# EXPERIMENTAL INVESTIGATIONS OF THE X-SHAPED TAIL ROTOR MODEL AIMED AT IMPROVING AERODYNAMIC CHARACTERISTICS THEREOF

Valery A. Ivchin, Konstantin Yu. Samsonov

Mil Moscow Helicopter Plant, JSC,
2, Sokolnichy val, Moscow, 112125, Russia
E-mail: mvz@mi-helicopter.ru

**Keywords:** X-shaped tail rotor, upper module, lower module, different pitch of modules.

**Abstract.** In 1980 A.M. Grodzinsky from Mil Moscow Helicopter Plant, JSC, developed the X-shaped tail rotor model incorporating two modules of two blades in each one. This model was tested on aerodynamic adjustable bench. On the basis of the performed investigations main geometric parameters were selected with regard to Mi-28 helicopter main rotor having been designed, manufactured and installed on the helicopter successfully. Modernization of the serial helicopters, increase of the engines' power and installation of X-shaped rotor on other helicopters (Mi-24, Mi-8MT and Mi-38) required the improvement of aerodynamic characteristics of the tail rotor to provide necessary route control margins. To solve this problem experimental investigation based on the X-shaped tail rotor model developed by A. M. Grodzinsky were carried out on aerodynamic adjustable bench. The influence of differential blade pitch angle of two modules on aerodynamic characteristics of the rotor of the kind was investigated. The rotor similar from the geometric point of view to the series tail rotor of Mi-28 helicopter having got different blade pitch angles of the upper and lower modules was examined. The report presents the basic results of the conducted study and recommendations enabling improvement of the thrust characteristics of the X-shaped tail rotor consisting of two modules.

## MAIN SYMBOLS

| | | |
|---|---|---|
| $\varphi_{в}$ | - | blade pitch angle of the upper module, degrees; |
| $\varphi_{н}$ | - | blade pitch angle of the lower module, degrees; |
| $c_t$ | - | rotor thrust ratio, b/r; |
| $c_{t1м}$ | - | thrust ratio of one separate module, b/r; |
| $c_{tвм}$ | - | thrust ratio of the upper module incorporated in the rotor, b/r; |
| $c_{tнм}$ | - | thrust ratio of the lower module incorporated in the rotor, b/r; |
| $m_{к}$ | - | rotor torque, b/r; |
| $m_{к1м}$ | - | rotor torque of one separate module, b/r; |
| $m_{квм}$ | - | rotor torque of the upper module incorporated in the rotor, b/r; |
| $m_{кнм}$ | - | rotor torque of the lower module incorporated in the rotor, b/r; |
| $T_{рв}$ | - | tail rotor thrust, kg |
| $M_{к}$ | - | rotor torque, kgm; |
| $F_{рв}$ | - | tail rotor blade-swept area, m2; |
| $R_{рв}$ | - | tail rotor radius, m; |
| $H_{вн}$ | - | distance between the upper and lower modules, m; |
| $\psi_{вн}$ | - | pitch angle between the upper and lower modules, degrees; |
| $\lambda_{л}$ | - | blade lengthening, b/r; |
| $\sigma$ | – | rotor solidity, b/r. |

## INTRODUCTION

When developing the project of the single rotor Mi-28 helicopter, as a tail rotor an X-shaped structure of two-module rotor was selected, each module consisting of two blades. In 1980 in order to select parameters of this rotor Mil Moscow Helicopter Plant, JSC, conducted a number of investigations, including the experimental ones. A.M. Grodzinsky developed the X-shaped tail rotor model based on a two-bladed centrally-hinged tail rotor of the Mi-2 helicopter. The hub structure allowed changing the distance between the modules and the horizontal angle between the upper and the lower modules. For reasons of the structure the modules pitch angles were varied in such a way that the blade pitch of the upper and lower modules was the same.

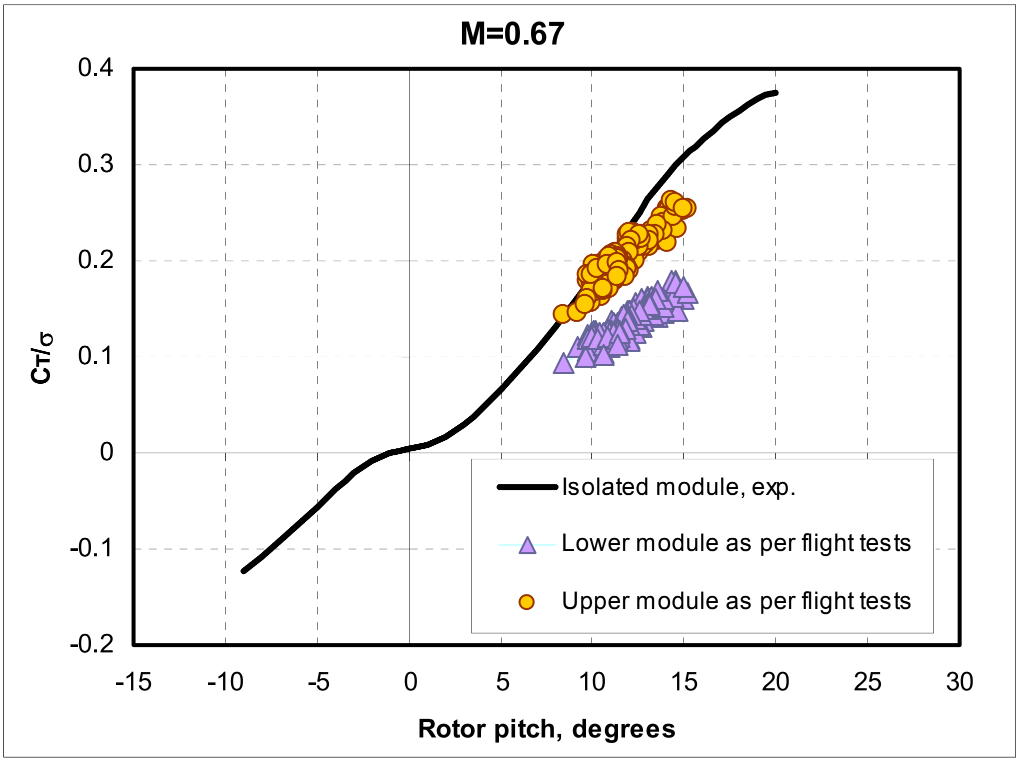



**Fig. 1**

In 1981 on the rotor adjustment test bench Mil Moscow Helicopter Plant headed by A.S. Braverman carried out experimental investigations with the elaborated tail rotor model to confirm the design results aimed at selecting the main structural parameters of full-scale tail rotor ([1]). The experimental parametric investigations accomplished on the rotor adjustment test bench with regard to aerodynamic characteristics of X-shaped rotor model depending on the distance and angular position between the modules allowed to specify the structural parameters of full-scale tail rotor for Mi-28 helicopter.

Further investigations of the full-scale tail rotor on the full-scale test bench of Mi-24 helicopter showed the advantages of the latter in comparison with the series one, three-bladed tail rotor used before on Mi-8 and Mi-24 ([2]) helicopters. This allowed considering the issue of application of a new X-shaped tail rotor on the above helicopters taken into account some structural upgrading. Further modification of the series helicopters, development of more powerful engines, as well as searching possibilities to install the above rotor on the new Mi-38 helicopter prototype required the improvement of technical characteristics of the existing X-shaped tail rotor.

The authors of this article developed the computational procedure which allowed determining the distribution of the main rotor overall thrust between the modules thereof by means of measuring the torque in the bottom part of the blade of each module within the flight tests of the helicopter. For hovering mode the results of flight tests of Mi-38 and Mi-24 helicopters were analyzed, which showed that given the similar blade pitch angles of the upper and of the lower modules the thrust between them is not shared equally. In fig.1 for illustration are shown experimental results obtained on X-shaped tail rotor having been installed on Mi-38 helicopter prototype and on aerodynamic rotor adjustable test bench of Mil Moscow Helicopter Plant, JSC ([3]).

The presented results and the accomplished estimations showed that the lower main rotor module which is under the inductive influence of the upper module has got the thrust which is 30…50 % lower than the established. The theoretical analysis showed that for the flat rotor which blades revolve in the same plane the interaction between the blades is primarily determined by the influence of the previous blade tip vortex. For the double-level X-shaped rotor to the above influence are also added inductive velocities proceeding from the upper module. As a result the inductive current downwash at the lower couple of blades gives rise to reduction of the angles of incidence in the blade's profile and to reduction of the lower module thrust correspondingly.

The performed analysis suggested an idea that by means of appliance of the higher blade pitch angles of the lower module in comparison with the upper module it is possible to improve aerodynamic characteristics of X-shaped tail rotor. To check up this idea the series of experimental investigations was carried out on the rotor adjustable test bench of Mil Moscow Helicopter Plant, JSC, with the same X-shaped tail rotor, however the modules had different pitch angles. The results of these investigations are shown in this report.

## 1. X-SHAPED TAIL ROTOR MODEL AND PROCEDURE OF ACCOMPLISHING THE TESTS

As a test item it was used an X-shaped tail rotor model having been developed by A.M. Grodzinsky on a basis of a two-bladed centrally-hinged tail rotor of the Mi-2 helicopter. He developed a special hub allowing modifying within the wide range the distance and horizontal angle between the modules (fig.2).

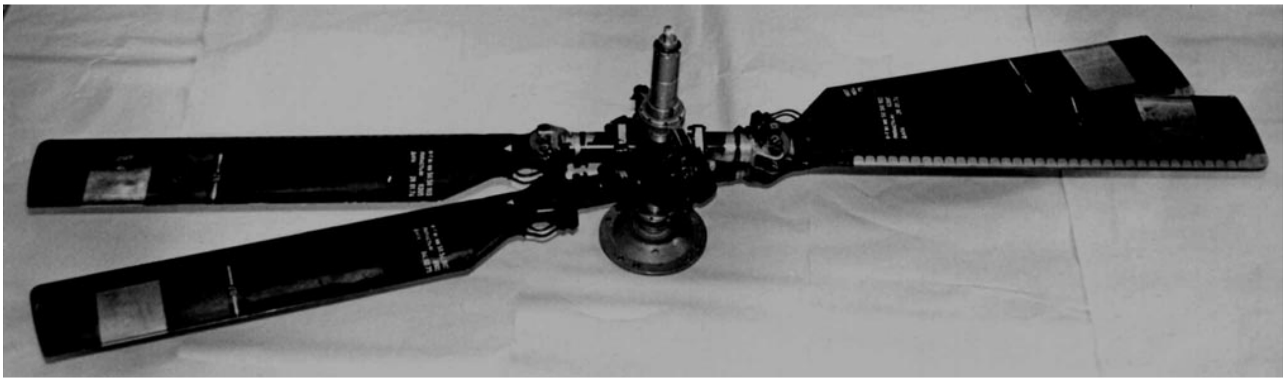


**Fig. 2**

Tail rotor blades of Mi-2 helicopter have got the following technical parameters:

- rotor diameter, 2.7 m
- blade chord, 0.22 m
- blade profile NACA00-12
- number of blades, 2 pcs.

The operating speed of the model and full-scale rotor corresponds to the alteration of Mach number of the blades' tips with overall conditions within the range of $0.5<M<0.7$.

The range of alteration of the rotor blade pitch in experimental investigations changes within the range of $-13°\leq\varphi°\leq+26°$. However as a result of limited engine torque the maximum value of the modules pitch was limited depending on Mach number.

When accomplishing the experimental investigation the following module designation system is adopted. The module located above in the direction of a positive value of the rotor thrust is called “upper module”. The angle between the higher and the lower modules is considered positive if the higher module is behind the lower one.

Experimental studies carried out in 1982 demonstrated excellent properties of the tail rotor design and made it possible to select parameters for the full-scale tail rotor of the Mi-28 helicopter. During testing this model tail rotor its configuration changed only with respect to spacing $H_{BH}$ and angle $\psi_{BH}$ between the modules. The higher and the lower modules pitch maintained the same with any rotor configuration. With the object of checking the idea on possible improvement of characteristics of X-shaped rotor the actual work aimed at determining the influence of difference in the pitch angle between the higher and the lower modules for the assigned X-shaped rotor configuration, the results of the above work are presented below.

As basic configuration the rotor version was selected so that it would correspond as per its relative parameters to full-scale Mi-28 helicopter tail rotor which has got the following parameters: the relative distance between the modules constitutes H/R (tail rotor radius) = 0.1, while the angle between the higher and the lower modules $\psi = 42°$. As a result of structural distinctive features of the hub the actual angle between the modules of the model rotor has been adjusted a slightly smaller, i.e. $\psi = 38°$. Besides that there also exists the difference between the blade extensions as follows: full-scale blades have got the extension $\lambda = 8{,}125$, while the model rotor blades - $\lambda = 6{,}125$. The last circumstance affects the difference of aerodynamic characteristics of full-scale and model rotors, but analysis of its influence was beyond the scope of this work. The tests were carried out on the rotor test bench of Mil Moscow Helicopter Plant, JSC. The general aspect of the test bench which has got installed a separate module is shown in fig.3.

**Fig. 3**

The tests of each version were being carried out consecutively starting with the lower boundary of the tail rotor pitch envelope every two degrees to the limit set by the torque capacity of the rotor test bench. The tail rotor thrust and torque were measured under each condition at three values of the Mach number. The tests covered five variants of the X-shaped tail rotor with different setting angles of the upper and lower modules: -2.38°; -0.15°; +2.05°; +3.11°; +4.21°. For comparative analysis the rotor consisting of a single two-bladed module was tested.

## 2. RESULTS OF TESTS FOR DETERMINING THE INFLUENCE OF THE INCREASED LOWER MODULE PITCH ON AERODYNAMIC ROTOR CHARACTERISTICS

The results of testing each variant were obtained in a dimensional form and were then converted into nondimensional coefficients, following which the coefficients were plotted versus the setting angle and Mach number. Originally, the tail rotor consisting of a single module was tested for evaluation of its aerodynamic characteristics and for subsequent comparison with the variants of the two-module four-bladed tail rotor. The obtained results are given in fig.4.

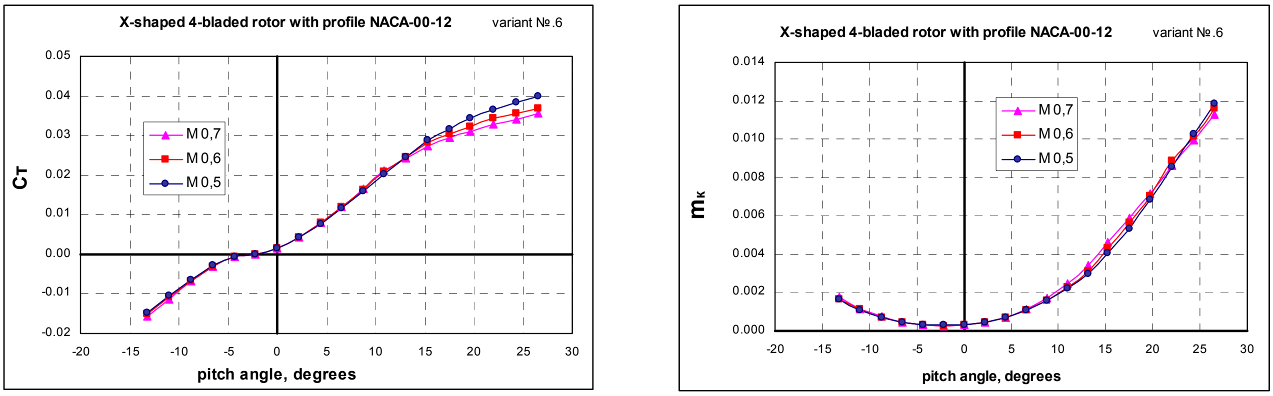



**Fig. 4**

Later, subject to testing were two-module four-bladed variants of the X-shaped tail rotor, whose parameters are described above. As an example in fig.5 are given such dependencies for the rotor variant with practically similar upper and lower modules pitch angles ($\psi_{BH}$ = -0.15°).

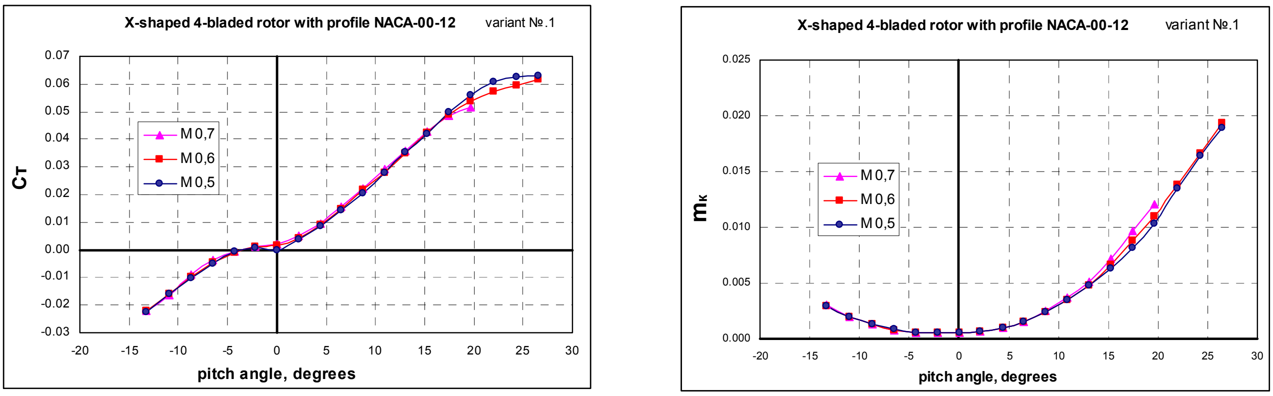



**Fig. 5**

In 1994 V.A. Ivchin and M.A. Gringauz tested on the same rotor test bench the full-scale X-shaped rotor of Mi-28 helicopter including the single-module two-blade variant. Due to the higher geometric dimension and higher loads exceeding the power of the rotor test bench, these tests were carried out within a fairly limited scope, however it will be interesting to compare aerodynamic characteristics of full-scale rotor and its close model. In fig.6 are given the dependencies of aerodynamic coefficient of the single module two-bladed full-scale rotor and its model, obtained for Mach number M=0.6.

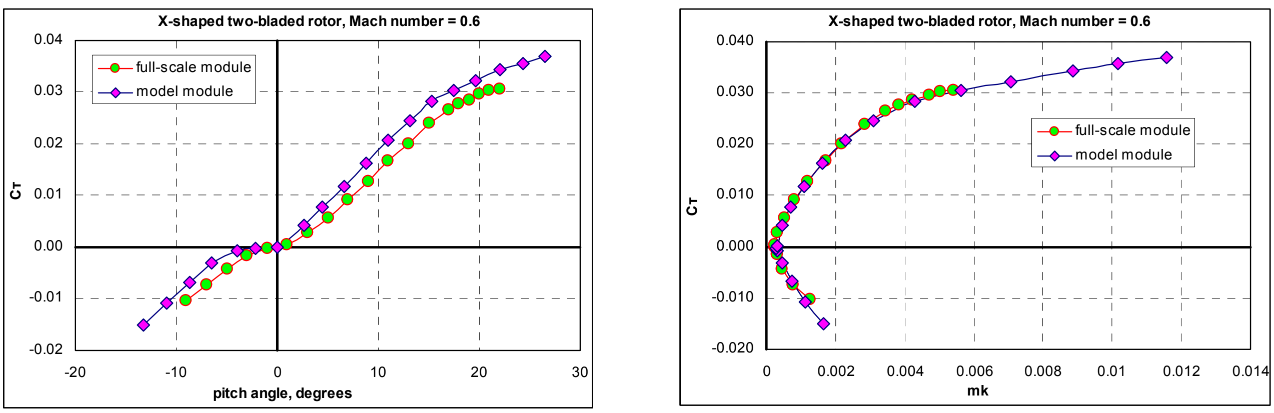



**Fig. 6**

From the graphs it can be seen that empirical relations between the thrust coefficient and the collective pitch of the full-scale tail rotor and its model are different. The reason is that the geometric parameters of the rotors are different both in elongation and in the blades profile as mentioned before. As a result the rotors have got different solidity and thrust coefficient, that's why their characteristics are different. The solidity of the model two-bladed rotor amounts to $\sigma_m$= 0.1038, while of full-scale rotor – to $\sigma_n$=0.0784. From the right-hand chart in fig.6 appears that the rotors' polar lines are very close though the full-scale two-bladed rotor has got somewhat higher values of the thrust ratio given the same values of the torque ratio.

Figure 7 presents similar graphs for four-bladed tail rotors, one of which is full-scale tail rotor of Mi-28 helicopter, while another one is a model rotor. From the graphs it can be seen that conclusions drawn for single-module tail rotors can, with good reason, be applied to X-shaped four-bladed tail rotors. At the same time one should take into account the difference in the four-bladed rotors solidity: for the model rotor it amounts to $\sigma_m$= 0.2076, while for full-scale rotor - $\sigma_n$=0.1568.

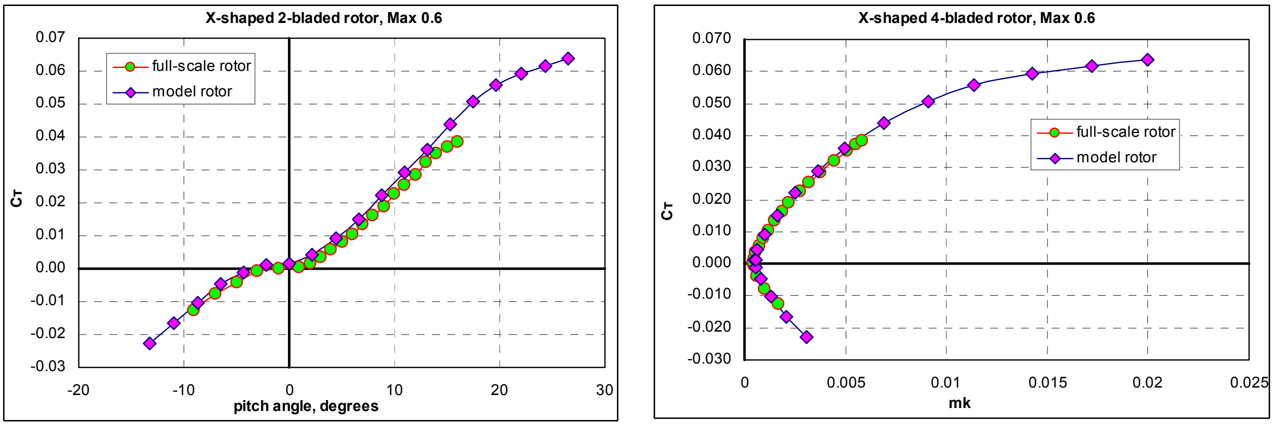



**Fig. 7**

As the rotor polar lines shown in the right-hand chart in fig.6 and 7 don't reflect perfectly well the difference in aerodynamic quality of rotors, fig.8 gives a comparison of relative performance indexes of rotors for the same test conditions. For the two-bladed rotor the relative performance index is practically similar for full-scale and model two-bladed module in spite of the fact that on full-scale blades the higher quality profile is fitted out. However the model two-bladed module has got 32% greater solidity, owing to which its relative performance index is compared with relative performance index of full-scale two-bladed rotor.

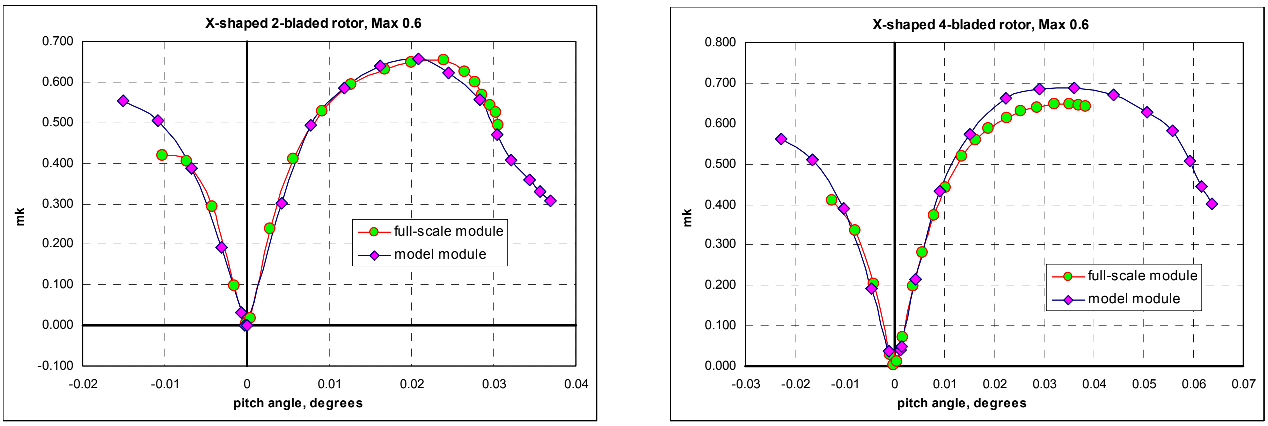



**Fig. 8**

For four-bladed X-shaped tail rotors, the picture is different. In this case the increased solidity of the model rotor predominates over the best quality profile of full-scale rotor, and its relative performance index is 4% higher than the latter. In general the given comparative results of experiments suggest that the experiments with the model of the X-shaped tail rotor will ensure a good correlation with aerodynamic characteristics of full-scale rotor.

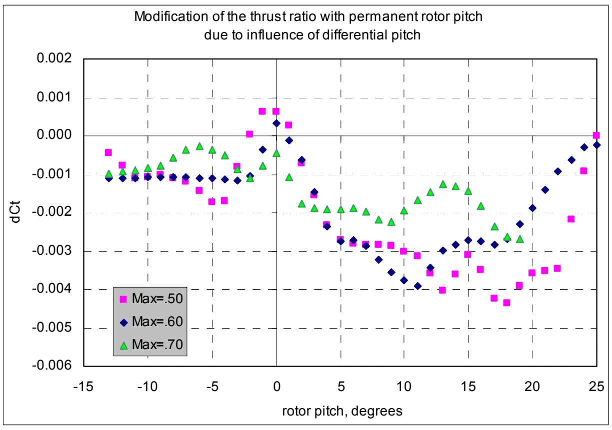
The main problem set in the given experimental investigations was aimed at determining a possibility to increase the thrust characteristics of the tail rotor by means of introducing the structural difference in the pitch angle between the upper and the lower modules. The full-scale tail rotor of Mi-28 helicopter was designed with similar pitch angles of the upper and the lower modules blades. This variant is considered as the basic one (fig.5) and all the rest of the variants were analyzed in comparison with the basic one in the form of modification of aerodynamic coefficient of the rotor collective pitch.

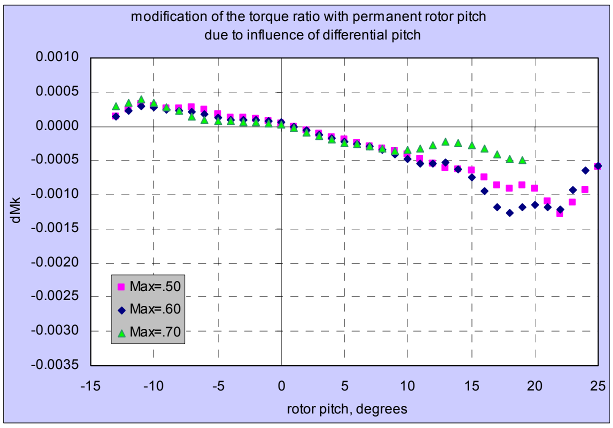
In connection with the fact that in all the rotor variants except the basic one the upper and lower modules have got different pitch angles, the rotor pitch to be applied as a parameter is considered as a pitch angle of the upper module blades.

In fig.9 are given the charts of modification of thrust and torque coefficient of the X-shaped tail rotor depending on difference in the module pitch angles, rotor collective pitch and Mach number. In the left-hand charts are given the relations of the rotor thrust ratio increment, while in the right-hand charts are given the relations of the torque ratio increase.

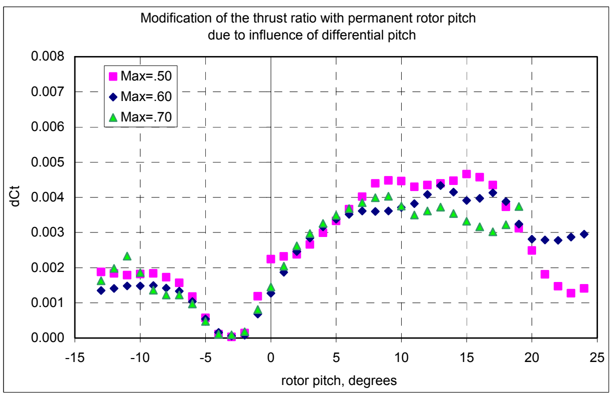
Comparison of variants with different pitch angle of the blade lower module allows making some qualitative conclusions. In the first place it is seen that given the lower pitch of the lower module the total rotor thrust decreases, while given the higher pitch – the latter increases. It does not depend on the direction of the overall rotor force, upward or downward. It is possible to make analogous conclusions for the rotor torque ratio, i.e. with the lower module pitch increase the torque also increases. The next conclusion can be made as follows: the effect originated due to the lower module pitch increase is not permanent, but it has got the pronounced maximum which is within the range of 10° … 15° of the rotor pitch (equivalent to the pitch angle of the upper module).

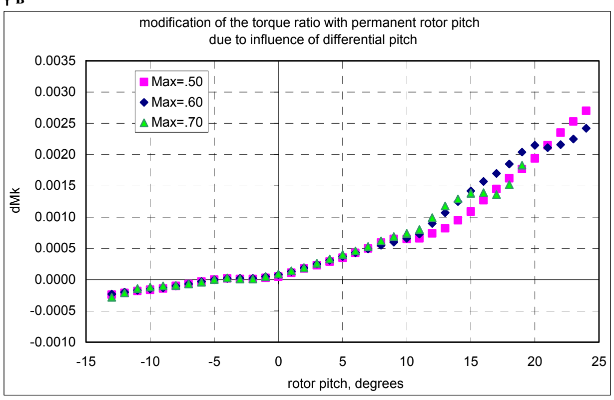
**Variant 1, $\varphi_{\text{н}}-\varphi_{\text{в}}=-2.38^\circ$**



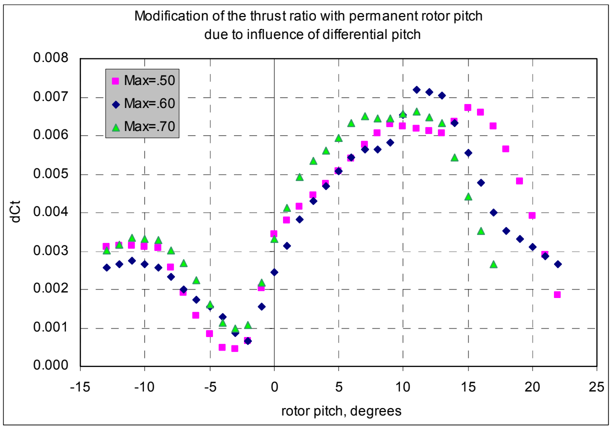



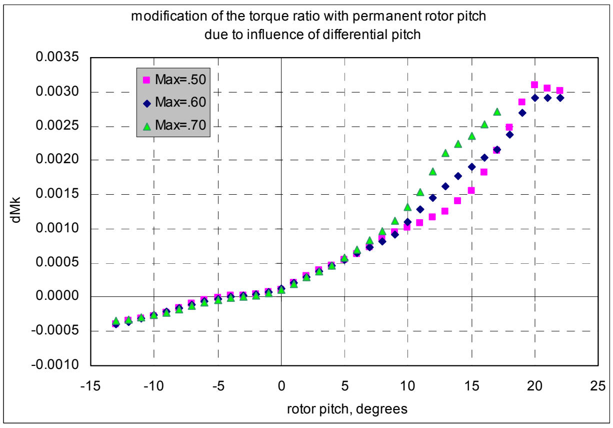

**Variant 2, $\varphi_{\text{н}}-\varphi_{\text{в}}=+2.05^\circ$**



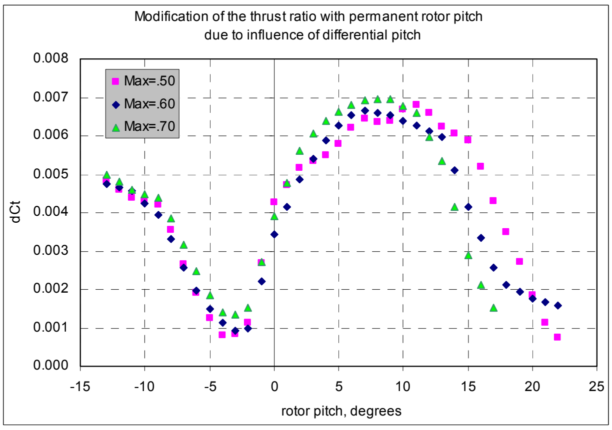



**Variant 3, $\varphi_{н}-\varphi_{в}=+3.11°$**




**Variant 4, $\varphi_{н}-\varphi_{в}=+4.21°$**



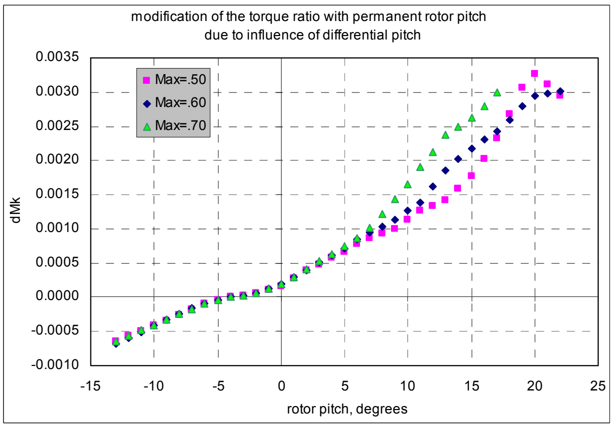
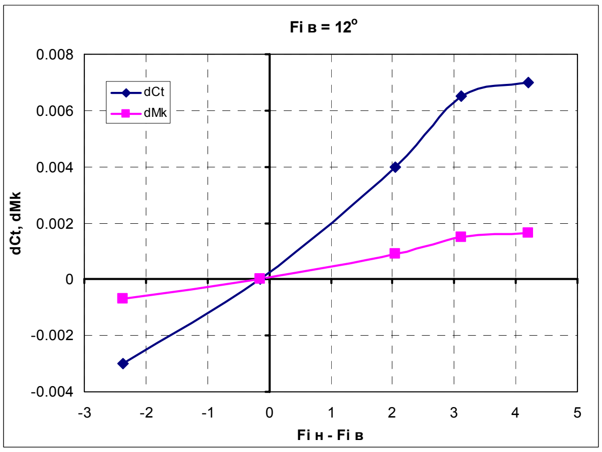




**Fig. 9**

Further on it can be seen that the maximum increase of the rotor thrust increment is obtained with the difference in the pitch angle between the modules amounting to $\varphi_{н}-\varphi_{в}=+3.11°$, and then comes saturation, and later on increase of the difference in the modules pitch does not result in the increment of the rotor thrust. In fig.8 it is also seen that in the section of the beginning of derangement on the blades ($\varphi>15°$) the effect caused by the increment of the lower module pitch decreases abruptly. The maximum increase of the rotor thrust for the third variant, given $\varphi_{н}-\varphi_{в}=+3.11°$ and $\varphi=12°$ amounts to 18% from the original variant thrust, while for $\varphi=22°$ the increase of the thrust amounts to 6% approximately. In fig.10 are given the integral charts of modification of the thrust ratio and the rotor relative performance index depending on the difference in pitch angles of the upper and the lower modules for the rotor pitch amounting to $\varphi=12^{o}$ . From the right-hand chart in fig.8 it is also evident that the difference in the upper and lower modules pitch results in decreasing the rotor relative performance index. However for the tail rotor it is not fundamentally important.



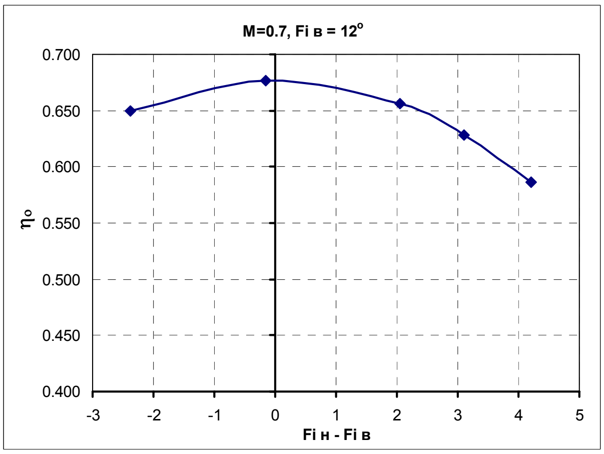




**Fig. 10**

The obtained results also show that the increase of Mach number slightly reduces the effect caused by the increase of the lower module pitch. It is better seen with φ>10° (fig.8). The phenomena revealed in the experiment are sequent of interaction between the modules which depends mainly on the interaction of the blade tip vortexes with the following blades.

## 3. PRELIMINARY EVALUATION OF THE INFLUENCE OF DIFFERENT MODULE PITCH ON DISTRIBUTION OF X-SHAPED ROTOR THRUST BETWEEN THE MODULES

Analysis of the flight tests of Mi-38 helicopter which has got installed X-shaped tail rotor of Mi-28 helicopter, made it possible to determine the correlation between the upper and the lower modules. This value was determined by means of measuring torque in the thrust plane in the blade butt of the upper and lower blade modules. Like it was mentioned before this rotor has got similar blade pitch angles. Fig.11 shows the results of these tests in the form of total rotor thrust-torque relation in the thrust plane of every module measured in two butt sections of the rotor. To evaluate the thrust distribution between the modules of X-shaped rotor was accepted the following approach: the lower module with the positive rotor thrust value influences the upper module only from the point of view of inductive current downwash proportional to $\Delta v_{ind} \sim \sqrt{c_T}$, off tip vortexes of the lower module. In this case we will assume that the inductive current downwash is equivalent to the upper module pitch modification.

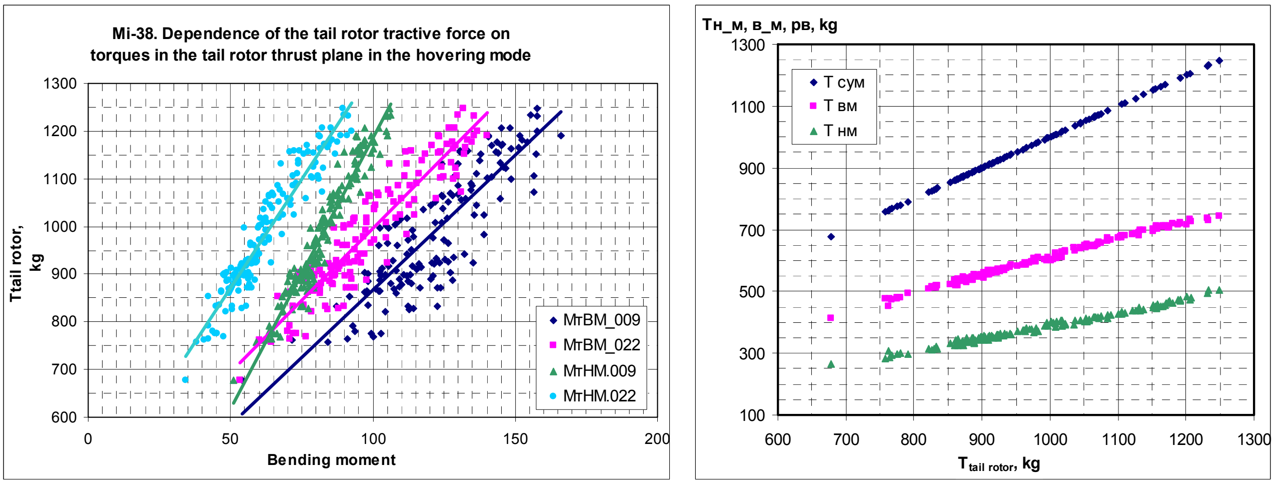



Fig. 11

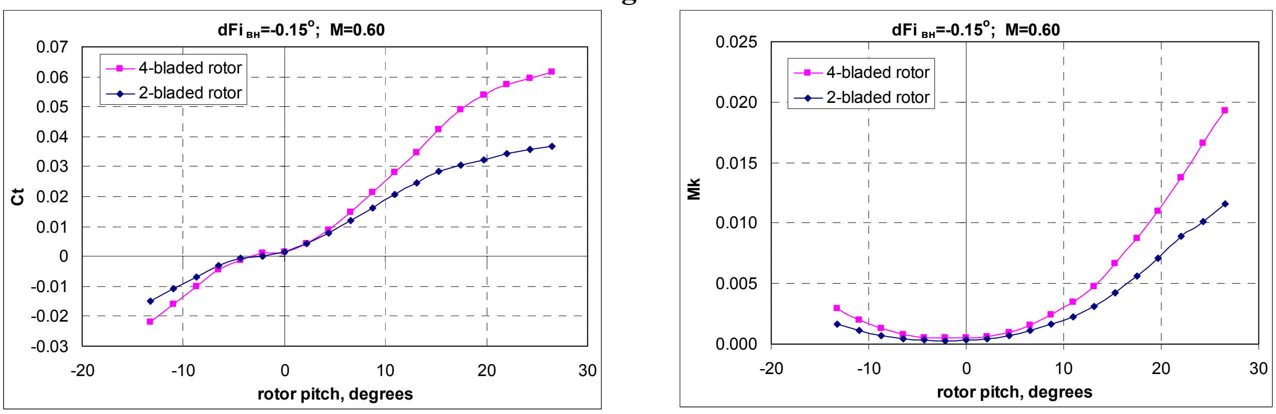



Fig. 12

Such approach allows determining aerodynamic characteristics of the upper module according to dependences obtained for isolated single-module rotor:

$$c_{t\,вм} = c_{t1м}(\varphi - \Delta\varphi_{вн})$$

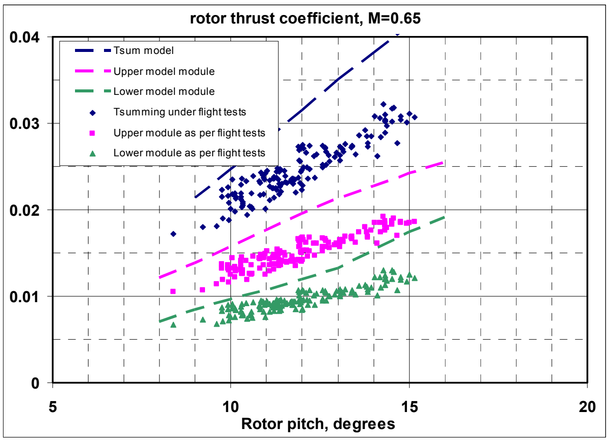
$$m_{k\,вм} = m_{k1м}(\varphi - \Delta\varphi_{вн})$$

$$\Delta\varphi_{вн} = \kappa_{вн}\sqrt{c_T}$$

The ratio of influence of the lower module on the upper one was determined from the analysis of flight tests of full-scale tail rotor on Mi-38 helicopter (right-hand chart in fig.11).

The above approach was checked up on the model X-shaped rotor for the variant of the rotor with similar module pitch angles. Figure 12 presents comparative experimental characteristics for this variant of the tail rotor and characteristics of the single-module model tail rotor at Mach number equal to M=0.6

Applying the empirical dependences according to interaction of the rotor modules given before, was determined the correlation of thrust between the upper and the lower modules for the model variant of the rotor. In the left-hand chart in fig.13 are given the comparative charts of modification of the thrust ratio depending on the rotor pitch for the full-scale and model rotors with similar upper and lower pitch angles. In the right-hand chart in fig.13 is given the ratio of the thrust distribution between the modules in the relative value to the total value of the rotor thrust. In fig.13 it is seen that though the chart for the model rotor differs from the chart for the full-scale rotor, however the correlation of the thrust between the upper and the lower modules is similar for both rotors. The difference in the tendency of modification of relative coefficient is observed with the increase of the model and full-scale rotors pitch. This difference is explained by different lengthening and distinction in the blades profiles.



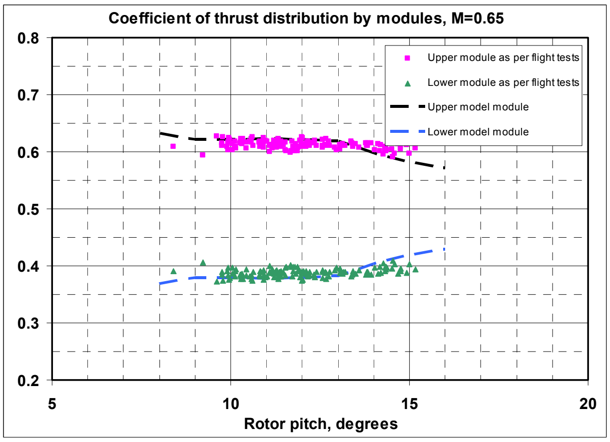
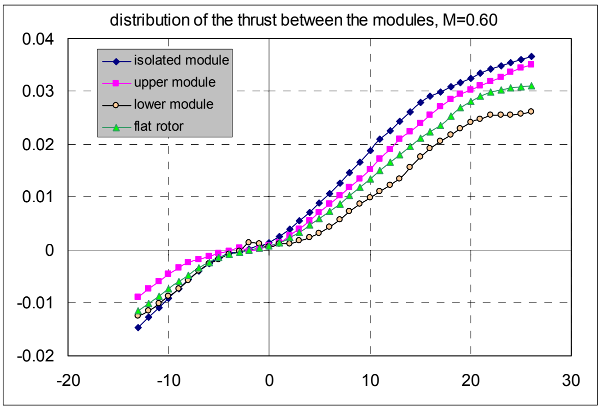



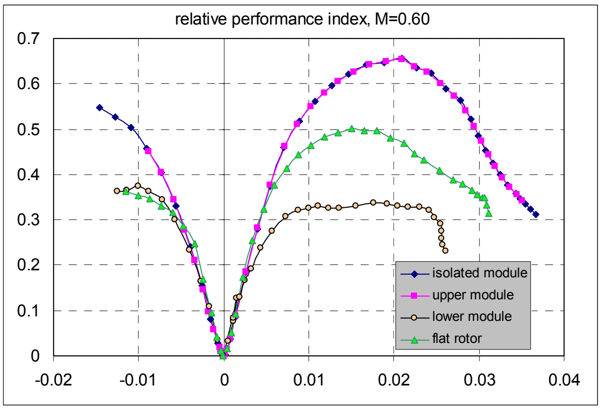

**Fig. 13**

The analyzed approach was widely used for other variants of model rotors for the purpose of preliminary evaluation of the influence exerted by the difference in the blade pitch angles on the distribution of the rotor thrust between the modules. In fig.14 are given the charts of modification of the coefficient of the modules thrust and their relative performance indexes depending on the modification of the pitch for the versions of the model rotor, having been tested within these investigations. The data are given for the value of the Mach number of the blade tips as follows: M=0.6. For reference in fig.14 are given the charts for the single-module rotor and for one pair of blades of ordinary plane four-bladed rotor with available blade geometry identical to the model rotor blades. The last chart has been made by means of recalculation of characteristics of the single-module rotor on the basis of computation procedure.

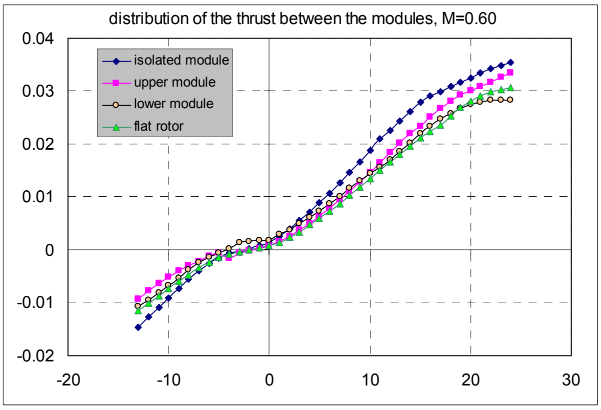
The obtained calculation results show that given the similar modules pitch angle the upper module has the higher thrust than the pair of blades of an ordinary plane rotor, while the lower one has the lower thrust. At the same time the relative performance index of the lower module is less than that of the pair of blades of the flat four-bladed rotor. The relative performance index of the upper module coincides with the single-module rotor, which is determined by the adopted design approach to the definition of the thrust distribution between the modules. At the same time it is evident that the single-module two-bladed rotor will have the higher relative performance than the pair of blades of the flat four-bladed rotor. It is also seen that the increase of the lower module pitch in comparison with the upper module pitch will result in incrementing its thrust in all the pitches, however, given the higher rotor pitches the increase of the thrust gradually diminishes. This is the sequent of the increased inductive downwash and incremented influence of the upper module tip vortex (as a result of its drawing near to the lower module) with increase of the rotor pitch.

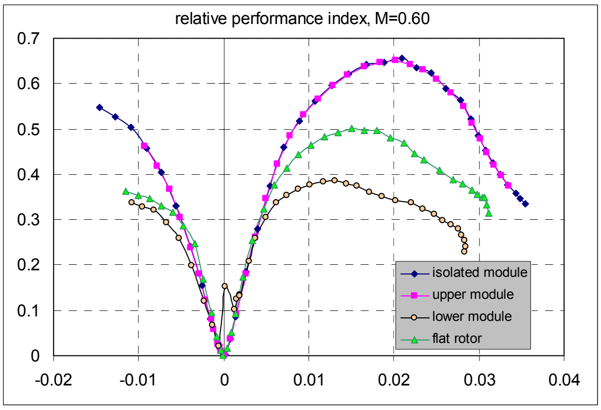
**Variant 1, $\varphi_{н}-\varphi_{в}=-2.38^\circ$**



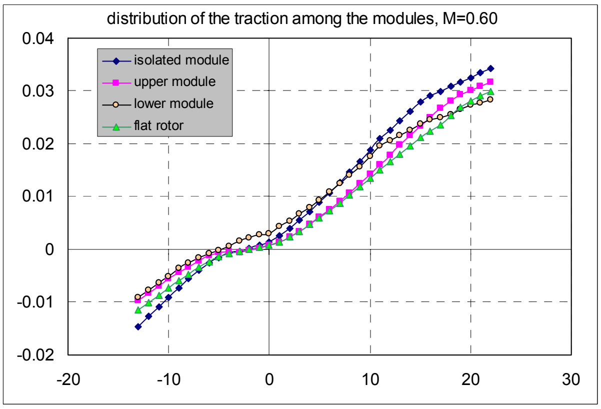



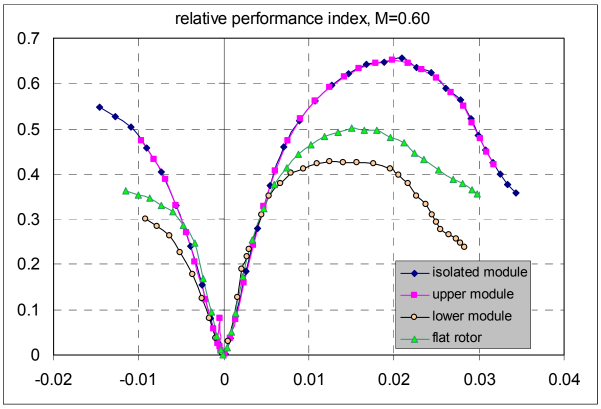

**Variant 0, $\varphi_{н}-\varphi_{в}=-0.15^\circ$**



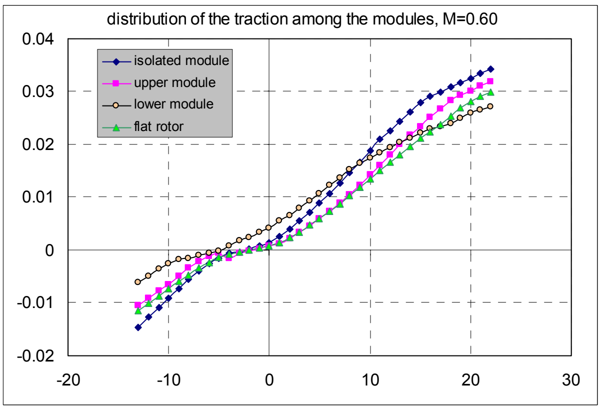



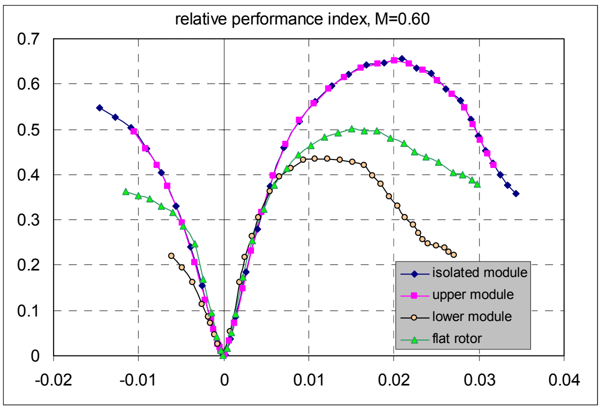

**Variant 2, $\varphi_{н}-\varphi_{в}=+2.05^\circ$**




**Variant 3, $\varphi_{н}-\varphi_{в}=+3.11^\circ$**



**Variant 4, $\varphi_н$-$\varphi_в$=+4.21°**

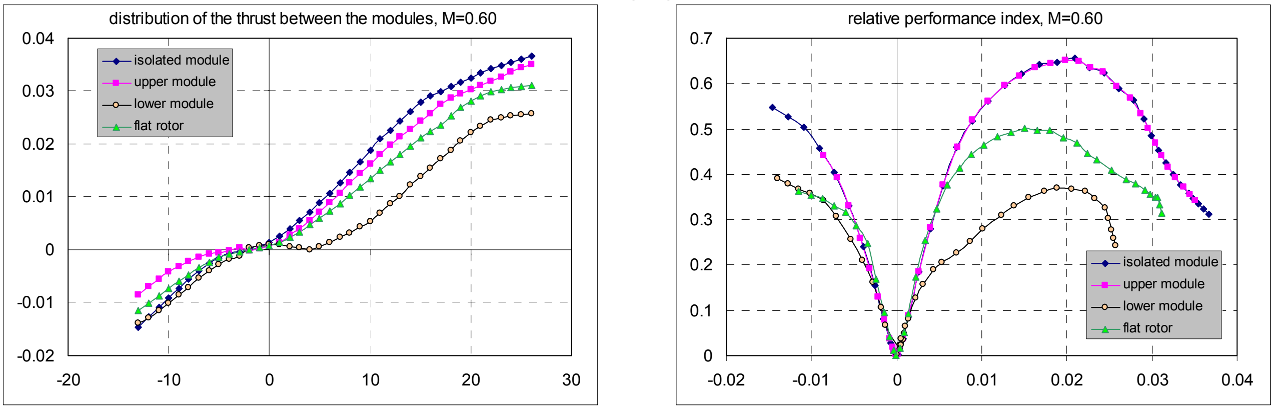



**Fig. 14**

It is also interesting to emphasize at a negative value of the rotor thrust the curves of the relative performance index are not symmetrical with regard to the rotor pitch corresponding to the thrust zero value, though the profile of the model rotor blades is symmetrical. Such phenomenon is explained by the configuration of the X-shaped tail rotor whose upper blade trails behind the lower one. At a positive thrust value, the inductive velocity is directed downward and the tip vortex of the upper rotor passes far from the trailing blade of the lower module. At a negative thrust, the inductive velocity is directed upward and the tip vortex of the lower rotor passes close to the trailing blade of the upper module. This results in increasing the tip losses and reducing the relative rotor performance index at negative thrust coefficients.

## 4. CONCLUSIONS

1. The accomplished experimental investigations showed that the increase of the lower module pitch angle in comparison with the upper module increases the total thrust of the X-shaped rotor up to 18 % at φ=12° and up to 6 % at high angles φ=22°.
2. A positive effect of increasing the setting angle of the upper module can be practically achieved at the difference in the modules pitch angles Δ φ=+3°.
3. The lower module pitch angle increase in comparison with the upper module also results in reducing the relative performance index of the X-shaped tail rotor by $\Delta\acute{\eta}_o$=-0.05, at the difference in the modules setting angles Δ φ=+3°, which is not a critical weakness of the tail rotor.
4. By means of recalculation of the rotor experimental characteristics it was found out that the two-bladed rotor variant has the higher performance index than the pair of blades of the four-bladed flat rotor.

## REFERENCES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