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COMPUTATIONAL MODELING OF HELICOPTER'S MAIN AND TAIL ROTOR INTERFERENCE ON THE BASE OF NON-LINEAR BLADE VORTICAL MODEL

Ignatkin Y.M., Makeev P.V., Shomov A.I
Moscow Aviation Institute (National Research University), Russia

Keywords: non-linear vortical model, low-speed horizontal flight, flight with slide, interference between main and tail rotors, aerodynamic characteristics.

Abstract

Exploitation of single-rotor helicopters with tail rotor demonstrates that on some flight regimes tail rotor is highly influenced by vortical wake of main rotor. Under such circumstances changes of main rotor's aerodynamic characteristics become possible and they can lead to uncontrolled rotation of a helicopter.

The paper contains some results of aerodynamic characteristics' computational modeling of main and tail rotor combination for a single-rotor helicopter with consideration of mutual interference between rotors.

To solve the task of computational modeling non-linear blade vortical model with diffusion of free wake is used. Both this model and software created on its base for computational modeling of helicopter's rotors' aerodynamics were designed by the staff of Helicopter Design Department at the Moscow Aviation Institute (National Research University).

A number of helicopter's flight regimes under which interference between rotors is demonstrated most of all and main rotor is highly influenced by vortical wake of main rotor was considered in the paper. The regime of helicopter's flight with low horizontal speed with cross wind (or flight with angle of slide) were considered.

As a result of research for considered regimes a form of free vortical wake of main and tail rotor with consideration of their mutual interference was constructed, also visualization of rotor flowing was obtained and aerodynamic characteristics were calculated. The obtained data was estimated from the viewpoint of helicopter's safety and directional control.

Nomenclature

T	- rotor thrust, kg;
Q	- rotor torque, kg;
c_T	- rotor thrust coefficient, $(2\cdot T)/(\rho\cdot(\omega R^2)\cdot\pi R^2)$;
c_Q	- rotor torque coefficient, $(2\cdot Q)/(\rho\cdot(\omega R^2)\cdot\pi R^3)$;
V	- flight velocity, m/s;
V_y	- climb velocity, m/s;
V_x	- horizontal velocity, m/s;
ω R	- rotary axis speed, m/s;
υ_i	- induced velocity (at a rotor disc plane);
υ_{ih}	- hover induced velocity, m/s; $\upsilon_{ih}=\omega R\cdot 0,5\sqrt{c_T}$
$\tilde{\upsilon}_y$	- non-dimensional induced velocity, υ_i/υ_{ih};
$\tilde{V}$	- non-dimensional flight velocity, V_0/υ_{ih}
μ	- non-dimensional flight mode characteristic, $\mu=\dfrac{V\cdot\cos\alpha_H}{\omega\cdot R}$
$\alpha_H{}^\circ$	- angle of rotor attack, degree;
$\varphi_7{}^\circ$	- collective pitch angle, degree;

$\Delta\varphi_{\Sigma}{}^{\circ}$	- blade twist, degree;
ψ°	- azimuth angle, degree;
$\beta_{H}{}^{\circ}$	- angle of rotor slide, degree;
R	- rotor radius, m;
n_b	- number of blades;
σ	- rotor solidity, $n_b \cdot b/\pi R$;
ρ	- air density, kg/m^3;
TR	- tail rotor;
MR	- main rotor;
FLH	- flapping hinge;
FTH	- feathering hinge;
CW	- clockwise;
CCW	- counterclockwise,
VRS	- vortex ring state.

Introduction

Problem of promotion of safety for a single-rotor helicopter in case of tail rotor working in critical modes, when its thrust and effectiveness decrease, is very actual, because significant percentage of air crashes is connected with helicopter piloting in hard conditions.

European Helicopter Safety Team (EHEST) in the air crash analysis [1] identifies a number of situations when the pilots most often could not find the correct helicopter control strategy. Some of these reasons can be identified with loss of tail rotor effectiveness, including vortex ring state mode, which can cause uncontrolled rotation of the helicopter.

For single-rotor helicopter the reason of loss of tail rotor thrust and helicopter directional control, and as the result – uncontrolled rotation of helicopter may be aerodynamic interference between the main and tail rotor in case of contact of tail rotor with the main rotor wake .

Aerodynamic interference between main and tail rotor of helicopter is connected with the specifics of formation of the vortex wake behind the main rotor at horizontal flight mode and mostly appears at low speeds of flight. As experimental results [2] the vortex system of a rotor already at low speeds is transformed into a system of two powerful secondary twist vortices (Fig. 1). The circulation of this vortices increases rapidly at low speeds and reaches a maximum at a relative velocity $\tilde{V} \approx 1$ ($\mu \approx 0,05$), and then, with increasing flight speed, its circulation decreases.

Experimental and flight research of aerodynamic interference of helicopter rotors at critical flight modes is a difficult, expensive and unsafe problem. That's why the possibility to analyze this problem using various computational methods is very actual today. Recently in connection with rapid development of computers computational (digital) researches of helicopter rotors aerodynamics have become more and more significant. Together with development of new and actual theoretical models it makes possible to come closer to solve practical problems of modeling the helicopter's rotors aerodynamic interference.

This paper contains the result of computational modeling of inductive effect of helicopter main rotor's free wake on aerodynamics of the tail rotor that is aerodynamic interference between main and tail rotors, at the horizontal flight modes with slide or at hover with crosswind.

The research is made with usage of software developed by authors on basis of non-linear blade vortical model of helicopter rotor (free-wake model) with diffusion of free-wake vortices [3, 4].

The object of research is the model of main and tail rotors of MIL Mi-2 helicopter [5].

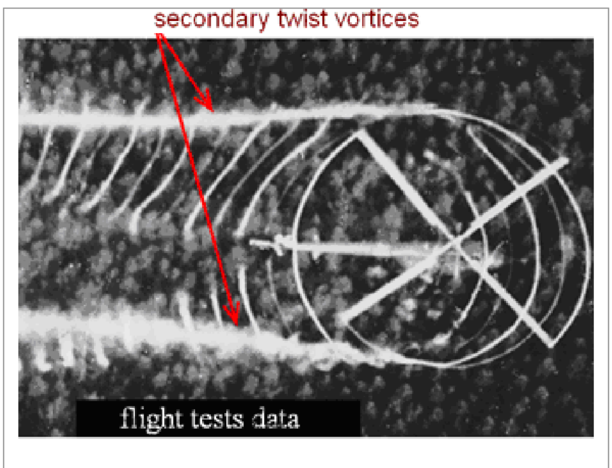

Fig. 1. Results of a smoke flow visualization of vortex wake of helicopter.

Non-linear blade vortical model of a rotor

Non-linear blade vortical model of rotor (free-wake model) is the basis of computational model [Ref. 1]. In this model every blade is composed by lifting line and adjoined vortex located on quarter of chord (Fig. 2). Rotor blade is modeled by set of plane rectangle elements. Rotor hub has flapping hinges, blades, related to them, make flapping motions and also hub has feathering hinges which allow blade pitch angles to change.

While the rotor is moving, blade generates the system of longitudinal and transversal vortices, which are making free vortex wake (Fig. 2). The wake looks like a net made of vortex rectangles.

For calculation of aerodynamic characteristics hypothesis of plane section is used. Aerodynamic characteristics of airfoils are evaluated basing on the data of wind tunnel tests under relevant values of Re and M numbers.

In this model vortex segments of vortex wake grid are modeled by diffusing vortex lines. Taking into account the vortex diffusion allows to model physical processes at the vortex wake more precisely and to avoid producing mathematical peculiarities which lead to fast destroy of the grid.

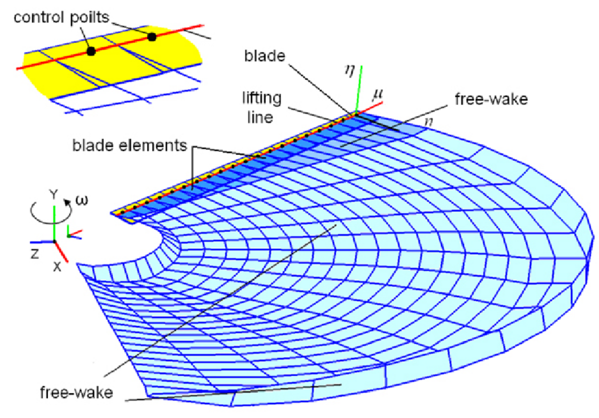

Fig. 2. Non-linear blade vortical model of helicopter rotor (free-wake model).

To find the deformation of free vortex wake behind rotor blades it is necessary to evaluate induced velocities in grid points of all vortex segments in every moment. Non-linear free vortex wake behind the rotor is built step by step as a result of calculation.

Model of the main and tail rotor combination used in the research

Fig. 3 shows the model of the main and tail rotor combination (MR-TR) of MIL Mi-2 helicopter used in the presented research. Main rotor of helicopter was modeled with taking a blade motion into consideration. Tail rotor was modeled as inflexible.

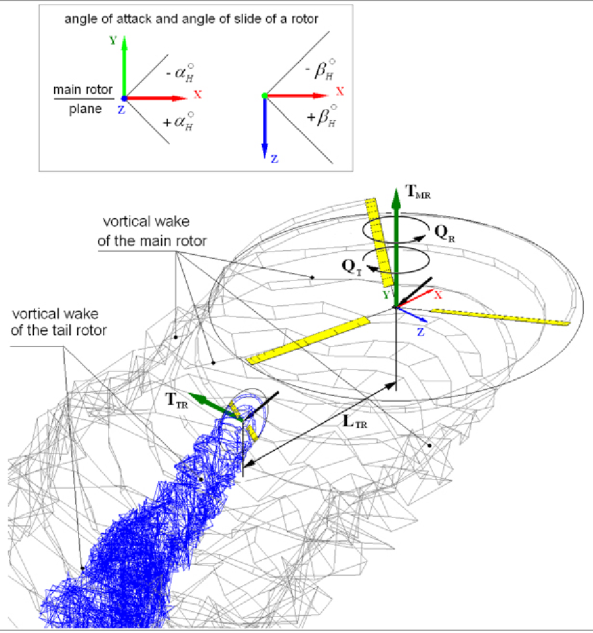

Fig. 3. Model of main and tail rotor combination.

During the flight, the helicopter tail rotor makes several revolutions during one revolution of the main rotor. Thus, for a correct simulation of two rotors the elements of the vortex wake of the main rotor must be increased during the time. In addition, to accelerate calculations of MR-TR combination, TR has started to work not with the MR starting time but since the regime of MR has been stabilized.

In this paper, we consider two variants of the rotational direction of the tail rotor: counterclockwise - CCW (upper blade moves back) and clockwise - CW (upper blade moves forward), see fig. 4.

All calculations were performed for horizontal flight modes for angle of attack of a rotor $\alpha_H = 0°$ and flight speed V = 10 mps. Angle of slide of a rotor ranged from $\beta_H = -90°$ to $\beta_H = +90°$ with step of 10°.

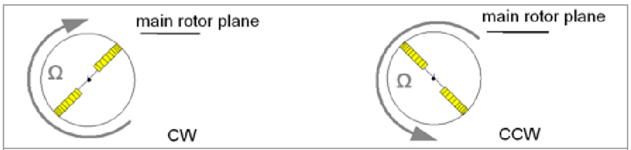

Fig. 4. Two variants of the tail rotor rotational direction using in the research.

Features of MR-TR vortex wake interaction for helicopter flight with slide at low speeds (hover with the crosswind)

Inductive effect of the secondary twist vortices of MR on TR depends on the position of TR on these vortices.

Fig. 5 schematically illustrates the position of the left vortex of MR when the helicopter was flying with slide.

Obviously the position of the left vortex relative to TR-area depends on the value and sign of the slide angle MR β_H. The same is true for the right vortex of MR.

When the slide angle is in the range from about β_H = -40 … -60 degrees TR goes directly to the left vortex of MR as shown in Fig. 5. Thus the TR operates in a complex velocity inductive field which can be schematically divided into a rotational velocity component of vortex $V\Omega$ and an axial component V_n. The same is true for the right vortex of MR (for β_H = -40 … -60).

In fact, the velocity field of the vortex rope is more complicated and changes over time.

Fig. 6 shows a vortex wake of isolated MR (without TR working) in horizontal flight with a speed of 10 mps. Powerful secondary

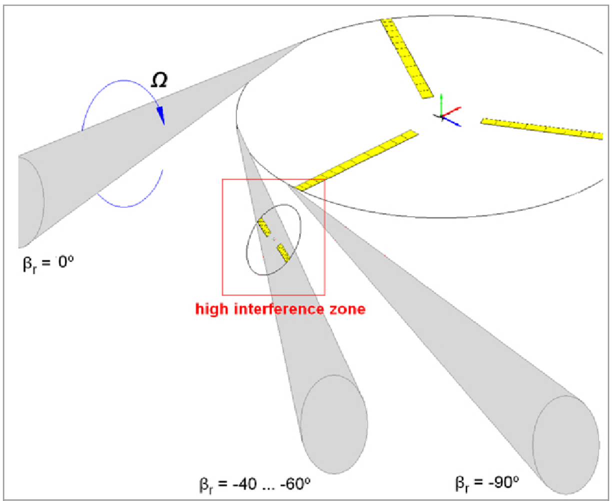

Fig. 5. Position of the left secondary twist vortex of MR, depending on the slide angle β_H.

twist vortices are clearly seen. There are also diagrams of inductive velocities from the vortex wake of MR whose analysis can show the nature of the inductive effects on TR. Fig. 6 also shows the diagram of an inductive speed in a plane perpendicular to the MR vortices. There is a slight upward flow in the outer part and intense downdraft flow in the internal (between the vortices), reaching values of 20 mps. Directly in the area of the MR-vortex, if it enters into TR-area, it can cause a change in the peripheral speed of rotation of the TR. We can also see a powerful inductive axial flow directed along the axis of the MR-vortex (see Fig. 6), reaching a speed of 20 mps. This inductive flow significantly modifies the flow velocity in the direction perpendicular to the plane of the disk TR and angles of attack of its blades.

Fig. 6 shows that at different slide angles β_H TR take a different position relative to the secondary twist vortices of MR. And the greatest part of the TR-area is occupied by these vortices at $\beta_H = -50°$ and $\beta_H = 50°$, getting into the left or right vortex, respectively.

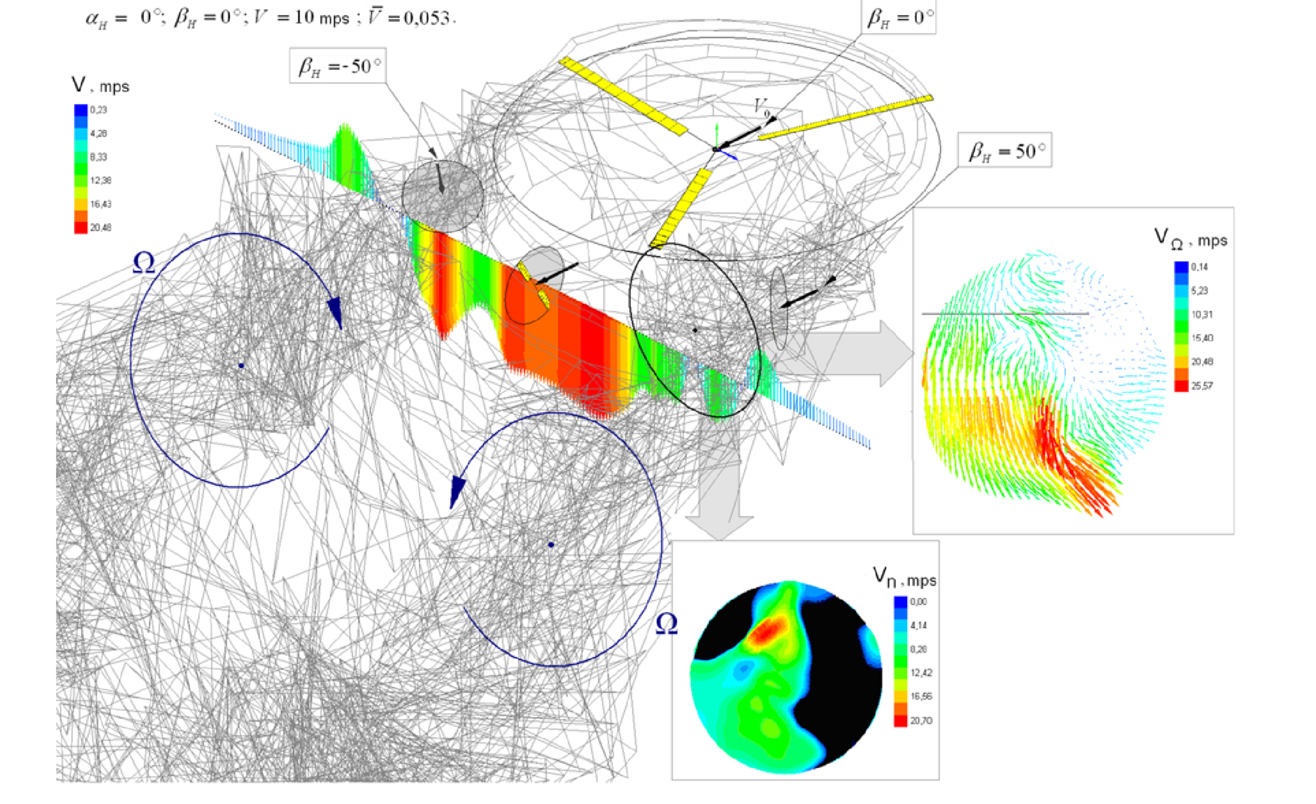

Fig. 6. Inductive velocity fields from secondary twist vortices of main rotor (V=10 mps)

The detailed computation results of aerodynamic interference between main and tail rotor in horizontal flight modes: V=10 mps, βн = -50°; βн = 50°

Let us consider the results of a study of aerodynamic characteristics of the main and tail rotor combination in horizontal flight mode with angle of slide βн = -50°, when the left vortex runs directly through the tail rotor.

Fig. 7 shows the form of the vortical wake of the main and tail rotor in two projections: the side and top. The figure shows that the tail rotor and its vortex wake (blue color) get directly into the left vortex of main rotor (gray color). In this case the tail rotor vortical wake is strongly deformed under the influence of the inductive velocity field of main rotor.

Fig. 8 shows the comparison form of vortical wake of isolated tail rotor (working without the main rotor) and the form of the tail rotor with aerodynamic interference. We can see significant difference in the form of the vortex wake of isolated tail rotor and the tail rotor under the influence of the main rotor. Strong deformation of the vortex wake of the tail rotor under inductive influence by the main rotor will change its aerodynamic characteristics.

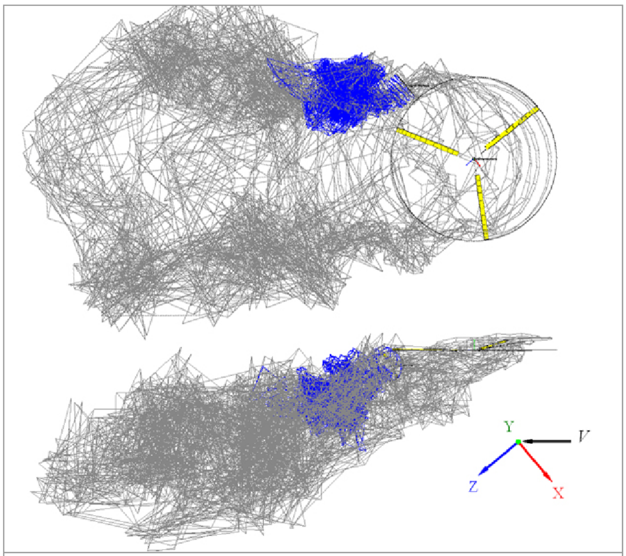

Fig. 7. Vortical wake of the main and tail rotors with aerodynamic interference (αн = 0°; βн = -50°; V = 10 mps).

Fig. 9 shows diagrams of the tail rotor thrust depending on the number of its revolutions. The diagrams are constructed for the isolated tail rotor and tail rotor considering interference for two different rotational directions (CW and CCW) of the rotor with equal pitch angles. It can be seen that the thrust of the tail rotor with interference has significant pulsations, reaching 40-50% of rotor thrust. For the tail rotor with CW rotational direction drop in the average thrust by 26% compared with isolated tail rotor is observed.

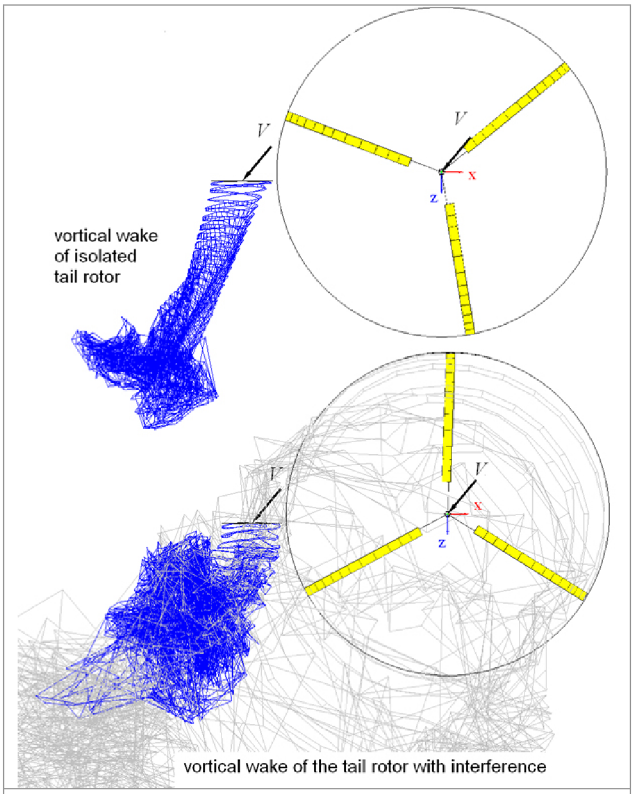

Fig. 8 Vortical wake of the isolated tail rotor and tail rotor with aerodynamic interference ($\alpha_H = 0°$; $\beta_H = -50°$; V = 10 mps).

Falling the rotor thrust is caused by a decrease of peripheral speed of rotation of the tail rotor ωR and changing its mode of operation under inductive influence by the main rotor. Pulsing of the tail rotor thrust cause a complex and non-stationary field of inductive velocity of the main rotor vortex wake. For the tail rotor with CCW rotational direction increase in the average thrust by 10% is observed in comparison with isolated tail rotor. In this case, the tail rotor thrust increases because inductive field of main rotor increases the rotational speed of the tail rotor ωR.

Thus, the total difference in the thrust of a tail rotor according to the direction of rotation in this mode is 36%.

Balancing combination of main and tail rotor considering interference is necessary to change the collective pith angle of the tail rotor. According to the main and tail rotor balancing calculations for the CW tail rotor are necessary to increase collective pitch angle of rotor. For CCW tail rotor collective pitch angle of the tail rotor can be reduced.

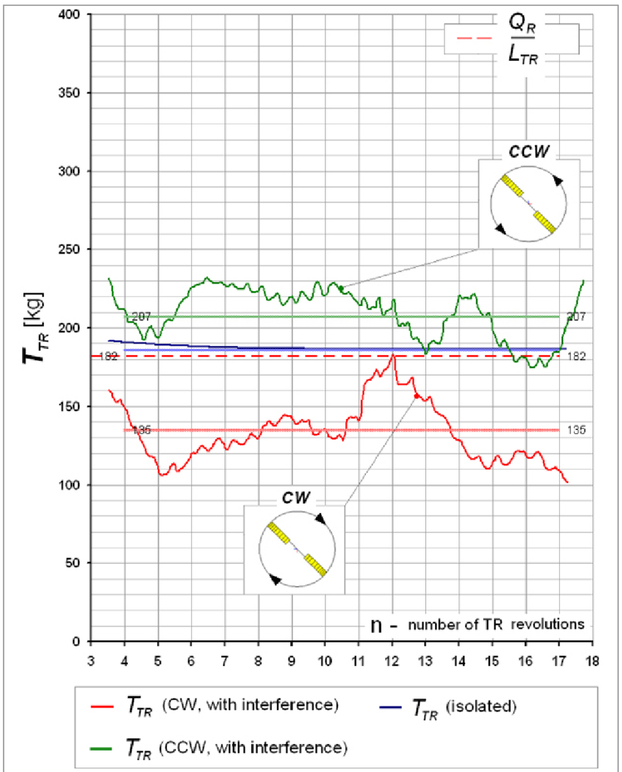

Fig. 9. Depends of tail rotor thrust on the rotor revolutions number $T_{TR} = f(n)$ for isolated rotor and rotor with interference ($\alpha_H = 0°$; $\beta_H = -50°$; V = 10 mps).

Below are the results of a study of aerodynamic characteristics of the main and tail rotor combination in horizontal flight mode with angle of slide $\beta_H = 50°$, when the right vortex runs directly through the tail rotor.

Fig. 10 shows the form of the vortical wake of the main and tail rotor. The figure shows that the tail rotor and its vortex get directly into the right secondary twist vortex of main rotor. In this case the tail rotor vortex wake is strongly deformed under the influence of the inductive velocity field of main rotor.

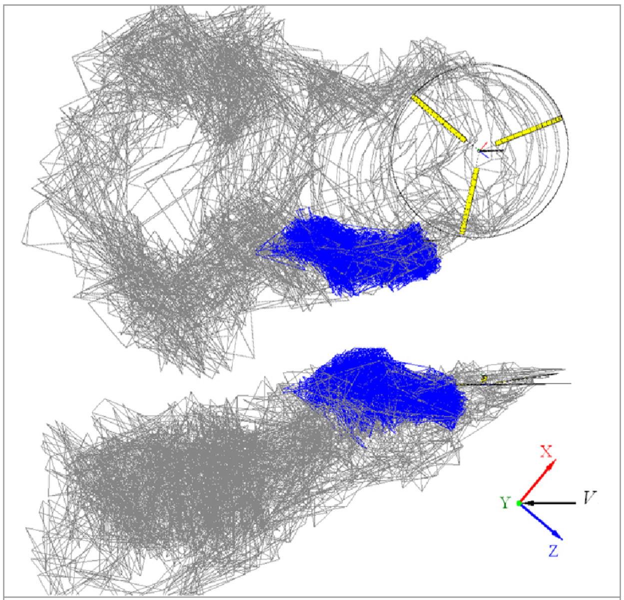

Fig. 10 Vortical wake of the main and tail rotors with aerodynamic interference ($\alpha_H = 0°$; $\beta_H = 50°$; V = 10 mps).

Fig. 11 shows the comparison forms of vortex wake isolated tail rotor and the tail rotor vortex wake in the presence of the vortex wake of main rotor (with aerodynamic interference). We can see significant difference in the form of the vortex wake of isolated tail rotor and the tail rotor under the influence of the main rotor. Strong deformation of the vortex wake of the tail rotor under inductive influence by the main rotor will change its aerodynamic characteristics.

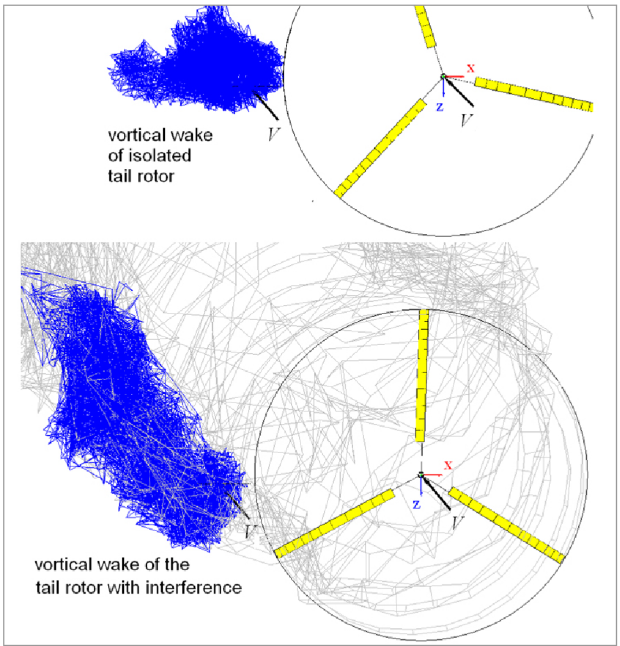

Fig. 11 Vortical wake of the isolated tail rotor and tail rotor with aerodynamic interference ($\alpha_H = 0°$; $\beta_H = 50°$; V = 10 mps).

Fig. 12 shows diagrams of the tail rotor thrust depending on the number of its revolutions (at: $\alpha_H = 0°$; $\beta_H = 50°$; V = 10 mps). The diagrams are constructed for the isolated tail rotor and tail rotor considering interference for two different rotational directions (CW and CCW) of the rotor with equal pitch angles. It can be seen that the thrust of the tail rotor with interference has significant pulsations, reaching 30-50% of rotor thrust. For the tail rotor with CW rotational direction increase in the average thrust by 26% compared with isolated tail rotor is observed. Falling the rotor thrust is caused by a decrease of peripheral speed of rotation of the tail rotor and changing its mode of operation under inductive influence by the main rotor. Pulsing of the tail rotor thrust cause a complex and non-stationary field of inductive velocity of the main rotor vortex wake. For the tail rotor with CCW rotational direction increase in the average thrust by 48% is observed in comparison with isolated tail rotor. In this case, the tail rotor thrust increases because inductive field of main rotor increases the rotational speed of the tail rotor.

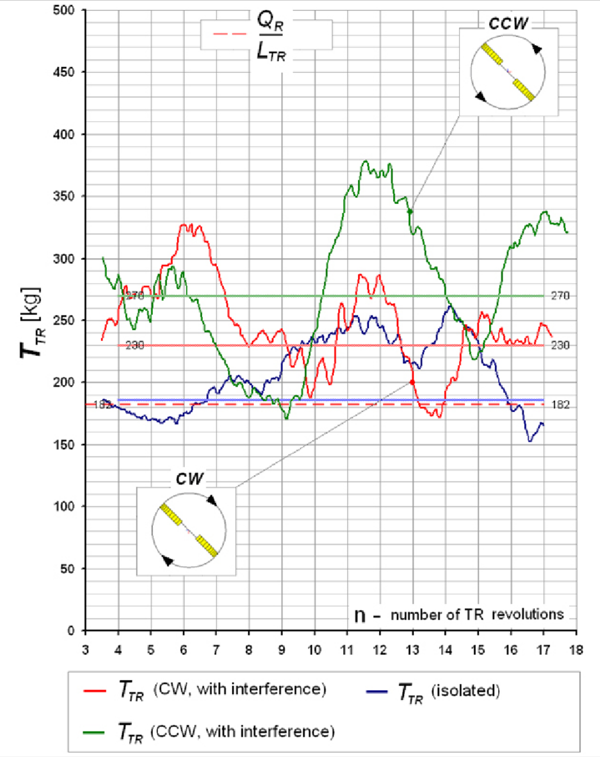

Fig. 12. Depends of tail rotor thrust on the rotor revolutions number $T_{TR} = f(n)$ for isolated rotor and rotor with interference ($\alpha_H = 0°$; $\beta_H = 50°$; V = 10 mps).

Balancing combination of main and tail rotor considering interference is necessary to change the collective pitch angle of the tail rotor. According to the main and tail rotor balancing calculations for the CW tail rotor for angle of slide $\beta_H = 50°$ are necessary to decrease collective pitch angle rotor. For CCW tail rotor collective pitch angle of the tail rotor can be also reduced.

The general computation results of aerodynamic interference between main and tail rotor in horizontal flight modes: V=10 mps, $\beta_H = -90…50°$

Fig. 13 shows graphs of the tail rotor thrust dependence on angle of slide β_H with taking into account interference. Tail rotor thrust presented in percentage ratio relative to isolated tail rotor thrust.

As it is seen on fig. 13 thrust of tail rotor with CW rotational direction with interference and thrust of isolated tail rotor are equal, and this demonstrates that there are no inductive effects from main rotor vortical wake. At the $\beta_H = -70…-30°$ thrust of tail rotor with interference drops to 74% of isolated tail rotor thrust. At the $\beta_H = -30…-20°$ thrust of tail rotor with interference and isolated tail rotor thrust are equal again. At the $\beta_H = 0°$ thrust of tail rotor with interference increases up to 107% of isolated tail rotor thrust.

Then, at the $\beta_H = 30…90°$ thrust of the tail rotor with interference increases up to 148% ($\beta_H = 50°$) and 159% ($\beta_H = 70°$) of isolated tail rotor thrust, next at the $\beta_H = 90°$ thrust decreases a bit up to 120% of isolated rotor thrust value.

Received results indicate significant inductive influence of main rotor vortical wake on aerodynamic characteristics of the tail rotor at the angle of slide $\beta_H = -60…-40°$ and $\beta_H = 20…80°$ for CW rotation, and also at $\beta_H = -70…90°$ for CCW rotation.

For the tail rotor with CW rotation at the $\beta_H = -60…-40°$ drop of the tail rotor thrust caused by interference is observed, but for other angle of slide β_H thrust is constant or increases.

For the tail rotor with CCW rotation the tail rotor trust increases significantly at the almost all angles $\beta_H = -70…90°$.

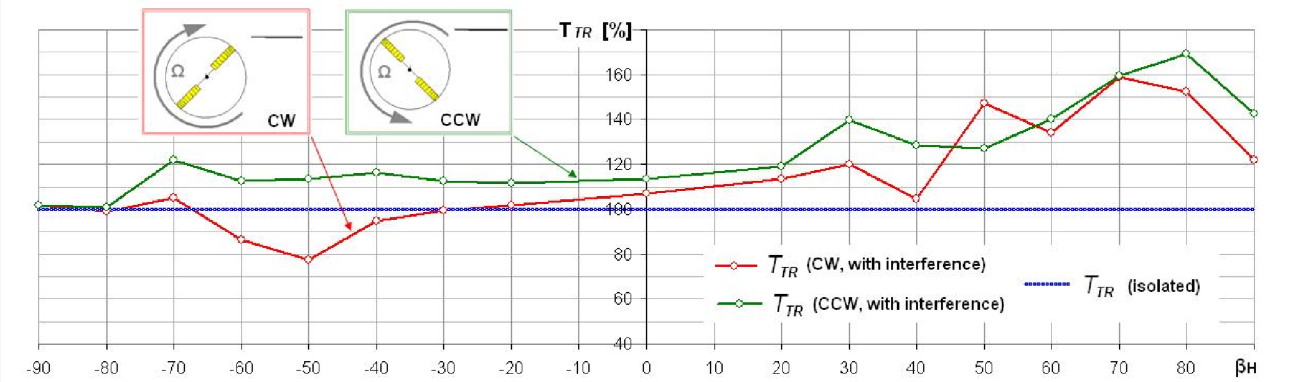

Fig. 13. Depends of tail rotor thrust on the angle of slide β_H $T_{TR} = f(\beta_H)$ for case of isolated rotor and for case of aerodynamic interference ($\alpha_H = 0°$; $\beta_H = 50°$; V = 10 mps).

Fig. 14 shows dependence of balance collective pitch angles on the tail rotor with interference. It gives possibility to estimate the interference effects on collective pitch angle of the tail rotor needed for balancing the main rotor torque. Graph demonstrates the results obtained for both variants of tail rotor rotation's direction. That's why if tail rotor rotates CCW, a helicopter has more control margin then with CW rotation of tail rotor.

As it follows from fig. 14 the CCW rotational direction of the tail rotor is more advantageous then CW rotation at all considered angles β_H.

At fig. 14 we can observe the area of flight modes where aerodynamic interference effects has maximum value, in particular, there are cases when tail rotor is coming close to one of the secondary twist vortex of the main rotor. In that case for CW rotation increases of collective pitch angle for $\varphi_7 = 2°$ at β_H=-50° and for $\varphi_7 = 0{,}5°$ at $\beta_H = 40°$ is needed.

Rise of needed collective pitch of the tail rotor to value that is more then available may cause loss of balance of helicopter and uncontrolled rotation around its vertical axis. Also it is necessary to take into account that fast and unexpected increase of tail rotor thrust because of interference is dangerous too, and needs fast and true reaction from the pilot.

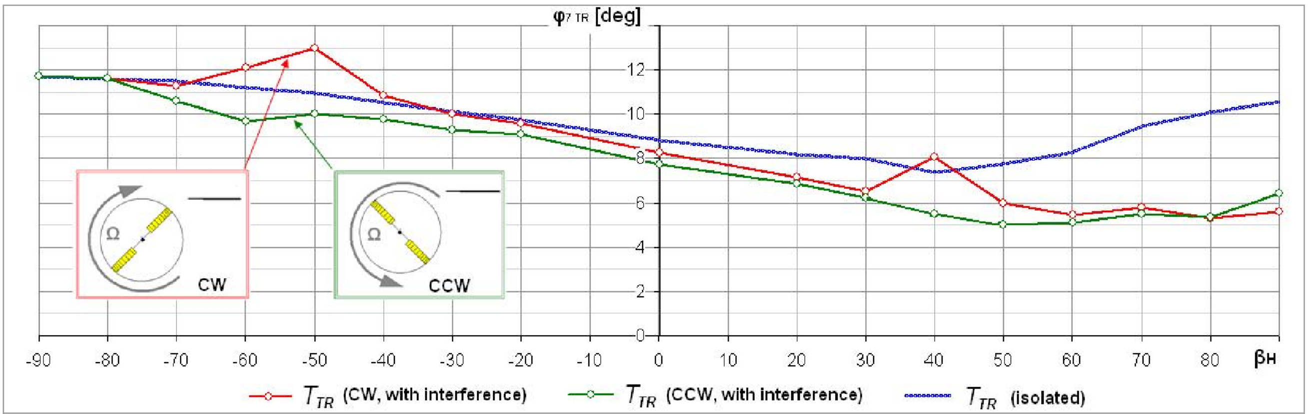

Fig. 14 Depends of collective pith angle of the tail rotor thrust needed for balancing of main rotor torque on the angle of slide β_H $\varphi_{7TR} = f(\beta_H)$ for case of isolated rotor and for case of aerodynamic interference ($\alpha_H = 0°$; $\beta_H = 50°$; V = 10 mps).

Conclusions

To assess the effect of interference between the MR and TR of single-rotor helicopter we performed computational studies for MIL Mi-2 helicopter as an example.

Calculations are based on non-linear blade vortical model (free-wake model) with diffusion of free vortical wake. Calculations are made for the rotor thrust corresponding with take-off weight of the helicopter for angle of rotor attack $\alpha_H = 0°$, angle of rotor slide $\beta_H = -90…+90°$ and horizontal speed is V = 10 mps.

For each helicopter flight mode there was received a form of the free vortical wake for isolated TR, taking into account aerodynamic interference from the wake of MR.

For the fixed thrust value of MR were received a torque of MR and collective pitch angle of isolated TR that is needed to balance MR torque. For the collective pitch angles of MR and TR obtained for isolated rotors there was received a thrust of TR with aerodynamic interference for various TR rotational directions: CW and CCW.

Significant interference effect from MR wake to TR at considered flight modes was defined. The effect depends on flight mode, vortical structure of MR wake, location of MR secondary twist vortex about TR and rotational direction of TR (CCW or CW).

At angle of helicopter slide $\beta_H = -0…+90°$. TR works at positive angle of a rotor attack and may get info VRS-mode.

CCW rotational direction of TR is defined as optimal. At this direction the TR thrust is growing up by interference effect of MR vortical wake at all considered flight modes.

For positive angle of slide of a rotor is $\beta_H = +50°$ (V = 10 mps) thrust of TR with interference is growing up by 48% (CCW rotational direction) and up by 26% (CW rotational direction) as compared with isolated rotor.

For negative angle of slide of a rotor $\beta_H = -50°$ (V = 10 mps) thrust of TR with interference is growing up by 10% (CCW rotational direction) and decrease by 26% (CW rotational direction) as compared with isolated rotor.

Received data may be used for selection of TR optimal rotational direction and analysis of helicopter controllability and safety.

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