixation, compounding, blending, conversion, and coinage.

4. Findings and Discussion

The terms used in the research have been analyzed to find which are the common morphological patterns presented in the corpus. Each term was categorized in terms of its characteristics. The following categories were formed:

1) Simple words.
2) Compound words.
3) Complex words and
4) Compound adjectives.

The result was quite interesting- most of the terms in the corpus are simple words (47%), followed by the compound and complex nouns (33% and 12% respectively). The lowest percentage of appearance in the corpus is 8%, that of the compound adjectives category. Figure 1 shows graphically the distribution of these classifications, used to describe the morphological structures in the corpus:

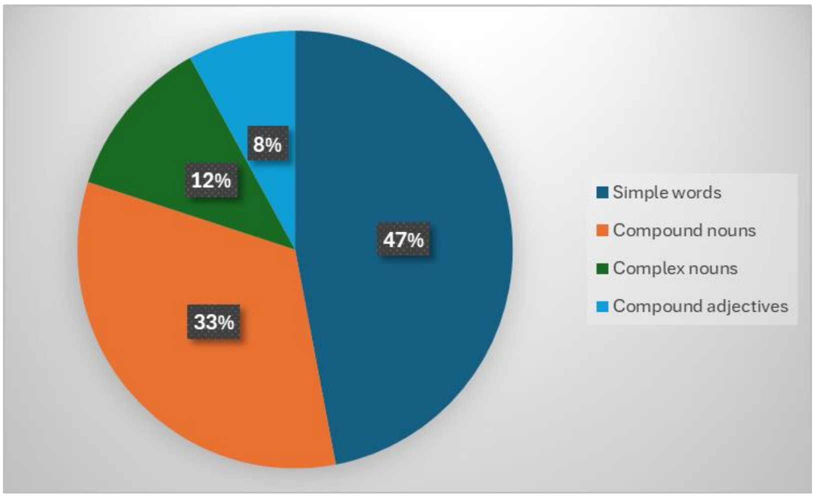

Fig. 1 Categories in the corpus

In our opinion, the highest percentage of simple words can be explained by the fact that the Pilot's Handbook of Aeronautical Knowledge is a book that provides the fundamental information that is essential for pilots.

4.1 Simple words

Some 86% of the simple terms in the corpus are nouns, while 14% are verbs. Some of the terms are used as both nouns and verbs. Only one term is used as a noun and an adjective. The following are given as examples:

→'Climb'- as a noun 43 times, as a verb- 26 times.
→'Bank' -as a noun 73 times, as a verb- 15 times.
→'Dive'- as a noun 12 times as a verb- 4 times.
→'Tail'- as a noun 42 times, as an adjective- 13 times.

These results confirm the well-known fact that nouns dominate in the field of aviation terminology.

According to the given data in Sketch Engine, *'yaw'* is used only as a verb, and appears 41 times in the corpus. The particle that is once used with it, is '*around'*. We compared the other two terms usually discussed with yaw- '*pitch' and 'roll'* and the results were as follows:

→'Pitch' is used 44 times as a noun and it is 4 times modified by 'geometric'. As a verb 'to pitch' can be seen 19 times, the particles *'down'* and *'up'* are used twice after it.

→'Roll' is used as a noun 26 times and it also collocates with Dutch, thus creating the compound term '*Dutch roll*' with the meaning of '*a combination of rolling and yawing oscillations that occurs when the dihedral effects of an aircraft are more powerful than the* *directional stability*'. As a verb 'to roll' is used only 7 times and the particle *'off'* is used once after it.

Although the corpus is small- two chapters of a book and 60 aviation terms extracted from them, it is still surprising that 'pitch' and 'roll' are used as a noun and verb, but 'yaw' is met only as a verb. Due to the size of the corpus, a generalised conclusion cannot be reached, but it is worth researching how these three terms 'behave' in the terminological field.

As can be seen from the above results some of the simple words are more often used than the others. On analysing the occurrence of the terms in the corpus, it was found out that several terms are used more than 100 times whereas there are terms that can be seen only 5 times or less (*to taxi (v)* and *to land (v)* are used only once, *slat (n)* is mentioned in the corpus 5 times). Figure 2 shows the terms that are in the corpus more than 100 times.

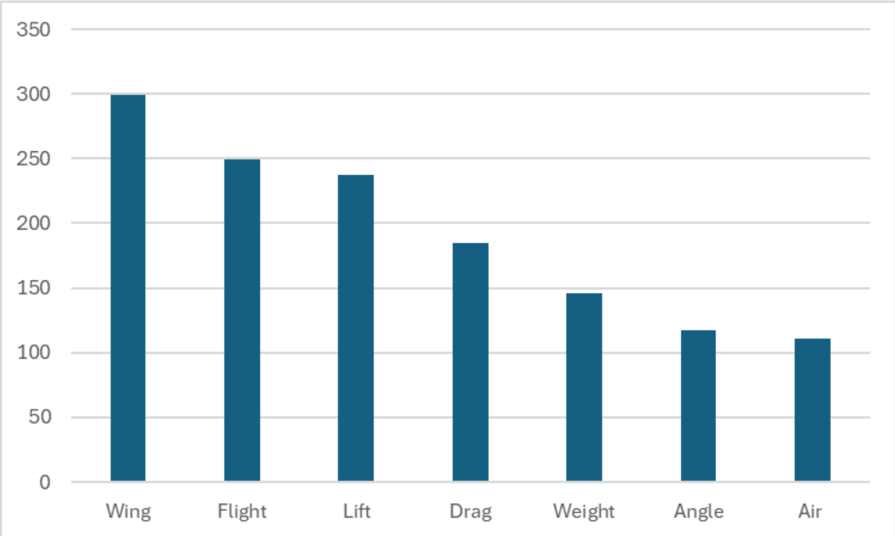

Figure 2. The most frequently used terms in the corpus

The most frequently used term in the corpus is 'wing' (299 times), followed by 'flight' and 'lift' (249 and 237 times respectively), 'drag' appears 185 times,' weight' 146 times, 'angle' 117 times and 'air' 111 times. Interestingly, three of the four forces that affect the aircraft while flying are included in the list. The fourth force 'thrust' is used 96 times. Overall, the results are not surprising since all these terms are considered to be key elements in the subjects of aircraft construction and aerodynamics. It is worth noting that these terms are often used in the formation of other aviation terms. Some will be discussed below.

'Wing' is the term that is mentioned most in the corpus. The fact that this term can be used in both aircraft construction and aerodynamics makes it really productive, for example, '*elliptical wing', 'rectangular wing',' wing root', 'wing planforms'*.

If we take the term 'flight', we can find a lot of examples of terms used in aviation theory, for example: '*flight path', 'level flight',' straight-and-level flight', 'transonic flight',' high-speed flight', 'flight controls',* and so on.

'Drag' is another interesting example of compounding. It forms compound terms using specific modifiers to distinguish different types of drag: '*interference drag', 'parasite drag', 'friction drag'*.

'Angle' is really productive in the field of aerodynamics. We can talk about '*bank angle',' climb angle', 'blade angle', 'pitch angle',* and it is used with '*-of* 'construction in '*angle of attack'* and *'angle of incidence'*.

'Air' is undisputedly one of the most commonly used with other words to form terms related to aviation: for example, '*aircraft', 'airflow', 'airborne', 'airspeed'*.

4.2 Compound words

The second group that predominates in the corpus is that of the compound words. Compound words are two or more root morphemes combined to form a new word, which has a specific meaning. For example, the term 'wingtip' is a combination of 'wing '+'-tip'. Knowing the meaning of these two words, the newly formed term is easily recognized, namely 'the outer end of an airplane wing'. Most of the terms included in this category were introduced to aviation language at the beginning of the 20th century. Figure 3 shows how the patterns identified in this group are distributed in this category.

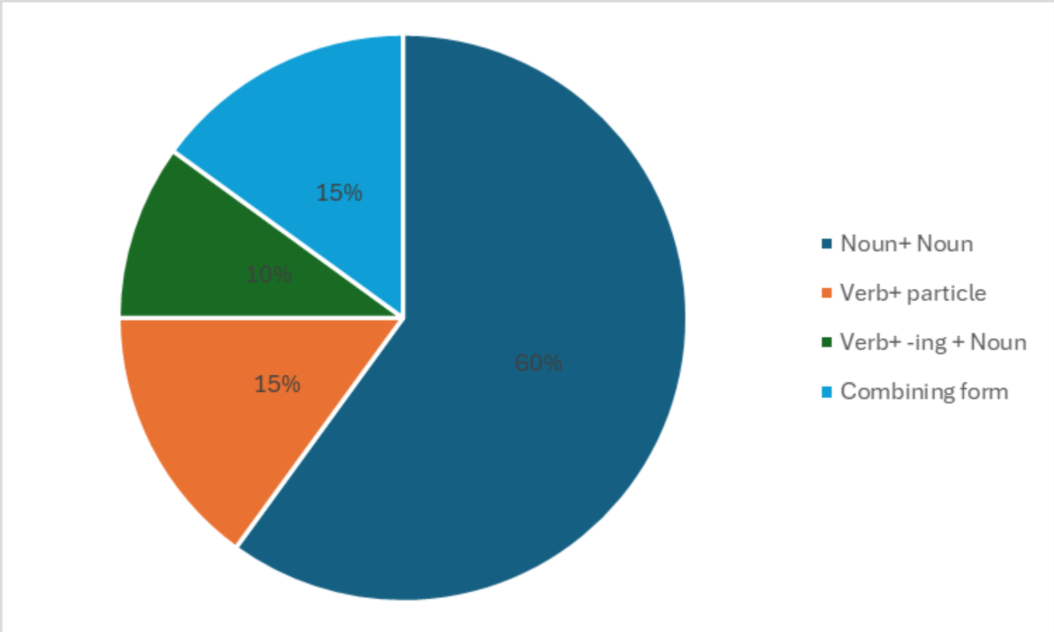

Figure 3. Patterns identified in the category 'Compound words'

The patterns identified in this group are as follows:

- Noun + Noun- this pattern is 60% of all compound nouns in the group. Examples include:

→ 'flight *path' ('flight'+ 'path')* with the meaning of 'a line, course or track along which an aircraft flies'.

→*'airstream' ('air'+ 'stream')* with the meaning of 'the flow of air caused by the movement of the aircraft through the air'.

→*'airflow' ('air'+ 'flow')* with the meanings of '1.) The movement of air over the aircraft as it travels through the atmosphere. 2.) A current of air flowing through or past an object or body'.

→*'boundary layer' ('boundary' + 'layer')* with the meaning of 'the layer of fluid next to the surface over which it is flowing and, because of friction, travelling more slowly than layers further from the surface'.

- Verb+ particle- this pattern is 15 % of all compound nouns.

→*'touchdown' ('touch '+ 'down')* meaning 'the moment, after a flight, when the aircraft makes control contact with the landing surface'.

→*'takeoff' ('take'+'off')* with the meaning 'the procedure when an aircraft leaves the ground'.

- Verb+ -ing+ Noun– this pattern makes up 10% of all compound nouns.

In the structure Verb + -ing, an adjective is formed which modifies the noun that follows it.

→*'leading edge' ('lead' + -ing + 'edge')* meaning 'the front part of the wing which meets the oncoming air first'.

→*'trailing edge' ('trail' + - ing + 'edge')* meaning 'aft part of an aerofoil.'

- Two terms are formed by the combining form 'alti-':' altitude' and 'altimeter'. The prefix 'alti-' is a word-forming element meaning 'high' from Latin 'altus', literally 'grown tall'.

→ *'altitude'* means 'the vertical distance between the aircraft, or a point or a level, and mean sea-level'.

→ *'altimeter'* means 'a radio instrument for measuring vertical distance or altitude'.

Another interesting example of combining form is *gyro-* in 'gyroscope'. This word-forming element is of Greek origin with 'gyros', meaning 'a ring, circle'. The meaning of 'gyroscope' is 'a device consisting of a spinning wheel, mounted on a base so that its axis can turn freely in one or more directions and thereby maintain its own direction even when the base is moved'.

When a close look is taken at the compound terms used in the corpus and their definitions, one would find that the combinations of the terms describe the new terms, and the new meaning is a result of this description. For example, 'touchdown' – the verb 'touch' shows that the aircraft touches something which is revealed by 'down'- something which is down i.e. the land. Leading edge- 'leading' is formed by the verb ' to lead' (to be in front) and -ing, 'edge' is the outer part of something.

4.3 Complex words

The third representative group in the corpus is that of complex terms. Complex term means a word that consists of a root (base form) and one or more affixes.

The terms used in the corpus have the structure root+ suffix. The suffix is used to change the part of the speech or the meaning of the term. Some interesting examples can be found.

→*'winglet' consists of* 'wing' + '-let': -let is a diminutive noun-forming element, that originates from Old French ('-elet)'. The meaning it conveys is 'small one'. It changes the definition of 'wing' from 'the main horizontal aerofoil or mainplane' to 'an upturned wing tip or small additional vertical aerofoil on a wing tip'.

→*'spoiler'* is formed by the verb 'to spoil' and the suffix '-er'. This suffix is an English agent noun ending, corresponding to Latin '-or'. It provides the following meanings: 1.) person occupationally connected with 2.) person or thing belonging to or associated with 3.) one that does or performs (a specified action). The meaning of 'spoiler' in aviation is 'a hinged surface on the upper wing which, when opened, decreases lift and increases drag'.

→*'Elevator'* is formed by the verb 'to elevate' and the suffix '-or'. The suffix '-or' is of Latin origin and it is added to verbs to form nouns. It indicates the person or thing that performs the action. 'Elevator' has the following meaning: 'a movable control surface, usually attached to the horizontal stabilizer of an aircraft, used to produce the nose up/down motion of an aircraft in level flight known as pitch'.

It can be concluded that the used suffixes have changed the terms' grammatical categories and modified their meanings.

4.4 Compound Adjectives

The compound adjectives category is the smallest group in the corpus. A compound adjective comprises two or more words which modify the noun. Two of the compound adjectives 'nose-up' and 'nose-down' can be found in the corpus used as nouns, but we have decided to include them in this category because of the highest number of occurrences of these terms as adjectives. Examples include:

→ *'… this nose-down attitude'; '… overcome the nose-down pitching tendency';*

→ *a nose-up moment is produced'.*

The adjective that is most often used in the corpus is 'supersonic' which appears 10 times. For example:

→*supersonic flow, supersonic airstream.*

Researchers have already demonstrated that nouns, verbs, and prepositions predominate in aviation texts. The percentage of adjectives is low, which is also confirmed by this study.

5. Conclusion

This corpus-based research revealed various structural pattern characteristics for texts related to aviation. It also provided some insights into how aviation terms are constructed: there were examples of compounding, conversion, and derivational affixes. It was found out that most of the terms included in the corpus are simple terms and some of them take part in word formation processes in the terminological field.

Understanding the morphological structures of aviation terms enhances professionals' skills to comprehend aviation terminology better and grasp term meanings more easily which leads to more effective communication and reduce ambiguity.

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Effective Communication in Aeronautical Context

Vanya Katsarska

Air Force Academy, Dolna Mitropolia, Bulgaria
vkatsarska@af-acad.bg

Abstract: The diversity of the air force operational environment in the contemporary globalized world has increased the complexity involved in the present-day aviation training, including language training. Communication in a multicultural aviation context requires the intersection of language, professionalism and culture. English language communication between military pilots and air traffic controllers is challenging due to the intricate nature of professional duties and the multitude of factors influencing them, so it comprises a lot of layers. In this article, key competences of aeronautical English teaching are identified and four major competences are highlighted – linguistic, interactional, professional, and intercultural competence. Following James Reason's Swiss Cheese Model, it is suggested that all of these competences should be incorporated into the educational process.

Keywords: *aeronautical English, competences, communication*.

1. Introduction

English has firmly established itself as the lingua franca in the global realm of aviation, serving as the primary means of communication among individuals whose native languages vary. This status is not arbitrary but rooted in practicality and necessity, as clear and concise communication is paramount for ensuring the safety and efficiency of air travel. From pilots and air traffic controllers (ATCOs) to cabin crews, maintenance personnel, engineers, ground staff and airport managers, proficiency in English enables seamless coordination and collaboration across international borders, contributing to the harmonious operation of the global aviation industry.

However, aviation English is a broad term. It comprises all of the language uses of different professions within the aviation domain. Each of these areas is related to particular knowledge and requires certain skills. Peter Ragan from Embry-Riddle Aeronautical University calls aviation English "an umbrella term" and specifies its subdomains: flight, technologies, engineering, business, and finally education and training [1, p.26]. These aviation English subfields have their specific lexical, semantic, and syntactic language features, which allow specialists to communicate more precisely and accurately about aspects of their profession that outsiders sometimes find impenetrable.

Obviously aviation English is a hypernym and other terms are needed in order to specify the different branches of this scientific field. One of these branches is the radiotelephony communication between pilots and air traffic controllers, between pilots of different aircraft in the air, or between pilots/air traffic controllers and the ground staff. It consists of standardized phraseology and plain English. This article follows the terminology path of Borowska [2], Friginal, Mathews and Roberts [3], Ana Ligia Silva [4] and names the radiotelephony communication, standard phraseology and plain English, with the term "aeronautical English."

In 1951 the International Civil Aviation Organization (ICAO) unequivocally established English as the official language of aviation. In addition to this, it advised all airports and routes to have English available for international flights despite the fact that they can operate in their local language. With this ICAO actually affirms the role of English as both an international and intranational language. The role of English as the primary international language in aviation was further solidified with the implementation of the ICAO language proficiency requirements in 2011 [5], marking a pivotal shift from English proficiency being merely recommended to becoming an obligatory skill.

As the mandated language for radiotelephonic exchanges, aviation English plays a crucial role in ensuring effective and standardized communication across diverse linguistic backgrounds, enhancing safety and efficiency in air traffic operations worldwide.

The overview of theoretical and empirical studies devoted to the development of communicative competences in aeronautical English showed that researchers have so far considered only a limited range of aspects of the problems and have encompassed the problems in civil aviation predominantly. There are just a few articles which address the military aviation issues and civil versus military aspects of aviation English. Furthermore, it can be asserted that the problems of communicative competences of military ab-initio pilots and air traffic controllers in military schools have been under-researched in the world and they have not been the subject of any special study in Bulgaria.

2. Interrelation of competences in military aeronautical English

Pilots and air traffic controllers must adhere to the prescribed standardized phraseology in accordance with ICAO Document 9432 Manual of Radiotelephony [6]. This is an organized system for transmission of information, instructions, requests, clearances, and advice. It provides the phraseology for general operating procedures, including transmission of letters, numbers, time, callsigns and the structure of radiotelephony messages, a scale for readability of transmissions, readback requirements, etc. It also specifies the phraseology used during the different legs of the journey, the approach and area control, for the aerodrome information and even some phraseology for typical distress and urgency procedures. Standard phraseology is defined by ICAO as “the formulaic code made up of specific words that in the context of aviation operations have a precise and singular operational significance” [5]. This is a restricted and coded sublanguage where each word and phrase has a precise meaning that is often exclusive to the aviation domain.

One subfield of aeronautical English, which has been insufficiently researched so far, is the military aviation English. The roles of military pilots and ATCOs differ from the civilian ones. The most important task for the civilian pilot/ATCO is the safety of the aircraft while for the military pilot/ATCO it is achieving the assigned mission. Civilian pilots deal with passengers and their demands while military pilots engage in combat missions and combat or mock combat trainings related to surveillance, escorts, intercepts, bomb dropping, gun employment, etc. Civilian pilots take off and land on huge hubs while military pilots fly in formations and sometimes land on aircraft carriers. Fatigue and red-eye flights are persistent problems for civilian pilots, while G-tolerance and loss of consciousness for jet fighter pilots. The different tasks of civilian and military pilots ask for different language. STANAG 3817 is the NATO [7] supplement to the ICAO radiotelephony phraseology in Annex 10, volume II, Document 9432/AN952. It provides the unique phraseology used by military pilots, ATCO and ground personnel. No doubt it is not possible to provide every conceivable situation in the military environment but it recommends the additional military phraseology in most frequent air force situations.

In a normal, smooth flight all operations and activities are predictable. The ICAO and STANAG 3817 standardized phraseologies are in most cases sufficient for the routine flights, which military pilots and ATCOs undertake during their missions and training exercises. Nevertheless, it is not possible to have an all-encompassing list of phrases for a routine flight. It is not rational to expect that a standardized phraseology document can be definitive and include all the words and expressions for every possible routine situation. During non-routine situations such as an airplane in distress, engine failure, bird strike, unexpected bombing, enemy fire, accidental release of sonobuoys, etc., the standardized phraseology does not suffice and plain language is necessary instead. Plain English is spontaneous and creative, it resembles the everyday normal speech of common people but it is still not quite the same. Plain English is not meant to be natural English talk; it is rather simple English following as much as possible the guidelines provided by the phraseology and obeying the constraints of aeronautical communication. It aims at clarity, preciseness, and concision just like the standard radiotelephony phraseology.

Linguistic competence is essential for the aeronautical communication. The specialized lexis, the terms and phrases, the formulaic language distinguish it from general English and the other English for specific purposes fields. The syntax is simplified and marked by a lack of articles, auxiliary verbs, prepositions and pronouns [8, 9]. Nowadays in the world, non-native speakers of English outnumber native speakers and the aviation community is definitely international, which means that aviators listen to quite different accents. Pronunciation that is imitating native speakers from the UK or the USA is non-essential and unnecessary. Pilots and ATCOs are encouraged to practice until they reach intelligible pronunciation. The ICAO Doc 9835 identifies that the following features as crucial for comprehensible pronunciation: the distinction between short and long vowels (e.g. hit/heat); the correct placing of nuclear stress (e.g. radar); the marking of tone boundaries (e.g. voice pitch and intonation mark new components of a message); and the non-reduction of consonant clusters (e.g. test flight may be pronounced “tesflight”)[5, p.2-6]. Furthermore, prosody may positively or negatively impact the understanding of a message. Trippe and Baesse-Berk [10] observed that due to the fact that aviation English is concerned with predictable linguistic situations and uses restricted standard phraseology, its speakers talk faster than people commonly do in Standard English. Furthermore, they found out that has a more restricted pitch range, faster articulation rate and less variable vowel interval durations and more variable consonant interval durations[10, p.41].

Recently some scholars [11, 12, 13] have given empirical evidence that successful aeronautical radiotelephony communication is dependent on more competences than the linguistic one. Communication threats related to the use of English by aircrew members and air traffic controllers range from linguistic to discursive to strategic or cultural factors. Kim and Elder [13] address this issue and claim that the communicative needs of pilots and ATCOs extend beyond their language proficiency, requiring negotiation, collaboration and interaction, "These participants, whatever their language background, need to be able to adapt to the situation at hand and enlist a range of communicative resources to participate in and make sense of messages delivered by speakers with differing levels of English competence in situations which may range from routine to highly unpredictable" [13, p.14]. In order to understand the essence of efficient aeronautical English communication, we may go back to the term introduced by Claire Kramsch [14] "interactional competence" which specified that abilities, actions and activities are not possessed by one individual only; on the contrary, all involved in the communication process are responsible for its success. The interactional competence gives additional components to the communicative process such as negotiation, -recognizing and repairing communication breakdowns, paraphrasing and repetition in order to increase communicative efficiency, awareness of linguistic difficulties faced by aviation English speakers, etc. Therefore, in their language classroom aeronautical English speakers can demonstrate their interactional competence through discursive practice. In non-routine situations the pilot and the controller have certain expectations about the turn-taking and the organization of the exchanges – they know when to say their request and when to listen for a readback, when to jump in the talk and when to back off. They both assess the situation continuously, use specific vocabulary and grammar appropriate for the context; they know when and how to repair a conversation, etc. Monteiro [11] and Kim [13] also mention the shared responsibility of all speakers. They say that even highly proficient speakers and native speakers must be trained on developing skills of accommodation in speaking, skills of paraphrasing and reducing the usage of complex vocabulary and grammar, negotiation and mediation skills, etc.

Interactional competence in aeronautical English has several layers - communicative strategies for producing clear, concise and unambiguous speech; accommodation for adapting language to be closer to the other participants in order to avoid communication breakdowns and misunderstandings; negotiation between different members; shared commitment and joint effort of all participants for successful and efficient communication.

Competence in the aeronautical English context is the ability to perform various communicative tasks in a professional surrounding. If communication is not efficient, it will definitely lead to an unsatisfactory performance in other competences such as situation awareness or teamwork. Pilots and controllers are engaged in various professional tasks and their communication must not hinder the smooth process of flying/guiding the airplane. The interaction between pilots and ATCOs relies on context, technical knowledge, and professional skills. Radiotelephony communication relies on meaningful context and knowledge of navigation, aerodynamics, technical equipment, weather phenomena, and for military personnel – armament and combat operations. Linguistic competence is intertwined with professional competence. Emery [15] claims that "subject-matter knowledge is inseparable from language use, even more so in language for specific purposes. Therefore, we cannot expect entrants to aviation training to be able to speak 'ICAO aviation English' knowing that they do not have the associated subject-matter knowledge" [15, p.14]. In aviation English the linguistic knowledge and the background knowledge are closely entangled, it is merely impossible to detach one from the other. For example, as a member of a fighting team, the wingman may have to tell the lead what to do if he has the tally and the lead does not (tally = enemy traffic in sight). If the information is not critical, a standardized descriptive transmission is required, e.g. "069, bogey, right 2, 3 miles, high", which means "Call sign 069, unidentified airplane which is probably hostile is on the right side of my aircraft at 2 o'clock position, at about 3 miles range, high level." The language is simple, but it is loaded with a lot of implied meaning.

Intercultural competence is important for the air force as missions are flown to different locations in the world with a diversity of different teams. English is the lingua franca in the air force and all other military branches, but it would be too simplistic to build a direct correlation language-culture. Cross-cultural communication calls for a common language and for mutual understanding. It is beyond any doubt that when squadrons with diverse cultural backgrounds must work together, the differences among them can turn into crucial impediments to the success of their operation. Building an awareness of these cultural differences is a prerequisite for successful international missions and effective alliances. In most collaborative operations aircrew from diverse backgrounds are expected to interact in a common language as well as to know the core cultural values of their counterparts in order to promote efficient in-group relations and to achieve mission objectives. They should be able to adapt to new communicative practices, to negotiate ideas with personnel from various lingua-cultural background, and to respect different races, religions, and cultures. There are some studies, which have already addressed the topic of culture in aeronautical English communication [11]. However, the influence of culture on radiotelephony exchanges between pilots and air traffic controllers communicating in English is still not fully recognized, necessitating instruction in intercultural communication techniques.

Insights into the link between communication in a foreign language and culture were brought by the study of Geert Hofstede and his followers, his son Gert Jan Hofstede and the Bulgarian scholar Michael Minkov [16]. These scholars discuss the three facets of culture: the culture of a nation and a society, the culture of an organization and the culture of a profession. The three cultures shape one’s actions, attitudes, and language. These three facets of culture play their significant roles in aviation – a high-risk multi-cultural environment that requires excellent coordination among members. The culture of a nation, with its set of common values, concepts and beliefs, and of a society, with its knowledge, patterns of behavior and practices, are deep-seated in the human mind and in most cases, they are highly resistant to change. This means most representatives of a given national culture have common personality characteristics that stand out when they meet with representatives of other nations. The culture of an organization and the culture of a profession are more flexible and can be modified if there are strong incentives [16].

Language and cultural barriers may lead to miscommunication. For instance, Helmreich and Merritt [17] pointed out that power distance had been one of the critical factors that contributed to the fatal disaster of Avianca flight 052 . The scheduled Avianca Flight 052 from Bogota, Colombia to New York on 25 January 1990 is a tragic example of how cultural legacy can lead to disaster. In addition to weather and fuel miscalculations, investigators blamed the crash that led to the death of 8 crew members and 65 passengers on the crew members’ proficiency in English and their culture. According to Hofstede’s scale, Colombia has a high PDI, and it is a masculine and collectivist country. Before the missed-approach procedure, the first officer said to the air traffic controller, “We're running out of fuel, sir,” when he should have declared an emergency due to a shortage of fuel. After the missed approach, the ATCO told Avianca 052 that he was going to “...bring you about 15 miles northeast and then turn you back for the approach. Is that fine for you and your fuel?” The first officer replied, “I guess so, thank you very much.” Actually, instead of this reply, he should have asked for a priority landing – “MayDay MayDay MayDay. 052 declaring an emergency due to lack of fuel. Request priority landing.” However, the first officer was too deferential, too soft and respectful to the air traffic controller because he considered him superior. Due to his culture, he spoke politely and non-directly and he was reluctant to object to the ATCO’s suggestion for a new route. In high power distance countries, there is hierarchy and all members expect and accept willingly power rankings and inequality. Subordinates never refute the opinion of their commanders directly. The cultural background of the first officer influenced his English and his choice of words. Culture-bound, he never explicitly informed the ATCO of their emergency situation although the situation was desperately urgent.

3. James Reason’s Swiss Cheese Model of Accident Causation

James Reason [18], a professor of psychology at The University of Manchester, realized that in complex systems such as aviation, nuclear power plants, or health care many components interact with each other. As safety has always been a priority in all these industries, Reason developed the Swiss Cheese Model of Accident Causation in order to address organizational accidents. Up until that moment individuals had been blamed for most of the systematic failures and the unsafe acts in aviation accidents. Errors or procedural violations had been due to person’s ignorance, forgetfulness, negligence, recklessness, etc. Reason’s model changed the focus from the individual to the organization. It tracks accident causation at different levels of the organization but system failures are not pinned on individuals. Moreover, Reason’s contribution was the idea that aircraft accidents are not caused by a single factor but by a chain of events i.e. a complex interplay of multiple factors. The Swiss Cheese Model of Accident Causation [18] determines the true causes of an accident by linking different contributing factors to a rational sequence that runs bottom-up in causation and top-down in investigation. Reason presents his model as slices of Swiss cheese in a sequence (see Fig. 1) where the slices represent the defenses and safeguards of the system against something going wrong, and the holes represent active failures and latent conditions. Active failures are human errors and violations – they have a direct impact on the safety of the system. Latent conditions such as product defects, training or control failures, equipment problems, etc. may lie dormant for hours, days, or years before they combine with active failures and create an accident trajectory. Some latent conditions can be prevented before an accident happens by training, planning, scheduling, etc. These Swiss cheese holes move all the time, opening and shutting or changing their location. The presence of holes in a slice of cheese does not normally bring about a bad outcome. This can only happen when the holes in successive layers line up to permit a pathway of accident opportunity. "Organizational accident trajectories can just as easily slip through the small and apparently insignificant cracks in the system as they can through the yawning gaps" [18, p.21]. Accidents result from an alignment of conditions and events each of which is necessary, but yet none is sufficient on its own.

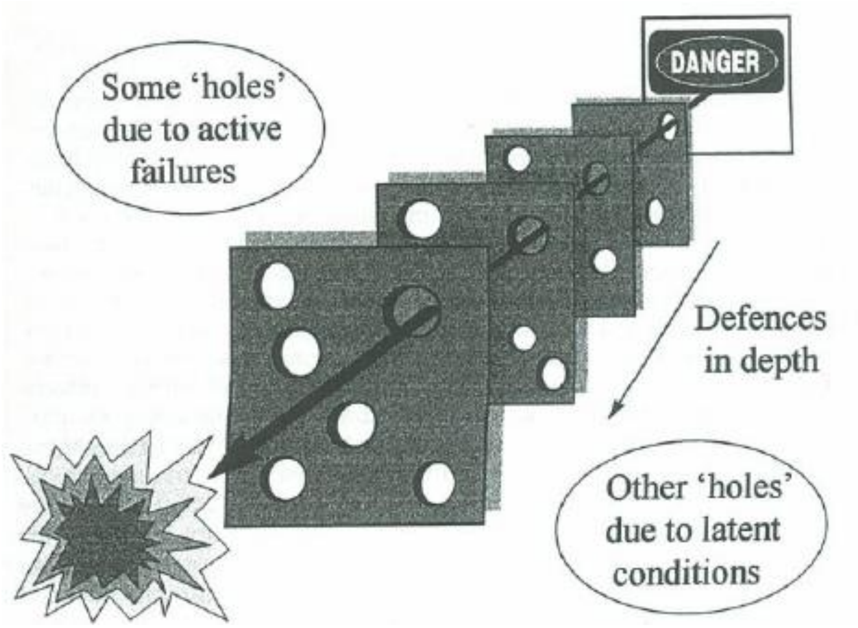

Fig.1. Reason's model of accident causation [18]

No human system is perfectly safe, so these possibilities for accidents occur, though rarely. However, their consequences can be detrimental. "Defences can be dangerous. The best people can make the worst mistakes. The greatest calamities can happen to conscientious and well run organizations" [18, p.21]. Nevertheless, Reason's idea is that in any complex organization all layers should operate harmoniously in order to achieve a safe and efficient system.

4. Reason's model within aeronautical English environment

The diversity of the air force operational environment in the contemporary globalized world has increased the complexity involved in the present-day aviation training, including language training. English communication in the aviation context is complex and there are a lot of layers. The aeronautical English discourse between pilots and air-traffic controllers (ATCOs) is remarkably different from other registers of professional language. The difference is not only in linguistic characteristics such as vocabulary and syntax, but it is also in prosodic characteristics and various human factors such as stress, workload, fatigue and working memory constraints.

Miscommunication in the radiotelephony exchanges between pilots and air traffic controllers is not usually caused by a single factor but rather by a combination of multiple factors; the problem is not using one word incorrectly, or not applying a grammar rule well, or breaching one procedure, or ignoring the cultural background of the other pilot. Miscommunication is usually caused by a sequence of language mistakes, human errors and embarrassing blunders.

Aviation accidents would not happen unless there were latent weaknesses in the system. These weaknesses may exist in the barriers and defences as well as in the established practices of work. The logic is that by identifying the potential weaknesses of a system in advance, it may be possible to intervene before an accident takes place.

Taking the Swiss Cheese Model as a metaphor, it is further applied to communication in aeronautical English. Considering the characteristics of the multicultural aviation environment, it can be concluded that a more comprehensive notion of aeronautical English teaching is needed in order to cope with ab-initio military pilots' and air traffic controllers' communicative needs. The overall idea is to promote an awareness and formation of an aeronautical English teaching, which merges the development of various competences and juxtaposes linguistic and scientific components. The layers of defense in aeronautical communication include four competences – linguistic, interactional, cultural, and professional. By developing the language knowledge, skills, and attitudes and by raising the interactional competence of students, by making them aware of the cultural differences and their influence on communication, and by involving background professional competences into the communication process, teachers can boost the foreign language communicative success in the classroom and minimize future miscommunications in the workplace.

Military pilots and air traffic controllers communicate using standard phraseology, a specific coded tool, and in cases of emergency plain aviation English, a sublanguage of aviation English. The problematic issues, or holes as James Reason calls them, in the linguistic layer may be components such as intelligible accent and pronunciation, language structures, ambiguous language, phraseology, language proficiency, etc. The interactive competence of students is an indispensable component of the communicative competence. The holes of the interactional layer can be hearback and readback messages, code-switching, information omission, vague instructions, etc. The professional competence includes indicators such as complying with the rules and regulations, keeping up professional behavior and attitude, using appropriate tone of speech, etc. The professional layer can be compromised by deficiencies or holes such as lack of radiotelephony procedures, deviations of the required format, which comprises the communication loop, content imprecisions, patterns of turn-taking, etc. Furthermore, efficient aeronautical English teaching implies raising pilots and ATCOs' awareness for multilingualism and diversity of cultures in the aviation English context because it can have a great impact on communication. Cadets must learn to be aware of the responsibility of being communicators in an international, cross-cultural, and multilingual environment. Cultural competence is a process that develops gradually over an extended period of time. The role of the teacher is not to make students accept a particular culture or behave in accordance with its conventions. Cultural relativism refers to not judging a culture to our own standards of what is right or wrong, strange or normal as well as not judging according to the native-speakers' culture. Instead, we should try to be sensitive to cultural practices of other groups and be aware of their influence on communication in radiotelephony. Cultural and professional competences complement the linguistic and interactional competence and contribute to efficient and safe communication during task performance. The culture layer may have "holes" such as stereotypes, power distance, gender equality, organizational issues, etc. All layers or defenses are components of the complex and dynamic process of aeronautical communication. All of them and all their aspects are important. At a particular moment the small issues in communication from the different layers align and only one aspect of these layers may exceed as a factor which generates the communicative problem. None of these layers or holes is exclusive; each of them may be used to perceive the predominance of a communicative problem.

This model of an aeronautical English construct, based on Reason's model of accident causation, reveals the dynamic and interdependent interaction of language, culture and professionalism. By developing students' communicative competence we try to reduce human errors in radiotelephony exchanges in future real life situations and optimize at least one aspect of human performance that is one of the leading causes for aircraft accidents and incidents.

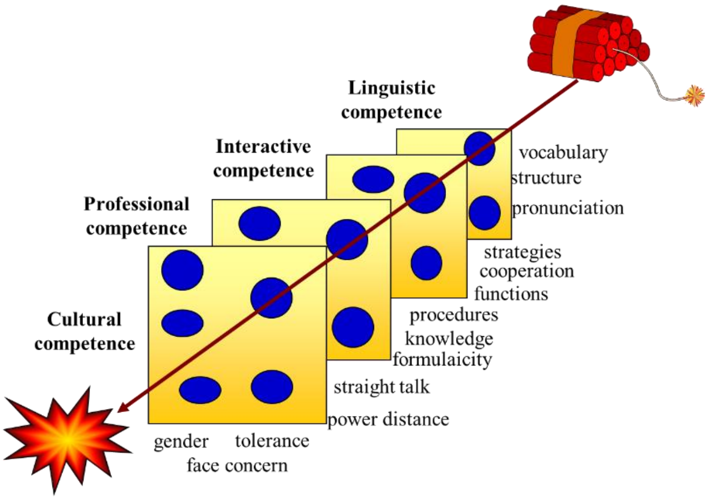

Fig.2. Interaction of language, culture and professionalism in an aeronautical English construct

This model could be taken as a starting point for the aviation English language classroom. Classroom task-types, which are based on the communicative demands of pilots and ATCOs and resemble situations encountered in real life, are suggested: role-plays, simulations, picture narrations, pre-flight briefings, case studies, mission planning, debriefs, pyramid discussions, and mini-meetings. The key characteristics of classroom tasks should be authenticity and the need for interaction between language knowledge, aviation content knowledge, and culture awareness. The individual qualities of the classroom tasks are important but they should not be evaluated independently and out of context. Task-types and particular tasks should be considered in terms of their combined effect on the overall usefulness of the course. All task-types should build up to a robust, relevant and useful aeronautical English course.

5. Conclusions

Effective communication in English between pilots and air traffic controllers is an important factor for flight safety. Although having good English language proficiency is essential, successful exchanges within the aeronautical domain surpasses mere linguistic adeptness. In an intercultural aviation context a broad array of knowledge, skills, and attitudes are needed for successful communication. This article highlights four major competences that should be developed during the aeronautical English teaching and training. In order to function efficiently as international communicators, military pilots and air traffic controllers must completely develop linguistic, professional, intercultural, and interactional competence. This entails grasping linguistic subtleties and specialized termnology on one hand; and on the other hand, mastering interpersonal dynamics, possessing thorough familiarity with industry-specific protocols, and adeptly navigating cultural differences. The objective is not only to deliver cadets who do well in their classroom and in the final English language exam but also to deliver pilots and ATCOs who can perform well in their authentic environment and communicate efficiently in English in both routine and non-routine situations. Following the Swiss Cheese Model all of these competences are incorporated into the aeronautical English classroom, representing the complex characteristics of the target-language use domain. Thus, future military pilots and air traffic controllers will be able to successfully practice their profession in a multinational, multilingual and multicultural environment.

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