TWENTYFIFTH EUROPEAN ROTORCRAFT FORUM

Paper n° P3

ANALYTICAL AND EXPERIMENTAL STUDIES OF TWO TIP-SWEPT BLADE VERSIONS

BY

Dr. V. IVTCHIN
MIL MOSCOW HELICOPTER PLANT, RUSSIA
Dr. A. LISS
KAZAN SCIENTIFIC INDUSTRIAL ENTERPRISE, RUSSIA

SEPTEMBER 14-16, 1999
R O M E
ITALY

ASSOCIAZIONE INDUSTRIE PER L'AEROSPAZIO, I SISTEMI E LA DIFESA
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

ANALYTICAL AND EXPERIMENTAL STUDIES OF TWO TIP-SWEPT BLADE VERSIONS

Dr. V.A. Ivtchin
Team Leader, Aerodynamics Dept
Mil Moscow Helicopter Plant
Russia

Dr. A.Y. Liss
Head, Aerodynamics Dept
Kazan Scientific Industrial Enterprise
Russia

The paper presents some basic results of analytical studies and flight tests for two swept-tip blade versions: for a swept tip having no twist without anhedral, and an anhedral swept tip. The target objective of the anhedral swept-tip blade development is to find a way to reduce pitch link load and control loads and, at the same time, to improve aerodynamic characteristics of helicopter main rotors in hover and in level flight. The contribution to the reduction in the pitch link load was theoretically substantiated by Yu. A. Liss (Kazan) in 1984. The tapered tip shape tested on full-scale the main rotor blades for the Mi-28 attack helicopter and its possible alteration to have an anhedral blade tip were offered by V.A. Ivtchin (Moscow) in 1985 and 1993 respectively.

Within the framework of a research programme the Mil Moscow Helicopter Plant (MMHP) developed all-composite main rotor blades for the Mi-28 attack helicopters and conducted comparative flight tests of two versions of the swept-tip main rotor blades.

1. NOTATION

R	main rotor radius, m
ω	rotor angular velocity, s^{-1}
b_7	blade chord at 0.7R, m
r	design cross section radius, m
Z_l	number of blades
σ	rotor solidity ratio along 0.7R
a_o	coning angle, deg
D_1, D_2	swashplate kinematics coefficient
x_l	blade rotation axis in feathering hinge relative to blade nose coinciding with axis of spar stiffness, m.
α_{mn}	equivalent rotor angle of attack in blade tip plane, deg
ψ	rotor blade azimuth, deg
l_{tip}	tip length along blade longitudinal axis, m
r_{tip}	radius of tip center of pressure relatively to rotor axis of rotation, m
b_{tip}	tip inboard chord, m
b_{otip}	tip outboard chord, m
χ_{tip}	tip sweep angle along leading edge, deg; + sign mean backward
ξ_{tip}	tip anhedral, deg, + sign means downward
α_{tip}	tip angle of attack, deg
$\alpha_{av\ tip}$	average anhedral tip angle of attack, deg
$\alpha_{V\ tip}$	tip angle of attack versus blade azimuth and airspeed, deg
S_{tip}	tip area, m^2
l_{tip}	location of tip pressure centre along blade longitudinal axis relative to beginning of tip, m
x_{tip}	location of tip pressure centre relative to blade axis about feathering hinge, m
y_{tip}	location of tip pressure centre relative to blade chord plane, m
R_{sw}	swashplate radius, m
l_l	blade pitch arm radius, m
C_{lmax}	airfoil maximum lift coefficient
C_{xd}	profile drag coefficient
C_y^{α}	angle of attack airfoil lift coefficient derivative
α	angle of attack airfoil, deg
K_a	blade section lift-drag ratio
m_{zo}	longitudinal moment coefficient at airfoil zero lift
x_f	airfoil aerodynamic centre relative to blade nose, m
ρ	air density, kg/m^3
ωR	blade tip speed, m/s
M	Mach number
V	airspeed, km/h
V_r	radial component of flow velocity along blade longitudinal axis, km/h
P_{sl}	constant portion of collective pitch sleeve loads, n
M_{tsw}	total swashplate constant moment, Nm
M_{zsw}	constant portion of swashplate longitudinal moment, Nm
M_{xsw}	constant portion of swashplate lateral moment, Nm
P_m	amplitude of main rotor blade pitch link load, N
P_{mo}	amplitude of constant portion of main rotor blade pitch link load, N
P_{m1c}	coefficient of cosine component of main rotor blade pitch link load 1/rev, N
P_{m1s}	coefficient of cosine component of main rotor blade pitch link load 1/rev, N
P_{m1}	amplitude of main rotor blade pitch link

load 1/rev, N

V_n component of flow velocity normal to blade chord plane, km/h

ΔP_m amplitude of variable portion of main rotor blade pitch link load, N

2. INTRODUCTION

Helicopter high aerodynamic performance is achieved by improving the aerodynamic configuration of the main rotor helicopter blades. The most effective trend here is to develop new blade airfoils possessing high lift coefficient and L/D ratio. However, the introduction of new airfoils in the conventional rectangular blade planform results in quite a significant increase in control loads. Ref. 1 presents criteria to be used in estimating helicopter control loads versus the main rotor figure of merit for Mil helicopter rectangular blades. At the same time it shows that better aerodynamic performance of rotors having rectangular blades results in a considerable growth of control loads. This problem becomes more acute when critical loads are found out in the process of full-scale flight tests (when the blades themselves and the required tooling have already been manufactured). Therefore a proper selection of the blade geometric and aerodynamic configuration on the design stage is of paramount importance.

Ref. 1 presents the results obtained from studies devoted to a new component in the blade configuration, i.e. the "glove" on the Mi-28 full-scale rotor made of composite materials. The "glove" is a change in the blade root configuration due to which the centre of the blade root section has bee moved forward in relation to the feathering hinge axis. This feature has allowed the pitch link load and control loads to be reduced by 25-40%.

The main objective in the development of an anhedral main rotor blade tip is also an attempt to find new ways of reducing the pitch link load and control loads with improved helicopter main rotor performance in hover and level flight. This blade tip was developed and tested by the Mil Moscow Helicopter Plant in several steps to be used in the Mi-28 attack helicopter all-composite blades.

A favourable effect of the anhedral tip on the rotor relative figure of merit in hover was obtained from the Mi-26 eight-blade main rotor whirl tower tests conducted at M.N. Tischenko's initiative in 1978 [12]. The aerodynamic effects caused by the tip of this type, from the point of view of reducing the cosine component of the pitch link load, were theoretically proved by A.Yu. Liss in 1984. These were followed by parametric studies of the anhedral tip angle by using a four-blade model rotor conducted by M.G. Rozhdestvensky [2].

The tapered tip shape testes on the full-scale main rotor blades of the Mi-28 combat as well as the possibility to replace this tip shape by an anhedral one were proposed by V.A. Ivchin in 1985 and 1993 respectively.

The results of the analytical studies presented in the paper show the main principles lying in the effect produced by the helicopter rotor blade anhedral tip.

The results of the flight tests conducted by the Mil Moscow Helicopter Plant on the Mi-24 flying test bed fitted with the Mi-28 rotor system in which both tip shapes, i.e. a tip having no twist and an anhedral tip, are presented. They substantiated the concept of the anhedral blade tip in real operating conditions of the main rotor.

The reduction in the pitch link loads caused by the application of the anhedral rotor blade tip leads to an increase of the helicopter control system service life. It is well known that the service life of any component is proportional to the value of the component loads to the sixth power. Therefore, a reduction in the control system loads by 10 % in cruise can lead to an increase in the service lives of the rotating parts of the swashplate by 3-4 times and those for bearings, by 6-8 times.

3. MI-28 EXPERIMENTAL MAIN ROOTOR BLADE AERODYNAMIC CONFIGURATION AND CHARACTERISTICS OF PITCH LINK LOADS

While designing the main rotor for the Mi-28 attack helicopter, the Mil Moscow helicopter plant in collaboration with the TsAGI developed a new aerodynamic configuration for that main rotor. It was conceived at the very beginning of the work that the main rotor having that new aerodynamic configuration could be used to upgrade the Mi-24 helicopter, that was why the diameter, tip speed and the number of the blades were taken as those of the prototype helicopter. The general arrangement of the blade is shown in Fig. 1, while its geometric twist, in Fig. 2.

These blades featured a high twist with a gradient $\Delta\varphi$ =-9.7°, new airfoils TsAGI SB(-6*6) and KS(-4.5*6), composite materials. As the new airfoils have trailing edge plates, the blade chord became wider by 0.04 m (the width of the plates) as compared to that of the Mi-24 rotor blade. To improve the rotor aerodynamic performance in hover, the blade tip starting at 0.9R was twisted by 0.9°, as shown in Fig. 2. The same figure shows the Mi-24 production main rotor geometric twist for comparison.

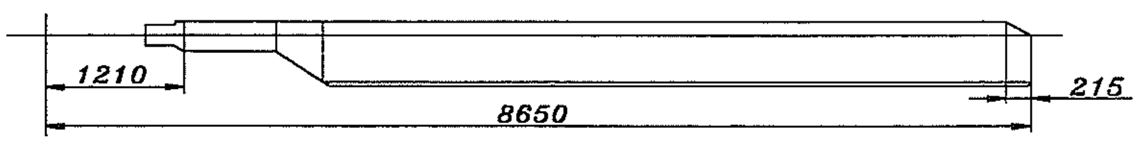

Fig. 1

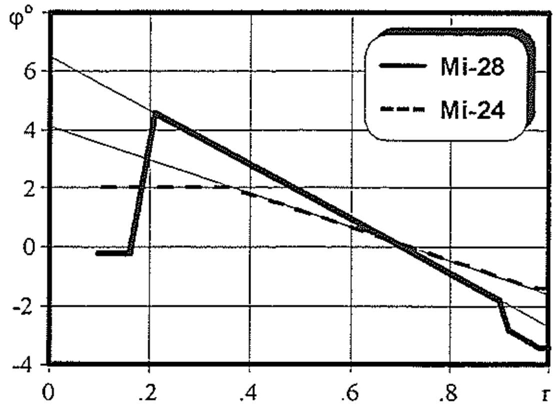

Fig. 2

M=0.6, especially the SB lifting airfoil. A little higher value of C_{xp} for C_l=0 and C_l=0 for the SB airfoil can be attributed by its 1.7% higher thickness ratio. However, this airfoil is a lifting one and it runs up to R=0.9 of the blade, and even at maximum helicopter speeds Mach number of such values will never occur. The application of these airfoils as well as a higher geometric twist of the blade have contributed to better figure of merit and L/D. It should be noted here that a favourable effect of the KS tip airfoil starting at 0.9 R is a significant reduction in the $\partial m_{zo}/\partial M$ derivative at a critical Mach number of 0.85. As can be seen from Table 1, the m_{zo} value for the NACA-230M airfoil reduces by -0.035 with the increase of Mach number from 0.6 to 0.85, while that for the new airfoil, by -0.014.

To investigate the new main rotor, a flying tested based on the Mi-24 was made. It was fitted with an experimental set of composite main rotor blades from the Mi-28 and its wing consoles were removed.

Table 1

Airfoil	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	$\partial m_{zo}/\partial M$ M=0.6	m_{zo} C_l=0 M=0.6	m_{zo} 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

The new blade was fitted with a tip fairing featuring the leading edge with a 30° sweep and a relative width equal to 2.5% of the radius to reduce the noise level and wave drag produced by the blade tip. The rotor blade on the prototype was fitted with a rounded tip of conventional shape, but of lesser size (by about 1%).

New airfoils developed by the TsAGI in particular were used in the new rotor design. Their aerodynamic performance was obtained in the TsAGI T-104 wind tunnel. The main data are presented in Table 1 in comparison with the NACA-230M airfoil with a 10% thickness ratio, which was used in the Mi-24 production main rotor blade. The new airfoils feature quite a wide plate running along the airfoil trailing edge to adjust the value of longitudinal moment. The plate parameters are shown in the airfoil designation in the brackets (the first digit refers the plate bend angle in degrees, the minus sign means upward bending), and the second digit, the plate size in the main chord percentage. For the experimental set of the composite blades, the metallic leading edge plate was used to change the bed angle in the process of flight tests. The plate is made of composite materials for the production blades, and it does not change its the bend angle in operation.

As can be seen from Table 1, the new airfoils with the reference bend angles of the plate have a 21-26% better L/D ratio. The value of the longitudinal moment coefficient for airfoil KS is higher by Δm_{zo}=+0.014, while that for lifting airfoil SB is lower by Δm_{zo}=-0.005 than for airfoil NACA-230M. The new airfoils have a much greater derivative $\partial m_{zo}/\partial M$ at

The first test results of the initial version of the experimental blade set showed that the main rotor control loads had substantially increased as compared to those of the Mi-24 production blades. The level of constant forces of control system was so high that an installation of more powerful hydraulic actuators /boosters/ had to be made and new design features had to be found to reduce pitch link loads.

Fig. 3 shows comparison made for blade pitch link loads versus airspeed for two sets of blade [3]. Pitch link loads for the Mi-28 composite blades are presented for one of experimental sets that later on was used with non-anhedral and unheard swept tips. The curves demonstrate that the gradient of the constant derivative of the new blade pitch link moment versus airspeed has a negative sign. The value of the sine component of the pitch link load per revolution for the new rotor gas a much higher dive gradient with airspeed, that that for the Mi-24 production rotor. These changes in the components of the pitch link load fore the new blades can be attributed to a more inboard and stable location of the SB and KS airfoil aerodynamic center relative to the NACA-230M airfoil, as well as to a more substantial dependence of the m_{zo} value upon airflow Mach number. For the Mi-24 production main rotor blade, the positive gradient of the sine component of the pitch link load per revolution with airspeed is determined by the aerodynamic center of the NACA-230M airfoil shifting forward with Mach number increasing on the advancing blade.

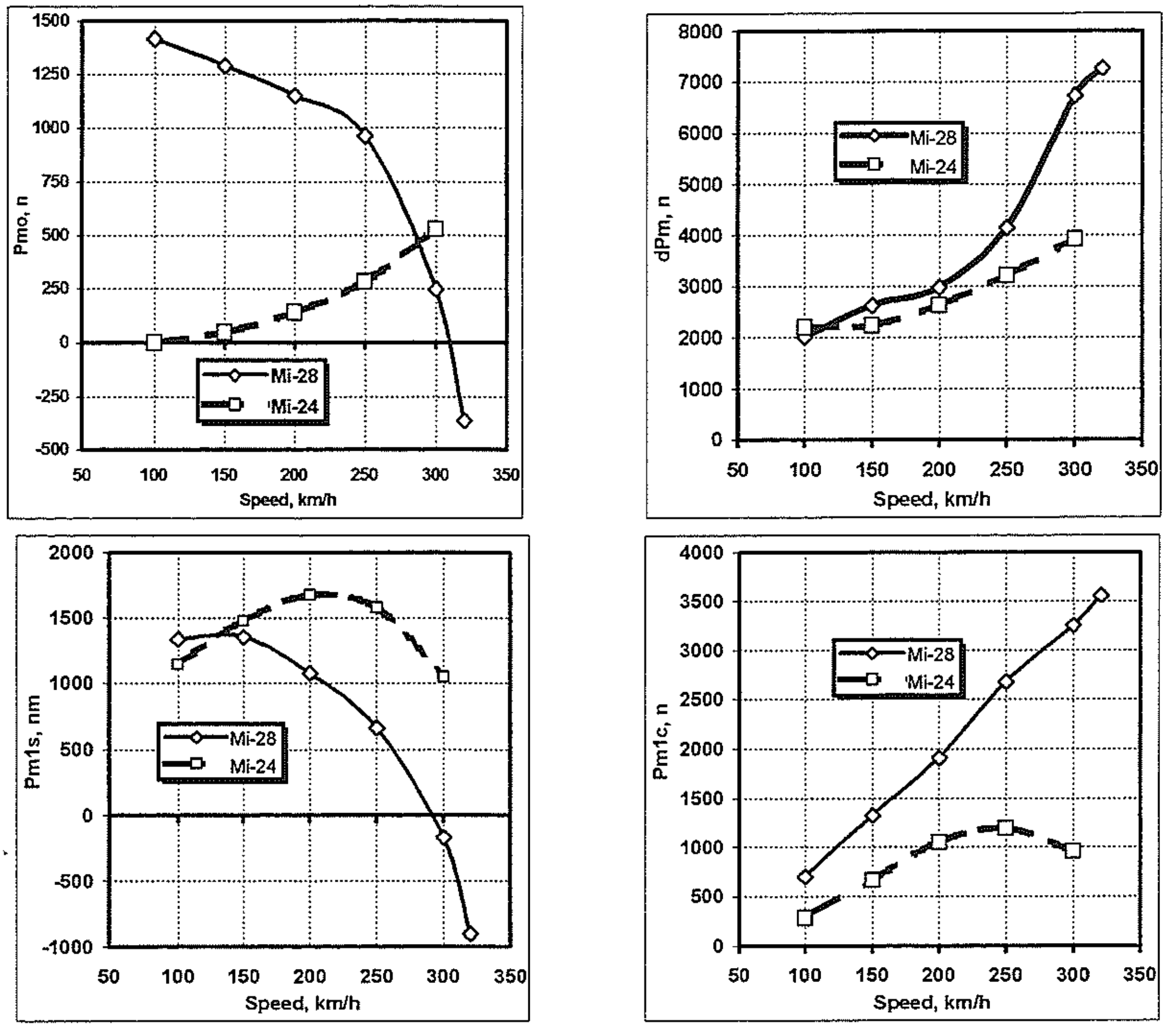

Fig. 3

As can be clearly seen from the curves in Fig. 3, the sine component of the 1/rev and the variable portion of the pitch link load differ quite substantially. For the experimental blades, the values of these parameters have increased by 2-2.5 and 1.7 times respectively at a the maximum speed of 300 km/h. The increase in the cosine derivative of the pitch link load 1/rev is attributed by a higher geometric twist of the experimental blades increasing this component of the blade pitch link load when the blade sections are in the slipstream.

The geometric twist of the new blade is 1.67 times higher than that of the Mi-24 production blade. Another reasons for increasing the experimental blade pitch link loads is as follows: they have a wider chord and lower torsional elasticity. This is due to the application of composite materials as well as the requirement to develop blades of minimum weight. The application of composite materials leads to an increase in the thickness ratio of the blade root end sections by 7-8%, which, in its turn, contributes to a growth of the blade pitch link loads.

Blade manufacture, and that of composite blade in particular, is a sophisticated and expensive process. It requires a long-term pre-production stage, manufacture of special tools, fixtures and equipment, development of inspection methods, etc. Therefore the results obtained from the flight tests raised an issue of finding relatively cheap and fast means to alter the experimental blades (without manufacture of expensive and sophisticated tools and fixtures) to reduce the flight control system loads.

To study the possibility of a reduction in pitch link loads, a programme of introducing design changes in the experimental set was drawn up under Professor M.N. Tischenko, General Designer. It resulted in solving the above problems at the lowest costs and with maximum reliability, as the test results were obtained from tests on full-scale blades. A series of design, analytical and experimental studies on the instruction of the Mil Moscow Helicopter Plant was carried out in the TsAGI Helicopter Division within the frame of the above programme. The were oriented to study possibilities leading to reduce pitch link loads in the blades with a new aerodynamic configuration provided the main rotor aerodynamic performance remains the same or even improves. In those studies, both conventional methods of correcting blade pitch link load characteristics (control of the airfoil mass characteristics by selecting a rational spanwise distribution of the tail trimming plate bending angle, varying the blade cg position, etc), and an absolutely new method developed by the TsAGI and related to the application of a new root end fitting shale were considered. The results of those studies were presented at the 1996 European Forum [1]. Further studies conducted in the direction of reducing pitch link loads within the framework of the above programme involved changes in the blade tip of the experimental composite blades.

4. THEORETICAL ANALYSIS OF THE EFFECT PRODUCED BY THE MAIN ROTOR BLADE SWEPT TIP ON ITS PITCH LINK LOADS

The analysis of the flight test results has shown that the blade tip portion occupying about 10% of the radius produces about 40% of the cosine component of the pitch link load in flight at cruise and maximum speeds. This is attributed to the design features of the blade tip portion, airfoil variable geometry, as well as the features of the flow around them at high speeds. The simplest and most widely used technical means to

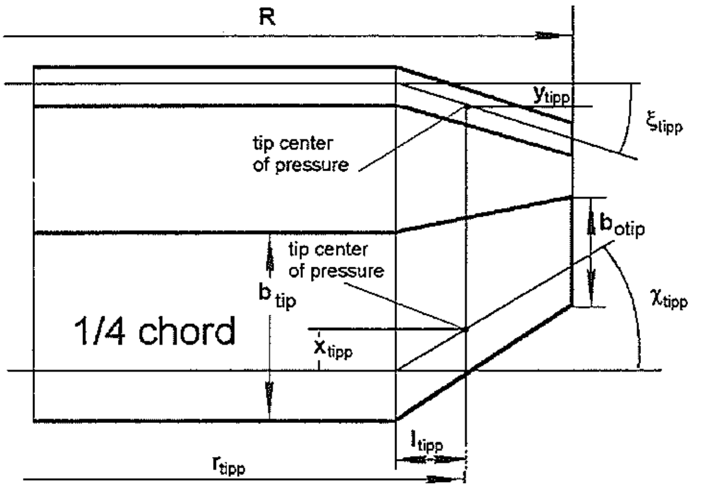

Fig. 4

improve blade pitch link load characteristics in the main rotor control system is upward bending of the trim tabs running along the trailing edge. However, this has not produced the desired effect as this action provides correction of the constant portion and sine component of the blade pitch link load 1/rev only. Besides, it leads to quite a substantial deterioration of the blade airfoil aerodynamic performance and, thus, to a lower figure of merit and efficiency of the main rotor.

A search for new design features aimed at reducing the blade tip hinge moments is an important task whose solution can help to lower loads in the main rotor control system, increase its service life and widen the helicopter flight envelope.

One of the new designs was conceived and theoretically proven by one of the authors of this paper, A.Yu Liss, in 1984. The main concept was to use a swept tip bent downward. As has been stated in [Ref. 1], main rotor blade pitch link load 1/rev defines the swashplate moment constant:

$$M_{tsw} = \sqrt{M_{zsw}^2 + M_{xsw}^2} = k\sqrt{P_{m1c}^2 + P_{m1s}^2}$$

$$P_m = P_{mo} + P_{m1s} * \sin\psi + P_{m1c} * \cos\psi + \Delta P_{mhg},$$

where $k = \frac{R_{an} Z_l}{2}$ is a constant depending upon the control system geometry and number of blades.

The P_{m1s} component can be easily affected by changing the value of the blade airfoil lateral moment coefficient c_{mo}. It can be achieved, for instance, by bending the trim tabs running along the blade trailing edge. Similar simple means of affecting the P_{m1c} coefficient at 1/rev cosψ in the P_m. Furrier-series expansion are unknown yet. Therefore in some cases the attempts at reducing the constant of the moment acting on the swashplate failed and the blade design already developed and manufactured had to be rejected (composite blades for the Mi-28 developed in the 80s).

The blade tip shown below is swept and bent downward relative to the chord plane (of a wing anhedral type), it is an effective maenad to affect the M_{m1c} value, thus the constant portion of the swashplate moment. Fig. 4 presents a version of this blade tip. At first, the other author of this paper, V.A. Ivchin, suggested another flat tip planform. It was selected proceeding from the analysis of the experimental results obtained in studies for the main rotor blade tip shape that had been conducted both in Russia and abroad. The main objective of the development of this type of the blade tip was improvement of the main rotor aerodynamic and noise performance and some lowering of blade pitch moments. The blades with these tips were tested at the Mil Moscow Helicopter plant [6]. Let us consider the principle of operation of a swept anhedral tip. Let the helicopter fly at a V speed the main rotor of attack α_{HB} relative to the blade tip plane. The radial component of the V speed along the blade axis equals $V_r = V\cos\alpha\cos(\psi-\chi)$, and the airflow component normal to the tip axis is $V_n = V\cos\alpha\cos(\psi-\chi)\sin(\xi_{tip}-a_o)$. The above statements are illustrated by Fig. 5.

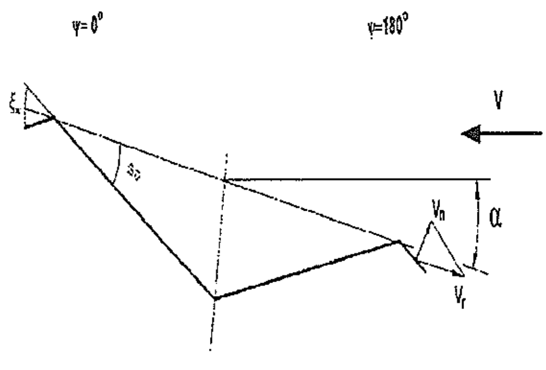

Fig. 5

The airflow velocity in the main rotor tip plane and normal to the blade tip is defined by the value $V_r = \omega r + V\cos\alpha * \sin(\psi - \chi)$. Then the angles of attack in the design cross-section of the blade tip α_{tip} for level flight at the V speed could be roughly defined by the following equation:

$$\alpha_{tip} = \alpha_{otip} + \alpha_{Vyip} = \alpha_{otip} + \frac{V_n}{V_t} =$$

$$= \alpha_{otip} + \frac{V * \cos\alpha * \sin(\xi - a_o) * \cos(\psi - \chi)}{\omega r + V * \cos\alpha_{нв} * \sin(\psi - \chi)}$$

Taking into account only the constant portion and 1/rev of the aerodynamic forces, the blade tip lift could be roughly defined by the following equation:

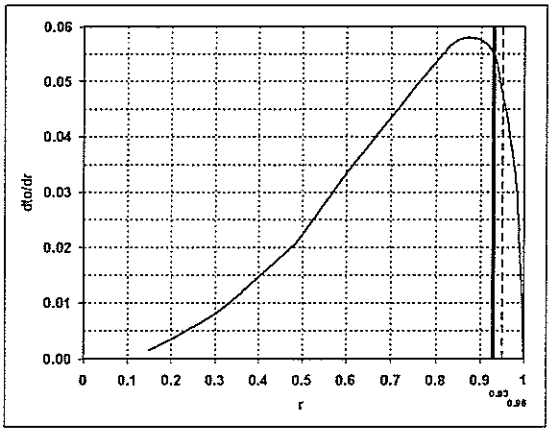

Fig. 6

$$Y_{tip} = C_y^\alpha(\alpha_{otip} + \alpha_{Vtip}\frac{\rho V_{tip}^2}{2}S_{tip} =$$

$$= C_y^\alpha \frac{\rho}{2} S_{tip}\left[\alpha_{tip} + \frac{V\cos\alpha\sin(\xi - a_o)\cos(\psi - \chi)}{\omega r_{tip} + V\cos\alpha\sin(\psi - \chi)}\right] \times \left[\omega r_{tip} + V\cos\alpha\sin(\psi - \chi)\right]^2 =$$

$$= C_y^\alpha \frac{\rho}{2} S_{tip}\left\{V\cos\alpha\sin(\xi - a_o)\cos(\psi - \chi) \times \left[\omega r_{tip} + V\cos\alpha\sin(\psi - \chi)\right] + \alpha_{otip} \times \left[\omega r_{tip} + V\cos\alpha\sin(\psi - \chi)\right]^2\right\} =$$

$$= C_y^\alpha \frac{\rho}{2} S_{tip}\left\{V\cos\alpha\,\omega r_{tip}\sin(\xi - a_o)\cos(\psi - \chi) + \alpha_{otip} \times \left[\omega r_{tip} + V\cos\alpha\sin(\psi - \chi)\right]^2\right\}$$

while drag could be roughly defined by the following equation:

$$X_{tip} = C_{xo}\frac{\rho V_{tip}^2}{2}S_{tip} = C_{xo}\frac{\rho}{2}S_{tip} \times \left[\omega r_{tip} + V\cos\alpha\sin(\psi - \chi)\right]^2 =$$

$$= C_{xo}\frac{\rho}{2}S_{tip} \times \left[(\omega r_{tip})^2 + 0.5(V\cos\alpha)^2 + 2\omega r_{tip} * \sin(\psi - \chi)\right].$$

As can be seen from the above equation, lift for an anhedral swept tip with the blade cross-section constant setting changes mainly under the cosine law, while drag, under the sine law with the main rotor speed (i.e. under 1/rev). In addition, the blade tip drag has a constant portion. These components of aerodynamic forces applied to the blade tip will result in an appropriate torsional moment made simple conversions:

$$\Delta M_{tip} = -\Delta Y_{tip} x_{tip} - \Delta X_{tip} y_{tip}$$

Simple conversions can give us equations determining the value of the constant portion, sine and cosine components of the blade tip appropriate torsional moment:

As can be seen from the equations obtained, the application of a swept tip without any anhedral with the design sweep angel equal to χ_{tip} changes the constant portion and the tip sine component of the blade pitch link load 1/rev to negative pitching, while the cosine component to positive pitching. If the blade tip is bent downward by an angle ξ_{tip}, only the constant portion and sine component of the blade pitch link load 1/rev change. The cosine component of the blade pitch link load 1/rev could be changed to negative pitching only if the blade tip is swept and bent downward at the same time.

The equations obtained contain the centre of tip pressure. As it has been mentioned above, the blade tip operates in a 3-d airflow and therefore it is necessary to a theoretical basis to determine correctly the centre of tip pressure in compliance with the suggested method of the tip pitch link load estimation. Taking into account the 3-d airflow effects is quite a challenge, and it requires calculations to be made by using special analytical methods. To make a preliminary estimation of the blade

$$\Delta M_{tipo} = -\frac{\rho}{2}S_{tip}\left[(\omega r_{tip})^2 + \frac{1}{2}(V\cos\alpha)^2\right] \times (C_{xo}y_{tip} + C_y^\alpha \alpha_{otip} x_{tip})$$

$$\Delta M_{tip1s} = -\frac{\rho}{2}V\cos\alpha \times \omega r_{tip} S_{tip} 2 \times (C_{xo}y_{tip}\cos\chi + C_y^\alpha x_{otip}\alpha_{otip}\cos\chi)$$

$$\Delta M_{tip1c} = -\frac{\rho}{2}V\cos\alpha \times \omega r_{tip} S_{tip} \times (C_y^\alpha x_{tip}\cos\chi\sin\xi - 2C_y^\alpha x_{tip}\alpha_{otip}\sin\chi)$$

tip efficiency, we shall use calculations of the blade spanwise distribution of the linear aerodynamic force with the help of the main rotor blade vortex theory method developed by M.N. Tischenko. Fig. 6 shows dt_o/dr for the Mi-28 main rotor blade in cruise at a speed of 260 km/h. The blade tip under consideration starts from 0.93r, as shown in the diagram. Having integrated thrust distribution over the tip area, an approximate value of the tip pressure centre is obtained. The point of application of the tip lift x_{tip} will be located at an outboard distance $0.4l_{tip}$. Let us take 0.7 of the tip span as the point to which drag is applied, as the blade tip drag is mainly affected by friction and velocity of the free stream.

Taking into account the above assumptions, the location of the centres of aerodynamic forces and area for a swept anhedral tip can be found from:

$$x_{tip} = 0.4 l_{tip} \times tg\chi_{tip}$$
$$y_{tip} = 0.7 l_{tip} \times tg\xi_{tip}$$
$$S_{tip} = \frac{b_{tip} + b_{etip}}{2} l_{tip}$$

To make a quantitative estimate of the effect of the swept anhedral tip on blade pitch link loads, let us consider, as an example, the Mi-28 blade tip tested on the Mi-28 test bed y the Mil Moscow Helicopter Plant. The geometry of the blade tip is a s follows: R = 8.6 m; C_y^{α} =6.2; $C_y^{\alpha}\alpha_o$ =.21; C_{xo} =0.02; l_{tip}=0.6 m; S_{tip}=0.32 m^2; x_{tip}=0.11 m; y_{tip}=0.05 m; χ_{tip}=23.8°; ξ_{tip}=7°. Assuming that ρ=0.125 kgf^2/m^4; $\cos\alpha_{mn} \approx 1$; ωr_{tip} =210 m/s, the values of the constant portion and components of the blade pitch link load 1/rev for a swept, swept anhedral and non-anhedral tip can be obtained for speeds of 270 km/h (75 m/s) and 320 km/h (89 m/s):

Table 2 shows quantitative estimates of the effect produced by the blade tip shape on the constant portion and components of the torsional moment 1/rev. For the swept tip without anhedral, the changes in the components of the torsional moment 1/rev are given in relation to a rectangular tip without anhedral, while for the swept anhedral tip, in relation to the swept tip without anhedral. The estimates presented can lead to a conclusion that the swept tip without anhedral for the main rotor blades affects mainly the constant portion and sine component of the torsional moment 1/rev, all other things being the same. For comparison, the Mi-28 main rotor blades at speeds of 320 km/h obtain additional negative pitching P_{mo} = -1070 N in the constant portion and P_{m1s} = -780 m. In addition the sine component of the torsional moment 1/rev increases by P_{m1c} = +340 N (about 10%).

Thus, the swept tip with a 7° anhedral does not actually change the constant portion and the torsional moment 1/rev, as the presented estimate show. But anhedral does affect the cosine component of the torsional moment 1/rev.

In general, it should be noted that the swept anhedral blade tip while producing a favourable effect on the cosine component of the blade pitch link load 1/rev results in a significant nose down in the constant portion and sine component of the blade pitch link load 1/rev. But this unfavourable effect can be eliminated by bending the trim tabs running along the trailing edge and consisting 7% of the chord.

The equations presented in this paper are quite simple and take into account the basic physical essence of the swept anhedral tip, but they do not account for some effects related to 3-d airflow around the blade tip that produce a favourable influence on the blade pitch link load of the swept anhedral blade tip. These effects include the influence of the variable induced wake at the blade tip for azimuths ψ=0° and ψ=180°, airflow around the end surface of the blade tip at an azimuth ψ=180, flexible blade twist, etc. Their consideration requires numerical methods to be used and labour-consuming calculations, which are beyond the scope of this paper.

5. FLIGHT TEST RESULTS SHOWING THE EFFECT PRODUCED BY THE SWEPT TIP OF THE MAIN ROTOR BLADE ON ITS PITCH LINK LOADS

To verify in practice the results obtained from the analysis, as well to continue the search for further reduction if the blade pitch link loads of the main rotor composite blades for the Mi-28 attack helicopter, the flight test programme went on for an experimental blade set that had been and initiated under M.N. Tischenko [1]. At first the blades were modified to have untwisted tip without anhedral. The geometry and size of the tip were offered by one of the authors of this paper, Mr. V. Ivchin, proceeding from a theoretical analyse, as well as the analysis of research into different blade tip shapes done by the TsAGI, Mil Moscow Helicopter Plant and foreign researchers. A swept tapered blade tip ensuring the best aerodynamic performance in hovering and cruise in level flight was chosen. The view of the blade planform thus modified is shown in Fig. 7, and its geometric twist, in Fig. 8. This was done to reduce the interaction of the airflow slipping along the blade and

Table 2

Speed	270 km/h			320 km/h		
Blade tip	ΔM_{mo}	ΔM_{m1c}	ΔM_{m1s}	ΔM_{mo}	ΔM_{m1c}	ΔM_{m1s}
Swept, without anhedral	-21.6	+5.8	-22.6	+6.9	-15.8	-13.3
Swept, anhedral	-0.9	-24.3	-0.9	-28.+8	-0.8	-0.7

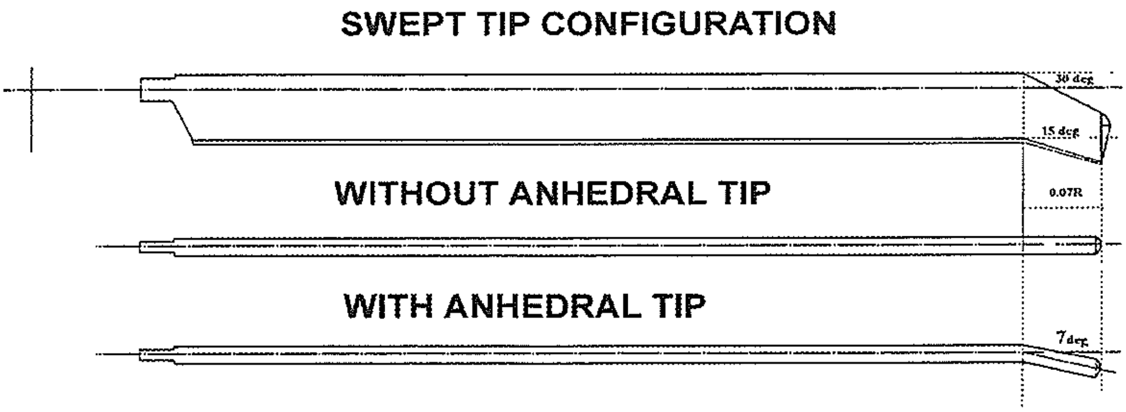

Fig. 7

the twisted blade producing in the end an increase in the cosine component of the blade pitch link load.

All the flight tests of the three blade tip configurations were conducted on the Mi-24 test bed equipped with the Mi-28 all composite main rotor blades. As soon as the flight tests of one configuration were completed, the blades were modified to have the next blade tip configuration. The untwisted swept tip was attached to the main blade by means of a special adapter having an untwisted shape. The author of this presentation suggested that new angular adapters should be manufactured which made it possible to manufacture an anhedral tip with low labour consumption. In addition to an improved cosine component of the blade pitch link loads, the anhedral tip improves the aerodynamic performance of the main rotor which was shown by the experimental research done on the Mil Moscow Helicopter Plant whirl tower.

Blade pitch link loads were measured during the flight tests of the swept blade tips, and later an analysis of their harmonic content was made. In this case the constant portion, 1/rev sine and cosine components as well as the amplitudes of the blade pitch link loads were compared. The results obtained are given in Fig. 9.

As can be seen from the diagrams, the flight tests have shown that the swept blade tip without anhedral resulted in nose down in the constant portion of the blade pitch link loads by -970 to -730 N depending on the airspeed. These results are in disagreement with the

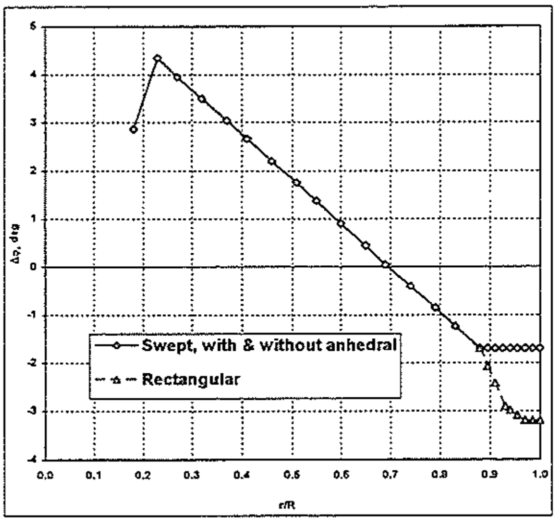

Fig. 8

quantitative estimate of the constant portion of the blade pitch link loads made above. The P_{mo} versus V in Fig. 9 shows that the difference in the constant portion of the blade pitch link loads for the rectangular blade tip and swept blade tip without anhedral decreases with airspeed while according to the calculations it should virtually be the same. This can be attributed to the fact

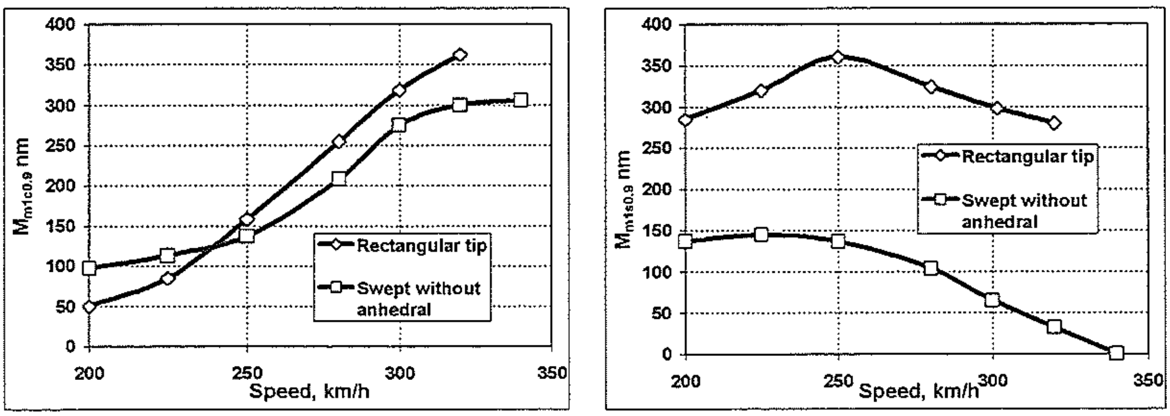

Fig. 9

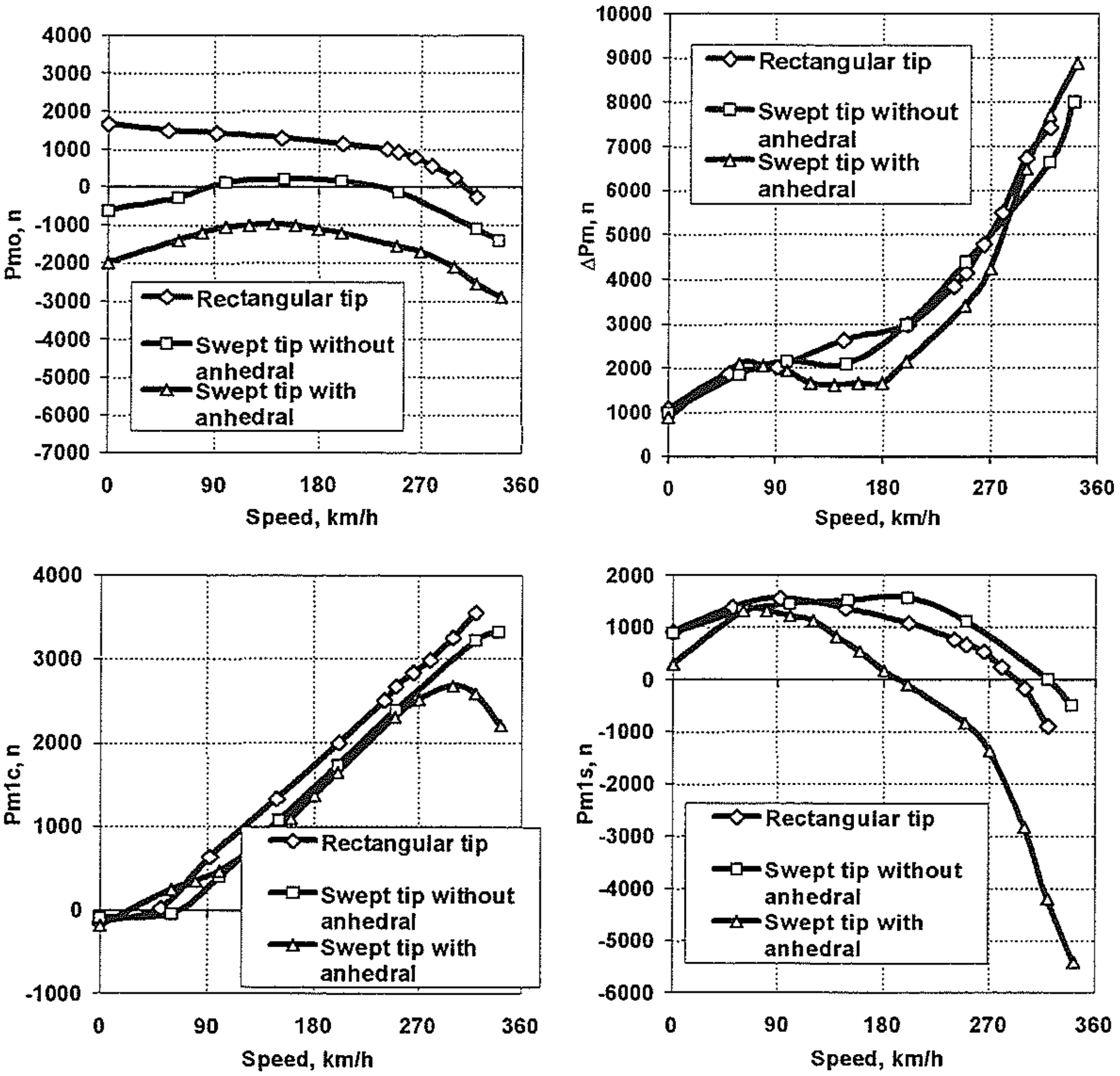

Fig. 10

the above equations do not take into account the blade torsional flexure. According to the analytical and experimental data, composite blades have half the torsional flexure as compared to that of the Mi-24 duraluminium blade. At the same time, a higher value of the negative pitching moment produced by the swept blade tip will lead to a substantial change in the blade geometric twist, to the redistribution of the aerodynamic loads applied along the blade and, thus, to a change in the blade pitch link load. This is substantiated by the comparison of the constant portion of the blade pitch link load versus airspeed for the swept tip with and without anhedral. The diagrams of P_{mo} versus V in Fig. 9 for these blade tips are almost equidistant in airspeed, as the distribution of the twisting moment applied along the blade, and, thus, elastic twist is the same for them.

The value of the sine component of the blade pitch link load 1/rev after fitting the blade with a swept tip without anhedral has change to nose up ΔP_{m1s} =+970 N at a speed of 320 km/h. The numeral results obtained above give a value equal to –770 N. This difference can be caused by a few reasons. The first one was given above and attributed to low stiffness of composite blades, which had been ignored in the numerical estimate. The second one lies in the fact that the blade cross-section airfoils have trailing edge tabs whose consist equals to 7% of the blade chord running along the whole span of the blade. These tabs are intended for adjusting the level of the blade pitch link load by their bending that is why they are made of metal. These tabs were recent by using special templates in the process of modification of the blade to accommodate different tips and during the flight tests. However, due to insufficient supervision and poor accuracy of the templates, no reliable information on actual table setting is available. Yet another reason lies in the fact the swept blade tip without anhedral was also fitted with a tab but no fixture to use for adjusting the tab and checking its setting was made. Therefore, it may happen that a change in the tip tab setting can lead to a change in the sine component of the blade pitch link load 1/rev.

These conclusions are substantiated by the flight test results. The twisting moment measured at the cross-section located at 0.9R of the reference blade with a rectangular tip was 280 Nm at a speed of 320 km/h. The same moment for the blade with a swept tip without anhedral was 30 Nm [6]. It means that the swept tip without anhedral resulted, according to the analytical predictions, in a change in the sine component of the blade pitch load 1/rev by - 250 Nm.

As for the cosine component of the blade pitch load 1/rev, the flight test results were opposite to those obtained analytically. The flight test results showed a decreases in the cosine component of the blade pitch link load 1/rev by –290 N, while the analysis had shown its increase by +340 N. The reason for this phenomenon is the effect of the interaction between the slipstream flowing around the blade tip and a change in the blade geometric twist. M.N. Tischenko predicted the presence of this effect in the process of flight tests of the Mi-28 new rotor system on the flying test bed.

Reference [7] shows that, for a twisted wing, the equivalence hypothesis is not valid, and the airfoil performance obtained in 2-D airflow are not acceptable in this case. Therefore in calculation of the helicopter rotor twisted blade it in necessary to consider the effect produced by the slipstream on the airfoil aerodynamic performance in case the blade has a geometric twist. Equations required to obtain corrections for the aerodynamic performance of airfoils obtained in 2-D airflow when they operate on a twisted blade under the slipstream effect were derived in Reference [8] proceeding from the lifting line theory. The following equation is suggested for calculating the airfoil value of Δm_{zo} in Reference [8]:

$$\Delta m_{zo} = 2\frac{\partial\varphi}{\partial r}\left[(0.7-\bar{x}_l)m_z^{\alpha} - 0.0625c_y^{\alpha}\right]\frac{b_7}{R}\frac{V\cos\alpha_{mn}}{\omega r_{tip}}tg\chi =$$

$$2\frac{\partial\varphi}{\partial r}\left[(0.7-\bar{x}_l)m_z^{\alpha} - 0.0625c_y^{\alpha}\right]\frac{b_7}{R}\frac{V\cos\alpha_{mn}}{\omega r_{tip}}$$

Taking into account that for the considered blade m_z^{δ}=-1.6, x_l/b=0.21, b/R=0.07, $d\varphi/dr$=-0.26, the following equation for the cosine component of the tip torsional moment can be obtained:

$$\Delta M_{m1c\Delta\varphi} = \Delta m_{zo} 0.5 * \rho(\omega r_{tip})^2 S_{tip} b_{tip} \bar{V}\cos\alpha_{mn}$$

For a speed of 320 km/h, the value of the cosine component of the torsional moment 1/rev obtained by using the equation will be +110 Nm. For a swept tip without anhedral and geometric twist the total value of the cosine component change is determined by the following value:

$$M_{m1c} = M_{m1c\chi} + M_{m1c\Delta\varphi} = +69 - 136 = -67[Nm]$$

That is, the value of the cosine component of the torsional moment 1/rev for a swept tip without anhedral when compared to that of the initial blade with a rectangular tip is close to the total value obtained from flight test results (Fig. 9) which equals -70 Nm.

This is also substantiated by flight test results. The measured torsional moment M_{m1c} at the blade cross-section at 0.9R of the initial blade with the rectangular tip was 370 Nm at a speed of 320 km/h. The value of the swept tip without anhedral was 300 Nm [6], so that the difference was - 70 Nm.

Thus, the effect of a reduced M_{m1c} obtained in flight tests is determined not by a swept tip, but by the fact that the tip has no geometric twist.

Fig. 10 shows changes in 1/rev components of the torsional moment obtained by measuring it at 0.9R in flight tests for a rectangular tip and a swept tip without anhedral. The relations presented substantiate well the effects produced by the swept tip on the blade pitch link loads obtained analytically.

Let us consider the effect produced by a swept anhedral tip. As can be seen from the diagram in Fig. 9, the flight tests have shown an occurrence of an additional negative pitching in the constant portion of the blade pitch link load by -1220 Nm. Qualitative estimates show that this should not take place. An analysis of potential causes has shown that when the blade was modified, the trailing edge tab settings were adjusted in the shop by using protractors. Those settings should have been in compliance with the settings established for the swept tip without anhedral, but our attempts to obtain reliable information on actual settings on the modified blade failed. The following has actually been found out. The tab setting on the blades with swept anhedral tips that were intended for adjusting the rotor blade track and implemented on three sections on each blade, were reduced by 1° in average. The result was an additional negative pitching moment in the constant portion of the blade pitch link load by –195 N. Bending the tip downward leads to an additional negative pitching moment in P_{mo} produced by resistance on the arm y_{tip} by another -50 N. An increase in the tip moment of inertia produces an approximately the same value of the negative pitching moment due to a longer distance between the blade rotation axis and the tip centre of mass. Thus, these data can explain an occurrence of a 25% additional negative pitching moment in the constant portion of the blade pitch link load. The comparison of the relations P_{mo} and P_{m1s} presented in Fig. 9 for tips with and without anhedral shows that this nature of the curves is inherent in the change of the value m_{zo} of the blade sections. Therefore it is most probable that the blades with and without anhedral tips had different tab settings due to which an additional negative pitching moment was produced for the blades having anhedral tips.

The tip anhedral has affected most effectively the cosine component of the blade pitch link load 1/rev at airspeeds higher than 270 km/h. As can be seen from the diagrams in Fig. 9, at a speed of 320 km/h the M_{m1c} has reduced by 20%, and at a speed of 340 km/h, by 35%, although these values are lower that those obtained from the qualitative estimates. Now let us consider the effect of the blade tip shape on the amplitude of the variable portion of the blade pitch link load. As can be seen from the diagrams in Fig. 9, at airspeed up to 280 km/h the rectangular tip and the swept tip without anhedral virtually have the same dP_m, but at airspeeds exceeding 320 km/h this value for the swept tip without anhedral is 970 Nm lower. At the same time the tip anhedral reduces the amplitude of the amplitude of the variable portion of the blade pitch link load at airspeeds lower than 280 km/h and increases it at higher speeds. For instance, the dP_m value reduced by 20% at a cruise speed of 260 km/s and increased by 10% at a speed of 340 km/h. As cruise makes up about 50% of the helicopter life cycle, it is quite clear that a reduction in the variable portion of the blade pitch link load can result in quite a substantial extension of the service life of the helicopter rotor and flight control system components.

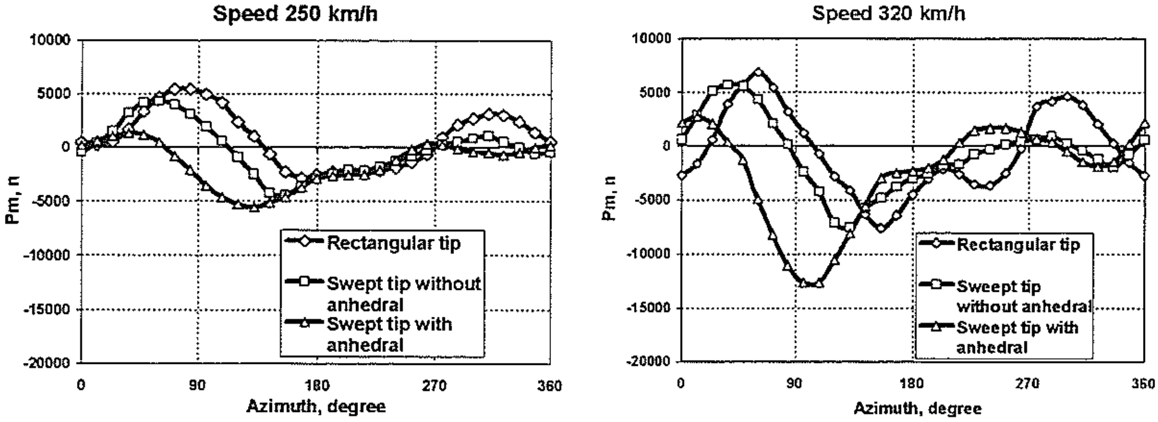

Fig. 11

To illustrate the change in the blade pitch link load in azimuth, Fig. 11 shows dependencies $P_m(\psi)$ for the tips being considered for speeds of 250 km/h and 320 km/h obtained from the flight tests. As can be seen from the diagram, there exists quite a considerable negative pitching moment within the azimuth range from 90° to 130°. The P_m value becomes as high as 1270 Nm for the blade with the swept anhedral tip at speeds of 320 km/h. At the same time, the amplitude of the blade pitch link load for the swept anhedral blade tip does not practically differ from that for blade s without the anhedral tip within the azimuth range from 180° to 360°. It means that the m_{zo} values of the cross-section airfoil of this blade are more negative than for the previous tip version. In accordance with the analytical data [9], as well as the flight test results [3] a change in the m_{zo} value of the airfoil caused by bending downward trailing edge and trim tabs results in a change only in the value of the constant and sine components of the blade pitch link load 1/rev. Therefore, using the expressions from Ref. 9 to determine the m_{zo} versus the trailing edge tab setting, we shall obtain that to half the M_{mls} value at a speed of 320 km/h, it is necessary to bend downward all the tabs running along the blade trailing edge by 1°. At the same time this will lead to an increase in the constant portion of the blade pitch link load (+1700 N). The result would be some degradation of the main rotor aerodynamic performance, but it would be negligible.

6. EFFECT OF A SWEPT ANHEDRAL TIP ON HELICOPTER PERFORMANCE

During flight tests of different blade tips, the effect of the swept anhedral tip on the helicopter performance was studied. To do that, comparative tests were conducted in hover and in level flight for several versions of the main rotor blades. The results obtained were reduced to standard conditions at sea level by using the procedure developed by Mr. Ivchin, co-author of the paper. Fig. 11 presents maximum relative TOW in standard conditions at the engine takeoff power rating versus hovering height above the ground. The data is given for the Mi-28 main rotor with the swept anhedral tip (for three versions of the trailing edge tab setting, the Mi-28 main rotor with the rectangular tip [10] and two versions of the Mi-24 production main rotor [11]. The relative TOW was determined in relation to the maximum TOW of the Mi-24 equipped with a production main rotor obtained in the above conditions while hovering out of ground effect. The diagram shows that the thrust characteristics of the main rotor having a rectangular tip were virtually those of the Mi-24 production main rotor. The swept anhedral blade tip in combination with the most favourable trailing edge tab setting leading to an increase of the helicopter TOW by 4% and 5% when hovering out and in ground effect respectively. However, it necessary to take into account the fact, that for this version of the main rotor the blade pitch links load components would be much higher as it has been discussed above which is presented in Fig. 8. Therefore, to reduce the blade pitch link load the tabs running along the tailing edge of the blade with the swept anhedral tips were bent downward. The result was a reduction of the trust characteristics of this main rotor to 2.5%-4%, as shown in Fig. 12.

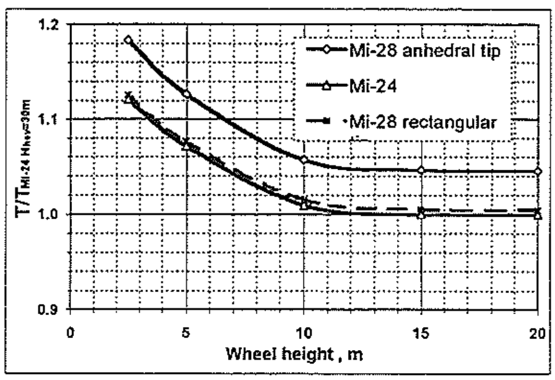

Fig. 12

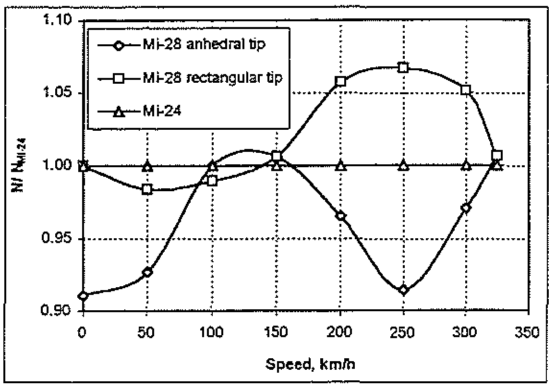

Fig. 13

To assess the effect of the swept anhedral tip on the power required for level flight, comparative tests of the Mi-24 main rotor were conducted. Fig. 13 presents the test results in the dimensionless form. The presented relations were obtained by establishing the relation between the Powerplant power required for the helicopter equipped with different sets of main rotor blades and that for the helicopter having an Mi-24 production main rotor. As can be seen from the diagrams, the power required for the Mi-28 helicopter equipped with a main rotor with a rectangular tip has increased by 7.5% at higher speeds and decreased by 2.5% at lower speeds when compared with the helicopter equipped with an Mi-24 production main rotor. In hover, there is almost no gain, which is in a good agreement with the diagrams in Fig. 11. The swept anhedral tip makes it possible for the power required in hover and in cruise to be reduced by 9.5% and almost 14% respectively. It is of interest to note, that the power required for all the blade sets under consideration does not actually change at the best economy cruising power.

Proceeding form the data presented in the paper, the following conclusions can be made.

7. CONCLUSIONS

1. The swept anhedral tip allows the cosine component of the blade pitch link load to be reduced due to the fact that it has no geometric twist. However, quite considerable negative moments occur in the constant and sine components of the blade pitch link load 1/rev.
2. The swept anhedral tip allows the cosine component of the blade pitch link load to be reduced by 20-35% at speeds exceeding 300 km/h.
3. The swept anhedral tip allows the amplitude of the variable portion of the blade pitch link load to be reduced by 20% at cruise speed of 260 km/h.
4. An additional negative pitching moment occurring in the constant and sine components of the blade pitch link load 1/rev for blades having a swept anhedral tip can be attributed to a change in the setting of the tabs running along the blade trailing edge.
5. Blades having a swept anhedral tip allow the blade thrust characteristics be increased by 4-5% in hover or the power required to be reduced by 8-9%.
6. Blades having a swept anhedral tip allow the powerplant power required be reduced by 10-14% in cruise flight.

8. REFERENCES

1. V. A. Ivchin, M. N. Tischenko, V.A. Animitsa, V.A. Golovkin, Analysis of Model and full-scale Investigation Results of Helicopter Blade Aerodynamic Configuration Effect on Pitch Link Load, 22nd European Rotorcraft Forum, London, England, 1996.
2. М.Г. Рождественский, Комплекс работ, направленных на повышение летных характеристик вертолетов МИ, Труды опытно- конструкторского бюро им М.Л. Миля 1997 г.
3. Акт № 56-86 по результатам замера нагрузок на опытных унифицированных лопастях несущего винта черт.280-2903-00СБ установленных изд. “245”, Технический Акт 56-89, Московский вертолетный завод им. М.Л. Миля, 1987 г.
4. Результаты летных испытаний объекта 80МТ со стеклопластиковыми лопастями несущего винта. Технический отчет 54-87, КВПО, 1987 г.
5. Результаты летных работ на объекте 80МТ N 93158 по определению нагрузок в управлении и крутящих моментов опытных стеклопластиковых лопастей несущего винта. Технический отчет 32-88, КВПО, 1988 г.
6. Результаты летных испытаний экспериментальных лопастей со стреловидными законцовками на летающей лаборатории изд. 242, Технический отчет 5-89, Московский вертолетный завод им. М.Л. Миля, 1989 г.
7. В.А. Ивчин, В.В. Пржебельский, Исследование аэродинамических характеристик профиля крученой лопасти при наличии скольжения, Труды научных чтений посвященных памяти академика Б.Н. Юрьева, Теоретические основы вертолетостроения, Москва, ИИЕТ АН СССР, 1987 г.
8. В.А. Ивчин, Влияние скольжения на m_z и c_y профиля закрученной лопасти, Технический отчет МВЗ №1390, 1987 г.
9. В.А. Ивчин, Влияние закрылков на

аэродинамические характеристики профиля опасти вертолета, Технический отчет МВЗ №12, 1987 г.

10. Отчет по результатам сравнительных летных испытаний двух комплектов лопастей несущего винта изд. 280 на летающей лаборатории, Отчет № 104-86 МВЗ им. М.Л. Миля, 1987 г.

11. Летные испытания по сравнению тяговых характеристик изд. 245 №1108 на режиме висения с серийными и опытными лопастями изд. 280 (комплект № 2901 , профиль NACA и СБ с наплывом), Отчет № 3-86 МВЗ им. М.Л. Миля, 1986 г.

12. Аэродинамические испытания модельного винта с отгибом вниз концевой части лопастей, Технический отчет МВЗ им. М.Л. Миля, 1978 г.