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SIMULATION INVESTIGATION OF OPERATIONAL CONDITIONS OF ROTOR FOR HIGH-SPEED COMPOUND HELICOPTER

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Abstract

The article presents results of simulations concerning possibilities of rotorcraft performance enhancements for compound helicopters with introduced additional wings and propellers. The simple model of helicopter including a point mass of fuselage and a rotor treated as a disk was used for calculations of helicopter flight equilibrium conditions. For the defined flight states, the more detailed model of elastic blade was applied to compute magnitude of rotor loads and level of blade deformations. The model of elastic blade includes out-of-plane bending, in plane bending, and torsion effects due to variable aerodynamic and inertial loads of rotor blades. Equations of motion of rotor blades are solved applying Runge-Kutta method. Taking into account Galerkin method, parameters of blade motion are computed as a combination of assumed torsion and bending Eigen modes of the rotor blade. The six-bladed rotor with stiff connections of blades and hub was applied for comparison of flight envelope for conventional helicopter and versions of compound rotorcraft with additional propellers and with wings and propellers. Simulations indicate that, in the case of compound helicopter configuration, achieving the operational flight conditions at high speed of 400 km/h is possible without generating excessive loads and blade deformations. The results of calculations of rotor loads and generated blade deflections are presented in form of time-run plots and as rotor disk distributions, which depend on radial and azimuthal positions of blade elements. The simulation investigation may help to define demands for rotor of high-speed helicopter.

Keywords: *compound helicopter, rotor loads, blade deformation*

1. Introduction

For classical configuration of helicopter, with main rotor and anti-torque tail rotor, the speed of flight is limited in comparison to fixed wing aircraft. The maximum speed of conventional helicopter is restricted due to high drag associated with compressibility effects for advancing rotor blade and stall phenomenon, which occurs at retreating blade zone. A compound helicopter configuration with added lifting wings and separate source of thrust for propulsion may help to unload main rotor and enhance speed range of rotorcraft. Initial development programs of compound helicopters [6], such as the Bell 533, the Lockheed XH-51A fitted with wings and additional turbojet engines, or the Lockheed AH-56A Cheyenne with wings and pushing propeller and after flight tests were not passed to serial production. Emerging demands for improved performance and progress in composite materials and aerodynamics of rotor blades gave impulse to return to compound helicopter concept. In the last decade, the new experimental compound helicopters with additional propulsion were tested [3]: the American Piasecki X-49 Speedhawk, the Sikorsky X2 and the French Eurocopter X3. It should be mentioned that the Eurocopter X3 achieved speed of 472 km/h setting an unofficial speed record for propeller helicopters. Analytical and experimental research works were performed to examine features of compound helicopters, which included effects of varying main rotor tip speed [1], wing-rotor lift share [7, 8] and investigation of dynamic stability characteristics [2]. Basing on collected experiences, the next generation of operational compound helicopter designs are being developed. The American Sikorsky S-97 Raider made the maiden flight in 2015 [4] and the European Airbus Helicopter Racer's configuration was revealed in 2017 [5].

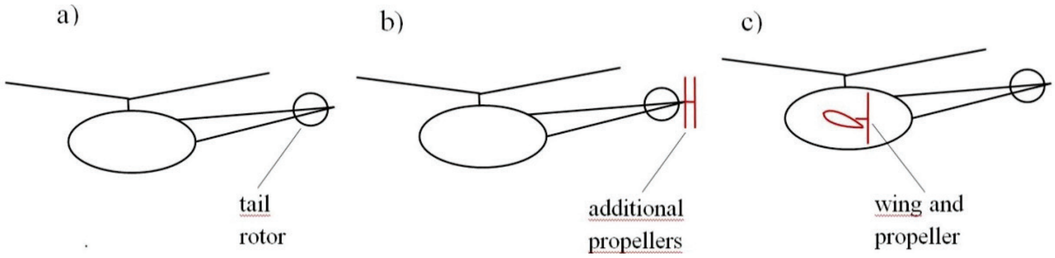

Fig. 1. Configurations of helicopter versions: a) conventional, b) compound with additional propellers, c) compound with wings and propellers

The results of calculations, presented in this article, were obtained for data of hypothetical versions of light helicopter with mass of 2500 kg. The cases for nominal and reduced rotational speed of rotor were assumed. The all versions of considered helicopters (Fig. 1) were fitted with the same six-bladed main rotor. Thrust of additional pushing propellers, which overcomes aerodynamic drag of helicopter, enables reduction of the horizontal component of main rotor thrust. In high-speed conditions, applying additional wings allows to decrease the vertical component of rotor thrust. For the compound helicopter configurations, the results of simulations show the range of power required for flight and rotor thrust generated within enlarged up to 400 km/h scope of operational flight speed. For several states of the helicopter, flight envelope the comparison of rotor loads and blades deflections is shown in form of time-run plots or rotor disk distributions.

2. Model of helicopter

A simplified model was applied for helicopter performance calculations. The simplified model of helicopter includes main rotor treated as a disk area with average value of induced velocity and aerodynamic coefficients. The fuselage of helicopter is assumed as a mass point with assigned aerodynamic characteristics. The simplified model was used to define following parameters due to flight speed: helicopter equilibrium conditions, rotor thrust components, rotor-wing lift proportion, power required for flight and power share for rotor and propellers driving.

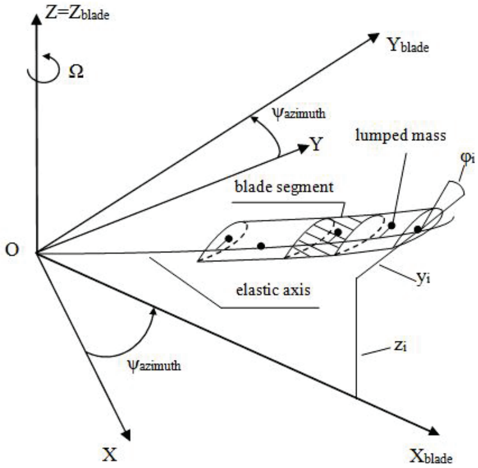

Fig. 2. Model of rotor blade includes elastic axis with set of lumped masses

For chosen flight states, the more precise of main rotor with elastic blades is applied. Individual rotor blade is treated as a set of lumped masses segments distributed along elastic axis, which allows for torsion and bending in-plane and out-of-plane deformations (Fig. 2). Parameters of blade motion, in accordance with Galerkin method, are treated as combinations of considered blade torsion and bending Eigen modes. The deflections of the blade elastic axis *y, z,* φ are equal to superposition of modal components:

$$y(x,t)=\sum_{i=1}^{I}\rho_i(t)y_i(x),\quad z(x,t)=\sum_{j=1}^{J}\delta_j(t)z_j(x),\quad \varphi(x,t)=\sum_{k=1}^{K}\eta_k(t)\varphi_k(x),\tag{1}$$

where:
y_i, z_j, φ_k – Eigen modes of in plane, out-of-plane bending and torsion, respectively,
ρ_i, δ_j, η_k – time dependent shares of Eigen modes, which are determined in computing process,
I, J, K – numbers of considered bending and torsion Eigen modes.

The Runge-Kutta method is applied for solution the equations of motion of elastic blades with introduced effects of variable blade aerodynamic and inertial forces. Repeating the cycle of calculation for subsequent azimuthal position allows defining the distributions of blade deformations and loads on the rotor disk. Aerodynamic forces acting on segment of blade at given azimuth position on the rotor disk are computed applying the blade element theory. The local angle of attack at blade cross-section depends on control of pitch angle and on temporary conditions of airflow:

$$\alpha=\varphi_o+\varphi_x\cos\Omega t+\varphi_y\sin\Omega t+\varphi_{geom}+\Delta\varphi_{torsion}-\mathrm{arctg}(u_z/u_x),\tag{2}$$

where:
φ_o – blade collective control angle,
φ_x, φ_y – cyclic control angle due to roll and pitch deflections of the swashplate,
φ_{geom} – blade geometric twist,
$\Delta\varphi_{torsion}$ – local torsion deformation,
u_z, u_x – components of the cross-section airflow of rotor blade: out-of-plane and in plane.

The considered configurations of conventional and compound helicopter versions are fitted with six-bladed hingeless main rotor with stiff blade-hub connection. For all variants of helicopter the take-off, mass of 2,500 kg is assumed. The basic data of the main rotor, tail rotor and propulsive propellers with nominal blade tip speed are collected in Tab. 1.

Tab. 1. Basic data of rotors and propeller

	number of blades	radius [m]	blade tip speed [m/s]	blade chord [m]
main rotor	6	4.91	218.5	0.264
tail rotor	4	0.95	210	0.179
propeller	6	1.00	210	0.15

The tail rotor is preserved even for compound helicopter with pushing propellers located at tip of wings (Fig. 1c). However, in this case, the different thrust of propellers could be enough for directional control helicopter, it seems that limited function of additional propellers assumed only for propulsion and preservation of tail rotor used for directional control may help to achieve the helicopter control system without coupling effects of propeller thrust changes on longitudinal and directional motion of rotorcraft.

Calculations of rotor loads and blade deformations in chosen flight states were performed using the model of elastic rotor blade which includes data of blade Eigen modes and frequencies. The values of the considered frequencies of rotor blade modes are collected in Tab. 2. Symbols used in Tab. 2 to sign blade Eigen modes are as follows: F – out-of-plane bending mode, C – in-plane bending mode, T – torsion mode, digits after mode symbol are equal to the number of nodes. It should be noticed that frequency values are related to the corresponding rotational speed of rotor.

3. Results of simulation

The results of calculations of required power, rotor thrust and equilibrium conditions for considered configurations of helicopters with the same six-bladed main rotor are shown in Fig. 3-5. The comparison of total power required for flight for conventional and compound helicopters for

Tab. 2. Eigen mode frequencies of rotor blade due to rotor rotational speed

Rotor rotational speed	Rotor blade frequency [ν/ω]							
	F0	F1	F2	F3	C0	C1	T0	T1
100%	1.072	2.659	4.941	7.497	0.616	3.884	4.553	11.191
90%	1.076	2.682	4.963	7.519	0.675	4.101	4.913	12.094

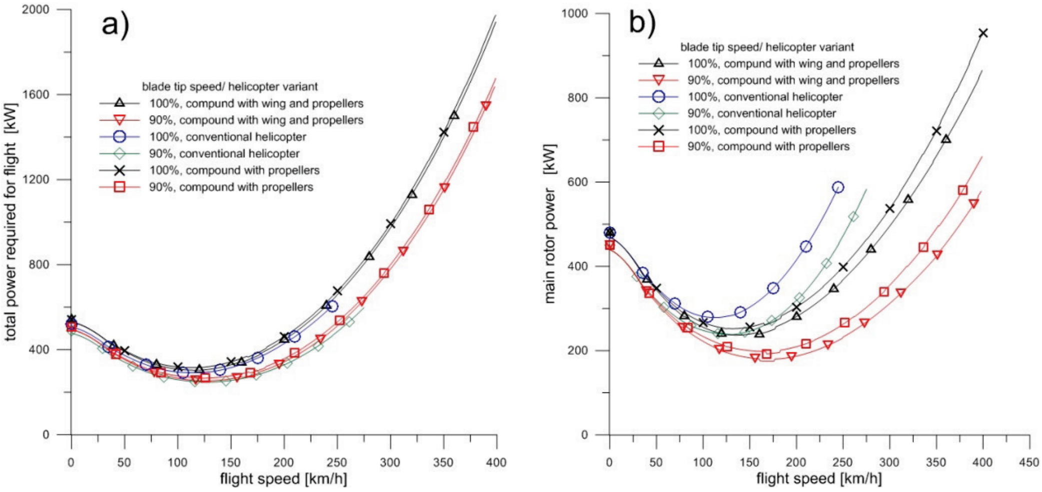

Fig. 3. Comparison for different helicopter configurations: a) total power required for flight, b) power required to drive main rotor

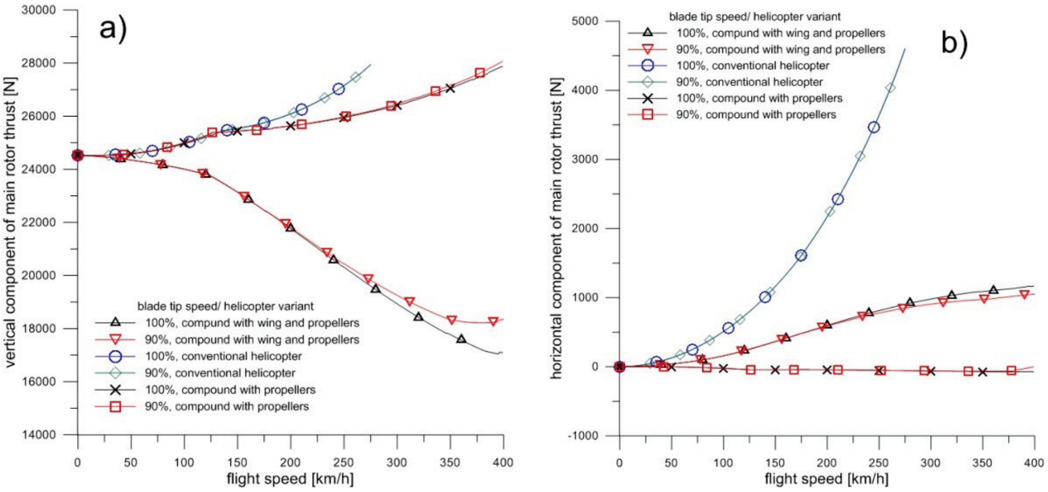

Fig. 4. Comparison of main rotor thrust for different helicopter configurations due to flight speed: a) vertical component of rotor thrust, b) horizontal component of rotor thrust

nominal and reduced rotational rotor speed is presented in Fig. 3a. The total required power reaches value of 2,000 kW for flight at speed of 400 km/h in the case of compound helicopter. It can be noticed that lesser total power is required for flights with reduced rotor rotational speed.

For conventional helicopter, the only source of propulsive force is horizontal component of rotor thrust (Fig. 4b). In the considered case of conventional helicopter the maximum flight speed is limited below value of 300 km/h due to high growth rate of main rotor power (Fig. 3b), which depends on collective pitch of rotor blades (Fig. 5b), longitudinal deflection of swashplate and fuselage pitch angle(Fig. 5a). Introduction of additional wings and propulsive propellers allows the compound helicopter to fly at high-speed conditions with fuselage pitch angle close to level position (Fig. 5a) and with lesser value of vertical and horizontal components of rotor thrust (Fig. 4). For high-speed flights, the reduction of rotor blade collective pitch can be noticed for winged version of compound helicopter (Fig. 5b).

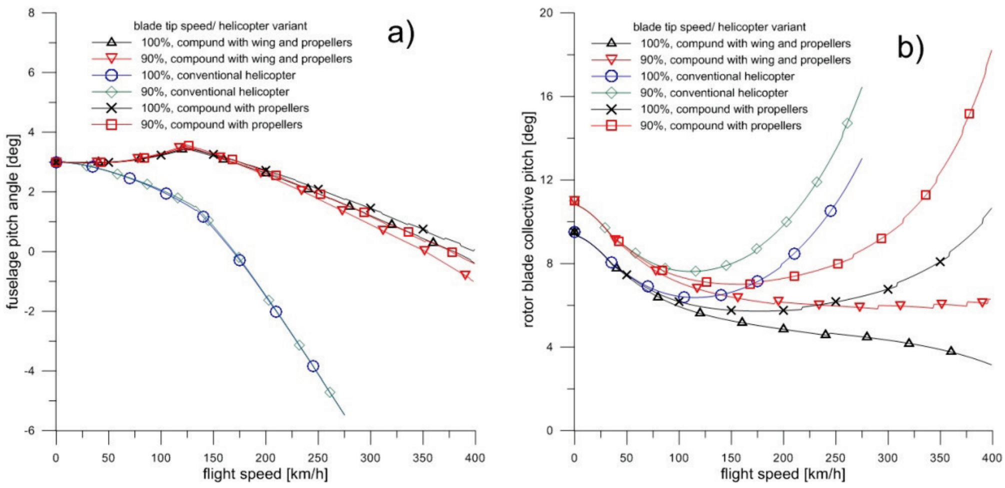

Fig. 5. Comparison of equilibrium conditions for different helicopter configurations: a) fuselage pitch angle, b) collective pitch of rotor blade

The more detailed model of elastic rotor blades was applied to calculate rotor loads and blade deflections for the winged compound helicopter flying with unloaded rotor at speed 200, 300 and 400 km/h with nominal and reduced rotor rotational speed. The simulations were performed for periods corresponding to 40 revolutions of the main rotor with applied step change of azimuthal position for each blade equal to $\Delta\psi = 5^{o}$. The results for the last two rotor revolutions are shown in Fig. 6 for time-runs of rotor thrust and in Fig. 7 for time-runs of torsion deflections at the tip of the blade.

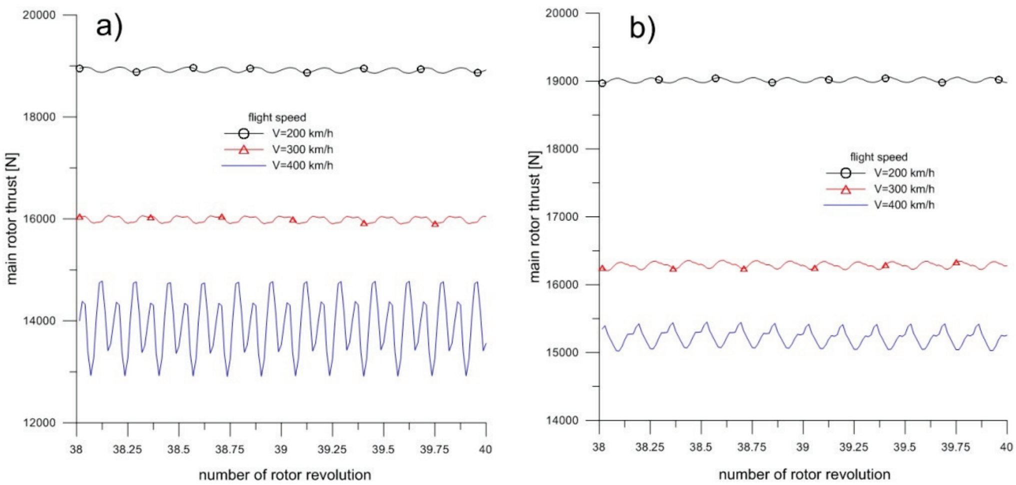

Fig. 6. Main rotor thrust time-runs for compound helicopter with wings and additional propellers in level flight at speed of 200, 300, and 400 km/h: a) for nominal rotor rotational speed (Ω = 44.4 rd/s), b) for reduced rotor speed to 90% of nominal value (Ω = 39.96 rd/s)

Comparing the results of simulations for level flight at speed of 400 km/h, the smaller oscillations of the main rotor thrust can be observed for compound helicopter with reduced the rotor rotational speed (Fig. 6). Lowered velocity of the blade tip diminishes effects of airflow compressibility for the advancing blade, which also can influence on decrease of torsion blade deflection. In the case of nominal rotor speed the blade torsion deflection at tip reaches -4º at azimuth of 90º (Fig. 7a), while for the reduced rotor speed the blade torsion deflection at tip for advancing zone is limited to angle of -2.25º (Fig. 7b). Details of blade deflection and load changes at flight speed of 400 km/h are shown in plots of rotor disk distribution of following blade parameters: torsion deflection, bending out-of-plane deflection, blade torsion moment and local angle of attack (Fig. 8-11).

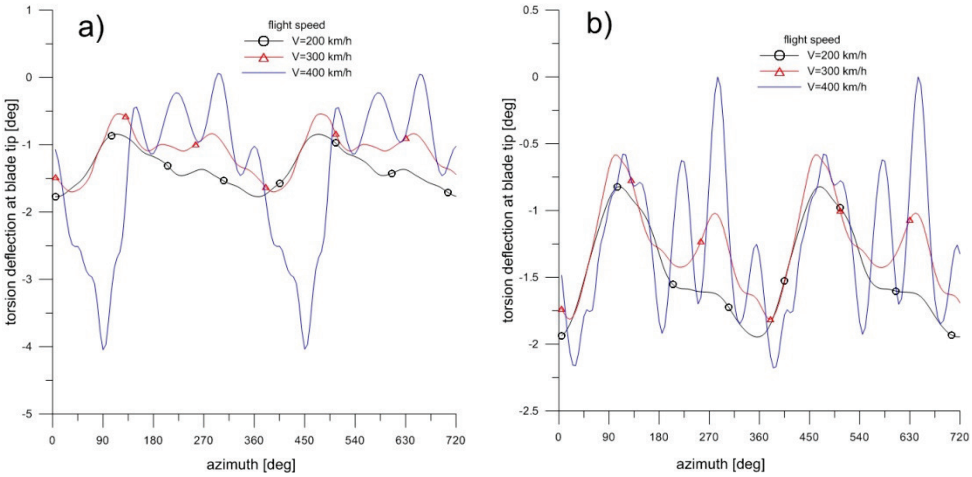

Fig. 7. Time-runs of torsion deflections at blade tip for compound helicopter with wings and additional propellers in level flight at speed of 200, 300 and 400 km/h: a) for nominal rotor rotational speed (Ω = 44.4 rd/s), b) for reduced rotor speed to 90% of nominal value (Ω = 39.96 rd/s)

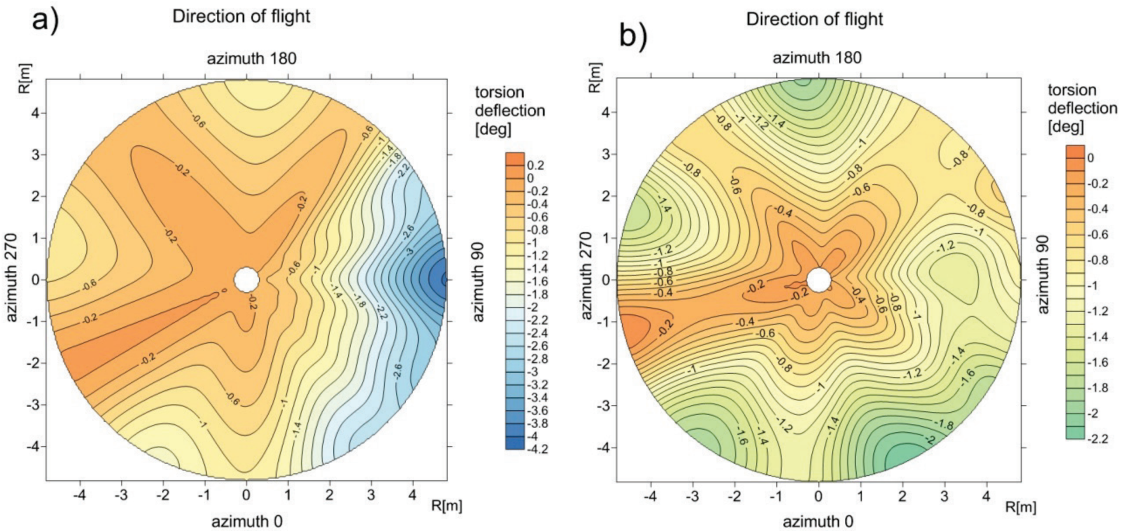

Fig. 8. Rotor disk distribution of blade torsion deflections in level flight at speed of 400 km/h for compound helicopter with wings and additional propellers: a) nominal rotor speed, b) reduced l rotor speed to 90% of nominal value

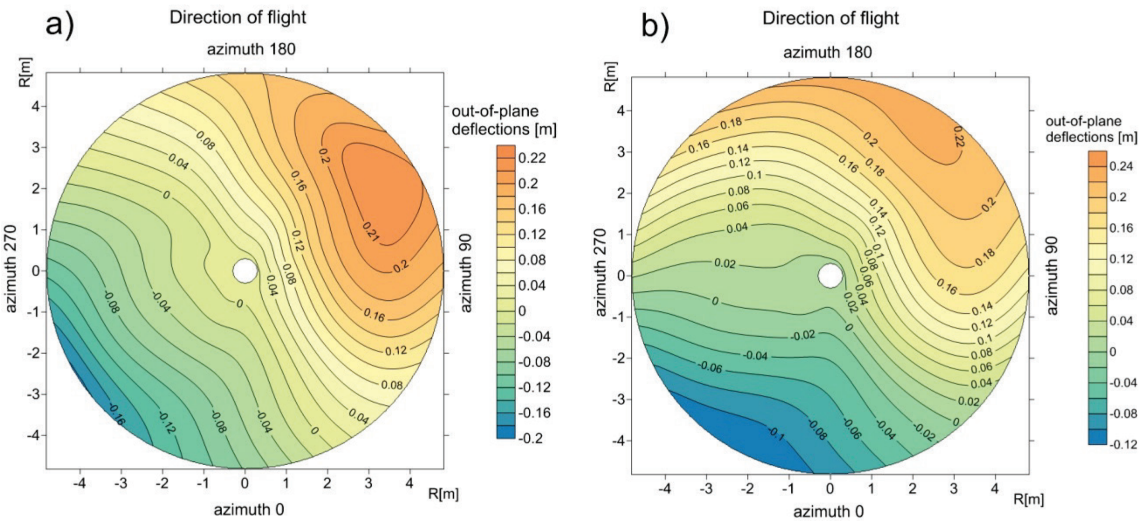

Fig. 9. Rotor distribution of blade bending out-of-plane deflections in flight at speed of 400 km/h for helicopter with wings and additional propellers: a) nominal rotor speed, b) reduced rotor speed to 90% of nominal value

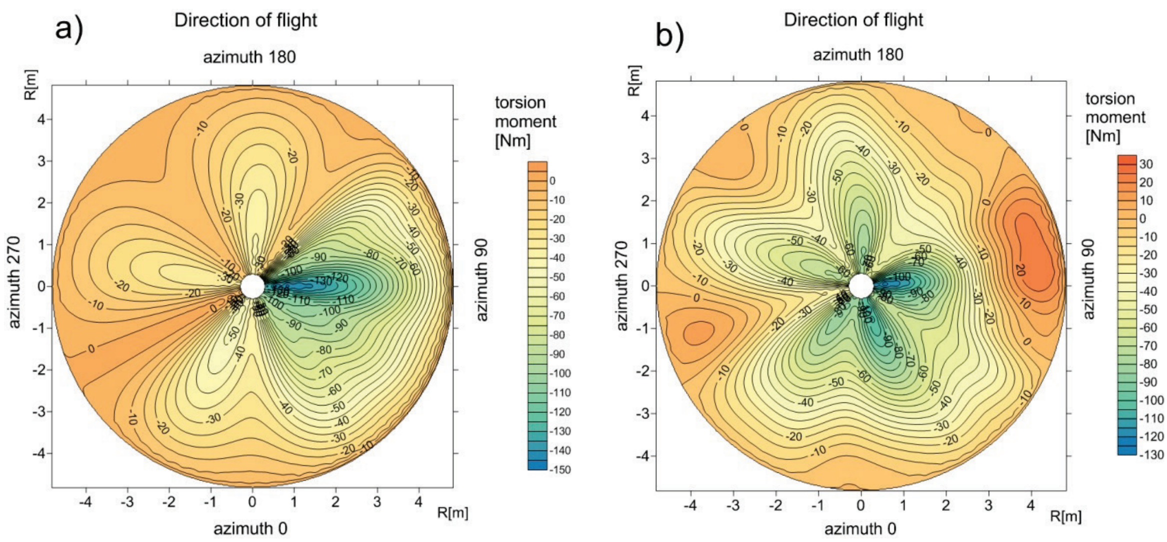

Fig. 10. Rotor disk distribution of blade torsion moments in level flight at speed of 400 km/h for compound helicopter with wings and additional propellers: a) nominal rotor speed, b) reduced rotor speed to 90% of nominal value

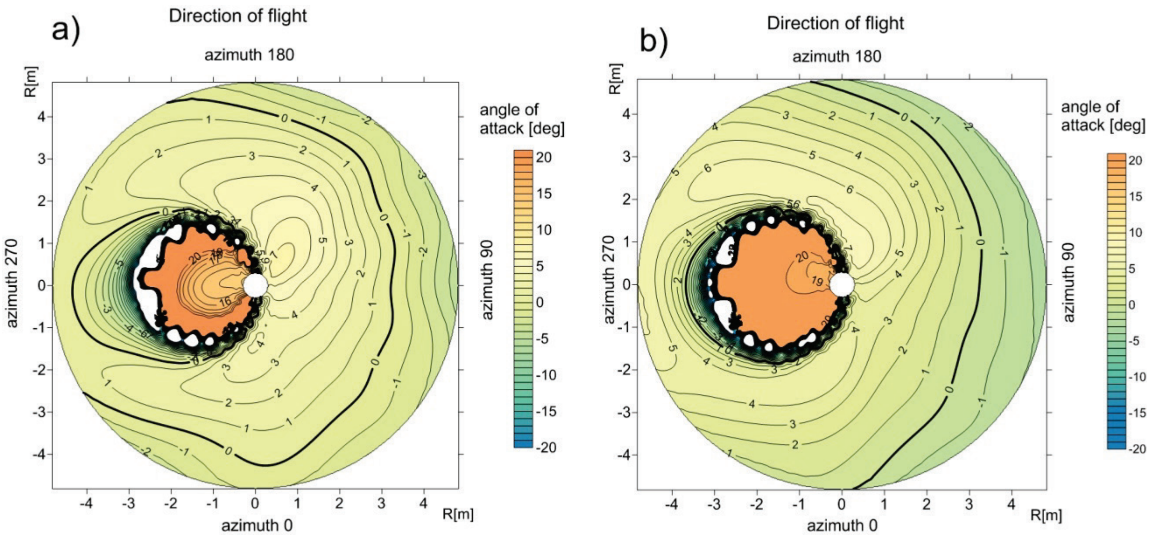

Fig. 11. Rotor disk distribution of blade local angle of attack in level flight at speed of 400 km/h for compound helicopter with wings and additional propellers, a) nominal rotor speed, b) reduced to 90% rotor speed

For the case of nominal rotor speed (Fig. 8a) the range of oscillation of torsion deformation at blade tip includes between -4º at azimuth of 90º for advancing blade and 0.05º at azimuth of 300º for retreating blade zone. The weakened oscillation of blade torsion deformations, between -2.2º and 0º, can be noticed for the case of reduced rotor speed (Fig. 8b). Number of cycles of torsion deformation observed in rotor disk distributions corresponds to frequency of the first Eigen mode of blade torsion vibration. Similar pulsation is perceived in disk distribution of blade torsion moments (Fig. 10). Decrease of rotor speed influences on mutual changes of distribution of blade out-of-plane deformations (Fig. 9) and distribution of local attack angles of blade (Fig. 11). Preservation of rotor thrust at lowered blade speed requires greater collective pitch. Additionally, reduced centrifugal forces involve change of blade balance increasing the angle of rotor blade cone. In these conditions, the changed components of airflow passing from lower to upper side of rotor disk increase angles of attack at blade sections. Reduction of rotor rotational speed enables flight of compound helicopter at high velocity conditions without generation excessive oscillation of rotor loads and blade deflections.

4. Conclusions

The simulation calculations for compound helicopters indicate that high-speed flights, which enlarge operational envelope of rotorcrafts, are possible. For configuration of compound helicopter additional wings and propulsive propellers, which unload the main rotor, help to achieve the range of high-speed flights without excessive growth of vibrations. Power required for high-speed flight at 400 km/h is approximately three-times greater than the power in hover conditions. Slower rotor with reduced blade tip speed allows diminishing negative effects of airflow compressibility in zone of advancing blade. Application of rotor with enlarged number of blades effects on low level of vibrations generating in high-speed flights. Introduction of compound helicopters may enlarge range of rotorcraft usage.

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