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ESSENTIAL RESULTS OBTAINED FROM RESEARCH INVOLVED IN SCISSORS ROTOR

BY

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ESSENTIAL RESULTS OBTAINED FROM RESEARCH INVOLVED IN SCISSORS ROTOR

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ABSTRACT

The paper is devoted to one of the main areas of research done at the Mil Helicopter Plant to improve rotor aerodynamic configuration, i.e. investigations in the performance of a rotor whose blades are spaced at irregular azimuth angles.

The paper presents the analysis of the results obtained from the 4-bladed experimental rotor tests conducted on the whirl tower in the flight condition corresponding to hovering. The rotor blades had a variable scissors angle. The influence of the chordwise angular blade position as well as the distance between the blades along the rotor shaft on the rotor performance is shown. Essential difference in rotor aerodynamic characteristics depending upon the fact which blade, the upper or the lower one, is the leading one is presented.

Optimal combinations of parameters required to obtain the maximum increase in hovering thrust and figure of merit of the rotor in comparison with the conventional rotor configuration have been defined.

The conclusions of the paper are compared with those of the paper presented by Walter G.O. Sonneborn and J.M. Drees at the 30th Annual Forum of the American Helicopter Society in 1974; their principal difference is shown; an attempt to explain the reason due to which the influence of the blade angular position and the distance between the planes of rotation on the rotor performance was not discovered in the paper of our American colleagues is made.

Flight test results of a scissors tail rotor and those of a three-bladed conventional one installed on one and the same helicopter are compared; changes in the load level in rotor structural members and pitch trim are presented.

Using comparative flight test results, changes in the sound pressure spectrum and external noise level are shown when a scissors rotor is used instead of a three-bladed conventional one.

INTRODUCTION

Research aimed at improving helicopter rotor aerodynamic configuration is done at the Mil Helicopter Plant in different areas. This work done in close cooperation with the Central Aerohydraudynamic Institute covers such areas as development of new more advanced airfoils having a higher efficiency at relatively small pitch moments, search for optimal blade planforms (this was shown in comprehensive research involved in investigations of blade tip shapes).

This paper presents an analysis of the essential results obtained from investigations of the performance of a rotor whose blades are spaced at irregular azimuth angles (the so-called scissors or X-shaped rotor).

In spite of the fact that the scissors rotor concept is quite well known now and it was first implemented in the Apache helicopter tail rotor design twenty years ago, the results obtained from experimental investigations here noticeably differ from those published earlier and therefore they are of interest for experts.

NOTATION

D	rotor diameter, m	M	Mach number	ΔM_c	chordwise variable bending moment, kgf*m
R	Rotor radius, m	Re	Reynold's number	ΔM_f	flapwise variable bending moment, kgf*m
k	number of blades	θ	blade pitch, deg	V	airspeed , km/h; $\overline{V}=V/\omega R$
b	blade chord, m	T	rotor thrust, kgf	$\Delta\beta$	angle of blade flapping motion, deg
σ	solidity	$\Delta\eta_o$	figure of merit in hovering	TR	tail rotor
$\Delta\varphi$	blade twist, deg	ωR	blade tip speed, m/s	MR	main rotor
Ψ	scissors angle, deg	mk	torque moment coefficient	f	frequency, Hz
h	vertical spacing, m	C_T	thrust coefficient	C_DS	equivalent flat-plate drag area, m²

1. INVESTIGATIONS OF SCISSORS ROTOR AERODYNAMIC CHARACTERISTICS

The Mil Helicopter Plant started to do research involved in the scissors rotor concept about sixteen years ago. At that time preference was given to experimental research, which was expected to produce the result quite quickly. It was evident, that analytical and theoretical studies, involved in development of analytical techniques using the blade vortex theory which considered the blade interference, would take rather a long time especially if the then relatively low level of computerization was to be considered. Besides, only those results obtained analytically and theoretically could be convincing that would be substantiated experimentally. Thus, an experimental check of the concept and its advantages obtained by analysis was unavoidable.

The Mi-2 tail rotor was chosen for tests because its geometric, thrust and power characteristics suited best the experimental whirl tower capabilities. To explore the influence of the azimuth angle between the two sets of blades in the plane of rotation and the vertical spacing between them on the aerodynamic characteristics of a scissors rotor, a special hub was designed and manufactured which allowed to vary the above parameters.

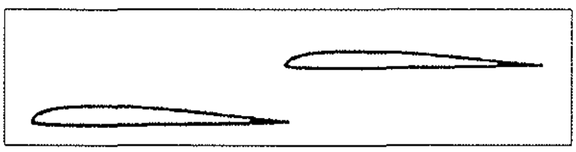
Table 1 shows geometric parameters of the experimental rotor.

Table 1

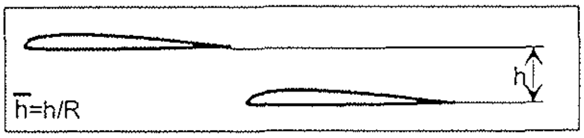
Rotor diameter	D=2.7 m	
Number of blades	k=2	k=4
Blade planform	rectangular	
Blade chord	b=0.22m	
Solidity	σ =.1038	σ =.2076
Blade twist	0 deg.	
Airfoil	NACA-0012	
Smaller angle between two pairs of blades	Ψ=0, 15, 23, 38, 60, 90.	
Vertical spacing between two planes of rotation	h/R= .074; .0807; .102; .126	

The hub design allowed to assemble the rotor in two configurations and to conduct their tests:

– L-configuration in which the lower blade was in front of the upper blade; and



Shape 1. L-configuration



Shape 2. U-configuration

– U-configuration in which the upper blade was in front of the lower blade.

The rotors were tested on the whirl tower at full-scale rotor rpm. The blade tip speed corresponded to Mach numbers 0.6 and 0.65.

The tests revealed a noticeable influence of the blade azimuth (scissors) angle on the rotor performance. Fig.1 shows rotor thrust versus azimuth blade angle for the same vertical spacing

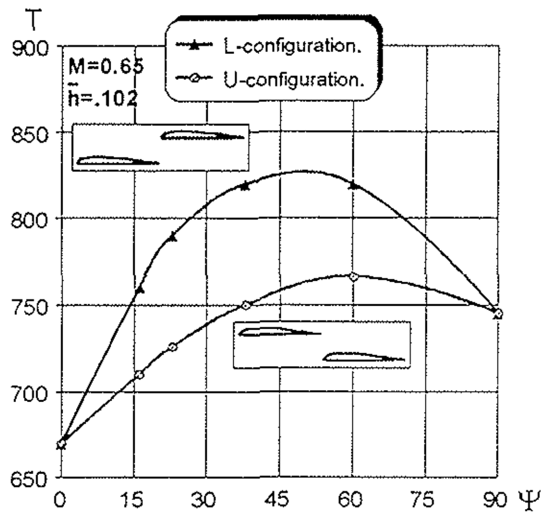


Fig. 1. Rotor thrust versus scissors angle

between the planes of rotation.

The tests showed that the optimal rotor configuration is that with the lower blade leading, i.e. the L - configuration, while the optimal range of the blade azimuth angle for obtaining the greatest increase in thrust was within 35÷55 degrees. And vice versa, as can be seen from the diagram, minimum thrust was obtained for the blade sets arranged one above the other, i.e. in the biplane configuration. In this case blade negative inductive interference became evident.

Maximum increase of the rotor thrust with azimuth blade angle reached about 10% relative to the value obtained for Ψ= 90 deg. The results of rotor thrust measurements are given for the maximum blade pitch of 18 deg. set in the tests conducted, at which the highest rotor thrust increment was obtained; but thrust increase was obtained at lower blade pitch as well. As can be seen from Fig. 2, the influence of the azimuth blade angle on rotor thrust has been found in the entire range of the blade pitch covered.

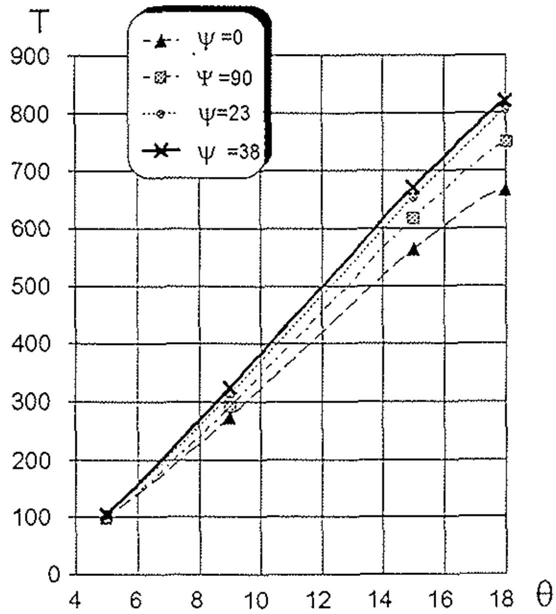


Fig. 2. Effect of scissors angle on rotor thrust versus blade pitch

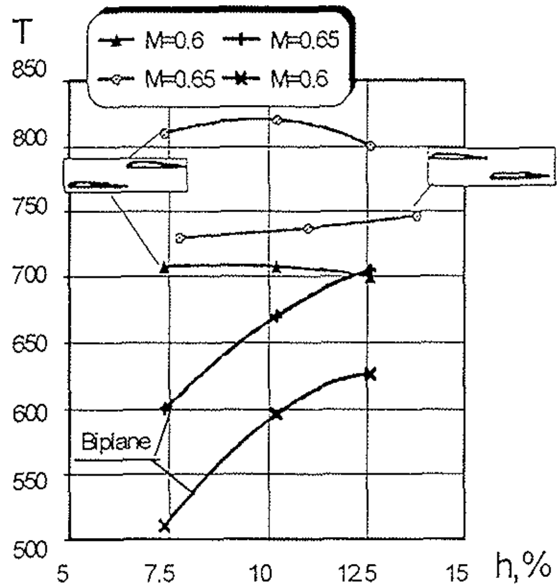


Fig. 3. Rotor thrust versus relative vertical spacing

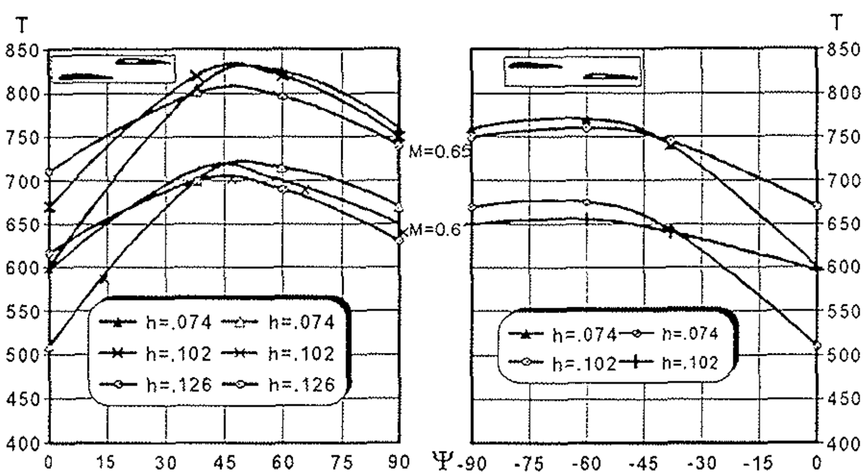


Fig. 4. Rotor thrust versus angle for different vertical spacing

During the tests the influence of the vertical spacing between the two sets of blades on rotor thrust characteristics was investigated for different azimuth blade angles. Diagrams in Figure 3 show some results of these studies for the two rotor configurations from which quite definite conclusions can be made. It can be clearly seen, that for the L-configuration the ptimum of the T(Ψ) dependence lies within 35÷55 degrees for all the values of the relative vertical spacing between the two pairs of blades. As for the U-configuration, this optimal region lies within 50÷70 degrees, but the maximum rotor thrust is 7÷8% lower.

As pointed out above, the lowest rotor thrust was obtained for the rotor blades arranged in the biplane configuration.

From the diagram in Fig. 4 it is clear that the blade adverse inductive interference becomes noticeably lower when the vertical spacing between the two pairs of blades is increased thus leading to a thrust increase. The T($\bar{h}$) curves presented in the same diagram show that for the L-configuration there is a he maximum, although not well defined, while there is none for the U-configuration.

The aim of the analysis given above was to reveal the dependence of rotor thrust on variation of rotor parameters. At the same time the issue how these parameters affect the power required and rotor figure of merit in hovering was not touched upon. However, it was noted that the dependence of rotor thrust coefficient on rotor azimuth blade (scissors) angle for constant torque (Fig. 5) reveals a distinct optimum similar to that shown by $C_T/(\sigma)$ curves considered above.

This approach is justifiable for the helicopter tail rotor which requires a maximum gain in rotor thrust to provide the necessary maneuvering characteristics in hovering and low speed flight. In this case, as a rule, the rotor figure of merit is of secondary importance.

As for the main rotor, the matter of gaining the maximum rotor figure of merit in hovering evidently becomes of primary importance.

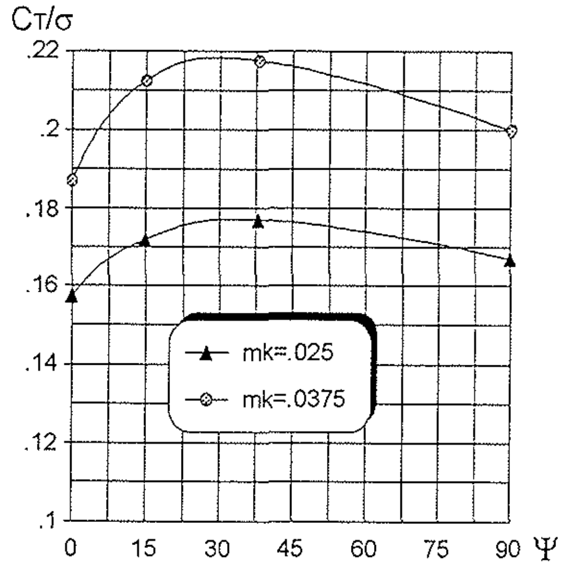


Fig. 5. Rotor thrust coefficient versus scissors angle for constant mk

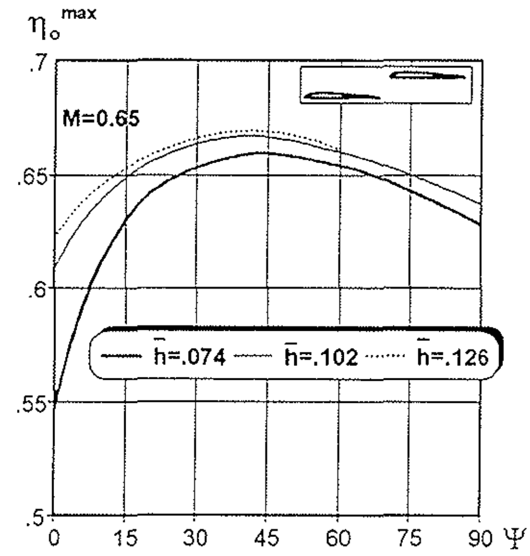


Fig.7. Effect of vertical spacing on rotor maximum figure of merit

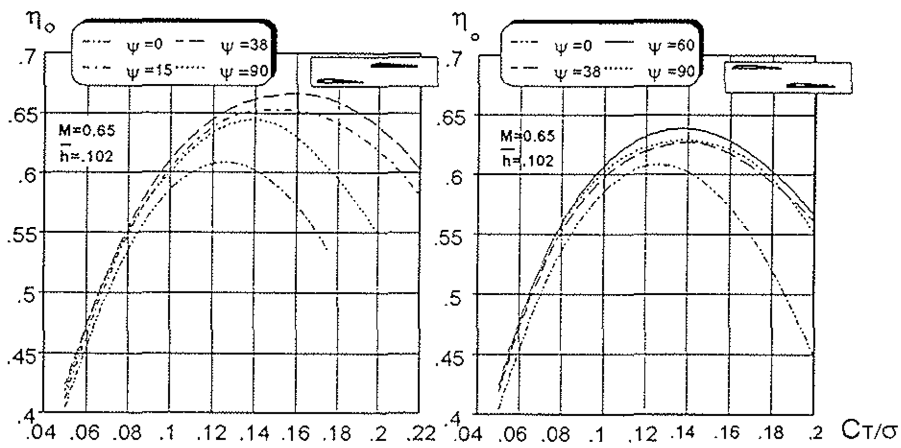


Fig.6. Effect of azimuth blade angle on η(Cт/σ) rotor

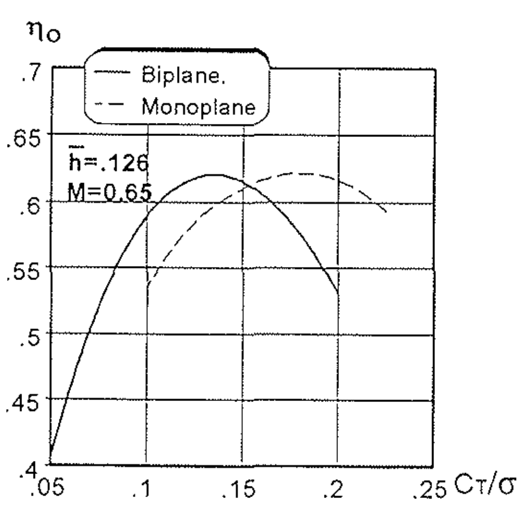


Fig.8. Figure of merit for monoplane and biplane rotors

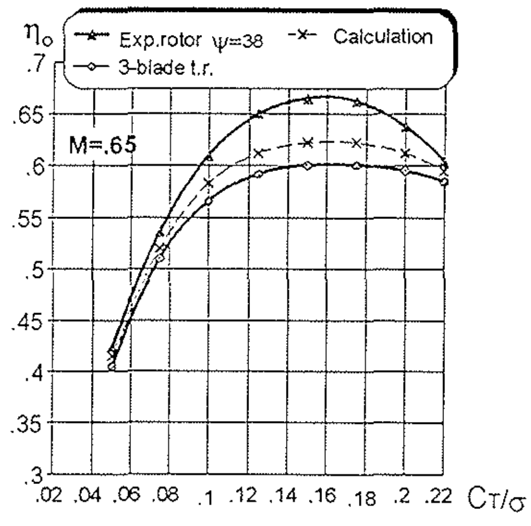


Fig.9. Figure of merit for Mi-24 production tail rotor and experimental rotor

Fig. 6 shows the rotor figure of merit versus thrust coefficient at different azimuth blade angles for the two configurations. It can be seen that the maximum figure of merit obtained for the L-configuration is 0.03÷0.04 higher than that for the U-configuration.

If we are to consider the maximum figure of merit versus the scissors angle for the L-configuration which is presented in Fig. 7, we can see that the optimum is within the angles ranging from 35 to 50 degrees, i. e. it is within the range of the optimum for thrust. When comparing the figure of merit for scissors angles of 90 and 40 degrees shown in Fig. 7, we can also see that the rotor figure of merit increase caused by using the scissors rotor concept is expressed in terms of the increase of the maximum rotor figure of merit by about 0.03. The tests have demonstrated that the increase in the vertical spacing of the two pairs of blades higher than 0.1 m does not virtually result in any increase of the figure of merit in the area of the maximum value of the dependence which is reflected in Fig. 7. However, for Ψ= 0 degree, i.e. for the biplane configuration, the maximum figure of merit continues to increase when the vertical spacing between the two pairs of blades increases higher than 0.1 m reaching the maximum figure of merit inherent in the monoplane rotor whose solidity is twice lower. This phenomenon is illustrated in Fig. 8, where $\eta(\sigma)$ curves are given for the monoplane and biplane rotors.

From theoretical and experimental investigations it is well known that an increase in the number of the blades with the rotor solidity being equal results in an increase in the rotor figure of merit in hovering. For example, research done by V.F. Antropov and P.I. Radchenko [1] has shown that the increase in the number of the blades from two to four causes an increase of the figure of merit by about 0.025 to 0.03.

Unfortunately, the design of the hub used in our experiments did not allow us to obtain the performance of the four-bladed rotor with the blades arranged in the same plane, thus, it is impossible to find out the pure effect of the planes of blade rotation on the rotor performance. Nonetheless, the comparison of experimental results obtained in previous investigations [1], which have shown that the increase in the number of the blades from two to four with constant rotor solidity leads to an increase of the figure of merit by 4%, with those of our experiments reveals an adverse inductive blade interference for the biplane configuration which is equivalent to a reduction in the rotor figure of merit by about 0.03.

Research of the aerodynamic efficiency of the scissors rotor was done not only to gain an insight into the inherent features of the rotor configuration which was new to us at that time. It was connected with the development of the Mi-28 combat helicopter which required a new tail rotor, as the existing Mi-24 tail rotor could not meet the requirements for maneuvering and altitude performance.

In connection with this development the results obtained in the investigations were compared with the Mi-24 production tail rotor performance.

Fig. 9 shows $\eta(C_T/\sigma)$ curve for the rotor used in the studies of the scissors rotor in its optimal configuration, and for the Mi-24 tail rotor. The comparison of these results clearly shows that the scissors rotor maximum figure of merit is higher by 0.06÷0.07. However, it is necessary to bear in mind that this gain can be attributed not only to the features of the scissors rotor which has a vertical spacing between the two pairs of blades and an optimal scissors angle, but to a 1.4 times higher solidity. The same figure shows a calculated h versus C_T/σ for a conventional three-bladed tail rotor whose solidity was that of the experimental rotor. Proceeding from the comparison of the results obtained from the tests of these two rotors a forecast was made: the scissors rotor features would allow to increase the figure of merit of the rotor being designed by 0.03÷0.04.

At present when the Mi-28 was built long ago and it is flying showing off its maneuvering capability check tests of the tail rotor of this helicopter have been conducted.

The Mi-28 tail rotor geometric data are given in Table 2.

Table 2

Rotor diameter	D=3.84 м
Number of blades	k=4
Solidity ratio	σ=0.159
Azimuth blade angle	ψ=36 degrees
Relative vertical spacing	h=0.07

The rotor was tested on the same whirl tower which had been used for testing the experimental rotor with variable azimuth blade angle. Fig. 10 shows the figure of merit in hovering versus thrust coefficient for the scissors rotor and for a two-bladed module of the same rotor. The comparison of the test results obtained for the scissors rotor with those of the three-bladed one makes it clear that the maximum figure of merit of the new rotor was by about 0.05 or 10% higher within the operating thrust coefficient range.

Fig. 11 presents thrust versus blade pitch curves for the Mi-28 and Mi-24 tail rotors that were obtained from the tests conducted on one and the same whirl tower. It can be seen that the scissors rotor has a noticeable advantage in thrust over the Mi-24 tail rotor. It should be noted here, as is seen from Fig. 12, that the figure of merit of the new rotor is much higher within the whole range of the thrust coefficient variation.

The comparison of the scissors rotor thrust characteristics shows the difference in the

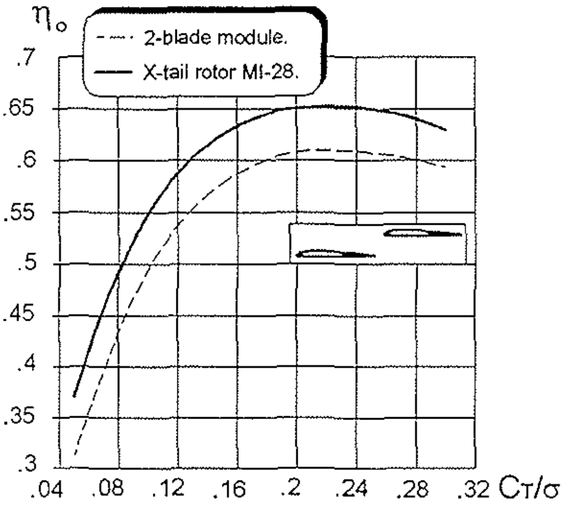


Fig. 10. Figure of merit for Mi-28 tail rotor using scissors rotor concept

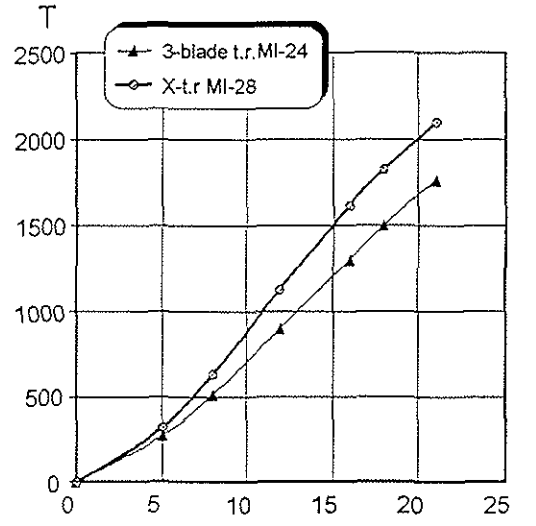


Fig. 11. Mi-24 and Mi-28 tail rotor thrust versus blade pitch.

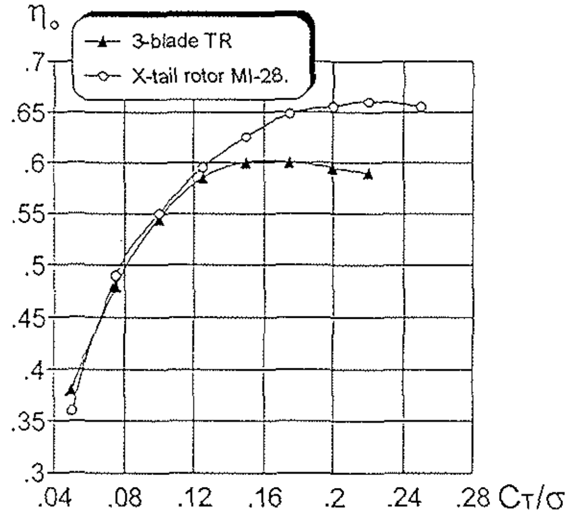


Fig. 12. Mi-28 and Mi-24 tail rotor figure of merit in hovering versus thrust coefficient

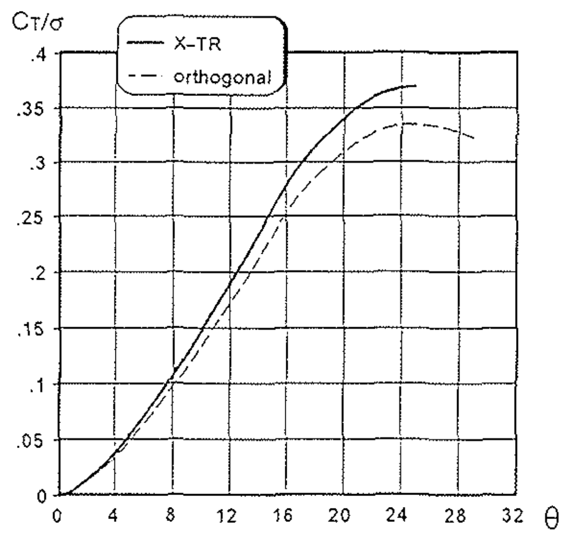


Fig. 13. Rotor thrust coefficient versus blade pitch for scissors rotor and rotor with orthogonally arranged blades

performance of the two tail rotor designs; however, an independent answer to the following question would be of interest: what would the performance of the Mi-28 tail rotor have been, if it had been designed as a conventional rotor with the blades arranged orthogonally in the plane of rotation. Proceeding from the analysis of the experimental data and calculations for such a rotor, C_T/σ versus θ has been obtained which is presented in Fig. 13. It can be seen that the X-shaped rotor concept has allowed to derive a much more effective tail rotor possessing higher thrust capabilities.

Completing the description and analysis of the results obtained from the studies devoted to the aerodynamic features of the scissors rotor, it should be noted that these results significantly differ from those given in the paper presented at the 30th Annual National Forum of the American Helicopter Society by Walter G. Sonnerborn and Jan M. Drees [2]. According to the authors, the scale model rotor tests had given a surprising result: "neither a change in azimuth spacing from 90 degrees to 30 degrees nor a change in the vertical spacing of the aft scissors blades above the leading blades produces measurable changes in hovering efficiency."

As was shown above, our studies of the aerodynamic characteristics of the scissors rotor have led to another result. In our opinion, "the surprising result" obtained in publication [2] can be attributed to two factors: first, a small size of the scale model rotor (D = 61 cm) which was tested, and therefore extremely small values of the forces and moments measured; second, the values of

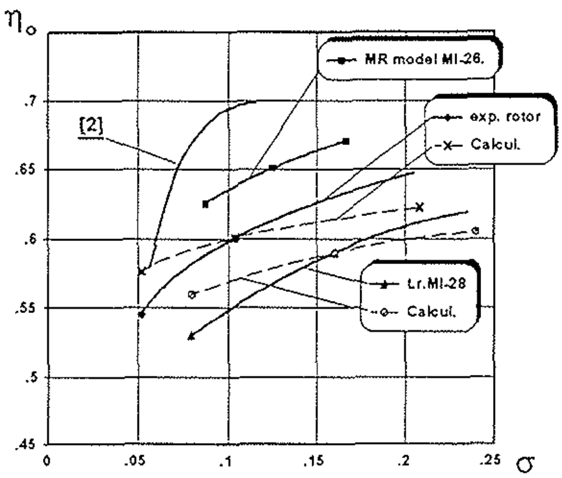


Fig. 14. Effect of rotor solidity on figure of merit in hovering

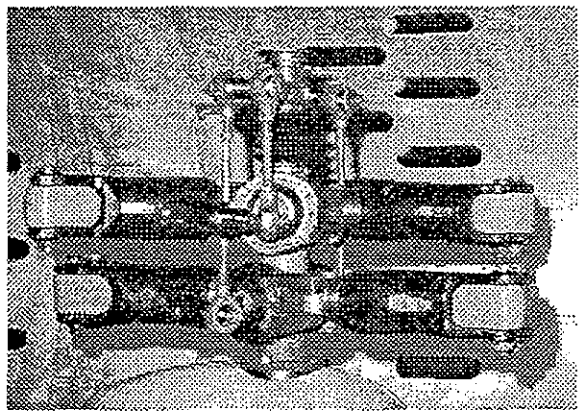


Fig. 15. Mi-28 tail rotor hub in wind tunnel test section

Reynolds number and Mach number were 7 and 3 times lower respectively as compared to those used in our tests.

The experience gained during research done by the aerodynamics department of the Mil Helicopter Plant has proved time and again that it is necessary to be very accurate in following the test procedures and the rules of self-similarity. Insufficiently full satisfaction of these requirements could sometimes result in wrong conclusions.

As an example, we can give you some results of parametric studies devoted to the effect of rotor solidity on hovering figure of merit that are presented in publication [1]. The experiment was carried out for a scale model rotor of 2.5 m diameter, the rotor blade chord varied from 0.056 m to 0.149 m and the blade tip speed was 73 m/s. Reynold's number calculated for $r = 0.7$ varied within $Re \cong (0.2 \div 0.5) * 10^6$. Fig. 14 presents η versus σ taken from this publication.

Attention should be paid to an extremely drastic change in rotor figure of merit with solidity variation from 0.06 to 0.09. The diagram also shows versus curves obtained from the results of the scissors rotor tests conducted on our full-scale whirl tower with rotor solidity being twice as high due to the increase in the number of the blades from 2 to 4. The η versus σ curve for the Mi-26 main rotor scale model is shown as well; it was obtained from the investigations of the Mi-26 main rotor scale model characteristics for the number of blades equal to 4, 6 and 8. These tests were conducted at Reynold's number of $Re \cong (0.2 \div 0.5) * 10^6$ and Mach number equal to $0.5 \div 0.65$. Our experiment differed from that described in publication [1] in the following: here virtually two parameters were changed simultaneously, i.e. the number of the blades and solidity.

To reveal the effect of solidity itself, for the same number of the blades, the existing experimental data were used and calculations were made. The diagram in Fig. 14 shows $\eta(\sigma)$ curves for the constant number of the blades ($k=4$). It can be clearly seen that the experimental values obtained for full-scale Reynolds and Mach numbers, as well as the calculated values have a much smaller change gradient for solidity variation than the dependence presented in publication [1]. Therefore, the conclusions made in publication [1] should be treated with a certain degree of caution.

An investigation of a possible reduction of the tail rotor hub drag was another field of studies of the scissors rotor performance. The calculated value of the tail rotor hub drag showed that the hub with two blade modules arranged in two different planes spaced vertically should have 1.5 higher drag than that of the Mi-24 three-bladed tail rotor hub.

To determine the actual drag value, full-scale hubs were tested in the wind tunnel belonging to the Mil Helicopter Plant. The Mi-28 scissors tail rotor is shown in Fig. 15; it is installed in the wind tunnel test section.

Fig. 16 shows the results of the studies carried

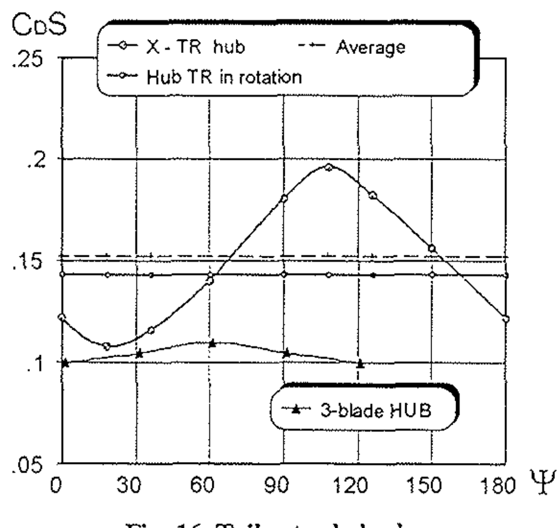


Fig. 16. Tail rotor hubs drag

out to determine the drag of the hub installed at different angles to the flow. As can be seen from the data shown in the diagram, the drag change for the X-shaped tail rotor hub which has quite a significant asymmetry is almost twofold with the change of its position relative to the flow. In connection with this, the X-shaped rotor hub drag was also determined for the hub rotating. Fig. 16 presents the drag level for the rotating hub, the value being about 1.4 times higher than the average level of the three-bladed rotor hub drag. The tests showed that the drag of the X-shaped rotor hub rotating was by 7% lower than the average value. To reduce drag, a few versions of the X-shaped rotor hub fairings were designed and manufactured that covered both the central part of the hub and its separate components. But, unfortunately, none of them contributed to drag reduction.

2. INVESTIGATION OF SCISSORS ROTOR LOADING

In parallel with investigating the aerodynamic features of the scissors rotor concept an analysis

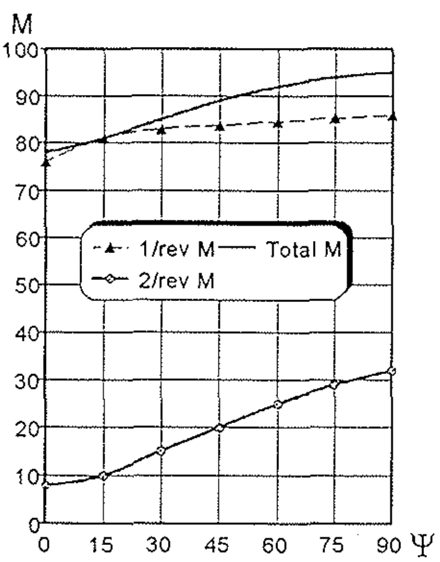


Fig. 17. Chordwise bending moment amplitude versus scissors angle

aimed at revealing possible changes in the rotor component loads was carried out in developing a new tail rotor for the Mi-28 helicopter. The main results of this analysis, procedures used are given in the publication prepared by the author and presented at the 18th European Rotorcraft Forum [3].

The analysis showed that since in the plane of rotation the X-shaped rotor is characterized by the axial symmetry similar to that of the two-bladed rotor, the level of chordwise loads should be lower than that for the 4-bladed rotor with the conventional orthogonal arrangement of the blades. It applies mainly to the loads produced by the action of 2/rev aerodynamic and inertia forces. As the X-shaped rotor design can be considered as two pairs of two-bladed rotors installed one above the other with some vertical spacing along the axis of rotation, one two-bladed rotor in this case will be called a module.

Fig. 17 shows the analytical results for the maximum oscillatory chordwise bending moments applied to the tail rotor hub sleeve during hovering turns at different azimuth blade angles in the plane of rotation. The azimuth blade angle affects noticeably the 2/rev bending moment. When this angle changes from 90 degrees to 0 the moment amplitude becomes almost 4 times lower. However, the amplitude of the total bending moment changes only by 20%. This is attributed by the fact that the blade loading occurs mainly in the 1st harmonic, the component of the bending in the 2nd harmonic in the total value of the bending moment being 33% and 10% for Ψ=90 degrees and 0 respectively.

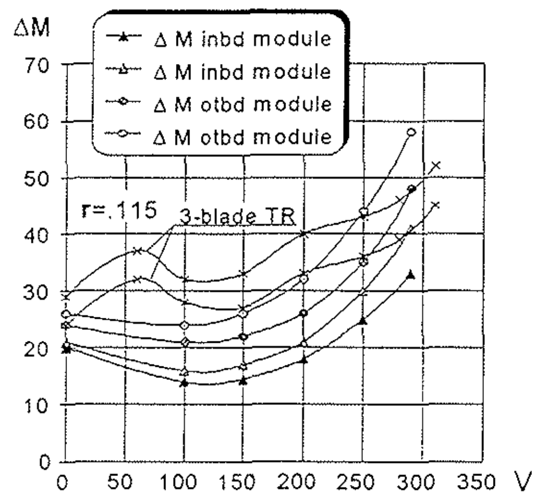


Fig. 18. Oscillatory flapwise bending moment

Here the problems of the scissors tail rotor loading are highlighted proceeding from the flight test results. As the new tail rotor for the Mi-28 was intended to replace the three-bladed tail rotor taken from the Mi-24 and installed on the Mi-28 to start flight tests, it is quite natural to compare these two rotors. It should be noted that the Mi-28 tail rotor is of pusher type, therefore the blade plane located most outboard of the tail pylon corresponds to the lower plane for a horizontally arranged rotor producing upward thrust. Fig. 18 shows flapwise bending moment applied to the hub sleeve (at $r = 0.115$) versus airspeed.

As can be seen, bending moments are lower for the scissors rotor than for the three-bladed rotor almost throughout the airspeed range. From the test results presented on the diagram, the difference in the level of the bending moments on the hub sleeves belonging to different modules is clear. The bending moment produced on the hub sleeve belonging to

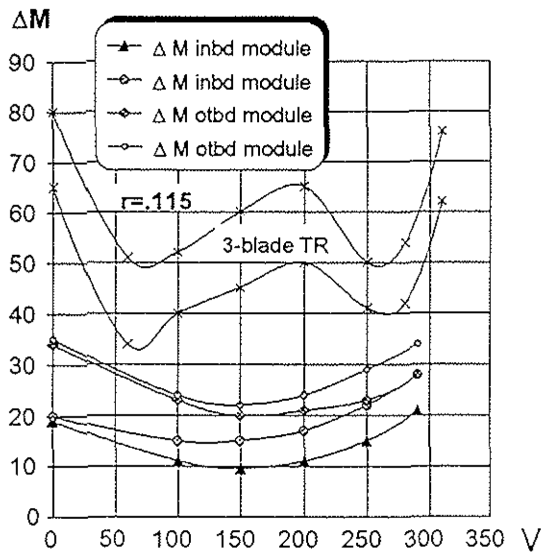


Fig. 19. Oscillatory chordwise bending moment

the rotor module outboard of the rotor pylon are 20-45% higher.

Fig. 19 shows the amplitude of chordwise bending moments produced on the rotor sleeves at r = 0.115 versus airspeed. The bending moments measured are 3÷5 times lower than those of the three-bladed rotor at the same radius station. Chordwise loads applied to the outboard rotor module also happened to be higher, but the difference reduces with airspeed. It should be noted here that the bending moment variation with airspeed occurs much smoother in contrast with the three-bladed rotor.

Measurements of the blade flapping motion made during the tests have also shown that the outboard rotor module has a higher amplitude of

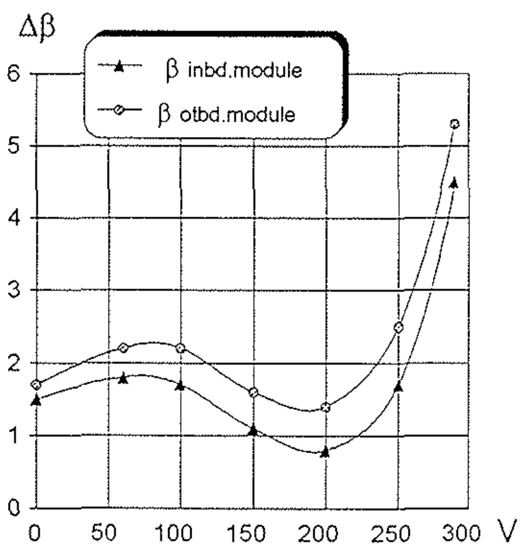


Fig. 20. Blade flapping motion versus airspeed

oscillation whose frequency corresponds to 1/rev. Although the difference in the amplitude turned out to be not more than 0.5 degrees almost throughout the airspeed range, nonetheless it substantiates different operating conditions of the blades located in different planes along the rotor axis (Fig. 20).

3. SCISSORS ROTOR NOISE INVESTIGATIONS

The helicopter acoustic far field is composed of the superposition of the main and tail rotor acoustic fields plus the acoustic fields produced by the engines, gearboxes and drive shafts. In the total spectrum of sound pressure measured on the ground there are noise radiation components containing both a discrete and a broadband spectrum. The frequencies of the discrete components are multiples to the main and tail rotor blade passage frequencies and they fall into the frequency ranges of 20÷160 Hz and 100÷500 Hz for the main and tail rotors respectively. Radiation containing continuous frequency spectrum can be seen throughout the entire sound frequency range, however its maximum intensity can be noted in the 500÷3,000 Hz range.

Comprehensive investigations of the single rotor helicopter acoustics have been carried by the author in close cooperation with V.F.Samokhin [4].

The source of acoustic harmonic radiation can easily be identified by the harmonic frequency which corresponds to either the main or tail rotor passage frequency. The matter is much more complicated when we deal with the broadband radiation component, although it is this particular factor that determines the external Effective Perceived Noise Level (EPNL) produced by the helicopter in many cases. Possible sources of this radiation could be the main and tail rotors as well as the helicopter turbulent wake. To find out the radiation source of continuous frequency spectrum whose noise level is the dominating one in the helicopter external noise level, as well as to identify the difference in the noise levels that is caused by the design changes in the tail rotor, the noise levels produced by flyover of the Mi-28 equipped with different tail rotors, i.e. the three-bladed tail rotor and the scissors rotor, were measured. Fig. 21 compares one-third octave spectra of sound pressure obtained for these two rotors. The data presented here demonstrate clearly that the tail rotor as a noise source is responsible for the helicopter acoustic radiation in the wide frequency range from 150 to 3,000 Hz.

The tail rotor design changes resulted in changed levels of sound pressure spectral components. Broadband noise level versus airspeed is worthy of interest. In transition from low airspeeds ($\bar{V}$ = 0.13÷0.21) to high airspeeds ($\bar{V}$ = 0.3÷0.37) sound pressure levels in the 600÷2,000 Hz range increase by 10 dB for the helicopter equipped with the three-bladed rotor and by 3 dB only for the helicopter equipped with the scissors rotor. At the

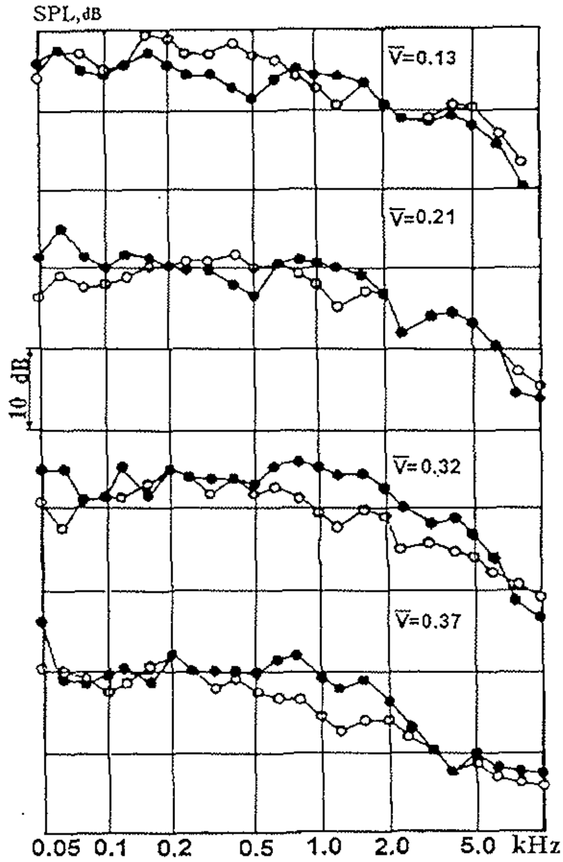


Fig. 21. One-third octave spectra of sound pressure for helicopters with production (•) and scissors (∘) tail rotor (H=1000m , $\tau=\tau_{PNLTM}$)

same time, the levels of sound pressure in this frequency range remain up to 10 dB lower for the helicopter having the scissors tail rotor as compared with the helicopter equipped with the three-bladed rotor while the helicopter external noise reduction was 3÷5 TPNdB.

The tests reveald that the tail rotor harmonics were present throughout all the considered directions of sound propagation within narrowband spectra of sound pressure (f = 1.25 Hz) obtained for the 0÷500 frequency range. Fig. 22 presents a spectrum of sound pressure recorded during a flyover of the Mi-28 helicopter equipped with the scissors rotor at the moment when its velocity vector was at an angle of 34 degrees relative to the line running from the helicopter to the microphone. The 1/rev frequency of the helicopter external noise, with due account of the Doppler effect, was 36 Hz which corresponded to the noise radiation produced by the two-bladed tail rotor for the given rpm. Thus, in terms of frequency, the four-bladed scissors tail rotor generates the same harmonic radiation as the two-bladed rotor does, but in terms of time it acts as two two-bladed rotors being rigidly attached in the disc plane.

Harmonic radiation of the tail rotor takes up a relatively narrow frequency range in the whole spectrum of the helicopter radiation, and in the range exceeding 600÷800 Hz, the helicopter radiation spectrum becomes broadband for all directions of noise propagation.

Thus, the tests have shown that one of the main sources of broadband noise greatly affecting the helicopter external noise level is the helicopter tail rotor. In the tests conducted, both rotors were operated in the same flight conditions, therefore the reduction of the broadband radiation intensity registered for the scissors rotor in comparison with that of the three-bladed rotor can be attributed to the scissors rotor design features that resulted in reduced intensity of sound pressure pulsations on its blades.

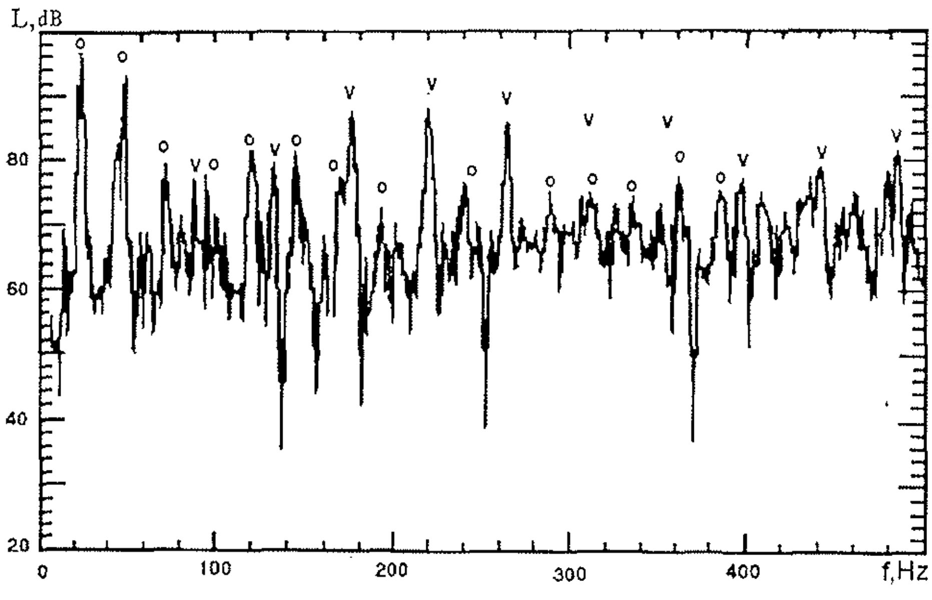


Fig. 22. Acoustic emission spectrum of Mi-28 with scissors tail rotor (1000m altitude, $\bar{V}$=0.324, φ=34 deg.) (o - MR hamonics; v - TR harmonics)

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