DEVELOPMENT OF NEW GENERATION MAIN AND TAIL ROTORS BLADE AIRFOILS

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Keywords: *helicopter, rotor, airfoil*

Abstract

A numerical and experimental study on the design new generation main and tail rotors blade airfoils was performed. Design objectives for the blade sections at several rotor stations are discussed based on the mission requirements and today's state of the art. The tail rotor airfoil design was aimed specifically to obtain higher C_{Lmax} than conventional NACA airfoils for the Mach number up to 0.6. Aerodynamic inverse method and direct iterative design optimization used in the design process are described.

The numerical aerodynamic characteristics of the designed rotor airfoils are compared to advanced rotor airfoils family VR12÷VR14. This comparison shows the benefits of the new developed airfoils in relation to the VR airfoils family.

Presented numerical efforts led to a new tail rotor airfoil that offers about 40 percent increase in C_{Lmax} value at Mach number of 0.6 in relation to conventionall NACA 0012 or 23012 airfoils.

A two-dimensional wind tunnel test has been conducted on the newly designed main rotor blade airfoil having thickness of 12% to confirm the numerical design results. The experimental results are compared with the aerodynamic characteristics of other advances rotor airfoils and with numerical results. The agreement of the wind tunnel and calculated results is quite good and it confirms that new developed rotor airfoils family achieved or exceeded the design objectives.

1 Introduction

Rotor aerodynamics plays a very important part in successful design of advanced helicopters. Blades of rotor have to work in a most complicated flow with extremely complex aerodynamic phenomena associated with a large spectrum of different flow conditions. On the advancing portion of the rotor disk, the flow around the blade tip reaches up to transonic Mach number leading up to a shock-wave / boundary layer interaction. On the other hand, on the retreating portion of the rotor disk the flow speed over blade is low. In consequence, for acquisition helicopter roll stability, the local lift has to be high enough to balance the advancing blade in high dynamic pressure. It leads occasionally to local flow separation on the outer region of the retreating blade. Based on the performance goals of the rotor, the rotor blade airfoils should possess high aerodynamic characteristics throughout the wide range of Mach numbers and angles of attack.

Generally speaking, the rotor blade airfoils should have high maximum lift coefficient at low and medium subsonic Mach numbers and low drag up to high or transonic Mach numbers at lift close to zero. In addition, in order to minimize blade torsion and the load to the control system, the rotor blade airfoils have to maintain very low pitching moment coefficient. Furthermore, the hover conditions (i.e. local Mach numbers of up to 0.6 at medium values of lift coefficient) should be taking into account. It leads to maximize of the airfoil lift to drag ratio at these conditions.

The tail rotor plays an important part in the operation of the conventional helicopter. The thrust generated by the tail rotor provides the torque to counterbalance the torque generated by the main rotor. A possibility of the tail rotor improvement lays in design a new tail rotor airfoil to give a higher maximum lift coefficient up to Mach number of 0.6 than conventional airfoils like NACA 0012 or NACA 23012.

Since the beginning of the eighties research work has been undertaken in the Aviation Institute for developing advanced airfoils for helicopter rotors. Two rotor families have been designed which are designated ILH1xx [14,15] and ILH2xx [16-17]. The experience which has been gained in the design process of previous airfoil families and possession of the new CFD codes offer the possibility to improve some aerodynamic characteristics of ILH2xx airfoils family in order to better meet rotor requirements.

This study is focused to develop of a helicopter main and tail rotors blade airfoils shape with required aerodynamic performances subject to both aerodynamic and geometric constraints in view of the better performance of both rotors.

2 Design criteria for main and tail rotor blade airfoils

It can be stated that the main rotor blade airfoil operating environments could be quite different for different flight states and for different airfoil locations along blade radius. The advanced main rotor blade airfoils should meet often opposed requirements for efficient rotor performance. The following design criteria should be fulfilled:

1. High maximum lift coefficient C_{Lmax} at Mach number of 0.4 to delay stall on the retreating portion of rotor disc and to reduce the vibration at high speed flight.
2. High drag divergence Mach number M_{dd} at C_L=0 and low drag coefficient at transonic speed to reduce the required horsepower in the forward flight and the high speed impulsive noise
3. High lift to drag ratio C_L/C_D at Mach number of 0.6 and C_L of 0.7 to reduce the hover horsepower and to improve the hover efficiency
4. Very low pitching moment coefficient at zero lift C_{mo} at subcritical Mach number to reduce blade torsion and the load to the control system - nosedown $|C_{mo}| \leq 0.01$

Development of the composite materials technology allows today to fabricate a rotor blades with varying airfoil sections. It can be found three distinct regions of the flow over the main rotor blade. In this study we are focused on the design airfoils optimized for the flow conditions at three radial positions along blade radius i.e. inboard, outboard and tip regions.

The most important criterion for airfoils at inboard region is high CLmax coefficient at M=0.4. For airfoils at outboard portion of the blade the key criterion beside high C_{Lmax} are high drag divergence Mach number boundary and high C_L/C_D ratio. High drag divergence Mach number at C_L=0 is of the greatest value to the blade tip airfoils. For these airfoils the high C_{Lmax} is also important. Very low value of C_{mo} coefficient is of great significance to the airfoils at all three region of the rotor blade.

3 Numerical tools and design procedure

In realizing the numerical design procedure of the main and tail rotor blade airfoils satisfied above requirements several CFD codes were used. Their features and calculation possibilities are outlined below:

1. MSES [9] – two dimensional analysis and design code, which is based on Euler equations and boundary layer interaction method. This code has following possibilities:

- calculates the flow about airfoils up to and beyond stall, giving the value of C_{Lmax} in Mach number range up to 0.6.
- calculates the airfoil geometry with the specified pressure distribution for compressible inviscid flow

2. HCZMAX [10] – two dimensional analysis code which is based on matching external non-viscous flow and the boundary layer interaction and the artificial separation region. This code calculates the value of C_{Lmax} with reasonable accuracy for comparative purposes with short calculation time on a personal computer.

3. H [8] – modified Bauer/Garabedian/Korn two dimensional analysis code, which is based on a finite difference approximation of the full potential equation with viscous effects taken into account by adding the boundary layer displacement thickness to the contour of airfoil. This code calculates the flow about airfoils up to transonic Mach numbers at given angle of attack or lift coefficient and allows us to determine the value of drag divergence Mach numbers with reasonable accuracy.

4. CODA [11] – CAD type application dedicated to airfoil shape design.

5. INV [13] – based on a panel method code for designing an airfoil with specified pressure distribution in potential, incompressible flow.

6. OPT – airfoil optimization package using genetic algorithm and coupled with HCZMAX and H codes for aerodynamic coefficients prediction.

To have successful results in an airfoil design process, which applies numerical tools, the designer must have confidence in the used CFD codes. Two basic for our design procedure CFD codes i.e. MSES and H codes were validated prior to airfoils design start. Calculated results were compared with the wind tunnel results to check if making use of these codes for the practical airfoil design is sensible. In this study the most important is correctness of the calculated aerodynamic coefficients and parameters, especially maximum lift coefficient C_{Lmax} and the drag divergence Mach number at $C_L=0$. The variations of the maximum lift coefficient against the Mach number of the NACA0012 were compared with experimental results in fig.1. The calculated C_{Lmax} of the NACA0012 agree well with experimental results from over 40 wind tunnels taken from McCroskey [3]. The same conclusion can be drawn to the drag divergence Mach numbers at $C_L=0$ of the NACA0012 and VR12-14 airfoils calculated by H code (see table 1).

Table 1.
Comparison of calculated and experimental drag divergence Mach number at $C_L=0$.

Airfoil	NACA 0012	ILH 212	ILH 209	VR12	VR13	VR14
M_{dd} cal. A	0.765 4	0.790 4	0.815 4	0.800 4	0.820 4	0.840 4
M_{dd} exp. A	0.775	0.795 4	0.825 4	0.805 ~8	0.812 ~8	0.835 ~8

$A=Re\cdot10^{-6}/M$

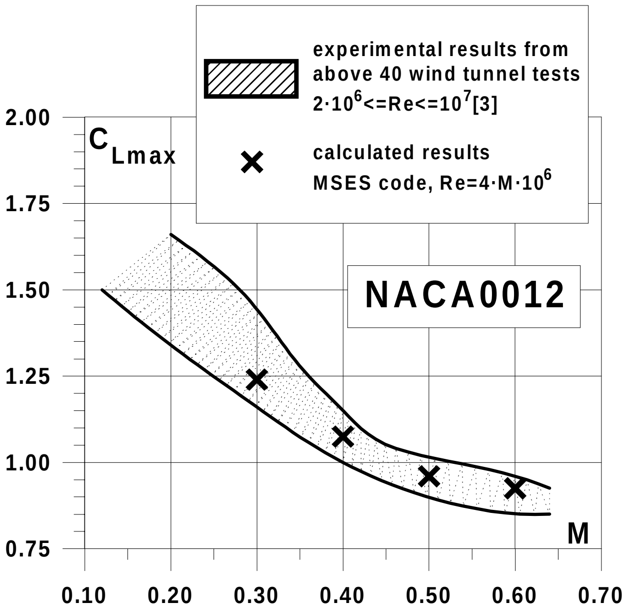

FIG.1 Comparison of calculated and experimental variation maximum lift coefficient versus Mach number

4 Design objectives

Based on the design criteria and on the performances of the third generation main rotor blade airfoils like VR12-VR14 family, DM-H3 and H4 or OA-3xx [6] the practical design objectives were established.

Tip blade airfoil

Thickness: **9% and 8%**
Maximum lift at M=0.4: **$C_{Lmax}\geq1.3$**
Lift to drag ratio at M=0.6 and $C_L=0.7$: **$C_L/C_D\geq60$**
Zero lift drag divergence Mach number: **$M_{dd}\geq0.84$**
Nosedown pitching moment at $C_L=0$, M=0.4: **$|C_{m0}|\leq0.01$**

Outboard blade airfoil

Thickness: **12%**
Maximum lift at M=0.4: **$C_{Lmax}\geq1.5$**
Lift to drag ratio at M=0.6 and $C_L=0.7$: **$C_L/C_D\geq60$**
Zero lift drag divergence Mach number: **$M_{dd}\geq0.80$**
Nosedown pitching moment at $C_L=0$, M=0.4: **$|C_{m0}|\leq0.01$**

The design goals for inboard blade airfoil put demands on: C_{Lmax} at M=0.4 should be greater than 1.6 and nosedown $|C_{m0}|$ at C_L=0 and M=0.4 should be lower then 0.01. The other parameters should be as close as possible to given above objectives for outboard blade airfoil.

For tail rotor blade airfoil the main objective was considerable increment the maximum lift coefficient in range Mach number of M=0.5 to 0.6. The less attention was paid to moment coefficient constraint. Consequently the following design criteria were established:

Tail rotor blade airfoil

Thickness:	**12%**
Maximum lift at M=0.5,0.6:	**C_{Lmax}≥1.3**
Nosedown pitching moment at C_L=0, M=0.5:	**$\lvert C_{m0} \rvert$ ≤0.04**

5 Numerical and experimental results of main rotor blade airfoils design

Analysis of the advanced rotor airfoil performances presented in fig.13 allows us to make conclusion that the VR12-14 airfoils family has the best aerodynamic performances. This VR family was assumed as the references airfoils to new design airfoils. The aim of the design procedure is acquisition desired airfoils with aerodynamic parameters important for rotor's high performance of the same or better values than for airfoils of above VR family.

At first step the desired improvement of maximum lift coefficient at M=0.4 of the inboard and outboard airfoils was considered. We assumed design point (Mach number of 0.4 and high angle of attack of 10°) and design pressure distribution which was the changed inviscid pressure distribution on ILH212 airfoil at M=0.4 and α=10°. To delay separation and to improve the C_{Lmax} value the local small supersonic region was extended and peak Mach number was decreased. Using the design option of MSES code the MOD1 airfoil was designed. The gained improvement of the MOD1 airfoil C_{Lmax} has been shown in fig.2 in comparison to the initial ILH212 and VR12 airfoils.

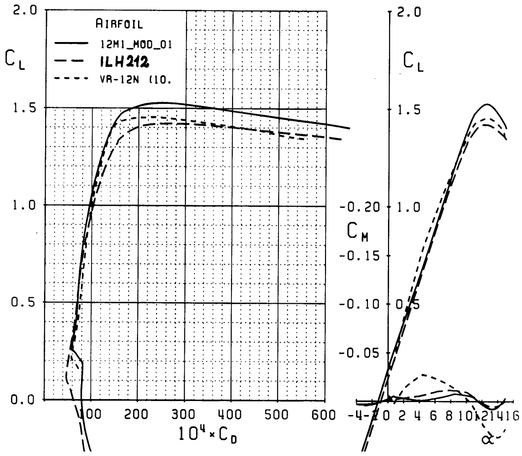

FIG.2 Comparison of calculated performances of initial (ILH212), VR-12 and MOD1 airfoils by MSES code at M=0.4 and Re=1.6·10^6

It is important that C_{Lmax} of MOD1 airfoil is greater even than VR12 airfoil and zero lift pitching moment coefficient is very small C_{mo}=-0.002. On the other hand the drag divergence Mach number of MOD1 airfoil is lower than VR12, as it can be seen in fig.3.

The direct interactive design procedure was applied as the second step in design process. In the course in this procedure the MSES, H, CODA, INV and OPT codes were used and selected group of the aerodynamic coefficients and parameters were analyzed. This group included C_{Lmax} , C_{mo} and C_{Dmin} at M=0.4 , C_L/C_D and C_m at M=0.6 and C_L=0.7 ; M_{dd} at C_L=0 ; C_{DO} at M=0.75, 0.78, 0.8.

The selected and final results obtained in the course of direct interactive design is presented in fig.3 in comparison with reference airfoils.

It can be concluded that all considered aerodynamic parameters for outboard airfoil ILH312 are better than for reference airfoil VR-12. Fig.4 presents calculated drag polar and variation C_L and Cm versus on angle of attack at Mach number of 0.4 . Drag polars are nearly the same for both airfoils but C_{Lmax} and the moment characteristic are better for the ILH312 airfoil than the VR–12 airfoil. Some improvement of ILH312 airfoil transonic characteristics has been obtained i.e. greater drag divergence Mach number M_{dd} (C_L = 0) – fig.3 and lower wave drag coefficient.

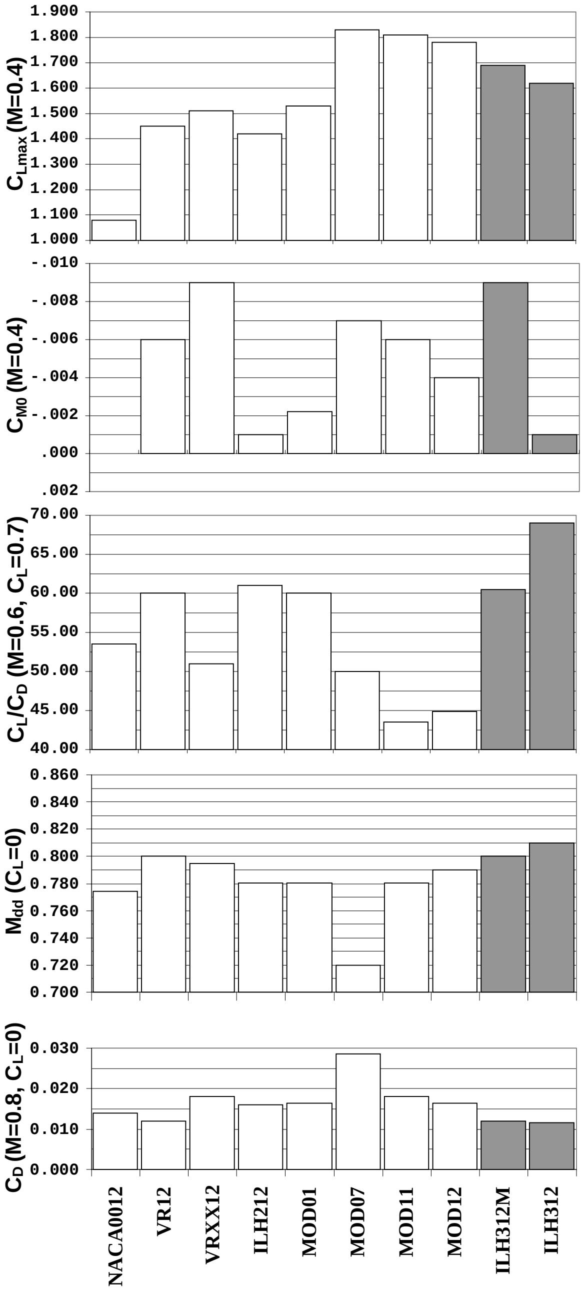

FIG.3 Comparison of calculated aerodynamic parameters of reference airfoils (VR), several chosen modification obtained in direct iterative optimization and final design - ILH312M and ILH312 airfoils of 12% thickness; Re=4·M·10^6

The overall performances boundaries i.e C_{Lmax} boundary and drag divergence of the ILH312 airfoil are summarized in fig.5 in comparison with the VR–12 airfoil. The inboard airfoil ILH312M distinguishes higher maximum lift coefficient than previous airfoils. For the ILH312M airfoil C_{Lmax}=1.69 and other considered aerodynamic parameters are the same as for VR-12 airfoil.

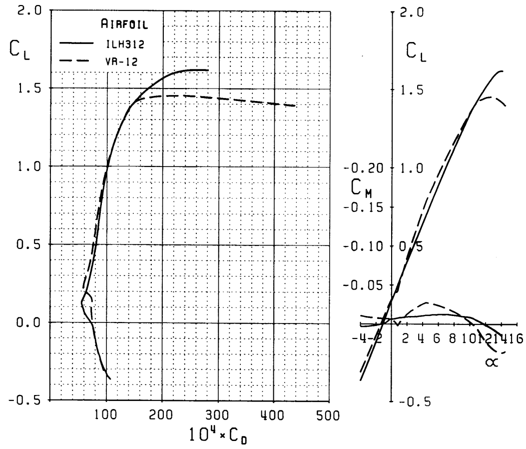

FIG.4 Comparison of calculated performances of reference airfoil VR-12 and final design 12% thickness airfoil ILH312 at M=0.4 and Re=1.6·10^6

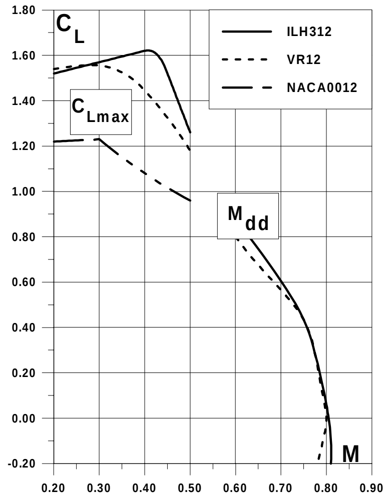

FIG.5 Calculated performance boundaries of reference VR12 and new designed airfoils ILH312 in terms maximum lift coefficient and drag divergence Mach number at Re=4·M·10^6

The tip blade airfoils with thickness of 9% and 8% were designed in the direct iterative design process, in which the main goal was the increase of the zero lift drag divergence Mach number. The airfoils determined from the ILH312 airfoil by simple geometrical recalculation were the start point in this process. Some selected airfoils obtained in design process were presented in fig.6 with the appropriate reference VR airfoils and final design ILH309 and ILH308 airfoils. The improvement of the zero lift drag divergence

Mach number and lift to drag ratio is worth note.

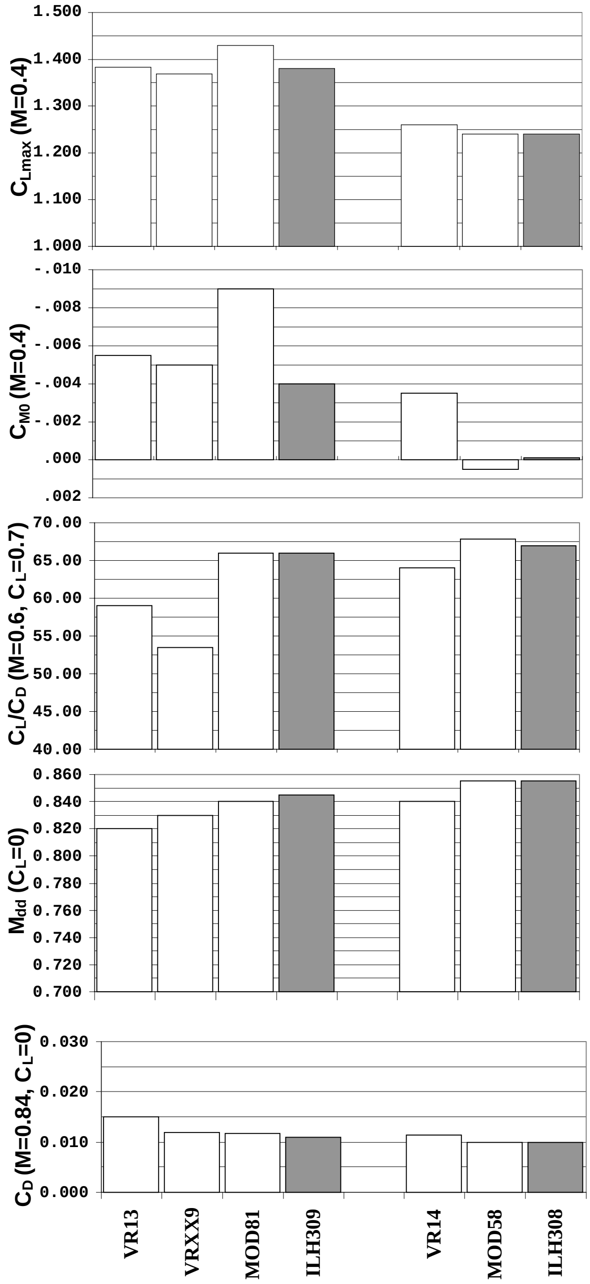

FIG.6 Comparison of calculated aerodynamic parameters of reference airfoils VR13 (9.5%) and VR14 (8%) and final design ILH309 and ILH308 airfoils of 9% and 8% respectively; Re=4·M·10^6

The favorable aerodynamic performance improvements of the ILH3xx airfoils family through comparison with the VR12-14 family are presented in fig.7, in terms of calculated maximum lift coefficient at M=0.4 versus zero lift drag divergence Mach number.

The ILH312 airfoil, as main airfoil of ILH3XX family, was chosen to experimental verification. The experimental test have been performed in the Trisonic Wind Tunnel N–3 of the Aviation Institute in Mach number range of M = 0.3 to 0.86. The N–3 wind tunnel is of blowdown type, which has the test section of 60 cm by 60 cm with perforated top and bottom walls and solid side walls. It allows testing of airfoil models with chord lengths to 20 cm and span of 60 cm. In this test, 20 cm chord length model of ILH312 airfoil has been used and Reynolds number of Re = 4 × M × 10^6 was achieved.

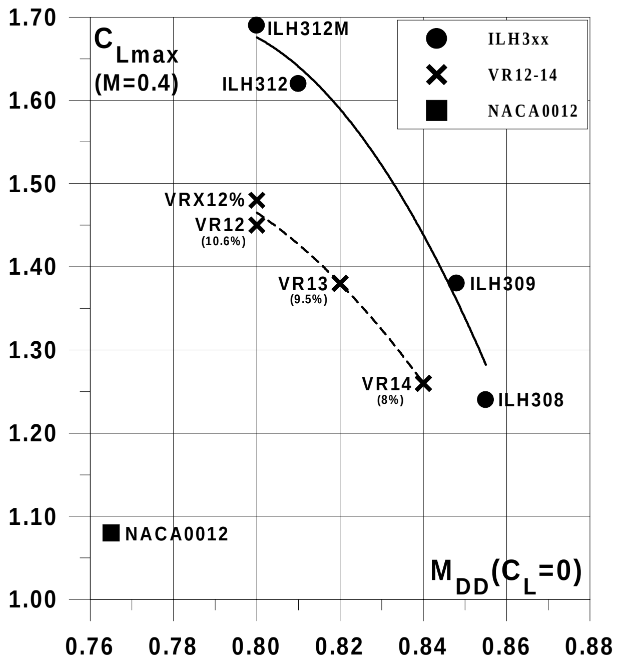

FIG.7 Calculated aerodynamic performance of new designed ILH3xx and reference VR12-14 airfoils families of main rotor in terms of C_{Lmax} at M=0.4 versus M_{DD} at C_L =0

The following data was measured in the experiment:

- static pressure on the model contour at 62 points on the contour and 7 on the tab, which length amount to 4.7% chord length
- total and static pressure in the wake at one chord length behind airfoil trailing edge

Lift and pitching moment coefficients were determined from the contour pressure integration. Drag coefficient was evaluated from the pressure distribution in the wake. The wind tunnel tests have been performed at Mach number range of M = 0.3 to 0.5 in test section with solid all walls. At Mach number greater than 0.5 the tests have been carried out in the test section with perforated top and bottom walls. The lift interference corrections in linear range and blockage corrections were applied to the test results. All wind tunnel tests were performed in the condition of free transition.

The overall performance of the ILH312 airfoil based on the experimental test in the N–3 wind tunnel are summarized in fig. 8 ÷ 10. In these figures the maximum lift coefficient $C_{Lmax} = f(M)$, drag divergence boundary $M_{DD} = f(C_L)$, determined by $dC_D/dM=0.1$ at constant C_L and lines of C_L values at constant drag coefficient of C_D = 0.01 and 0.02 for ILH312 airfoil are compared with other advanced, second and third generation airfoils with approximately the same thickness ratio of 12% [1,2,5,7].

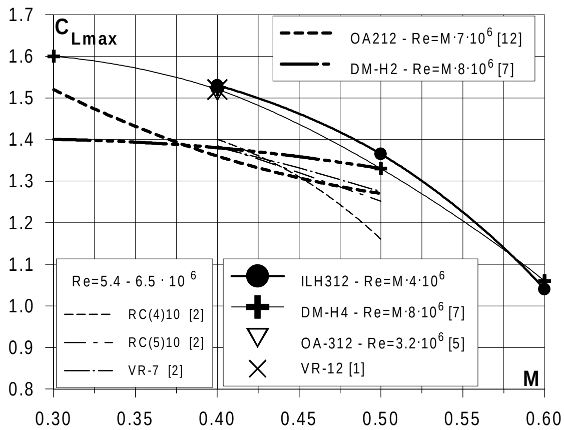

FIG.8 The maximum lift coefficient C_{Lmax} versus Mach number M for some advanced airfoils. Experimental results.

For the ILH312 airfoil a maximum lift coefficient at M=0.4 of C_{Lmax}=1.53 and a drag divergence Mach number at zero lift of M_{DD}=0.822 are achieved. The corresponding values for the VR12, OA312 and DM-H4 [1,5,7] third generation airfoils are presented below in the table 2.

Table 2.
Comparison of experimental drag divergence Mach number at C_L=0.

Airfoil	ILH312	VR12	DM-H4	OA312
C_{Lmax} at M=0.4	1.53	1.52	1.52	1.51
M_{DD} at C_L=0	0.822	0.802	0.795	0.780
$Re{\cdot}10^6$	4.5-4.25	na	8·M	8·M

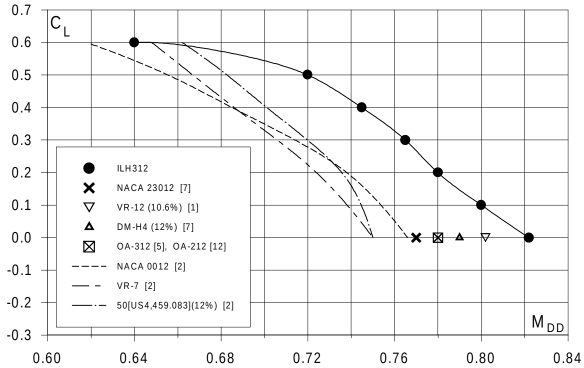

FIG.9 The lift coefficient C_L versus drag divergence Mach number M_{DD} for some advanced airfoils. Experimental results.

For all compared airfoils the maximum lift coefficient at M=0.4 are nearly the same but the drag divergence Mach number at C_L=0 of the ILH312 airfoil is considerable higher than these of the VR12, DM-H4 or OA312 airfoils.

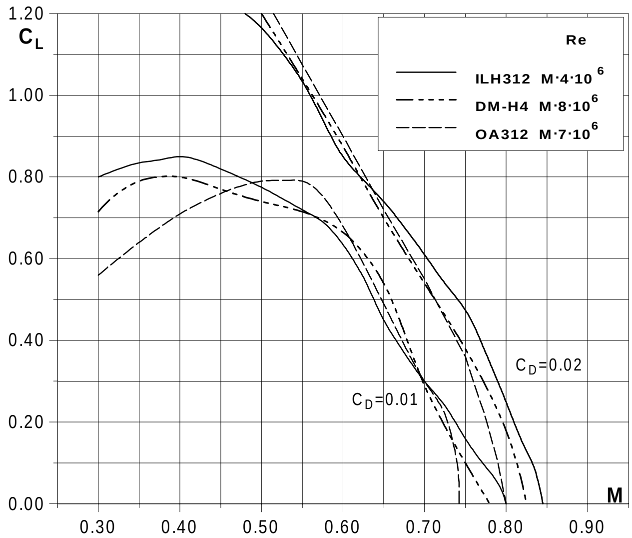

FIG.10 The dependence of C_L and Mach number M for constant drag coefficient C_D= 0.01,0.02. Experimental results for airfoils: ILH312, DM-H4 and OA312.

An excellent transonic performance of ILH312 airfoil is confirmed in fig.10, which shows that the C_D level of 0.01 or 0.02 is reached by ILH312 airfoil at greater Mach number or lift coefficient than by DM-H4 or OA312 airfoil [5,7].

The comparison of zero lift drag coefficient ILH312 and DM-H4 airfoils plotted versus Mach number is presented in fig.11. This comparison indicates that the drag coefficient C_{D0} for ILH312 airfoil is lower than that of

DM-H4 in the range of Mach numbers greater than 0.78. The moment coefficient variation C_M with lift coefficient at M=0.4 of ILH312 and DM-H4 airfoils are very similar up to values of C_L=0.8, as it has shown in fig.12. For both airfoils the moment coefficients at zero lift are C_{M0}=-0.006.

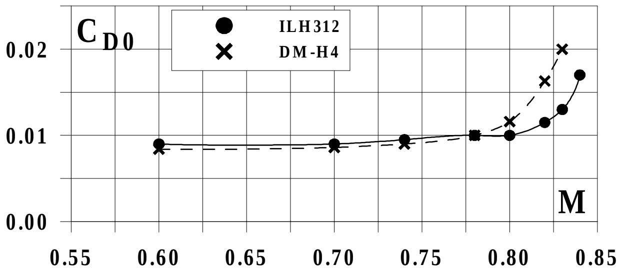

FIG.11 The comparison of zero lift drag coefficient C_{D0} versus Mach number for ILH312 and DM-H4 airfoils.

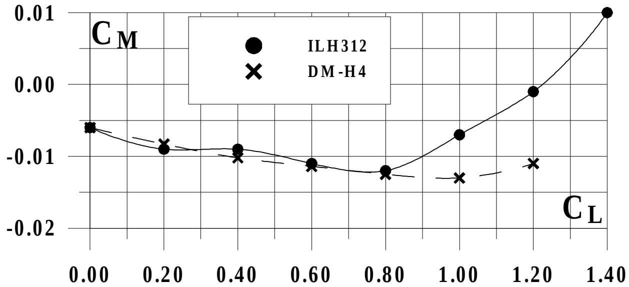

FIG.12 The comparison of moment coefficient C_M versus lift coefficient C_L at M=0.4 for ILH312 and DM-H4 airfoils.

For the ILH312 airfoil the lift to drag ratio C_L/C_D of 65 is achieved at Mach number of M=0.6 and lift coefficient of C_L=0.7

It is worth to note that comparisons of airfoil test results obtained in different wind tunnel are uncertain especially in case of different Reynolds numbers. The effect of the differences in Reynolds number is especially important to the maximum lift and drag coefficients. Experimental values of these coefficients for ILH312 airfoil have been obtained at Reynolds numbers nearly twice lower than for other compared airfoils. It leads to unfavorable influence on C_{LMAX} and drag coefficients of ILH312 airfoil.

Comparing experimental aerodynamic performance of ILH312 airfoil presented above with design objectives introduced in Chapter 4 for outboard airfoil, it can be concluded that ILH312 airfoil completely meets the stated aerodynamic requirements.

The improved experimental aerodynamic performance of the newly developed ILH312 airfoil are presented in comparison with other advanced blade rotor airfoils [1,4,5,6] in fig.13, in terms of maximum lift coefficient at M=0.4 versus zero lift drag divergence Mach number.

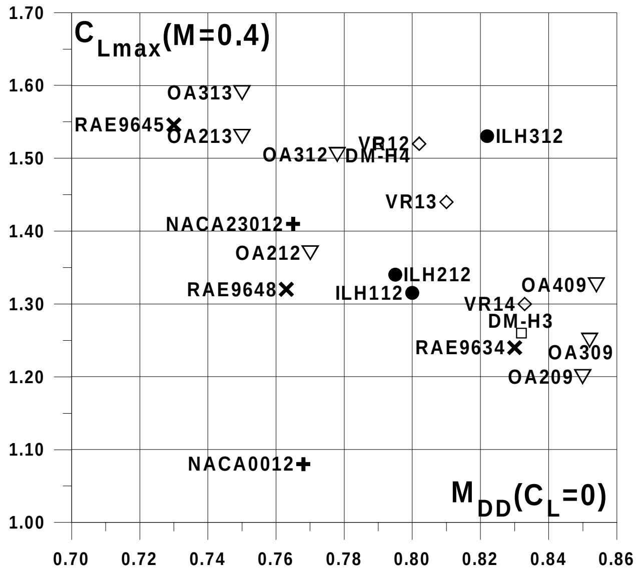

FIG.13 Maximum lift coefficient at M=0.4 versus drag divergence Mach number at C_L=0 of advanced main rotor blade airfoils

6 Numerical results of tail rotor blade airfoil design

The main objective in iterative design procedure of the improved tail rotor airfoil was considerable increment the maximum lift coefficient in range Mach number of M=0.5 to 0.6 with as much as possible improvement of lift to drag ratio. The less attention was paid to moment coefficient constraint. To obtain this goal the idea of avoiding the local supersonic flow region or shock wave on the upper surface airfoil nose at high lift coefficient of C_L=1.0 in range of Mach number up to 0.6 was introduced. One of the rotor blade airfoil - ILT112, designed in this study, was assumed as initial solution. The inverse mode of the MSES code, INV code based on a inverse panel method, OPT code based on genetic algorithm and direct optimization methodologies were used in the design procedure course. Result of this design process is ILT212 airfoil with thickness ratio of 12%. The calculated pressure distribution on the ILT212 airfoil in comparison with classical NACA23012 and initial ILT112 airfoil is presented in fig.14. The supersonic region (at M=0.5) and even the shock wave (at M=0.6) were practically avoided.

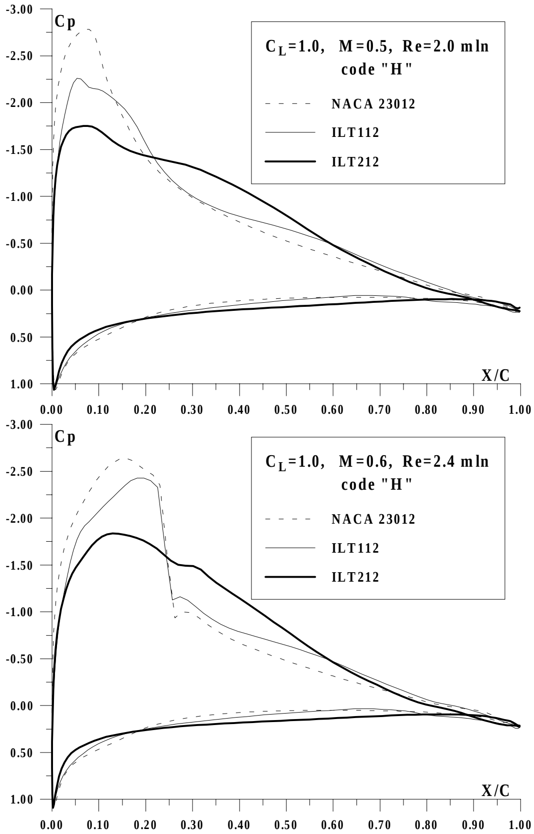

FIG. 14. Pressure distribution on the ILT212, ILT112 and NACA23012 airfoils calculated at C_L=1, M=0.5,0.6, Re=4·M·10^6.

The desired improvement of the maximum lift coefficient for the ILT212 airfoil is shown in fig.15. In this figure variation C_{Lmax} versus Mach number for ILT212 airfoil is compared with classical, widely used in tail rotor NACA23012 and NACA0012 and new advanced tail rotor airfoils RAE9671 and OAR9 [4,5]. The C_{Lmax} for ILT212 airfoil is considerably higher than for NACA23012 of 15% to 38% in the Mach number range of M=0.5 to 0.6, respectively.

Based on the experimental results of the RAE9671 and NACA0012 drawn from [4], the increment of ΔC_{Lmax} of RAE9671 airfoil (experimental) and ILT212 airfoil (numerical) in reference to NACA0012 airfoil have been compared in table 3.

Table 3.
Comparison of ΔC_{Lmax} and C_M (at C_L=0 and M=0.5)

Airfoil / M	RAE9671 (experimental)	ILT112 (numerical)	ILT212 (numerical)
ΔC_{Lmax}= (C_{Lmax} – $C_{LmaxNACA0012}$)/ $C_{LmaxNACA0012}$ %			
0.500	42	41	41
0.550	48	27	40
0.629	29	18	45
C_M at C_L=0 and M=0.5			
0.500	na	-0.01	-0.03

It can be expected that C_{Lmax} for ILT212 airfoil at M=0.6 may be greater than for special advanced RAE9671 tail rotor blade airfoil.

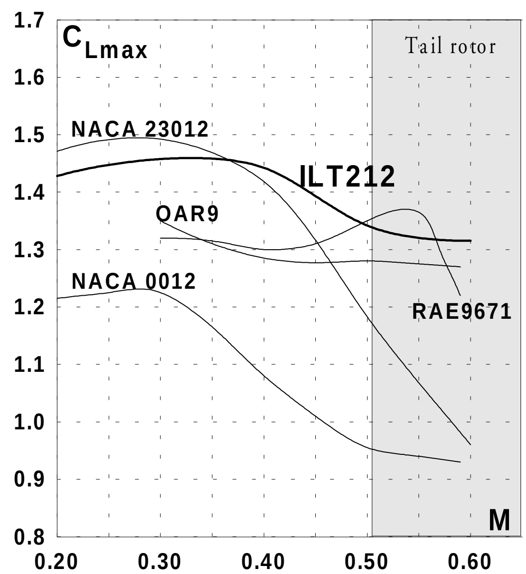

FIG. 15 Comparison of the maximum lift coefficient of new designed ILT212, classical and advanced tail rotor airfoils.

For the ILT212 airfoil the calculated lift to drag ratio was compared with NACA23012 airfoil at Mach number of M=0.5,0.6 in fig.16. The ILT212 airfoil exhibits a very great gain of lift/drag ratio in reference to NACA23012 airfoil, especially at Mach number of M=0.6 (increment of L/D_{max} is above 100%).

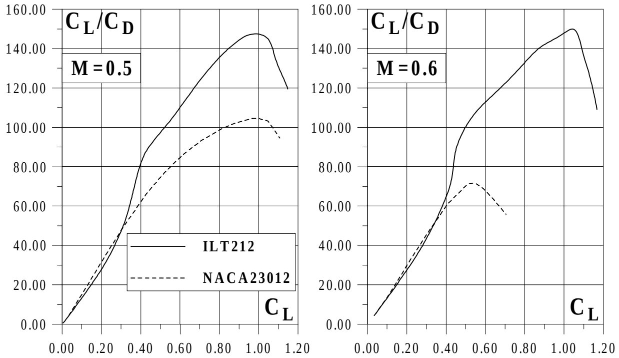

FIG. 16 Lift to drag ratio C_L/C_D versus lift coefficient C_L calculated for ILT212 and NACA23012 airfoils. Mach number M=0.5,0.6.

7 Concluding Remarks

By using several CFD codes the family of rotor airfoils denoted ILH3XX and tail rotor airfoil denoted ILT212 have been designed. Numerical aerodynamic characteristics show that stated design objectives are completely fulfilled. The basic rotor family airfoil ILH312 of 12% thickness ratio was investigated in the wind tunnel. Experimental results indicate that the aerodynamic performance of ILH312 airfoil are on the same level or even better than third generation advanced rotor blade airfoils like VR12, DM-H4 or OA312. Numerical results of the tail rotor airfoil ILT212 show a very great improvement of C_{Lmax} and lift/drag ratio in relation to the conventional tail rotor airfoil NACA23012.

Acknowledgements

This work has been supported by the State Comitee for Scientific Research (KBN) Grant PB545/T12/97/13

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