AERODYNAMIC DESIGN AND OPTIMISATION OF MAIN ROTORS FOR LIGHT ROTORCRAFTS

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Abstract
The main goal of the presented research has been to prove that optimal design of main-rotor blades may significantly improve a performance of light rotorcraft. The paper presents results of several studies aimed at improvement of performance of several rotorcrafts including: UAV helicopter, light gyroplane and ultralight helicopter. All the presented studies have been conducted using similar methodologies of optimal parametric design of main rotor. Blades of all main rotors have been built based on the airfoils optimised towards specific design criteria and conditions resulting from the priority flight conditions and assumed primary mission of the designed rotorcraft. Whole the design process has been conducted based on advanced computational methods and software.

1. INTRODUCTION

Aerodynamic properties of the main rotor blades have a strong influence on the performance, operational properties and environmental impact (including noise emission) of rotorcraft. Hence, it is generally believed that improving the aerodynamic properties of main rotor and its blades, can significantly improve the overall operational properties of rotorcraft and their competitiveness within the small-aircraft-transport area. Therefore, investigations on improving the aerodynamics of the rotors of the rotorcraft currently in use or designed is still an important part of modern rotorcraft engineering.

The presented paper discusses examples of this type of research and design works that have recently been implemented with the significant contribution of the Authors of the article. The works have been conducted based on the specific methodology developed by the Authors.

The design and optimisation of main-rotor blades is a very complex process involving many domains and disciplines such as aerodynamics, acoustics, dynamics or structural mechanics. The presented study is focused on an aerodynamic design, so the other aspects are not discussed in this paper.

In a modern approach, the process of design and optimisation of main-rotor blades is based on advanced computational methods. This concerns methods Computational Fluid Dynamics (CFD), Computational Structural Mechanics (CSM) or Flight Dynamics. Increasingly, the design process is automated, using numerical methods of parametric optimisation.

Although many works have already been devoted to the design and optimization of rotorcraft airfoils, the search for new, more and more advanced solutions in this area is still an important element in improving the aerodynamic and aeroacoustic properties of rotorcraft.

In the design of modern blades, special attention is paid to a shape-optimisation of the blade tip. This includes an optimisation of such elements of blade-tip shape as: sweepback, taper, forward notch area, parabolic tip and anhedral. This subject is discussed thoroughly in [10] and [11].

The research described in this paper has been inspired mainly by designers of several small rotorcrafts. The research aimed at an improvement of overall operational properties of the rotorcrafts through aerodynamic redesigning of blades of main rotor.

2. METHODOLOGY

In the presented studies, the design of airfoils intended for blades of given main rotor has been conducted simultaneously with the main rotor design. The airfoil-design process has utilised the following computational tools:

- CODA - in-house, CAD-type code supporting airfoil design,
- INVDES - in-house code solving the inverse-airfoil-design problem,
- XFLR-5 [2] and MSES [3] - commonly used codes for aerodynamic analysis of airfoils,
- ANSYS FLUENT [1] - commonly used solver of various approximations of Navier-Stokes Equations.

During the design process, initial shapes of airfoils were designed using the CODA4W software. Next the airfoils were redesigned and smoothed aerodynamically by the solution of Inverse-Airfoil-

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Design problem. Aerodynamic properties of subsequent variants of airfoils were analysed using the XFLR-5 or MASES software. For selected, most promising airfoils, their aerodynamic characteristics were analysed using the ANSYS FLUENT (2D) code.

The developed and implemented methodology of parametric design and optimisation of rotorcraft rotors is presented in Figure 1. In the presented approach, the design process is managed by the designer, who may be either the human or the computer code. The designer generates sequential sets of design parameters, which are processed by the parametric-modelling software, giving as a result the digital representation of the main-rotor blade. Next, physical properties of the main rotor are evaluated by dedicated software. Based on results of this evaluation the designer decides, which variant of optimised object is the best, from point of view of given criteria of the optimisation.

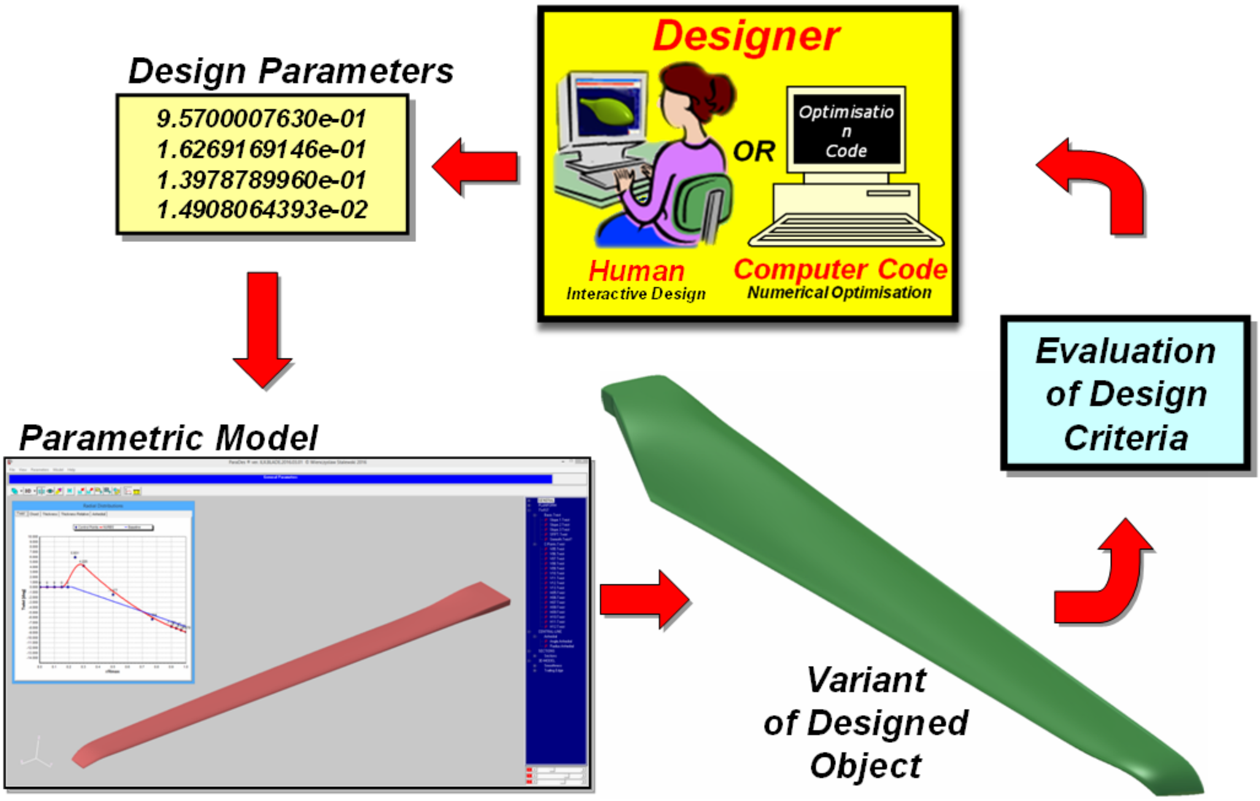

Figure 1. The general scheme of the developed and applied methodology of parametric design and optimisation of rotorcraft rotors.

The parametric model is realised using the in-house software PARADES [4]. Evaluation of aerodynamic properties of the main rotor has been conducted using two alternative approaches, both based on a solution of Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations.

The simplified approach has been based on Virtual Blade Model (VBM) method [5]. In this approach real rotors are replaced by volume discs influencing the flow field similarly as real rotating blades. Time-averaged aerodynamic effects of rotating lifting surfaces are modelled using momentum source terms placed inside the volume-disc zones placed in regions of activity of real rotors. The momentum-source intensities are evaluated based on the Blade Element Theory, which associates local flow parameters in the blade sections with databases of two-dimensional aerodynamic characteristics of blade airfoils. New, added possibilities of the VBM module include, among others, physical modelling of blade flapping as well as modelling of flight of rotorcraft in autorotation.

High-fidelity CFD analyses of flow around main rotor have been conducted using the ANSYS FLUENT and formerly developed and implemented in-house UDF module Virtual-Rotor-3D [6]. In this approach, the rotor flight simulation consists in the solution of URANS equations in the domain surrounding the rotating rotor (with truly modelled geometry of blades) by the use of ANSYS FLUENT code. All rotorcraft-specific activities are realized by

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the module Virtual-Rotor-3D. The computational mesh is divided into several subdomains. Around each blade, the cylinder-conical volume zone is defined. Such zones are embedded in a cylinder-volume zone which is embedded in a far-field modelling zone. The motion of individual computational meshes are carried out using the Overset Mesh, Dynamic Mesh and Sliding Mesh techniques implemented in the ANSYS FLUENT. Among others, the module Virtual-Rotor-3D enables to model a dynamic control of rotor-blade pitch, blade flapping and lead-lag motion as well as the trimming the rotor for required thrust or accessible power driving the rotor.

3. DESIGN AND OPTIMISATION OF MAIN ROTORS FOR LIGHT ROTORCRAFTS

3.1. Main Rotor for UAV Helicopter

The subject of the research was newly-designed unmanned helicopter equipped with 3-blade main rotor. The overall purpose of the research was to improve the performance of the helicopter in a hover, through redesigning of blades of its main rotor. The optimisation problem has been formulated as follows: for a given power driving the rotor, to maximise the rotor thrust in hover at altitude 100 m.a.s.l.

The preliminary stage of the design process has been focused on design and optimisation of family of airfoils used for the blade design. As base airfoils, the formerly developed family ILH3XX [7] has been selected. The following criteria of airfoil design were assumed:

- maximization of maximum lift coefficient (C_{Lmax}) at Mach number M=0.4,
- maximization of drag-divergence Mach number (M_{dd}) at lift coefficient C_L=0,
- maximization of lift to drag ratio at Mach number M=0.6 and lift coefficient C_L=0.7,
- very low level of pitching moment coefficient in all typical flight conditions.

Figure 2 shows favourable aerodynamic performance improvements of the ILH3XX airfoils compared to the high-performance airfoil family VR12-VR14 (Boeing-Vertol) [8].

Airfoils was the base airfoils for designing the rotor blades of an UAV helicopter. Based of airfoils ILH3XX (slightly modified at trailing edge), the parametric model of the main-rotor blade was developed, using the PARADES software. The model took into consideration the design parameters influencing: spanwise distribution of blade chord, twist, thickness, trailing-edge thickness of as well as the blade-tip anhedral (see Figure 3).

Using the above parametric model, the rotor-blade-optimisation process has been conducted. In initial stages of this process, to assess aerodynamic properties of designed variants of main rotor, the simplified approach, based on Virtual Blade Model, has been applied. In final stage of the designing, the approach utilising the Virtual-Rotor-3D module, has been applied. For every single variant of main rotor, the CFD simulations of helicopter hover focused on an adjustment of the blade collective pitch so as to obtain the given power driving the rotor. The goal of these activities was to design of the rotor generating maximum thrust.

The final result of the above design process was the main rotor, marked by "FINAL DESIGN". The optimised rotor, in relation to the BASELINE has been characterised by 4.6% higher thrust, at the same power driving the rotor. This result has been partially confirmed in experimental research conducted in a whirl tower. Geometrically, blades of rotors BASELINE and FINAL DESIGN differ significantly from each other in respect to both the blade cross-sections as well as radial distributions of chord and geometric twist, as shown in Figure 4.

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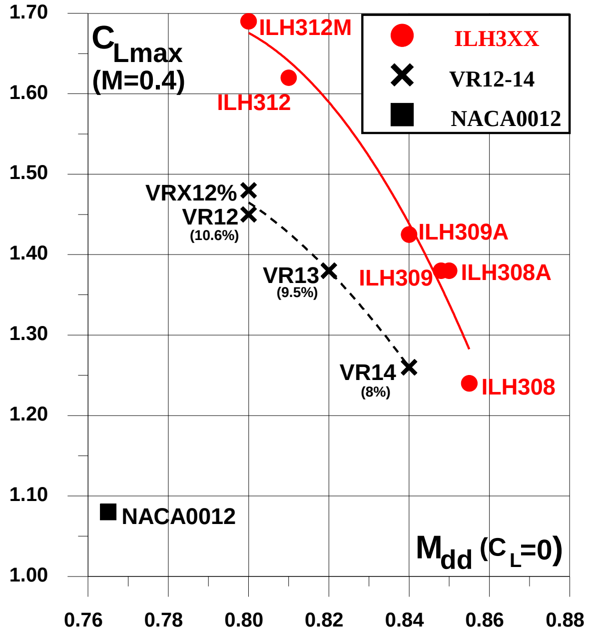

Figure 2. Computational aerodynamic characteristics of designed airfoil family ILH3XX and reference family VR12-14. Dependency C_{Lmax} at M=0.4 versus M_{dd} at C_L =0 [7].

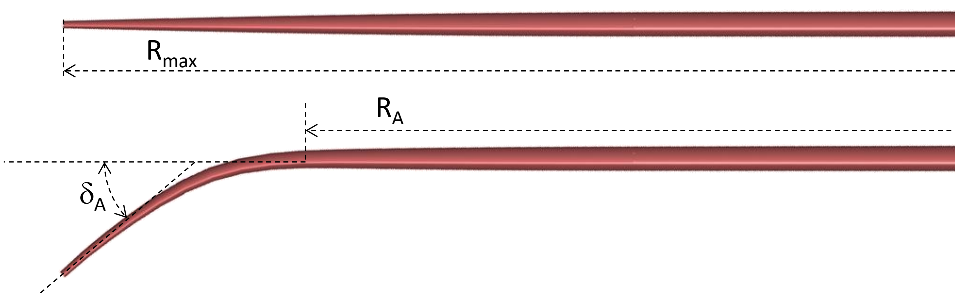

Figure 3. Explanation of design parameters influencing the blade-tip anhedral.

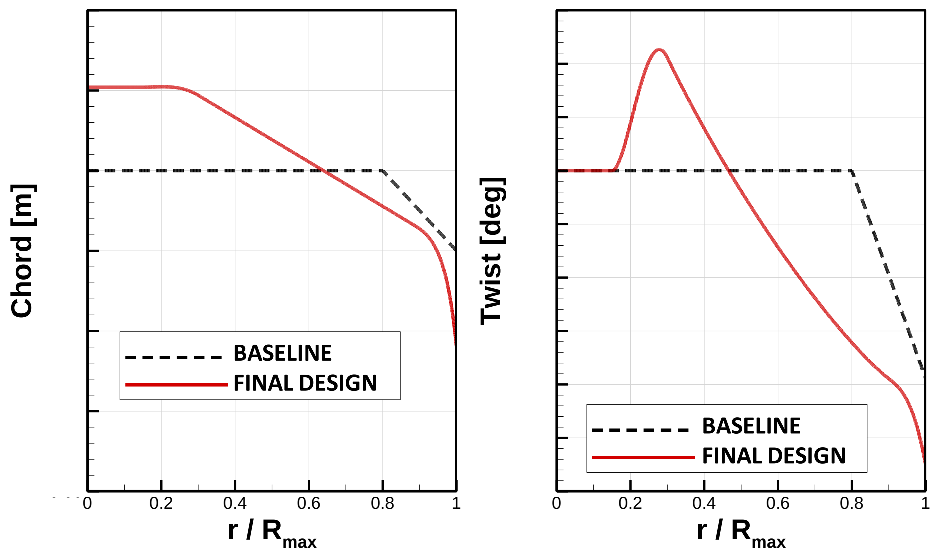

Figure 4. Comparison of radial distributions of blade chord (left graph) and geometrical twist (right graph), for the BASELINE blade and eventually designed blade (FINAL DESIGN).

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3.2. Main Rotor for Ultralight Helicopter

It was assumed, that the main rotor for ultralight helicopter would characterise by a simple design, i.e. its blades would be rectangular and built based on a single airfoil. In such a case, the main-rotor optimisation focused on the design an airfoil possibly optimal for use on the main-rotor blades of ultralight helicopter.

The main objective of the research was to design an airfoil/airfoils of main-rotor blades that could improve a performance of the ultralight helicopter, especially in fast-flight conditions. The airfoil-design process was carried out for flow conditions determined through computer simulations of a fast flight of isolated main rotor, using the ANSYS FLUENT and Virtual-Blade-Model module. As reference airfoils for the design process, the airfoils NACA0012 and NACA23012, commonly used in ultralight helicopters, were selected.

As a result of conducted optimisation process, two new airfoils, marked by ILULH11 and ILULH11, have been designed. Their main aerodynamic characteristics compared with reference airfoils, are presented in Figure 5 and Figure 6.

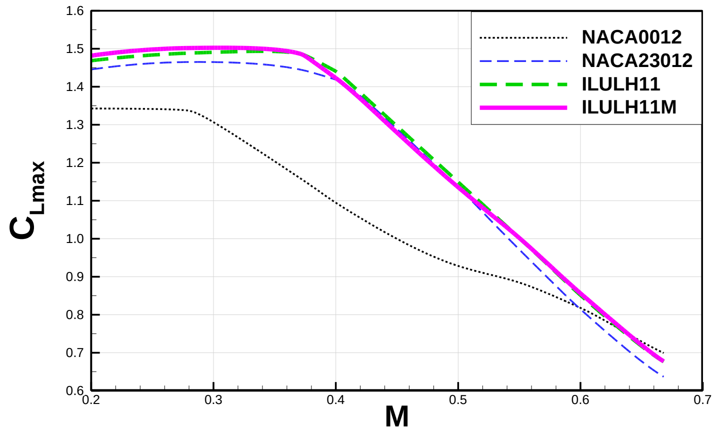

Figure 5. The dependency: maximum lift coefficient (C_{Lmax}) versus Mach number (M) determined computationally for the airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012.

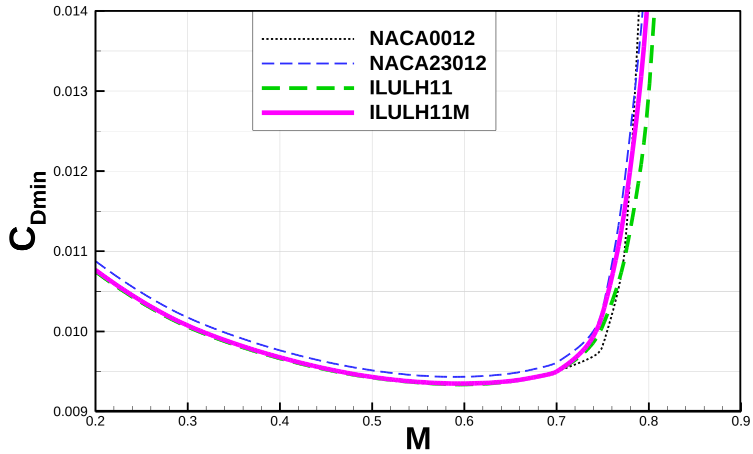

Figure 6. The dependency: minimum drag coefficient (C_{Dmin}) versus Mach number (M) determined computationally for the airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012.

To evaluate the potential benefits of application of the airfoils ILULH11 or ILULH11M on the blades of a main rotor of the ultralight helicopter, a series of simulations of fast flight of the helicopter has been conducted, using the VBM approach. The results of these simulations let to conclude that in fast flight of the ultralight helicopter:

- rotor ILULH11, with respect to the rotor NACA23012, for the same generated thrust characterises by 0.67% ÷ 1.00% lower the power necessary to drive the rotor and by 0.68% ÷ 0.99% higher the power loading,

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- rotor ILULH11, with respect to the rotor NACA23012, for the same generated thrust characterises by 0.73% ÷ 1.14% lower the power necessary to drive the rotor and by 0.73% ÷ 1.16% higher the power loading,
- with respect to the rotor NACA0012, the above advantages of newly designed rotors are significantly higher.

Moreover, it is expected that the rotors ILULH11 or ILULH11M can reach higher maximum flight velocity compared to the NACA23012 rotor and significantly higher compared to NACA0012 rotor.
Main rotor with blades built based on airfoil ILULH11M has been put into production and has already achieved marketing success. This way it has proven its good performance properties in practice.

3.3. Main Rotors for Light Gyroplane

The research aimed at designing of two independent main rotors for light gyroplane. Blades of these rotors differed with each other in manufacturing technology, which primarily influenced the diversity of the construction limitations and freedom in shaping the blades. In aerodynamic projects of both rotors a lot of innovative aerodynamic solutions have been applied. It concerns, among others: a designed family of high-performance gyroplane airfoils, and, in the case of the rotor with composite blades, also an unconventional blade planform.
Family of airfoils designed especially towards gyroplane applications include three airfoils:

- ILW-LT-11.0 of relative thickness 11%.
- ILW-LT-10.0 of relative thickness 10%,
- ILW-LT-09.0 of relative thickness 9%.

Their basic aerodynamic characteristics are presented and compared to the NACA9H12M airfoil (commonly used in gyroplane applications) in Figure 7.

The rectangular duralumin blades of the rotor ILW-RECTANGULAR have been built based on airfoil ILW-LT-11.0. In the case of the second rotor ILW-VARIABLE-CHORD, its composite blades (see Figure 8) have been built based on all three above airfoils. In this case the design process consisted in an optimal design of blade cross-sections, optimal distribution of these airfoils along the blade span as well as optimal design of blade planform.

Figure 9 presents obtained computationally (using ANSYS FLUENT and VBM module) dependency of drag force acting on the main rotor versus flight velocity, during the flight of the gyroplane of total mass 600 kg. The presented computational results concern the optimised rotors ILW-RECTANGULAR and ILW-VARIABLE-CHORD as well as the reference rotor NACA9H12M. Based on presented results it may be concluded that for the flight speed 160 km/h and gyroplane mass 600 kg, the newly designed rotors ILW-RECTANGULAR and ILW-VARIABLE-CHORD are characterised by 7.5% and 13.8% reduction in drag force, compared to the reference rotor, respectively.

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

- the gyroplane equipped with the rotor ILW-RECTANGULAR 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 speed 100 km/h, the rotor ILW-RECTANGULAR 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-RECTANGULAR was shorter by approximately 10 sec compared to the gyroplane with the reference rotor.

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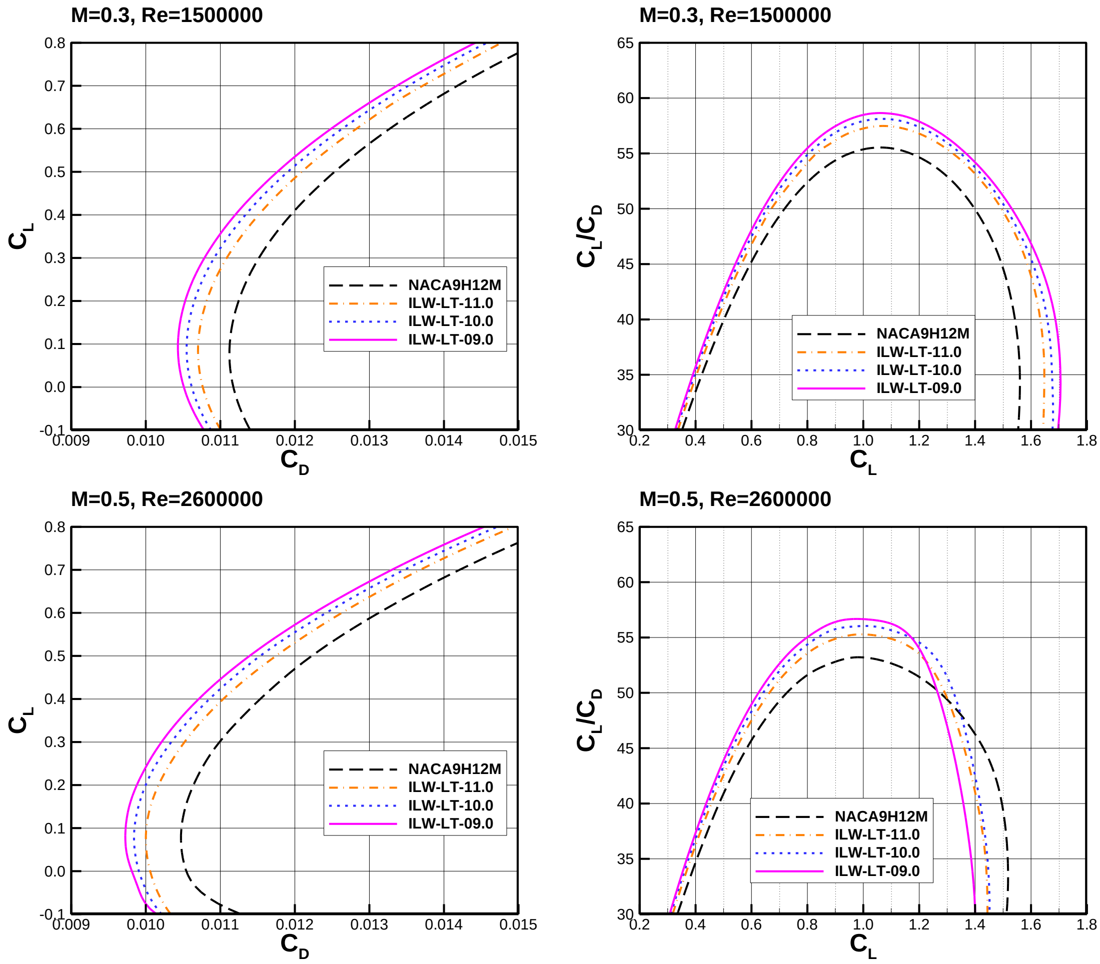

Figure 7. Comparison of aerodynamic characteristics of gyroplane airfoils ILW-LT-09.0, ILW-LT-10.0, ILW-LT-11.0 and NACA 9H12M, for flight conditions M=0.3, Re=1500000 and M=0.5, Re=2600000.

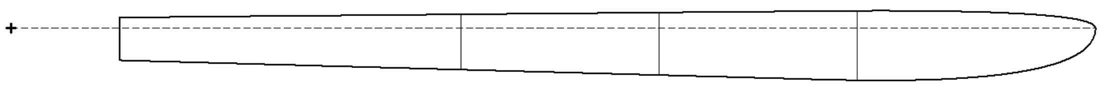

Figure 8. The planform of the blade of the rotor ILW-VARIABLE-CHORD.

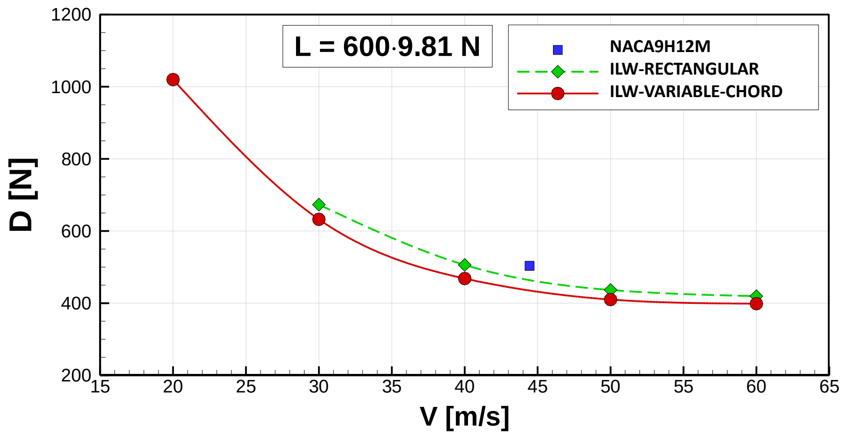

Figure 9. Total drag force (D) acting on the rotor versus flight velocity (V), during the flight of the gyroplane of total mass 600 kg. Comparison of computational results for reference rotor NACA9H12M and for newly designed and optimised rotors ILW-RECTANGULAR and ILW-VARIABLE-CHORD.

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4. CONCLUSIONS

An advanced methodology of aerodynamic design and optimisation of rotorcraft main rotors has been developed. The methodology has been applied to improve a performance of several light rotorcrafts through redesigning of their main rotors. Presented research has focused on three light rotorcrafts: UAV helicopter, light gyroplane and ultralight helicopter. In all discussed cases, the redesigned main rotors compared to baselines have characterised by moderate or significant improvement of performance which should also lead to the performance improvement of the rotorcrafts. Presented results have been partially confirmed experimentally or even in real flights of rotorcrafts. This lets to conclude, that the presented methodology and approach is worth recommendation as a valuable tool supporting modern rotorcraft engineering.

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