Numerical analysis of the support platform for an unmanned aerial vehicle

Z Czyż¹, S Suwala¹, P Karpiński² and K Skiba²
¹ Aeronautics Faculty, Military University of Aviation, 35 Dywizjonu 303 St., 08-521 Dęblin, Poland
² Department of Thermodynamics, Fluid Mechanics and Aviation Propulsion Systems, Faculty of Mechanical Engineering, Lublin University of Technology, 36 Nadbystrzycka St., 20-618 Lublin, Poland
z.czyz@law.mil.pl

Abstract. The study investigates a thin-walled support platform for an unmanned aerial vehicle, i.e. aluminum beams connected by flat bars and angle irons. The construction is a kind of frame for a propulsion unit of the designed aircraft which is a combination of a multi-copter and a gyrocopter. This construction was tested for various load patterns to investigate the stresses and strains its profiles are connected. The load patterns correspond to different operation modes of the propulsion system, and the finite element method (FEM) and the SolidWorks software were used for the numerical calculations. The research was done for elastic operation of the individual components of the support platform. The analysis enabled to verify the state of stresses on the critical spots of the construction and to develop a construction for ground and flight tests to verify the correct operation of the propulsion control system and optimize its operation in different flight states.

1. Introduction
Verified by the factor of safety [1], material strength in aircraft constructions is a fundamental issue for safety. Aircraft constructions need to be strong enough to withstand any stresses. Their critical components are made of aluminum alloys of steel and titanium. The strength-to-weight ratio is the primary selection criterion for materials for aircraft structures and propulsion [2] so aluminum alloys are highly important because they can guarantee sufficient strength at relatively low weight and good corrosion resistance [3]. Fibrous composite materials, however, show a number of advantages and the percentage of composites in the construction of modern aircraft significantly increases [4]. The paper [5] compares metallic and composite skin panels in aircraft constructions. Grishkevich [6] used the finite-element method to investigate a composite aircraft beam element.

Virtual testing analysis methods can be used to test aircraft structural strength. These are simulations of aircraft constructions using an advanced nonlinear finite element analysis [7]. Such methods allow for an accurate, fast and inexpensive testing of various load patterns applied to aircraft components. The FEM fatigue life analysis of aircraft structural components was discussed in [8]. A fatigue analysis is fundamental because fatigue is one of the main factors behind service failures in aircraft components [9]. Besides domain methods like FEM, this kind of analysis uses boundary methods such as the dual boundary element method (DBEM) [10]. The finite element method can be used to analyze stress in certain aircraft components, e.g. wings [11,12]. FEM can also be used for an aeroelasticity analysis of
an aircraft [13, 14]. Some research was also done on mechanical joints such as bolted joints [15, 16] or riveted joints [17, 18] in the aircraft construction.

A strength analysis means investigating defects in aircraft constructions. Analyzing and modeling cracks that occur in the supporting structure are particularly important [19]. The researched phenomena include fatigue crack growth in aluminum alloys under aircraft loading [20] as well as cracks in thin-walled aircraft constructions using the extended finite element method [21].

This study focuses on the strength analysis of the support platform for an unmanned aerial vehicle using the finite element method (FEM). This type of analysis evaluates stresses and strains that occur in this construction, identifies its critical points, and finally allows for optimizing it for the adopted pattern of loadings generated by a propulsion system. A geometric model of the support platform was created in line with the construction assumptions for the designed aircraft, and then several load patterns were defined, see Section 2. The next step involved numerical calculations for the created model, and the obtained results and their analysis are discussed in Section 3. The conclusions of the research are at the end of this paper.

2. Research object and methodology

A numerical analysis was performed for a support platform for an unmanned aerial vehicle. The designed aircraft will be a combination of a multi-rotor and a gyrocopter. This hybrid unmanned aerial vehicle is equipped with an autorotating main rotor and four propellers mounted at the front and rear of its fuselage (figure 1). Each propeller and the tail rotor can generate thrust up to 20 N and 50 N, respectively. The tail rotors are also capable of changing their axis of rotation, which changes load patterns applied to the fuselage. Such a solution enables a vertical take-off and landing as well as a hover. The main rotor has no drive shaft and rotates by autorotation. The aircraft can switch to horizontal flight immediately after its take-off or after switching from a hover, and then its rear engines need to turn by 90 degrees, which changes thrust vectoring and its front engines deactivate.

The support platform will be built to test the propulsion system in terms of aircraft control and stability; however, the above mentioned different flight states and different loads acting on the aircraft during these states indicate that the strength analysis of the designed support platform is indispensable.

![Figure 1](image)

**Figure 1.** Forces generated by the propulsion system acting on the designed aircraft in flight.
The support platform was modeled using thin-walled PA38 aluminum profiles of a rectangular cross-section. Profiles 1 and 2 in figure 2 are the profiles of cross sections of 35 x 20 mm, 20 x 13 mm, respectively, whereas profiles 3 and 5 are the profiles of a cross section of 25 x 15 mm. The profile wall is 1 mm. The selected physical properties of PA38 aluminum are given in Table 1.

| Parameter             | Value        |
|-----------------------|--------------|
| Density               | 2.7 g/cm³    |
| Young modulus         | 69 500 MPa   |
| Kirchhoff modulus     | 26 100 MPa   |
| Poisson ratio         | 0.33         |
| Yield point           | min. 60 MPa  |
| Yield strength        | min. 120 MPa |
| Elongation            | max. 14%     |

A transverse beam for the front rotors was modeled in the front section of the construction. A similar transverse beam was created for the tail rotors, but it was positioned higher to reflect the location of these tail rotors on the empennage of the real aircraft construction. The lifting rotor is mounted at the end of the mast that is installed between the longitudinal beams in the middle section of the support construction. A frame is at the front of the support platforms for mounting the control system and power supply for the propulsion system. The location of the rotor mounting points corresponds to their real location on the aircraft fuselage. The CAD model of the support platform is shown in figure 2.

**Figure 2.** Support platform for the propulsion system of the designed aircraft: 1 - mast, 2 - beam for the front engines, 3 - beam for the rear engines, 4 - rack to mount the control and powering system for the propulsion system, 5 - other supporting beams.

Flat bars and angle irons were used to connect the beams (figure 3) to make the whole construction highly stiff and as light as possible. The individual elements of the construction will be finally connected with stainless steel blind rivets.
Figure 3. Samples of the connections for the beams of the support platform.

Four load patterns that correspond to different operation modes of the propulsion system are defined for the created construction (figure 4). The first load pattern (A) corresponds to the pair of operating front engines mounted on the transverse beam. The mounting points for the engines are loaded with 20 N (purple arrows). The other load patterns, i.e. B and C correspond to the pair of operating rear engines generating vertical and horizontal thrust of 20 N (along the longitudinal axis of the aircraft). The last load pattern (D) corresponds to a vertical tensile force of 50 N applied to the mast end. The method of mounting the main rotor requires an additional element, i.e. a steel cuboid to mount the rotor with two flat bars and a bolt. In all the cases, the rest of the construction, i.e. its longitudinal sections is permanently connected to the ground (green arrows).

Figure 4. Defined load patterns of the support platform.
Defining the load patterns was followed by generating a mesh from the created geometric model and the samples of the generated mesh mapping the connections of the aluminum profiles are shown in figure 5. A tetrahedral mesh cell size of 1 mm is applied due to the thickness of the aluminum profile wall of the support platform. The calculations were then performed and the results were post-processed to generate the stress and strain distribution on the surface of the tested construction.

![Figure 5. Samples of the generated mesh mapping the connections of the aluminum profiles.](image)

3. Results and analysis

The first part of the research focuses on the analysis of stresses that occur in the construction. Figure 6 shows the distribution of equivalent stresses according to the von Mises yield criterion for the selected parts of the support platform for the defined load patterns. The material according to this criterion starts yielding when the von Mises stress reaches a value known as yield strength. The von Mises stress for the general stress state without constraints for the boundary conditions is equal to:

$$\sigma_v = \sqrt{\frac{1}{2} [(\sigma_{11} - \sigma_{22})^2(\sigma_{22} - \sigma_{33})^2(\sigma_{33} - \sigma_{11})^2] + 3(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)}$$

(1)

The successive sigma values with indices correspond to the components of the Cauchy stress tensor. The components with the same indices are normal stresses, whereas the ones with different indices are shear stresses.

For the first load pattern (figure 6A) that corresponds to the operation of the front engines, the highest stresses of 37.5 MPa are observed at the connection between the transverse beam and the longitudinal beam. Significant stresses are also recorded on the surface of the transverse beam at the connection with the longitudinal beam as well as in the case of the load pattern corresponding to the pair of rear engines generating vertical thrust (B). The maximum stresses are recorded in the steel angle that connects the transverse beam with the longitudinal beam, but their value is higher and reaches 58.4 MPa. Steel is much stronger than aluminum, so there is no risk of structural failure. There is no significant increase in stress in the other beams. For the load pattern corresponding to the operation of rear engines generating horizontal thrust (C), the highest stresses of 16.9 MPa are in the corner that connects the transverse beam and the vertical beam. In addition, certain elevated stresses of approximately 5 MPa occur in the transverse beam at the contact points with the vertical beams. For the last load pattern (D) that simulates the operation of the lifting rotor, a maximum stress of 4.5 MPa is recorded in the transverse beam at the contact point with the flat bars that connect it to the mast.
Figure 6. Distribution of the equivalent stresses according to the von Mises yield criterion for the selected sections of the support platform for the defined load patterns.
The next step is the analysis of displacement of the construction components for the defined load patterns (figure 7). In all the cases, the highest displacement occurs at the end of the loaded beam. When the front motors (A) operate, the maximum displacement reaches approximately 0.40 mm. When the rear motors generate vertical thrust (B), the maximum displacement is lower and reaches 0.30 mm. This results from the fact of using a different profile section, i.e. 25 x 15 mm. When the loading force changes to horizontal (C), the maximum displacement significantly decreases to 0.23 mm. The displacement of the mast loaded by the vertical tensile force (D) is negligibly small and amounts maximally to 0.005 mm.

![Figure 7](image.png)

**Figure 7.** Resultant displacement for the selected sections of the support platform for the defined load patterns.

The results of the numerical calculations of the selected sections of the support platform for the defined load patterns are used to create a demonstrator of the platform with the elements of the propulsion system of the designed aircraft (figure 8). This demonstrator will be used for a series of ground and flight tests to verify the correct operation of the propulsion control system and optimize its performance in different flight states.
4. Conclusions
The paper discusses the numerical analysis of the support platform for an unmanned aerial vehicle verified for various load patterns. The model of the test object is created by mapping the real available components of the construction. Investigated with the finite element method (FEM), the analyzed phenomena include the stresses generated by the operating front rotors, tail rotors and main rotor. The obtained stresses do not exceed the yield point for the analyzed material. The highest deformation of the construction is recorded for the front and tail rotors with a vertical thrust vector. The load from the main rotor do not generate dangerous stresses and deformations. The highest stresses occur at the connections of the profiles and angle irons.

The applied research method allows for a quick and low-cost strength verification of the construction, and the obtained test results show that the construction does not need to be modified by applying different cross-sections of aluminum profiles or additional flat bars and angle irons. It is found that the platform is strong enough to withdraw any loading forces generated by the propulsion system. A real support platform with elements of drive, control and power systems has been created, and the next step involves testing these systems in terms of aircraft stability and the efficiency of the control algorithm.

Acknowledgments
This work has been financed by the Polish National Centre for Research and Development under the LIDER program Grant Agreement No. LIDER/27/0140/L-10/18/NCBR/2019.

References
[1] Zhu T L 1993 *Comput. Struct.* 48(4) pp 745-748
[2] Kumar S and Padture N P 2018 Materials in the aircraft industry *Metallurgical Design and Industry* (Cham: Springer)
[3] Duncheva G V, Maximov J T, Ganev N and Anchev A P 2020 *Strength Mater.* 52(1) pp 1-15
[4] Vlasova V 2019 *AIP Conference Proceedings* 2171 030020
[5] Kalanchiam M and Chinnasamy M 2012 *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* 6(11) pp 2428-2432
[6] Grishkevich P M, Govorkov A S and Yakhnenko M S 2020 *J. Phys. Conf. Ser.* 1661 012207

Figure 8. Demonstrator of the support platform with the propulsion system components of the designed aircraft.
[7] Ostergaard M G, Ibbotson A R, Le Roux O and Prior A M 2011 *CEAS Aeronaut. J.* 1(1) pp 83-103
[8] Maksimović S 2005 *Sci. Tech. Rev.* 55(1) pp 15-21
[9] Bhaumik S K, Sujata M and Venkataswamy M A 2008 *Eng. Fail. Anal.* 15(6) pp 675-694
[10] Oliveira T A, Gomes G and Evangelista Jr F 2019 *Eng. Anal. Bound. Elem.* 104 pp 107-119
[11] Atmeh G M, Hasan Z and Darwish F 2010 Design and stress analysis of a general aviation aircraft wing *Excerpt from the Proceedings of the COMSOL Conference 2010 Boston*
[12] Rabbey M F, Rumi A M, Nuri F H, Monerujjaman H M and Hassan M M 2014 *Adv. Mat. Res.* 906 pp 318-322
[13] Guo S 2007 *Aerosp. Sci. Technol.* 11(5) pp 396-404
[14] Saltari F, Riso C, Matteis G D and Mastroddi F 2017 *J. Aircr.* 54(6) pp 2350-2366
[15] Oskouei R H, Keikhosravy M and Soutis C 2009 *Proc. Inst. Mech. Eng. G J. Aerosp. Eng.* 223(7) pp 863-871
[16] Oskouei R H, Keikhosravy M and Soutis C 2010 *Aeronaut.* 114(1155) pp 315-320
[17] De Castro P M S T, De Matos P F P, Moreira P M G P and Da Silva L F M 2007 *Mater. Sci. Eng. A* 468 pp 144-157
[18] Yunus M A, Rani M A, Sani M S M and Shah M A 2018 *AIP Conference Proceedings* 1952 020013
[19] Iyyer N, Sarkar S, Merrill R and Phan N 2007 *Int. J. Fatigue* 29(9-11) pp 1584-1607
[20] DuQuesnay D L, Underhill P R and Britt H J 2003 *Int. J. Fatigue* 25(5) pp 371-377
[21] Wyart E, Coulon D, Pardoën T, Remacle J F and Lani F 2009 *Eng. Fract. Mech.* 76(1) pp 44-58