Tilted Tail Rotor Advantages And Problems To Solve

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Abstract

Some aspects of the problems brought in by the tilted tail rotor are discussed in the paper. Both advantages gained by the helicopter in this case and challenges are considered.

The most attractive advantage is an increase in the helicopter lift almost without any increase in the engine power required for hover.

The challenges are as follows:

- Extra yaw-pitch cross-coupling in the flight control system;
- Provision of acceptable longitudinal trim and dynamic stability of the helicopter;
- Provision of acceptable level of the main rotor blade flapping;
- Increase in loads applied both to the main rotor hub and mast.

Different ways of solving the above problems are considered in the paper both for existing helicopters whose flight performance can be improved by introducing the above design feature and new helicopters.

Introduction

It is well known that some Sikorsky helicopters have such a unique design feature as tilted tail rotors. The first look at this design can easily show that the tail rotor thrust vertical component provides the helicopter with some extra lift, which is very attractive for the designers wishing to get an increase in the helicopter payload capacity.

But there are few cases when a new design feature or an invention brings in only benefits and does not make the designers deal with technical problems involved.

Modernization of the production helicopters is the least expensive and fastest way to improve flight performance of the aircraft. This is the shortest way to increase the efficiency of Russian helicopter units operating mainly the MI-24 combat helicopters and of commercial airlines operating different modifications of the MI-8 helicopters.

The Mil Helicopter Plant designers have been considering a tilted tail rotor as a way to improve flight performance of Mil helicopters.

Advantages Of Tilted Tail Rotor Concept

A helicopter tail rotor requires up to 14% of the engine power at hover. This is quite a considerable value to pay for the asymmetrical aerodynamic configuration of a single-rotor helicopter. So one can easily understand the designers' efforts to make up for this helicopter disadvantage to some extent.

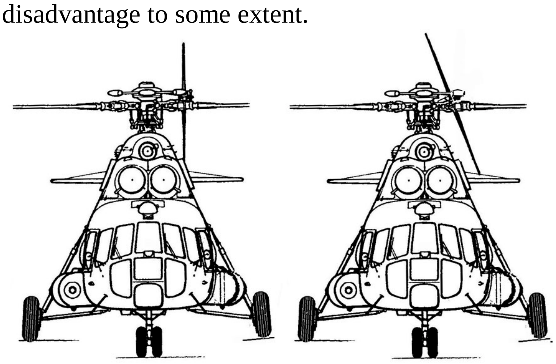

Fig. 1. MI-8 helicopter front view

One of the attempts is such a unique design feature as the installation of a tail rotor at an angle relative to the helicopter longitudinal axis in such a way that the tail rotor thrust would give an upward vertical component (Figs 1 and 2). As can be easily seen, an

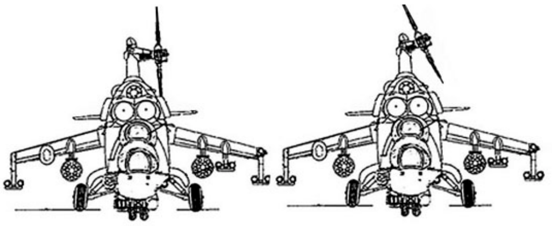

Fig. 2. MI-24 helicopter front view

extra helicopter lift can be obtained for quite a slight increase in the tail rotor power required to counteract the main rotor torque. It will be shown below that one can talk about a slight increase in the TR power required only up to some TR tilt angle. The analysis made for the MI-8 and MI-24 helicopters has shown that the total lift of the two helicopters could be increased by 200+ kgf. These helicopters have been chosen for the analysis as they have already been in production for a long time and their different upgrades are under consideration. Besides, the helicopters are equipped with the same kind of the tail rotor. The impact of the TR tilt angle on the helicopter total lift is shown in Figs.3 and 4. Change in the total lift of the MI-24 is presented by the ratio of the total lift of the aircraft with the tilted tail rotor to the total lift of the helicopter of the initial configuration. Attention should be paid to the fact that the total lift of each of the helicopters grows with the TR tilt angle increase to a certain value although the vertical component of the TR thrust still increases.

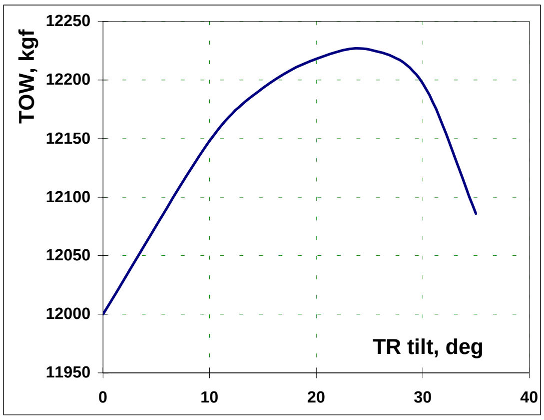

Fig. 3. MI - 8 total lift vs. TR tilt angle

This fact is explained by the increase in the TR power required, as shown in Figs. 5 and 6, because the necessary horizontal component of the TR thrust must be provided to counteract the main rotor torque. An analysis was made for the helicopter hovering at the OGE ceiling where the full takeoff power of both engines is required. If the engine power remains constant the redistribution of the total power between the main and tail rotors occurs so an increase in the required TR power takes place at the expense of the main rotor power loss.

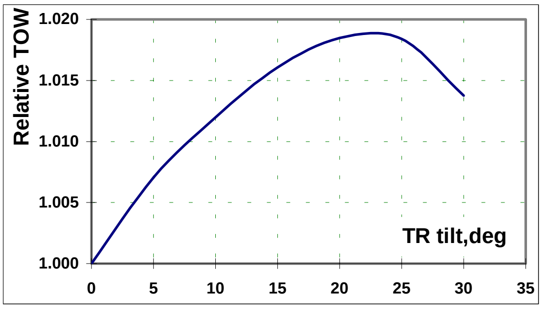

Fig. 4. MI-24 relative total lift vs. TR tilt angle

Calculations of the TR thrust and power required in hover were carried out assuming that the horizontal component of the TR thrust should be sufficient to counteract the main rotor torque. Figs. 5 and 6 show that the required TR power starts to drastically grow at the tilt angle exceeding 10°.

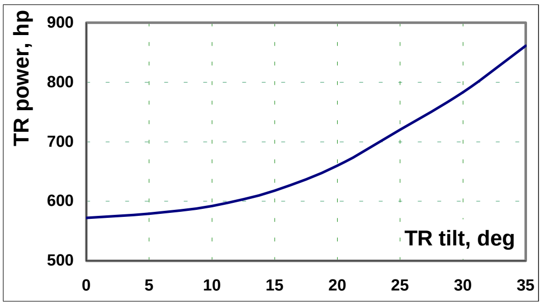

Fig. 5. MI -8 TR power required for hover ceiling vs TR tilt angle

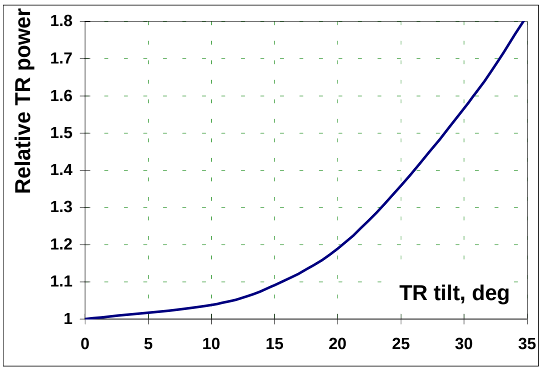

Fig. 6. MI-24 TR power required for hover ceiling vs. TR tilt angle

And here the following question is to the point. What TR tilt angle can be considered as an acceptable one from the point of view of power reasons? It is obvious that some extra lift equal to the vertical component of the tilted TR can be obtained by increasing the main rotor power. Calculations of the main rotor lift in hover were made to answer the raised question. The power of the main rotor in hover was increased by the values equal to the TR power required at different TR tilt angles. Calculations were performed for the most critical flight condition corresponding to hovering of each of the two helicopters at the OGE hover ceiling.

Let us consider the diagrams in Figs. 7 and 8, where the results of these calculations are presented together with the diagrams from Figs. 3 and 4.

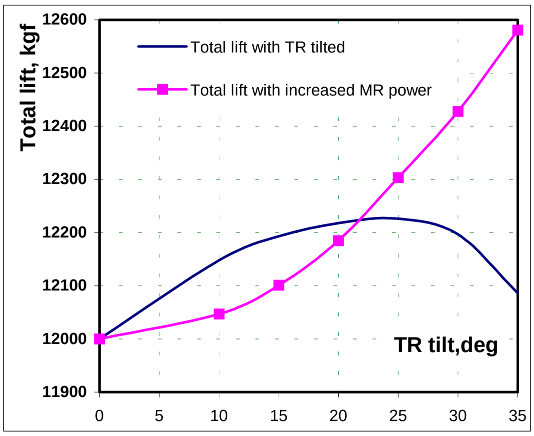

Fig. 7. Increase in MI-8 total lift due to both TR tilt and increase in power transmitted to MR

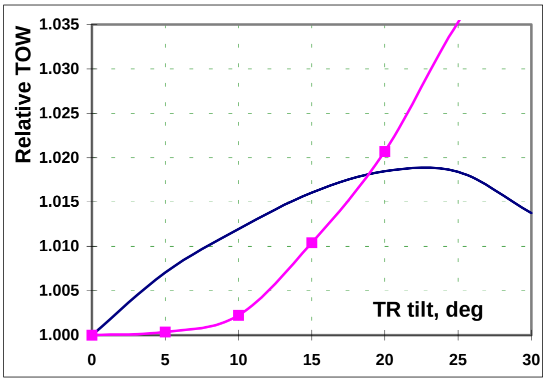

Fig. 8. Increase in MI-24 total lift due to both TR tilt and increase in power transmitted to MR

As can be seen, the tilt of the MI-8 and MI-24 tail rotors exceeding 22° and 24° respectively are disadvantageous from the power point of view. The fact is that the increase in the main rotor power corresponding to the values of the extra power consumed by the tilted TR at the above angles produces a higher main rotor lift than that of the tilted TR power leading to an increase in the vertical component of the TR thrust.

The same conclusion can be obtained considering the ratio of the increase in the total helicopter lift to the increase in power for a conventional helicopter and a helicopter equipped with a tilted tail rotor. For instance, the curves obtained for the MI-8 are shown in Fig. 9.

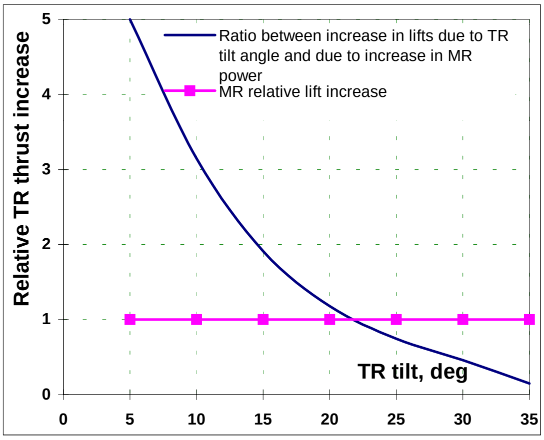

Fig. 9. Tilted TR concept efficiency

It is obvious that the TR tilt optimal from the power point of view depend on the aerodynamic performance of the TR and on the TR Figure of Merit in hover in particular.

The Mil Design Bureau is developing a new medium lift helicopter at the moment. The possibility of the tilted TR implementation in this helicopter has been thoroughly considered. In this connection a similar analysis was made for this helicopter too. The aerodynamic layout of the TR of this helicopter is much better than that of the MI-8 and MI-24 tail rotors. This is a result achieved by using new improved blade airfoils and optimal geometric blade twist.

It has turned out, that an optimal TR tilt angle providing the helicopter with the maximum growth of the total lift is within the range of angles from 32° to 38° and, as can be seen from Fig. 10, an increase in the helicopter lift can be achieved up to 3% of the TOW. The results of the calculations presented in Fig. 11 show that an intensive growth of the TR power required begins only at the tilt angle exceeding 20°.

Thus an improved aerodynamic layout of the

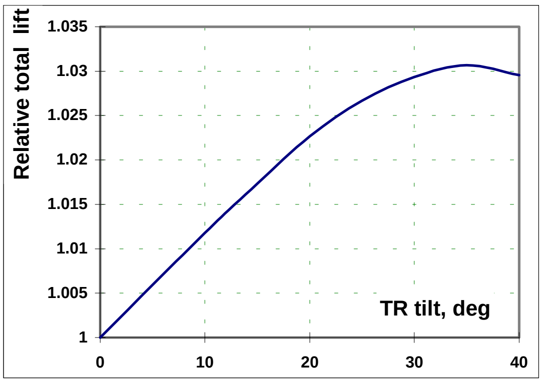

Fig. 10. New helicopter total lift vs. TR tilt

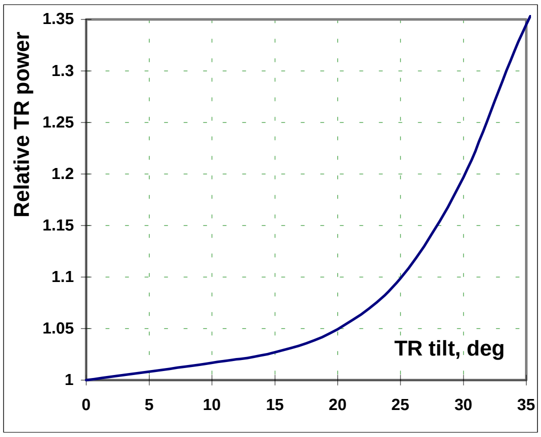

Fig. 11. Impact of TR tilt of a new light helicopter on TR power required

TR blades results in a possibility of obtaining the extra lift at the power consumption lower than that of the MI-8 and MI-24 helicopters.

We believe that the advantages provided by the tilted TR are not only limited to an increase in the total lift of the helicopter. There are other positive aspects of the tilted TR for the helicopter. They are applicable to design features that can ensure some weight saving of the helicopter structure.

The tail and main rotors flap in flight. Therefore the tail rotor should be placed at a safe distance from the helicopter structure to provide the necessary rotor blade-to-tail boom clearance in all flight conditions. As a rule, the TR shaft of selected length solves the problem. When the tail rotor is tilted, the distance between the blade tips and the tail boom increases in case of the tail rotor used as a tractor and therefore a shorter drive shaft of the tail rotor can be used. As a result, the weight of the TR gearbox can become lighter too. Besides, in this case loads transmitted to the tail boom from the tail rotor become lighter resulting in a lighter tail boom structure. However, if the decrease in the loads applied to the tail boom can be taken into account only for a new helicopter being under development, as the structure of the modified production helicopter, mainly, remains the same, so some weight saving in the TR gearbox can be achieved in both cases.

Let us consider another feature that can lead to some weight saving of the helicopter structure.

The TR thrust vertical component providing the helicopter with the extra lift produces an extra negative pitching moment as well. The moment should be counteracted anyhow. We believe that one of the most efficient ways to do that is a shift of the helicopter center of gravity relative to the main rotor axis backward at the expense of shifting the cargo and crew cabins, in particular. As a rule this move leads to a shorter center section of the fuselage and, consequently, to weight saving. It is clear that such a change in the helicopter's layout can be brought about while developing only a new helicopter.

As far as we can see, these are all the advantages that the tilted TR concept can provide. Problems inherent in this concept and the ways of their solution will be considered below.

Taking into account the results of the power analysis discussed above, the angle of the TR tilt equal to 20° has been assumed as the optimal one both for the MI-8 and MI-24 helicopters.

Problems To Solve

The vertical component of the tilted TR thrust provides the helicopter with a negative pitching moment. Tilting the main rotor thrust vector backward as well as shifting the helicopter CG position can counteract the moment. The moment can be completely counteracted only if there is a sufficient range of the swash-plate tilt angles. And in this case the level of the blade flapping motion should meet the following conditions:

- Loads applied to the main rotor head and mast should not exceed permissible values;
- The safe clearance between the main rotor blades and the tail boom must be provided in maneuvers and transitions;
- The main rotor blade roots should never touch the flapping stops in the main rotor head in steady-state flight.

The second problem to be solved in implementation of the tilted TR concept is that of the helicopter sufficient controllability. The yaw-pitch cross coupling occurs in helicopter motion as a result of the TR tilt. This cross coupling makes the helicopter piloting more difficult, so one of the very first problems to solve is how to minimize the impact of yaw control on the pitch motion. And this action should not demand too many efforts from the pilot during flight transitions as well as during the flight in the turbulent atmosphere.

As the longitudinal helicopter trim changes very much owing to the tilt of the tail rotor, the following new problem arises. It is the problem of ensuring helicopter controllability within the whole airspeed envelope including maneuvers.

The results of investigations made to find out whether the implementation of the TR tilt concept in the MI-8 and MI-24 helicopters is possible are described below.

First of all the investigations of the impact of the TR tilt on the longitudinal and lateral trim were conducted for the MI-8. The investigations were carried out for the extreme forward and aft positions of the helicopter CG in all level flight conditions and within the whole airspeed range.

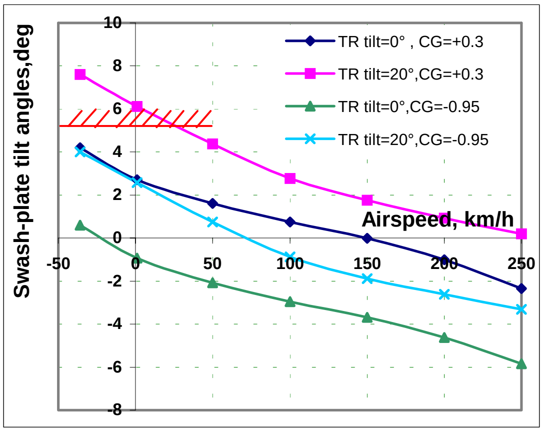

Fig. 12. Swash-plate angles need for level flight

Curves of the swash-plate tilt required to maintain the helicopter trim in level flight are shown in Fig. 12. The diagrams show that the swash-plate tilt angle required in hover and at low airspeeds at the helicopter extreme forward CG position exceeds the existing maximum angle of tilt of the swash-plate backward equal to 5°.

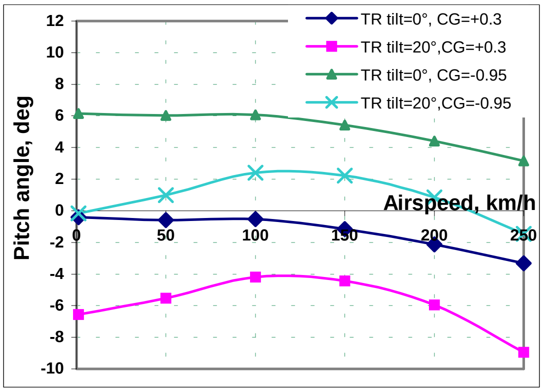

Fig. 13. Pitch angles of MI-8 helicopter

The helicopter trim pitch angles versus airspeed are shown in Fig. 13. As can be easily seen, the range of the trim pitch angles has shifted towards the negative pitch angles. It is clear that in this case the power required to perform level flight will increase. For instance, the MI-8 helicopter power required for the level flight at 250-km/h speed, with the extreme forward CG position, will increase by more than 10%.

Changes in the pitch trim angles could not help changing the flapping motion of the main rotor blades. The curves of the first coefficient $\mathbf{a_1}$ Fourier-series expansion of the flapping motion versus airspeed for the MI-8 helicopter equipped with the conventional tail rotor and the tilted one are shown in Fig.14. As can be seen the main rotor

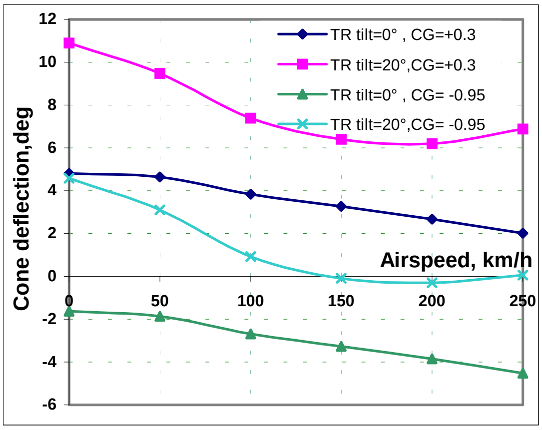

Fig. 14. Longitudinal tilt of MI-8 MR cone

cone of the helicopter with the tilted tail rotor has deflected backwards much more than that of the conventional helicopter. The range of the flapping angles in the longitudinal plane greatly changes too. Fig. 15 shows that the flapping angles increase within the whole airspeed range.

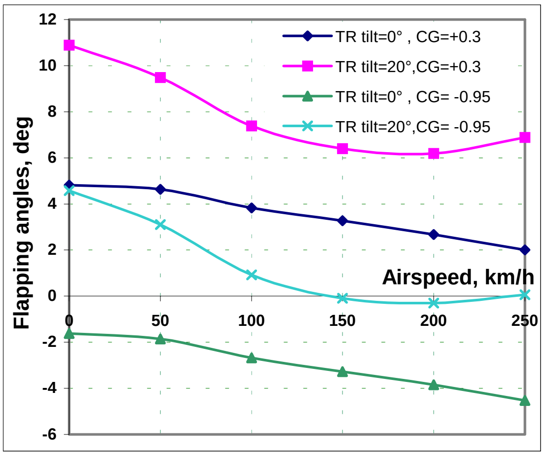

Fig. 15. MR blades flapping angles at 180° azimuths vs. airspeed.

Therefore very much attention should be paid to the safe clearance provided between the main rotor blades and the tail boom in all conditions of the helicopter flight. Changes in the flapping motion alter the loads applied to the main rotor head. The results of the calculation of the moments versus airspeed in level flight are shown in Fig. 16. It is easy to come to the conclusion on a drastic increase in the loads applied to the main rotor head.

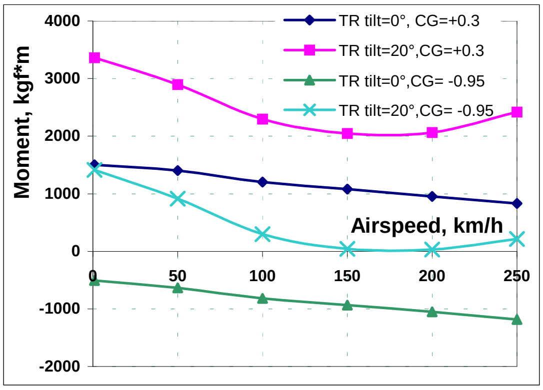

Fig. 16. MI-8 MR head longitudinal moment

Proceeding from the above the TR tilt in the MI-8 helicopter leads to a considerable increase in the following:

- Swash-plate tilts required to trim the helicopter;
- Flapping motion;
- Loads applied to the main rotor head.

The analysis of possible ways of solution of the problem has shown that the most effective way is a shift of the CG position towards its negative values.

Similar research made for the MI-24 helicopter has lead to a conclusion that in case of using a tilted tail rotor in the helicopter it will be necessary to solve practically the same problems as those for the MI-8 helicopter. So, to cut the story short, we will not dwell on the specific features of the problems concerned with the MI-24 but our attention will be fixed on the discussion of the problems described above.

MI-8 and MI-24 Design Changes Required

It was necessary to find design solutions to solve the above problems to neutralize the negative impact of the longitudinal moment produced by the vertical component of the TR thrust. The criterion of minimal changes to be introduced in the aircraft structure was a must so that they would be implemented in the existing layouts of the MI-8 and MI-24 production helicopters.

The second criterion was a requirement that there should be only minor increases in loads applied to the main rotor units and flight control system.

It is well known that the possibility of controlling the helicopter in all flight conditions has been determined by the compliance of the required and available ranges of the swash-plate tilt. Therefore first of all the changes in the swash-plate design that could be carried out within the existing parameters were considered. Then, having analyzed the possibility of implementation of the design changes, a possible widening of the swash-plate tilt has been determined.

Design Changes With Account Of Existing Swash-plate Parameters

One of the very first questions to answer was: what TR tilt angle is allowable without any changes in the flight control system and the swash-plate in particular. The fact is that the design of the MI-8 and MI-24 swash-plates does not allow a great increase in the tilt angle ranges. Hence, the first requirement is as follows: the tilt of the swash-plate required to get the aircraft trimmed should not exceed the existing ranges of this parameter.

Another requirement for safe aircraft operation, and probably a stricter one, is that of counteracting the tilted tail rotor longitudinal moment produced any helicopter turn in hover when the pedals are fully displaced.

These two requirements first of all determine how the helicopter upgrading under consideration can be implemented.

The design parameters that could affect the helicopter trim and the necessary controllability margins are as follows:

- The helicopter CG location;
- The horizontal stabilizer area;
- The horizontal stabilizer setting angle.

As for hover, the only parameter, i.e. the shift of the helicopter CG position, remains out of the three parameters above. That is why this particular flight condition determines how far the CG could be shifted.

The greatest imbalance occurs in turns in hover when the right pedal moves to the limit of travel. In this case the TR thrust reaches its maximum so the negative pitch moment caused by the tilted tail rotor is also the maximum.

The solid line in Fig. 17 shows the maximal forward CG location of the MI-8, calculated so as to find out the possibility to counteract the moment, versus the TR tilt angle. The diagram shows that the extreme forward CG location should be shifted backwards from plus 0.3 m to minus 0.17 m. This shift is much greater than that allowable for the helicopter. The main requirement here is as follows: the helicopter with the extreme forward CG location, when hovering in the tail wind, should possess some margin of the control

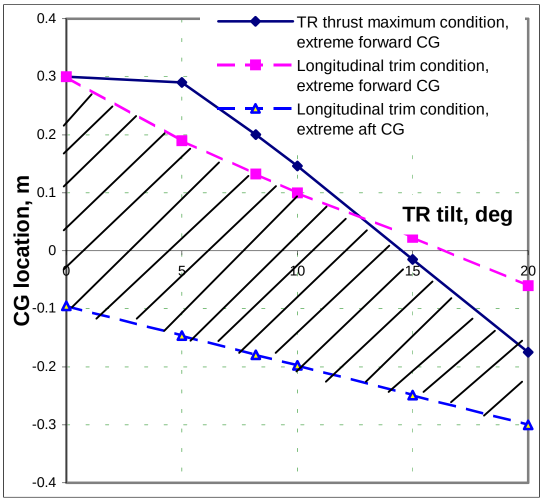

Fig. 17. MI-8 CG location allowable

stick travel to its full limit, for example, 10%. The allowable change of the extreme forward and aft CG locations calculated for the conditions of the helicopter trim versus the TR tilt angle is shown by dash lines in Fig. 17. The hatched area of the diagram is the allowable range of the helicopter's CG for different angles of the TR tilt. As can be seen the more the tilt angles the narrower the range of the CG locations is.

Thus, comparing the requirements for the helicopter controllability with the helicopter flight control system capabilities the following conclusion can be made. The MI-8 and MI-24 tail rotors can be tilted by 5° maximum at the existing parameters of the flight control system.

Design Changes With Account of Existing CG Locations

It was shown above that there is a requirement to considerably change both the CG locations and the range of their variation to realize the TR tilt maintaining the maximum existing swash-plate tilt angles. It is quite logical to raise the question: is there a possibility to keep the existing ranges of the CG locations of the two helicopters at the expense of increasing the range of the swash-plate tilt angles?

Figs. 18 and 19 demonstrate the impact of the extreme forward CG location on the swash-plate tilt angles calculated for the MI-8 and MI-24 controllability in hover when their tail rotors are either tilted (solid lines) or not tilted (dash lines).

It can be seen that the existing trim tilt of the MI-8 swash-plate, for instance, is equal to 2.5° when hovering in still air at the extreme forward CG location equal to +0.3 m. But to counteract the longitudinal moment only at the maximum thrust of the tilted tail rotor the swash-plate tilt should exceed 7.0°

Thus, to provide the helicopter with the required controllability when hovering in still air the maximal swash-plate tilt angle of tilt should be 9.5° and 8.0° minimum for the MI-8 and for the MI-24 helicopters respectively (Figs. 18, 19).

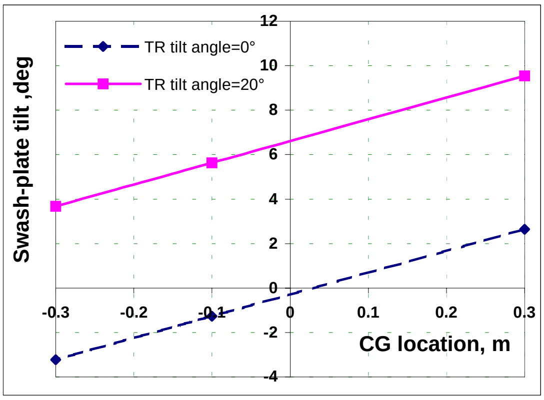

Fig. 18. MI-8 swash-plate tilt vs. CG location

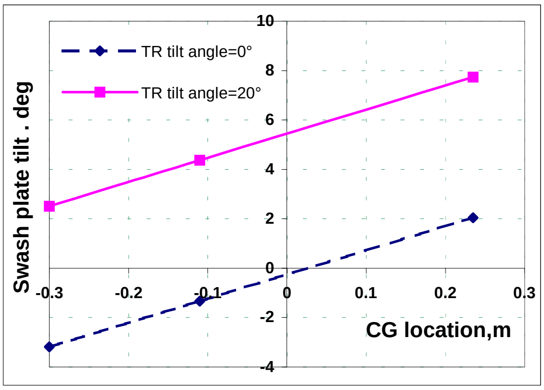

Fig. 19. Mi-24 swash-plate tilt vs. CG location

These angles should be even greater in case of tail wind blowing in hover. Providing the swash-plates with the above angles of tilt is a challenge. This can be attributed to the following reasons:

- There are design limits for the existing swash-plates;
- It is impossible to provide the sufficient safe clearance between the main rotor blades and the tail boom in flight;
- There is a considerable increase in loads applied to the main rotor head and flight control system units.

Helicopter Design Changes With Account of Changing Both Swash-plates Parameters And CG Locations

The safe clearance between the main rotor blades and the tail boom in flight can be provided by incorporating a movable versus airspeed stop in the flight control system to limit the maximum cyclic stick displacement backward. At the same time the swash-plate can tilt within the whole range of swash-plate tilt angles. When the movable stop is incorporated the swash-plate tilt of the MI-8 and MI-24 helicopters can become as high as 6.5°.

Proceeding from the obtained restriction on the maximal swash-plate tilt angle and according to the diagrams in Figs. 18 and 19 the extreme forward CG location of the MI-8 helicopter should be 0 m maximum instead of + 0.3 m in the production helicopter, as for MI-24, it should be +0.1 m maximum instead of +0.235 m.

The extreme aft CG location was calculated proceeding from the following conditions:

- The maximum angle of the swash-plate tilt should not be changed;
- The helicopter dynamic stability should be similar to that of the production helicopter;
- The range of the CG locations should not decrease as compared to the existing one;
- Loads applied to the main rotor hub and to the flight control system units should remain at the existing level.

The analysis has shown that these conditions could be met by an increase in the horizontal stabilizer area and by the proper selection of its setting angle. At the same time the angle of the right side slipping should be limited at airspeeds above the cruising airspeed. It can be expected that dynamic stability of the MI-8 and MI-24 helicopters to be upgraded would be similar to that of the production helicopters.

If above design changes are realized the MI-8 and MI-24 helicopters with tilted tail rotors can possess about the same margins of the control stick displacement as the production ones. Fig. 20 and 21 demonstrate the swash-plate tilt versus airspeed required to trim the MI-8 and MI-24 in level flight. And Figs. 22 and 23 show angles of the helicopter longitudinal trim versus airspeed. The solid and dash lines of the diagrams show dependences related to the helicopters with tilted tail rotors and production helicopters respectively.

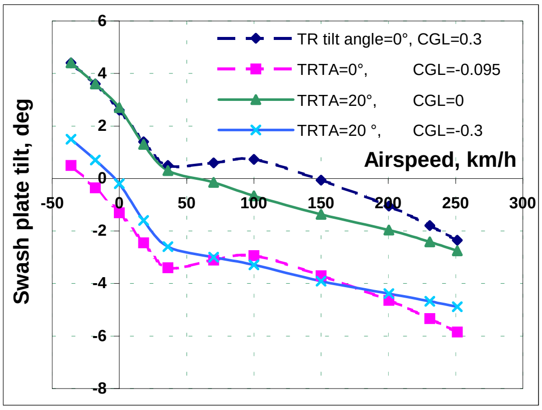

Fig. 20. MI-8 swash-plate tilt vs. airspeed

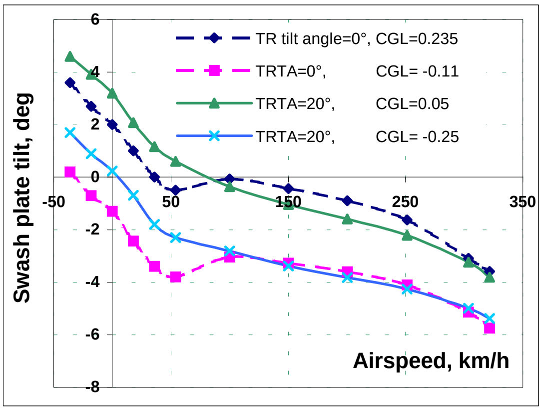

Fig. 21. MI-24 swash-plate tilt vs. airspeed

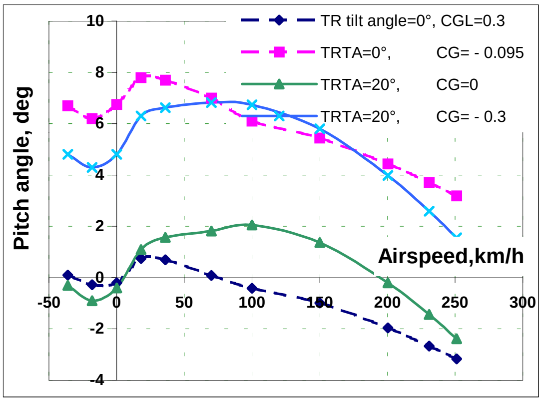

Fig. 22. MI-8 pitch angle vs. airspeed

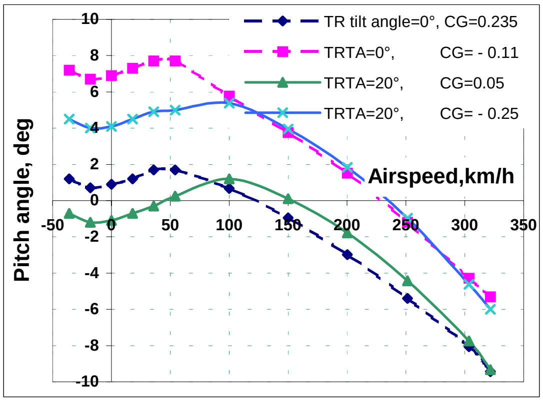

Fig. 23. MI-24 pitch angle vs. airspeed

As can be easily seen, if the design changes described above are introduced into the helicopters being developed they will have the same trim performance as the production ones.

The shift of the CG location backwards results in another consequence that should be paid attention to: redistribution of the loads between nose and main landing gear struts takes place. If one assumes that the permissible main LG strut load limits do not change the helicopter takeoff weight should be limited. Fig. 24 shows the variation

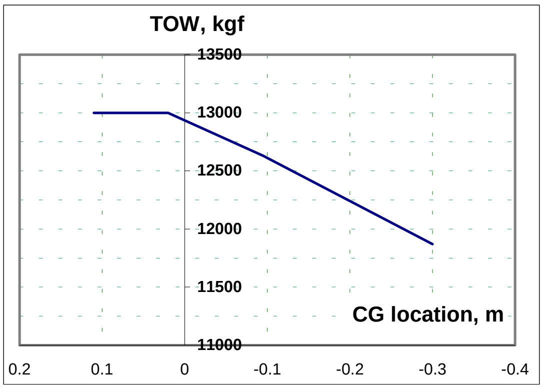

Fig. 24. MI-8 maximum TOW vs. CG location

of the MI-8 helicopter takeoff weight versus the extreme aft CG location calculated for the condition that the permissible load limitations on the main landing gear remain the same. As can be seen the permissible takeoff weight of the MI-8 helicopter for the CG position equal to minus 0.3 m should be reduced to 11,850 kgf against 13,000 kgf as compared to the existing one. In other words the takeoff weight reduction greatly exceeds the increase in the total helicopter lift.

CONCLUSIONS

1. The optimal tail rotor tilt angle for the MI-8 and MI-24 helicopters is 20° for the maximum increase in the total helicopter lift at the minimal power required and provision of sufficient control margins.

2. The flight conditions determining the required range of the swash-plate tilt angles are as follows:
   - Turns in hover that require maximum tail rotor thrust with the minimal helicopter TOW and the extreme forward CG location;
   - Right side sliding level flight at the extreme aft CG;

3. To make the advantages of the tilted tail rotor come true it is necessary:
   - To widen the ranges of the swash-plate tilt angles and tail rotor blades setting angles;
   - To shift the CG location range backwards;
   - To increase the horizontal stabilizer area and its setting angle;
   - To install a device minimizing the yaw-pitch cross-coupling in the flight control system;
   - To reinforce the main rotor system components whose strength depends on the main rotor flapping.

4. These design changes of the MI-8 and MI-24 helicopters can allow the tail rotor tilt to be realized.