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DEVELOPMENT OF THE DESIGN OF AN EXPERIMENTAL LONG-RANGE FIXED WING UAV

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Abstract

The goal of the article is the design and assembly of a flight-capable platform for testing an experimental hybrid drive developed within the grant project. The input for the entire work is designed for the highest take-off weight of 10 Kg and a pair of driving electric motors with a thrust of 5 Kg each (49,05 N). The content of the article includes basic theory, analyses, simple structural calculations and design methods, the design itself, construction methodology and work results. Analyzes in the article include analyzes of currently used types for the design and construction of hybrid unmanned aerial vehicles and analyzes of materials used for UAV structures with a piston propulsion unit, on the basis of which the design and construction of the UAV was proposed. As part of the design, the construction and design are recalculated and simulated both aerodynamically and strength-wise. Several software were used in the design and simulations: AutoCAD Inventor for modeling and strength analyses, Autodesk CFD for airfoil simulations and XFLR5 for the aerodynamics simulation of the UAV design. In the practical part, the production methodology is described in detail and illustrated with original photographs.

Keywords

unmanned aerial vehicle, maximum take-off weight, structural analysis, design aerodynamics, hybrid propulsion, strength analysis, simulation, production, flight tests, flyght envelope, weight and balance, performnce

1. INTRODUCTION

A hybrid UAV with fixed support surfaces is a winged unmanned aerial vehicle using a combined energy source to drive propulsion units from the rule of electric motors with propellers. Currently, the most widespread technology for hybrid systems is an electric generator set that is driven by an internal combustion piston engine similar to hybrid cars in the automotive industry.

2. ANALYSYS OF THE FIXED WING UAVS CONSTRUCTIONS

Most fixed-wing UAVs have a structure comprising wings (fixed wing) with lift mechanism, "winglets" and ailerons, Fuselage, Tail (Tail surfaces, Vertical Stabilizer, Rudder, Elevator) and Landing Gear. Landing gear is not normally found in the lower weight categories of UAVs, because most UAVs have a VTOL function or are launched using a catapult or take off in the so-called with a "throw from the hand" and lands on the torso. When comparing classic UAVs with an electric energy source for their drive and hybrid gasoline-electric UAVs, there are fundamental differences in the construction used. Because hybrid UAVs, in addition to being more massive, are also stressed differently, especially by heat and vibrations from the combustion engine. Another difference is the MTOW, which for hybrid UAVs can be tens of kilograms (depending on the purpose) and the operating speed (CS – cruise speed), which can exceed up to 100 km/h. Depending on the performance requirements, the design of a hybrid-powered UAV may vary. Most battery electric UAVs with a fixed support surface have a simple hull shell construction with structural partitions mainly for storage of the battery, controls and hardware, while the wings are made in one piece without a strength coating similar to tail surfaces. The most widespread construction material of civil UAVs with a low weight category is polystyrene or balsa wood or composite and plastic materials. The tail is simply connected to the fuselage using a plastic or carbon beam. [2] In the case of the construction of hybrid UAVs, mainly composite materials are used, which can withstand higher temperatures and cyclic stress, and at the same time are suitable for the application of aircraft with a higher MTOW (maximum take-off weight). The unit must be placed between the partitions, which simultaneously form the shape and strength element of the UAV fuselage. Wings require strength cover and beams. Beams are usually designed as carbon hollow logs ("tubes") or web beams ("I" beams). The cover is made of composite carbon or fiberglass, similar to the fuselage and tail surfaces, or wood slats, made of alder wood covered with foil. [3] Compared to standard fully electric UAVs with fixed support surfaces, this brings considerable complications in production, which is reflected in the production costs of the hybrid UAV itself. Overall, it can be assessed that within the design and subsequent production of a flight-capable structure, it will be necessary to use composite materials at least for the production of the fuselage where the hybrid unit is located. It will also be necessary to consider the complexity of the design and construction in relation to production possibilities and available funds.

2.1. General categorization of hybrid UAVs according to EASA legislation

In general, hybrid UAVs have a maximum take-off weight exceeding 2 kg, therefore they are classified according to EASA in subcategory A3 (< 25 kg, CS > 19 m/s) or higher category (if MTOW > 25 kg). This means that the operation of such UAVs is significantly limited by legislation. Every operator of UAV subcategory A3 is obliged to register such UAV, insure it and provide training for the UAS pilot. Also, the UAV of this subcategory must not be operated in built-up areas with a high density of people and at least 150 m from it, for safety reasons. [1]

2.2. Current use of hybrid fixed wings UAVs

Currently, unmanned aerial vehicles are generally widely used, especially for aerial work, sports acrobatics, hobby flying or in defense. Hybrid UAVs with fixed airfoils, due to their high endurance, range and performance, are mainly used for:

- Experimental purposes (technology demonstrator)
- Atmospheric research
- Mapping and land surveying
- Monitoring of border areas
- Agricultural work (spraying)
- Shipping works [3] [4]

Individual hybrid UAVs often differ in concept. However, most of the currently produced UAVs of this concept use rectangular or trapezoidal wings with a "boom tail" concept of tail surfaces and an arrangement of propulsion units that allows vertical take-off and landing (e.g. quadcopter arrangement) [3]. Hybrid UAVs with a fixed support surface belong to larger aircraft not only in terms of weight but also in terms of size. They have a span from 2 m to 4 m and more, and a total length from 1.5 m to 3 m or more, despite the fact that they are high-performance motor planes, which makes their compactness difficult [3].

2.3. Theory of hybrid drones design and construction development

When developing the design of an unmanned aerial vehicle, it is necessary to take into account, in particular, the required performance of the aircraft (maximum take-off weight, maximum cruise airspeed, max. stall speed, stability, etc.), the budget for construction, the availability of materials and production technology, and the purpose of the unmanned aerial vehicle . On the basis of individual input parameters and options, a basic preliminary design is established, which refers to the aerodynamic, geometric and strength characteristics of individual structural units, such as:

- Wings and its mechanization
- Hull and its elements
- Tail
- Tail surfaces
- Landing gear (undercarriage)

Individual characteristics directly define the performance of the UAV. Their results are obtained by different methods:

- Calculation by simplified equations
- complex detailed calculation (through MATLAB software, etc.)
- using modeling and simulation software (AutoCAD Inventor, Autodesk CFD, XFLR5, Flow 5, etc.)
- by direct measurement in laboratory conditions (in wind tunnels)
- direct flight test in the field

Currently, it is customary to apply design elements and UAVs proven by practice, the functionality of which is verified by basic preliminary calculation, model creation and simulation in computer CAD software or in other simulation analysis software, and finally by flight test in the field.

3. PROPOSAL AND DEVELOPMENT OF THE HYBRID EXPERIMENTAL UAV CONSTRUCTION

The initial requirement for the development of the structure is dimensioning for a maximum take-off (operating) weight of 10 kg, installation of an aggregate with a GP38 combustion engine and a FOXY G2 C5340-7 195KV electric motor-generator, two FOXY C4125-9 drive propulsion units with G-SONIC Sport 40-propellers 30cm/16-12", with an assumed maximum usable pull of 5 Kg (48.05 N) each. The cruising speed was preliminarily selected at 54.612 km/h. Since the structure is to be implemented and tested in the field, the development will emphasize the reliability of the structure, the simplicity of production due to limited financial and production capacities, the high stability of the UAV due to the filling of the structure itself, which will serve primarily to test the functionality of the hybrid unit in the field and its efficiency. The UAV concept will be addressed as the traditional concept of most multi-engine UAVs with a CTOL-type fixed airfoil and a conventional tail.

3.1. Wing and ailerons proposal

The wings will be realized as combined, rectangular in 1/3 and trapezoidal in 2/3 of the wing span, while the trapezoidal ends of the wings will have a positive lift of $\Phi = 3°$. The wing tip termination will be conventional, without "winglets". The wing-fuselage arrangement will be solved in the upper-airplane concept, while there will be an adjustment angle of $\phi = 2°$ between the longitudinal axis of the fuselage and the chord of the wing profile The trapezoidal part of the wing will be geometrically twisted negatively by an angle $\varepsilon = -3°$ Since the wing will be removable from the fuselage along its entire length and the UAV will not have high cruising speeds, the interference resistance will be neglected and therefore the shape transitions between the wing and the fuselage (and other parts) will not be realized.

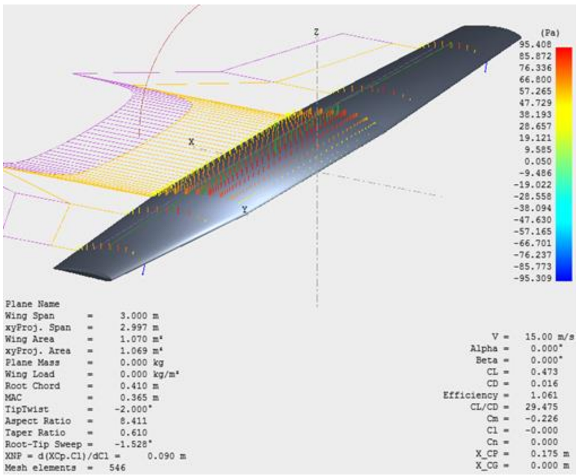
The selected airfoil for the main airfoil is the NACA 4412 airfoil, which is generally used for UAVs with fixed airfoils and general aviation aircraft. [6] The wing of the long-range UAV will not be aerodynamically twisted, the NACA 4412 profile will be used in the cross-section of the entire wing. Tilt control mechanization - the ailerons will be differentiated and will be located approximately 80% of the length of the trailing edge of the trapezoidal parts of the wing. Overall, the wing solution will bring the advantage of lift distribution with an area of effect closer to the root of the wing thanks to the trapezoidal end of the wing, and thus the wing, together with its attachment to the fuselage, will be stressed by a smaller bending moment. At the same time, the wing will not be complicated to manufacture in terms of design due to the absence of aerodynamic twist. The positive lift and upper-plane arrangement of the wing-fuselage will ensure high lateral stability, and at the same time the ailerons with a relatively large span at the trapezoidal ends of the wing will ensure effective pitch control. The negative twist of the trapezoidal part of the wing will bring better directional controllability and reduce the induced aerodynamic resistance, which will also contribute to the tension of the trapezoidal ends of the wing. Therefore, with the given parameters, it will not be necessary to end the wings with "winglets". The FOXY C4125-9 propulsion units with G-SONIC Sport 40-30cm/16-12" propellers will be located parallel to the fuselage axis in the straight part of the wing, with the propeller axis 350 mm away from the straight line crossing the center of the wing plan. Propulsion engines with propellers are attached to the nacelle in the leading edge or as traction drive units. The physical proportions and aerodynamic properties of the wing and ailerons were calculated by simple calculation and simulation in XFLR5 software. Construction modeling and strength analyzes were performed in AutoCAD INVENTOR software. The results of the wing design are summarized in tables and illustrations.

Table 1 - Aerodynamical and geometrical properties of proposed wing

Parameter	**Symbol**	**Value**	**Unit**
Wingspan	b	3	m
Root chord	C_{root}	0,41	m
Typ chord	C_{typ}	0,25	m
Wing surface	S	1,07	m^2
Geometrical twisting	ε	-3	°
Aerodynamical twisting	-	-	-
Arrov angle	χ	-1,53	°
Dihedral	Φ	3	°
Aspect ratio	AS	8,4	-
Tapering	λ	0,61	-
MAC	C_{SAT}	0,365	m
Wing set angle	φ	+2	°

Table 2 - Aerodynamical and geometrical properties of aileron

Parameter	**Symbol**	**value**	**Unit**
Aileron root chord	$C_{a\ root}$	0,085	m
Aileron typ chord	$C_{a\ typ}$	0,065	m
Aileron span	b_a	0,8	m
Max positive deviating angle	$+\ \delta_{max}$	25°	°
Max negative deviating angle	$-\ \delta_{max}$	5°	°
Differentiation ratio	$-\ \delta_{max}/+\ \delta_{max}$	1/5	-
Aileron surface	S_a	0,06	m^2
Aileron tapering	λ_a	0,765	
Maximum lift coefficient of deviated wing	C_{La}	0,65	-
Span ratio	b_a / (0,5 * b_w) * 100	53,3	%
Surface ratio	S_a / (0,5 * S_w) * 100	11,2	%



```
Plane Name
Wing Span        =     3.000 m
xyProj. Span     =     2.997 m
Wing Area        =     1.070 m²
xyProj. Area     =     1.069 m²
Plane Mass       =     0.000 kg
Wing Load        =     0.000 kg/m²
Root Chord       =     0.410 m
MAC              =     0.365 m
TipTwist         =    -2.000°
Aspect Ratio     =     8.411
Taper Ratio      =     0.610
Root-Tip Sweep   =    -1.528°
XNP = d(XCp.Cl)/dCl =      0.090 m
Mesh elements    =   546
```

```
         V =   15.00 m/s
     Alpha =    0.000°
      Beta =    0.000°
        CL =    0.473
        CD =    0.016
Efficiency =    1.061
     CL/CD =   29.475
        Cm =   -0.226
        Cl =   -0.000
        Cn =    0.000
      X_CP =    0.175 m
      X_CG =    0.000 m
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Figure 1 - XFLR5 wing aerodynamical simulation

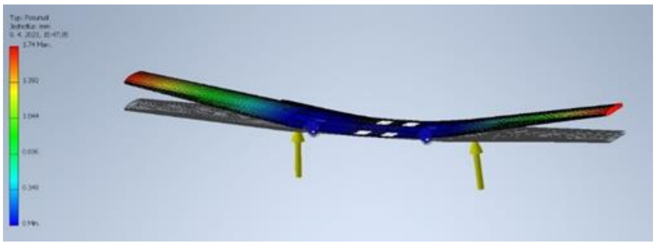


Figure 2 - AutoCAD INVENTOR wing strength analysis

The areas of influence of lift on the half-spans of the wing are derived by a graphical method.

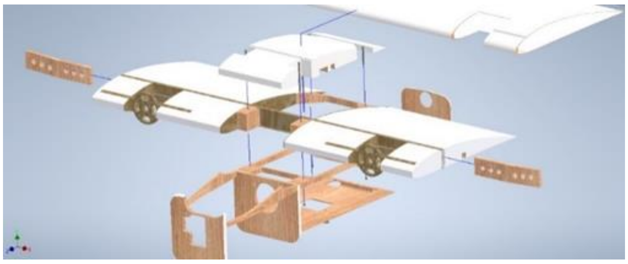


Figure 3 - AutoCAD INVENTOR central rectangular part model

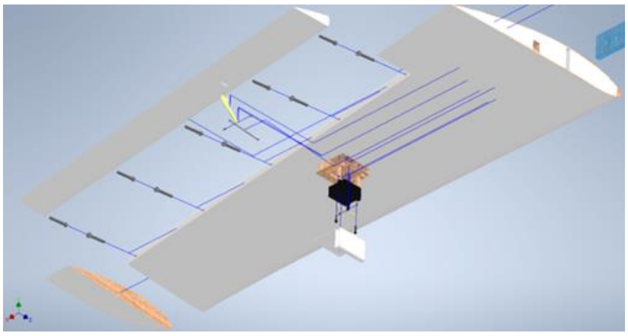


Figure 4 - AutoCAD INVENTOR wing tapered part model

3.2. Fuselage proposal

The hull is designed to be symmetrical with a square cross-section and rounded edges. The design is inspired by a design analysis for a UAV with a fixed airfoil. [5] The tail will be circular in cross-section, conical in shape and will be embedded in the fuselage as an integral part of the fuselage. Geometric parameters are dimensioned with respect to the size and location of the aggregate, fuel tank, battery, and control and monitoring hardware.

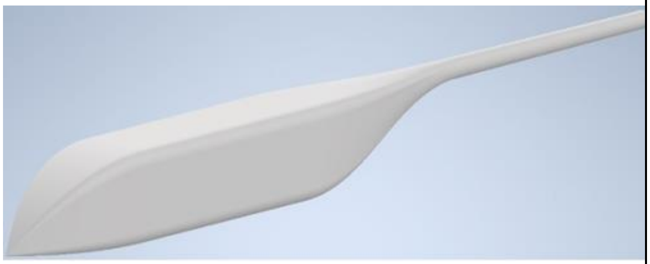


Figure 5 - AutoCAD INVENTOR fuselage design model

Table 3 - Geometrical properties of UAV fuselage.

parameter	**Symbol**	**Value**	**Unit**
Fuselage lenght	L_F	2	m
Maximum fuselage width	W_F	0,2	m
Maximum equivalent ratio	$d_{e\,f}$	0,22	m
Maximum fuselage cross section surface	$S_{p\,F}$	0,0386	m^2
Štíhlosť trupu	λ_F	11,1	%
Wetted surface	$S_{om\,F}$	0,846	m^2

Figure 6 - AutoCAD INVENTOR fuselage wooden inner construction

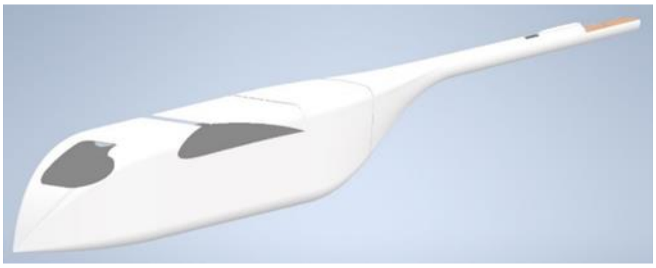


Figure 7 - AutoCAD INVENTOR fuselage composite shell

3.3. Tail surfaces proposal

The tail surfaces were chosen over conventional trapezoidal tail surfaces because they are simple to manufacture, durable, provide relatively good stability and, despite being more sensitive to propeller blow-by and trailing water at higher angles of attack and during the landing phase ("FLARE"), provide good directorship. Another reason for the choice is that it will not be necessary to use a different concept of tail surfaces for UAV purposes and arrangement of propulsion units. As a profile for the tail surfaces, a neutral symmetrical profile NACA 0008, with 8% thickness, was chosen, which, although it has a low critical angle of attack (limited sensitivity to stabilization in case of larger disturbances), but provides minimal resistance compared to thicker profiles [9]. For the selected tail concept, the NACA 0008 profile is sufficient.

Table 4 - Geometrical properties of UAV tail surfaces

Parameter	HTS		VTS		Unit
	Symbol and value				
Root chord	C_{Hroot}	0,24	C_{Vroot}	0,19	m
Typ chord	C_{Htyp}	0,14	C_{Vtyp}	0,13	m
Span	b_H	0,9	b_V	0,27	m
Elevator and rudder soan	b_e	0,9	b_r	0,25	m
Elevator and rudder width	C_E	0,06	C_R	0,07	m

The tail surfaces of long-range UAVs are designed as structural. The leading and trailing edges, including transitions between stabilizers and rudders, are designed as beams, connected by profiled ribs, between which are diagonally placed rod reinforcements. The transitions between stabilizers and rudders are rounded to a radius from the outside. The tail surfaces do not have a strength coating. The cover is made of iron-on modeling white foil.

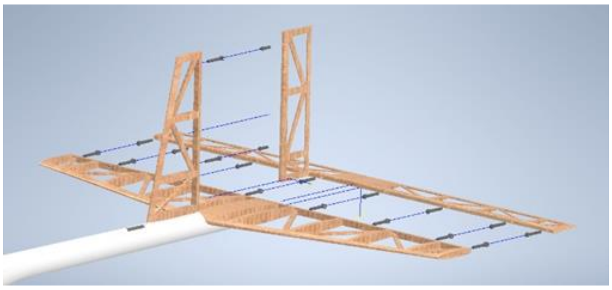


Figure 8 - AutoCAD INVENTOR tail surfaces construction model

3.4. Propulsor engine and hybrid agregath bed

Both engines load the wing with additional torque from thrust, weight, and reaction and gyroscopic torque. Therefore, the engines will be bolted crosswise to the nacelle, which will be embedded in the wing and which will be part of the strength box. The reinforced case is formed from the rear by the main wing beam with an "I" profile made of spruce flanges and a web made of cardboard wood. On the sides, the strength box will be formed by walls made of cardboard wood in the shape of a profile, and in the front part the nacelle itself, which will also have side projections embedded in the core of the wing. On the inside, the strength box will be additionally reinforced with a U-shaped wooden reinforcement made of spruce wood. The strong box with the nacelle will form the motor bed individually for the drive electric motors.

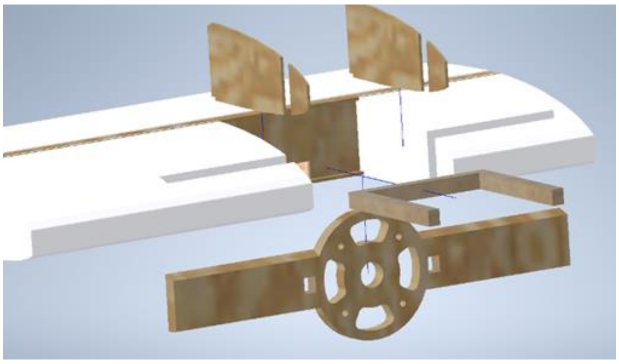


Figure 9 - AutoCAD INVENTOR engine bed construction model

The position of the hybrid unit was chosen in view of the long-range UAV design concept, in the front part of the fuselage ("in the nose"). The unit is located with the piston engine at the tip of the UAV nose, due to the roundness and the need to expose the largest possible area of the piston to the air flow, as the GP38 engine is air-cooled. The entire unit is composed of a piston engine, a flexible coupling without starting the electric motor-generator flange and the electric motor-generator itself. The entire assembly is stored in a cage formed by four screw rods with a diameter of 4 mm and fixed with M4 nuts. The cage with the aggregate is stored in silent blocks and attached to the partitions that are part of the internal structure of the UAV fuselage.

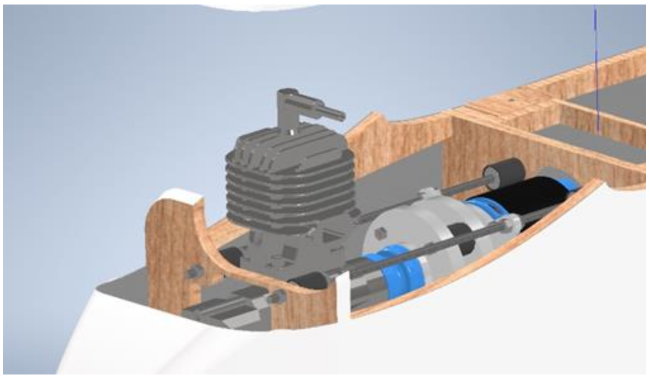


Figure 10 - AutoCAD INVENTOR hybrid agregath bed

3.5. Landing gear propose

The landing gear - the landing gear of the long-range UAV is designed based on the prototype of the tricycle landing gear for transport aircraft [7]. The exact position is developed based on the position of the center of gravity of the balanced UAV and, within the prescribed intervals, the selected angles of the wheel tangents and the vertical axis passing through the center of gravity.

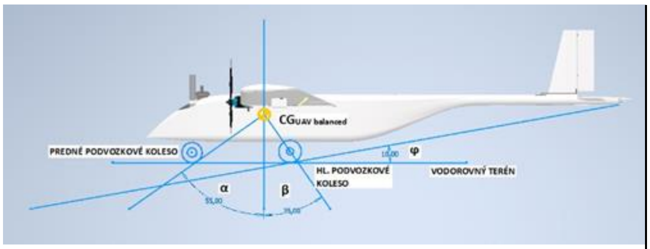


Figure 11 - AutoCAD INVENTOR Landing gear position sketch

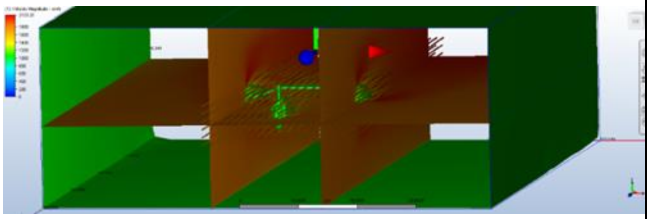


Figure 12 - AutoCAD INVENTOR Landing gear CFD airfoil simulation

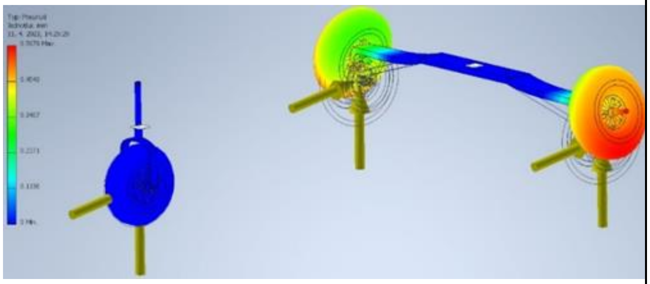
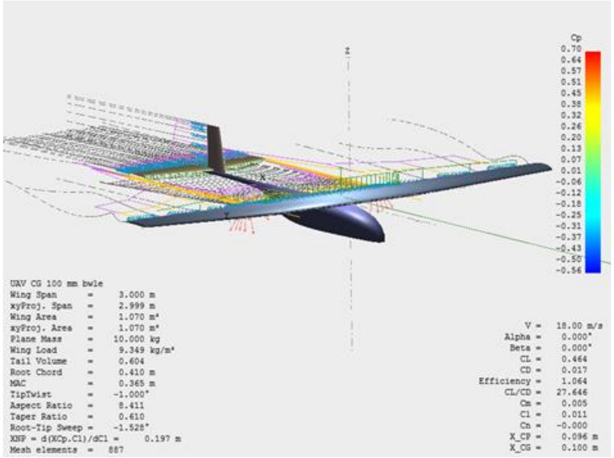


Figure 13 - AutoCAD INVENTOR Landing gear strength analysis

3.6. UAV propose results

Design elements were simulated in CFD software, their influence is negligible. The design was simulated in XFLR5 software and assembled in AutoCAD INVENTOR software. The model was used in the creation of drawings and in the construction of the UAV. Weight and balance, performance and flight envelope have been recalculated.



```
UAV CG 100 mm bwle
Wing Span       =    3.000 m
xyProj. Span    =    2.999 m
Wing Area       =    1.070 m²
xyProj. Area    =    1.070 m²
Plane Mass      =   10.000 kg
Wing Load       =    9.349 kg/m²
Tail Volume     =    0.604
Root Chord      =    0.410 m
MAC             =    0.365 m
TipTwist        =   -1.000°
Aspect Ratio    =    8.411
Taper Ratio     =    0.610
Root-Tip Sweep =   -1.528°
XNP = d(XCp.Cl)/dCl =     0.197 m
Mesh elements  =   887
```

```
         V =   18.00 m/s
     Alpha =    0.000°
      Beta =    0.000°
        CL =    0.464
        CD =    0.017
Efficiency =    1.064
     CL/CD =   27.646
        Cm =    0.005
        Cl =    0.011
        Cn =   -0.000
      X_CP =    0.096 m
      X_CG =    0.100 m
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Figure 14 -XFLR5 analysis of proposed UAV analysis

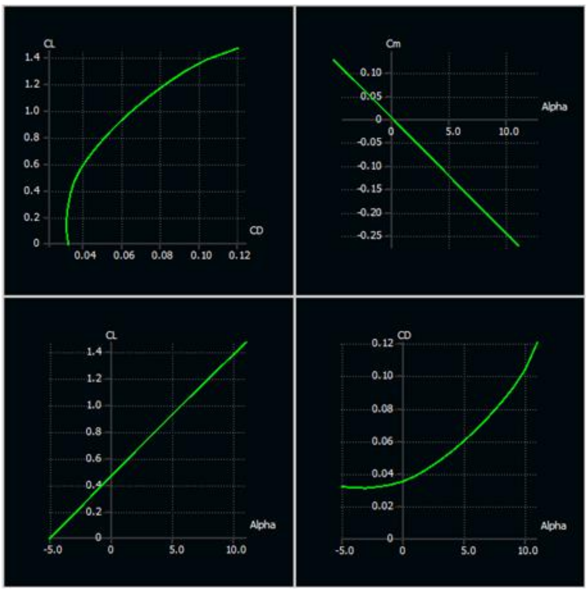

Figure 15 - Aerodynamical properties od proposed UAV design

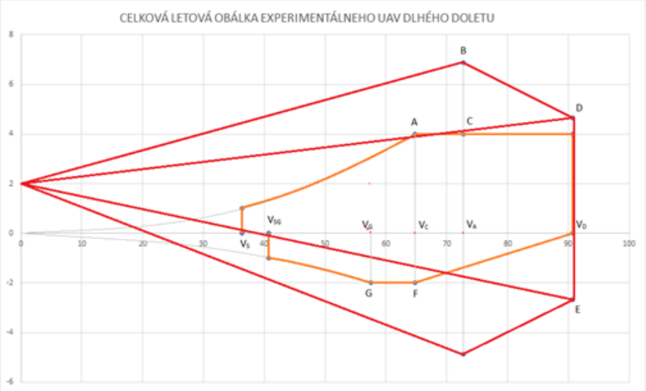

Figure 16 - Calculated UAV flight envelope

Figure 17 - AutoCAD INVENTOR done UAV model

4. VÝROBA KONŠTRUKCIE HYBRIDNÉHO UAV

4.1. Production of UAV wing

The wings were made by resistance cutting from polystyrene blocks. They were covered with balsa wood sheets and finally covered with white modeling foil. Parts of the wing, engine nacelles, servo motor mounts were thrown out of cardboard wood on a CNC mill. The wings were cut and made similar to a wing.

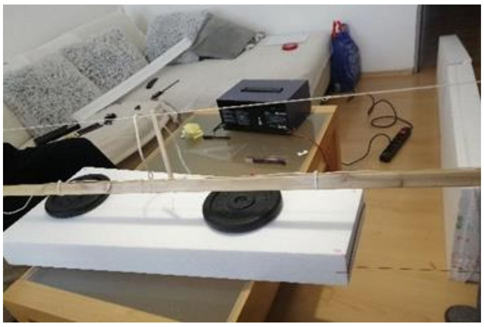

Figure 18 -Process of wing cutting

Figure 19 -Applied wing balsa cover

Figure 20 -Mounted aileron on tapered wing part

Figure 21 -Done UAV wing

4.2. Production of fuselage

The hull is made of fiberglass with epoxy and the internal structure is made of wood. The molds for the fuselage were made of polystyrene covered with foil, and separated with wax during the lamination process. The shell merged with the tail and the shape transition de-laminated. The seat for the wing and the front cover were cut with a flexi sander. Parts of the internal structure were made on a CNC mill and glued into the machined shell.

Figure 22 -Positive UAV hull forms

Figure 23 - Laminated part of UAV hull

Figure 24 -Done UAV fuselage shell

Figure 25 - Fuselage Inner construction mounting

4.3. UAV tail surfaces production

Due to unfavorable circumstances, the tail surfaces had to be made non-profiled as it was not possible to mill the profiled ribs on the available CNC mill. The aerodynamic properties of the UAV are not significantly affected, and due to the purpose of the experimental UAV, the unprofiled tail surfaces are sufficient. Similar design solutions are also found on ultralight aircraft and motorized aircraft with STOL characteristics, such as the Piper P-18 "super cub" or Laser 230 aircraft [8].

Figure 26 - Horizontal stab with elevator assembly

Figure 27 - Done horizontal tail surface

Figure 28 - Done vertical tail surface

Figure 29 -UAV tail surfaces mounted on fuselage integrated tail

4.4. UAV landing gear production

The landing gear of the UAV was made on the basis of available semi-finished materials and production equipment. The material used for the production of the landing gear axles is finally available aluminum 6063. Due to the circumstances, the design was used primarily for inspiration in the production of the landing gear for the experimental long-range UAV. Therefore, some shape elements will be slightly different from the design. Despite this, the properties of the landing gear will not change significantly and the landing gear will fulfill its purpose.

Figure 30 -Main gear springs parts

Figure 31 -Main gear mounted on UAV fuselage

Figure 32 - Front gear servo engine ride system mounted on UAV

4.5. UAV production result

The hole in the front cover for the GP38 engine piston will be cut after the first flight test.

Pic. No. 33: Done UAV flyable construction

5. CONCLUSION

The structure is recalculated, simulated and ready for mounting the drive and steering. The first test flight is planned for May 8, 2023.

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