Numerical investigation of rotor loads of a shipborne coaxial-rotor helicopter during a vertical landing based on moving overset mesh method

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ABSTRACT
Coupled ship/coaxial-rotor simulations have been conducted to investigate the rotor loads of a shipborne coaxial-rotor helicopter during a vertical landing based on Reynolds-averaged Navier-Stokes (RANS) solver. In order to achieve two-way coupling and overcome the limitations of the momentum source method in solving the unsteady aerodynamic problems, the moving overset mesh method is employed to simulate the complex highly unsteady aerodynamic interactions between the lower/upper rotor, flight deck and hangar-door through the vertical descent. To identify pilot workload and control strategy during this phase, the results in terms of time-averaged and root-mean-square (RMS) rotor loads are discussed. The time-averaged loads show that the coaxial-rotor helicopter suffers an increase in thrust and a sharp decrease in torque difference between lower and upper rotors during the vertical landing. It suggests that the pilot has to reduce not only the collective control input, but also the differential collective pitch, to stabilize the heading of the coaxial rotors helicopter. The RMS results indicate that the aerodynamic loads of the lower and upper rotors could couple with each other, and may eventually magnify the overall unsteady loading levels of the coaxial rotor. In addition to the ground effect, the recirculation flow regime will get stronger and lead to a sharp increase in RMS roll as the rotor moves along the vertical descent path. Furthermore, the influences of hangar-door state and the location of landing spot are investigated. The findings imply that opening the hangar-door can significantly reduce the pilot workload, and descending a helicopter to a landing spot which is more closed to the hangar can decrease the RMS load levels, especially during the latter stage of vertical descent. However, the helicopter tends to be pulled towards hangar-door more easily due to greater reduction in pitch moment.

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1. Introduction
Although helicopters have been deployed in navy for decades, the launch and recovery of shipborne helicopter is still a difficult task for even the most experienced pilots. Unlike land-based operations, the confined landing areas just behind the ship superstructure leave little margins for error. More importantly, the unstable shear layers and vortices of different scales will be formed as air flow passes over the ship superstructure. These turbulent structures will propagate downstream and interact with each other, thus creating a highly complex airwake over the flight deck (Forrest & Owen, 2010; Lawson, Crozon, Dehaze, Steijl, & Barakos, 2012; Shi, Xu, Zong, & Xu, 2017; Thornber, Starr, & Drikakis, 2010). As the pilot performs take-offs and landings, the highly turbulent airflow will induce large perturbations in the rotor load and response (Lee & Zan, 2004, 2005).

In general, a shipborne helicopter landing process involves a lateral translation (i.e. A) and a vertical descent (i.e. B) as shown in Figure 1. To date, a lot of numerical studies have been carried out on the aerodynamic interference between ship airwake and shipborne helicopter during a lateral traverse phase. Some researchers employed one-way coupled strategy to investigate the rotor loads of a single-rotor shipborne helicopter (Forrest, Kääriä, & Owen, 2016; Kääriä, Forrest, Owen, & Padfield, 2009; Scott, White, & Owen, 2015). Results in terms of rotor loads, helicopter response and pilot workload were discussed for different wind angles and hover positions (Kääriä et al., 2009), and the effects of ship superstructure (Forrest et al., 2016) and ship size (Scott et al., 2015) were also considered. Nevertheless, these studies were all focused on the lateral traverse phase, and the rotor-on-ship effect was ignored. Bridges, Horn, Alpman, and Long (2007) also applied one-way coupling to determine control inputs for a single-rotor helicopter under specified landing trajectory. However, the findings suggested that one-way coupling may obtain inaccurate
result. This implies that it is necessary to conduct two-way coupled simulation, in which both ship-on-rotor and rotor-on-ship effect are considered. Alpman, Long, Bridges, and Horn (2007) and Oruc, Shenoy, Shipman, and Horn (2016) carried out two-way coupled calculations by using the momentum-source method (Bontempo & Manna, 2017; Rajagopalan & Mathur, 1993). Again, a ship/single-rotor helicopter configuration was employed to perform the research. The recirculation flow regime, which could not be captured by one-way coupling method, was successfully simulated. The effects of this phenomenon on the dynamic response and control inputs for the single-rotor helicopter were also analyzed. However, the momentum-source method used in the researches is quasi-steady in nature and, therefore, is not satisfactory for high fidelity simulations (Crozon, Steijl, & Barakos, 2014), especially for the highly unsteady interactions between rotor blades and ship airwake (such as ship-vortex/rotor-blade interaction).

All these researches are of great sense to understand the effects of ship airwake on shipborne aircraft. However, it should be noted that these studies were focused on the disturbances in a conventional single-rotor helicopter through the lateral translation. The rotor loads of a shipborne coaxial-rotor helicopter (such as Ka-28 helicopter) through a vertical descent have not yet been found in published literatures. In fact, the new coaxial-rotor configuration, such as S-97, has obvious advantage over the conventional configuration in the further marine application due to its high-speed characteristics. Thus, it is of great significance to study the effects of airwake on a coaxial rotor configuration. Generally, the height of a medium-sized helicopter is much less than the hangar height of a large-scale ship. For example, the hangar height of LPD-17 reaches 10 m, while only about 3.5 m for the height of the Lynx helicopter. Furthermore, in addition to the turbulent airwake, the phenomena (i.e. ground effect and recirculation flow regime), which are always ignored during the lateral translation, will become important and could impose disturbances on the helicopter during the vertical descent. As a result, although it is just a short displacement compared to a lateral translation, it will still take considerable time and effort for the pilot to execute a vertical descent in such confined area. How significantly these phenomena may influence the pilot workload, and what difference might exist between the single-rotor and coaxial-rotor helicopters during a vertical descent remain unknown.

This is the motivation behind conducting the present research. A ship/coaxial-rotor configuration is used in the paper to characterize the rotor loads of a shipborne coaxial-rotor helicopter during the vertical landing. In order to achieve two-way coupling and overcome the limitations of the momentum source method in simulating unsteady aerodynamic interactions, the moving overset mesh method (Meakin, 1991) is employed to investigate the effects of the highly unsteady phenomena (i.e. ground effect and recirculation flow regime) on the coaxial-rotor helicopter through this phase. First, coupled simulations are conducted for various rotor heights along a vertical descent path. Results in terms of time-averaged and Root-Mean-Square (RMS) loads are analyzed to identify the pilot workload and control strategy as the coaxial-rotor helicopter moves to the landing spot. Also, the influences of ground effect and recirculation flow regime are studied in this process. The distributions of turbulence intensity and the velocity over the flight deck are analyzed to explore the reasons behind the results. Then, the effects of hangar-door state and the landing spot location on the rotor loads of the coaxial rotor are discussed in detail. By the present investigation, it is shown that the ground effect and recirculation flow regime have significant influence on control margins and unsteady loading levels. Opening the hangar-door or descending...
a helicopter to a landing spot which is more closed to the hangar can decrease the RMS levels considerably, especially during the latter stage of vertical descent.

2. Numerical methodology for two-way coupled simulation

2.1. CFD method

The computations are performed using the commercial software STAR CCM+. The ship/coaxial rotor coupled flowfield is solved by the Reynolds-averaged Navier-Stokes (RANS) equations. For each simulation, the location of coaxial rotor keeps constant relative to the ship. The forward motion of the ship and rotor is applied through the boundary condition at the inlet surface so that the center of rotation is fixed. The rotation of the rotor is taken into account when adding a velocity of blade grid to the fluid velocity. Therefore, the integral of coaxial rotor keeps constant relative to the ship.

\[
\frac{\partial}{\partial t} \iiint_V W dV + \iiint_{\partial V} (F_c(W) - F_v(W)) dS = 0
\]

where \( W \) is introduced into Equation (1) as follows:

\[
\frac{\partial}{\partial \tau} \iiint_V W dV + \frac{\partial}{\partial t} \iiint_V W dV + \iiint_{\partial V} (F_c(W) - F_v(W)) dS = 0
\]

where \( \tau \) is a locally varying pseudo-time used in the time-marching procedure, and \( t \) denotes the physical time-step which is applied uniformly to all cells in the domain. The pseudo-time and physical-time derivative terms in Equation (2) are discretized by means of a first-order and a second-order backward difference schemes, respectively. The dual-time equation is then written as follows:

\[
W_i^{m+1} V_i^{n+1} - W_i^m V_i^n = \frac{\Delta \tau}{3} (WV)^{n+1} - 4(WV)^n + (WV)^{n-1} \frac{2\Delta t}{2} W_i + \Delta W_i \quad (3)
\]

by defining \( \Delta W = W_i^{m+1} - W_i^m, \ RES_i(W_i^{m+1}) = \iiint_{\partial V} (F_c(W_i^{m+1}) - F_v(W_i^m)) dS \) and using \( W_i^{n+1} = W_i^m + \Delta W_i \), Equation (3) can be written as follows:

\[
\left( \frac{1}{\Delta \tau} + \frac{3}{2\Delta t} \right) V_i^{n+1} \Delta W_i + RES_i(W_i^{m+1}) = 0 \quad (4)
\]

\[
RES_i^m(W_i^{m+1}) = \frac{3W_i^mV_i^{m+1} - 4W_i^mV_i^n + W_i^{n-1}V_i^{n-1}}{2\Delta t} + RES_i(W_i^{m+1}) \quad (5)
\]

where \( m \) and \( n \) are pseudo-time and physical-time iterations, respectively. \( V_i^n \) represents the volume of grid, and \( RES_i^m(W_i^{m+1}) \) denotes residual. When inner iterations (i.e. pseudo-time iterations) converge, the solution at the next physical time level \( W_i^{n+1} \) is given by \( W_i^{m+1} \).

To improve the simulation fidelity, the moving overset mesh method is used to study the coupled flowfield. This technique is able to capture many phenomena that the momentum source method cannot, such as the interactions between blades and ship shedding vortices (Shi, Xu, & Wei, 2016). In the present method, a two-step process (i.e. hole-cutting and Donor Search) takes place to identify the topological relationship between the background grid and blade grids. In addition, a linear interpolation algorithm (Tang, 2006) is adopted to exchange information between the two types of grids. A schematic of moving overset mesh is shown below Figure 2.

It should be reiterated that the RANS is used in this paper to reduce the computation effort of the ship/coaxial
rotor coupled simulations. Generally, the RANS solver is indeed not as satisfactory as Detached Eddy simulation (DES) and Large Eddy Simulation (LES) solvers in simulating the unsteady characteristics of ship airwake. However, a comparative study between RANS and LES in simulating velocity distribution over the flight deck has been performed by Muijden, Boelens, Vorst, and Gooden (2013), and it is demonstrated that the simulation accuracy between these two methods is of no significant difference. The reality level of RANS for the airwake determination is regarded as acceptable. In addition, another numerical study for the airwake of LHA ship model has been carried out by Polsky and Bruner (2001), using both the RANS (using SST $k - \omega$ turbulence model) and Monotone Integrated Large Eddy Simulation (MILES) methods. The result also indicates that the URANS is capable of capturing the unsteady flowfield characteristics. As a result, the two-equation $k - \omega$ turbulent model (Lee, 2018; Menter, 1993) is employed in the current study for RANS closure.

2.2. Numerical method validation

Due to a lack of experimental data for ship/coaxial rotor coupled flowfield, simulations of isolated ship and coaxial rotor are carried out to demonstrate the effectiveness of the method. Furthermore, unlike operating a helicopter through a lateral translation, a phenomenon named ‘ground effect’ will occur and impact the rotor loads significantly as the coaxial helicopter moves close to the landing spot during a vertical landing. Therefore, it is necessary to perform validation on the simulation accuracy of coaxial rotor in ground effect (IGE) and out of ground effect (OGE).

(1) Isolated ship simulation

In the simulation, the SFS2 model is used because of its available experimental data (Zhang, Xu, & Ball, 2009). The calculation is carried out with a velocity of $V_\infty = 12.87$ m/s for a headwind. Figure 3 shows the comparisons of time-averaged streamwise velocity distributions between the experimental data (Zhang et al., 2009) and current calculation over the flight deck. As can be seen, the computed results agree well with the measurements. In addition, the hangar shows great blockage effect on the air flow, which would influence the helicopter control margins adversely.

Furthermore, to analyze grid independence, another two meshes of different grid density (i.e. coarse grid and refined grid) are also constructed with the same growth rate of cells (i.e. 1.1). The target cell sizes ($\Delta_0/H$) around the ship are $8.33 \times 10^{-2}$, $6.25 \times 10^{-2}$ and $4.17 \times 10^{-2}$ for the coarse, baseline and refined grids, respectively, where $H$ is hangar height. As a result, cell counts of the three sets are approximately $2.8 \times 10^6$, $4.5 \times 10^6$ and $7.2 \times 10^6$, respectively. The quantitative comparisons are presented in Figure 4. It can be clearly seen that none of the three meshes provide remarkable improvement in the prediction of velocity distribution. The similarity of the results of three sets indicates grid-independent solutions.

(2) Isolated coaxial rotor simulation

The experimental data of coaxial rotor in the OGE condition used here is provided by Nagashima (Coleman, 1997). This experimental setup consists of two 2-bladed rotors, and each blade has an aspect ratio of 6.33. Figure 5 shows the comparisons between computed and

![Figure 2. Details of overset grid system.](Image)

![Figure 3. Time-averaged streamwise velocity distributions over the flight deck.](Image)
the measured mean thrust and torque against advance ratio, respectively. As can be seen, both the thrust and torque of the lower rotor are seen to be well predicted. Although the performance characteristics of the upper rotor are slightly under-predicted, the trends are all in agreement with the experimental measurements.

The experiment of coaxial rotors in the IGE condition is performed in Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China. Two 4-bladed rigid rotors with an aspect ratio of 15 are consisted in the experimental setup. The blade uses an OA212 airfoil section along the entire span and has a twist angle of $-16$ degrees. Figure 6(a) shows the variations of total thrust with RPM at different rotor heights, and the thrust of both lower rotor and upper rotor against free-stream velocity are shown in Figure 6(b). Again, the computed results agree well with the measurements, although there is some discrepancy in the thrust of upper rotor. Furthermore, the results in Figure 6(a) also indicate that the ground effect will increase with the decrease of the rotor-to-ground height.

2.3. Numerical set-up and data analysis

A 1/5 scale model of the SFS2 (Zhang et al., 2009) is chosen for this study because this model represents a good compromise between geometric realism and mesh complexity, and its airwake can generally reflect the typical flow features of a frigate over the flight deck. The deck length ($L$), ship beam ($B$) and hangar height ($H$) are 5.44, 2.74 and 1.2 m, respectively. The coaxial rotor, which has been used for the measurement of the coaxial rotor flowfield in the National Key Laboratory of Science and Technology on Rotorcraft Aeromechanics (Tang, Li, Gao, & Mei, 1998), NUAA, China, consists of two 2-bladed rotors with a radius ($R$) of 1.89 m. The solidity of each of the rotors is 0.05 with rotor spacing ($h/R$) = 0.185. Each blade uses a NACA0012 airfoil section along the entire span. The tip Mach number is 0.347 and the blade collective pitch is set as $10.27^\circ$. The upper rotor is clockwise, and the lower rotor rotates counter-clockwise (viewed from the top).

In general, there are two or more landing spots on the flight deck for an amphibious landing ship for the shipboard operation of helicopters. For this reason, two landing spots are studied in current research. The front one is at the location of 35% deck length behind the hangar on the centerline of the SFS2, and the other is on the mid-deck region, denoted by landing spot 1 and landing spot 2, respectively. In addition, two hangar-door
states (i.e. the initial SFS2 model and SFS2 with hangar-door open) are also considered due to the fact that the hangar-door plays an important role in the development of Ship-Helicopter Operating Limits (SHOLs). The coaxial-rotor helicopter is then located at 7 points along the two vertical descent paths as shown in Figure 7. At each rotor position \((x, y, z)\), calculation is conducted with a same velocity of \(V_\infty = 15 \text{ m/s} \) for a headwind. In the discussions to follow, the height of the coaxial rotor is defined as the distance between the lower rotor and flight deck. Velocity and turbulence intensity are normalized by free-stream velocity.

A 10\(L_s\) 8\(L_s\) 6\(L_s\) rectangular computational domain (Park, Yang, & Rhee, 2017) is generated by the STAR CCM+ (Figure 8), where \(L_s\) is ship length. The inlet and outlet boundaries are specified as velocity inlet and pressure outlet, respectively, and the ship body is designated as a no-slip wall condition. As all the simulations in the following are carried out with uniform velocity profiles, the sea surface and the other three domain boundaries (i.e. upper, right and left domain boundaries) are given as slip wall conditions. Prism layers are extruded on the ship surface for the viscous boundary layer. The wall unit values, which represent spacing normal to the ship surface, are set to 1.5 mm, thus the \(y^+\) is within a range of 25–320. All four blade grids are embedded in the background grid using overset mesh method to allow rotation. The blade grid is refined towards the blade surface to improve the vortex preservation. An interpolation algorithm is then used to exchange information between the two types of grids as discussed before, thus realizing the two-way coupling in the ship/coaxial-rotor simulation. In addition, the refined grid is clustered over the flight deck to capture the detailed flow features of coupled flowfield.

Figure 6. Thrust comparison for the IGE condition, (a) total thrust versus RPM, (b) thrust versus free-stream velocity.

Figure 7. Sketch of SFS2 model and 7 rotor locations along two vertical descent paths relative to the flight deck.
giving cell counts of approximately $8.0 \times 10^6$ for each simulation.

Each simulation of isolated ship airwake is initiated by a steady-state solver. The result can be used to initialize the unsteady simulation to speed up the calculation process. The solution convergence is determined by monitoring the residuals. Roughly, 2500 iterations are necessary for convergence. After that, the simulation is restarted for the unsteady calculation. The time step is set to 0.002 s based on the guidelines given by Muijden et al. (2013). A complete unsteady calculation consists of 7500 time-steps, with 5000 used for recording the ship airwake data. For the coupled ship/ coaxial rotor simulations, because of a large difference in frequency between the rotor aerodynamics and the ship airwake, 150 rotor revolutions (i.e. 7.5 s) are required to obtain the fully developed flowfield, with 120 rotor revolutions (i.e. 6 s) used for recording the aerodynamic loads of the coaxial rotor and the coupled flowfield data. In each solution using the moving overset mesh method, one revolution is divided into 360 time steps, equivalent to $1.39 \times 10^{-4}$ s per time step. All the calculations are run on a computing cluster (IBM X440), which consists of 7 workstations with 168 processors in total.

After the time-histories of the aerodynamic loadings are obtained through the calculations, the root-mean-square (RMS) method, which has been adopted by Lee and Zan (2004, 2005), is employed to analyze the effect of the unsteady loadings on pilot workload. In the method, the power spectral density (PSD) plot is first calculated from the transient data of rotor loads and then integrated between the closed-loop frequency bandwidth of 0.2–2 Hz. The square root of the value is regarded as a measure of RMS loading (e.g. RMS Pitch). This integration is shown graphically in Figure 9. Time-averaged analysis of the aerodynamic loads (i.e. rotor thrust, pitch, roll and torque) is also carried out in this paper, and these rotor loads are normalized by $\rho \pi R^2 (\Omega R)^2$ and $\rho \pi R^3 (\Omega R)^2$ accordingly, where $\Omega$ is rotor rotation speed. In the paper, thrust is positive upward and pitch moment is positive as the front part of the rotor is nose-up. For convenience, the roll moment and torque are presented as an absolute value in the next to identify the difference in these two moments between the lower and upper rotors.

3. Results and discussions

3.1. Rotor load characteristics

3.1.1. Time-Averaged rotor load characteristics

Figure 10 presents the vorticity iso-surfaces of ship/ coaxial rotor coupled flowfield for different rotor positions, which are colored by normalized velocity magnitude. It can be seen that the ship airwake imposes less influence on the coaxial rotor at $z/H = 1.0$ compared with other rotor position cases. The rotor flow characteristics, such as centered tip vortex and rotor wake can be clearly distinguished from the coupled flowfield.
Figure 10. Vorticity iso-surfaces of ship/coaxial rotor coupled flowfield for different rotor positions. (a) $z/H = 1.0$ (b) $z/H = 0.875$ (c) $z/H = 0.75$ (d) $z/H = 0.625$.

As the coaxial rotor moves vertically to the landing spot, the well-known phenomenon named ground effect gets stronger and directs the rotor wake to expand along the flight deck. The forward part of rotor wake then flows along the hangar-door, thus forcing the iso-surfaces of vorticity, located between coaxial rotor and hangar, to roll up as shown in Figure 10(c) and (d). Similarly, the lateral part of rotor wake interacts with deck-edge vortex and then rolls up, indicating a recirculation movement.

Figure 11 shows the time-averaged load coefficients of the lower and upper rotors along the vertical descent path for the landing spot 2 (see Figure 7). It is evident that the thrust reduces first as the coaxial rotor moves from the rotor position $z/H = 1.0$–0.875, and then increases approximately by 6% during the rest stage of descent. Meanwhile, there is also a significant decrease in torque difference between the lower and upper rotor, between $0.875 < z/H < 0.5$. This suggests that the pilot has to reduce not only the collective control input to keep the equilibrium of force in vertical direction, but also the differential collective pitch to stabilize the heading of the coaxial rotors helicopter relative to the ship. Furthermore, during the entire vertical descent phase, the mean pitch moment has reduced by 152% and 113% for lower and upper rotors as shown in Figure 11, respectively. This is equivalent to adding a nose-down moment to the rotor and would push the helicopter toward hangar. The conclusion also concurs with the pilot comments that the aircraft is pulled towards the hangar during the flight trials (Forrest, Owen, Padfield, & Hodge, 2012).

To identify the origin of these variations, Figure 12 presents the contours of mean longitudinal velocity in the symmetrical plane, where the position of rotor disc has also been shown for $z/H = 0.875$ and 0.50 for landing spot 2 (see Figure 7). For brevity, only the lower rotor is presented. As can be seen, the coaxial rotor will be gradually immersed in the lower velocity region when it descends toward the landing spot, leading to a reduction in thrust between $1.0 < z/H < 0.875$. However, the ground effect will increase with the decrease of rotor-to-deck distance, thus causing a significant increase in thrust between $0.875 < z/H < 0.5$ (Figure 11). It is well known that the ground effect will reduce the induced
velocity at the rotor disk, thus increasing the angle of attack of the rotor blades, especially the lower rotor blades for the coaxial system. As a result, the torque of the lower rotor increases simultaneously in this area and, therefore, the torque difference between the lower and upper rotor decreases remarkably.

In addition to the ground effect, when the helicopter operates near the flight deck, the forward part of rotor wake, after impinging on the deck, flows upward along the hangar door and recirculates as downwash at the front of the rotor, forming a well-known phenomenon called 'recirculation flow regime' (Oruc, Horn, Shipman,

**Figure 11.** Mean forces and moments for lower rotor (—□—) and upper rotor (—△—).

**Figure 12.** Contours of longitudinal mean velocity in the symmetrical plane for a headwind.
& Shenoy, 2016). To examine this phenomenon further, Figure 13 shows the vertical velocity component along a longitudinal line just over the rotor disk for various rotor positions, in which the longitudinal range of the upstream half of the rotor disk has also been indicated. It is clear that the upwash on the front of the rotor gradually decreases as the rotor moves towards flight deck, and turns to a downwash at \( z/H = 0.50 \), thus resulting in a decrease in the growth rate of mean thrust for lower rotor between \( 0.625 < z/H < 0.5 \). Furthermore, these interactions between the recirculating flow and the leading edge of the rotor will manifest themselves as disturbances in the roll moment of the rotor as a result of 90° phase shift, leading to a sharp decrease in the mean roll moment of lower rotor in this area as shown in Figure 11.

### 3.1.2. Unsteady rotor load characteristics

The time-averaged rotor loads as well as the corresponding control strategies during the vertical descent have been discussed above. However, the ship airwake is unsteady in nature and contains different scales of time-varying turbulent structures which could induce instantaneous perturbations in aerodynamic loadings. Figure 14 shows the time histories of thrust in last 60 revolutions for \( z/H = 0.75 \). It is obvious that two distinct fluctuations of different time scales are contained within the time-histories. The long-term fluctuation, caused by unsteady turbulent structures in the airwake, is concentrated in the range 0.2–2 Hz. This bandwidth covers the range of pilot closed-loop control frequencies and, therefore, will impact the handling qualities significantly. The short-term fluctuation is mainly induced by the rotation movement of rotor in the airwake of large spatial velocity gradients. Also, the ground effect will introduce high frequency fluctuations into the thrust (Benjamin, Ulrich, Manuel, & Ewald, 2012). This will be analyzed in more detail below. It should be noted that these peaks occur at frequencies above 20 Hz, thus having little effect on pilot workload.

Figure 15 shows unsteady loading variations during the vertical descent for the coaxial-rotor helicopter. It can be seen that the RMS thrust, pitch, roll and torque of the lower rotor, on average, are 33%, 42%, 84% and 35% greater than that of the upper rotor, respectively. This is because the lower rotor is located between the upper rotor and flight deck, and will be exposed to much more turbulent airflow. Furthermore, the RMS loads of coaxial rotor are much higher compared with the lower rotor and the upper rotor. The result implies that the aerodynamic loads of the lower and upper rotors could couple with each other and might eventually magnify the unsteady loading levels of the coaxial rotor. This is a particular phenomenon for coaxial rotor configuration, and does not exist in the conventional single-rotor helicopter.

As the coaxial rotor moves along the vertical descent trajectory, between \( 1.0 < z/H < 0.75 \), the unsteady loading levels increase considerably. However, as discussed in the time-averaged analysis, this area also corresponds to the region of significant reduction in mean pitch moment. Thus the pilot has to continuously correct control inputs, especially the longitudinal cyclic control input, to maintain an appropriate helicopter-to-hangar distance in such confined area.

In order to analyze these variations in RMS loadings, Figure 16 shows the map of vertical turbulence intensity in the symmetrical plane, in which the longitudinal range of rotor disc has also been indicated for three locations. It is clear that the highly unsteady area of the flowfield is located around the position \( x/L = 0.5 \), which is caused by the time-varying turbulent structures and the reattachment of unstable shear layer. The coaxial rotor will be gradually immersed in the highly turbulent airwake as it moves close to the landing spot. However, obvious reductions in RMS loadings are observed in the region...
z/H < 0.75, and a sharp increase in RMS roll occurs between 0.5 < z/H < 0.625. These variations cannot be derived from the aerodynamics of the isolated ship airwake. It means that the coaxial rotor wake has significantly changed the flow characteristics over the flight deck.

Figure 17 shows vertical turbulence intensity along five longitudinal lines over the flight deck in the plane y/b = 0 for various coaxial rotor positions, in which z/h represents the height of longitudinal line relative to the deck. As can be seen, at z/H = 0.75, the highly unsteady region is located between 0.35 < x/L < 0.4, under the

Figure 15. RMS loads for lower rotor (—□—), upper rotor (—△—) and coaxial rotors (—○—).
Figure 17. Vertical turbulence intensity along the longitudinal lines of different height relative to the flight deck in the plane y/b = 0 for various coaxial rotor positions, (a) z/H = 0.75, (b) z/H = 0.625, (c) z/H = 0.5.

Forward part of the lower rotor. This high turbulent airwake can continuously change the effective angle of the main rotor blades, thus leading to large fluctuations in aerodynamic loads and eventually increasing the pilot workload. In addition, another peak vertical turbulence intensities are observed between 0 < x/L < 0.05, just close to the hangar. These peak values are caused by the unsteady recirculation flow regime in front of the rotor.

When the coaxial rotors translate along the vertical descent path, the overall unsteady velocity levels in the airflow increases substantially. However, the highly unsteady area gradually moves out of the inner region of the rotor disk (Figure 17(b)) and, therefore, has less effect on the rotor compared with the case at z/H = 0.75, thus leading to considerable reductions in RMS levels as shown in Figure 15. Furthermore, the degree of unsteadiness in the recirculation flow regime also increases remarkably during the vertical descent. This unsteady recirculating flow will cause fluctuations in vertical velocity on the forward part of the rotor, resulting in peak vertical turbulence intensity at the leading edge of the rotor (Figure 17(c)). Due to 90° phase shift, these interactions will manifest themselves as disturbances in the roll of the rotor, thus leading to a sharp increase in RMS roll between 0.5 < z/H < 0.625 (Figure 15).

As mentioned earlier, the helicopter will experience ground effect when it vertically descends to the landing spot, and this effect will also introduce remarkable unsteadiness into the rotor thrust. In Figure 18 the amplitude of thrust coefficient is mapped against the frequency normalized with the rotor frequency. The thrust frequency spectrum shows very high peaks around 2 and 4 per rev due to the fact that the coaxial rotor consists of two 2-bladed rotors. Unlike land-based operation in ground effect, all the peak values occur at slight higher frequencies than the corresponding multiples of the blade passing frequency (i.e. 2 per rev) as a result of the influence of turbulent airwake. In addition, Figure 18 also shows that the peak values of z/H = 0.75 are much lower than those of z/H = 1.0 and 0.5 because of a reduction in thrust between 1.0 < z/H < 0.875 (Figure 11). Again, these peaks occur at frequencies above 2 per rev (i.e. 40 Hz), thus having little effect on pilot workload.

3.1.3. Difference between single-rotor and coaxial-rotor helicopters

Figure 19 shows the mean and RMS roll for lower rotor, upper rotor and isolated lower rotor. It can be seen that unlike coaxial rotor case, a sharp reduction in mean roll moment is not observed in the single-rotor
case, and the RMS roll decreases monotonically between $0.5 < z/H < 0.75$. This is to be expected, as the recirculation flow regime is strongly related to the rotor wake. It is known that the velocity of the lower rotor wake is lower than that of coaxial rotor of same parameters. Thus the recirculation flow regime has less effect on the rotor loads in the single-rotor case. To examine this further, Figure 20 presents the comparison of vertical turbulence intensity along the longitudinal lines of different height relative to the flight deck in the plane $y/b = 0$ for rotor position $z/H = 0.5$. It is obvious that the overall unsteady velocity level of single-rotor case is much lower than that of the coaxial rotor case as a result of a reduction in the interactions between the rotor wake and flight deck. This reduction in the interactions also leads to a decrease in the unsteadiness of the recirculation flow regime. Therefore, a sharp increase in RMS roll no longer occurs between $0.5 < z/H < 0.625$ (Figure 19).

**3.2. Effect of hangar-door state**

The hangar-door state is an important factor in the development of Ship-Helicopter Operating Limits (SHOLs). As a result, the effect of hangar-door state on the rotor loads of coaxial rotor is investigated in this section. Figure 21 shows the unsteady loading variations against vertical rotor position for the lower and upper rotors under the condition of opening hangar-door, in which the original RMS loads are also presented for comparison. It is obvious that RMS levels decrease considerably as the hangar-door is open, for example by 35%, 25.6%, 34% and 53.5% on average in RMS thrust, pitch, roll and torque for the lower rotor, respectively. The same levels of reductions are also observed for upper rotor. The findings imply that opening the hangar-door can significantly reduce the pilot work during the vertical descent.

In order to identify the origin of differences in the RMS loads between the two hangar-door states, Figure 22 shows the maps of longitudinal and vertical turbulence intensity in the symmetrical plane. It is clearly visible that the turbulent intensities, especially the vertical turbulent intensity, decrease considerably as the hangar-door is open. Moreover, the area of the high turbulent air-wake has also reduced remarkably, for example by 40% in a longitudinal range of high lateral turbulence intensity. Although the rotor wake will eventually change the flow characteristics over the flight deck, the coaxial rotor will...
still experience less turbulence during the vertical descent as a result of reduction in overall unsteadiness of the airwake, compared with the case in which the hang-door is closed.

Note that, unlike a sharp increase in RMS roll between $0.5 < z/H < 0.625$ in the case of hangar-door closed, the RMS roll decreases monotonically between $0.5 < z/H < 0.75$ when the hangar-door is open. As discussed earlier, this increase is caused by the strong unsteady recirculation flow regime. When the hangar-door is open, the forward part of rotor wake, after impinging on the flight deck, will no longer flow upward along the door and instead flow into the hangar as shown in Figure 23, thus affecting the rotor little. To explain this further, Figure 24 shows the vertical turbulence intensity along the longitudinal lines of different height relative to the flight deck for the rotor position $z/H = 0.5$. It is clear that the peak turbulent intensities no longer exist between $0 < x/L < 0.05$, and the overall unsteadiness of coupled flowfield decreases obviously. This is quite favorable to the pilot when landing a helicopter just before touchdown.

**Figure 21.** RMS loads for lower rotor and upper rotor under two hangar-door states.
3.3. Effect of landing spots

As discussed before, the helicopter will be directed to the hangar-door during the vertical descent due to a significant reduction in pitch moment. When descending a helicopter to the landing spot of 35% deck length behind the hangar (i.e. landing spot 1, see Figure 7), the pilot would be more sensitive to this effect because of much narrower space between the helicopter and hangar. Figure 25 shows the comparisons of mean pitch moment at different rotor heights for the two landing spots. It can be clearly seen that there is a considerable reduction in pitch moment when the coaxial rotor moves vertically from the rotor position \( z/H = 0.75 \) for the landing spot 1, while only 20% for the landing spot 2. It means that the helicopter will be directed to the hangar more easily when the landing spot moves closer to hangar door.

Moreover, large differences also occur in the unsteady loading levels. Figure 26 shows the variation of rotor thrust coefficient in 50 revolutions at rotor position \( z/H = 0.5 \) for the two landing spots, in which the corresponding Power Spectral Density (PSD) of thrust is also
presented. It is obvious that the amplitudes of long-term fluctuations reduce significantly as the rotor moves to the front landing spot. The spectral analysis in PSD plots also shows that less energy is contained in fluctuations within 0.2–2 Hz for the landing spot 1. In addition, the comparisons of RMS moments between the two landing spots are shown in the Figure 27. As with RMS thrust, there are significant reductions in RMS moments at rotor position $z/H = 0.75$. This is because when the coaxial rotor moves to the front landing spot, most of rotor disk is immersed in the much lower turbulent area, especially during the latter stage of vertical descent (Figure 16). These results imply that vertically descending a helicopter to a landing spot which is more closed to the hangar door will experience less unsteady disturbances for the pilot.

It should be noted that although the hangar door is closed, there is a sharp decrease in RMS roll as the coaxial rotor moves vertically from $z/H = 0.75–0.5$ for the landing spot 1. As discussed earlier, the unsteady recirculating inflow could cause significant increase in RMS roll just before touch down. However, the overall unsteady loading levels of the rotor reduce considerably as it moves to the front landing spot, leading to a corresponding decrease in the unsteadiness of the recirculation flow regime. As a result, this unsteady recirculating flow has less effect on the RMS roll.

4. Conclusions

Numerical investigation of aerodynamic loading characteristics of a shipborne coaxial-rotor helicopter during a vertical descent has been conducted in a headwind using moving overset mesh CFD method. Results in terms of time-averaged and RMS loadings have been discussed to identify how the ground effect as well as the recirculation flow regime affects the rotor loads and pilot workload during the vertical descent. The influences of hangar-door state and the location of landing spot have also been analyzed in the paper. From the above, the conclusions can be obtained as below:

1. The RMS loading levels suffers a sharp increase in the first half stage of the vertical descent, during which the coaxial-rotor helicopter would experience a considerable decrease in pitch moment. Thus the pilot has to continuously correct control inputs, especially the longitudinal cyclic control input, to prevent the helicopter from being directed to the hangar-door and maintain an appropriate helicopter-to-hangar distance as well as attitude relative to the flight deck in such confined area.

2. The unsteady loading levels of coaxial rotor are much higher than that of its lower or upper rotor during the entire vertical descent phase. This finding implies that the aerodynamic loads of the lower and upper rotors could couple with each other and might eventually magnify the unsteady loading levels of the coaxial rotor. This is a particular phenomenon for shipborne coaxial rotor configuration, and do not exist in conventional shipborne single-rotor helicopter.

3. The coaxial-rotor helicopter will suffer a remarkable increase in thrust and a sharp decrease in torque difference between lower and upper rotors during the
vertical descent. It means that the pilot has to reduce not only the collective control input to keep the equilibrium of force in vertical direction, but also the differential collective pitch to stabilize the heading of the coaxial rotors helicopter relative to the ship.

(4) The influence of recirculation flow regime will get stronger as the coaxial rotor moves close to the flight deck. This phenomenon can cause not only a considerable decrease in mean roll moment of lower rotor, but also a sharp increase in RMS roll due to the interactions between the recirculating inflow and the leading edge of rotor disk. While this behavior is not observed in the single rotor configuration due to the fact that velocity of the single rotor wake is relative lower, compared with the coaxial rotor of same parameters.

(5) Opening the hangar-door can significant decrease the RMS levels in all three axes as a result of the reduction in overall unsteadiness of the airwake. Also, descending a helicopter to a landing spot which is more closed to the hangar door will experience less unsteady disturbances, especially during the latter stage of vertical descent. However, the helicopter tends to be directed to the hangar-door more easily due to much greater reduction in pitch moment.

Although the rotor loads of a shipborne coaxial rotor during a vertical descent have been studied, it should be borne in mind that the simulations have so far only been performed for a single headwind condition. In addition, a uniform velocity profile is chosen for the inlet boundary, so the effect of Earth’s atmospheric boundary layer (ABL) is ignored in current study. Therefore future work will adopt a power law velocity profile to model a more realistic inlet condition, and investigate the aerodynamic loading characteristics of the shipborne coaxial rotors helicopter for different wind angles.

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