Model of Airflow Field on the Deck for Shipborne Helicopter Flight Dynamics Analysis

Hu Guocai[1*], *Xu Guang*[1,2], *Wang Yunliang*[1], *Liu Shuyan*[1]

1. Department of Airborne Vehicle Engineering, Naval Aeronautical and Astronautical University, Yantai 264001, P. R. China; 2. Troops 92074 PLA, Ningbo 315000, P. R. China

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Abstract: For the research of helicopter/ship dynamic interface, the method of combining steady flow and stochastic flow is adopted to establish a flow field model applied to the flight dynamics analysis of shipborne helicopter. The steady flow is calculated by computational fluid dynamics (CFD) method, while the stochastic flow is composed of the compensation velocity derived from ship motion and turbulence above the deck. The accuracy of the proposed flow field model is verified by comparing the helicopter response in the proposed flow field with the results calculated by US Army′s Military Specifications (MIL) model which is commonly used in engineering. Meanwhile, it also shows the proposed flow field model is more appliable to flight dynamics analysis of shipborne helicopter. On that the basis, ship deck flow field is simulated at different sea conditions by adjusting the wind speed on the deck, mother ship movement and shipboard turbulence, etc. And helicopter angular rate response is calculated. The results show that the difference of dynamic stability between helicopter′s roll and pitch leads to the facts that the influence of above factors on the helicopter′s roll angular rate response is greater than that of pitch angular rate, that the frequency and amplitude of mother ship roll motion are much greater than those of pitch motion, and that the disturbance caused by roll motion on the air has greater influence on the helicopter response. The shipboard turbulence is the main disturbance factor that influences helicopter flight stability and its intensity determines the amplitudes of angular rate response.

Key words: shipborne helicopter; flight dynamics; airflow field on the deck; time-space characteristics; sea condition

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0 Introduction

The nonlinear and inhomogeneous characteristics of shipboard flow field has a great influence on aerodynamic loads, flight stability and trim characteristics of helicopter, and challenges helicopter/ship dynamic interface. Therefore, the establishment of an accurate airflow model is the basis of the flight dynamics analysis of shipborne helicopter in the shipboard flow field.

The research of airflow on the deck is a challenge because of its complexity and countless origins. So far, the airwake model from MIL-F-8785C has been widely used in engineering calculation[1]. This engineering model is developed for fixed-wing aircraft. In dynamics analysis, the aircraft is considered as a particle. For any given point of aircraft at any time, the wind speed is considered as the airflow value at the center of mass. That is to say, the synthetic airflow velocity of the whole aircraft components is the same in dynamics analysis at any time. This method is obviously not suitable for rotorcraft dynamics analysis because of its poor calculation accuracy. Owing to the airflow gradient, the airflow values of helicopter modules, including main rotor, fuselage, tail rotor and empennages, are different at the same time. Especially for the main rotor

* Corresponding author, E-mail address: guocaihu11@sina.com.

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module, the rotor disk diameter is far longer than the scale of airflow field, resulting in the different airflow values of blade elements. These differences have more or less influence on aerodynamic loads calculation, thus changing the aerodynamic characteristics of helicopter modules.

With the development of computer simulation technology, computation fluid dynamics (CFD) has been widely applied to airflow simulation. Nowadays, research on airflow model on flight deck and airwake model before the ship has been the research hotspot. However, These usually cost significant computational resources and storage space, which is the limitation of real-time simulation. Additionally, it also found that loading readily available CFD solutions took a large amount of time in the flight simulation[2-4]. In an effort to reduce the computational resources and also provide a method for experimental determination of the airflow field, a stochastic airwake model was proposed[5]. In this model, filters were derived on the basis of the vehicle response and pilot control activity. The filters could then recreate similar disturbances as the airwake when driven by white-noise. This model reduces the computation cost, only when the stochastic filter coefficients are stored in memory. Gaonkar proposed a method to extract auto-spectral densities and cross-spectral densities from baseline data[6,7]. The research is to accurately depict a stochastic airwake from either CFD or flight test baseline data. With an equivalent airwake model employed by UH-60 black hawk disturbance[8], Xin and He proposed another method that considered the turbulence field as a sum of cosine functions with equal energy spaced frequencies and uniformly distributed phase angles[9]. The study integrated the stochastic airwake into FLIGHTLAB and demonstrated similar stochastic winds as the baseline CFD model. Sparbanie also developed a stochastic model of unsteady ship airwake disturbances, which relied on stochastic filters that were derived from the vehicle response and pilot control activity when hovering at a particular location relative to the ship deck[10]. In this study, the stochastic filters were derived from flight simulations by using a CFD database.

These studies focused on patrol crafts and training ships, and played little attention to large-scale warships and carriers as well. In addition, Military Specifications (MIL) model described the airwake before the ship, while failed in accurately representing characteristics of airflow on the deck. Therefore, we propose an airflow model which is divided to steady flow and stochastic flow, and the shipboard flow field at different sea conditions simulated by changing wind-over-deck (WOD), ship motion and free-air turbulence on the deck.

1 Airflow Field Modeling on the Deck

1.1 Airflow model designation

Steady flow field is the deterministic component of the proposed model and it also accounts for the known steady effects of the airflow, such as blockage, the flight deck and recirculation effects behind the hangar structure. CFD tools are adopted for the calculation of steady flow. As for large ships, especially for a destroyer or a carrier, they have steady navigation attitude and longer periodic motion than helicopter. That is to say, there is no remarkable differences without considering the ship motion in steady flow computation, for its influence on airflow structure is little.

Stochastic flow field is the unsteady component and it is mainly composed of the compensation velocity component derived from ship motion and free-air turbulence on the deck. WOD is parallel to the flight deck in steady flow computation. There is an angle change derived from the ship motion between the flight deck plane and sea level plane. The coordinate transformation of WOD from space axes to ship axes results in a relative velocity. The compensation velocity component is the compensation for the reality wind in coordinate transformation. With the consideration of ship pitch-rolling coupling motion, there is a pitch angle in pitching motion and a roll angle in rolling motion. The compensation velocity component can be obtained by vector calculus. On the other hand, free-air turbulence component has nothing to do with the position of helicopter and ship, because it relies on the filters that are derived from the Dryden turbulence model[11]. These filters are set in different height above the deck and excited with a white noise input to create the stochastic airflow. For any given point in space, there are three wind velocities in this turbulence model, which can be stored in memory prior to the calculation by the functions of height and time. In fact, this is a two-dimensional turbulence model of height and time, or ship speed, and the disturbance extent is determined by the intensity of Dryden model.

1.2 Steady flow computation model

In this paper, a 3-D ship CAD model is simplified for CFD computation, and the CFD computation follows the principle of fluid mechanics and adopts the finite volume method by FLUENT tools.

An elliptic cylinder is set for the placement of the 3-D ship model in the computational domain center, as shown in Fig. 1. In this topology structure, the wind direction is controlled and changed by the regulation of longitudinal boundary velocity and horizontal boundary velocity to avoid the grid re-division[12].

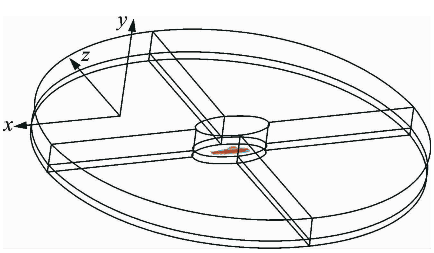


Fig. 1 Network topology structure for CFD computation

In the condition of $V_{\mathrm{WOD}}=15$ m/s and $\Psi_{\mathrm{WOD}}=60°$, the steady flow can be computed by CFD tools. Horizontal velocity vector distribution of a certain cross section lane is shown in Fig. 2, and the computing result of CFD is shown in Fig. 3.

It could be seen from Figs. 2,3, when the incoming flow passes through the high buildings on the deck, there are vortexes forming near the buildings and downwash forming after the buildings, which shows the accuracy of this model. The airflow structure is changed on the deck, greatly influencing helicopter flight quality.

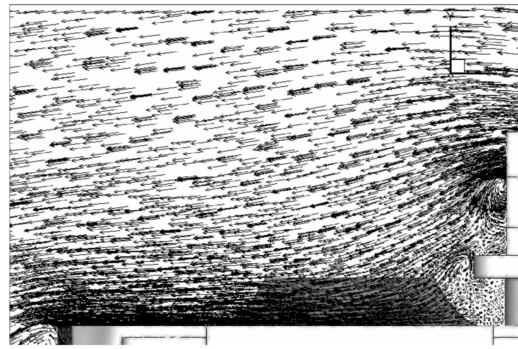


Fig. 2 Horizontal velocity vector distribution

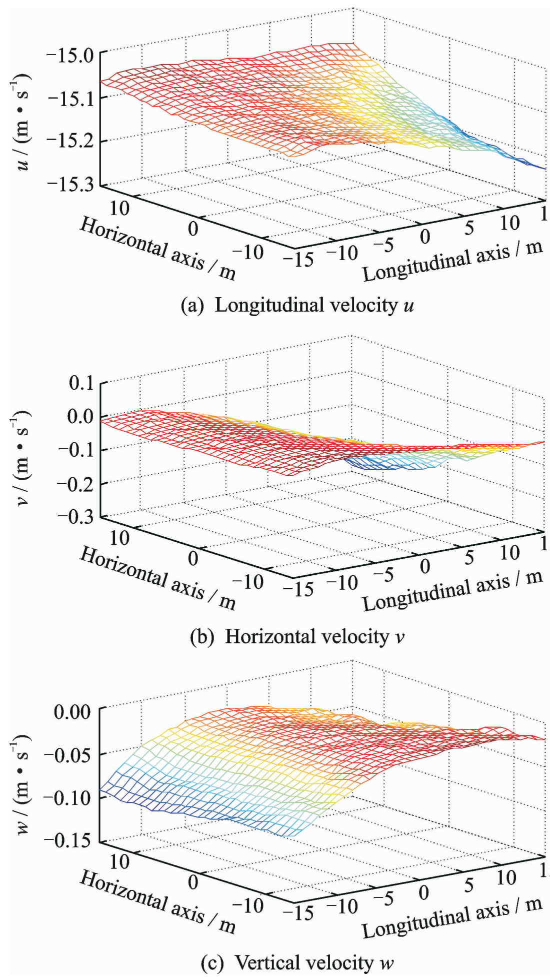


Fig. 3 The computing result of CFD

Due to asymmetric grid modeling in CFD computation, with the consideration of the requirement on airflow valuing and interpolation calculation for any given point in space, the results from CFD computation are transformed to a uniform and regular formation which is stored in three-dimensional matrix. Any node in this formation includes longitudinal, horizontal and vertical velocities, which are stored in the data matrix. Then for any given point in the space, there are some nodes around it and the wind values of them are stored in data matrix. The wind values of this point can be calculated by interpolation method.

A three-dimensional space

$$\boldsymbol{\Omega}:\left\{(x,y,z)\left|\begin{array}{l}x\in[x_{\min},x_{\max}]\\ y\in[y_{\min},y_{\max}]\\ z\in[z_{\min},z_{\max}]\end{array}\right.\right\}$$

can be divided into $l\times m\times n$ grids, where $l=(x_{\max}-x_{\min})/\Delta d$, $m=(y_{\max}-y_{\min})/\Delta d$, and $n=(z_{\max}-z_{\min})/\Delta d$ are respectively the numbers of the whole grids in three directions; Δd is the grid spacing. The results from CFD computation are transformed to $\boldsymbol{U}(i,j,k)$, $\boldsymbol{V}(i,j,k)$, $\boldsymbol{W}(i,j,k)$, which are the three-dimensional matrix in storage of three direction velocities, where $i=1,2,\cdots,l$; $j=1,2,\cdots,m$; $k=1,2,\cdots,n$.

For any given point $P(x,y,z)$ in this space, there are 8 grid nodes A, B, C, D, E, F, G, H around it, as shown in Fig. 4. Owing to the same calculation method of the longitudinal, horizontal and vertical velocities of P, here the longitudinal velocity is taken for example. The longitudinal velocity of these 8 grid nodes can be read directly from the data matrix, which can be expressed as the three-dimensional matrix. Suppose the longitudinal velocity of A, B, C, D, E, F, G, H as $\boldsymbol{U}(i+1,j,k)$, $\boldsymbol{U}(i,j,k)$, $\boldsymbol{U}(i+1,j+1,k)$, $\boldsymbol{U}(i,j+1,k)$, $\boldsymbol{U}(i,j,k+1)$, $\boldsymbol{U}(i+1,j,k+1)$, $\boldsymbol{U}(i+1,j+1,k+1)$, $\boldsymbol{U}(i,j+1,k+1)$, respectively, where $i=\lceil\Delta x\rceil$ $j=\lceil\Delta y\rceil$, $k=\lceil\Delta z\rceil$. "$\lceil\ \rceil$" is the opreation of rounding up.

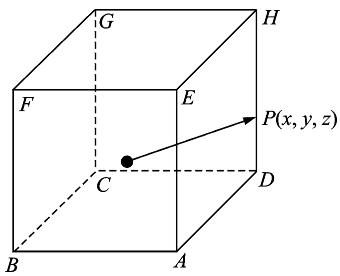


Fig. 4 Three-dimensional linear interpolation

$\Delta x=(x-x_{\min})/\Delta d$, $\Delta y=(y-y_{\min})/\Delta d$, $\Delta z=(z-z_{\min})/\Delta d$. Then, the longitudinal velocity of P can be calculated by the three-dimensional linear interpolation method, namely

$$\begin{aligned}u_P=&(i+1-\Delta x)\left\{(j+1-\Delta y)\begin{bmatrix}(k+1-\Delta z)\boldsymbol{U}(i,j,k)\\+(\Delta z-k)\boldsymbol{U}(i,j,k+1)\end{bmatrix}+\right.\\&\left.(\Delta y-j)\begin{bmatrix}(k+1-\Delta z)\boldsymbol{U}(i,j+1,k)\\+(\Delta z-k)\boldsymbol{U}(i,j+1,k+1)\end{bmatrix}\right\}+(\Delta x-\\&i)\left\{(j+1-\Delta y)\begin{bmatrix}(k+1-\Delta z)\boldsymbol{U}(i+1,j,k)\\+(\Delta z-k)\boldsymbol{U}(i+1,j,k+1)\end{bmatrix}+\right.\\&\left.(\Delta y-j)\begin{bmatrix}(k+1-\Delta z)\boldsymbol{U}(i+1,j+1,k)\\+(\Delta z-k)\boldsymbol{U}(i+1,j+1,k+1)\end{bmatrix}\right\}\end{aligned}\tag{1}$$

The horizontal velocity v_P and the vertical w_P can be also calculated by similar equations, which are not repeated in this paper. By the same token, the airflow values at any time of other aerodynamic components can be calculated.

1.3 Stochastic flow computation model

Pitching motion and rolling motion are the main periodic motions of ship motions. Based on the experimental formula, the ship motion can be expressed by the function of frequencies and amplitudes of rolling and pitching motions. At any time t, the pitching angle can be expressed as $\vartheta_s(t)$ and $\phi_s(t)$. In ship pitching motion, the WOD of ship pitching motion is shown in Fig. 5. In this figure, $u_{s\mathrm{WOD}}$ is the longitudinal velocity in ship axes system, and is also the input of steady flow model computation. Meanwhile, u_{WOD} is the longitudinal velocity in space axes system, and is also the actual wind speed. There is a pitch angle derived from ship pitching motion between space axes system and ship axes system, so the relative velocity Δu_{WOD} makes up for the transformation from space axes system to ship axes system. Based on vector calculation principle, the calculation equation is $\Delta u_{\mathrm{WOD}}=u_{\mathrm{WOD}}-u_{s\mathrm{WOD}}$. By the same token, the compensation velocity derived from ship rolling motion can be calculated by $\Delta v_{\mathrm{WOD}}=v_{\mathrm{WOD}}-v_{s\mathrm{WOD}}$.

Thus, the compensation velocity in space axes system can be calculated by

$$\Delta \boldsymbol{W}_s(t) = u_{\mathrm{WOD}} \cdot \begin{bmatrix} \cos\vartheta_s(t) - 1 \\ 0 \\ -\sin\vartheta_s(t) \end{bmatrix} + v_{\mathrm{WOD}} \cdot \begin{bmatrix} 0 \\ \cos\phi_s(t) - 1 \\ \sin\phi_s(t) \end{bmatrix} \quad (2)$$

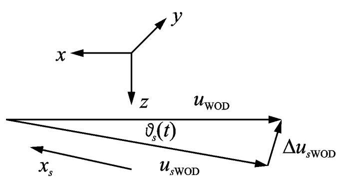


Fig. 5 WOD of ship pitching motion

Due to different locations of helicopter relative to the ship deck at any time and the different heights of helicopter modules, a two-dimensional turbulence model is developed in this paper. It can be seen from Fig. 6 that a series of filters are set between the top of the structure and the deck based on the ship size, and the whole space above the deck is covered by the filters. When excited with a white noise input, the filters will recreate disturbances to the helicopter as the unsteady airflow. Meanwhile, the airflow value of any nodes in space is stored by the function of time and height, such as $\boldsymbol{U}(i,k)$, $\boldsymbol{V}(i,k)$, $\boldsymbol{W}(i,k)$, where $i=1,2,\cdots,N$ is the number of storage time and $k=1,2,\cdots,M$ the number of filters.

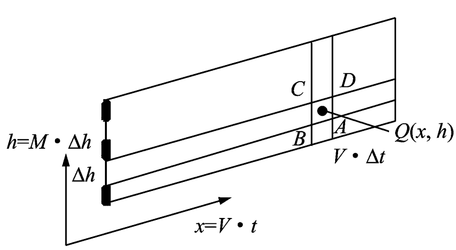


Fig. 6 Free-air turbulence model on the deck

For any given point $Q(x,h)$ in this space, the airflow value can be calculated by interpolation method. Here the longitudinal velocity of Q is taken for example. There are 4 grid nodes A, B, C, D around the point Q, and their longitudinal velocity can be read directly from the two-dimensional storage matrix. Suppose the longitudinal velocity of A, B, C, D as $\boldsymbol{U}(i+1,k)$, $\boldsymbol{U}(i,k)$, $\boldsymbol{U}(i,k+1)$, $\boldsymbol{U}(i+1,k+1)$, respectively, where $i=|\Delta x|$, $k=|\Delta z|$, $\Delta x=(x-x_{\min})/(V\cdot\Delta t)$, $\Delta z=(z-z_{\min})/\Delta h$.

Then, the longitudinal velocity of Q can be calculated by the two-dimensional linear interpolation method, as shown in

$$u_Q = (i+1-\Delta x)\begin{bmatrix}(k+1-\Delta z)\boldsymbol{U}(i,k) \\ +(\Delta z-k)\boldsymbol{U}(i,k+1)\end{bmatrix} + (\Delta x - i)\begin{bmatrix}(k+1-\Delta z)\boldsymbol{U}(i+1,k) \\ +(\Delta z-k)\boldsymbol{U}(i+1,k+1)\end{bmatrix} \quad (3)$$

The horizontal velocity v_Q and the vertical w_Q can be also calculated by similar equations. By the same token, the airflow values at any time of other aerodynamic components can be calculated.

2 Helicopter Nonlinear Flight Dynamic Model

Considering the airflow influence on helicopter, a flight dynamics model for shipborne helicopter in time-space airflow on the deck[12, 13] is developed. In main rotor module modeling, based on blade element theory, the velocity of every element consists of the body movement velocity, blade movement velocity and main rotor induced velocity. The rigid blade two-order dynamics model[14], with the consideration of flap-lagging coupling blade model, is employed in rotor blade movement model. The blade twist is simulated by experiential dynamic equations. Dynamic inflow model[15] is employed in main rotor inflow calculation. When the airflow model is integrated into main rotor module, the relative velocity of any blade element is changed with the addition of airflow velocity, resulting in the change of incidence, sideslip angle and Mach number. Therefore, the aerodynamic loads of main rotor module are recalculated.

The formulas of the relative velocity of any blade element should be modified. The local advance ratio of blade element is drawn into load calculation instead of the advance ratio of rotor. Then for No. j element of No. i blade, the calculation equations of airflow velocities $U^{ij}_{T,P,R}$ of blade span are shown as

$$U^{ij}_T = \mu^{ij}_{xs}\sin(\Psi+\zeta)_i + \mu^{ij}_{ys}\cos(\Psi+\zeta)_i - \frac{\xi}{\Omega}\cos\zeta_i(r_s-\Omega) + \frac{y^j_2}{\Omega}(\dot\zeta_i\cos\beta_i + \sin\beta_i(p_s\cos(\Psi +$$

$$\zeta)_i - q_s\sin(\Psi+\zeta)_i) - \cos\beta_i(r_s-\Omega))$$

$$U_P^{ij} = -\mu_{xs}^{ij}\sin\beta_i\cos(\Psi+\zeta)_i + \mu_{ys}^{ij}\sin\beta_i\sin(\Psi+\zeta)_i + \mu_{zs}^{ij}\cos\beta_i + \frac{\xi}{\Omega}(\cos\beta_i(p_s\sin\Psi_i + q_s\cos\Psi_i) - \sin\beta_i\sin\zeta_i(r_s-\Omega)) + \frac{y_2^j}{\Omega}(-\dot\beta_i + p_s\sin(\Psi+\zeta)_i + q_s\cos(\Psi+\zeta)_i) - v_i\cos\beta_i$$

$$U_R^{ij} = \mu_{xs}^{ij}\cos\beta_i\cos(\Psi+\zeta)_i - \mu_{ys}^{ij}\cos\beta_i\sin(\Psi+\zeta)_i + \mu_{zs}^{ij}\sin\beta_i + \frac{\xi}{\Omega}(\sin\beta_i(p_s\sin\Psi_i + q_s\cos\Psi_i) + \cos\beta_i\sin\zeta_i(r_s-\Omega)) - v_i\sin\beta_i \tag{4}$$

Eq. (4) is a dimensionless formula, where $\mu_{x,y,z}^{ij}$ is the local advance radio; Ω the rotation rate of main rotor; ξ the hinge offset; y_2^j the length of No. j element; and v_i the induced velocity of main rotor. β_i,ζ_i,Ψ_i are the flapping angle, lagging angle, azimuth angle of No. i blade; $\dot\beta_i,\dot\zeta_i$ the flapping angular rate, lagging angular rate of No. i blade; and p_s,q_s,r_s the angular rates of hub. ξ, y_2^j,v_i are all dimensionless.

Suppose that the local airflow value of element is $\boldsymbol{W}_{x,y,z}^{ij}$, and the local advance of element is

$$\boldsymbol{\mu}_{x,y,z}^{ij} = \frac{\boldsymbol{V}_{x,y,z} - \boldsymbol{W}_{x,y,z}^{ij}}{\Omega R_T} \tag{5}$$

where $\boldsymbol{V}_{x,y,z}$ is the helicopter velocities and R_T the radius.

The aerodynamic loads of fuselage, horizontal tail and vertical tail rely on the table look-up functions of incidence, sideslip angle and Mach number. Bailey model[16] is put to use in tail rotor module modeling. When the airflow model is integrated into fuselage module, the airflow value of its aerodynamic center is regarded as that of the whole module, and the relative velocity of fuselage module is recalculated by

$$\boldsymbol{V}_{WF} = \boldsymbol{V}_b - \boldsymbol{W}_{WFb} + \boldsymbol{V}_{IWF} \tag{6}$$

where $\boldsymbol{W}_{WFb}$ is the airflow values in body axis and $\boldsymbol{V}_{IWF}$ the aerodynamic interference velocities.

On this basis, the incidence, sideslip angle and dynamic pressure are also recalculated. This method is also employed in the calculation of other modules, such as tail rotor module and empennage modules.

In summary, the whole nonlinear state equations of helicopter are shown as

$$\dot{\boldsymbol{X}} = f(\boldsymbol{X},\boldsymbol{U},\boldsymbol{W},t) \tag{7}$$

where $\boldsymbol{X} = \begin{pmatrix} u,v,w,p,q,r,\phi_b,\vartheta_b,\Psi_b, \\ \lambda_0,\lambda_c,\lambda_s,\lambda_{TR},\beta_{0,c,s},\dot\beta_{0,c,s}, \\ \zeta_{0,c,s},\dot\zeta_{0,c,s},\Psi,\theta_{dytip} \end{pmatrix}$ is the state vector; Ψ the azimuth angle, and θ_{dytip} the pitch angle derived from blade elastic dynamic twist. u, v, w, p, q, r are the linear velocities and angular velocities; $\phi_b,\vartheta_b,\Psi_b$ the body Euler angle; λ_0,λ_c, λ_s,λ_{TR} the inflow ratios of main rotor and tail rotor; $\beta_{0,c,s},\dot\beta_{0,c,s}$ the flapping angles and angular rates; and $\zeta_{0,c,s},\dot\zeta_{0,c,s}$ the lagging angles and angular rates. $\boldsymbol{U}=[\theta_{col},\theta_{lat},\theta_{lon},\theta_{ped}]$ is the manipulated variables, and $\boldsymbol{W}$ the wind vector of airflow field. Among them, for any given element of blade, its airflow value is $\boldsymbol{W}_{MR}^{ij}=\boldsymbol{W}_{x,y,z}^{ij}$, which relies on its location of main rotor. The airflow value of other modules relies on its aerodynamic center.

3 Airflow Evaluation of Helicopter Modules

For any given element of blade, its location in space changes with the rotation of main rotor, which is the reflection on the variety of the azimuth angle. For this reason, the location of any given element in space-time should be recalculated real-timely.

Without consideration of the inclination angle and the flapping angle in this paper for their little influence on results[17], the azimuth angle of No. i blade at time t can be written as

$$\Psi_i = \int_0^t \Omega \mathrm{d}t + 2\pi\left(\frac{i-1}{NBS}\right) \tag{8}$$

At the time t, the coordinate location of the No. j element of No. i blade in rotor shaft axes system can be shown in

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_s^{ij} = R_T^j \begin{bmatrix} -\cos(\Psi+\zeta)_i \\ \sin(\Psi+\zeta)_i \\ 0 \end{bmatrix} + e\begin{bmatrix} -\cos\Psi_i \\ \sin\Psi_i \\ 0 \end{bmatrix} \tag{9}$$

where R_T^j is the radial distance from No. j element to the hinge, and e the hinge offset.

The location of this element in space axes system can be calculated through coordinate transformation. By the same token, the coordinate locations of the aerodynamic center of other modules are calculated, and the airflow values of the corresponding locations are calculated by the above-mentioned method in Section 2. These values are the external inputs as the airflow conditions for the helicopter flight dynamics model.

4 Analysis of Flight Characteristics in Airflow on the Deck

4.1 Comparison and analysis of airflow models

The air wake model from MIL-F-8785C is widely applied in engineering calculation. The airflow field in flight deck derived from the MIL model is calculated for comparison with the proposed airflow model. The results of helicopter response in the proposed model and MIL model are all transformed into the formation of power spectrum density (PSD) with the Bartlett method for comparison in following analysis.

The following results are all simulated in the same sea conditions. The sea conditions are provided as follows: The WOD conditions are $V_{\mathrm{WOD}}=15$ m/s and $\phi_{\mathrm{WOD}}=0°$. The helicopter height when hovering above the deck is $h=5$ m. The ship pitching motion equation is $\vartheta_s(t)=0.5\cdot\sin(0.6t)+0.3\sin(0.63t)+0.25$, without consideration of ship rolling motion, and the pitch-rolling axes is determined by the ship structure. The intensity of free-air turbulence model on the deck is $\sigma_w=0.5$ m/s, and its scale relies on the flight height.

The vertical airflow velocity distribution of element is shown in Fig. 7. The distribution of the element velocity presents irregular circular frequency with the change of blade azimuth angle. The variable amplitudes of inner element velocity are small and well-distributed while those of external element velocity increase with the radial direction of element.

The outermost element vertical flow velocity is shown in Fig. 8. When the helicopter hovers and follows up with the ship, the location of element is variable periodically, so its airflow value is also variable periodically. Besides, as the result of ship periodic motion, the relative velocity component derived from the ship motion is variable periodically, too. Therefore, without the turbulence, the element vertical flow velocity presents a periodically variable regularity. The introduction of free-air turbulence model increases the stochastic characteristics of the airflow, which is the representation of nonlinear and irregular airflow model in the deck.

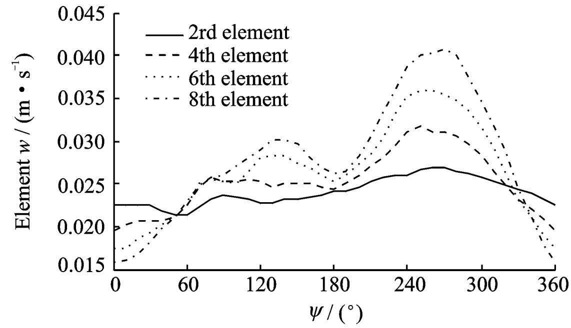


Fig. 7 Vertical airflow velocity distribution of element

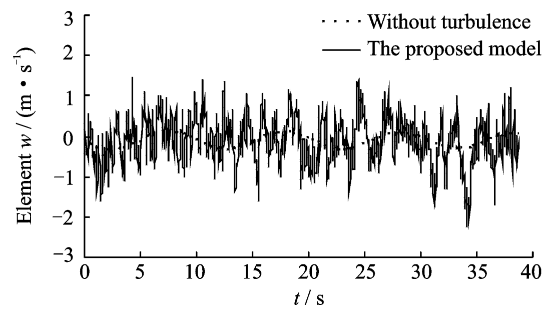


Fig. 8 Element vertical flow velocity of the outermost segment

The PSD comparison of main rotor flapping motion in MIL model and the proposed model can be seen in Fig. 9. From this figure, the results of main rotor flapping angle are the same order of magnitude in these two models. In MIL model, the velocities of all elements are regarded as the same value, while in the proposed model the velocities of different elements rely on its location and time. On this basis, the aerodynamic loads of any one blade are different in these two models.

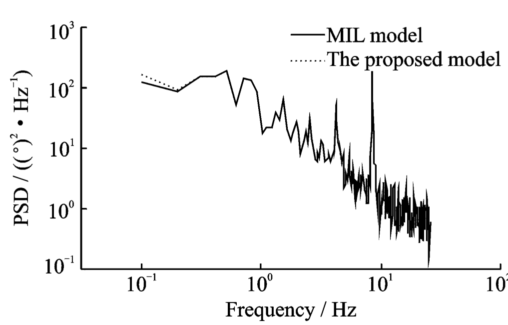


Fig. 9 Comparison of PSDs of main rotor flapping angle

The differences have influence on the flapping motion of blade. However, in rotation cycle of main rotor, all the blade motions are added to the main rotor module, and the differences are partially eliminated as a result of the symmetrical distribution of blades. Therefore, the differences of airflow models have little influence on periodic flapping motion of main rotor.

The PSDs of helicopter angular rates are shown in Fig. 10. From this figure, the amplitudes of the results in this proposed model are obviously bigger than that in MIL model. Because of the same free-air turbulence model on the deck in MIL model and the proposed model, the main-differences are the response to the steady flow component and the relative velocity component derived from ship motion. The conclusions from analysis of Fig. 10 are as follows: The response of helicopter to free-air turbulence on the deck makes a great contribution to the whole response energy of helicopter in airflow on the deck. Meanwhile, the response energy derived from the steady flow component occupies part of the whole energy, indicating that the differences of element velocities in different space-time have a great influence on the helicopter flight attitudes. In addition, the response energy from ship motion is bigger in pitch channel than that in the roll and yaw channels. In conclusion, the proposed model has great representation of the characteristics of airflow field on flight deck, which has a better applicability than MIL model.

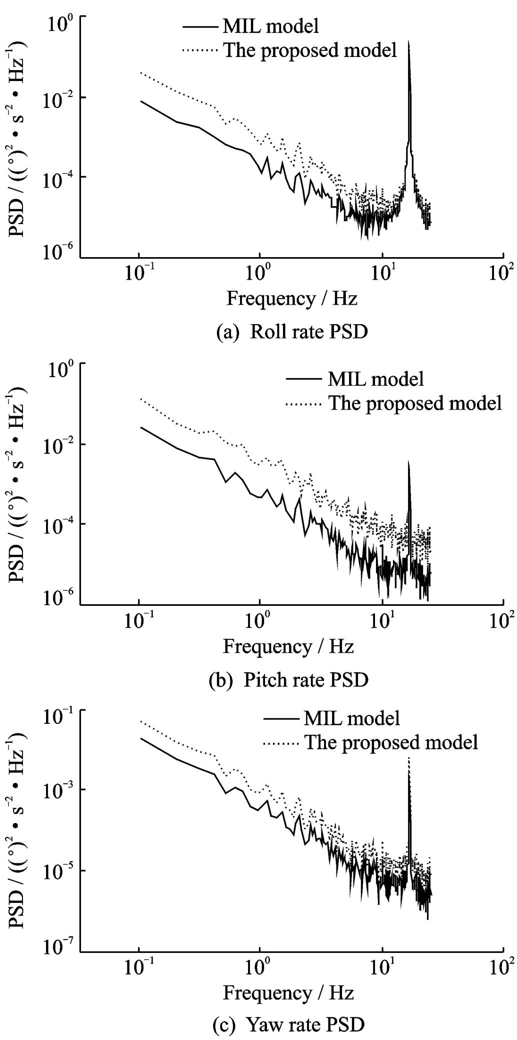


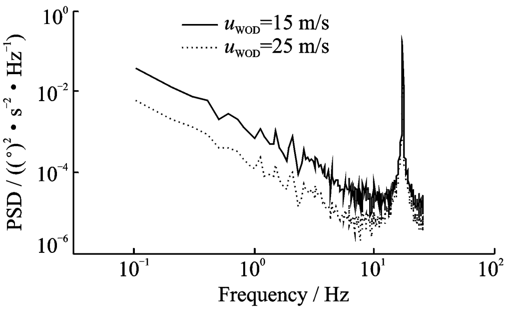
Fig. 10 Comparison of PSDs of helicopter angular rate response

4.2 Calculation and analysis in different sea conditions

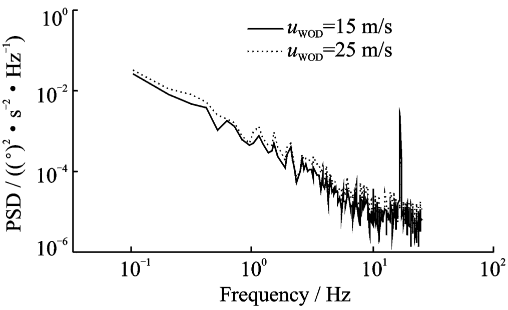
In the proposed model, the airflow in different sea conditions relies on WOD, ship motion and free-air turbulence on the deck.

The velocity and direction of WOD are the decisive factors of steady flow component. Change the speeds of WOD, and keep the other conditions unchanged, the responses of roll and pitch rates are calculated, respectively. The comparison of PSDs in two different conditions of WOD is shown in Fig. 11. Change the direction of WOD and keep the other conditions unchanged, the responses of roll and pitch rates are calculated, respectively. The comparison of PSDs in two different conditions is shown in Fig. 12. It can be seen from Figs. 11,12 that the roll rate and pitch rate of shipborne helicopter are all affected by the WOD conditions, both the speed and the direction. Additionally, it has greater influence on the characteristics of roll channel than that of pitch channel. The reason lies in the worse helicopter dynamic stability in roll channel in comparison with pitch channel.

The compensation velocity component derived from ship periodic motion is one part of stochastic flow. There are three conditions of ship

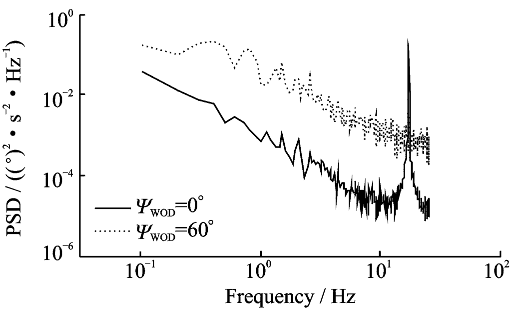


(a) Roll rate PSD

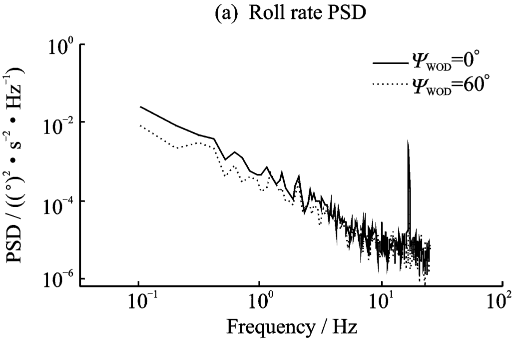


(b) Pitch rate PSD

Fig. 11 Comparison of PSDs in different u_{WOD}



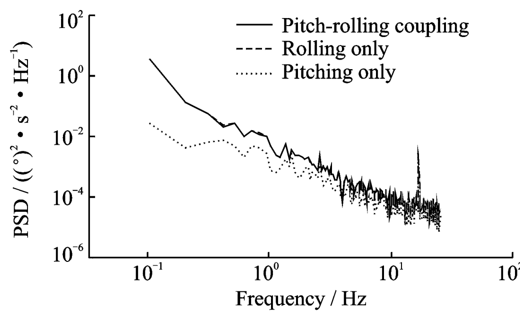
(a) Roll rate PSD



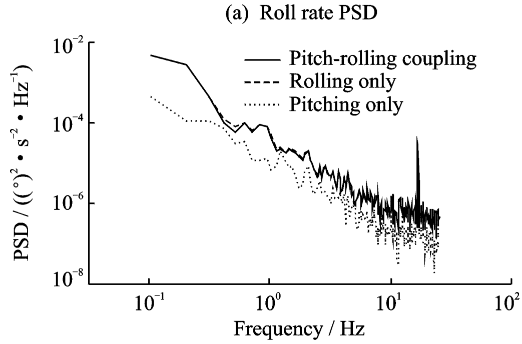
(b) Pitch rate PSD

Fig. 12 Comparison of PSDs in different Ψ_{WOD}

motion that can be chosen, including pitch-rolling coupling motion, rolling motion only and pitching motion only. Keep the other conditions unchanged as follows: The speeds of WOD is $u_{\mathrm{WOD}}=7.5$ m/s and $v_{\mathrm{WOD}}=13$ m/s, respectively, the free-air turbulence intensity is $\sigma_w=0.1$ m/s. The responses of roll and pitch rates in these conditions are calculated, respectively, and the comparison of PSDs shown in Fig. 13. From this figure, the results are similar and the same order of magnitude, which indicates that the disturbance derived from ship motion makes a little contribution to the whole helicopter response. Besides, because of the bigger frequency and amplitude of ship rolling motion, the disturbance from ship rolling motion has a greater influence on helicopter response and flight quality in comparison with the ship pitching motion.



(a) Roll rate PSD



(b) Pitch rate PSD

Fig. 13 Comparison of PSDs in different conditions of ship motion

Change the free-air turbulence intensity on the deck while the other conditions remain unchanged, and the models are simulated and computed in different conditions. The responses of roll rate and pitch rate in two different conditions are calculated, respectively, and the comparison of PSDs is shown in Fig. 14. From this figure, both the responses of roll rate and pitch rate increase with the turbulence intensity. In fact, the response of helicopter to free-air turbulence on the deck makes a great contribution to the whole response energy. Therefore, the amplitudes of angular rate responses rely on the intensity of free-air turbulence. Additionally, due to the difference in dynamic stability, the free-air turbulence on the deck has a greater influence on the characteristics of roll channel.

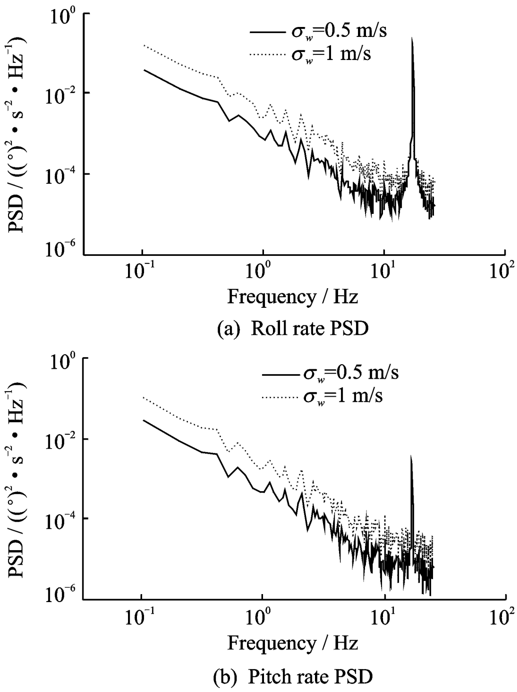


Fig. 14 Comparison of PSDs in different conditions of free-air turbulence on the deck

5 Conclusions

(1) The airflow velocities of helicopter modules are stored by the function of space-time in the proposed model, and the aerodynamic load calculations of these modules also have space-time characteristics. The introduction of free-air turbulence model increases the stochastic characteristics of the airflow.

(2) Based on space-time calculation of element aerodynamic loads, the proposed model's applicability is better than MIL model. Additionally, the response of helicopter to free-air turbulence makes a great contribution to the whole response energy in airflow on the deck.

(3) The airflow mainly affects roll angular rate, for there is the difference of dynamic stability between roll channel and pitch channel. Based on the bigger frequency and amplitude of ship rolling motion than those of pitching motion, ship rolling motion has a greater influence on the helicopter response. The amplitudes of angular rate responses rely on the intensity of free-air turbulence, for it is the main factor affecting the helicopter flight stability.

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Prof. **Hu Guocai** received his Ph. D. degree in Aeronautics Engineering from Beijing University of Aeronautics and Astronautics, Beijing, China, in 2004. From 1988 to present, he teaches at Naval Aeronautical and Astronautical University, where he is currently a full professor and doctoral supervisor. He has been long engaged in the study and research of helicopter dynamics, and has published over 50 related papers in academic journals at home and abroad.

Dr. **Xu Guang** received his Ph. D. degree in Aeronautics Engineering from Naval Aeronautical and Astronautical University, Yantai, China, in 2015. His research is focused on helicopter flight dynamics.

Dr. **Wang Yunliang** received his Ph. D. degree in Aeronautics Engineering from Northwestern Polytechnical University, Xi'an, China, in 2006. His research is focused on vehicle aerodynamics.

Mr. **Liu Shuyan** received his M. S. degree in Aeronautics Engineering from Beijing University of Aeronautics and Astronautics, Beijing, China, in 2009. His research is focused on vehicle dynamics.

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