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AERODYNAMIC DESIGN OF MODERN GYROPLANE MAIN ROTORS

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Abstract

Process of aerodynamic design and optimisation of main rotors intended for modern gyroplanes has been presented. First stage of the process was focused on development of family of airfoils, designed and optimised especially towards gyroplane applications. In next stage, based on developed family of airfoils, two alternative gyroplane main rotors were designed. The main optimisation criterion was to minimise aerodynamic drag of the rotor, for assumed flight velocity and lift force generated by the rotor, balancing the weight of the gyroplane. The paper discusses the applied methodology of design and optimisation as well as presents geometric and aerodynamics properties of designed main rotors.

Keywords: gyroplane, main rotor, rotor blade, airfoil, aerodynamic design and optimisation, Virtual Blade Model.

1. INTRODUCTION

A gyroplane is a type of rotorcraft which uses an unpowered rotor operating in autorotation to develop lift and an engine-powered propeller to provide thrust necessary to balance the gyroplane drag force.

The pitch control of the gyroplane is conducted by tilting the rotor fore and aft while lateral tilting of the rotor is used for the roll control. A gyroplane main rotor is designed in such a way, that during the flight the air flowing around rotating blades generates aerodynamic reaction, which vertical component balances the gyroplane weight, while the aerodynamic moment is able to drive the rotor with necessary rotational speed.

Typical gyroplane main rotors are characterised by simple design, especially in case of rotors of light gyroplanes. They are usually two-bladed, teetering rotors. Their blades have rectangular planform, uniform spanwise distribution of airfoil and usually are not twisted. Typical airfoils used on gyroplane-main-rotor blades are NACA 8H12 or NACA 9H12. Usually, the gyroplane rotor has fixed collective pitch of the blades and does not have a blade-cyclic-pitch control.

A natural question is: is it possible to significantly improve aerodynamic properties of gyroplane main rotor through application of modern methods of computational design and optimisation? Answer to this question was one of the main objectives of the research described in this paper.

The presented study has been conducted within the project ”Modern Gyroplane Main Rotor” co-financed by the European Regional Development Fund. The main goals of the study were:

- to investigate possibilities of improvement of performance-and-exploitation properties of light gyroplane through aerodynamic modification and optimisation of its main rotor,
- to assess the impact of various design parameters of the gyroplane main rotor on its aerodynamic properties,
- to design aerodynamically improved main rotors intended for light gyroplanes,
- to deliver geometric and aerodynamic data necessary for gyroplane manufacturers to implement new rotors.

The study has been conducted based on computational methods of aerodynamic analysis, design and optimisation.

2. RESEARCH METHODOLOGY

The process of design and optimisation of main rotors intended for light gyroplanes has been conducted within three main stages. The first stage was focused on design of family of airfoils intended for gyroplane applications. The second stage concerned the design and optimisation rotor blades, developed based on the newly designed family of airfoils. The third stage was focused on aerodynamic design and optimisation of gyroplane main rotors. This stage included studies on optimal strategy of blade-collective-pitch control as well as studies on optimal strategy of rotor-pitch-and-roll control in various stages of the gyroplane flight.

2.1. Methodology of design of gyroplane-airfoil family

The design of airfoils intended for gyroplane-main-rotor blades has been conducted simultaneously with rotor blades design. The new airfoils were designed so as to fulfil requirements defined based on analysis of aerodynamic properties of subsequent variants of gyroplane main rotors.

The starting point for the airfoil design was the airfoil NACA 9H12M which was a slightly modified version of the airfoil NACA 9H12 commonly used for design of gyroplane-rotor blades. The optimisation of airfoils has been conducted using the following computational tools:

- CODA4W – in-house code supporting airfoil design,
- INVDES – in-house code solving the Inverse-Airfoil-Design problem, i.e. design of airfoil shape based on assumed pressure distribution on airfoil surface,
- ANSYS FLUENT [1] – commonly used Navier-Stokes-Equation solver,
- XFLR-5 [2] – the code commonly used for aerodynamic analysis of airfoils, especially in low-speed conditions.

During the design of new family of airfoils, their initial shapes were designed using the CODA4W software. Next they were redesigned and smoothed aerodynamically by the solution of Inverse-Airfoil-Design problem, conducted using the INVDES code. Aerodynamic properties of subsequent variants of airfoils were analysed using the XFLR-5 software. For selected airfoils, the databases of aerodynamic characteristics (necessary for 3D CFD simulations) were built using the ANSYS FLUENT code. Though evaluation and analysis of aerodynamic characteristics has been conducted for both the natural and forced laminar-turbulent transition, all results presented in this paper concern the fully turbulent flow around gyroplane-rotor-blade airfoils. Such type of air flow is expected to be dominating in real conditions of gyroplane flight.

2.2. Methodology of design and optimisation of gyroplane main rotor and its blades

The design and optimisation of the rotor and its blades have been conducted based on in-house methodology of parametric design of aerodynamic objects, formerly developed and implemented in Institute of Aviation [3]. A parametric model of the designed rotor and blades has been developed using the specialised, in-house software PARADES [4]. The Graphical User Interface of this software is presented in Fig. 1.

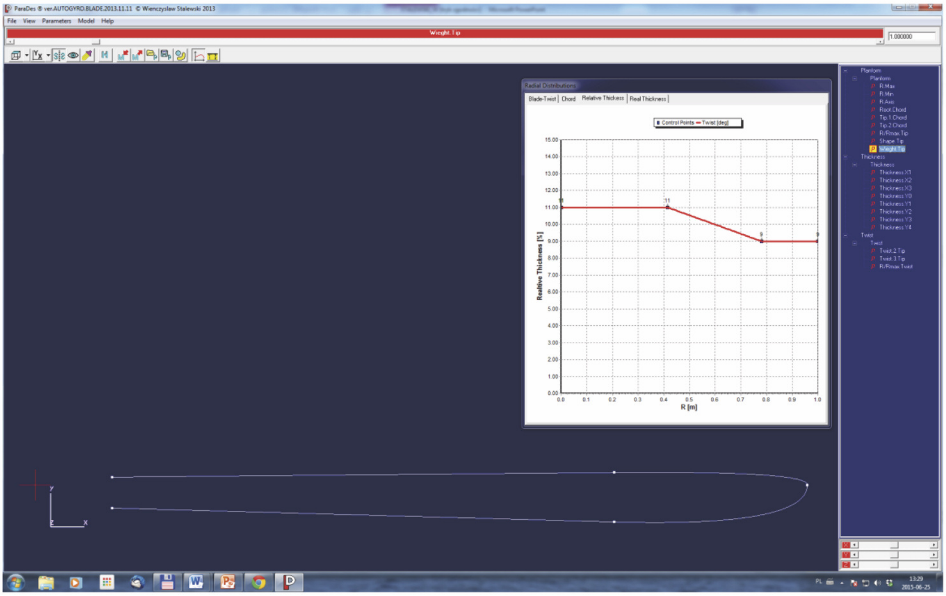

Fig. 1. Graphical User Interface of the software PARADES, used to develop parametric model of the rotor blade [Aut., 2015]

In the presented study the developed general parametric model of the rotor blade consisted of set of design parameters described in Tab. 1. The process of optimal design of gyroplane rotor consisted in successive changes of selected design parameters and analysis how these changes affect the changes of aerodynamic characteristics of the rotor. In different stages of the design process, some of design parameters listed in Tab. 1 were frozen so as to obtain simplified parametric model of the gyroplane rotor.

Tab. 1. Set of Design Parameters used in developed general parametric model of the rotor and blades

Property	**Number of Design Parameters**
Collective pitch of blades	1
Blade planform	9
Radial distribution of blade relative thickness	8
Radial distribution of blade twist	3

Aerodynamic properties of subsequent variants of gyroplane main rotor were evaluated using the ANSYS FLUENT code and User-Defined-Function module Virtual Blade Model (VBM).

Generally, the VBM module is responsible for modelling flow effects caused by rotating blades. In this approach real rotor is replaced by volume disc influencing the flow field similarly as real rotating blades, which is shown in Fig. 2. Time-averaged aerodynamic effects of rotating blades are modelled using momentum source terms placed inside the volume-disc zones established in regions of activity of real rotor. The intensities of momentum sources are evaluated based on the Blade Element Theory, which associates local flow parameters around the blade sections with databases of 2D-aerodynamic characteristics of airfoils – cross-sections of the blade. Typical computational mesh used in such simulations is presented in Fig. 3. Compared to the original version, the VBM module used in presented research has been significantly modified and expanded by the author of the paper. The most important modifications concerned:

- solving the equations of blade flapping and coning,
- modelling of rotorcraft flight in autorotation,
- automatic control of rotor pitch so as to obtain required lift force generated by rotor for given flight velocity.

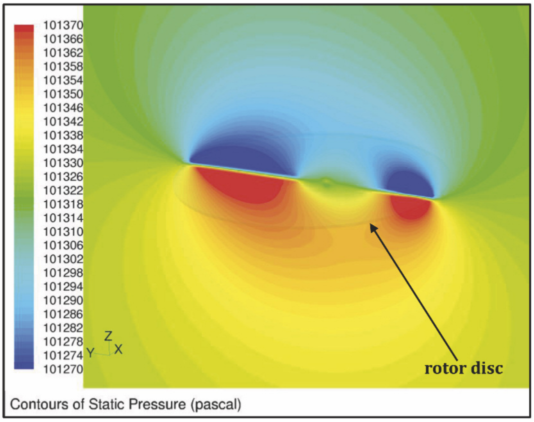

Fig. 2. Contours of static pressure around the rotor disc modelling the real rotor in Virtual-Blade-Model approach [Aut., 2015]

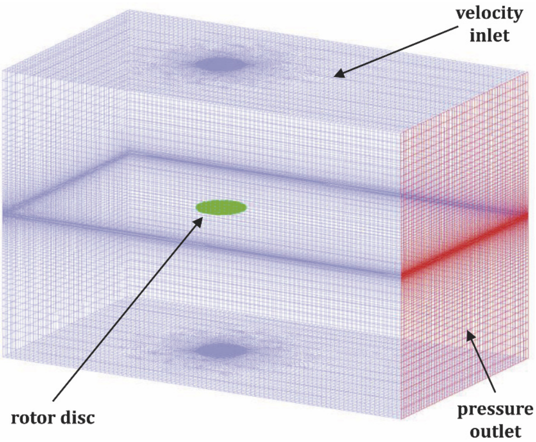

Fig. 3. Computational mesh used in CFD simulations of flight o gyroplane main rotor, conducted using the Virtual Blade Model and ANSYS FLUENT solver [Aut., 2015]

3. IMPROVEMENT OF AERODYNAMIC PROPERTIES OF GYROPLANE MAIN ROTOR

Research on improvement of performance and exploitation properties of gyroplane main rotor focused on analysis of possibility of the modernisation of the rotor by:

- design and application of modern family of airfoils developed specifically for gyroplane applications,
- design of optimal as well as non-conventional blades of gyroplane main rotor,
- optimisation of collective pitch of rotor blades,
- optimisation of pitch-and-roll control of the rotor in various phases of gyroplane flight.

3.1. Design of airfoil family intended for gyroplane applications

First stage of airfoil design was focused on development of airfoils especially useful for the design of typical rectangular, untwisted blades intended for gyroplane main rotor. The reference airfoil for the design process was NACA 9H12M (Fig. 4) – slightly modified version of airfoil NACA 9H12, commonly used for design of gyroplane-rotor blades.

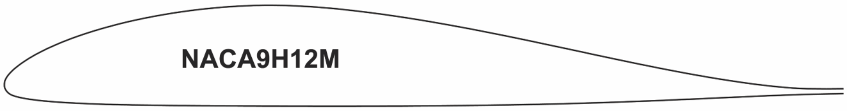

Fig. 4. NACA 9H12M – the reference airfoil for the design of gyroplane-airfoil family [Aut., 2015]

The actual process of airfoil design was preceded by studies aimed at defining the adequate design objectives and flow conditions typical in gyroplane-rotor flight. Results of these analyses are presented in Fig. 5 - Fig. 7. The analyses led to the conclusions, that during fast flight of typical light gyroplane:

- the largest share in driving of the rotor has a retreating blade on which the 2D air flow around blade cross-sections is characterised by the following conditions, described by the lift coefficient (C_L) and Mach number (M):

$$C_L \approx 1.2 \div 1.5,\ M \approx 0.2 \div 0.35 \tag{1}$$

- the largest share in generating a harmful torque of the rotor has an advancing blade on which the 2D air flow around blade cross-sections is characterised by the following conditions:

$$C_L \approx 0.2 \div 0.4,\ M \approx 0.4 \div 0.55 \tag{2}$$

It was assumed that the airfoil-design process would aim at minimisation of airfoil drag coefficient, in flow conditions (1) and (2).

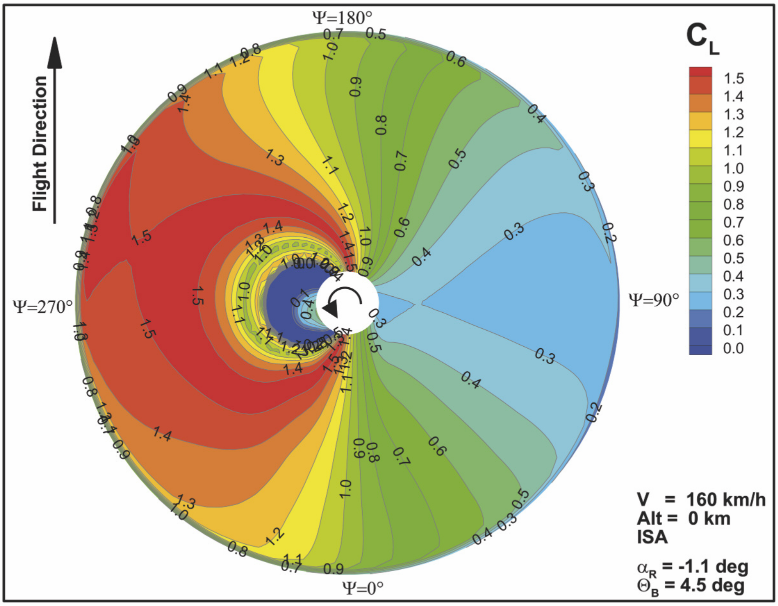

Fig. 5. Distribution of local lift coefficient (C_L) generated by the blade cross-sections on the rotor disc. The case of fast flight of gyroplane main rotor

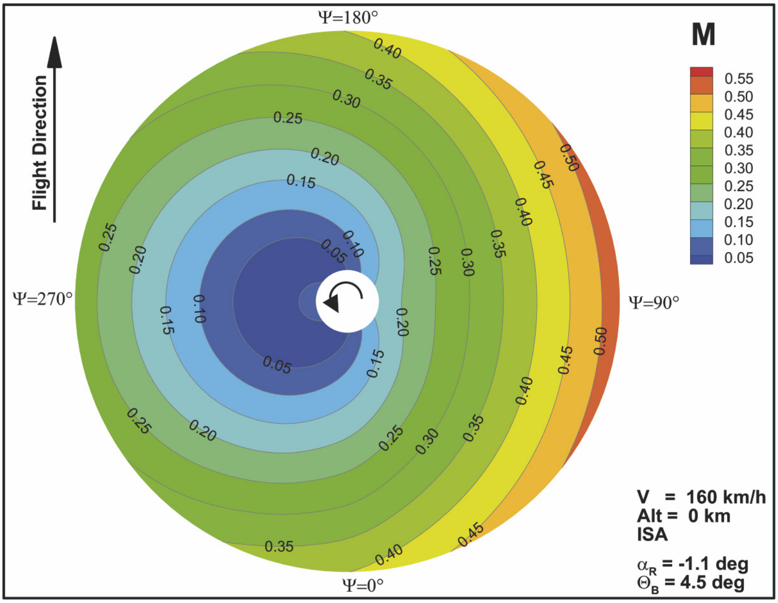

Fig. 6. Distribution of local Mach number (M) corresponding to the blade cross-sections on the rotor disc. The case of fast flight of gyroplane main rotor [Aut., 2015]

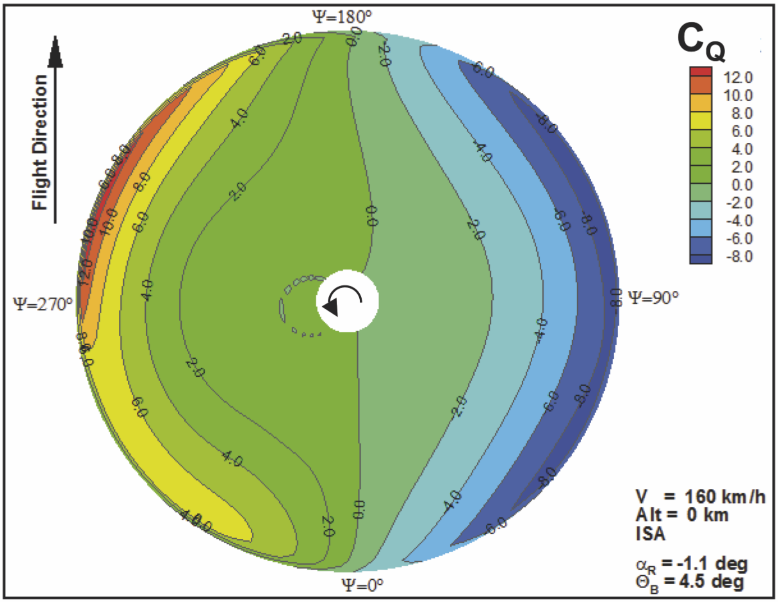

Fig. 7. Distribution of local torque coefficient (C_Q) generated by the blade cross-sections on the rotor disc. $C_Q > 0$ – corresponds to driving part of the rotor disc; $C_Q < 0$ – corresponds to driven part of the rotor disc. The case of fast flight of gyroplane main rotor [Aut., 2015]

Using the methodology described in Paragraph 2.1, the following three modifications of the reference airfoil NACA 9H12M were designed:

- ILW-LT-12.0 of relative thickness 12% of airfoil chord,
- ILW-LT-11.6 of relative thickness 11.6% of airfoil chord,
- ILW-LT-11.0 of relative thickness 11% of airfoil chord.

Shapes of these airfoils are presented in Fig. 8. Selected aerodynamic characteristics of the designed airfoils and the reference airfoil NACA 9H12M are compared in Fig. 9 and Fig. 10.

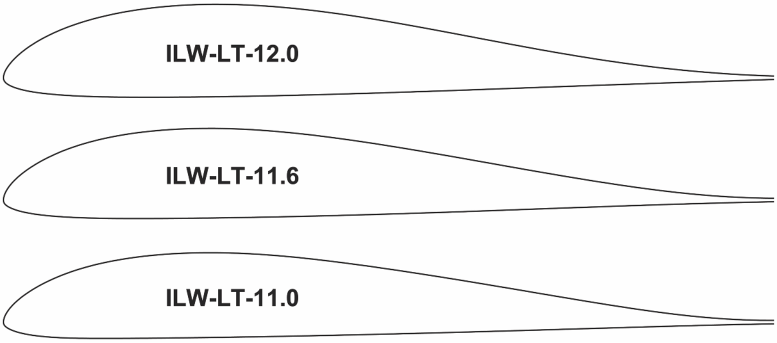

Fig. 8. New airfoils designed and optimised for gyroplane applications [Aut., 2015]

Analysing aerodynamic characteristics of newly designed airfoils, one may conclude that in assumed flow conditions (1) and (2), these airfoils have preferably reduced drag coefficient in comparison to the reference airfoil NACA 9H12M, which is favourable from point of view of gyroplane applications.

When designing a variable-chord blade of gyroplane main rotor (described in next paragraphs) it was necessary to design additional base airfoils, thinner than ILW-LT-11.0. To meet this requirement, the following additional gyroplane airfoils have been designed and optimised:

- ILW-LT-10.0 of relative thickness 10% of airfoil chord,
- ILW-LT-09.0 of relative thickness 9% of airfoil chord.

The sub-family of gyroplane airfoils intended for the variable-chord blade is presented in Fig. 11. Selected aerodynamic characteristics of these airfoils as well as the reference airfoil NACA 9H12M are presented in Fig. 12 and Fig. 13. Similarly as in the previous case, one may conclude that in assumed flow conditions (1) and (2), these airfoils are characterised by preferably reduced drag coefficient in comparison to the reference airfoil NACA 9H12M.

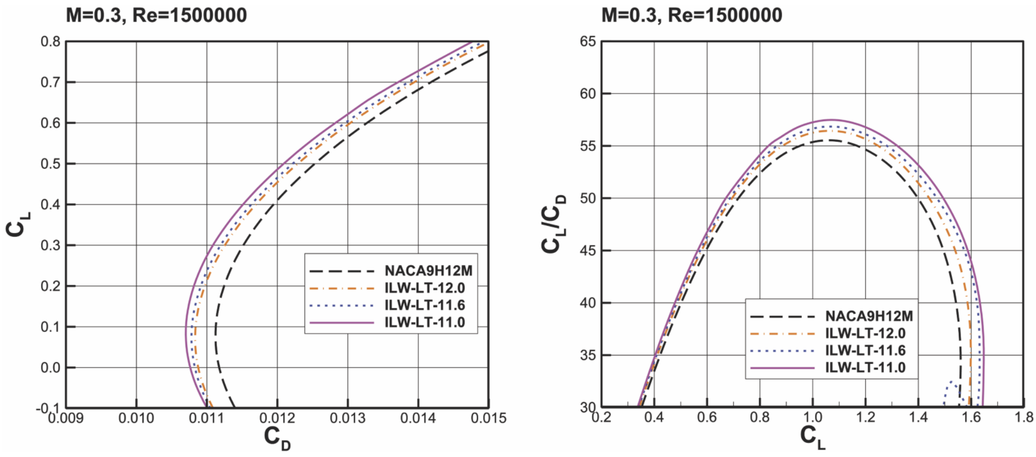

Fig. 9. Comparison of aerodynamic characteristics of airfoils NACA 9H12M, ILW-LT-12.0, ILW-LT-11.6 and ILW-LT-11.0 for flight conditions M = 0.3, Re = 1 500 000. Results of CFD calculations conducted using the ANSYS FLUENT code [Aut., 2015]

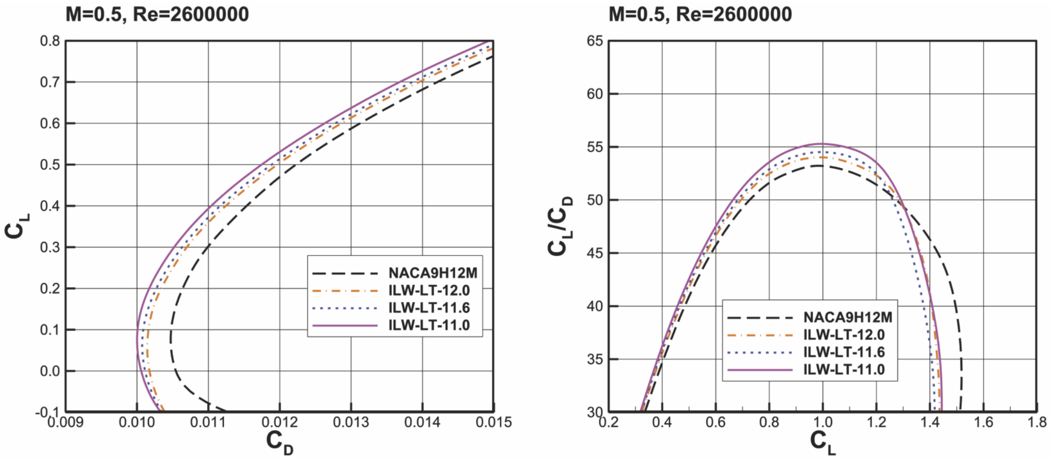

Fig. 10. Comparison of aerodynamic characteristics of airfoils NACA 9H12M, ILW-LT-12.0, ILW-LT-11.6 and ILW-LT-11.0 for flight conditions M = 0.5, Re = 2 600 000. Results of CFD calculations conducted using the ANSYS FLUENT code [Aut., 2015]

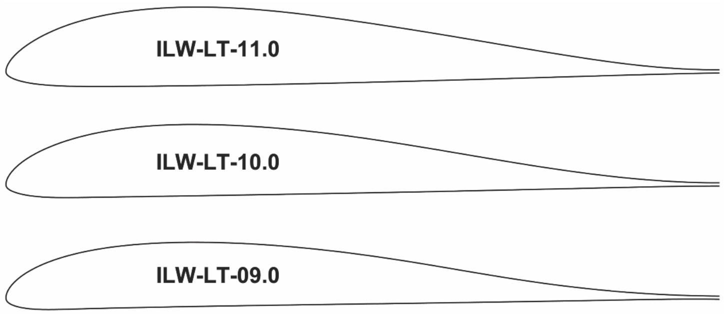

Fig. 11. Sub-family of airfoils designed for a variable-chord blade of gyroplane main rotor [Aut., 2015]

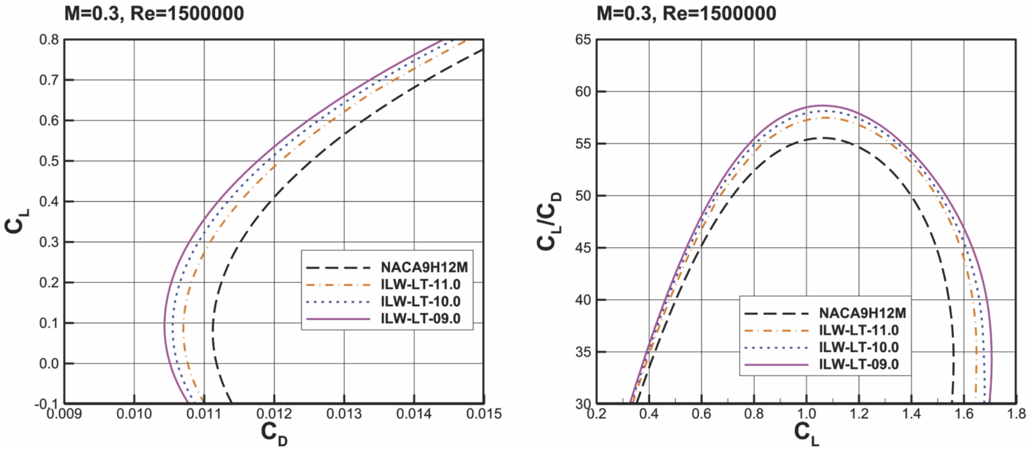

Fig. 12. Comparison of aerodynamic characteristics of airfoils NACA 9H12M, ILW-LT-11.0, ILW-LT-10.0 and ILW-LT-09.0 for flight conditions M = 0.3, Re = 1 500 000. Results of CFD calculations conducted using the ANSYS FLUENT code [Aut., 2015]

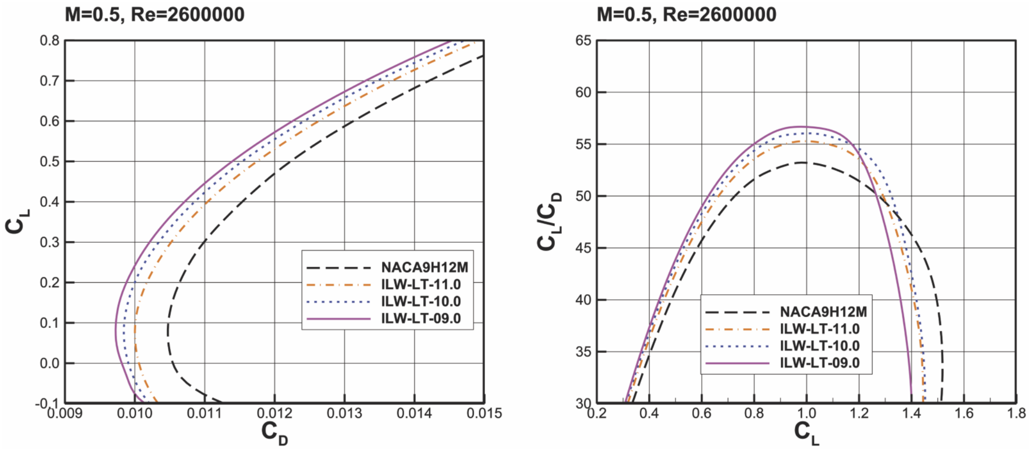

Fig. 13. Comparison of aerodynamic characteristics of airfoils NACA 9H12M, ILW-LT-11.0, ILW-LT-10.0 and ILW-LT-09.0 for flight conditions M = 0.5, Re = 2 600 000. Results of CFD calculations conducted using the ANSYS FLUENT code [Aut., 2015]

3.2. Design of gyroplane main rotor with rectagular blades

Blades of the first optimised rotor were to be made of aluminium alloy, which required the application of uniform spanwise distribution of blade chord and airfoil, as well as the lack of geometric twist of the blades. In this case, the process of design and optimisation of the blades consisted in:

- optimal choice of blade airfoil,
- optimisation of blade dimensions,
- optimisation of blade collective pitch.

Concerning the selection of airfoil, three potential candidates were taken into consideration – the airfoils: ILW-LT-12.0, ILW-LT-11.6, ILW-LT-11.0. Fig. 14 compares Lift-to-Drag ratio (L/D) versus blade collective pitch (q_0) for gyroplane main rotors equipped with rectangular blades built based on these airfoils as well as based on the reference airfoil NACA 9H12M.

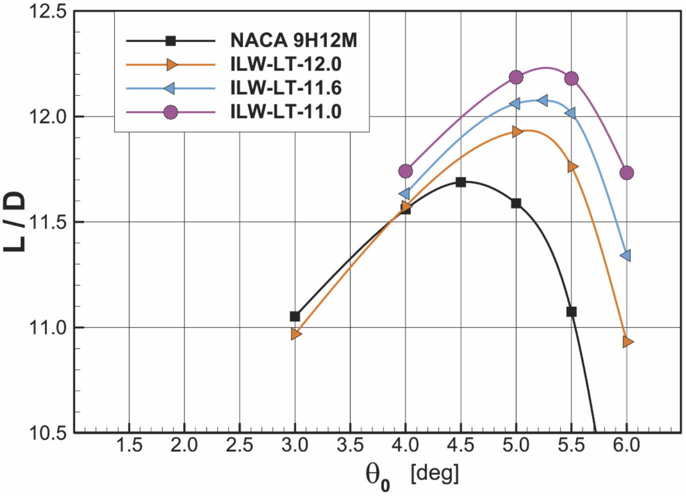

Fig. 14. Lift-to-Drag ratio (L/D) versus blade collective pitch (q_0) for gyroplane main rotors equipped with rectangular blades built based on airfoils: ILW-LT-12.0, ILW-LT-11.6, ILW-LT-11.0 and reference airfoil NACA 9H12M. The case of fast flight of gyroplane main rotor [Aut., 2015]

Based on results presented in Fig. 14, the airfoil ILW-LT-11.0 was selected as base airfoil for the rectangular, uniform blade of gyroplane main rotor. The rotor built based on this airfoil had the highest aerodynamic efficiency. Additionally, the reduced relative thickness of the airfoil ILW-LT-11.0 was assessed as acceptable for the gyroplane blades. Finally, the dimensions of rectangular, uniform blade built based on airfoil ILW-LT-11.0 were optimised. As a result of these activities, the rotor ILW.11/11/11.D10.0 has been developed. The geometry of the blade of this rotor is presented in Fig. 15. In fast flight of gyroplane, the optimum blade collective pitch for this rotor is 5 degrees.

Fig. 16 presents dependency of drag force acting on the rotor versus flight velocity, during the flight of the gyroplane of total mass 600 kg. The presented computational results concern the optimised rotor ILW.11/11/11.D10.0 and the reference rotor NACA9H12M/D9.4/C0.2 having: 9.4 m diameter, 0.2 m chord of rectangular blades and uniform spanwise distribution of blade airfoil NACA 9H12M. Based on conducted CFD simulations it may be concluded, that for the flight speed 160 km/h and gyroplane total mass 600 kg, the newly designed rotor ILW.11/11/11.D10.0 is characterised by 7.5% reduction in drag force, relative to the reference rotor.

Good performance-and-exploitation properties of the rotor ILW.11/11/11.D10.0 have been proven during conducted flight tests [5], where two alternative main rotors was mounted and tested on the same gyroplane. The first rotor was the newly designed ILW.11/11/11.D10.0 and the second, reference rotor, had blades having the same planform but another base airfoil: NACA 9H12M. During the flight tests the following phenomena have been noticed:

- gyroplane equipped with the rotor ILW.11/11/11.D10.0 reached a higher by 20 km/h (≈10%) maximum flight speed in comparison to the gyroplane equipped with the reference rotor,
- during a flight with constant speed 100 km/h, the rotor ILW.11/11/11.D10.0 was rotating slower by approximately 16 rpm than the reference rotor,
- during the majority of flights, the time of take-off of gyroplane with rotor ILW.11/11/11.D10.0 was shorter by approximately 10 sec compared to the gyroplane with the reference rotor,
- in case of the rotor ILW.11/11/11.D10.0, the application of slightly thinner blades (due to application of thinner airfoil) did not affect much on overloads and deformations of the blades.

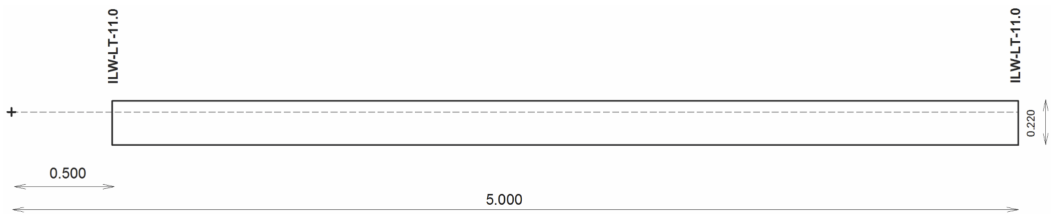

Fig. 15. Geometry of the designed rectangular, uniform blade of the rotor ILW.11/11/11.D10.0 [Aut., 2015]

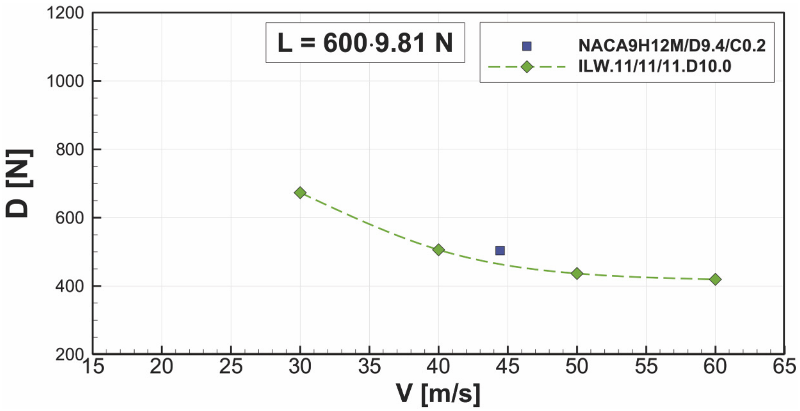

Fig. 16. Total drag force acting on the rotor versus flight velocity, during the flight of the gyroplane of total mass 600 kg. Comparison of computational results for reference rotor NACA9H12M/D9.4/C0.2 and newly designed rotor ILW.11/11/11.D10.0 [Aut., 2015]

3.3. Design of gyroplane main rotor with variable-chord blades

In the case of the second designed gyroplane main rotor, its blades were to be made in the composite technology. This allowed significantly expand the scope of design parameters of the rotor blades. In particular, the parametric model of the blade allowed taking into consideration changeable along the blade span:

- airfoils (i.e. relative thickness of the blade),

- blade local chord,
- blade geometric twist.

In this case the design process consisted in searching for optimal values of design parameters describing the above geometric properties of the blade. As a result of this process, the rotor ILW.11/10/09.D10.0 was developed. The geometry of the blade of this rotor is presented in Fig. 17. The blade is built based on airfoils ILW-LT-11.0, ILW-LT-10.0 and ILW-LT-09.0 and it is distinguished by an unconventional planform, with maximum chord placed at 80% of the rotor radius. The blade is not twisted. In fast flight of gyroplane, the optimum blade collective pitch for the rotor ILW.11/10/09.D10.0 is 5 degrees.

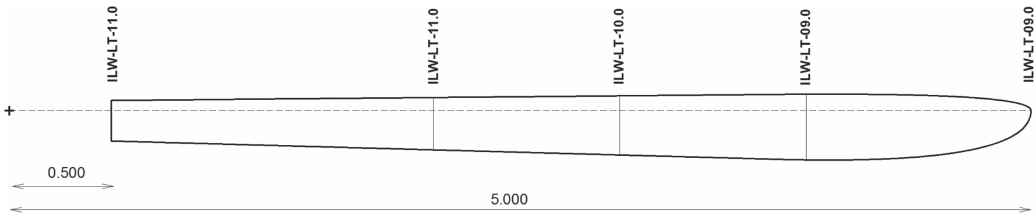

Fig. 17. Geometry of the variable-chord blade of the rotor ILW.11/10/09.D10.0 [Aut., 2015]

Fig. 18 presents dependency of drag force acting on the rotor versus flight velocity, during the flight of the gyroplane of total mass 600 kg. The presented computational results concern the optimised rotors ILW.11/11/11.D10.0 and ILW.11/11/11.D10.0 as well as the reference rotor NACA9H12M/D9.4/C0.2. Based on presented results it may be concluded that for the flight speed 160 km/h and gyroplane total mass 600 kg, the newly designed rotor ILW.11/10/09.D10.0 is characterised by 13.8% reduction in drag force, relative to the reference rotor.

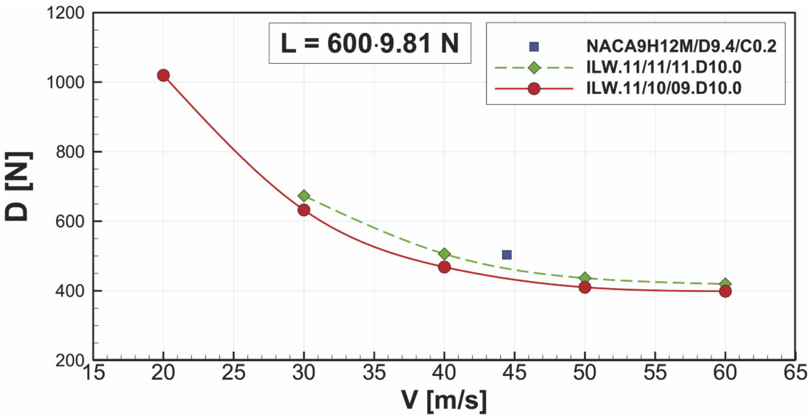

Fig. 18. Total drag force acting on the rotor versus flight velocity, during the flight of the gyroplane of total mass 600 kg. Comparison of computational results for reference rotor NACA9H12M/D9.4/C0.2 and newly designed and optimised rotors ILW.11/11/11.D10.0 and ILW.11/10/09.D10.0 [Aut., 2015]

4. SUMMARY AND CONCLUSIONS

Two alternative modern main rotors intended for light gyroplanes have been developed, utilising the methods of Computer Aided Design and Optimisation and methods of Computational

Fluid Dynamics. Blades of both developed rotors have been built based on specially designed and optimised family of gyroplane airfoils.

The blades of the first designed rotor were to be made of aluminium alloy which limited the design process to selection of blade airfoil and to definition of optimal dimensions of the blades. In fast flight of the gyroplane, for assumed total mass of the gyroplane 600 kg, the designed rotor ILW.11/11/11.D10.0 is characterised by a 7.5% reduction in drag force, compared to the reference rotor of blades built based on airfoil NACA 9H12M. Good performance-and-exploitation properties of the rotor ILW.11/11/11.D10.0 have been proven during flight tests, where the newly designed rotor had have the maximum flight speed by 20 km/h (≈10%) higher and take-off time by 10 sec shorter than the reference rotor of blades built based on airfoil NACA 9H12M.

The blades of the second designed rotor were to be made in composite technology. This allowed building the blades of variable chord and relative thickness along a blade span. Compared to the reference rotor, the newly designed variable-chord-blade rotor ILW.11/10/09.D10.0 is characterised by 13.8% reduction in drag force, in fast flight of the gyroplane of total mass 600 kg. Flight tests of the rotor ILW.11/10/09.D10.0 are starting soon.

The presented results of the research have confirmed that traditional design of light-gyroplane main rotor may be significantly improved from point of view of gyroplane performance and exploitation properties. The improvement may be achieved by means of re-designing of rotor blades, especially through the design and optimisation of the blade planform as well as through application of specialised gyroplane-blade airfoils.

SYMBOLS

D – drag force generated by the rotor
C_D – drag coefficient
C_L – lift coefficient
C_Q – local torque coefficient
L – lift force generated by the rotor
M – Mach number
Re – Reynolds number
V – flight velocity
q_0 – collective pitch of rotor blades

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PROJEKTOWANIE AERODYNAMICZNE NOWOCZESNYCH WIRNIKÓW AUTOROTACYJNYCH

Streszczenie

Przedstawiono proces aerodynamicznego projektowania i optymalizacji nowoczesnych wirników autorotacyjnych. Pierwszy etap prac dotyczył opracowanie rodziny profili lotniczych zaprojektowanych i zoptymalizowanych specjalnie pod kontem zastosowania ich na łopatach wirnika nośnego wiatrakowca. W kolejnym etapie, w oparciu o opracowaną rodzinę profili, zaprojektowano i zoptymalizowano dwa alternatywne wirniki nośne. Głównym kryterium optymalizacji było zminimalizowanie oporu aerodynamicznego wirnika, dla zakładanej prędkości lotu i siły nośnej generowanej przez wirnik, równoważącej ciężar wiatrakowca. Omówiono zastosowaną metodykę projektowania i optymalizacji konstrukcji lotniczych, jak również przedstawiono geometryczne i aerodynamiczne własności zaprojektowanych wirników nośnych.
Słowa kluczowe: wiatrakowiec, wirnik nośny, łopata wirnika, profil lotniczy, aerodynamiczne projektowanie i optymalizacja, Virtual Blade Model.

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