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DESIGN AND OPTIMISATION OF MAIN ROTOR FOR ULTRALIGHT HELICOPTER

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Abstract

A modern main rotor, dedicated to the ultralight helicopter, has been designed and optimised. Due to assumed simplicity of the rotor design and taking into account some technological constraints, the principal purpose of the presented research was to design a dedicated airfoil which, when applied on the main-rotor blades, would influence satisfactory improvement in a performance of the ultralight helicopter, especially in fast flight. The design and optimisation process has been supported by a computational methodology. The in-house software has been used for direct and inverse design of shapes of the rotor-blade airfoils. Aerodynamic properties of the airfoils as well as the helicopter main rotor were evaluated based on both the two-dimensional and three-dimensional flow simulations conducted using the ANSYS FLUENT software that was used to solve U/RANS equations. Based on the results of conducted computational simulations of fast flight of the ultralight helicopter, it can be concluded that the newly designed main rotor, compared to the baseline, may give certain improvement in helicopter performance in fast flight. In addition, the application of this newly designed rotor may lead to increase of a maximum speed of the helicopter flight, due to the greater lift force achievable by this rotor on the retreating blade, which is favourable from point of view of keeping of a lateral balance of the helicopter in fast flight.

Keywords: *rotorcraft, ultralight helicopter, main rotor, airfoil, computer-aided design and optimisation*

1. Introduction

In theory, when designing new helicopter main rotor, one can use more or less available airfoils that are particularly suitable and designed specifically for this purpose. However, in many cases, the use of such airfoils can be problematic. First of all, the most advanced, optimised helicopter airfoils are usually protected by patent law and their legal use is either impossible or requires the purchase of the appropriate license. Secondly, in some situations, a new product (helicopter), both from a purely technical point of view and of a very important commercial one, may favourably stand out from others, due to application of modern, advanced airfoils on the main-rotor blades.

The initial stage of the main-rotor design involves, among other things, the process of selection or design of the airfoils dedicated to use on the rotor blades. In this area, it has become customary to design and optimise specialised airfoils dedicated not only to specific applications such as main rotor or tail rotor, but also individually tailored to the predicted range of mission of the aircraft. This trend is reflected in the design of the main rotor dedicated for the ultralight helicopter, which has been described in this article. Because of the assumed simplicity of the rotor and its blades and with respect to the required design constraints, the principal purpose of the described research was to develop an airfoil or airfoils which, when applied on the main-rotor blades, would influence satisfactory improvements in a performance of the ultralight helicopter in fast flight.

2. Methodology

The design of airfoils intended for the ultralight-helicopter-rotor blades was conducted simultaneously with the main rotor design. The new airfoils indented for ultralight-helicopter applications were designed so as to fulfil requirements defined based on an analysis of aerodynamic properties of subsequent variants of helicopter main rotors. The reference point for the airfoil design was the airfoil NACA23012 – very popular in ultralight-helicopter applications. The design and optimisation of airfoils was conducted with the use of the following computational tools:

- CODA4W – in-house code supporting airfoil design,
- INVDES – in-house code solving the inverse-airfoil-design problem,
- XFLR-5 [2] – commonly used code for aerodynamic analysis of airfoils in low-speed conditions,
- ANSYS FLUENT [1] – commonly used Navier-Stokes-Equations solver.

During the design of a new family of airfoils, their initial shapes were designed using the CODA4W software. Next, the airfoils were redesigned and smoothed aerodynamically by the solution of Inverse-Airfoil-Design problem. Aerodynamic properties of subsequent variants of airfoils were analysed using the XFLR-5 software. For selected, most promising airfoils, the databases of aerodynamic characteristics were built with the use of the ANSYS FLUENT code.

The helicopter-flight-simulation methodology has been based on a solution of Unsteady-Reynolds-Averaged-Navier-Stokes (URANS) equations, which has been conducted by the use of ANSYS FLUENT solver. Flow effects caused by rotating lifting surfaces have been modelled by application of the developed Virtual Blade Model (VBM) [4]. In this approach, real rotors are replaced by volume discs influencing the flow field similarly as rotating blades. Time-averaged aerodynamic effects of rotating lifting surfaces are modelled by means of artificial 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. The original VBM code was significantly modified and expanded by the author of this article. In the presented research, the rotor-optimisation studies were focused on forward flight of separate main rotor.

3. Main-Rotor Design and Optimisation

Main-rotors of ultralight helicopters are characterised by a simple design. This particularly concerns their blades, which usually are rectangular and are built based on a single airfoil. Taking into account such simplifications, the process of the main-rotor design was focused mainly on the design an airfoil, which would be optimised for use on the main-rotor blades of ultralight helicopter.

The main objective of the research was to design an airfoil/airfoils which, when applied on the main-rotor blades, could significantly improve a performance of the ultralight helicopter, especially in fast-flight conditions. The airfoil-design process was carried out taking into account the flow conditions described by parameters such as Mach number, Reynolds number or the value of lift coefficient, specific to the selected cross sections of rotating blades of the rotor. Such flow conditions were determined through computer simulations of a fast flight of isolated main rotor, using the ANSYS FLUENT and Virtual-Blade-Model module.

At the beginning of the design work, basic design goals and constraints were defined. Based on the guidelines defined by the manufacturer of rotors dedicated for ultralight helicopters, the boundary conditions for design process were assumed. They are presented in Tab. 1.

Using the methodology described in Section 2, a series of simulations of a flight of the ultralight helicopter defined in Tab. 1 have been conducted. In the simulations, the collective-and-cyclic-pitch controls of the rotor-blade have been established through the trimming of the rotor to the required values of thrust (balancing a helicopter weight) as well as aerodynamic pitching and rolling moments generated by the rotor. The results of these simulations are shown in Fig. 1, 2 and 3, which show the predicted distributions of the local Mach number (M), Reynolds number (Re), and sectional lift coefficient (C_L) on the rotor disk.

Tab. 1. Selected parameters of blade/rotor/helicopter/flight conditions, assumed when designing a main rotor dedicated for ultralight helicopter

rotor type	teetering
number of rotor blades	2
diameter of the rotor	7 m
blade planform	rectangular
blade chord (C)	0.18 m
blade airfoil	the same along the whole blade span, to be designed and optimised; baseline airfoil: NACA23012 / NACA0012
relative thickness of the blade airfoil	≥ 11%C
relative thickness of the blade trailing edge	≥ 0.556%C
blade twist	linear: 0° at rotor-rotation axis, –10° at the blade tip
angular speed of the rotor	480 rpm
maximum take-off mass (MTOM)	480-500 kg
maximum flight speed	200-220 km/h

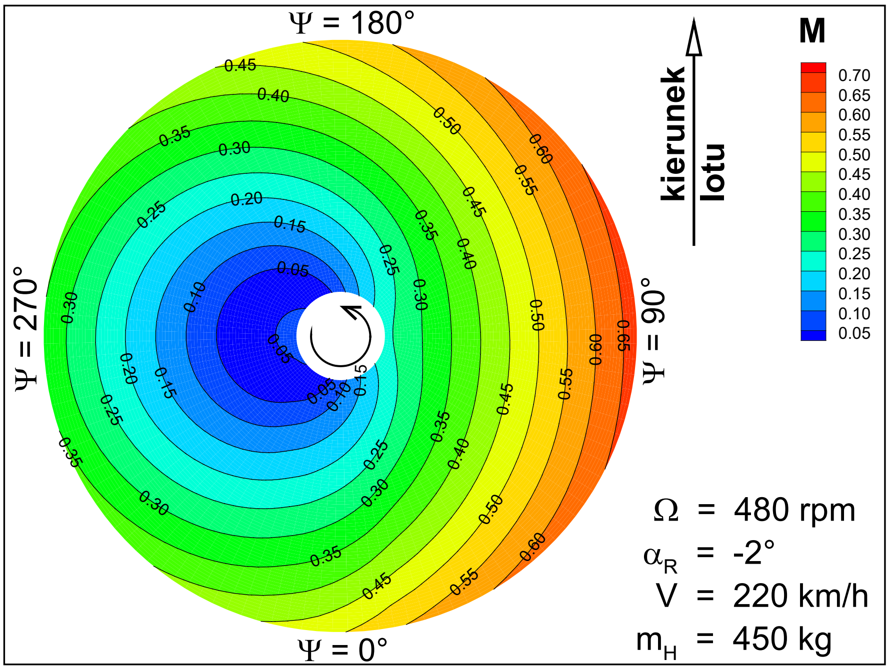

Fig. 1. Predicted distribution of the local Mach number of flow (M), on the rotor disk, determined on the basis of the computational simulation of the fast flight of the ultralight helicopter

Based on the results shown in above figures as well as the rotor manufacturer's guidelines, the following basic criteria and constraints for the airfoil-design process have been defined:

- on the advancing blade (Ψ = 90°), the expected quasi-two-dimensional flow conditions correspond to Mach range: 0.3-0.7, Reynolds numbers: $1.2 \cdot 10^6 - 2.6 \cdot 10^6$ and lift coefficient 0.0-0.4. For such flow conditions, new airfoils should be characterized by possibly the smallest values of drag coefficient (C_D),
- on the retreating blade (Ψ = 270°) the expected quasi-two-dimensional flow conditions correspond to Mach range: 0.1-0.35, Reynolds numbers: $0.2 \cdot 10^6 - 1.4 \cdot 10^6$. For such conditions, the maximum lift coefficient should fulfil the condition: $C_{Lmax} > 1.4$, which should ensure the lateral balance of the helicopter. High values of the lift coefficient should be achieved for the possibly smallest values of the drag coefficient (i.e., for the high aerodynamic efficiency of the airfoil),

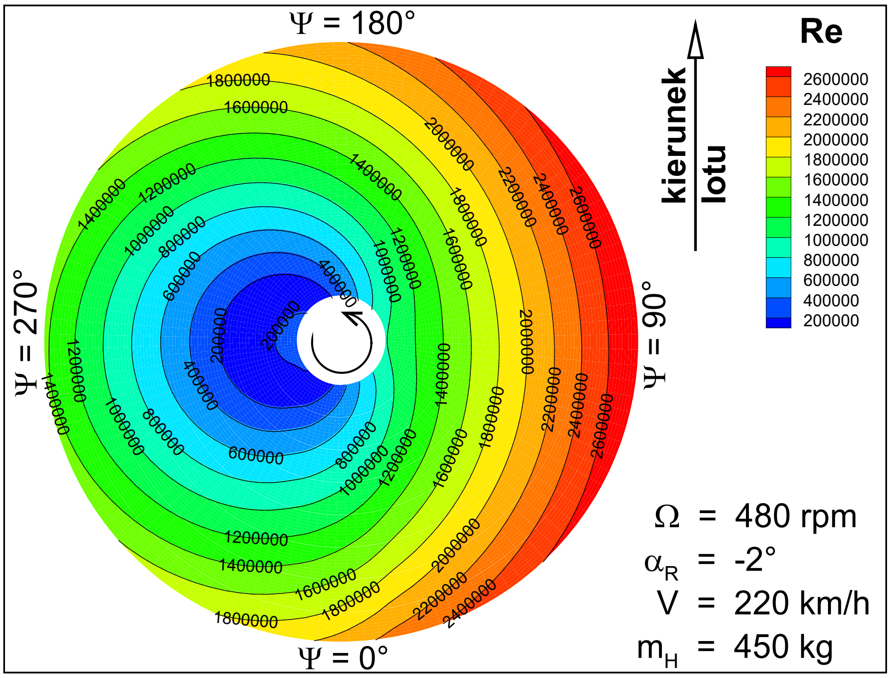

Fig. 2. Predicted distribution of the local Reynolds number of flow (Re), on the rotor disk, determined on the basis of the computational simulation of the fast flight of the ultralight helicopter

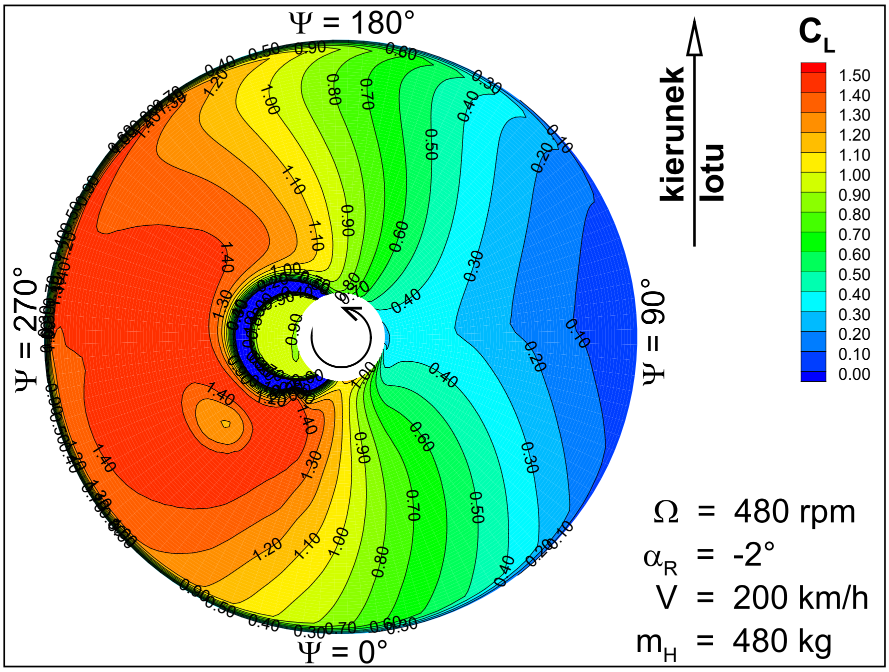

Fig. 3. Predicted distribution of the sectional lift coefficient (C_L), on the rotor disk, determined on the basis of the computational simulation of the fast flight of the ultralight helicopter

– for the entire operating range of the Mach and Reynolds numbers and the value of the lift coefficient, the pitching-moment coefficient of the airfoil should satisfy the following condition: $|C_m| < 0.01$.

As a reference (baseline) airfoils for the design process, the NACA0012 and NACA23012 - airfoils commonly used in ultralight-helicopter applications, have been selected. It has been assumed that the purpose of the design and optimisation process will be to design the airfoil that could show some improvement in aerodynamic properties, compared to the reference airfoils.

Following the guidelines described above, a process of the design of airfoils dedicated to the ultralight helicopter has been conducted. The airfoils selected from the formerly developed families of helicopter airfoils ILH3XX [5] and ILH4XX were taken as the starting point for the design process. It should be emphasized, however, that these of airfoil families were optimised primarily for the fast flight ($V_F = 300$ km/h) of a medium-size helicopter, with rotor blades of chord ≈ 0.5 m, and thus for significantly higher Mach and Reynolds numbers compared to those which were assumed for the ultralight helicopter.

These differences caused that the ultimately designed airfoil dedicated to the ultralight-helicopter main-rotor blades, was significantly different compared to the airfoils representing the ILH3XX or ILH4XX families. The newly designed airfoil was marked with ILULH11. After its design, a series of flight simulations for the main rotor with blades built based on the new airfoil, have been conducted. The results of these simulations have confirmed that some progress has been made in helicopter performance relative to the reference main rotors, with blades built based on reference airfoils. At the same time, however, it has been found that this progress in helicopter performance could be further improved through the increase of maximum lift coefficient of the airfoil, within the range of Mach numbers: 0.1-0.35. Following this guideline, a second cycle of design and optimisation was performed, resulting in a modification of the ILULH11 profile, which was designated as ILULH11M.

The basic geometric features of the newly designed airfoils ILULH11 and ILULH11M are summarised in Tab. 2. The contours of these profiles are shown in Fig. 4.

Tab. 2. Basic geometrical properties of the newly designed airfoils ILULH11 and ILULH11M

Property	ILULH11	ILULH11M
maximum relative thickness	11%C	11%C
chordwise position of maximum thickness	30.00%C	28.91%C
camber of mean line	2.00%C	2.06%C
relative thickness of blade trailing edge	0.556%C	0.556%C

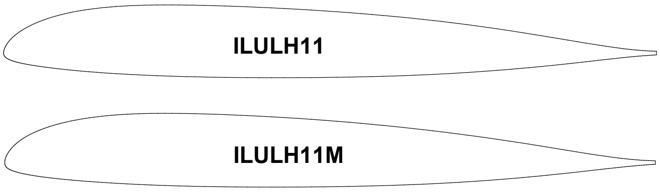

Fig. 4. Contours of the newly designed airfoils ILULH11 and ILULH11M

The aerodynamic characteristics of the newly designed profiles were determined by means of a two-dimensional version of the ANSYS FLUENT software, which was used to solve the RANS equations with the k-ω SST turbulence model. In addition to the ILULH11 and ILULH11M airfoils, the reference airfoils NACA0012 and NACA23012 were also analysed. Calculations were made for the Mach number range: 0.2-0.81 and for the Reynolds numbers associated with the Mach numbers through dependency: $Re = M \cdot 4 \cdot 10^6$ resulting from the assumed reference chord: $C = 0.18$ m. Fig. 5 compares the aerodynamic characteristics of airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012 in respect to the dependency: maximum lift coefficient (C_{Lmax}) versus Mach number (M). An analysis of the presented graphs leads to the following conclusions:

- within the range of Mach numbers: 0.1-0.35, the airfoil ILULH11M indicates higher values of maximum lift coefficient (C_{Lmax}), which was the main goal of the designing of this airfoil,
- newly designed airfoils ILULH11 and ILULH11M indicate higher values of maximum lift coefficient (C_{Lmax}), compared to reference airfoils NACA23012 and NACA0012,
- airfoil NACA0012 indicates the maximum lift coefficient less than 1.35, which disqualifies it for use in the considered flight conditions, because it does not meet the requirement $C_{Lmax} > 1.4$ in conditions corresponding to the retreating blade.

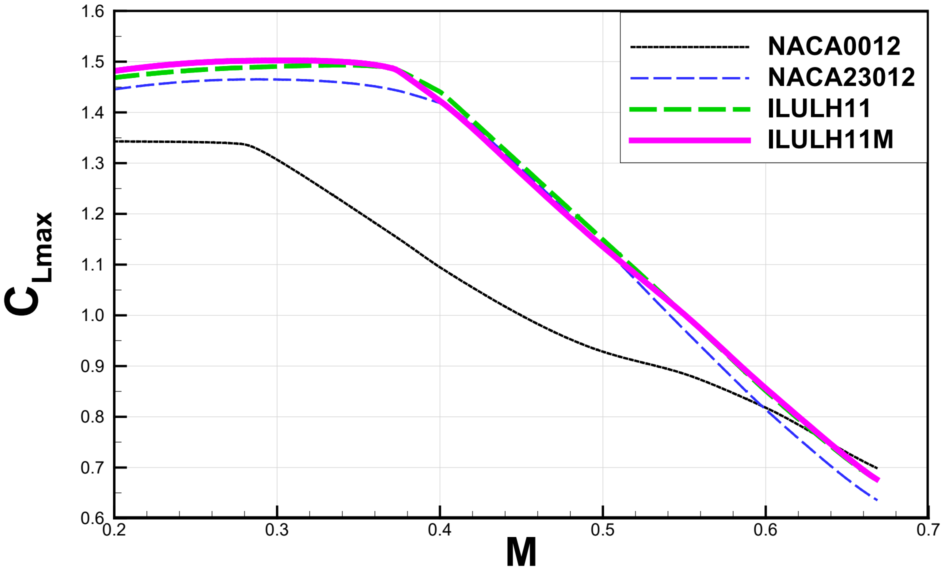

Fig. 5. Comparison of aerodynamic characteristics of airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012. The dependency: maximum lift coefficient (C_{Lmax}) versus Mach number (M)

Figure 6 compares the aerodynamic characteristics of airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012 in respect to the dependency: the minimum drag coefficient (C_{Dmin}) versus Mach number (M). Based on the presented results it may be concluded, that values of the coefficient C_{Dmin} for the airfoils ILULH11, ILULH11M, and NACA0012 are similar and slightly smaller than for the airfoil NACA23012.

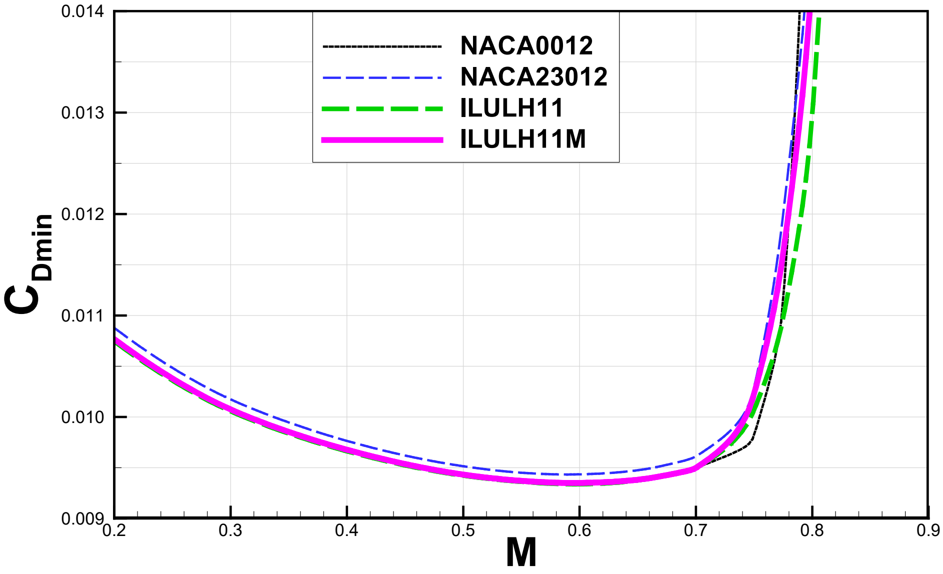

Fig. 6. Comparison of aerodynamic characteristics of airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012. The dependency: minimum drag coefficient (C_{Dmin}) versus Mach number (M)

Figure 7 compares the aerodynamic characteristics of airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012 in respect to the dependency: the Mach-drag-divergence number (M_{DD}) versus lift coefficient (C_L). Based on the presented graphs it may be concluded that:

- Mach-drag-divergence numbers evaluated for the airfoil ILULH11 are favourable higher than for the airfoil ILULH11M,
- Mach-drag-divergence numbers evaluated for the airfoil ILULH11M are favourable higher than for the airfoil NACA23012.

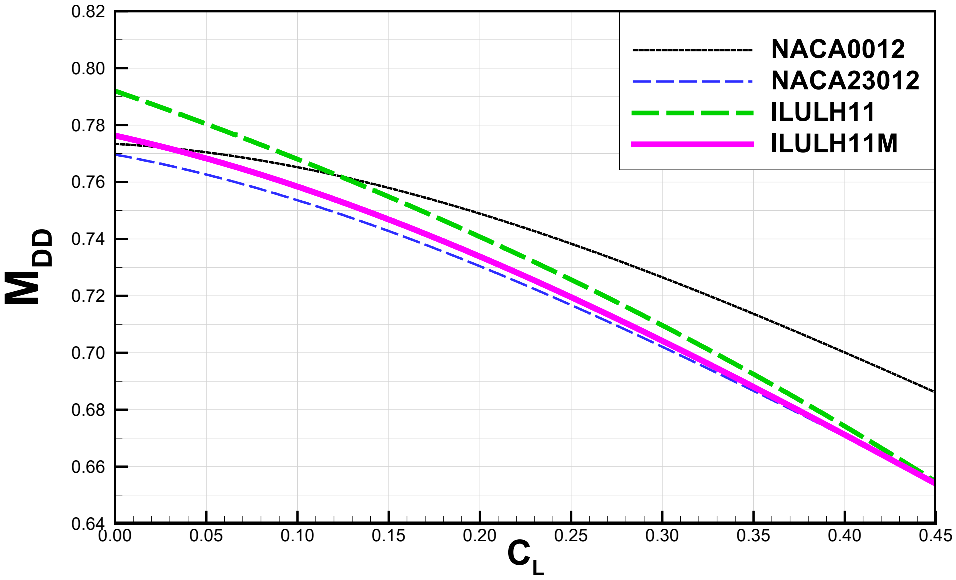

Fig. 7. Comparison of aerodynamic characteristics of airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012. The dependency: Mach-drag-divergence number (M_{DD}) versus lift coefficient (C_L)

Figure 8 compares the aerodynamic characteristics of airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012 in respect to the dependency: the pitching moment coefficient at zero lift (C_{m0}) versus Mach number (M). Based on the presented graphs it may be concluded that:

- airfoils ILULH11 and ILULH11M fulfil the requirement: $|C_{m0}| < 0.01$ within the whole range of Mach numbers ($M < 0.7$),
- airfoils ILULH11 and ILULH11M are characterised by a significantly lower level of the pitching moment compared to the airfoil NACA23012,
- Mach-pitching-moment-divergence numbers (at zero lift) of the airfoils ILULH11 and ILULH11M are significantly higher, than the Mach numbers expected on the rotor blades in fast flight of an ultralight helicopter, so there is not the danger that during the helicopter flight a significant growth of negative pitching moment will appear.

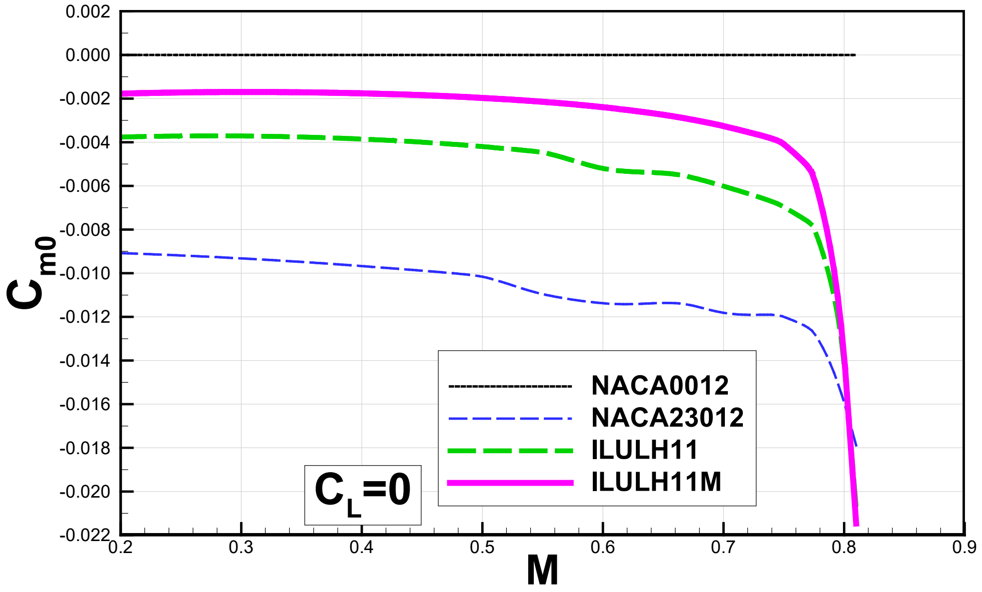

Fig. 8. Comparison of aerodynamic characteristics of airfoils: ILULH11, ILULH11M, NACA23012 and NACA0012. The dependency: pitching moment coefficient at zero lift (C_{m0}) versus Mach number (M)

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 defined in Tab. 1 has been conducted. Simulations were made based on the methodology described in Section 2. In the simulations, the collective-and-cyclic-pitch controls of the rotor blade have been established so as to obtain required values of the thrust (balancing a helicopter weight) and zero aerodynamic moments generated by the rotor. Four main-rotor configurations were taken into consideration. Each of them was related to the one of the airfoils (ILULH11, ILULH11M, NACA23012 and NACA0012) used to build of the rotor blades. Simulations were carried out for the following four selected conditions of helicopter flight, described by the flight velocity (V_F), total helicopter mass (m_H) and rotor angle of attack (α_R):

- Flight Conditions No. 1: $V_F = 220$ km/h, $m_H = 450$ kg, $\alpha_R = -2°$,
- Flight Conditions No. 2: $V_F = 200$ km/h, $m_H = 480$ kg, $\alpha_R = -2°$,
- Flight Conditions No. 3: $V_F = 200$ km/h, $m_H = 485$ kg, $\alpha_R = -2°$,
- Flight Conditions No. 4: $V_F = 200$ km/h, $m_H = 490$ kg, $\alpha_R = -2°$.

The results of the conducted simulations are summarized in Tab. 3 that shows obtained in individual cases values of: the rotor thrust (T) and the power (P) necessary to drive the rotor. For reliable comparison of the efficiency of individual main rotors, the Power Loading (PL) factor was applied. This factor expresses the ratio of thrust to power [3]:

$$\mathrm{PL} = \frac{\mathrm{T}}{\mathrm{P}}, \tag{1}$$

where:

T – thrust generated by the rotor,

P – power necessary to drive the rotor, so as to obtain the given thrust.

The Power Loading factor corresponds to the thrust generated by one unit of power. In the given flight conditions, the larger the factor is, the greater the rotor efficiency. As shown in Tab. 3, as predicted, in all considered flight conditions, it was impossible to trim the rotor (so as to obtain the required thrust as well to zero pitching and rolling moments generated by the rotor) of blades built based on the NACA 0012 airfoil. The same concerns the rotor of blades build based on the NACA23012 airfoil, for the Flight Conditions No. 4 (the highest total mass of the helicopter). Such problems in rotor trimming did not occurred in the cases of the main rotors with blades built based on ILULH11 or ILULH11M airfoils.

Tab. 3. Performance characteristics of the main rotors with blades built based on airfoils ILULH11, ILULH11M, NACA23012 and NACA0012, in selected states of flight of the ultralight helicopter

	V_F [km/h]	**220.000**	**200.000**	**200.000**	**200.000**
	m_H [kg]	**450.000**	**480.000**	**485.000**	**490.000**
	α_R [°]	**-2.000**	**-2.000**	**-2.000**	**-2.000**
ILULH11	**T [kgf]**	450.329	480.327	485.247	490.251
	P [ph]	76.138	82.975	84.583	86.252
	PL [kgf/hp]	**5.915**	**5.789**	**5.737**	**5.684**
ILULH12M	**T [kgf]**	450.336	480.244	485.353	490.289
	P [ph]	76.006	82.926	84.460	86.050
	PL [kgf/hp]	**5.925**	**5.791**	**5.747**	**5.698**
NACA23012	**T [kgf]**	450.335	480.255	485.325	---
	P [ph]	76.658	83.537	85.435	---
	PL [kgf/hp]	**5.875**	**5.749**	**5.681**	**---**
NACA0012	**T [kgf]**	---	---	---	---
	P [ph]	---	---	---	---
	PL [kgf/hp]	**---**	**---**	**---**	**---**

Based on the results presented in Tab. 3 it may be concluded that:

- in the considered flight conditions, the rotor with the blades built based on airfoil ILULH11, with respect to the rotor with the blades built based on airfoil NACA23012, for the same value of the generated thrust (T) is characterised by 0.67-1.00% lower the power (P) necessary to drive the rotor and by 0.68-0.99% higher the power loading (PL),
- in the considered flight conditions, the rotor with the blades built based on airfoil ILULH11M, with respect to the rotor with the blades built based on airfoil NACA23012, for the same value of the generated thrust (T) is characterised by 0.73-1.14% lower the power (P) necessary to drive the rotor and by 0.73-1.16% higher the power loading (PL),
- for the flight conditions: $V_F = 200$ km/h, $m_H = 490$ kg, $\alpha_R = -2°$, both newly designed rotors (ILULH11 and ILULH11M) were successfully trimmed to a given thrust and zero aerodynamic moments, while for the reference rotor with blades built based on the airfoil NACA23012 the trimming procedure failed. The reason for this failure was the inability to obtain a sufficiently high lift force on the retreating blade.

For the reference rotor with blades built based on the airfoil NACA0012 the trimming procedure failed in all considered flight conditions.

4. Summary and conclusions

Based on the results of conducted computational simulations of fast flight of the ultralight helicopter, it can be concluded that the application of the airfoil ILULH11M on the rotor blades gives slightly better helicopter-performance improvement than in the case of the airfoil ILULH11. For these reasons, the rotor ILULH11M (with blades built based on the airfoil ILULH11M) has been chosen as the final result of the research presented in this article. Compared to the reference rotors, whose blades were built on the basis of NACA0012 and NAC23012 airfoils, the finally designed rotor ILULH11M should indicate some improvement in aerodynamic efficiency, especially in fast flight of the helicopter. In addition, the application of this newly designed rotor may lead to increase of a maximum speed of the helicopter flight, due to the greater lift force achievable by this rotor on the retreating blade, which is favourable from point of view of keeping of a lateral balance of the helicopter in fast flight.

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