Analysis of Model and Full-Scale Investigation Results of Helicopter Blade Aerodynamic Configuration Effect on Pitch Link Load.

Dr. Valery A. Ivtchin
Head of Aerodynamic Section

Prof. Marat N. Tishchenko
Academician of RAS
President RHS
Professor of the Moscow Aviation Institute

Mil Moscow Helicopter Plant
2, Sokolnihesky Val, Moscow, 107113
RUSSIA

Dr. V.A. Animitsa
Head of Aerodynamic Sector

Dr. V.A. Golovkin
Deputy Chief of Helicopter Department
Head of Aerodynamic Division

TsAGI
Zhukovsky, Moscow reg.
RUSSIA

SUMMARY

The paper presents the main results of the research into an aerodynamic composition of a rotor blade with a fundamentally new LEBRE element a presented. The target of the research was the reduction of a pitch link load and a control system loading with simultaneous improvement of hover and a forward flight performance. The Leading Edge of Blade Root Extension element (LEBRE element) was developed by TsAGI and Mil Moscow Helicopter Plant for the composite blades of Mi-28 combat helicopter. The research consisted of a theoretical study, tests with large-scale rotor models conducted in TsAGI T-104 wind tunnel at actual Mach numbers and flight tests conducted by Mil Moscow Helicopter Plant and Kazan Helicopter Production Association.

The LEBRE element application is shown to give:

- reduction of the pitch link load;
- increase of figure of merit in hover and of the rotor aerodynamic quality in forward flight;
- increase of the blade flutter stability.

Thus LEBRE element application permits one to reduce the blade pitch link load and to improve the rotor performance at the same time.

NOTATION

R - rotor radius, m ;
b_7 - blade chord at radial coordinate 0.7R, m ;
b_{LEBRE} - LEBRE element chord (additional to blade chord at radial coordinate 0.7R), m;
Z_l - number of blades;
ψ - azimuth position of blade, rad;
σ - rotor solidity for radius, 0.7 R;
x_l - chordwise offset of the pitch axis, coinciding with span elastic axis, behind leading edge, m;
x_f - chordwise offset of the section aerodynamic centre behind leading edge, m;
C_{lmax} - maximum section lift coefficient;
C_D - section drag coefficient;
K_a - section lift to drag ratio;
c_{mo} - section at zero lift;
$\partial c_{mo}/\partial M$ - derivative of aerodynamic moment coefficient with respect to Mach number;
ρ - air density, kg/m^3;
ωR - blade tip velocity, m/s;
M - Mach number;
V - helicopter velocity, m/s;
α - rotor angle of attack, rad;
μ - rotor advance ratio, $\mu = \frac{V}{\omega R} \times \cos\alpha$;
Y - rotor lift, N:
X - rotor propulsive force, N:
T - rotor thrust, N:
t - rotor thrust coefficient, $t = \frac{T}{.5\rho(\omega R)^2 b_7 R z_l}$; $C_t = t \times \sigma$;
M_k - rotor shaft torque, Nm;
m_k - rotor shaft torque coefficient, $m_k = \frac{M_k}{.5\rho(\omega R)^2 b_7 R^2 z_l}$; $\overline{m}_k = m_k \times \sigma$;
m_{kEN} - engine torque coefficient;
K_R - aerodynamic quality of the rotor in forward flight, $K_R = \frac{Y \times V}{75N + X \times V}$;

η_o	-	figure of merit of the rotor in hover, $\eta_o = \frac{C_t^{3/2}}{2\overline{m}_k}$;
M_h	-	the blade pitch link load, Nm;
M_a	-	aerodynamic component of blade pitch link load, Nm;
m_h	-	coefficient of the blade pitch link load, $m_h = \frac{M_h}{.5\rho(\omega R)^2 R b_7^2 z_l}$;
m_{ho}	-	coefficient of the steady part of the blade pitch link load;
m_{h1c}	-	coefficient of the first harmonic cosine component of the blade pitch link load;
m_{h1s}	-	coefficient of the first harmonic sine component of the blade pitch link load;
m_{h1}	-	coefficient of the first harmonic of the blade pitch link load;
Δm_h	-	coefficient of the variable part of the blade pitch link load;
$m_{\Sigma ap}$	-	coefficient of the steady part of the total moment transmitted to the swashplate, $m_{\Sigma ap} = m_{h1} z_l$;
$\partial t_{o,1c,1s}/\partial r$	-	derivative of the steady part and the first harmonic lift coefficient with respect to span blade.

INTRODUCTION

The helicopter performance factors depend on a lifting system loading to a considerable extent. The most of boundary flight conditions (maximum speed, dynamic ceiling, manoeuvres with maximum overloading) as the service life of some lifting systems units are defined by the level of pitch link load transmitted from rotor blades.

The statistical dates [1] obtained at the Mil Moscow Helicopter Plant show that rotor performance improvement gives rise to the increase of the loading level in control system for the rotors with traditional rectangular blades. The evaluation of interconnection between the performance factors and the loading level becomes complicated significantly for helicopters of various weights because of scale effect. The proper criteria are needed for correct evaluation. Two typical flight conditions were considered: hover and flight at cruising speed. A figure of merit η_o for hover and a rotor aerodynamic quality K_R for the cruising condition [2] were chosen as the parameters which express rotor performance. The loading level in the rotor control system was represented by the steady part of total moment transmitted to the swashplate in flight at cruising speed. Reduced value $m_{\Sigma ap}$ of this moment may be used for comparative evaluation of the control system loading when helicopters of various weights are considered [1]. This value is proportional to coefficient of the first harmonic of the blade pitch link load and number of blades:

$$m_{\Sigma ap} = k^* m_{h1}^* z_l$$

The use of such criterion is significantly to reduce the influence of the kinematics parameters of the swashplate and the scale rotor on the evaluation of loading level in control system for helicopters of various weights. Figure of merit η_o and rotor aerodynamic quality depending on loading level in control system (Fig.1) were obtained by means of this criterion for the helicopters designed at Mil Moscow Helicopter Plant.

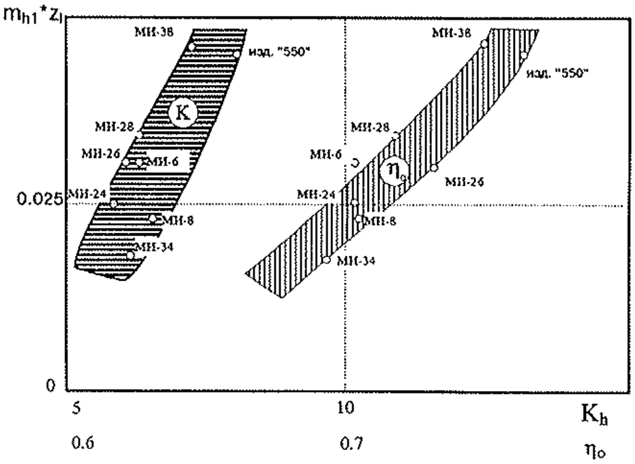

Figure 1 The level of swashplate loading vs. figure of merit in hover and rotor quality at cruising flying speed.

Fig.1 shows both data for helicopters in operational use and the predictions for designing Mi-38 civil helicopter and Mi-550 experimental helicopter. The application of LEBRE element improved the rotor performance in comparison with prototypes. There was 11% and 4% increases in rotor quality and figure of merit respectively for Mi-38 as well as 40% and 7% for Mi-550. However such performance improvement gave 80% increase in loading level of control system. The Mi-34 light helicopter has a comparatively low rotor quality and figure of merit as well as the lowest level of reduced loading among all presented helicopters. This attribute of Mi-34 rotor was predetermined at design stage and related with a practically reversible control system without servo-actuators. The forces transmitted to pilot's sticks through such control system should be restricted strongly. Therefore the lowest stick forces requirement had be critical at Mi-34 design and its fulfilment lowered the rotor performance.

Considered examples show the interconnection between aerodynamic quality of the rotor or figure of merit and loading level in control system. Therefore lowering of the blade pitch link load without helicopter performance degradation is a very important problem at the early stages of design.Modern development of rotor aerodynamics permits the reliable evaluation of the aerodynamic characteristics of the rotor, while model tests enable verification of calculation results. But the values of pitch link load and control system loading may be obtained with significant errors at the design stage. This fact is connected with both theoretical-calculation problems and the lack of dynamic similitude between the rotor models with their control systems and corresponding prototypes. Therefore initial flight tests give the control system loading and blade pitch link loads, which differ substantially from calculation.

The theoretical-calculation research as well as model and flight tests intended for decrease of the loading in control system by means of the modification of the blade root part are described below. The tests were conducted with rotor models and full-scale rotors of Mi-28 and Mi-8 helicopters.

PITCH LINK LOAD CHARACTERISTICS FOR EXPERIMENTAL BLADES OF Mi-28 HELICOPTER

The new aerodynamic composition of the blade was developed by Mil Moscow Helicopter Plant together with TsAGI during the rotor design for Mi-28 combat helicopter. Also the rotor with a new aerodynamic composition was planned for modification of Mi-24 helicopter. Therefore its radius, blade chord, tip speed and number of blades were accepted the same as for Mi-24. Fig.2 and Fig.3 show the blade geometry and twist respectively.

The distinctive features of these blades are great twist with gradient $\Delta\varphi=-9.7^\circ$, new helicopter airfoils TsAGI SB(-6*6) and KS(-4.5*6), construction manufactured from composite materials. Because new airfoils had a plate at trailing edge, blade chord was increased by 0.04m (plate width) compared to blade chord of Mi-24 helicopter. The twist on blade tip portion of 0.1R length was increased by 0.9° for improvement of rotor aerodynamic characteristics in hover (see Fig.3, where the geometric twist of the blade for Mi-24 serial helicopter shown for comparison).

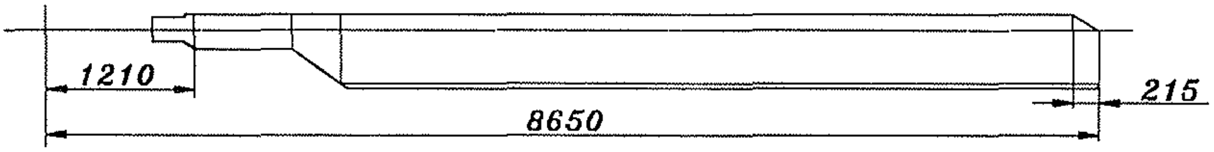

Figure 2 The plan view of the blade manufactured from composite materials for rotor of Mi-28 helicopter.

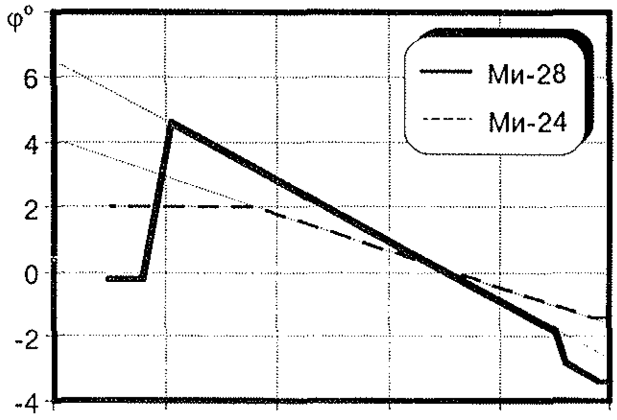

Figure 3 The geometric twist of rotor blades for Mi-24 and Mi-28 helicopters.

The new blade is provided with a tip cowling which has 0.025R width and the oblique leading edge with angle 30° to decrease blade tip wave drag and the noise level. The prototype blade has a rounded tip of traditional form but of lesser size (about 0.01R).

The airfoils specially developed at TsAGI were used in the new rotor design. Table 1 summarises their main characteristics obtained in TsAGI T-106 wind tunnel in comparison with corresponding characteristics of the airfoil NACA-230M. This airfoil with 10.3% reduced thickness is applied to the serial rotor blade of Mi-24 helicopter. The distinctive feature of a new airfoil is the trailing edge plate which serves to adjust the pitching moment value. The airfoil name contains the plate parameters: the first numeral in parentheses is angle between plate and blade chord in degree (minus sign means deflection upwards), the second numeral denotes the plate width in basic chord percents. In mass-production the plate is manufactured from composite materials and its deflection angle does not change in the operation. The serial blade has metallic deflecting plate in the neighbourhood of the section r=0.67R. This plates permit to attain the well tracked blades.

Table 1 shows that new airfoils with initial plate deflection angle have 20-26% increase in the lift to drag ratio K_a . The pitching moment coefficient c_{mo} is greater by 0.014 for the tip airfoil KS and smaller by 0.005 for the lifting airfoil SB then one for the airfoil NACA-230M. The derivative $\partial Cmo/\partial M$ for the new airfoil is much greater, specially this is true for the lifting airfoil SB. Somewhat greater c_d value for the airfoil SB at $c_l=0$ and M=0.9 is due to 1.7% greater value of the airfoil reduced thickness. But lifting airfoils SB are used inboard the section r=0.9R and so great Mach number values do not arise with this airfoil even at the maximum flight speed. The application of this airfoil

Таблица 1

Name profile	K_a / K_{aNACA} $C_l=0.5$ M=0.6	C_{lmax}/ $C_{lmaxNACA}$ M=0.4	C_{xp} $C_l=0$ M=0.9	$\partial c_{mo}/\partial M$ M=0.6	c_{mo} $C_l=0$ M=0.6	c_{mo} $C_l=0$ M=0.85	$\partial C_l/\partial\alpha$ M=0.6	x_f M=0.7
NACA-230M	1	1	0.042	0	0	-0.035	6.1	0.21
SB(-6*6)	1.21	1.05	0.055	-0.03	-0.002	-0.049	7.0	0.25
KS(-4.5*6)	1.26	0.94	0.038	-0.01	+0.014	0	6.8	0.23

as well enlarged blade twist increased the rotor quality and figure of merit (Fig.1).

The advantage of the tip airfoil KS, used outboard the section r=0.9R, is significant decrease of the derivative $\partial Cm_0/\partial M$ at critical Mach number M=0.85. The value Cm_0 decrease by 0.035 for airfoil NACA-230M and by 0.014 for new airfoil with Mach number increase from 0.60 to 0.85 (Tabl.1).

To test the new rotor, the flight laboratory was made on the basis of Mi-24 helicopter at Mil Moscow Helicopter Plant. The helicopter was provided with the set of experimental blades manufactured from composite materials and its wings was removed.

The first tests of new blades showed substantial growth of the loading level in control system in comparison with the blades of Mi-24 helicopter. The steady part of the loading was so high that the use of more powerful hydraulic actuators and the special constructive steps became essential. Fig.4 shows components of the blade pitch link load depending on flight speed for both new and serial blades. It is seen from the graphs that steady component m_{ho} derivative with respect to flight speed is negative for new blades. The first harmonic sine component m_{h1s} for the new rotor decreases with flight speed rise much more rapidly than that for Mi-24 helicopter rotor. Such behaviour of the pitch link load components for new airfoil is due to more back and more stable aerodynamic centre position than for airfoil NACA-230M as well to strong dependence of Cm_o on Mach number.

Fig.4 shows also the significant difference between first harmonic cosine components and between variable parts of the blade pitch link load. The cosine component for new blade is 2.0-2.5 times greater than that for serial blade. It is due to the greater reduced thickness of root profiles and to the effects of three-demensional flow past the composite experimental blade with enlarged twist. The new blade twist is 1.67 times greater than that for Mi-24 helicopter blade. Another cause of the pitch link load growth is that the new blade has enlarged chord and decreased torsional elasticity. These attributes are connected with use of the composite material and with requirement to have the blades of minimum weight. The use of the composite materials leads to 7-8% increase in reduced thickness of the blade root section. It promotes the growth of the blade pitch link load also.

The results of the flight tests set the task: to find relatively inexpensive and operational techniques of the blade remake (without creation of high-priced and complex equipment) for lowering of the loading level in control

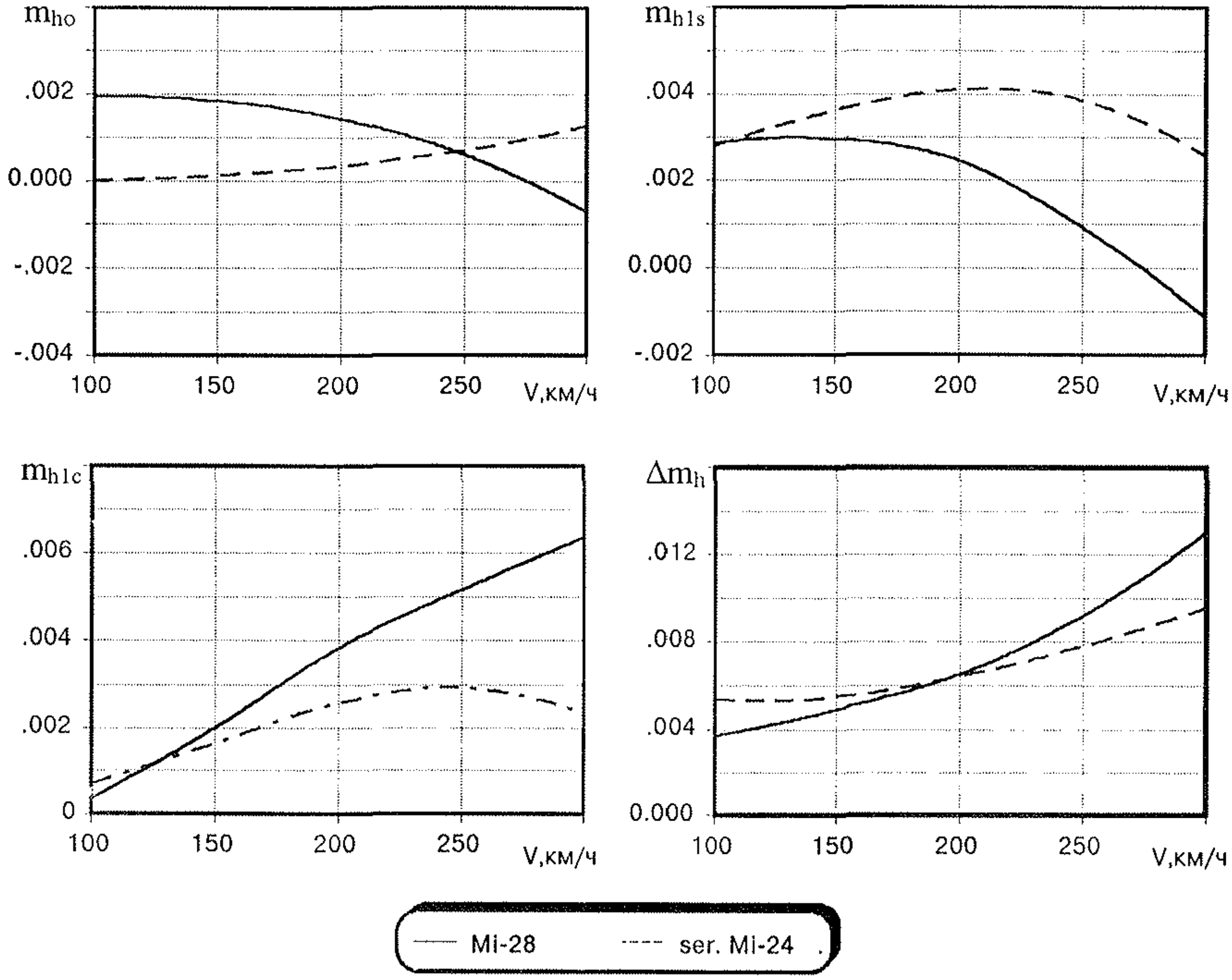

Figure 4 The feathering moment for blades of experimental rotors Mi-24 and Mi-28 helicopters

system. The primary attention was paid to decrease the steady part of loading because the control system was designed for lower loading level.

To manage the setting task, the program of a design remake and flight test of the new blade set was arranged under the supervision of General Designer Mil Moscow Helicopter Plant. Within the framework of this program, the theoretical and experimental research was fulfilled at TsAGI Helicopter division on an errand of Mil Moscow Helicopter Plant. The target of the research was an improvement of the blade pitch link load characteristics for blades with new aerodynamic composition under condition of the conservation or improvement of the rotor aerodynamic characteristics. There were considered both traditional methods of the adjustment of the pitch link load characteristics (an alteration of the spanwise distribution either of the deflection angle of the trailing edge plates-trimmers, or of the chordwise offset of the blade mass axis, an application of sweptback tips, et cetera) and the fundamentally new method developed by TsAGI and connected with the new shape of the blade root part.

THEORETICAL ANALYSIS: THE INFLUENCE OF THE LEBRE ELEMENT SHAPE ON THE BLADE PITCH LINK LOAD

The flight tests showed that a blade root part generates the great growth of the pitch link load at cruising and maximum flight speeds. It is due to design features of the blade root parts which distinguish themselves by significant change of the reduced sections thickness, by change of the sections profile itself, as well complicated three-dimensional flow past these blade parts at the great flying speeds with forming of the reverse flow region. The simplest and frequently used technical decision, permitting to improve the pitch link load characteristics and to decrease the loading level in the rotor control system, consists of the deflection of the trailing edge plates-trimmers upwards. However, this method is ineffective in the present case because only steady part and first harmonic sine component of the blade pitch link load are adjusted. Also, this decision leads to substantial deterioration of the aerodynamic characteristics of blade sections and, then, of rotor quality and figure of merit.

The possibility of a blade pitch link load decrease by means of the minimal changes of the aerodynamic composition of blade was theoretically examined at TsAGI. It was shown that the most effective method of the pitch link load decrease is the chord extension at the blade root part and an chordwise offset of its leading edge ahead. The blade root part, remade in such a manner, was named "LEBRE element" (Leading Edge of Blade Root Extention element). The conception of LEBRE element was proposed by TsAGI. The incorporation of LEBRE element in the blade provided with:

- the displacement of the aerodynamic centre of each sections ahead and corresponding decrease of the first harmonic cosine component of the blade pitch link load;
- the more slow decrease of the first harmonic sine component with flying speed and corresponding decrease of the pitch link load value at great flying speed;
- the growth of the rotor quality in forward flight and figure of merit in hover as a result of the decrease of the reduced sections thickness and the increase of Reynolds number at blade root part;
- the displacement of the blade section centre of gravity ahead and corresponding increase of the flutter stability.

These advantages are attained owing to rational use of a nature of the variable aerodynamic forces transmitting from blade root parts to the rotor control system in forward flight. It is known that loads of a control system element, located under the rotating ring of the swashplate, are determined mainly by the steady part and first harmonic of the pitch link load. The flight tests of various helicopters show that first harmonic amplitude amounts 50-60% of amplitude of the total blade pitch link load in forward flight. Therefore just the first harmonic of the pitch link load determines for the most part the loads of the control system elements located between the blade and swashplate.

The application of LEBRE element leads to the shift of the aerodynamic centre of the blade root section by about $0.75*b_{LEBRE}$ ahead blade strain axis. Also the section reduced thickness decreases and rotor solidity increases for the blade root part. As a result, both the blade pitch link load characteristics and aerodynamic characteristics of rotor improve. The analogous shift of the aerodynamic centre line ahead may be attained by the trailing edge displacement ahead for blade root part. However, the influence of the trailing edge displacement is much more poor and so the aerodynamic centre shift amounts about 0.25 of this displacement. At the same time, an approach of the leading edge to the blade spar increases the reduced sections thickness and decreases the rotor solidity for blade root part. As a result, rotor characteristics become worse. Therefore the trailing edge displacement ahead (for blade root part) should be implemented together with the application the LEBRE element with the chord is equal or greater than the trailing edge displacement. The LEBRE element influence on blade flap motion, blade dynamic twist, and corresponding helicopter trimming is poor because this element is close to the rotor hub. It is known that main component of the blade pitch link load is aerodynamic moment M_a determined by the formula

$$M_a = \int_{r_1}^{r_2} \partial T(r,\psi)(x_f - x_.) \qquad (1)$$

Other things being equal, the shift Δx_f of the aerodynamic centre of root sections (by means of LEBRE element) leads to the change of the aerodynamic component of the pitch link load. This change is created by the blade thrust derivative $\partial T(r,\psi)/\partial r$ at corresponding blade sections:

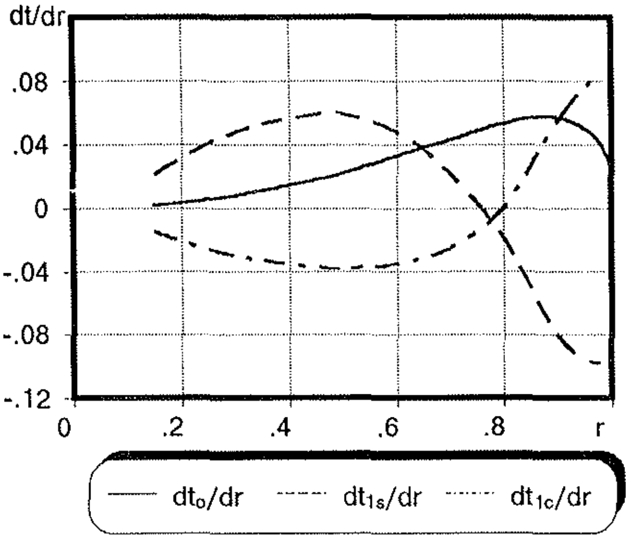

Figure 5 The steady part and first harmonic of thrust coefficient for helicopter rotor blade at cruising flying speed.

$$\Delta M_a(\psi) = \int_{r_1}^{r_2} T(r,\psi) \times \Delta x_f(r) dr \qquad (2)$$

Then the steady part and first harmonic of the aerodynamic moment are

$$\Delta M_{ao}(\psi) = \int_{r_1}^{r_2} \partial T_o(r,\psi) \times \Delta x_f(r) \qquad (3)$$

$$\Delta M_{a1c}(\psi) = \int_{r_1}^{r_2} \partial T_{1c}(r,\psi) \times \Delta x_f(r) \qquad (4)$$

$$\Delta M_{a1s}(\psi) = \int_{r_1}^{r_2} \partial T_{1s}(r,\psi) \times \Delta x_f(r) \qquad (5)$$

where r_1 and r_2 are radius of the blade sections restricting LEBRE element.

Fig.5 shows variation of the blade sections derivative of the coefficient thrust $\partial t/\partial r$ with radius calculated on the basis of the blade vortex theory. It is seen that sine and cosine components of the first harmonic of thrust attain the great values for blade root part. The chordwise displacement of the centre of lift renders the substantial influence on the aerodynamic component of the pitch link load.

As it follows from (4) and Fig.5, indicated aerodynamic centre displacement provides the decrease of the negative cosine component M_{a1c}. This decrease is most important. Also, LEBRE element application leads to growth of the steady component M_{ao} and sine component M_{a1s}, that permits to decrease the loading level in rotor control system. As a result, angles of the trimming plate deflection may be decreased and thus the aerodynamic characteristics of the blade sections and the whole rotor improved. Calculation and experimental research, performed at TsAGI, as well as full-scale blade development for various helicopters conducted at Mil Moscow Helicopter Plant, makes it possible shoose the optimum parameters of LEBRE element provided effective lowering of the pitch link load and simultaneous improvement of the aerodynamic characteristics of rotor. LEBRE element should be disposed at 0.2R<r<0.5R and its chord should be from $0.05b_7$ to $0.35b_7$. Within LEBRE element should be applied the airfoils with maximum profile thickness located from 0.35b to 0.5b.

EXPERIMENTAL RESEARCH WITH LARGE-SCALE ROTOR MODELS

For experimental verification of LEBRE element conception, two four-blade rotor models 4m in diameter were developed, prepared and tested in the wind tunnel at TsAGI. This models were named "rotor N1" and "rotor N2". Two versions of each model were tested: the model with LEBRE element and model with rectangular blades. The versions with LEBRE element were provided with the indices "rotor N1n" and "rotor N2n", respectively. All versions had streamlined leading edges in the root portions, the section contours in this portions remained invariable at the remakes in the middle and rear regione.

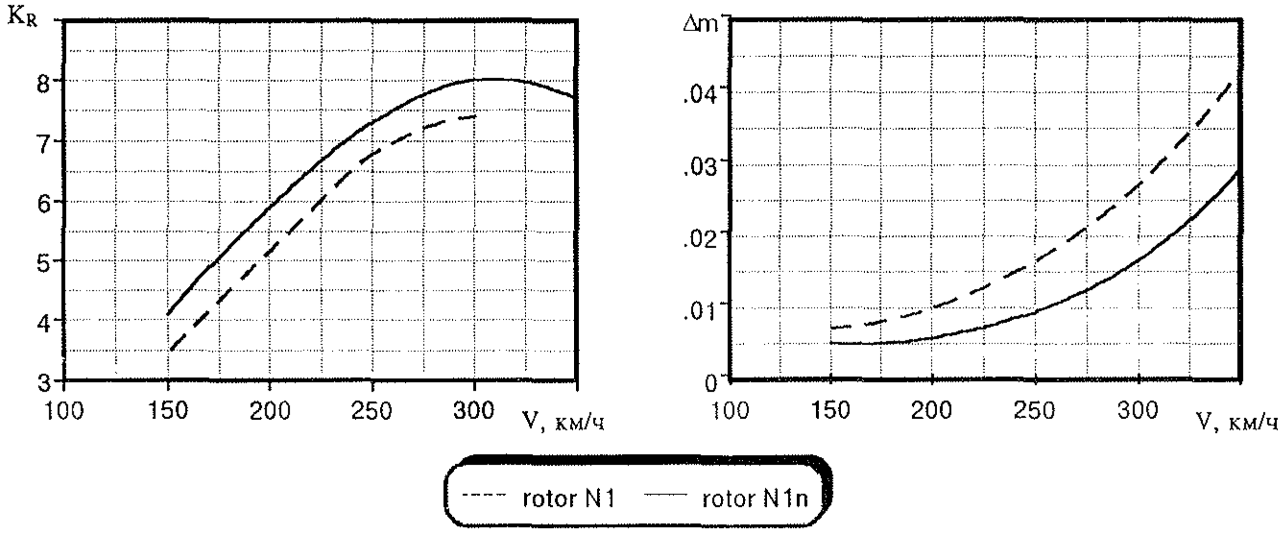

Figure 6 LEBRE element influence on aerodynamic quality of rotor and feathering moment amplitude for large-scale model of rotor for Mi-28 helicopter (. ωR=220 м/с; t_y=.14; t_x=-.12μ^2).

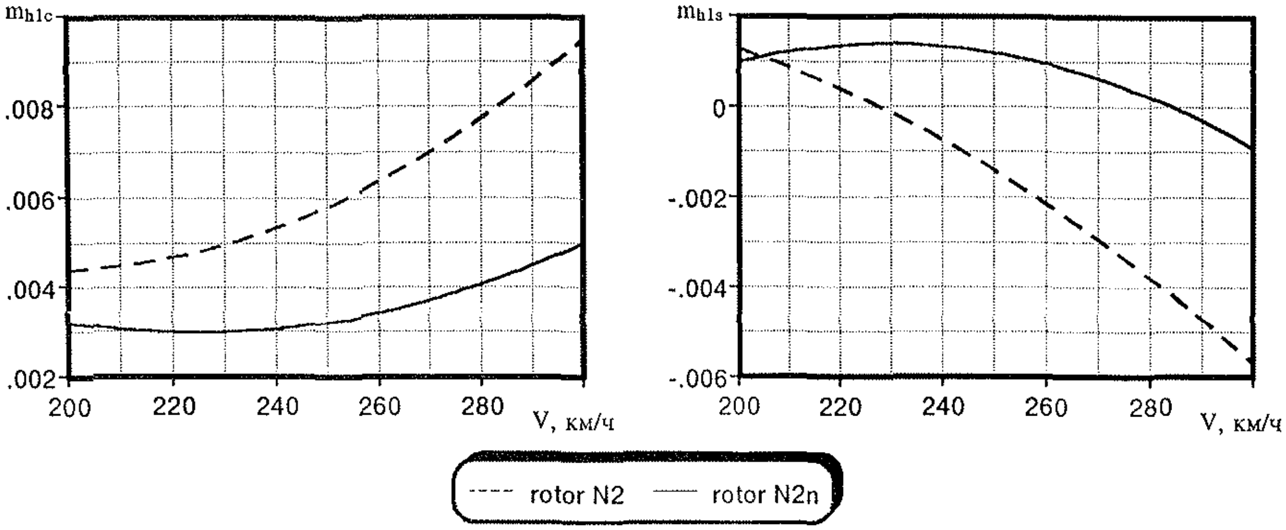

Figure 7 LEBRE element influence on aerodynamic quality of rotor in forward flight and on figure of merit in hover for large-scale model of rotor for Mi-8 helicopter (ωR=215 м/с; t_y=.15; α=-5°).

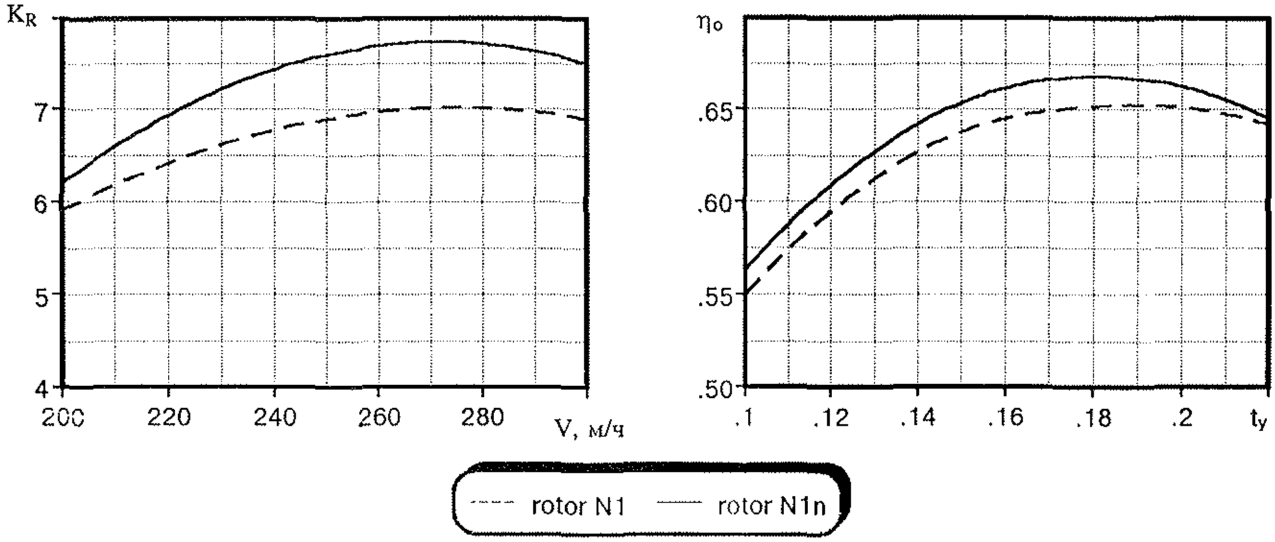

Figure 8 Figure LEBRE element influence on first harmonic of feathering moment for large-scale model of rotor for Mi-8 helicopter (ωR=215 м/с; t_y=.15; α=-5°).

At the tests of "rotor N1" simulated the Mi-28 experimental blade, the pitch link load amplitude m_h and rotor quality K_R were measured depending on the velocity V in wind tunnel working section. Fig.6 shows the main results. It is seen that amplitude Δm_h for "rotor N1n" (with LEBRE element) is 1.5-1.8 times less than that for "rotor N1" (without LEBRE element) at the same tunnel velocity. At the given Δm_h, the LEBRE element application permits the increase of the flight speed by 50-60 km/h. Aerodynamic quality for "rotor N1n" is 7-10% greater than that for "rotor N1" within speed range 200<V<300 km/h.

The combined application of LEBRE element and the displacement ahead (with respect to blade tip part) of the blade trailing edge in the root region was explored with "rotor N2" simulated the Mi-8 experimental blades. The special airfoils with enlarged relative thickness (c=15-18%), positive moment Cm_o, and maximum thickness located at 40% chord were developed of TsAGI. These airfoils ensure the favourable characteristics of the blade pitch link load and meet the constructive requirements for section thickness within LEBRE element which shifts the airfoil contours ahead with respect to spar.

At the tests of "rotor N2", the pitch link load components m_{h1s} and m_{h1c} were measured depending on the wind tunnel velocity. Fig.8 shows that combined application of the proposed technical decisions makes the cosine component 1.5-2.0 times less and substantially improves the sine component dependence on the tunnel velocity. The rational aerodynamic composition of the blade root part influences favourably the aerodynamic characteristics of rotor. As Fig.8 shows for "rotor N2n", figure of merit in hover is greater by 1.5-2.0% and aerodynamic quality of rotor within speed range 220 to 300 km/h is greater by 7-11% than for "rotor N2".

Thus, the wind tunnel tests confirmed the possibility of the very significant improvement in the pitch link load characteristics of the blade with simultaneous improvement in the rotor aerodynamic characteristics under basic flight

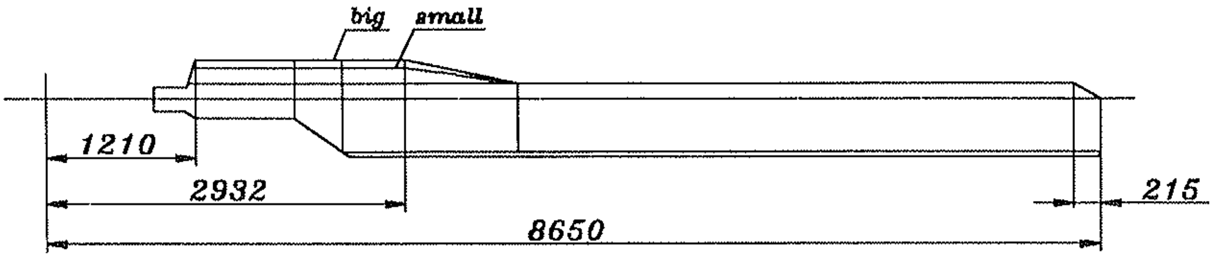

Figure 9 The plan view of two versions of rotor blade with LEBRE element for Mi-28 helicopter.

conditions by means of the application of the entirely new blade composition element - LEBRE element.

The results of this development were validated as an application for Russian Federation patent.

FLIGHT TESTS OF Mi-28 AND Mi-8 HELICOPTERS WITH FULL-SCALE EXPERIMENTAL BLADES

In accordance with the program of a design remake of the experimental blade set arranged under the supervision of General Designer Mil Moscow Helicopter Plant, the results of the theoretical and model explorations connected with LEBRE element were checked in flight tests. The wide scope of the experimental work was performed for a remake of the Mi-28 helicopter blades manufactured from composite materials as well as for preparing and testing of the Mi-8 helicopter experimental blades with enlarged chord for rotor of Mi-8 helicopter.

Fig. 9 shows the plan view of Mi-28 helicopter blade remade for LEBRE element. Two versions of a remake were prepared. First LEBRE element was designed with the chord which exceeded the initial chord 0.62 m by value of 0.20 m. For the blade remake, the foam plastic was glued on the spar leading edge after removal of the heating elements of the de-icing system, the blade tipping, and rubber pad. The foam plastic was worked according to given airfoil and several layers of the glass cloth were glued on the surface with subsequent puttying and coloration. At Fig. 9 the index "big" indicates this first version of LEBRE element with large chord. Such shape of the blade root part provided the decrease of the reduced section thickness from 14% to 10.5% and 8% shift of the sections aerodynamic centre with respect to the spar elastic axis.

The second version of LEBRE element with additional chord decreased to 0.13m was developed after some flight test series had been performed. At Fig. 9 the index "small" indicates this version of LEBRE element. Such remake resulted to the decrease of the reduced section thickness from 14% to 11.5% and 5.5% shift of the sections aerodynamic centre with respect to the spar elastic axis. This blade set was exposed to the whole flight test complex. Next a third blade remake was prepared in connection with the research of the blade section influence on the pitch link load. The modified airfoil NACA-230M was incorporated in the blade with "small" LEBRE element (Fig.9) in board the section r=3.865m. The modification was made by A.M. Lepilkin at Mil Moscow Helicopter Plant and consisted of the leading edge alteration of the airfoil NACA-230 in order to obtain the positive Cm_o at the operational Mach number M=0.65. The remake was also implemented by means of the foam plastic glued on the surface and then worked according to given airfoil. After the remake, the blade twist changed because of the substantial difference between airfoil NACA-230M and initial airfoil especially not far from the blade spar. Fig.10 shows the twist distribution for remade blade together with that for initial version. LEBRE element was removed and the blade plan view became rectangular after the flight test series in order to evaluat the LEBRE element influence for this blade set.

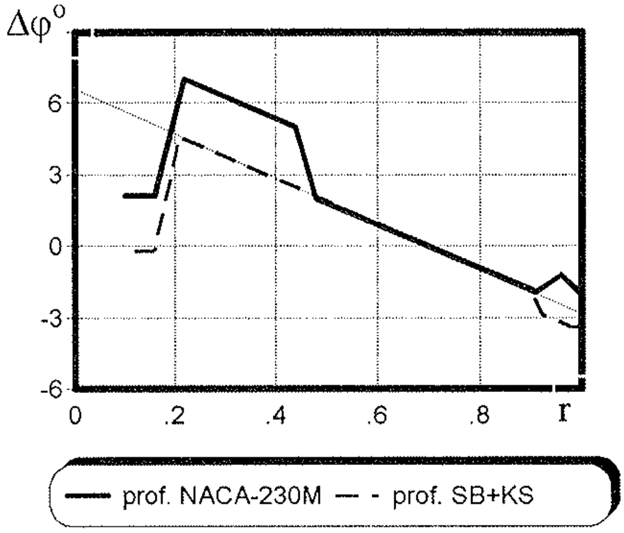

Figure 10 The geometric twist of two experimental blades with LEBRT element and different profil distributions.

The analogous research was fulfilled at Kazan Helicopter Production Association with the set of the experimental blade having the enlarge chord. The blades were manufactured from composite materials for Mi-8 helicopter. Fig.11 shows the plan view of such blade. Each blade of this set is prepared through lengthening of the root part of Mi-8 helicopter blade. The span distributions of the profiles and their chords coincide outboard r=5m with those for the Mi-28 helicopter blade. LEBRE elements were incorporated in the root parts of this blade and were removed after flight test. The flight tests were repeated with a rectangular blade set. The additional chord length of LEBRE element was 0.1m and the airfoil for LEBRE element sections was developed by TsAGI. The blade chord at radius r=0.7R amounted to 0.62m. The twist of the experimental blade for

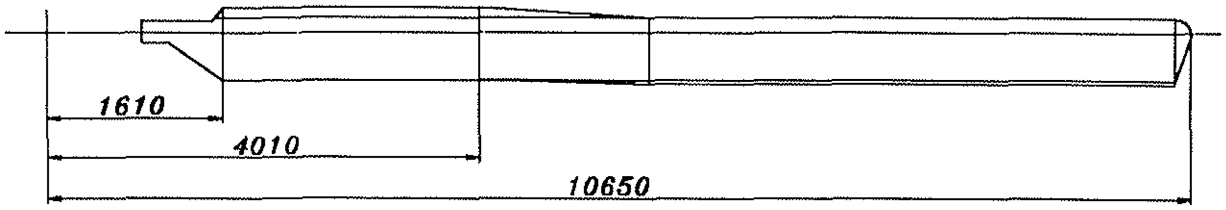

Figure 11 The plan view of experimental blade with LEBRE element manufactured from composite materials for rotor of Mi-8 helicopter.

Mi-8 helicopter was changed in order to decrease the influence of a slip flow past the blade tip. Towards this end, the blade tip was made flat (Fig.12).

All described blade versions were exposed to flight tests with measurements of the pitch link load and control system loading. For analysis of the LEBRE element influence, the following parameters were considered: - steady part of the pitch link load,

- steady part of the pitch link load,
- first harmonic sine component of the pitch link load,
- first harmonic cosine component of the pitch link load,
- amplitude of the variable part of the pitch link load.

Fig.13 presents these parameters depending on the flying speed for first and second versions of the blades with LEBRE element. The deflection angle of the trailing edge plates, was selected during the tests so that variation of the

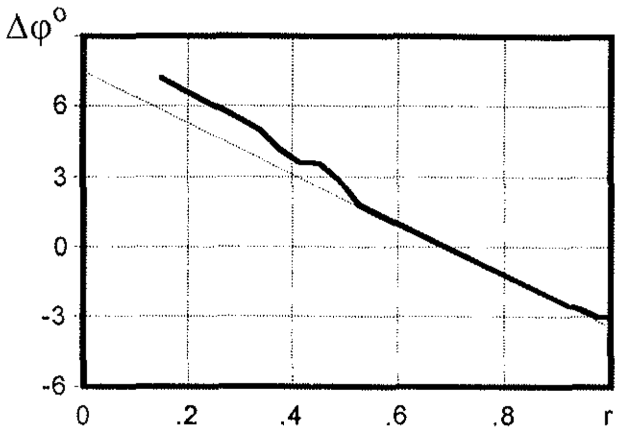

Figure 12 The geometric twist of experimental blade manufactured from composite materials for rotor of Mi-28 helicopter.

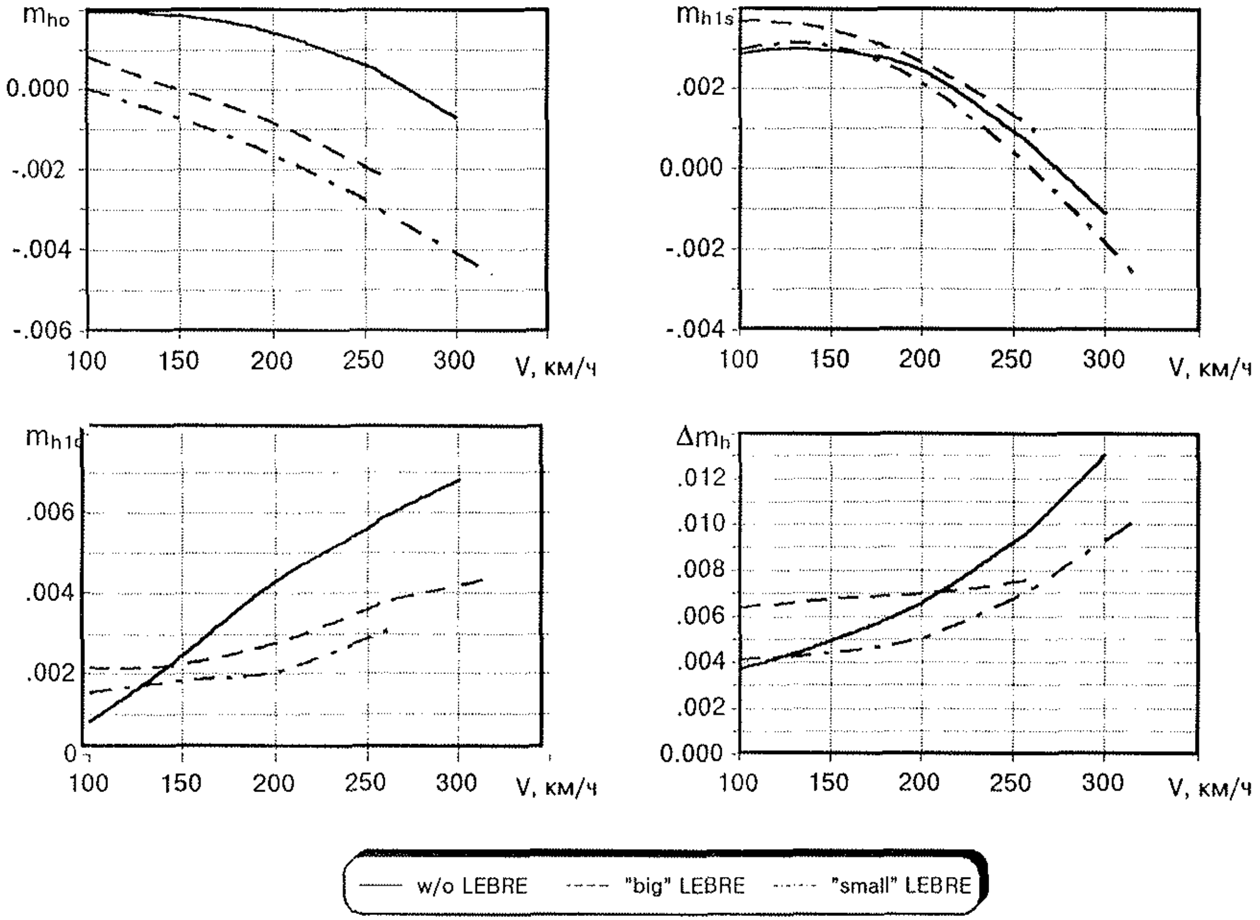

Figure 13 The the pitch link load is components for two versions of blade with LEBRE element and profiles KS and SB for Mi-28 helicopter.

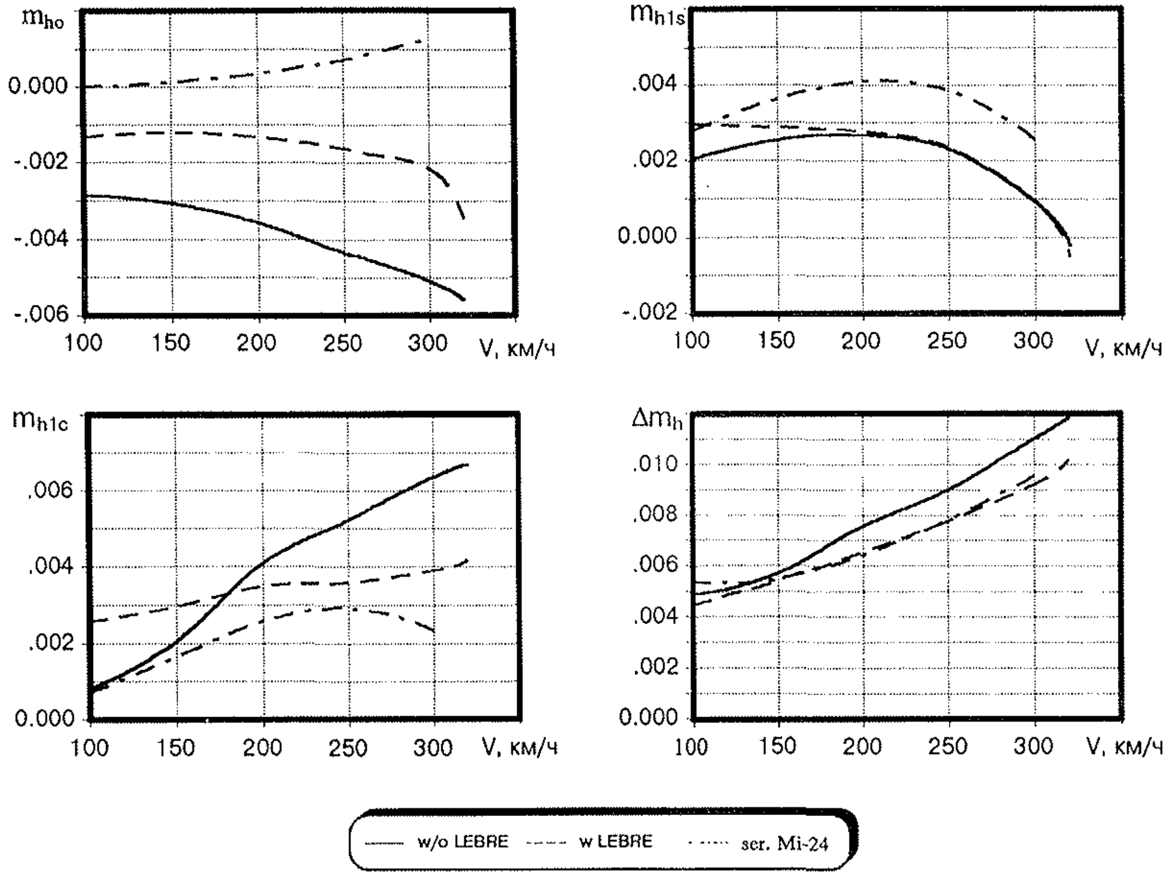

Figure 14 The pitch link load components for blade with LEBRE element and profile NACA-230.

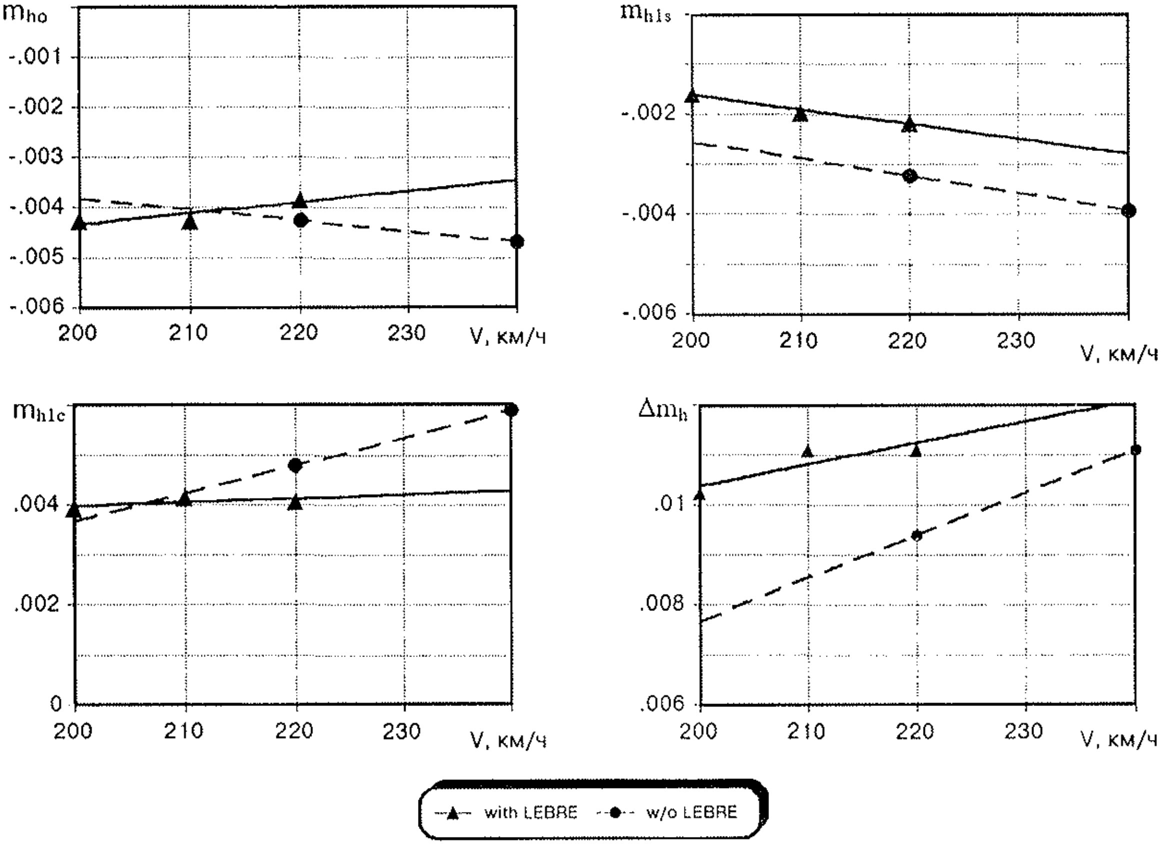

Figure 15 The pitch link load components for experimental blade with LEBRE element manufactured from composite materials for rotor of Mi-8 helicopter.

sine component was small at cruising speed 270 km/h. It is seen from Fig.13 that the absolute of the negative steady part of the pitch link load is greater by 0.002-0.003 for both versions of the blades with LEBRE element than that for initial blade. It is mainly connected with appearance of the additional pitch moment because of the mass growth and the shift of centre of gravity for blade root part owing to the LEBRE element incorporation. It is seen also that Δm_{ho} is less by 0.001 for "small" LEBRE element than that for "big" LEBRE element although the moment of inertia for former is less than that for latter.

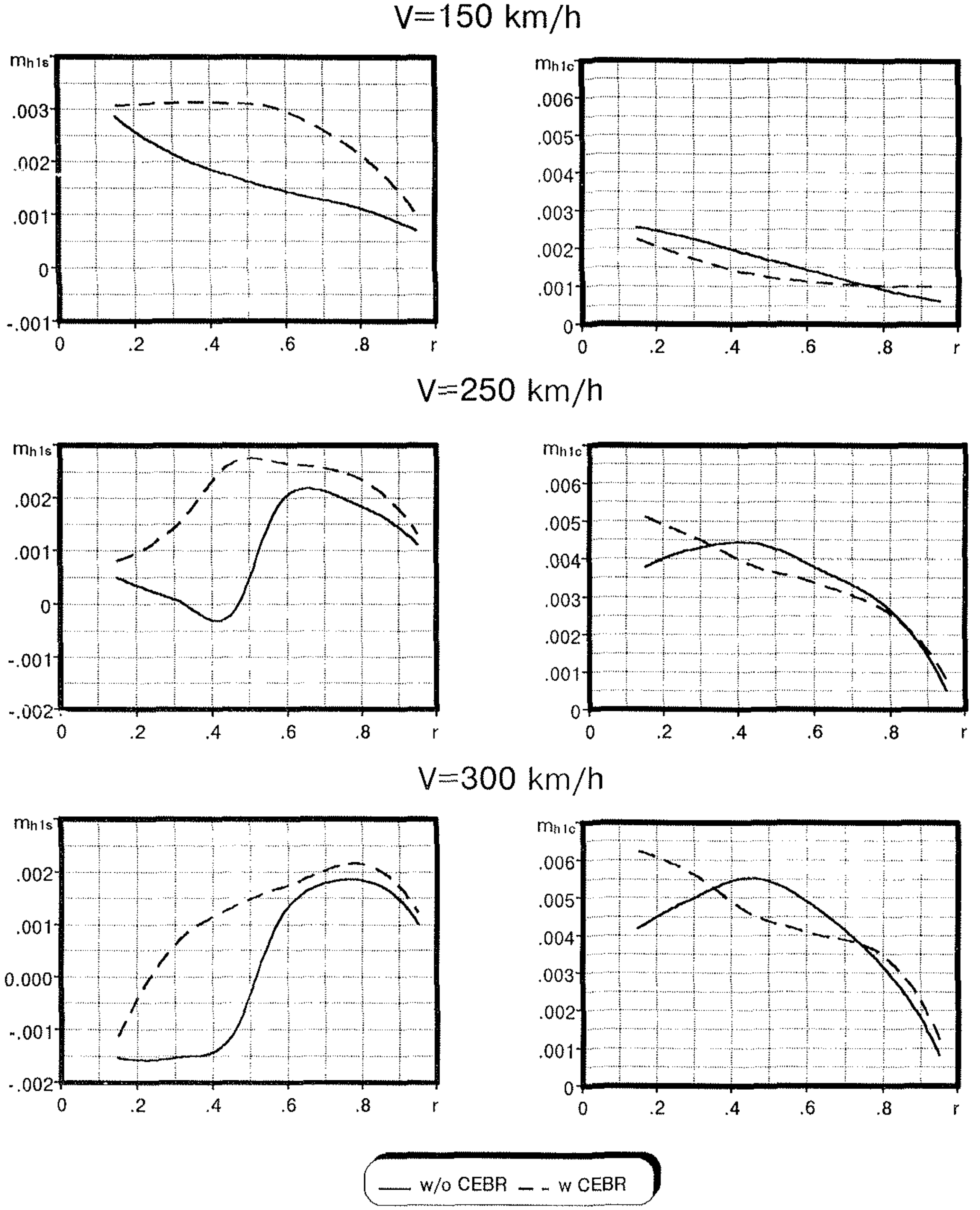

Figure 16 The first harmonic components of the torsional moment for rectangular blade and blade with LEBRE element of experimental blade set for Mi-28 helicopter.

This difference is due to the difference in the deflection angles of the trailing edge plates for two blade versions. The upward deflection of the plates is greater for blades with "big" LEBRE element. It increases Cm_o value for the blade sections and, consequently, the steady part of the pitch link load. The adjustment of the deflection angles of the trailing edge plates leads (see Fig.13) to the small differences in the first harmonic sine component between both blade versions considered and the initial blade. These differences do not exceed 0.001 at cruising flying speed 270 km/h.

The LEBRE element incorporation influences most effectively the first harmonic cosine component of the pitch link load. The value of Δm_{h1c} is 1.9 times less with "big" LEBRE element and 1.6 times less with "small" LEBRE element in forward flight at cruising speed (Fig.13). The influence of LEBRE element on the variable part of the blade pitch link load is analogous. The value of Δm_h at cruising speed 1.3 times less for both blade versions then that for initial blade. At maximum flying speed 300 km/h, the LEBRE element incorporation makes the cosine component 1.6 times less and the amplitude of the variable part 1.4 times less then those for initial blade.

The analogous influence of the LEBRE element on the blade pitch link load was discovered in the tests with blades provided with modified lifting airfoil NACA-230M. Fig.14 shows the components of the pitch link load depending on the speed in forward flight. It is seen that the LEBRE element incorporation gives the same results also for blade with traditional helicopter airfoil. It is noted that the pitch link load amplitude increases at the small flying speeds (V<150 km/h) and decreases at the great speeds including maximum.

At the maximum speed 300 km/h, this amplitude is 15-20% less for the blade with airfoil NACA-230M then that for the initial airfoil. The reason is that the aerodynamic centre of the airfoil NACA-230M is shifted ahead and the blade twist has the opposite gradient at the blade tip.

On the whole, the LEBRE element application led to the substantial improvement of the pitch link load characteristics for the composite experimental blades of Mi-28 helicopter. As a result, these characteristics agree practically with characteristics of the metallic serial blade of Mi-24 helicopter although chord and twist of the metallic blade are less. The composite experimental blade with LEBRE element (Figs.11,12) were tested by Kazan Helicopter Production Association [3,4] in forward flight on Mi-8 helicopter. The results showed the decrease of the pitch link load also. Fig.15 presents the pitch link load components within the

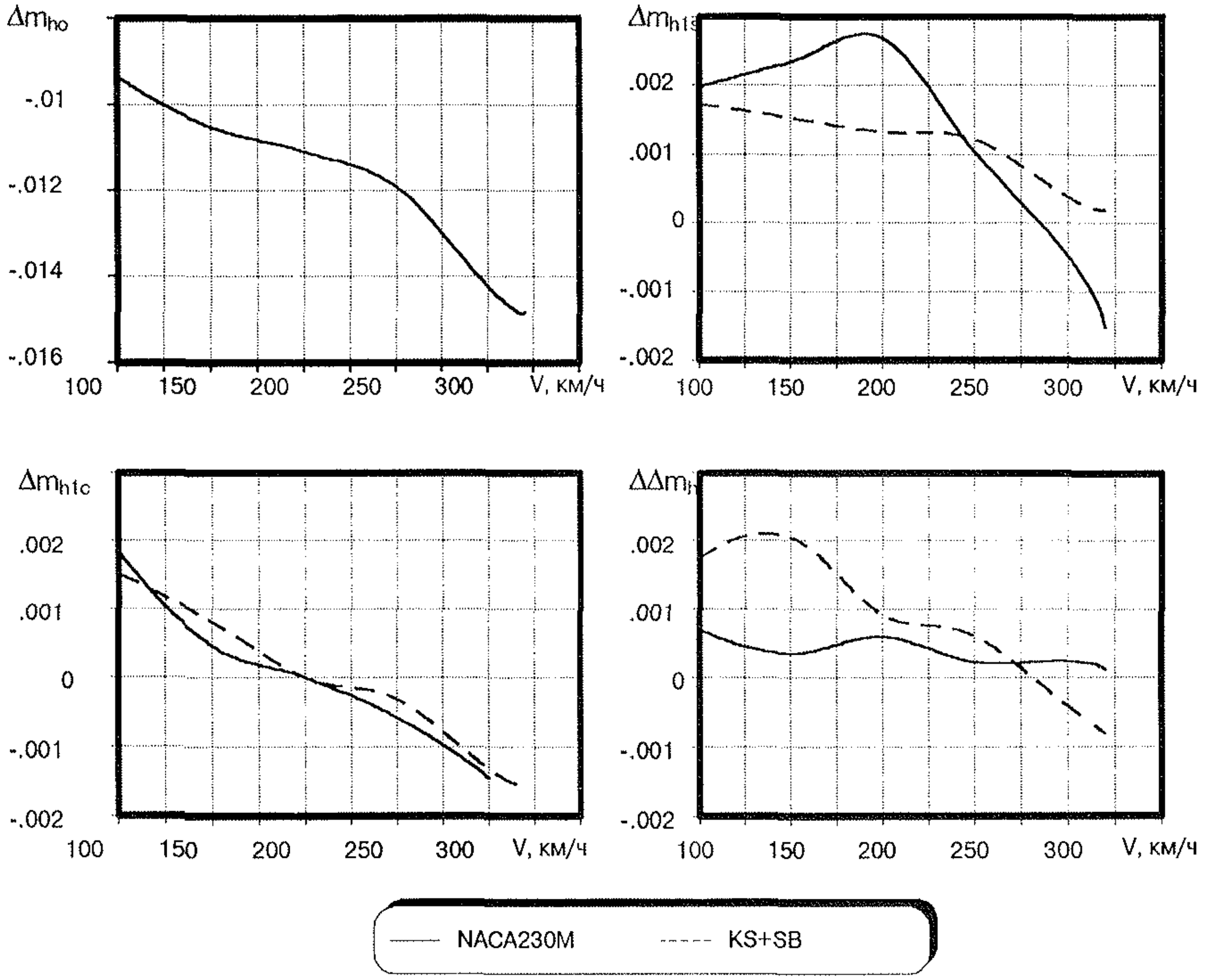

Figure 17 The components of the torsional moment generated by blade portion wich contains LEBRE element with two profile distributions.

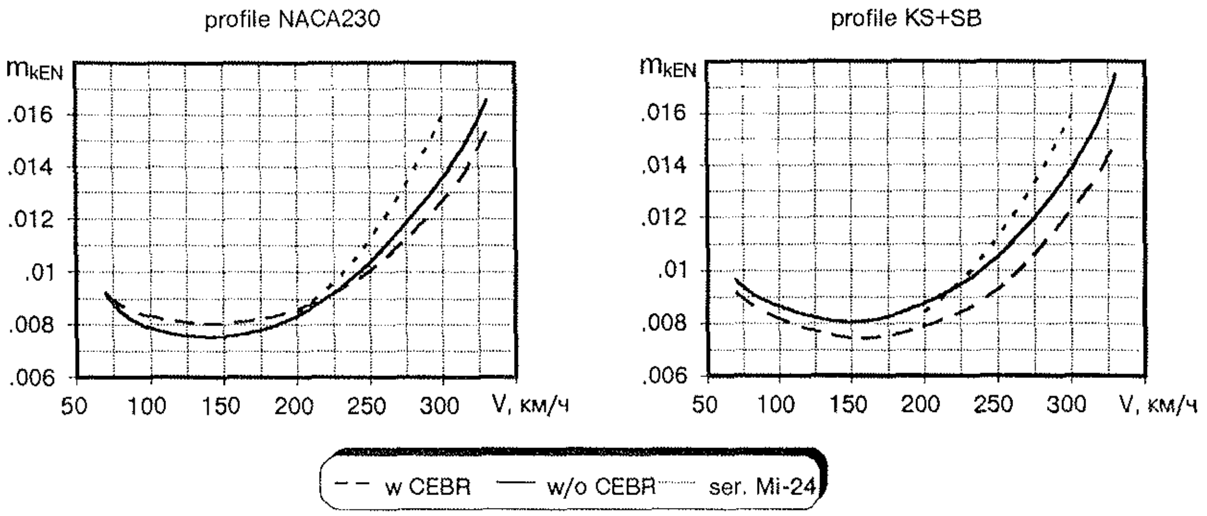

Figure 18 The engine power required in forward flight for rotor blade with LEBRE element and without it, with twu profile distributions.

speed range from cruising to maximum. It is seen that LEBRE element makes the cosine component of pitch link load 14% less and sine component 33% less at flying speed 220 km/h. The adjustment of the trailing edge plates was practically identical because the task to retain the value of the pitch link load sine component was not set. Therefore the growth of the pitch link load sine component, created by the LEBRE element incorporation, reveals itself in these tests immediately.

The steady component of the pitch link load did not change practically. The reason is that the LEBRE elements applied to different blade have various mass characteristics. The static balancing was made but the difference in the dynamic characteristics remained. It led to the growth of higher harmonics of the pitch link load and to the decrease of the LEBRE element effectiveness.

Furthermore, the LEBRE element effectiveness for this blade was less then that for remade blade used on Mi-28 helicopter because the LEBRE element size for this blade was decreased to 16% of the chord length. The pitch link load was measured at several blade sections in flight tests of Mi-28 helicopter for detailed analysis of its spanwise distribution. In accordance with the target of this research, the first harmonic components of the torque were found as the functions of the section radius. Fig.16 shows the spanwise distribution of the sine and cosine components of the pitch link load for initial blade and the blade with LEBRE element at three flying speeds.

LEBRE element is disposed in the region $0.15<r/R<0.45$ of the experimental blade for Mi-28 helicopter. The graphs on Fig.16 evaluates the LEBRE element influence on first harmonic of torsinal moment. It is seen from left graphs that LEBRE element application increases the sine components of the torsinal moment practically over whole speed range up to maximum speed. The root part influence on the sine components of the pitch link load is contrary for the rectangular blades: it is very slight at small speeds and becomes significant at great speeds, the absolute of the sine and cosine components increases very much for the root part. If the difference Δm_{h1s} of the sine components for the root part amounts to -0.0019 at the speed 150 km/h, then it amounts to -0.0023 at the maximum speed. For the blade with LEBRE element, this difference amounts to +0.0011 and +0.0008 respectively.

The right graphs on Fig.16 shows the LEBRE element influence on the cosine component of the torsinal moment. The Δm_{h1c} value increases from blade tip to root for the rectangular blade at all flying speeds. The Δm_{h1c} derivative with respect to radius increases with speed near the blade tip. This derivative is significant also near the blade root. The central part ($0.45<r/R<0.80$) of the blade influences Δm_{h1c} slightly. The LEBRE element incorporation decreases M_{a1c} substantially at the flying speeds which are greater than optimum speed. Therefore, the greater speed of the flight the higher its effectiveness.

Fig.17 shows the increments of the torsional moment components depending on the flying speed for two versions of the blades: first version has LEBRE element with airfoil NACA-230M, second version - with airfoils SB+KS. It is seen that LEBRE element influence on first of the harmonic torsinal moment depend on the airfoil very slight. The intetesting result was obtained with regard to variable part of the pitch link load. The left lower graph shows that LEBRE element with airfoil NACA-230M does not change Δm_h over the whole range of speeds. At the same time, LEBRE element with airfoil SB+KS causes some increase of Δm_h of small flying speeds ($V<200$ km/h). This difference is connected probably with the difference in the root part twist of two blades (Fig.10).

The measurementы of the engine power required for forward flight were made in flight tests of Mi-28 helicopter with the experimental blades manufactured from composite materials. The results were obtained for all versions of the blade remake. Fig.18 shows the torque coefficients for two blade section distributions. Each blade set was exposed to flight test both with LEBRE element and without it. It is seen from Fig.18 that LEBRE element gives the gain in the power required to forward flight for both section distribution at the great flying speeds and a version with airfoil KS+SB gives the gain within whole speed range. At the maximum flying speed of 330 km/h, the LEBRE element application gives 7-8% gain in the required power for blade with airfoil NACA-230M and 12-15% gain for blades with airfoil KS+SB. Obtained results suggest that LEBRE element application increases the rotor quality in forward flight noticeably. This opinion agrees well with the above experimental date.

CONCLUSIONS.

1. The fundamentally new LEBRE element (Leading Edge of Blade Root Extension element) of the aerodynamic composition of the helicopter rotor blade in developed. The new element makes it possible decrease essentially the pitch link load of the blade and loading in the rotor control system and at the same time to improve noticeably the aerodynamic characteristics of the rotor.
2. Model and flight tests of new LEBRE element element showed 1.5-2.0% increase of the figure of merit in hover and 7-15% increase of the rotor quality in forward flight as a result of a rise of the root solidity and Reynolds number as well as a decrease of the reduced thickness of the blade root sections.
3. The exceptional feature of the new LEBRE element element of the aerodynamic composition of the rotor blade is that its application gives 1.5-1.9 times decrease of the cosine component of the blade pitch link load at the flight speeds, which are greater than optimum, with simultaneous improvement of the characteristics of the sine component of the pitch link load and the integral aerodynamic characteristics of the rotor.
4. The model and flight tests showed that the LEBRE element element application provided the pitching increment of the blade pitch link load which is due to its steady and sine components. This increment gives the additional possibilities to improve the aerodynamic characteristics of the rotor.

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