

DESIGN OF THE MODERN FAMILY OF HELICOPTER AIRFOILS

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Summary

The paper presents results of numerical design and experimental validation test of the modern family of helicopter airfoils. As a result of the design process the ILT212 airfoil with a relative thickness of 12% has been developed, destined for the helicopter tail rotor, as well as the family of the ILH3XX airfoils with relative thickness of 12.2%, 12%, 9% and 8% destined for blades of lifting rotors. From the computational point of view the designed airfoils met the assumed designer's requirements and from the point of view of aerodynamic features they proved to be equal or even better than the best known helicopter airfoils. The aerodynamic characteristics of designed airfoils found their confirmation during wind tunnel tests performed with the ILH312 airfoil for the outer part of the lifting rotor blade and with the ILT212 airfoil for the tail rotor blade. In the light of performed experimental research and from the point of view of basic aerodynamic parameters deciding about the quality of airfoils for lifting rotor blades the ILH312 airfoil stands out among newest airfoils of the third generation. Similarly, results of experimental examination of the ILT212 airfoil put it in the first ranks of best known airfoils destined for tail rotor blades. This airfoil embodies, among other things, high values of lift coefficient for the range of Mach numbers from 0.5 up to 0.6 what can lead to the practical benefit in form of significant increase of the tail rotor thrust.

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1. INTRODUCTION.

Aerodynamics plays much more important role in design of helicopters than in case of other flying objects [1]. Especially important role it plays in the phase of developing helicopter lifting rotors. It can be illustrated by the fact that in 90s in the French scientific center ONERA the engagement in the development of lifting rotors exceeded 40% of total research effort and the further 20% appertained to acoustics, closely connected with aerodynamics [2].

Although from time to time some new concepts of helicopter configurations appear on the scene the classical lay-out with a single lifting rotor and a tail rotor still behaves its value and is dominating on the world helicopter market [3]. In this scheme, from the point of view of high helicopter performance, the basic problem presents the design of lifting rotor blades. One of factors which decide on a success of the new lifting rotor is the use of especially designed airfoils with aerodynamic features well met conditions of flow over the blade. Development of such airfoils is, however, not easy task and is joined with many difficulties arising from high variation of flow conditions around the blade, more differentiated and complex than in case of fixed-wing aircraft.

Typical for the flow around blades of the lifting rotor is high degree of asymmetry in distribution of flow velocities. For the rotating blade which moves forward in the same direction as the whole helicopter – defined as the advancing blade – the flight speed vector and the speed vector arising from rotation sum up what results in the high velocity of flow around airfoil which at the blade tip can reach values near to the speed of sound. On the contrary, for the blade moving away from the relative airflow (i.e. in the direction opposite to which the helicopter is flying) – defined as the retreating blade – flow velocities are low, because the speed vector arising from rotation is diminished by the flight speed vector. At the advancing blade, for small or near-to-zero values of the lift coefficient accompanying the transonic Mach numbers, the shock wave can arise leading to a violate increase of drag and even, in the extreme case, to the blade stall caused by the shock wave. It causes some limitations of helicopter performance and the strong increase of vibrations and higher noise due to the flow separation induced by shock wave / boundary layer separation. At the retreating blade, under conditions of low velocities and high values of lift coefficients the separation of flow can occur leading to drop of the rotor lift, to increase of its drag and even to stall at the retreating blade as well as to flutter which significantly limits the helicopter flight speed. Aerodynamic phenomena taking place in airflow around blades of the helicopter lifting rotor during the helicopter forward flight are presented schematically in Fig.1 below.

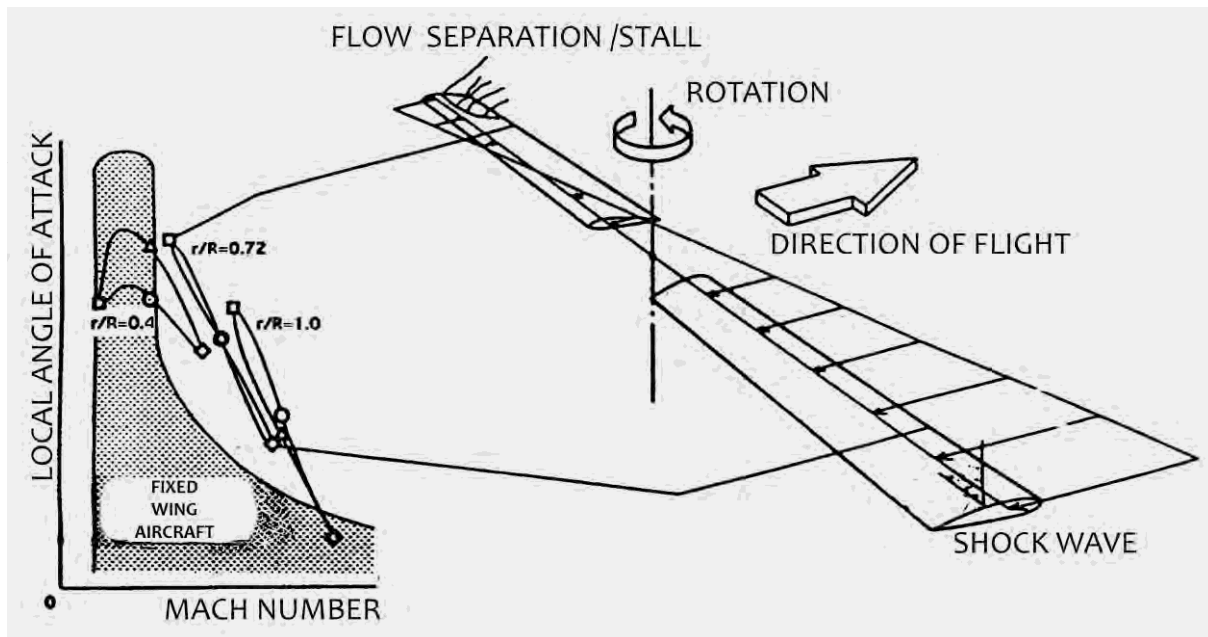


Fig.1. Flow conditions and aerodynamic phenomena appearing at blades of the helicopter lifting rotor in the forward flight [7]

In order to get high performance of the helicopter lifting rotor airfoils used in its blades they should feature good aerodynamic characteristics in the wide range of Mach numbers and angles of attack. In general, these airfoils, from the point of view of conditions appearing at the retreating blade, should produce evidence of high values of the lift coefficient C_{Lmax} at small and medium subsonic Mach numbers. From the point of view of conditions appearing at the advancing blade they should produce evidence of low drag coefficients up to highest possible transonic Mach numbers at near-zero lift coefficients, what would be equivalent to the highest possible value of the drag divergence Mach number under these conditions.

The important feature of airfoils used in lifting rotors is the near-zero value of the pitching moment for zero lift, because the pitching moment determines the magnitude of

forces acting in the control system of the blade pitch angles mechanism. The other, unfavorable effect of the too-high level of the pitching moment is the excessive blade twist causing undesirable aerodynamic effects which can lead to deterioration of helicopter performance. The other unfavorable effect can be the appearance of vibrations in the control system decreasing the service life of control system components.

When the helicopter hovers, i.e. when its forward speed is equal to zero, there is no need to change blade pitch angles during rotations as the velocity of flow around blades, though changing linearly along their radius, is constant. In this state of flight, in order to decrease the power demand to drive the rotor, it is to be desired that increase of an aerodynamic efficiency should be achieved, i.e. increase of lift to drag ratio of an airfoil in the range up to average values of the Mach number and the lift coefficient.

When considering the required aerodynamic features of airfoils for blades of the lifting rotor it is necessary to take into consideration the variability of flow conditions, i.e. of speed and Mach number, as well as of angle of attack and lift along the blade radius, what is connected with the linear change of speed due to rotation and with the finite length of a blade considered as a wing.

In the up-to-date helicopter technology the most popular method of counteracting the torque created by the lifting rotor is the use of a horizontal force acting in a proper distance from the lifting rotor axis. This force is usually produced as a thrust of a tail rotor. This tail rotor thrust should be big enough to balance the lifting rotor torque and should also dispose some reserve for realization of a directional control. In forward flight the tail rotor is augmented by a vertical fin. Flight conditions which determine the tail rotor performance are hover and/or vertical climb. Very important parameter in the tail rotor design is the speed of its blade tip. In the majority of contemporary helicopters it is contained in the range from ca. 160 m/s for multi-blade rotors up to 212 m/s for two-blade rotors [4].

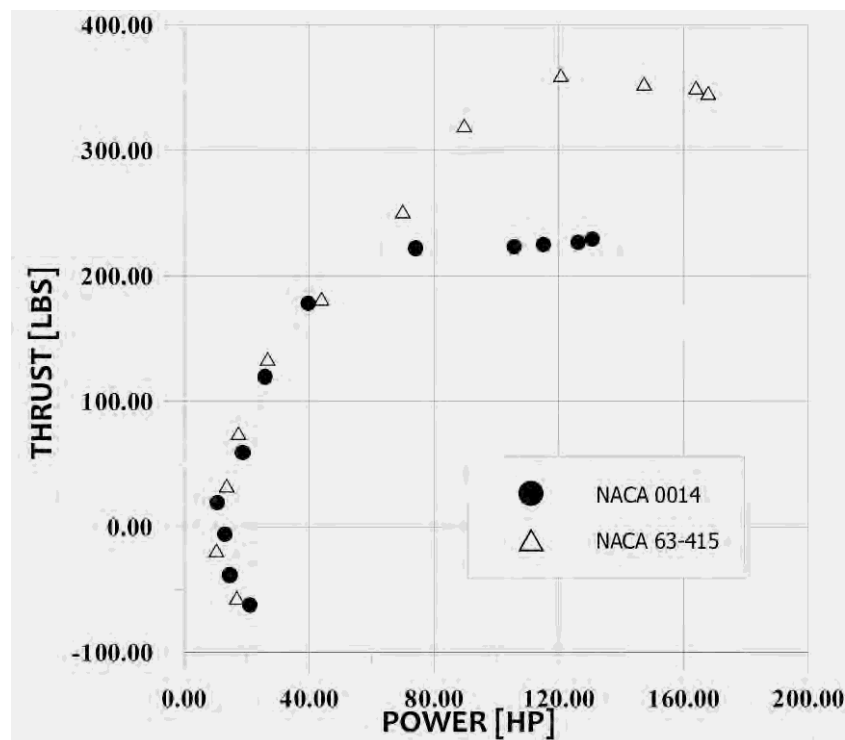


Fig.2 Comparison of thrust developed by the tail rotor with conventional airfoil and with airfoil featuring high values of the C_{Lmax} coefficient in the range of high Mach numbers. [6]

In case of a tail rotor, like for a lifting rotor, the application in its blades of especially aerodynamically designed airfoils, well adopted to existing flow conditions, can lead to improvement of the tail rotor performance. In the paper [6], published in the first half of 70s, it was demonstrated experimentally that the significant, from 30 to 50%, increase of the tail rotor thrust has been achieved thanks to use, instead of symmetrical NACA0014, of an especially selected NACA63415 airfoil, characterized by a pronounced camber – see Fig.2. This remarkable increase resulted from high values of the maximum lift coefficient C_{Lmax} of the applied NACA63415 airfoil in the range of high subsonic Mach numbers.

2. Design criteria and requirements for the lifting and tail rotors blade airfoils

It should be emphasized that the requirements presented above for airfoils destined for blades of the lifting rotor are contradictory. From the point of view of performance, however, in the course of designing these contradictory requirements should be met by way of compromise. It was assumed in this work that following general criteria should be met by the designed lifting rotor airfoil:

1. High value of the maximum lift coefficient C_{Lmax} at the Mach number $M = 0.4$ in order to delay stall at the retreating blade and to decrease vibrations at high flight speeds;
2. High value of the drag divergence Mach number M_{dd} at zero lift coefficient and low value of the drag coefficient in the transonic range in order to decrease power necessary for the forward flight and to reduce the high speed impulsive noise HSL;
3. High value of the lift to drag ratio C_L/C_D at the Mach number $M = 0.6$ and at the lift coefficient $C_L = 0.6 \div 0.7$ in order to decrease power necessary for hovering and to improve the coefficient of the hover efficiency;
4. Very low value of the pitching moment coefficient at the zero lift coefficient C_{m0} in the range of low Mach numbers in order to decrease loads in the control system and to reduce the blade twist – the coefficient of the pitching moment $C_{m0} \geq -0.01$.

The present state of the composite technology enables the production of lifting rotor blades with airfoils changing along the blade radius. It is therefore possible to recognize three blade areas for which a special emphasis on selected (of cited above) criteria had to be laid.

The most important criterion for airfoils used in the inner part of a blade would be the high value of the lift coefficient C_{Lmax} for the Mach number $M = 0.4$. For airfoils used in the outer part of a blade the key criterion, besides, as above, high value of the lift coefficient C_{Lmax} , would be high value of the drag divergence Mach number boundary, and high lift to drag ratio. For airfoils of the blade tip, however, the crucial criterion would be high value of the drag divergence Mach number. In case of these airfoils taken into consideration would be also the criterion of the lift coefficient C_{Lmax} . Obligatory for all designed airfoils would be the criterion of the near-to-zero pitching moment coefficient C_{m0} .

Aerodynamic requirements which are set in relation to airfoils used in the modern high-performance tail rotor are not so diversified as in case of the lifting rotor. The basic requirement is that the coefficient of maximum lift, in the range of Mach numbers $M = 0.5 \div 0.6$, should be as high as possible. For that reason that the tail rotor diameter is smaller than the diameter of the lifting rotor and that the stiffness of tail rotor blades is higher than the stiffness of lift rotor blades the imposed limitations of the pitching moment coefficient in case of tail rotors are not so severe [1, 4, 5].

It should be noted that on the way leading to achievement of high values of the lift coefficient C_{Lmax} for Mach numbers $Ma > 0.4$ some difficulties appear, induced by

compressibility effects and occurrence, at high angles of attack, of intensive shock waves. They cause speeding-up of stall and decrease of C_{Lmax} coefficient. Problems connected with the wave crisis increase as the Mach number arise producing a visible drop of the C_{Lmax} coefficient for Mach numbers above $M = 0.4$.

Basing on the above aerodynamic criteria relating to airfoils for blades of the lifting rotor and referring to aerodynamic parameters of best existing airfoils like VR12-VR14, OA-3XX or DM-H3&4 families practical requirements for to-be-designed airfoils have been established, separately for respective areas of a blade.

Airfoil of the blade tip

Relative thickness	8% - 9%
Maximum lift coefficient at $M = 0.4$	$C_{Lmax} \geq 1.3$
Lift to drag ratio at $M = 0.6$ and $C_L = 0.7$	$C_L/C_D \geq 60$
Drag divergence Mach number at $C_L = 0$	$M_d \geq 0.84$
Pitching moment (nose-down) coefficient at $C_L = 0$ and $M = 0.4$	$C_{m0} \geq -0.01$

Airfoil of the blade outer part

Relative thickness	12%
Maximum lift coefficient at $M = 0.4$	$C_{Lmax} \geq 1.5$
Lift to drag ratio at $M = 0.6$ and $C_L = 0.7$	$C_L/C_D \geq 60$
Drag divergence Mach number at $C_L = 0$	$M_d \geq 0.80$
Pitching moment (nose-down) coefficient at $C_L = 0$ and $M = 0.4$	$C_{m0} \geq -0.01$

Design requirements set for airfoils of the inner blade part lay stress on the increase of C_{Lmax} at $M = 0.4$ which should be greater than 1.6 and on maintaining requirements relating to moments – coefficient of the pitching moment (nose-down) C_{m0} for $C_L = 0$ and $M = 0.4$ should be greater than -0.01 . Other parameters should be as near as possible to values presented above for airfoils of the blade outer part.

Passing to setting-up the design requirements for airfoil foreseen for the tail rotor it must be accentuated that the most important parameter of such an airfoil is the coefficient of maximum lift. The basic requirement for a designed airfoil can be defined on the ground of an experimentally confirmed possibility of a significant improvement of the tail rotor thrust by the application of the NACA63-415 airfoil, characterized by extended values of the C_{Lmax} coefficient in the range of Mach numbers $M = 0.5 \div 0.6$ [6] – see Fig.2. This requirement sounds as follows:

- to obtain the possibly highest value of the maximum lift coefficient in the range of Mach numbers $M = 0.5 \div 0.6$, being at least similar to such up-to-date airfoils for tail rotors as REA9670, REA9671 and OAR9.

As already mentioned above the pitching moment limitations for tail rotor airfoils can be much more “mild” than those applied to airfoils for blades of lifting rotors. In the light of a complete lack of any published papers which could enable the assessment of a level of pitching moment coefficients of modern tail rotor airfoils it was assumed that the requirement for the designed airfoil will say about decreasing approximately two times the pitching moment coefficient for zero lift of the NACA63-414 airfoil used in the tail rotor blades of the AH-64 Apache helicopter. This airfoil has approximately the same features as the mentioned NACA63-415 airfoil. After accepting above requirements and after calculating the pitching moment coefficient of the NACA63-414 airfoil it became possible to formulate the moment criterion for the designed airfoil:

- the pitching moment (nose-down) should be less than -0.05 .

Having regard to decrease of the power demand necessary for driving the tail rotor the additional requirement has been formulated for the designed airfoil:

- to obtain high value of the lift to drag ratio at .

3 Computational methods and design procedure

Several CFD codes have been used in the course of design airfoils numerically. Their features and computational capabilities are briefly presented below.

1. **MSES** – the two dimensional analysis and design code, which is based on Euler equations and viscous – inviscid strong interaction method [8, 9]. This code has following computational capabilities:

- computation of flow around the airfoil and corresponding aerodynamic coefficients together with modeling of stall and determination of the maximum lift coefficient C_{Lmax} up to the Mach number $M = 0.6$;
- computation of flow around the airfoil and corresponding aerodynamic coefficients in the range up to transonic speeds and including the occurrence of a shock wave;
- calculation of the airfoil geometry with the specified pressure distribution in the range of inviscid compressible flows.

In the design mode the MSES program enables to reconstruct the airfoil geometry which under determined conditions of the inviscid and compressible flow produces the specified pressure distribution. The design pressure distributions were determined basing on the physical factors as well as on the searching analysis of correlation between selected computationally pressure distributions for the airfoil geometry determined initially and their total aerodynamic characteristics, (e.g. maximum lift coefficient, drag divergence Mach number, pitching moment coefficient etc). As a result of carrying out the inverse procedure an airfoil was received whose geometry was smoothed-out and normalized using for this purpose the CODA program presented below.

2. **HCZMAX** – the two-dimensional analysis code which is based on coupling the external inviscid flow and the boundary layers, with the empiric transition criterion. The code realizes the analysis of laminar and turbulent stall; if stall of the last type occurs the stall area is modeled by introduction of sources located on the airfoil behind the defined point of flow separation – this is done in successive iterations in which potential flow, boundary layer and stall area are taken into consideration. This code created the possibility to calculate in the short time with the reasonable accuracy the C_{Lmax} coefficient using PC computers only [10].

3. **H** - the modified Bauer/Garabedian/Korn code, the two-dimensional analysis of the transonic flow around airfoil based on the solution of equations of full potential using the method of finite differences with allowance for viscosity in the form of adding the linear loss of the boundary layer contribution to the airfoil contour and agreeing the potential flow and the boundary layer in successive iterations. This program enables to compute the transonic flow around airfoil at a given angle of attack or the lift coefficient – this makes possible the fast determination of the drag divergence Mach number [11].

4. **CODA** - The CAD-type software which enables to design the geometry of airfoils as well as to determine and to present geometric features of an airfoil [12]. This program has been applied, among others, to perform the following tasks:

- initial definition modification of airfoil geometry
- analysis and modification of thickness distribution and the camber of airfoil
- analysis and modification of distribution of curvature along the airfoil contour
- analysis of airfoil shape smoothness and smoothing it.

5. **INV** – the two dimensional code based on the panel method for fast determination airfoil geometry with specified pressure distribution in potential and incompressible flow.
6. **OPT** - airfoil optimization code based on genetic algorithms, developed for the purpose of the realized project. In this program the aerodynamic design of airfoils was carried out on the different way than in the MSES and INV programs. In this case the object of determination was not the distribution of pressure but total aerodynamic characteristics which have to be granted by airfoil under development. It meant practically that to be defined was so called the objective function combining various total aerodynamic coefficients of airfoil. The problem was in determining such an airfoil for which the objective function becomes maximum. The optimization problem was solved on the ground of so called genetic algorithms. In this type of approach the process of looking for the optimal geometry reflects in some respect the process of the species evolution based on the natural selection. In order to determine the values of the objective function two codes were used: H (transonic features of airfoils) and HCZMAX (assessment of the maximum lift coefficient).

Besides optimization based on genetic algorithms the optimization method was also used which was based on disturbing randomly the airfoil geometry. The computer software developed to meet the needs of the realized project is carrying out, in successive computational cycles, functions listed below:

1. function of disturbing the initial airfoil geometry;
2. activate of proper CFD code for determining aerodynamic characteristics of airfoil;
3. assessment, whether the modified airfoil demonstrates better aerodynamic features than the initial airfoil.

Basing on the developed software the process of design the airfoil proceeds in accordance with a scheme as follows:

1. Initiation of computation:

- 1.1. Approval of initial airfoil geometry;
- 1.2. Defining range and maximum amplitudes of disturbing functions;
- 1.3. Determining aerodynamic criteria of the airfoil selection (e.g. minimization of the drag coefficient for selected flow conditions with retaining the maximum lift coefficient)

2. Iterative process of optimization:

- 2.1. Random determination of the disturbed geometry;
- 2.2. Computation of proper aerodynamic characteristics;
- 2.3. Assessment, whether the disturbed airfoil demonstrates better aerodynamic features than the initial airfoil. If yes, in further proceedings the actual geometry of the disturbed airfoil is considered as initial geometry.

Steps 2.1., 2.2. and 2.3. are carried out several times randomly chosen. In case of lack of progress of optimization parameters of disturbing functions and/or aerodynamic criteria of airfoil selection should be modified.

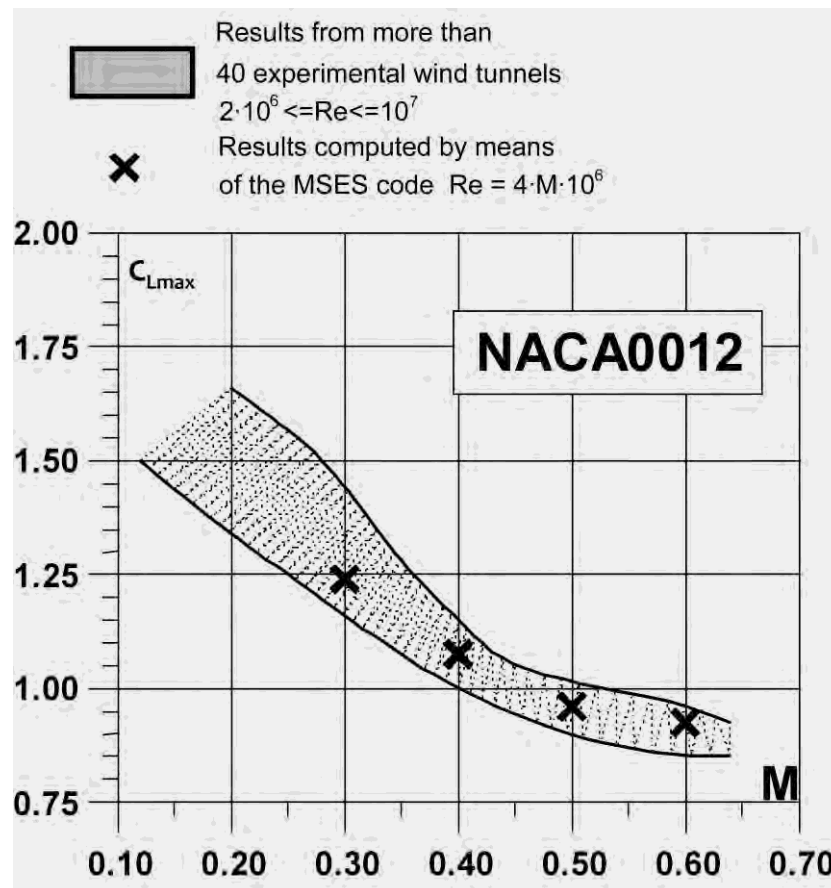


Fig.3. Comparison of relations between the maximum lift coefficient and Mach number determined by computation and experimentally. Airfoil NACA0012.

In order to reach success during the process of airfoil design in which CFD codes are used it becomes necessary to obtain the reliable computational results. As basic codes in this work were considered the MSES and H programs. For that reason both of them were validated just before the start of the process of design airfoils. To check if mentioned codes could be reliably applied to the practical design of airfoils results of computations with the use of these codes were compared with results of experimental wind tunnel tests. Most important in design process is the reliability of main parameters, especially the C_{Lmax} coefficient and the drag divergence Mach number at $C_L = 0$. Comparisons of the calculated maximum lift coefficient C_{Lmax} of the NACA 0012 airfoil by means of the MSES code with experimental results obtained in more than 40 wind tunnels [17] are shown in Fig. 3 and Fig. 4.

As mentioned above one of principal criterion-bound requirements in the process of design airfoils for the lifting rotor is the value of the C_{Lmax} coefficient for the Mach number $M = 0.4$. When comparing value of that parameter computed with the use of the MSES code for the NACA 0012 and NACA 23012 airfoils with experimental test data [5, 7, 15, 16] one can find very good agreement (see table below).

Table 1

Airfoil	C_{Lmax}				
	Computation MSES	Re·10 ⁶	Experiment	Re·10 ⁶	Source
NACA 0012	1.08	1.6	1.06	N/A	[5]
			1.08	N/A	[7, 16]
NACA 23012	1.42	1.6	1.40	2.0	[7]
			1.42	N/A	[15, 16]

Due to its speed of operation and simplicity the H program presented the attractive computational instrument, it was, however, necessary to check the reliability of computation of the drag divergence Mach number M_{dd} . To do it the computation by means of this code has been carried out to determine the drag divergence Mach number at $C_L = 0$ for some number of airfoils whose experimental results were in our disposal.

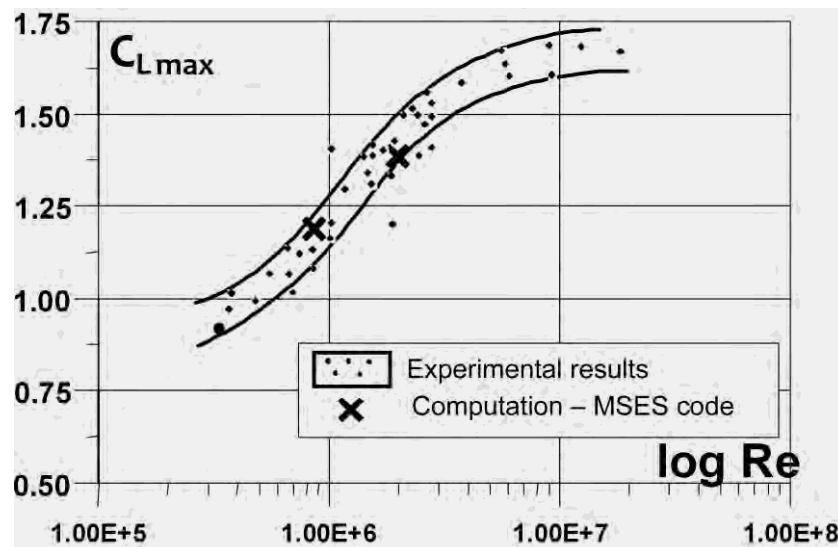


Fig.4 Comparison of relationships between maximum lift coefficient and Reynolds number for Mach numbers not higher than 0.25, determined by computation and experimentally. Airfoil NACA0012.

There were among them the mentioned above NACA0012 airfoil and the IL-designed ILH212 and ILH209 airfoils destined for the lifting rotor of the IS-2 helicopter. Both of these airfoils were earlier tested in the trisonic N-3 wind tunnel of the Institute of Aviation [18 ÷ 20]. In the process of validation the high-performance VR-12, 13 and 14 airfoils of Boeing-Vertol were also used. Their experimental aerodynamic data were taken from papers [7, 21, 22]. Computational and experimental results are compared in the table below.

Table 2

Airfoil	NACA 0012	ILH212	ILH209	VR-12	VR-13	VR-14
$M_{dd \text{ comp.}}$	0.765	0.790	0.815	0.800	0.820	0.840
$M_{dd \text{ exper.}}$	0.775	0.795	0.825	0.805	0.812	0.835

Basing on the above comparison it can be stated that the H program enables to determine the drag divergence Mach number M_{dd} at $C_L = 0$ with high degree of reliability. It can be stated that the value of the calculated M_{dd} at $C_L = 0$ is underpredicted only by about 0.005÷0.01.

In order to assess the quality of airfoils for lifting rotors, as mentioned above, the graph with axes of coordinates C_{Lmax} for $M = 0.4$ and M_{dd} for $C_L = 0$ has been constructed. Interesting is to carry out the comparison of such an assessment obtained from computation with experimental results taken from [21] for the airfoil family VR-12, 13, 14 considered as reference airfoils. It is presented in the table below.

Table 3

Airfoil		VR-12	VR-13	VR-14	$Re \cdot 10^6$
C_{Lmax} for $M = 0.4$	MSES-computed	1.45	1.38	1.26	1.6
	experimental	1.52	1.44	1.30	n.a.
M_d for $C_L = 0$	H-computed	0.80	0.82	0.84	4-M
	experimental	0.802	0.81	0.833	n.a.

In the process of design airfoils for blades of the tail rotor the same MSES code will be used to compute the C_{Lmax} coefficient. It would be therefore interesting, besides the analysis presented above for classic tail rotor airfoils, i.e. the NACA0012 and NACA23012, to carry out such a comparison also for the mentioned above airfoil NACA63414 used in the AH-64A Apache helicopter. It is characterized by high lift in the range of Mach numbers $M > 0.4$, as in case of modern, developed especially for tail rotors, airfoils RAE9670 and 9671 as well as OARA9. To carry out the comparison of computations performed for the NACA63414 a set of airfoil experimental data taken from paper [6] and corresponding to the NACA63415 airfoil (i.e. having thickness increased by 1% of a chord), was used. This comparison is presented in the table below for the Mach numbers $M = 0.4$ and $M = 0.5$. The cited difference in airfoil thickness shouldn't play any significant role.

Table 4

		C_{Lmax}	
M	Airfoil	NACA63414	NACA63415
		MSES-computed; $Re=4 \cdot M \cdot 10^6$	Experim. Re – n.a. [6]
0.4		1.36	1.33
0.5		1.34	1.31

Summing up the performed validation of main computational codes used to determine the aerodynamic characteristics of airfoils one can state that in the process of design airfoils for blades of the lifting and tail rotors they can be considered as reliable CFD code.

An outline of an airfoil design procedure employed in this study is described below. The procedure makes use of the inverse option of the MSES code and direct iterative design optimization.

In the first step an inverse design technique was used, where the required pressure distribution at Mach number of 0.4 and high angle of attack to delay flow separation and increase C_{Lmax} value was specified. The design option of the MSES code was used but it was limited to the inviscid flow. This led us to the direct iterative design optimisation for simulation of the viscous and transonic effects. The designed airfoil in first step was used as starting point in genetic and further direct optimization process. Based on the required aerodynamic parameters and the analysis by MSES and H codes the airfoil contour was iteratively changed until the final shape was obtained, which was the best compromise within the requirements given above.

In case of a lifting rotor, after performing the analysis of vital aerodynamic parameters, selection was done of airfoils destined for a designated part of a blade and composing an airfoil family. One of these airfoils, foreseen for the blade outer part and featuring the thickness of 12%, became then the object of experimental tests in the N-3 wind tunnel. Also in case of a tail rotor one airfoil was selected and experimentally tested in the N-3 wind tunnel.

4. Results of design the family of airfoils for blades of lifting rotors

Analysis of aerodynamic characteristics of modern airfoils destined for blades of helicopter lifting rotors, presented in many publications [21], indicates that best features belong to airfoils of the VR12-14 family. That was the reason why in the presented process of designing modern improved airfoils for lifting rotors belonging to that family were regarded as “airfoils of reference”. The principal aim of the undertaken work was the development of airfoils featuring aerodynamic characteristics, crucial

from the point of view of the lifting rotor performance, better or at least equal to those of airfoils of the VR12-14 family.

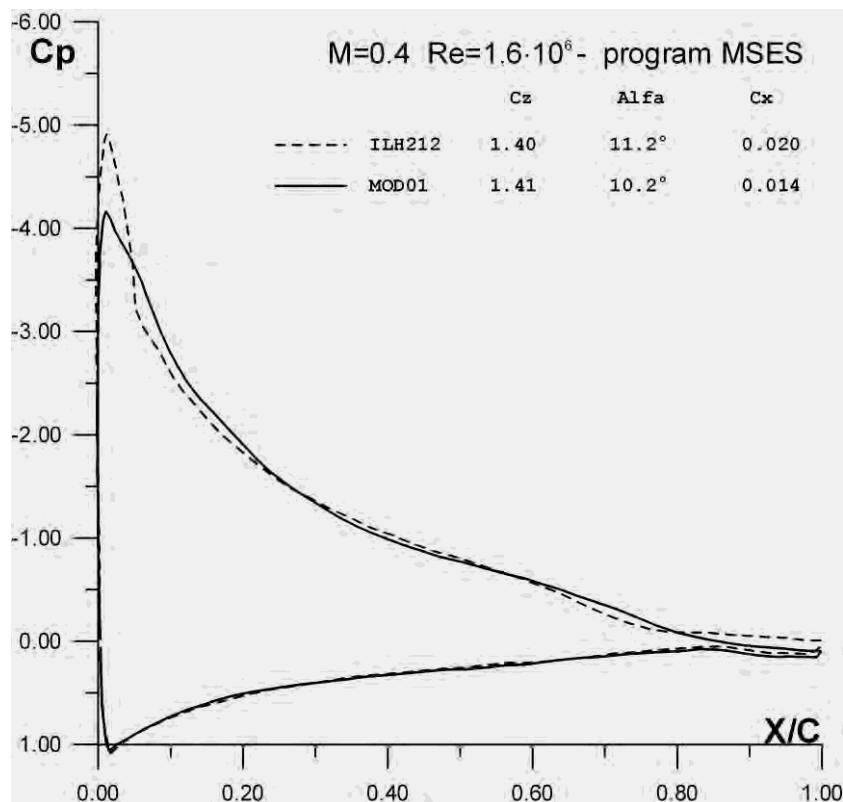


Fig.5 Comparison of pressure distribution at the initial ILH212 airfoil and at the MOD01 airfoil obtained by solving the inverse problem.

First of all, the thickness of 12% chord was chosen for the inboard and outboard blade airfoils. For the tip blade airfoil the thicknesses of 9% and 8% chord were foreseen. Analysis of the advanced lifting rotor performances allows us to make conclusion that the VR12-14 airfoils family has the best aerodynamic performance [1, 5, 7, 15]. This VR family was assumed as the reference airfoils to new design airfoils. The aim of the design procedure was development of airfoils with aerodynamic parameters, crucial for rotors's high performance, better or at least equal to VR12-14 airfoil family.

At the first step the desired improvement of maximum lift coefficient at $M=0.4$ for the inboard and outboard blade airfoils was considered. The design pressure distribution was derived from inviscid pressure distribution on ILH212 airfoil [18] calculated by using MSES code at $M=0.4$ and $\alpha=10^\circ$. To delay flow separation and to improve the $C_{L_{\max}}$ coefficient the local small supersonic region was extended and peak local Mach number was decreased. Using the design mode of the MSFS code the MOD1 airfoil was designed. Viscous pressure distribution for the MOD1 airfoil in comparison with initial the ILH212 airfoil was presented in Fig. 5 at the same high value C_L coefficient of 1.4. The small separation region on the aft part of the ILH212 airfoil can be seen, whereas the flow about MOD1 airfoil is fully attached.

Computed aerodynamic characteristics of the MOD-01 airfoil for the Mach number $M = 0.4$ are presented in Fig.6 and compared there with characteristics of the initial ILH212 and the VR12 airfoil, being the "airfoil of reference". It is worth to note that the visible increase of the $C_{L_{\max}}$ coefficient has been achieved as well as the decrease of the drag coefficient not only in reference to the initial airfoil but in reference to the VR12 airfoil too. More advantageous is also the character of changes of the pitching moment

coefficient C_m . On the other hand the drag divergence Mach number M_{dd} of MOD1 airfoil is lower than VR12 (see Fig.7).

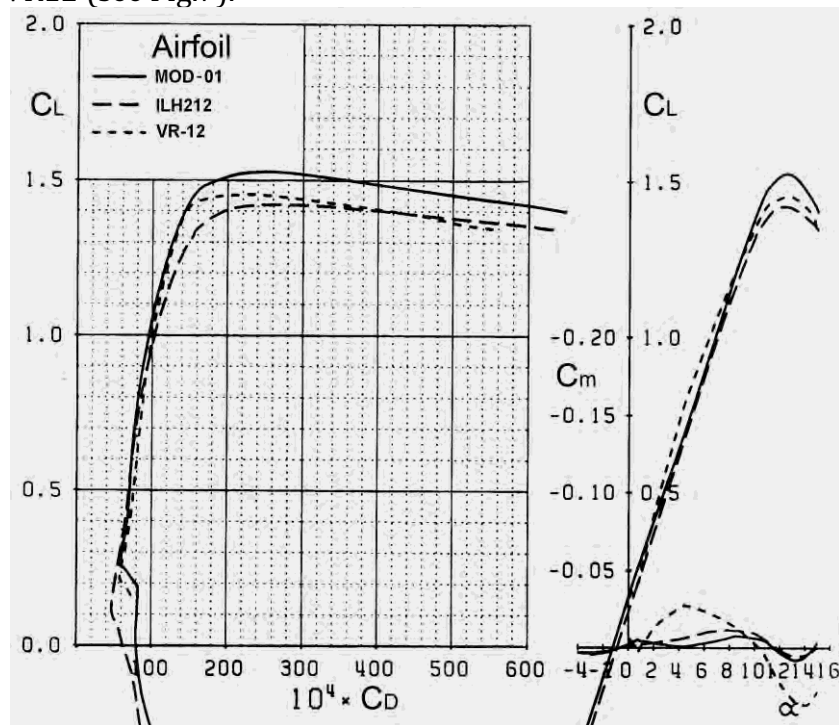


Fig.6 Comparison of aerodynamic characteristics of the ILH212, VR-12 and MOD-01 airfoils as determined by the MSES program. Conditions of flow: $M = 0.4$, $Re = 1.6 \cdot 10^6$.

In further course of design the iterative method of straight optimization was used as well as optimization including the random disturbances of the airfoil geometry realized by means of the MSES, H, CODA, INV and OPT codes. The selected group of aerodynamic parameters, being crucial from the point of view of general requirements and comprising C_{Lmax} and C_{m0} at $M = 0.4$, C_L / C_D at $M = 0.6$ and $C_L = 0.7$ and $C_{D(CL=0)}$ at $M = 0.80$ and the drag divergence Mach number M_{dd} at $C_L = 0$ has been analyzed.

Values of these parameters for a handful of specimens selected from some tens of designed airfoils are shown in Fig.7. Worth to note are airfoils denoted as ILH312 and ILH312M – these airfoils have been finally selected for the outer and inner part of the blade. Fig.7 presents also the respective data of the VR12 airfoil which is considered as an “airfoil of reference”. It’s easy to notice that in comparison with that airfoil the ILH312 features all aerodynamic parameters taken into consideration are better.

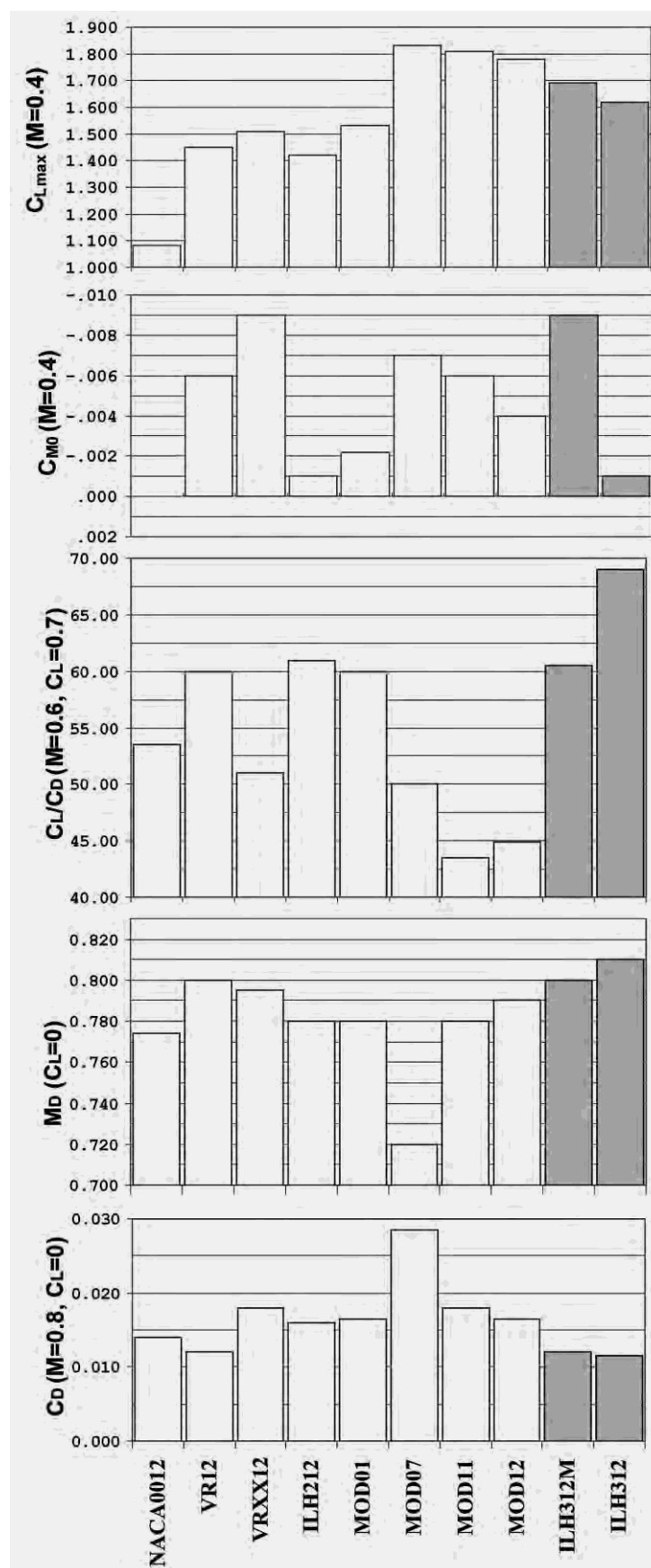


Fig.7. Comparison of aerodynamic criterion parameters of selected versions of airfoils obtained in the course of designing airfoils for outer and inner parts for blades of lifting rotors – computation by means of the MSES and H codes for $Re=4 \cdot 10^6$

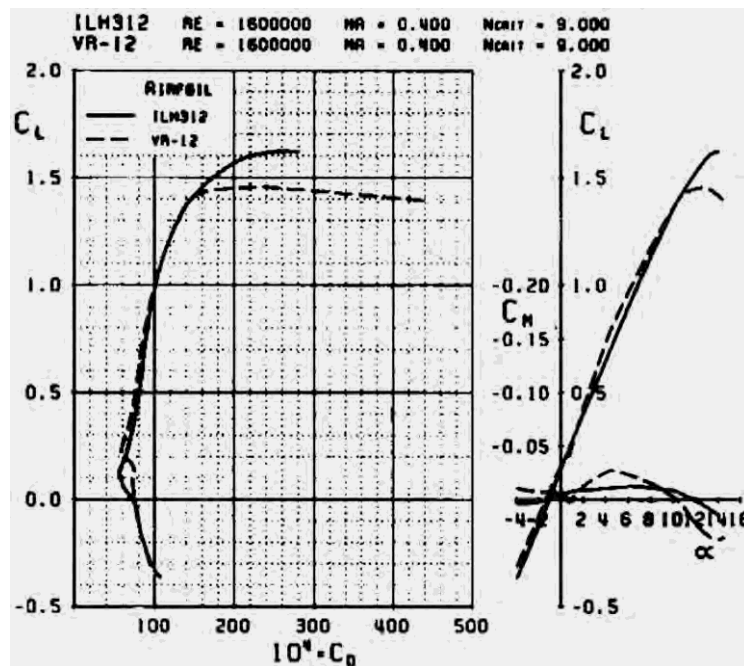


Fig.8. Comparison of drag polar and relations between the lift coefficient and the pitching moment characteristics for ILH312 and VR12 airfoils. Computation by means of the MSES code. $Re = 4 \cdot 10^6$, $M = 0.4$

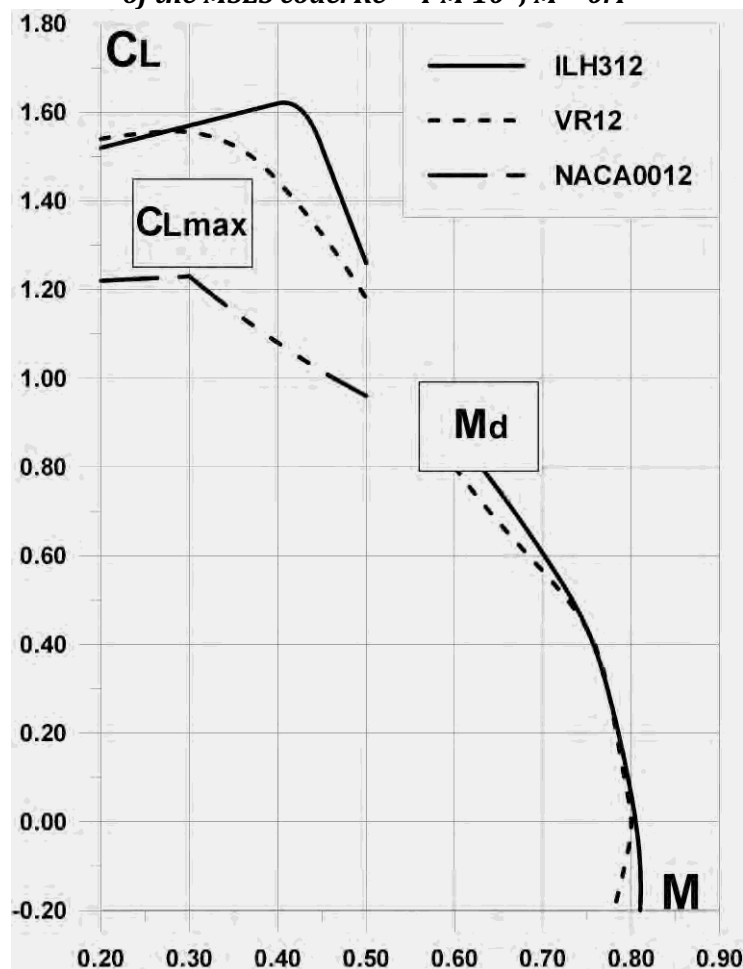


Fig.9. Comparison of relationships between the C_{Lmax} and the Mach number as well as comparison of the drag divergence Mach number $M_d = f(C_L)$ for ILH312, VR-12 and NACA0012 airfoils – computations by means of the MSES and H codes for the Reynolds number $Re=4 \cdot 10^6$

Fig.8 shows the comparison of drag polar $C_D(C_L)$ and lift and moment coefficients and characteristic $C_L = f(\alpha)$ and $C_m = f(\alpha)$, for both airfoils ILH312 and VR12 and at the Mach number $M = 0.4$. Drag polars $C_D(C_L)$ are very similar, however the ILH312 airfoil features the higher coefficient $C_{L_{max}}$ (by about 12%) and lower values of the pitching moment coefficient than the VR12 airfoil. In comparison with the VR12 some improvement has been also reached in transonic characteristics of the ILH312 airfoil i.e. value of the drag divergence Mach number M_{dd} for $C_L = 0$ is higher and values of the drag coefficients C_D are lower – see Fig.7. Comparison of the relationship of $C_{L_{max}} = f(M)$ and the drag divergence Mach number $M_{dd} = f(C_L)$ for both airfoils are presented in Fig.9 where the advantage of the ILH312 airfoil over VR12 is well visible.

The ILH312M airfoil, foreseen for the inner blade part, features the highest value of the $C_{L_{max}}$ coefficient, equal to 1.69, exceeding by 16% the value for the VR12 airfoil.

Values of other considered aerodynamic parameters of the ILH312M airfoil are approximately the same as for the VR12 airfoil.

Airfoils with the relative thickness of 8% and 9%, for the blade tips, were designed straight in the iterative optimization process aimed mainly on the increase of the drag divergence Mach number for $C_L = 0$. As starting point in the optimization process were assumed the airfoils obtained by simple re-scaling of the ILH312 airfoil. On this way two airfoils were obtained, ILH309 and ILH308, featuring the relative thickness 9% and 8% respectively. Aerodynamic performance of these airfoils are presented in Fig.10 together with comparison with thickness-similar airfoils VR13 ÷ R14.

The advantageous improvement of aerodynamic performance of the new-developed ILH3XX family of airfoils with relation to the VR12 ÷ 14 family is shown in Fig.11 as comparison of the $C_{L_{max}}$ coefficient for $M = 0.4$ and the drag divergence Mach number for $C_L = 0$. For the same value of the drag divergence Mach number for $C_L = 0$ airfoils belonging to the ILH3XX family demonstrate values of the $C_{L_{max}}$ coefficient higher by about 14% ÷ 16% than the VR12 ÷ 14 family. On the other hand, for the same value of the $C_{L_{max}}$ coefficient for $M = 0.4$, airfoils of the developed ILH3XX family feature the values of the drag divergence Mach number M_d for $C_L = 0$ higher by about 0.020 ÷ 0.035 than in case of the VR12 ÷ 14 family airfoils. Computational results quoted above justify the statement that the designed ILH3XX airfoils present a significant progress in the development of airfoils for blades of lifting rotors.

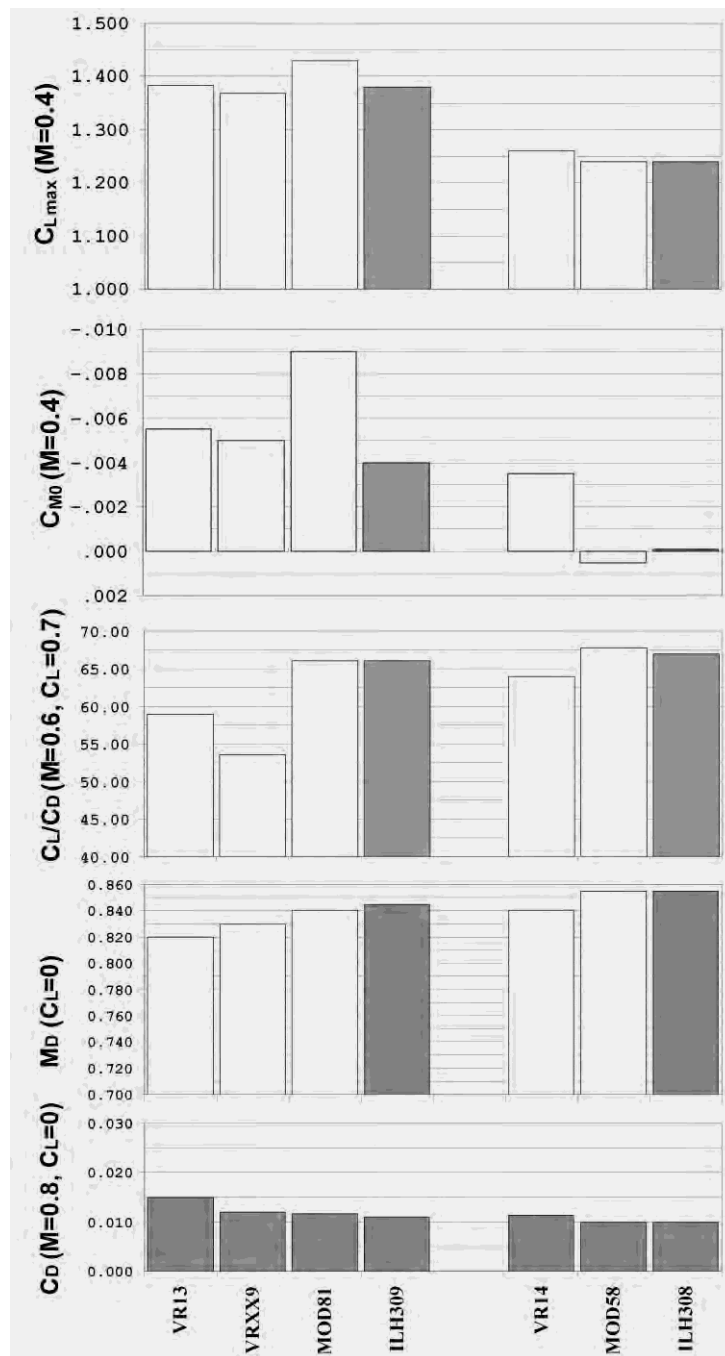


Fig.10 Comparison of aerodynamic criteria parameters of selected airfoil versions obtained in the course of design airfoils for tips of blades of lifting rotors – computations carried out by means of MSES and H codes for $Re=4 \cdot 10^6$.

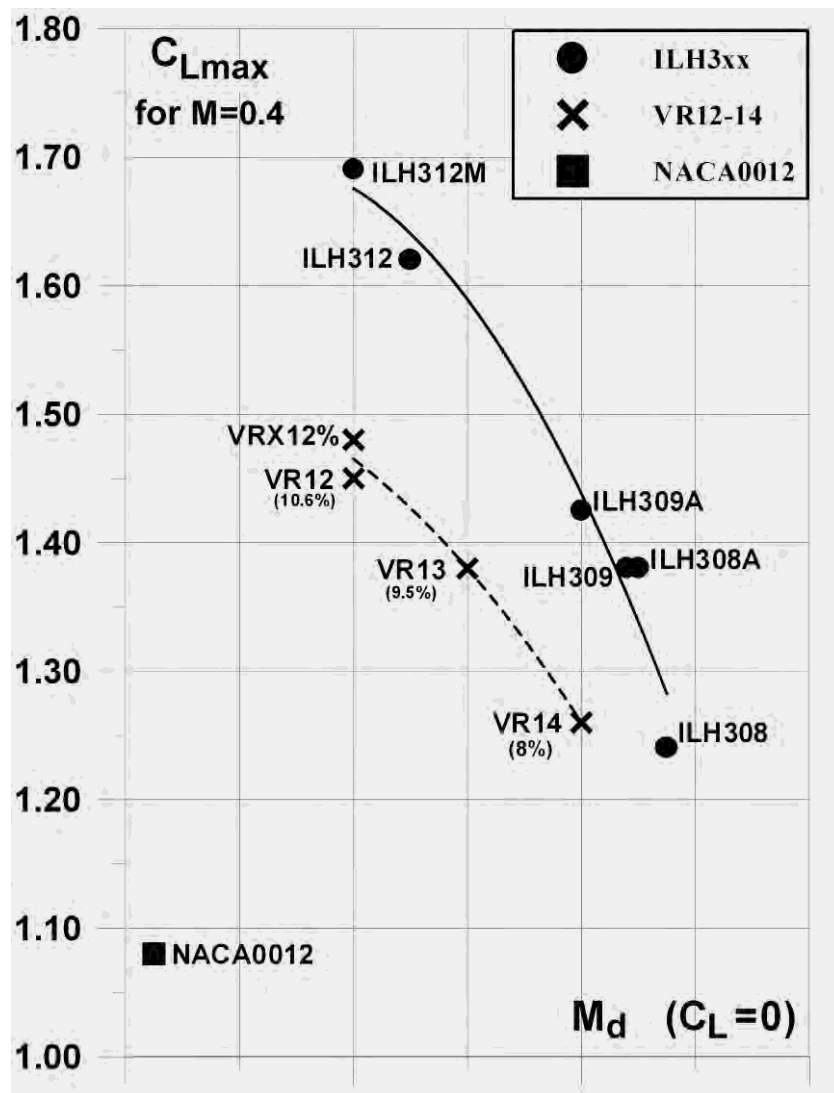


Fig.11 Relationships between coefficient C_{Lmax} for $M=0.4$ and drag divergence Mach number M_d for $C_L = 0$ featured by airfoils of the ILH3XX and VR12-14 families. Results of computations carried out by means of MSES and H programs.

5. Experimental wind tunnel test of the ILH312 airfoil model for lifting rotor blade

The ILH312 airfoil, assumed as a basic element of the ILH3XX airfoil family, became the object of experimental validation. The experimental test has been performed in the N-3 wind tunnel of the Institute of Aviation in the Mach number range of 0.3 - 0.86. It is blowdown wind tunnel with partial flow recirculation and Mach number range of 0.3 - 2.3. The subsonic and transonic test section has square cross section 0.6 x 0.6 m. The chord of the tested ILH312 airfoil model was equal 200 mm. The model was mounted between the side test section walls. The ILH312 airfoil model was equipped with 69 pressure taps of 0.5 mm diameter located on upper and lower model surfaces to measure pressure distribution and the lift and pitching moment coefficient determination. The drag coefficient determination was performed by using a 115-points rake of total and static pressure probes located in the wake one airfoil chord downstream of the model trailing edge. Tests in the Mach numbers range $M = 0.3$ up to $M = 0.5$ were carried out in the test section having all walls solid. For the Mach numbers, however, higher than 0.5 tests were carried out in the test section having upper and lower walls perforated. Tests were performed at the Reynolds numbers equal approximately to $Re = 4 \times M \times 10^6$.

Coefficients of lift and pitching moment were determined by integrating values of pressure distributions measured at the airfoil model. The drag coefficient was determined from pressure distribution in the aerodynamic wake. Results of tests presented below was corrected for the wall interference exerted on the stream deflection behind a wing in the range of linearity of the lift coefficient as well as for the flow blockage. Tests were conducted under conditions of free transition of the boundary layer.

Basic aerodynamic performance of the ILH312 airfoil, being the result of performed wind tunnel tests, are presented in Figs. 12 ÷ 14. They illustrate:

- maximum lift coefficient C_{Lmax} vs. Mach number
- drag divergence limit $M_d = f(C_L)$ defined by the criterion $dC_D/dM \geq 0.1$ for $C_L = \text{const.}$
- isolines of the lift coefficient C_L for the constant value of the drag coefficient $C_D = 0.01$ and 0.02.

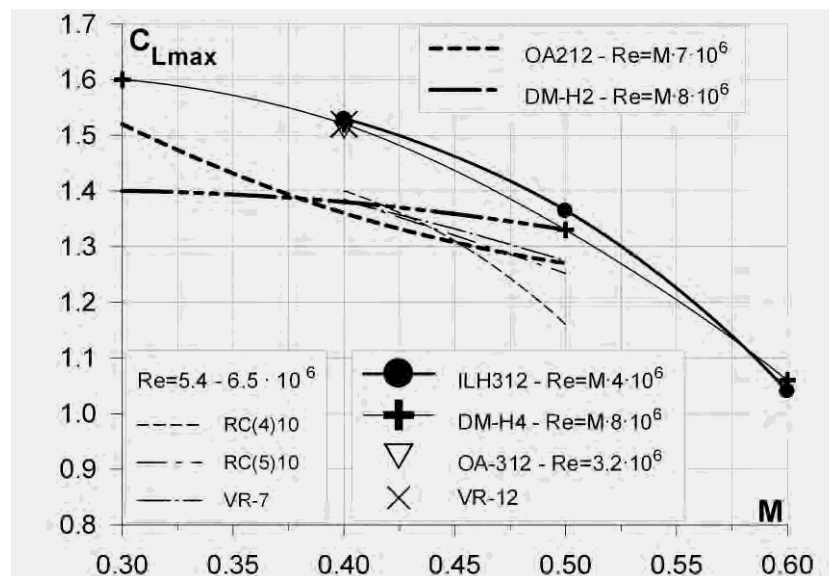


Fig.12. Maximum lift coefficient C_{Lmax} vs. Mach number of selected modern helicopter airfoils. Results of experimental investigation.

Presented performance have been compared with the corresponding characteristics of other modern airfoils for lifting rotors, belonging to the second and third generation and featuring identical (approximately) relative thickness of 12%. Experimental aerodynamic data for these airfoils were taken from papers [1, 15, 21, 23, 24].

When looking at the ILH312 airfoil from the point of view of the C_{Lmax} coefficient it would be interesting, first of all, to compare it with classic airfoils like NACA0012, and especially with NACA23012. Such a comparison, described in paper [25] and based on results of tests performed in the N-3 wind tunnel, indicates considerable increments of the C_{Lmax} coefficient for higher Mach numbers $M = 0.4 - 0.5$. In this range of Mach numbers the C_{Lmax} coefficients of the ILH312 airfoil are higher by about 46% - 62% than coefficients of the NACA0012 airfoil and by about 23% - 27% than coefficients of the NACA23012 airfoil. Less increments of the C_{Lmax} coefficient appear for the Mach number $M = 0.3$ - in reference to the NACA0012 and NACA23012 airfoils they amount to 36% and 13% respectively. In case of the ILH312 airfoil increment of the C_{Lmax} coefficient was achieved with maintaining the near-to-zero coefficient of the pitching moment for zero lift. At the Mach number $M = 0.4$ the C_{Lmax} coefficient for the ILH312 airfoil amounts to -0.006, for the NACA23012, however, -0.01.

In the table below results of experimental tests and results of numeric computations of the ILH312 airfoil are compared with design requirements which were the base for design airfoils numerically.

Table 5

	C_{Lmax} $M = 0.4$	C_L/C_D $M = 0.6$ $C_L = 0.7$	M_d $C_L = 0$	C_{m0} $M = 0.4$ $C_L = 0$
Requirements	>1.50	≥ 60	≥ 0.80	≥ -0.01
ILH312 airfoil N-3 wind tunnel	1.53	64	0.822	-0.006
ILH312 airfoil computations	1.62	69	0.805	-0.001

The above comparison gives the ground for a statement that experimental examination has confirmed that the ILH312 airfoil meets the design requirements for an airfoil for the outer part of the lifting rotor blade.

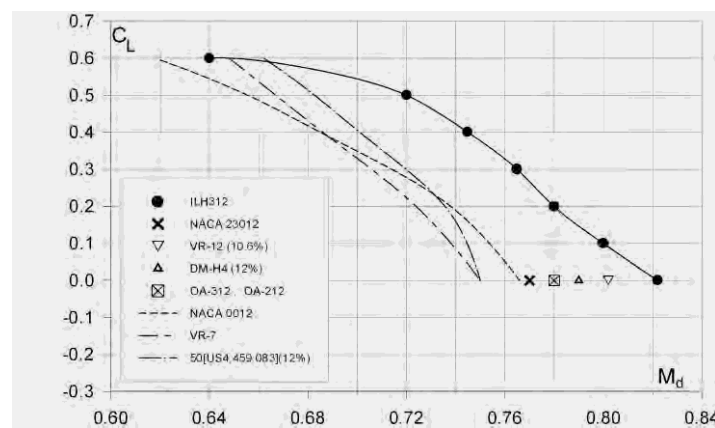


Fig.13. Lift coefficient C_L vs. Mach number for selected modern helicopter airfoils. Results of experimental tests.

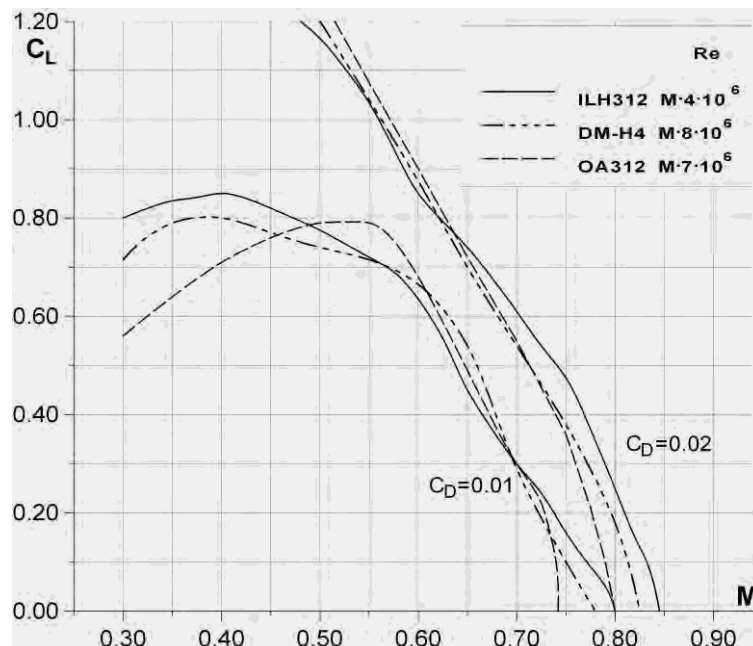


Fig.14. Lift coefficient C_L vs. Mach number for constant value of the drag coefficient $C_D = 0.01$ and 0.02 . Results of experimental test of ILH312, DM-H4 i OA312 airfoils.

The ILH312 airfoil features a high, amounting to 1.53, value of the maximum lift coefficient C_{Lmax} at the Mach number $M = 0.4$ and an equally high value of the drag divergence Mach number M_d for zero lift, amounting to 0.822. In the table below values of aerodynamic parameters of the ILH312 airfoil are compared with similar data corresponding to a handful of best airfoils for blades of lifting rotors [1, 15, 21] used in modern helicopters of last years, being in current production.

Table 6

Airfoil	ILH312	VR12	DM-H4	OA312
C_{Lmax} for $M = 0.4$	1.53	1.52	1.52	1.51
M_d for $C_L = 0$	0.822	0.802	0.795	0.780
$Re \cdot 10^6$	4.5-4.25	n.a.	8-M	8-M

Advantage of the ILH312 airfoil over other airfoils used in comparison is expressed, first of all, by the drag divergence Mach number. It's especially well visible in comparison with the DM-H4 and OA312 airfoils which feature the same relative thickness of 12% as the ILH312. It's worth to remember that the relative thickness of the VR12 airfoil amounts only to 10.6% what – it is well-known fact - leads to weakening the wave effects in the transonic flow. The compared airfoils, IL312, VR12, DM-H4 and OA312, are characterized by approximately the same value of the C_{Lmax} coefficient for the Mach number $M = 0.4$, the highest value belongs to the ILH312 airfoil. It's also worth to note that all tests of the ILH312 airfoil have been performed at the Reynolds number at least two times lower. It's common knowledge that the increase of the Reynolds number exerts the positive effect on the increase of the C_{Lmax} coefficient. Results of numerical computations of the ILH312 airfoil, carried out with the use of the MSES code, indicates that the mentioned difference in value of the Reynolds number leads to lowering value of the C_{Lmax} coefficient of the ILH312 airfoil by about 0.05 - 0.08 [25]. From the comparison in Fig.12 of the C_{Lmax} coefficients in function of the Mach number it's easy to recognize that in the range of Mach numbers up to 0.6 values of this coefficient for the ILH312 and DM-4H airfoils are approximately identical. Advantage of the ILH312 airfoil over airfoils of the second generation, like OA212, DM-H4, VR7 and RC(4)10, is unquestionable.

Excellent transonic features of the ILH312 airfoil are confirmed by comparisons shown in Figs. 13 – 15. Basing on them a statement is justified that in conditions reflecting flow at the advancing blade the ILH312 airfoil reaches values of the drag coefficient C_D equal to 0.01 and 0.02 for higher values of the lift coefficient than the airfoils DM-H4 and OA312 (Fig.14). In case of the ILH312 airfoil the drag coefficient for zero lift in the range of the Mach number reaching up to $M = 0.78$ is approximately the same as in case of the DM-H4 airfoil and distinctly lower in case of Mach numbers exceeding 0.78 (Fig.15).

Comparison of relationship of the moment coefficient C_m versus the lift coefficient C_L (for the Mach number $M = 0.4$) presented in Fig.16 indicates that for C_L coefficients less than 0.8 these relationships for both considered airfoils, i.e. ILH312 and DM-H4, approximately correspond each to other. In case of both airfoils the moment coefficient for zero lift amounts to $C_{m0} = -0.006$.

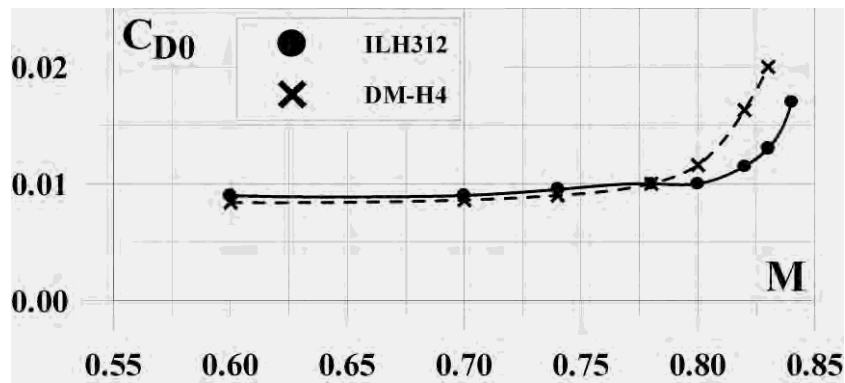


Fig.15 Comparison of experimental effects of Mach number on drag coefficient at zero lift for ILH312 and DM-H4 airfoils.

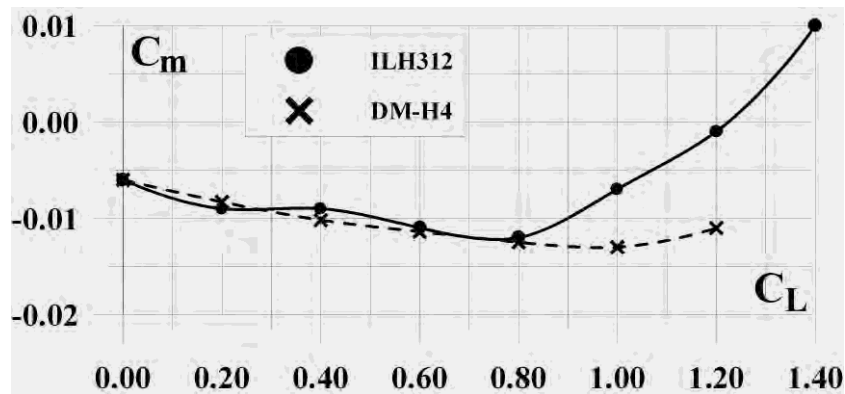


Fig.16. Comparison of changes of moment coefficients C_m in function of lift coefficient C_L for ILH312 and DM-H4 airfoils, determined in experiment. Tests carried out at $M = 0.4$.

Comparison of values of the $C_{L_{max}}$ coefficient for $M = 0.4$ (with the mentioned correction for the Reynolds number) as well as the drag divergence Mach number for $C_L = 0$ with similar parameters of classic NACA airfoils and known modern airfoils for blades of lifting rotors is shown in Fig.17. The above comparison gives the ground for a statement that from the point of view of the $C_{L_{max}}$ coefficient the ILH312 airfoil has a little advantage over best airfoils of the same relative thickness, i.e. 12%, and from the point of view of the drag divergence Mach number it can be placed among airfoils for blade tips featuring less thickness, i.e. 8% ÷ 9%.

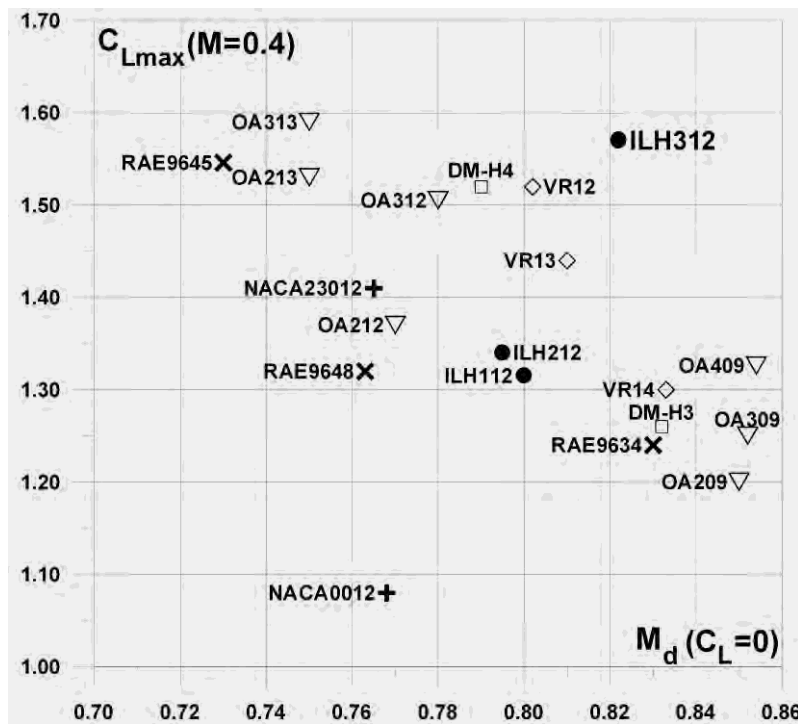


Fig.17 Values of the maximum lift coefficient (for Mach number $M = 0.4$) and drag divergence Mach numbers (for lift coefficient $C_L = 0$) for ILH312 airfoil and for selected airfoils for blades of lifting rotors featuring similar relative thickness.

6. Designing airfoil for the tail rotor blade numerically

The main objective in the iterative process of design airfoil for the tail rotor blade was a significant increase of the maximum lift coefficient in the range of Mach numbers $M = 0.5 \div 0.6$ with possibly high level of lift to drag ratio. The criterion of limiting the pitching moment coefficient was less restrictive in this case than the criterion valid for airfoils for blades of the lifting rotor. It's so because tail rotor blades are less susceptible to twist.

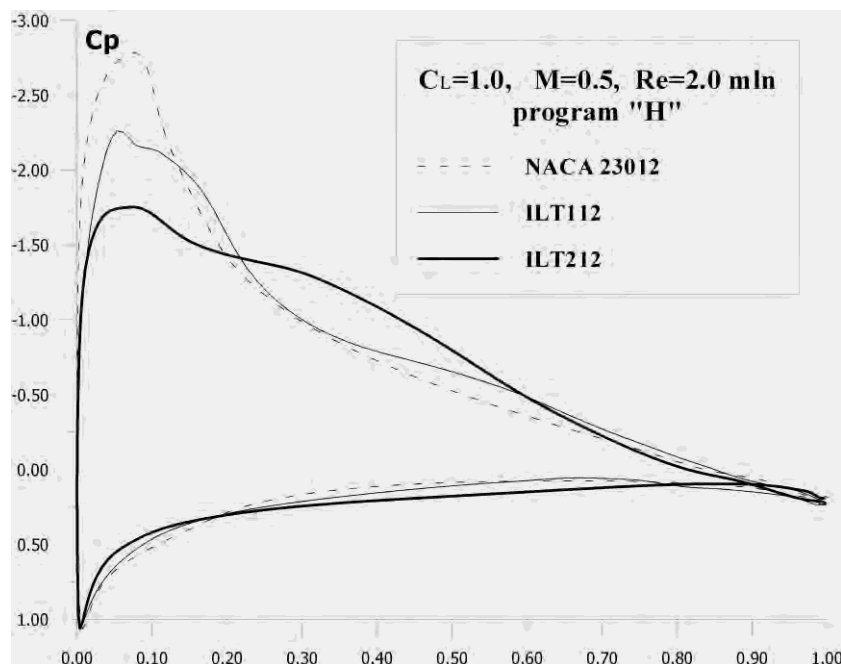


Fig.18 Pressure distribution for airfoils ILT212, ILT112 and NACA23012 at $C_L = 1.0$, $M = 0.5$.

To obtain above C_{Lmax} improvement the idea of avoiding the local supersonic flow field in the upper side airfoil nose region at Mach number of 0.5 – 0.6 and lift coefficient of 1.0 was used.

In the course of design and optimization the inverse mode of the MSES and INV codes as well as the optimization code based on genetic algorithms were used in design process of a tail rotor blade airfoil. In result the ILT212 airfoil has been developed with the relative thickness of 12%. The calculated pressure distribution by using MSES code on the designed ILT212 airfoil, classical NACA2312 airfoil and initial ILT112 airfoil at design conditions $M=0.5$ and 0.6 are compared in Figures 18 and 19. Presented results revealed that flow over designed ILT212 airfoil is subcritical at $M=0.5$ and without shock wave at $M=0.6$. In result of these favorable changes in pressure distribution, the ILT212 airfoil has produced the desired effect, i.e. the increase of the maximum lift coefficient in the considered range of Mach numbers, as it is shown on Fig.20. From the point of view of value of the maximum lift coefficient C_{Lmax} , at Mach numbers $M = 0.5 - 0.6$, the ILT212 airfoil has an advantage over the initial airfoil ILT112 and over both classic airfoils NACA0012 and NACA23012. It's especially well visible for Mach numbers near to 0.6. The advantage has been reached, however, for a price of a small decrease of the C_{Lmax} coefficient for lower values of the Mach number, $M = 0.1 - 0.37$ in comparison with the NACA23012 airfoil. That range, however, is usually located beyond the operational range of tail rotor blades therefore this loss isn't crucial. The ILT212 airfoil is superior over the classic NACA0012 and NACA23012 also from the point of view of aerodynamic efficiency. In particular in the range of $M = 0.5 \div 0.6$ the computed value of maximum aerodynamic efficiency of the ILT212 airfoil exceeds by about 100% the value for the NACA23012 airfoil.

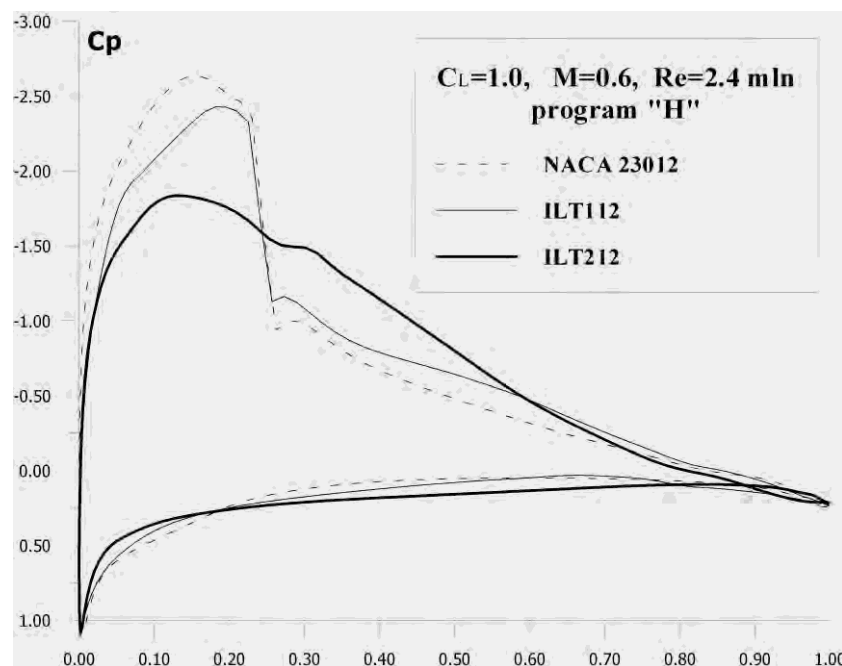


Fig.19 Pressure distribution created by flow with $C_L = 1.0$, $M = 0.6$ at ILT212, ILT112 and NACA23012 airfoils, at $C_L = 1.0$ and $M = 0.6$

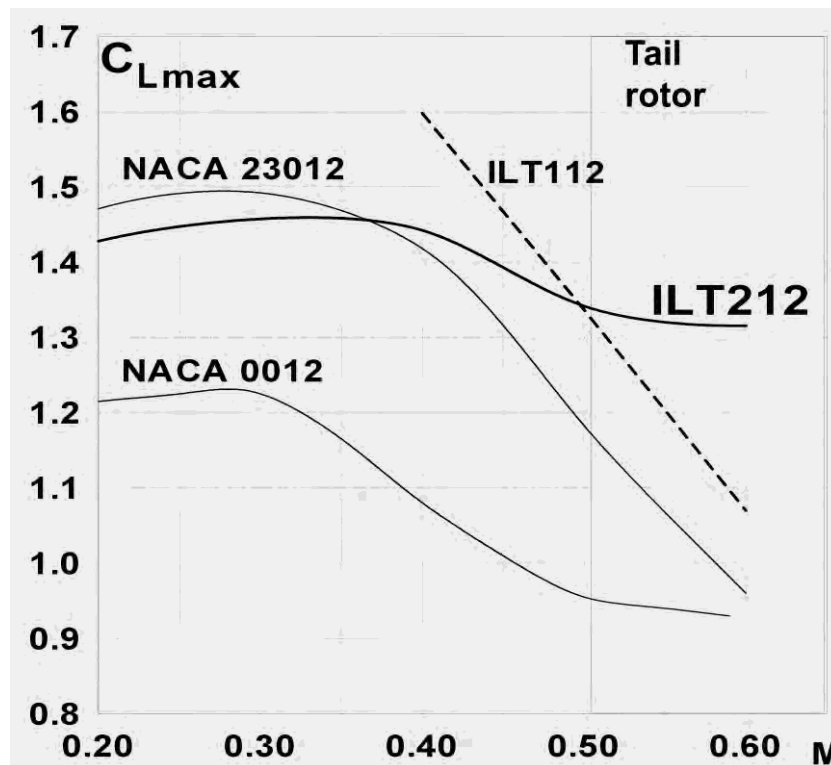


Fig.20. ILT212, ILT112, NACA0012 and NACA23012 airfoils - maximum lift coefficient C_{Lmax} vs. Mach number. MSES program – computed.

7. Experimental test of the model of the ILT212 airfoil for blades of tail rotors

Experimental test of the ILT212 airfoil has been performed in the N-3 trisonic wind tunnel of the Institute of Aviation, the same device where earlier tests of the ILH312 airfoil have been carried out, with the use of the same measuring technique and method of measuring data processing.

Basic aerodynamic characteristics, obtained in the wind tunnel tests, are summarized in Figs. 21 – 26.

The lift coefficient characteristics $C_L(\alpha)$ in the most interesting for a tail rotor range of Mach numbers, from $M = 0.5$ up to $M = 0.6$, is presented in Fig.21. In this range of Mach numbers the maximum lift coefficient exceeds 1.27 reaching the highest value of 1.41 at the Mach number $M = 0.55$. Relationships between the C_{Lmax} coefficients of the ILT212 airfoil and classic airfoils used in tail rotors, i.e. NACA0012 and NACA23012, as well as C_{Lmax} of the modern lifting rotor airfoil ILH312, presented above, and the Mach number are compared in Fig.22. Compared results were obtained in the N-3 wind tunnel at the same Reynolds numbers. Basing on this comparison one can state that the C_{Lmax} coefficient of the ILT212 airfoil features significantly less, adverse influence of the Mach number in the range $M = 0.3 \div 0.6$ than in case of other compared airfoils. In comparison with the NACA 23012, widely used in tail rotors, the C_{Lmax} coefficient of the ILT212 airfoil is higher by about 41% in the range of Mach numbers $M = 0.55 \div 0.6$. Comparison of the C_{Lmax} coefficient of the ILT212 airfoil with other modern airfoils for tail rotors, like RAE9670, RAE9671 and OAR9 in the range of Mach numbers $M = 0.3 \div 0.6$ is presented in Fig. 23. One can state that from the point of view of the C_{Lmax} coefficient the ILT 212 airfoil isn't inferior to comparable modern airfoils for tail rotors. In the range of Mach numbers $M = 0.55 \div 0.6$ the C_{Lmax} coefficient is even higher than the C_{Lmax} coefficient of the RAE9671 airfoil which features the highest value of C_{Lmax} among foreign airfoils for tail rotors used in comparison.

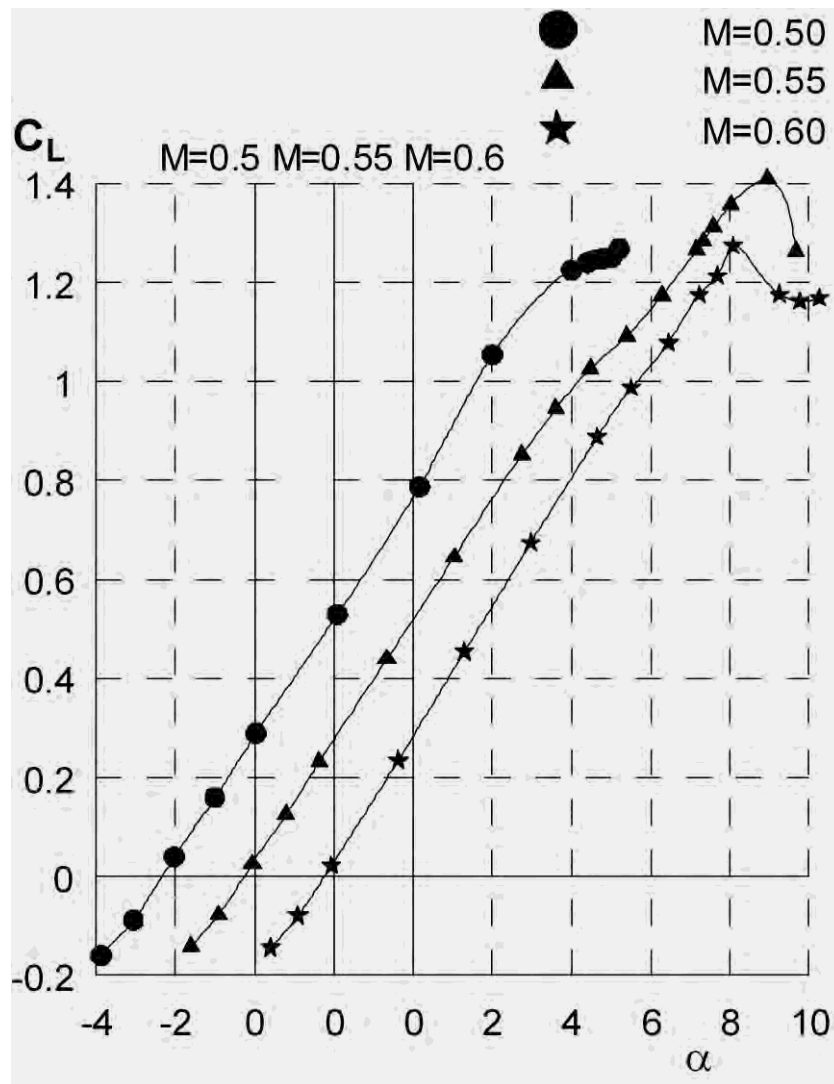


Fig.21 Relationship between lift coefficient C_L and angle of attack α for Mach numbers $M = 0.50, 0.55$ and 0.60 . Experimental results collected for ILT212 airfoil.

The pitching moment characteristics $C_m(\alpha)$ of the ILT212 airfoil at Mach number $M=0.5$ are shown on Figure 24. The zero lift pitching moment coefficient at Mach number $M=0.5$ amounts to -0.042 . It is to note that design requirements were assuming, as an aim to reach, values of C_{m_0} higher than -0.05 .

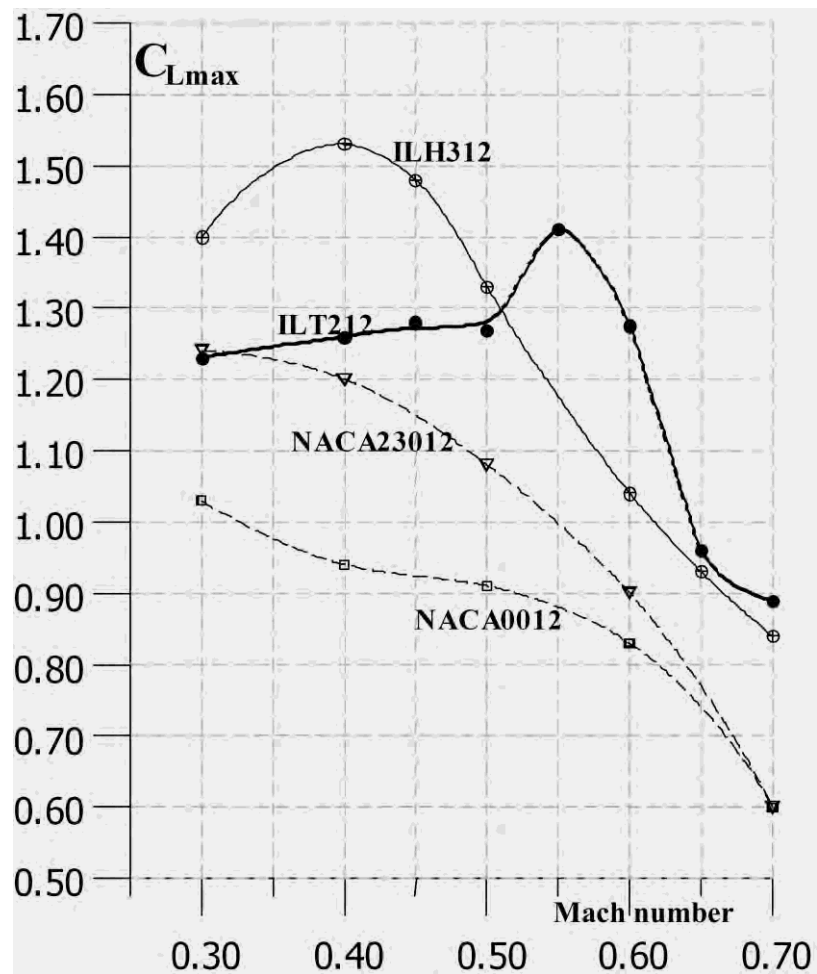


Fig.22 Relationship between maximum lift coefficient C_{Lmax} and Mach number. Experimental results collected for ILT212, NACA0012, NACA23012 and ILH 312airfoils from test in N-3 wind tunnel

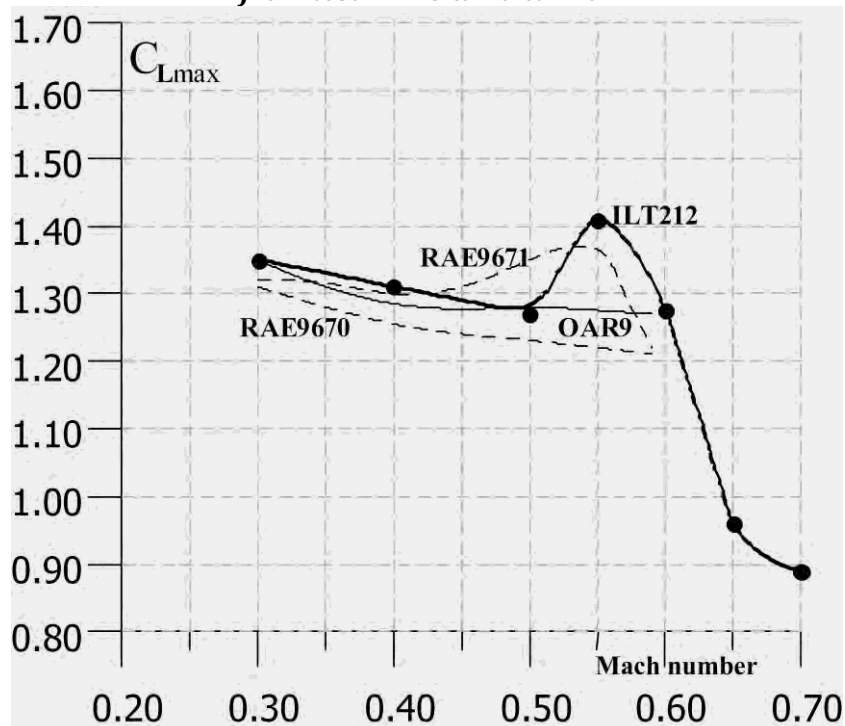


Fig.23 Relationship between maximum lift coefficient C_{Lmax} and Mach number. Experimental results for ILT212airfoil and foreign airfoils RAE9670, RAE9671 and OAR92

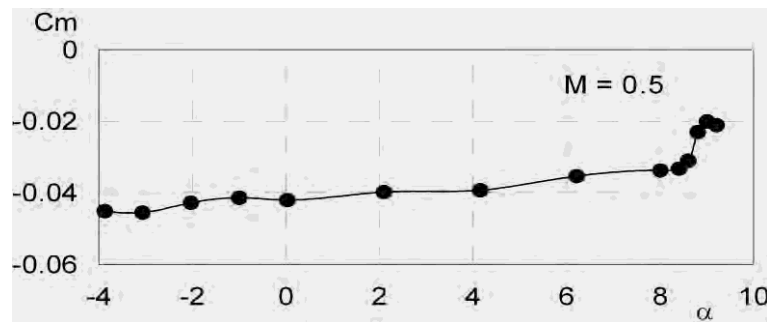


Fig.24 Pitching moment characteristic $C_m(\alpha)$ for the ILT212 airfoil. Experimental results for Mach number $M = 0.5$ (N3 wind tunnel)

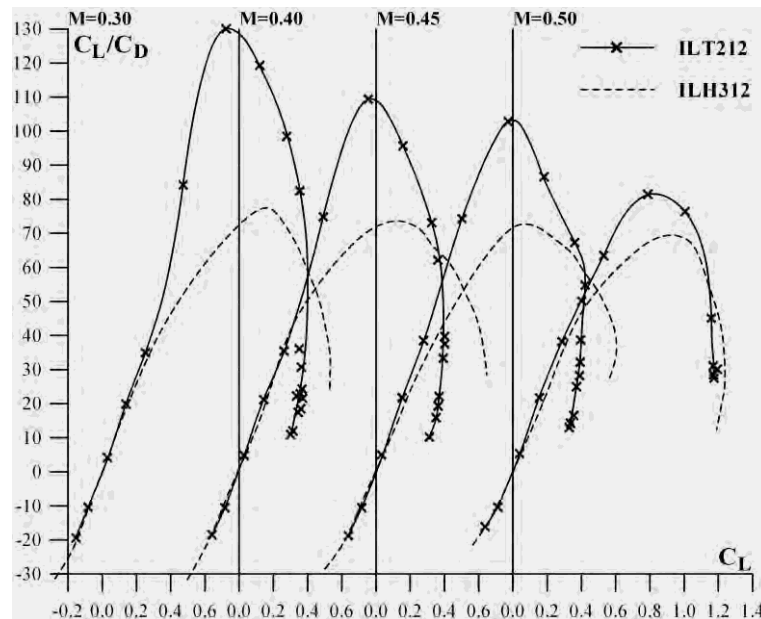


Fig.25 Comparison of experimental lift to drag ratio (C_L/C_D) in function of lift coefficient C_L for ILT212 and ILH312 airfoils. Results at Mach numbers $M = 0.3, 0.4, 0.45$ and 0.5 .

Fig.25 presents the comparison of lift to drag ratio C_L/C_D of the ILT212 airfoil with the ILH312 airfoil presented above, one of best modern airfoils for lifting rotors. It is to note that both airfoils were tested in the N-3 wind tunnel under identical conditions and with the use of the same measuring technique. One can state that from the point of view of aerodynamic efficiency the ILT212 airfoil shows the visible superiority. For C_L coefficients higher than 0.2 – 0.3 efficiency of the ILT212 airfoil exceeds that of the ILH312.

Relationship of the maximum value of lift to drag ratio and the Mach number for both airfoils, ILT212 and ILH312, is compared in Fig.26. Well visible is considerable superiority of the ILT212 airfoil over the ILH312 airfoil with a view to maximum lift to drag ratio which appears in the wide range of Mach numbers $M = 0.3 - 0.65$.

It should be emphasised that very high value of maximum lift to drag ratio – above 100 – appears at Mach numbers less than $M = 0.45$. In the table below lift to drag ratio of the ILT212 airfoil is compared with the conventional airfoil NACA23012 for the Mach number $M = 0.6$ and the lift coefficient $C_L = 0.6$, in both cases measured in the N-3 wind tunnel. What needs underscoring is the fact that lift to drag ratio of the ILT212 airfoil is higher by 58% than of the NACA23012 airfoil.

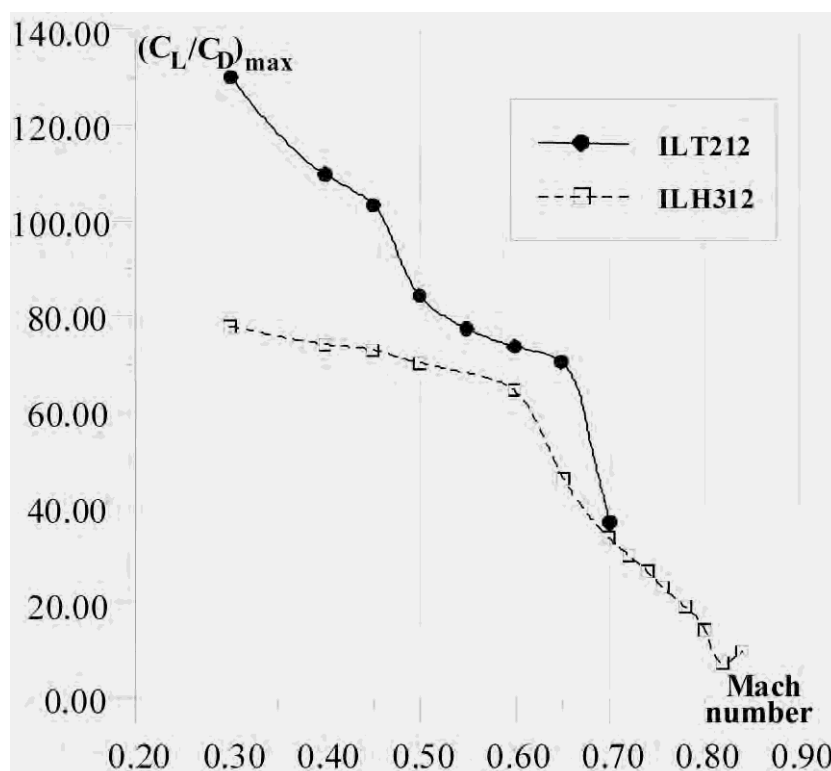


Fig.26 Comparison of changes of maximum efficiency in function of Mach number for ILT212 and ILH312 airfoils.

Table 7

Airfoil	ILT 212	NACA 23012
C_L/C_D for $C_L = 0.6$ and $M = 0.6$	68	43

On the basis of aerodynamic features of the ILT212 airfoil presented above a statement is justified that it fully meets design requirements and can be placed among best foreign airfoils destined for tail rotors. Aerodynamic features of the ILT212 airfoil, crucial for operation of tail rotors, are undoubtedly better than features of the conventional, still widely used, airfoil for tail rotors, NACA 23012.

8. Summary and conclusions

Results of tests performed in the N-3 wind tunnel on the ILH312 airfoil have confirmed that it features values of the C_{Lmax} coefficient in the range of Mach numbers $M = 0.4 \div 0.5$ higher by 46% ÷ 62% in comparison with the NACA 0012 and by 23% ÷ 27% in comparison with the NACA23012 airfoil. Increments of the C_{Lmax} coefficient observed at the Mach number $M = 0.3$ are less and amount to 36% and 13% in comparison with the NACA0012 and NACA23012 airfoils respectively.

Comparing aerodynamic parameters of the ILH312 airfoil and modern airfoils of lifting rotor blades, belonging to the second and third generation, one can state that when taking into consideration the influence of the Reynolds number the maximum lift coefficient C_{Lmax} of the ILH312 airfoil for $M = 0.4$ is higher by about 13% ÷ 17% than airfoils of the second generation and by about 3% ÷ 4% than airfoils of the third generation. The ILH312 airfoil features the highest value of the drag divergence Mach number M_{dd} for $C_L = 0$ (equal to 0.822) from all airfoils of the third generation being used in the main part of lifting rotor blades which feature the value of M_{dd} in the range $0.78 \div 0.802$. Very good transonic features of the ILH312 airfoil are best demonstrated in conditions of flow around the advancing blade ($C_L \leq 0.3$) where very probably, without

exceeding the level of the drag coefficient $C_D = 0.01$ or 0.02 , higher transonic speeds can be reached than in case of the DM-H4 and OA312 airfoils which are considered as belonging to best among airfoils of the third generation.

Basing on the comparison of computational and experimental values of considered aerodynamic parameters of the ILH312 airfoil expectations are justified that also other airfoils belonging to the ILH3XX family will confirm their superiority over airfoils of the VR12 ÷ 14 family in experimental examinations.

On the ground of results of performed wind tunnel tests on models of lifting rotors with the use of NACA23012 and CAGI airfoils of the third generation one can expect an increment of general technical rotor efficiency reaching some tens of percents, achieved by substitution of NACA230XX airfoils with airfoils of designed ILH3XX family. It's especially important for the Polish helicopter designs using so far widely the NACA230XX airfoils.

Results of tests performed in the N-3 wind tunnel on the model of the ILT212 airfoil for tail rotors have confirmed that this airfoil meets all designer's requirements. In general it can be stated that in the range of $M = 0.3 \div 0.6$ the ILT212 airfoil demonstrates much less unfavorable influence of the Mach number on the $C_{L_{max}}$ coefficient than classic helicopter airfoils of NACA and even modern airfoils for lifting rotors. In comparison with the NACA23012 airfoil, widely used in blades of tail rotors, the $C_{L_{max}}$ coefficient of the ILH212 is higher, for the Mach number $M=0.5$ and in the range $M = 0.55 \div 0.60$, even by about 40%. The ILT212 airfoil features also high lift to drag ratio. In the range of Mach numbers below 0.45 the maximum lift to drag ratio K_{max} of the ILT212 airfoil amounts more than 100 with the maximum value for $M = 0.3$ equal to $K_{max} = 130$. That value exceeds by about 67% the equivalent value of the ILH312 airfoil. In comparison with the classic NACA 23012 airfoil the lift to drag ratio of the ILT212 airfoil at $M = 0.6$ and $C_L = 0.6$ is higher by about 58%.

Comparison of relationships between the lift to drag ratio and the lift coefficients of the ILT212 and ILH312 airfoils indicates that higher values than in the ILH312 airfoil the lift to drag ratio of the ILT212 occur even at relatively low values of the C_L coefficients, equal to $0.2 \div 0.3$ and the visible superiority of efficiency of the ILT212 airfoil over the ILH312 airfoil is maintained up to the Mach number $M = 0.65$.

When comparing relation $C_{L_{max}} = f(M)$ between the maximum lift and the Mach number corresponding to both airfoils, ILT212 and mentioned above RAE9671, it is easy to note that they are very similar, in both cases the maximum value of the $C_{L_{max}}$ appears at the Mach number $M = 0.55$. In the range of Mach numbers $M = 0.3 \div 0.6$ the ILT212 is not in substance inferior, from the point of view of value of $C_{L_{max}}$ to the RAE9671 airfoil. This feature can favorably effects on the increase of the tail rotor thrust.

Summing up results of performed studies and experiments it is to emphasize that the designed airfoils of the ILH3XX family for blades of lifting rotors and the ILT212 airfoil for blades of tail rotors are distinctly superior, or are at least equal, to current world achievements in this area. It can be expected that using airfoils of the ILH 3XX family in lifting rotors instead of NACA230XX (so far applied in all Polish helicopters) will bring significant, reaching some tens of percents, rise of their general efficiency. It can be expected also that the visible improvement will occur in performance of rotors with ILH 3XX-blades in hovering and cruise.

Described above improvement of aerodynamic features of the ILT212 airfoil will produce the distinct increase of thrust and decrease of required power in the tail rotor fitted with the ILT212 airfoil instead of the NACA230XX airfoil (both rotors working with the same rpm).

Improved aerodynamic features of designed airfoils can be utilized not only for improvement of performance of lifting and tail rotors, but in the other way too. In accordance with analysis presented in this work, by lowering the rotational speed but maintaining performance on the same level as for classic airfoils, noise produced by the lifting or tail rotor can be reduced both in hovering and in forward flight.

At the end it is worth to underline the successful application in the designing process of this work of the new-developed optimization program based on the genetic algorithms, i.e. the modern method which arouses still rising interest in the world.

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PROJEKTOWANIE NOWOCZESNEJ RODZINY PROFILI ŚMIGŁOWCOWYCH

Streszczenie

W pracy przedstawiono wyniki projektowania numerycznego i badań eksperymentalnych nowoczesnej rodziny profili śmigłowcowych. W rezultacie procesu projektowania uzyskano profil łopaty śmigła ogonowego ILT212 o grubości względnej 12% oraz rodzinę profili ILH3XX łopaty wirnika nośnego obejmującą profile o grubościach względnych 12,2%, 12%, 9%, 8%. Na gruncie obliczeniowym zaprojektowane profile spełniały przyjęte wymagania konstrukcyjne a pod względem własności aerodynamicznych dorównywały bądź przewyższały najlepsze znane profile śmigłowcowe. Własności aerodynamiczne opracowanych profili zostały potwierdzone w badaniach tunelowych, które objęły profil zewnętrznej części łopaty wirnika nośnego ILH312 oraz profil łopaty śmigła ogonowego ILT212. W świetle przeprowadzonych badań eksperymentalnych profil ILH312 pod względem zasadniczych parametrów aerodynamicznych decydujących o jakości profili łopat wirnika nośnego wyróżnia się wśród najnowocześniejszych profili trzeciej generacji. Wyniki badań eksperymentalnych profilu ILT212 także stawiają go w czołówce najlepszych znanych profili łopaty śmigła ogonowego. Profil ten charakteryzuje się m.in. dużymi wartościami współczynnika siły nośnej dla liczb Macha w zakresie od 0.5 do 0.6 co w praktyce powinno zaowocować istotnym zwiększeniem siły ciągu śmigła ogonowego.

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ПРОЕКТИРОВАНИЕ СОВРЕМЕННОГО СЕМЕЙСТВА ВЕРТОЛЕТНЫХ ПРОФИЛЕЙ

Резюме

В работе представлены результаты численного проектирования и экспериментального исследования современного семейства вертолетных профилей. В результате процесса проектирования получен профиль лопасти хвостового винта ILT212 относительной толщиной 12% и семейство профилей ILHXX лопасти несущего винта охватывающих профили относительной толщины 12,2%, 12%, 9%, 8%. На расчетной основе спроектированные профили удовлетворяли принятым конструкторским требованиям в отношении аэродинамических качеств были на уровне или превосходили наилучшие известные вертолетные профили. Аэродинамические качества разработанных профилей подтвержденные трубными испытаниями, которые охватывали профиль внешней части лопасти несущего винта ILH312, а также профиль лопасти хвостового винта ILT212. В свете проведенных экспериментальных исследований профиль ILH312 в отношении основных аэродинамических параметров, имеющих решающее значение для качеству профилей лопастей несущего винта отличается среди наиболее современных профилей третьего поколения. Результаты экспериментальных исследований профиля ILT212, также ставят его в ряд наилучших известных профилей лопасти хвостового винта. Профиль этот характеризуется между прочим большими величинами коэффициента подъемной силы для чисел Маха в дйапозоне от 0,5 до 0,6, что на практике должно привести к существенному увеличению тяги хвостового винта.