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Numerical Investigation of the Aerodynamic Interaction between a Tiltrotor and a Tandem Rotor during Shipboard Operations

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Abstract: Complex rotorcraft-to-rotorcraft interference problems occur during shipboard operations, and have a negative impact on safety. A vortex-based approach is used here to investigate the flow field and unsteady airloads of a tiltrotor affected by the wake of an upwind tandem rotor. In this work, the blade aerodynamics is modelled using a panel method, and the unsteady behavior of rotor wakes is modelled using a vortex particle method. The effects of the ship and sea-surfaces are accounted for via a viscous boundary model. The method is applied to a 1/48th scaled model of a CH-46 operating on a model-scale Landing Helicopter Assault ship. The predicted vertical velocities at the location of the downstream V-22 are compared with Computational Fluid Dynamics and experiments carried out at NASA Ames Research Center. The results show that the predicted vertical velocities compare reasonably well with experiments and Computational Fluid Dynamics. A V-22 tilt-rotor placed in the wake of the CH-46 is also simulated, and rolling moments of the V-22 are calculated to show the effect of the upstream CH-46 wake.

Keywords: rotorcraft-to-rotorcraft interference; flow field; shipboard operation; vortex particle method; viscous boundary model

Nomenclature

b, f	= edge lengths of a rectangular panel, m
b_v	= the V-22 wing span, m
C_p	= pressure coefficient, dimensionless
C_P	= rotor power coefficient, dimensionless

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C_T	= rotor thrust coefficient, dimensionless
$C_k^{\text{tandem}}, B_k^{\text{tandem}}$	= influence coefficient of the tandem rotor, dimensionless
$C_k^{\text{tilt}}, B_k^{\text{tilt}}$	= influence coefficient of the tilt rotor, dimensionless
$C_k^{\text{tilt-tandem}}, B_k^{\text{tilt-tandem}}$	= influence coefficient of the tandem rotor induced by the tilt rotor, dimensionless
$C_k^{\text{tandem-tilt}}, B_k^{\text{tandem-tilt}}$	= influence coefficient of the tilt rotor induced by the tandem rotor, dimensionless
Cm_x	= rolling moment coefficient of the V-22, dimensionless
Cm_x^0	= rolling moment coefficient estimated to cause V-22 to lift a main gear, dimensionless
D	= deck width, m
F_k	= force on the rotor, N
G	= free-space Green's function, dimensionless
G_h	= three-dimensional heat kernel function, dimensionless
h_{xi}, h_{yi}, h_{zi}	= edge lengths of a integration cuboid, m
K_ε	= Biot-Savart kernel, dimensionless
$\mathbf{n}$	= outward unit normal vector of a surface, dimensionless
$N_B^{\text{tandem}}, N_w^{\text{tandem}}$	= number of panels on the tandem rotor blade and wake, dimensionless
$N_B^{\text{tilt}}, N_w^{\text{tilt}}$	= number of panels on the tilt rotor blade and wake, dimensionless
p, p_{ref}	= pressure and far-field reference pressure, Pa
$\mathbf{r}$	= position vector, m
RM_{ref}	= referred rolling moment, dimensionless
$S_r^{\text{tandem}}, S_{rw}^{\text{tandem}}$	= the tandem rotor blade and wake surfaces areas, m ²
$S_r^{\text{tilt}}, S_{rw}^{\text{tilt}}$	= the tilt rotor blade and wake surface areas, m ²
t	= time, s
$\mathbf{t}$	= tangential to the boundary, dimensionless
$\mathbf{v}_\infty$	= free-stream velocity, m/s
$\mathbf{v}_{\text{slip}}$	= induced velocity from vorticity, m/s

$\mathbf{v}_r, \mathbf{v}_B^{\text{tandem}}, \mathbf{v}_B^{\text{tilt}}$	= velocity of a point on the rotor surface, the tandem and tilt rotor surfaces, m/s
$\mathbf{v}_{\text{ref}}$	= referenced velocity of the rotor, m/s
$\mathbf{v}$	= fluid velocity, m/s
$\mathbf{x}_j, \mathbf{x}, \mathbf{y}$	= position of a particle, m
$\mathbf{x}_s, \mathbf{x}'_s$	= position of bound vortex sheet, m
$\boldsymbol{\alpha}_j$	= vector-valued vorticity of a particle, 1/s
γ	= bound vortex sheet, 1/s
ε	= smoothing radius, dimensionless
ζ_ε	= kernel function, dimensionless
$\mu^{\text{tandem}}, \mu_w^{\text{tandem}}$	= doublet of the tandem rotor blade and wake surface, m ⁴ /s
$\mu^{\text{tilt}}, \mu_w^{\text{tilt}}$	= doublet of the tilt rotor blade and wake surface, m ⁴ /s
$\mu_{\text{up}}^{\text{tandem}}, \mu_{\text{lower}}^{\text{tandem}}$	= upper and lower trailing edge doublets on the tandem rotor blades, m ⁴ /s
$\mu_{\text{up}}^{\text{tilt}}, \mu_{\text{lower}}^{\text{tilt}}$	= upper and lower trailing edge doublets on the tilt rotor blades, m ⁴ /s
ν	= kinematic viscosity, m ² /s
ξ	= integrated surface area, m ²
ρ	= air density, kg/m ³
$\sigma^{\text{tandem}}, \sigma^{\text{tilt}}$	= source of the tandem and tilt rotor blades, m ³ /s
τ	= integrated time, s
ϕ	= velocity potential, m ² /s
ϕ_{int}	= internal potential, m ² /s
ω	= vorticity of flow field, 1/s
ΔF_k	= aerodynamic load on the panel, N
ΔS_k	= panel area, m ²
$[\text{erfc}]$	= complementary error function, dimensionless
$[\text{ierfc}]$	= integral of error function complement, dimensionless

LHA	= Landing Helicopter Assault ship
CFD	= Computational Fluid Dynamics
WHOD	= Wheel-Height-Over-Deck
ROD	= Roll-On-Deck

1 Introduction

Helicopters are frequently operating from ships. Not surprisingly, maneuvering for safe landing onboard a ship is a complex problem since the rotor flow field, wake, and unsteady aerodynamic loads are altered by the presence of the ship deck, and ship wake. The pilot workload during helicopter shipboard landing and take-off is then significantly increased [1-3]. Moreover, during flight operations, especially for take-off and landing, numerous factors expose flight and ground crew to substantial risks [4]. Contrary to rotorcraft-ship interference, rotorcraft-to-rotorcraft interference problems are more complex during shipboard operations, where a rotor wake may interact with both the ship air-wake and other rotorcraft wakes. This is especially true for wakes of a heavy lift rotorcraft or tiltrotors with high disk loading. The V-22 aircraft on two occasions experienced an uncommanded roll, documented as the V-22 “Roll On-Deck” (ROD) problem, in response to a CH-46 landing two to three spots upwind of the V-22 during shipboard compatibility trials. Because of its potentially negative impact on the shipboard operations and safety, the V-22 uncommanded roll in response to the approach of an upwind rotorcraft was classified as a deficiency requiring correction prior to operational deployment [5]. This suggests that investigations of the flow field and the unsteady airloads of a rotorcraft operating in the shipboard environment and affected by the wake of other rotorcraft is an important research area for rotorcraft shipboard operational safety.

In the past, several experimental investigations were carried out to understand the effect of the ship airwake during shipborne operations. The loads on a rotor and a fuselage were measured in wind-tunnel experiments at the National Research Council of Canada (NRC) based on the Canadian Patrol Frigate (CPF) to give an indication of the corresponding pilot workload [6-8]. Furthermore, wind-tunnel investigations of the rotor-ship interaction were conducted at the Old Dominion University to assess the effect of the coupling between a ship and rotor wake [9, 10]. Also, far-wake characteristics were measured for a patrol ship, and a small-scale piloted helicopter model by researchers of the U.S. Naval Academy [11]. In addition to the rotorcraft-ship interaction studies, experiments with 1/48th-scale rotorcraft models on an amphibious assault ship were conducted by the Army/NASA Rotorcraft Division at Ames Research Center to investigate the interaction between rotorcraft, and with large structures and the

ground [5, 12, and 13]. Those experiments showed that rotor wakes had a strong influence on the flow field of a downwind rotorcraft.

Numerical simulations, including vortex-based and grid-based methods, if validated against experiments are an attractive way to investigate the rotorcraft-ship interference problem. In the past, a source panel method was developed and coupled into a real time simulation model of rotorcraft-ship interaction through a gain matrix of the dynamic inflow model, and harmonic analysis [14]. Also, a 3D panel model was coupled with a viscous vortex particle model to analyze the velocity distribution of a shipborne rotorcraft [15]. However, viscous effects of the ship were not taken into account. Then, Computational Fluid Dynamics (CFD) coupled with a viscous vortex particle model was used to describe the rotorcraft-ship aerodynamic interaction [16], while wake model augmentation was used to reduce the computational cost.

Flows around ships have so far been computed by several CFD tools (e.g. PHOENICS [17], FAST3D [18], the Finite Element Navier-Stokes Analysis Package (FENSAP) [19], Fluent [20], PUMA2 [21]) coupled with rotor aerodynamic models through one-way coupling, including mean wind velocity models [17, 18], three-dimensional approaches based on look-up table aerodynamics [19, 20], and time-varying flow model [21]. In other words, so far in published works, the rotorcraft experienced disturbances due to a pre-calculated CFD ship air-wake, but the ship air-wake CFD solutions were unaffected by the downwash of the rotor. The effect of the rotor downwash was then accounted for in the aerodynamics of the rotorcraft-ship system by including a ship wake from CFD tools such as the Rot3DC [22], PUMA2 [23], OVERFLOW [24], CRUNCH [25], and HMB [1], and coupling it into flight dynamic simulations. However, the unsteady mutual interaction between the ship air-wake and the rotor wake is not taken into account. This may be more severe when the aircraft has multiple rotors or if there are more than one aircraft in the vicinity of the ship. Also, the importance of coupling effects on the wake when the rotor is operating close to the ship and the invalidity of superposition methods were demonstrated in Ref. 1. A full two-way coupled method was then first developed in Ref. 2.

More recently, full-CFD approaches with overset grid systems [1, 26] were used to investigate the rotor flow field above the ship deck, and overcome the limitations of superposition method. However, the concentrated vorticity predicted by CFD is affected by several factors, such as excessive numerical dissipation, and lack of high-density grids, needed to capture the rotor wake. For the rotorcraft-ship interaction studies, the correct simulations of the trailed rotor wake strength and its position are very important [12]. With such methods, even the interaction

between a single rotor and a simple ship is considerably expensive. Therefore, efficient numerical investigations of the rotorcraft-to-rotorcraft interaction during shipboard operations are still challenging due to the computational cost, the flow unsteadiness, and the large number of rotor revolutions required for the flow field.

Given the importance of the problem at hand, there is a need for efficient and accurate methods that do not suffer from the aforementioned problems but can be used by engineers routinely, to find out safe distances to be kept between a rotor and an upwind rotorcraft. This paper is a step in studying the rotorcraft-to-rotorcraft interference problem during shipboard operations. Thus, a vortex particle method, coupled with a viscous boundary model, are developed to numerically investigate the rotorcraft-to-rotorcraft interference in the ship environment. In this method, the aerodynamics of the multi-rotor cases is modelled through an unsteady panel method, and the unsteady behaviour of the wake near the ship is modelled through a viscous vortex particle method [27]. The viscous effects of the ship and the sea surfaces are accounted for by a viscous boundary model. This is implemented by generating a vortex sheet on the ship and the sea surfaces and diffusing the vortex into the flow field. Following the method description, the flow field, the velocity profiles, and the wake structure of the tandem rotor, CH-46, which is operating in ship environment is computed and compared with experiments. Additionally, the unsteady airloads and rolling moment of a V-22 affected by the upwind CH-46 wake are computed to investigate the aerodynamic interaction between the tilt-rotor and the upwind tandem rotor.

2 Computational Method

2.1 Aerodynamic Model of the Multiple Rotorcraft

The aerodynamics of the rotorcraft is represented by an unsteady panel method [27]. **It is necessary to calculate the aerodynamic loads of multiple rotorcraft simultaneously, and the aerodynamic model is updated using the unsteady panel method for all rotorcraft.** Based on this method, the velocity potential of the rotor, ϕ , is defined in a global reference system (X, Y, Z) in Fig. 1, which shows the position of the rotorcraft with respect to the ship, as

$$\begin{aligned} \phi(x, y, z, t) = & \frac{1}{4\pi} \int_{S_t^{\text{tandem}}} \mu^{\text{tandem}} \mathbf{n} \cdot \nabla \left(\frac{1}{r} \right) dS - \frac{1}{4\pi} \int_{S_t^{\text{tandem}}} \sigma^{\text{tandem}} \left(\frac{1}{r} \right) dS + \frac{1}{4\pi} \int_{S_{rw}^{\text{tandem}}} \mu_w^{\text{tandem}} \mathbf{n} \cdot \nabla \left(\frac{1}{r} \right) dS \\ & + \frac{1}{4\pi} \int_{S_t^{\text{tilt}}} \mu^{\text{tilt}} \mathbf{n} \cdot \nabla \left(\frac{1}{r} \right) dS - \frac{1}{4\pi} \int_{S_t^{\text{tilt}}} \sigma^{\text{tilt}} \left(\frac{1}{r} \right) dS + \frac{1}{4\pi} \int_{S_{rw}^{\text{tilt}}} \mu_w^{\text{tilt}} \mathbf{n} \cdot \nabla \left(\frac{1}{r} \right) dS \end{aligned} \quad (1)$$

where σ^{tandem} and μ^{tandem} are the source and doublet distributions placed on the tandem rotor blades, and μ_w^{tandem} is the doublet on the tandem rotor wake surface. σ^{tilt} and μ^{tilt} are the source and doublet distributions placed on the

tilt rotor blades, and μ_w^{tilt} is the doublet on the tilt rotor wake surface. $\mathbf{n}$ denotes the outward unit normal vector of surfaces, and $\mathbf{r}$ is the position vector (x, y, z) . S_r^{tandem} and S_{rw}^{tandem} are the tandem rotor blade and wake surface areas, while S_r^{tilt} and S_{rw}^{tilt} are the tilt rotor blade and wake surface areas.

Fig. 1 Schematic of the multiple rotorcraft and the ship

The boundary conditions for the rotors require that the velocity component normal to the blades is zero. The boundary conditions at infinity require the flow disturbances to decrease to zero. Both can then be expressed as:

$$\begin{cases} \frac{\partial \phi}{\partial n} - \mathbf{v}_r \cdot \mathbf{n} = 0 & \text{rotor surface} \\ \lim_{r \rightarrow \infty} \nabla \phi = 0 & \text{far-field boundary} \end{cases}, \quad (2)$$

where $\mathbf{v}_r$ is the velocity of a point on the rotor surface. The boundary condition at infinity is automatically fulfilled through Green's function.

According to the Neumann boundary condition, the source strength is

$$\begin{cases} -\sigma^{\text{tandem}} = \mathbf{n} \cdot \mathbf{v}_B^{\text{tandem}} \\ -\sigma^{\text{tilt}} = \mathbf{n} \cdot \mathbf{v}_B^{\text{tilt}} \end{cases}, \quad (3)$$

where $\mathbf{v}_B^{\text{tandem}}$ and $\mathbf{v}_B^{\text{tilt}}$ are the velocity on the tandem and tilt rotor blades, respectively.

By dividing the tandem rotor blade surface into N_B^{tandem} panels and wake surface into N_w^{tandem} panels, the tilt rotor blade surface into N_B^{tilt} panels and wake surface into N_w^{tilt} panels, the integration on the surfaces in Eq. (1) can be equivalently written as the superposition of integrations on the panels that constitute those surfaces.

Quadrilateral geometry, constant-strength panels are used in the current study, and the internal potential is set to

$\phi_{\text{int}} = 0$. Thus,

$$\begin{aligned} \sum_{k=1}^{N_p^{\text{tandem}}} \mu_k^{\text{tandem}} C_k^{\text{tandem}} + \sum_{k=1}^{N_p^{\text{tandem}}} \mu_{w,k}^{\text{tandem}} C_k^{\text{tandem}} + \sum_{k=1}^{N_p^{\text{tandem}}} \sigma_k^{\text{tandem}} B_k^{\text{tandem}} + \sum_{k=1}^{N_p^{\text{tilt}}} \mu_k^{\text{tilt}} C_k^{\text{tilt-tandem}} + \sum_{k=1}^{N_p^{\text{tilt}}} \mu_{w,k}^{\text{tilt}} C_k^{\text{tilt-tandem}} + \sum_{k=1}^{N_p^{\text{tilt}}} \sigma_k^{\text{tilt}} B_k^{\text{tilt-tandem}} = 0 \\ \sum_{k=1}^{N_p^{\text{tilt}}} \mu_k^{\text{tilt}} C_k^{\text{tilt}} + \sum_{k=1}^{N_p^{\text{tilt}}} \mu_{w,k}^{\text{tilt}} C_k^{\text{tilt}} + \sum_{k=1}^{N_p^{\text{tilt}}} \sigma_k^{\text{tilt}} B_k^{\text{tilt}} + \sum_{k=1}^{N_p^{\text{tandem}}} \mu_k^{\text{tandem}} C_k^{\text{tandem-tilt}} + \sum_{k=1}^{N_p^{\text{tandem}}} \mu_{w,k}^{\text{tandem}} C_k^{\text{tandem-tilt}} + \sum_{k=1}^{N_p^{\text{tandem}}} \sigma_k^{\text{tandem}} B_k^{\text{tandem-tilt}} = 0 \end{aligned} \quad (4)$$

where the C_k^{tandem} and B_k^{tandem} are the influence coefficients of the tandem rotor induced by itself, while C_k^{tilt} and B_k^{tilt} are the influence coefficients of the tilt rotor induced by itself. The $C_k^{\text{tilt-tandem}}$ and $B_k^{\text{tilt-tandem}}$ are the influence coefficients of the tandem rotor induced by the tilt rotor, and $C_k^{\text{tandem-tilt}}$ and $B_k^{\text{tandem-tilt}}$ are the influence coefficients of the tilt rotor induced by the tandem rotor, respectively. All coefficients can be written as:

$$C = \frac{1}{4\pi} \int_S \mathbf{n} \cdot \nabla \left(\frac{1}{r} \right) dS, \quad B = -\frac{1}{4\pi} \int_S \left(\frac{1}{r} \right) dS, \quad (5)$$

where S is the integrated surface, and $\mathbf{n}$ denotes the outward unit normal vector of surface.

To close this problem, the wake doublets can be expressed in terms of the unknown surface doublets through the Kutta condition. Defining upper and lower trailing edge (T.E.) doublets as $\mu_{\text{up}}^{\text{tandem}}$, $\mu_{\text{lower}}^{\text{tandem}}$, $\mu_{\text{up}}^{\text{tilt}}$, and $\mu_{\text{lower}}^{\text{tilt}}$, respectively, the μ_w^{tandem} and μ_w^{tilt} are given as:

$$\begin{cases} \mu_w^{\text{tandem}} = \mu_{\text{up}}^{\text{tandem}} - \mu_{\text{lower}}^{\text{tandem}} \\ \mu_w^{\text{tilt}} = \mu_{\text{up}}^{\text{tilt}} - \mu_{\text{lower}}^{\text{tilt}} \end{cases}, \quad (6)$$

The source and doublet distributions of the tandem and tilt rotors are solved at the same time by combining Eqs. (4) and (6). The unsteady pressure on the tandem and tilt rotor blades can then be calculated using the velocity potential and flow velocity through Bernoulli's equation. Thus, the dimensionless form of the unsteady blade pressure C_p is given as:

$$C_p = \frac{p - p_{\text{ref}}}{(1/2)\rho(\mathbf{v}_{\text{ref}})^2} = 1 - \frac{(\mathbf{v})^2}{(\mathbf{v}_{\text{ref}})^2} - \frac{2}{(\mathbf{v}_{\text{ref}})^2} \frac{\partial \phi}{\partial t}, \quad (7)$$

where p_{ref} and ρ are the far-field reference pressure and air density, and $\mathbf{v}$, p , $\mathbf{v}_{\text{ref}}$ are the local fluid velocity, local pressure, reference velocity, respectively, at each rotor section of the rotor. ϕ is the velocity potential.

The aerodynamic forces on the panels of the rotors can then be computed as:

$$\Delta \mathbf{F}_k = -C_{pk} \left(\rho \mathbf{v}_{\text{ref}}^2 / 2 \right)_k \Delta S_k \mathbf{n}_k, \quad (8)$$

where $\Delta \mathbf{F}_k$ is the aerodynamic load on the panel, ΔS_k is the panel area, and $\mathbf{n}_k$ is its normal vector.

2.2 Wake Model for the Multiple Rotorcraft

The wake of the involved rotorcraft needs to be preserved over long periods of the time to capture their interaction with the ship. This is done by the viscous vortex particle method [27] which solves the Navier-Stokes equation with velocity-vorticity $(\mathbf{v}, \boldsymbol{\omega})$ in a Lagrangian frame using vector-valued particles. The governing equations are written as:

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + \mathbf{v} \cdot \nabla \boldsymbol{\omega} = \nabla \mathbf{v} \cdot \boldsymbol{\omega} + \nu \nabla^2 \boldsymbol{\omega}, \quad (9)$$

where ν is the kinematic viscosity, and $\boldsymbol{\omega} = \nabla \times \mathbf{v}$ is the vorticity field associated with the velocity field.

The second term on the left hand-side describes the vortex particle convection which is solved using a fourth-order Runge-Kutta scheme with the Biot-Savart law. The right hand-side includes the vortex particle stretching and viscous diffusion effects. In particular, the viscous diffusion $(\nu \nabla^2 \boldsymbol{\omega})$ is simulated through the Particle Strength Exchange (PSE) allowing for the Laplacian operator ∇^2 to be replaced by an integral operator [28, 29] as:

$$\nabla^2 \boldsymbol{\omega} \approx \frac{2}{\varepsilon^2} \int_V \zeta_\varepsilon(\mathbf{x} - \mathbf{y}) [\boldsymbol{\omega}(\mathbf{x}) - \boldsymbol{\omega}(\mathbf{y})] d\mathbf{y} \quad (10)$$

where ζ_ε is a kernel function with Gaussian distribution, and ε is the smoothing radius. **$\mathbf{x}$ and $\mathbf{y}$ is the position of particles.**

Vortex stretching $(\nabla \mathbf{v} \cdot \boldsymbol{\omega})$ is computed by a direct scheme where the velocity gradient can be expressed as a product of the kernel function and the position gradients [30]. Thus, the particle velocity gradient in Eq. (9) can be expressed as follows:

$$\nabla \mathbf{v}(\mathbf{x}, t) = - \sum_{j=1}^N \nabla [K_\varepsilon(\mathbf{x} - \mathbf{x}_j)] \times \boldsymbol{\alpha}_j \quad (11)$$

where K_ε is the Biot-Savart kernel for the velocity evaluation. $\mathbf{x}_j$ and $\boldsymbol{\alpha}_j$ are the position and the vector-valued vorticity, respectively.

Vortices are shed from the blade surfaces via the applied Neumann boundary condition and by converting shed-wake doublet panels to vorticity [27].

2.3 Viscous Model of the Ship and the Sea Surfaces

The aerodynamic models of the ship and the sea surfaces are crucial to the aerodynamic computation of the shipboard rotors. Here, a viscous boundary model, suitable for complex geometries, such as the combined ship plus the sea surfaces, is developed by considering the no-slip and no-penetration boundary conditions for a vorticity sheet [31-33].

The effects of the ship and sea surfaces can be summarized in two boundary conditions: the flow cannot go through the surfaces, which is a non-penetration boundary condition, and the tangential velocity of the flow on the surface is zero, which is a no-slip boundary condition. These are expressed as:

$$\begin{cases} \mathbf{v} \cdot \mathbf{n} = 0 & \text{non-penetration boundary condition} \\ \mathbf{v} \cdot \mathbf{t} = 0 & \text{no-slip boundary condition} \end{cases} \quad (12)$$

where $\mathbf{v}$, $\mathbf{n}$ and $\mathbf{t}$ represent the velocity, and the unit vectors normal and tangential to the boundary, respectively.

Also, there is a free-stream velocity at the far-field which is written as:

$$\mathbf{v}|_{x \rightarrow \infty} = \mathbf{v}_{\infty} \quad , \quad (13)$$

where $\mathbf{v}_{\infty}$ is the free-stream velocity.

Based on Poincaré's formula [30] and Eq. (12), a Fredholm equation of the second kind that justifies the no-slip condition can be written as:

$$\frac{\boldsymbol{\gamma} \times \mathbf{n}}{2} - \int_S K(\mathbf{x}_s - \mathbf{x}'_s) \times \boldsymbol{\gamma}(\mathbf{x}') dS = \mathbf{v}_{slip} \quad , \quad (14)$$

where $\mathbf{v}_{slip}$ is the induced velocity from the vorticity in the flow field. $\boldsymbol{\gamma}$ is the bound vortex sheet which enforces the no-slip condition, $\mathbf{x}_s$ and $\mathbf{x}'_s$ is the position of bound vortex sheet, and K is defined as:

$$K(\mathbf{x}_s, \mathbf{x}'_s) = \nabla G(\mathbf{x}_s, \mathbf{x}'_s) \quad , \quad (15)$$

with G the free-space Green's function.

Equation (14) defines the vortex sheet on the ship and sea surfaces that generate vorticity into the flow field. Furthermore, the tangential and the normal velocity conditions are satisfied for the non-rotating ship and sea surfaces based on the stream function vorticity relationship [31-33]. The vector sheet, $\boldsymbol{\gamma}$, is parallel to the ship and the sea surfaces, hence only two vorticity components need to be determined. By dividing the ship and the sea surfaces into the vortex sheet panels, integration on the surfaces using Eq. (14) can be, equivalently, written as the

superposition of integrations on the panels constituting those surfaces. Quadrilateral geometry, constant-strength panels are used in the current study. Although this model is similar to the vortex panel method, there are some differences. In the vortex panel method, the no-slip boundary condition is not satisfied, and the vorticity is not diffused in the flow field. Also, the present model is developed for low Reynolds number, and is suitable for ship and sear surface, but it not used to model the rotor blades. The aerodynamics of rotors is modelled by the source/doublet panel due to its high Reynolds number.

The viscous boundary conditions are transformed to algebraic equations that provide the vector vortex sheet distribution. In a viscous flow, the presence of the ship and sea surfaces affects the flow by forcing the fluid to decelerate to zero velocity on the surfaces. In other words, the surfaces are sources of vorticity, and this can be modelled by a flux of vorticity from them [31-35]. Therefore, after a vortex sheet on the boundary is obtained, transfer of the vorticity of the vortex sheet to the nearby particles in the fluid domain is carried out. This is accomplished by solving a diffusion equation with the correct boundary conditions:

$$\begin{aligned}\frac{\partial \boldsymbol{\omega}}{\partial t} - \nu \Delta \boldsymbol{\omega} &= 0, \\ \boldsymbol{\omega}(t - \delta t) &= 0, \\ \nu \frac{\partial \boldsymbol{\omega}}{\partial n} &= \frac{-\boldsymbol{\gamma}(s)}{\delta t}.\end{aligned}\tag{16}$$

The solution of the Eq. (16) can be computed in integral form [31] using:

$$\boldsymbol{\omega} = \int_0^t \int_S G_h(\mathbf{x}_s, t, \mathbf{s}, \tau) \boldsymbol{\gamma}(\xi, \tau) dS d\tau, \tag{17}$$

where $\mathbf{s}$ is the position of point in flow field, ξ and τ are integrated surface and time, and G_h is the three-dimensional heat kernel, with $\tau < t$

$$G_h(\mathbf{x}_s, t, \mathbf{s}, \tau) = (4\pi\nu(t - \tau))^{-3/2} \exp\left(-\frac{|\mathbf{x}_s - \mathbf{s}|^2}{4\nu(t - \tau)}\right), \tag{18}$$

This flux must be emitted during a time Δt . In effect, the vortex sheet $\boldsymbol{\gamma}$ must be distributed to neighbouring particles by discretizing Green's integral for the inhomogeneous Neumann problem corresponding to the diffusion equation. Then, a particle receives, from that panel, an amount of "vorticity $\times$ volume" given by:

$$\Delta \boldsymbol{\alpha}_i = \int_0^{\Delta t} \frac{d\boldsymbol{\alpha}_i}{dt} dt, \tag{19}$$

where

$$\frac{d\mathbf{a}_i}{dt} = \int_{x_i-h_{xi}/2}^{x_i+h_{xi}/2} \int_{y_i-h_{yi}/2}^{y_i+h_{yi}/2} \int_{z_i-h_{zi}/2}^{z_i+h_{zi}/2} \frac{d\boldsymbol{\omega}}{dt} dx dy dz, \quad (20)$$

and (x_i, y_i, z_i) and (h_{xi}, h_{yi}, h_{zi}) are the positions of the particles and the size of the integration cuboid, respectively.

The rate of change of the vorticity, $d\boldsymbol{\omega}/dt$, due to the rectangular panel of uniform strength γ and size $b \times f$, is shown in Fig. 2, and is equal to

$$\frac{d}{dt} \boldsymbol{\omega} = \frac{\Delta\gamma}{\Delta t} \frac{1}{2\sqrt{\pi}} \frac{1}{\sqrt{4vt}} \exp\left(-\frac{z^2}{4vt}\right) [\text{erfc}]_{(x-b/2)/\sqrt{4vt}}^{(x+b/2)/\sqrt{4vt}} [\text{erfc}]_{(y-f/2)/\sqrt{4vt}}^{(y+f/2)/\sqrt{4vt}}, \quad (21)$$

Then,

$$\begin{aligned} \frac{d\mathbf{a}_i}{dt} &= \frac{\Delta\gamma}{\Delta t} [\text{erfc}]_{(z_i-h_{zi}/2)/\sqrt{4vt}}^{(z_i+h_{zi}/2)/\sqrt{4vt}} \\ &\times \frac{1}{2} \sqrt{4vt} \left([\text{ierfc}]_{((x_i-b/2)+h_{xi}/2)/\sqrt{4vt}}^{((x_i-b/2)-h_{xi}/2)/\sqrt{4vt}} - [\text{ierfc}]_{((x_i+b/2)+h_{xi}/2)/\sqrt{4vt}}^{((x_i+b/2)-h_{xi}/2)/\sqrt{4vt}} \right) \\ &\times \frac{1}{2} \sqrt{4vt} \left([\text{ierfc}]_{((y_i-f/2)+h_{yi}/2)/\sqrt{4vt}}^{((y_i-f/2)-h_{yi}/2)/\sqrt{4vt}} - [\text{ierfc}]_{((y_i+f/2)+h_{yi}/2)/\sqrt{4vt}}^{((y_i+f/2)-h_{yi}/2)/\sqrt{4vt}} \right) \end{aligned} \quad (22)$$

where $[\text{erfc}]$ is complementary error function, and $[\text{ierfc}]$ is integral of error function complement.

The time integral in the Eq. (22) is evaluated numerically using a Gauss quadrature with four points.

Fig. 2 Diffusion of the vorticity of vortex sheet to particle

3 Numerical Results and Discussions

The V-22/Ship/Helicopter Aerodynamic Interaction Phenomena (VSHAIP) have a significant role in the V-22 “Roll-On-Deck (ROD)” scenario in which the V-22 aircraft on the deck of an L-class ship, with rotors turning, experienced an uncommanded roll in response to another rotorcraft landing upwind [13]. Therefore, a quantitative verification of the present numerical method is first carried out by simulating the flow field at location of the tilt-rotor (scaled-model of the V-22) under the influence of a tandem rotor wake. The tandem rotor is a scaled-model of the CH-46. Unsteady airloads of the V-22 under the aerodynamic interaction of the upwind CH-46 at different WHODs, Wheel-Height-Over-Deck, and lateral offsets, distance between the center of the CH-46 and the landing spot, are then presented.

The experiment of the aerodynamic interaction between the upwind CH-46 and the 1/48th-scale model of the LHA ship conducted in the Army 7- by 10-Ft Wind Tunnel at NASA Ames Research Center [12, 13, and 5] was used in the present work. The 3-component velocity field measurements of the combined wake of the CH-46 and the LHA ship were obtained using Particle Image Velocimetry (PIV) and more details about the tests can be found in [13, 5].

The tandem helicopter is an approximate 1/48th-scale model of the CH-46. The forward and aft rotors consist of three blades and employ a low Reynolds number airfoil. The rotor blade planform and twist are similar to the equivalent full-scale CH-46 blade [12]. The radius of the blade, solidity, tip chord, and tip speed are 6.311in, 0.057, 0.375in, and 233ft/s, respectively. The three-bladed hubs have counter-clockwise rotation on the forward rotor and clockwise rotation on the aft rotor as viewed from above. The relative height and shaft angles of the rotor hubs are modelled based on a full scale CH-46. Therefore, the aft rotor is higher than the forward, and the forward rotor is tilted 2.5° forward. The tandem rotors are modelled as rigid hubs with collective control only, no cyclic pitch control, and differential collective pitch are used to establish the desired aircraft center of thrust. Like in experiments, the C_T of the CH-46 is maintained at $C_T=0.0048$. Also, the fuselage of the CH-46, sting, and strut that were present in the experimental setup are not modelled. Each rotor is resolved using 3600 panels composed of 60 panels in the chordwise and 20 panels in the spanwise directions, and the CH-46 is modelled with a total of 7200 panels. The forward rotor of the CH-46 is centered at Landing Spot 6 on the ship with variation of lateral offset and Wheel-Height-Over-Deck (WHOD). The azimuthal angle step of the rotors is 2.5°.

The on-deck V-22 is an approximate 1/48th-scale of the V-22 Osprey. The rotor consists of three blades and employs a low Reynolds number airfoil. The rotor blade planform and twist are similar to a full-scale V-22 blade [12]. The radius of the blade, solidity, tip chord, and tip speed are 4.687in, 0.102, 0.446in, and 260ft/s, respectively. The three-bladed hubs have counter-clockwise rotation on the right rotor and clockwise rotation on the left rotor, viewed from above. The rotor hubs are rigid and use collective pitch only. Differential collective pitch is used to trim for rolling moments. **Each rotor is resolved using 3600 panels composed of 60 panels in the chordwise and 20 panels in the spanwise directions, and the V-22 is modelled with a total of 7200 panels.**

The ship geometry is based on shipyard drawings of the LHA [12]. The overall deck width, length, and height of the deck above the test section floor are 2.46 ft, 17.08 ft, and 1.34 ft, respectively. More details and key dimensions can be found in Ref. 12. The ship and the sea surfaces are shown in Fig. 1 and modelled with 9800

panels. The computation time with 10 rotor revolutions for the most complex case with CH-46, V-22, and LHA ship is 136 CPU hours on desktop using one CPU of Intel i7-3770 3.4GHz. Also, The relative error of the thrust coefficient of V-22, $\varepsilon_e = |C_T^{i+1} - C_T^i| / C_T^0$, for the most complex case with interaction of CH-46 and LHA is 2.28E-3.

It should be noted that the laser light sheet (LLS) optics during the experiments were located 4.53in downstream of Landing Spot 7 nose-wheel location. Consequently, the flow field in the present work is focused on a scan plane passing through the V-22 rotor axes, with an offset of 4.53 inches aft from the deck nose wheel reference point as shown in Fig. 3. The combined LHA and the CH-46 in the current work are computed at a single wind speed of 19.7 ft/sec, which corresponds to a wind speed of 35 knots at full scale, and yaw angle of 0° at Landing Spot 7.

Table 1 shows the parameters used for the computed cases. Cases 1-3 are for validation of the present method in Part 3.1, and cases 4-9 are for investigating the unsteady force of the V-22 under the aerodynamic interaction with the upwind CH-46 located at different WHODs (Part 3.2). Finally, cases 10-16 are for analyzing the unsteady force of the V-22 with the upwind CH-46 located at different lateral offsets (Part 3.3) to illustrate the rotorcraft-to-rotorcraft interference during shipboard operations.

Table. 1 Characteristics of the computational cases

No. case	Purpose	No. Figures	Ship	CH-46	WHOD of CH-46	Lateral offset of CH-46	V-22	Flow field or force of V-22
1	Validation	Figs. 4, 5, 6	Yes	Yes	10ft	$2(b_v/2)$	No	Flow field
2		Figs. 7, 8, 9	Yes	Yes	40ft	$2(b_v/2)$	No	Flow field
3		Figs. 10, 11	Yes	Yes	10ft	$4(b_v/2)$	No	Flow field
4	Rolling moment calculations	Fig. 12	Yes	Yes	10ft	$2(b_v/2)$	Yes	Force
5			Yes	Yes	20ft	$2(b_v/2)$	Yes	Force
6			Yes	Yes	25ft	$2(b_v/2)$	Yes	Force
7			Yes	Yes	30ft	$2(b_v/2)$	Yes	Force
8			Yes	Yes	40ft	$2(b_v/2)$	Yes	Force
9			Yes	Yes	50ft	$2(b_v/2)$	Yes	Force
10		Fig. 13	Yes	Yes	25ft	$-1(b_v/2)$	Yes	Force
11			Yes	Yes	25ft	$0(b_v/2)$	Yes	Force
12			Yes	Yes	25ft	$1(b_v/2)$	Yes	Force
13			Yes	Yes	25ft	$2(b_v/2)$	Yes	Force
14			Yes	Yes	25ft	$3(b_v/2)$	Yes	Force
15			Yes	Yes	25ft	$4(b_v/2)$	Yes	Force
16			Yes	Yes	25ft	$5(b_v/2)$	Yes	Force

Fig. 3 Schematic for the position of the ship, the CH-46, and the V-22

3.1 Flow field at the location of V-22 with upwind CH-46 and the ship

In this case, like in experiments, the on-deck V-22 is absent in an attempt to quantify the flow field disturbances due to the upwind CH-46, at the position where the V-22 would be. The vertical velocities at the V-22 tip-path-plane height, shown in Fig. 4(a), are acquired for the combined configuration of the LHA ship plus the upwind CH-46 adjacent to Landing Spot 6 with a lateral offset of $2(b_v/2)$, where b_v is the V-22 wing span, and a full-scale WHOD of 10ft. It should be noted that the individual mean velocity components have been normalized with the appropriate free-stream wind speed. The port and starboard sides of the left V-22 rotor are also shown in black for clarity. The experiment [5] and CFD results [22] from CFD found in a published open paper are plotted in Fig. 4(a) for comparison. The fluctuations of the vertical velocity compare reasonably well with experiments and CFD results. Although the CFD can be used to simulate the variation of induced velocity, it has difficulties capturing the rotor wake for long periods of time and resolving the unsteady airloads of the rotor blades at different azimuths based on the momentum source model. This is a key factor in the aerodynamic interaction between the CH-46, V-22, and LHA ship. Also, there are discrepancies for both the CFD and the present results in terms of lateral position in region C. This is possibly due to the absence of the fuselage of the CH-46. Also, the absence of the hub, sting, and strut in experiment may influence the result. Even though there are discrepancies, the overall comparison is still acceptable. Furthermore, the vertical velocity at the V-22 tip-path-plane height, which is well-captured, is the combination of a strong downwash and upwash in regions A and B of the left V-22 rotor. A highly nonlinear induced inflow due to the rolled-up tip vortex of the upwind CH-46 is also evident in the lateral direction, and is also well captured.

The predicted in-plane velocity at the scan plane passing through the rotor axes of the V-22 rotor is plotted in Fig. 4(b). All in-plane velocity predictions described in this part refer to the mean flow field, and have been normalized with the corresponding free-stream wind speed. The deck outline is included for clarity, and the forward and aft rotor disks of the CH-46 are shown in red. The downwash imposed on the V-22 at Landing Spot 7 can be determined by identifying the position of the left and right rotors of the V-22 in black. The rolled-up tip vortex of the CH-46 produces a strong downwash, indicated by the blue arrow, in region A of the left V-22 rotor and a strong upwash, which indicated by the red velocity vectors, in region B. However, as opposed to the left rotor of the V-22, the wake of the upwind CH-46 has a weak influence on the flow field of the right rotor of the V-22. Consequently, the effective angles in regions A and B of the left V-22 rotor will decrease and increase, respectively, causing a negative rolling moment on the left rotor. The variation of the rolling moment of the running V-22 is presented later in the paper.

Fig. 4 Vertical velocity and in-plane velocity at the scan plane for case 1 (the CH-46 landing at Spot 6 with the lateral offset= $2(b_v/2)$, WHOD=10ft, only the CH-46 and the ship)

In Fig. 5, the wake structure of the upwind CH-46 on the LHA ship is shown off the port side of the deck, symmetrically behind the tandem rotor. Even though the V-22 is not included in the simulation, the V-22 is shown in Fig. 5 to mark its position. It can be seen that the tandem rotor generates counter-rotating vortex pairs similar to that of a single rotor. However, unlike the tightly rolled-up tip vortices that form downstream from a single rotor, each rotor disk of the upwind CH-46 generates a pair of super vortices. Due to the proximity of the two rotor disks, the trailed vortices from the forward rotor disk amalgamate with, and reinforce those from the aft rotor disk, resulting in a pair of super vortices shown in Fig. 5, while the root vortices of both rotors interact with part of the tip vortex of forward and backward rotors resulting in the lower pair of vortices shown in Fig. 6. Furthermore, since the peak to peak velocity change is calculated along the center of super vortex, it indicates the strength of the super

vortex. The peak to peak velocity change in region C is slightly larger than in region A in Fig. 4(a), the port super vortex of the CH-46 is then apparently stronger than the starboard super vortex. Also, the port super vortex is located on the port side of the deck port edge, whereas the starboard super vortex is located above the deck port edge. Moreover, it is worth noting that the starboard super vortex impinges on the center of the left V-22 rotor, and it also interacts with the deck behind Landing Spot 7 shown in Fig. 5.

Figure 6 shows the flow visualization of the upwind CH-46 at xz sectional plane. The pair of the super vortices, which are rolled up from the tip vortices, are clearly identifiable in the xz sectional plane passing through the locations of the V-22 rotor axes. Furthermore, the starboard super vortex of the upwind CH-46 sweeps downstream and impinges on the hub of the left V-22 rotor, which is clearly visible in the xz sectional plane shown in Fig. 6, resulting in the strong downwash and upwash in regions A and B of the left V-22 rotor shown in Fig. 4(a). Also, the wake of the CH-46 is hampered by the deck as confirmed in Fig. 6.

Fig. 5 Wake structure of the CH-46 on the ship for case 1 (The CH-46 landing at Spot 6 with the lateral offset= $2(b_v/2)$, WHOD=10ft, the V-22 is not included in the calculation but only shown to mark its location)

Fig. 6 Flow visualization of the CH-46 on the ship for case 1 (The CH-46 landing at Spot 6 with the lateral offset= $2(b_v/2)$, WHOD=10ft, the V-22 is not included in the calculation but only shown to mark its location)

The condition described by Figs. 4-6 is a useful reference point from which to study the effect of moving the CH-46 in the 3D-space, on the velocity field at Landing Spot 7. The flow field at Landing Spot 7 after moving the upwind CH-46 to Landing Spot 6 with a lateral offset of $2(b_v/2)$ and at WHOD = 40 ft is shown in Fig. 7, keeping all other conditions constant (namely the C_T of the CH-46, yaw angle, and wind speed). Experiments [4] and CFD results [22] are also plotted in this figure for comparison. The predicted vertical velocity at the V-22 tip-path-plane height has a similar trend as the CFD results and the experimental measurements, while the present method and published CFD are less accurate and under-predict the peak of the downwash due to absence of the CH-46 fuselage, sting, and strut in computations. However, good agreement with the experimental peak of the downwash can be observed for the present computation. Furthermore, **The center of downwash and upwash is predicted well, suggesting that the position of rotor wake is well-predicted, while the peak to peak and slope of downwash and upwash are also predicted with good accuracy, indicating that the vorticity of rotor wake is also predicted. Then, since the complex downwash is well predicted, the wake is predicted satisfactorily.**

Clearly, as opposed to the previous case with a lateral offset of $2(b_v/2)$ and WHOD = 10 ft shown in Fig. 4, the rolled-up tip vortex of the CH-46 induces a small downwash in regions A and B of the left V-22 rotor. Also, the wake of the upwind CH-46 has a weak influence on the velocity flow field on the right rotor of the V-22. Therefore, the interactional effect of the wake from the upwind CH-46 is weaker than that of the previous cases.

The wake structure of the upwind CH-46 is shown in Fig. 8. The V-22 is also shown to mark its position. Similar to the previous case, the upwind CH-46 generates two super vortices. However, the wake of the upwind CH-46 sweeps downstream above the hub of the V-22 rotor (Fig. 9) instead of impinging on the hub like in the previous case (Fig. 6). Also, the interaction between the wake of the CH-46 and the deck of ship disappear. This is confirmed by the flow visualizations in the xz sectional plane passing through the V-22 rotor center shown in Fig. 9.

Fig. 7 Vertical velocity and **in-plane velocity** at the scan plane for case 2 (the CH-46 landing at Spot 6 with the lateral offset= $2(b_v/2)$, WHOD=40ft, only the CH-46 and the ship)

Fig. 8 Wake structure of the CH-46 on the ship for case 2 (the CH-46 landing at Spot 6 with the lateral offset= $2(b_v/2)$, WHOD=40ft, **the V-22 is not included in the calculation but only shown to mark its location**)

Fig. 9 Flow visualization of the CH-46 on the ship for case 2 (the CH-46 landing at Spot 6 with the lateral offset= $2(b_v/2)$, WHOD=40ft, **the V-22 is not included in the calculation but only shown to mark its location**)

The CH-46 is at an increased lateral offset of $4(b_v/2)$ from Landing Spot 6 and the vertical velocity distribution at the **scan plane** is shown in Fig. 10. The experiment measurements [4] and CFD results [22] are also shown for

comparison. The predicted velocity profiles are found to match with the experiment data and CFD results. The downwash and upwash are also captured reasonably well for this case.

Note that the large in-plane velocities associated with the rotor wake plotted in Fig. 10 are similar to the previous cases. Despite the fact that a strong downwash and upwash is produced below the CH-46 rotor plane, the downwash due to the upwind CH-46 has little effect on the deck of the ship, and at the V-22 location. Furthermore, contrary to the case with the lateral offset of $2(b_v/2)$ and WHOD = 10 ft, as shown in Fig. 4, there is a slight upwash in regions A and B of the left V-22 rotor due to the induced effect of the starboard super vortex of the upwind CH-46. Additionally, the effect of the wake of the upwind CH-46 on the V-22 location is weakened as confirmed by Fig. 11. This is because the wake from the upwind CH-46 sweeps far away from the port side of the V-22 and the deck.

Fig. 10 Vertical velocity and in-plane velocity at the scan plane for case 3 (the CH-46 landing at Spot 6 with the lateral offset= $4(b_v/2)$, WHOD=10ft)

Fig. 11 Wake structure of the CH-46 on the ship for case 3 (the CH-46 landing at Spot 6 with the lateral offset= $4(b_v/2)$, WHOD=10ft, the V-22 is not included in the calculation but only shown to mark its location)

3.2 Unsteady airloads of the V-22 under the interaction of the CH-46 and the ship at different WHODs

In this case, the on-deck V-22 is operating in an attempt to quantify the disturbance of the unsteady airloads on the V-22 rotors due to the wake of the upwind CH-46. The on-deck V-22 is first trimmed to an initial low thrust level as $C_T=0.0008$ since the V-22 is running on the deck, and the force of the V-22 is only affected by the LHA ship. The collectives of the V-22 rotors are then fixed, and the upwind CH-46 is trimmed at the desired thrust with $C_T=0.0048$, and traverses in a pre-programmed grid in the horizontal and vertical planes defined by scaled spot separation, lateral offset, and WHOD, while the on-deck V-22 force and moment are allowed to vary. On-deck force and rolling moment predictions, therefore, indicate the change in the force and the rolling moment due to the aerodynamic interaction with the upwind CH-46.

The referred rolling moment is defined as follows:

$$RM_{\text{ref}} = Cm_x / Cm_x^0 \quad (23)$$

where Cm_x is the rolling moment coefficient of the V-22, while the Cm_x^0 is the full-scale rolling moment coefficient estimated to be sufficient to cause a 43,000 lb V-22 to lift a main landing gear.

The absolute value of the referred rolling moment approaches 1, indicating that the rolling moment is larger than the full-scale rolling moment to lift the V-22 main gear, and the “Roll-on-Deck (ROD)” may be occurred.

Figure 12 shows the variation of the referred rolling moment of the V-22 under the combined configuration of the LHA ship plus the upwind CH-46 at different WHODs (offset= $2(b_v/2)$). The results of the isolated V-22 are also plotted for comparison. The average of the referred rolling moment of the isolated V-22 is small. In contrast, for the V-22 interacting with the upwind CH-46 at WHOD=10 ft, the moment is strengthened, and the maximum is greater than 1.0, indicating that the left and right rotors of the V-22 are pushed downwards and upwards, respectively. The main landing gear of the V-22 may be lifted, and this was also observed in the V-22 “Roll-On-Deck (ROD)” scenario during flight [4]. As the WHOD of the CH-46 increases, the fluctuations and the average of the referred rolling moments are reduced. This is because the CH-46 rolled-up vortex is also pushed upwards and convects downstream passing above the hub of the V-22. Then the fluctuation of the vertical velocity across the hub of the V-22 is reduced as shown in Fig. 7, and the unsteady airloads due to the interaction are weakened.

The referred rolling moment of the left and right rotors of the V-22 in Fig. 12 provides some insight into the effect on the left and right V-22 rotors of the interaction with the upwind CH-46. The variations of the referred rolling moment due to the right rotor are similar at different WHODs, and they are also small like the isolated V-22. However, the variation of the referred rolling moment due to the left rotor is different at different WHODs. Similar

to the whole V-22, as the WHOD of the CH-46 increases, the variation of the referred rolling moment of the left rotor is reduced. This is because the rolled-up tip vortex of the upwind CH-46 impinges on the left rotor and has a significant influence on its flow field, while the rolled-up tip vortex convects downstream far away from the right rotor and has a small influence on the right rotor flow field. Therefore, the variation of the referred rolling moment of the V-22 is dominated by the left rotor.

Fig. 12 Variation of the referred rolling moment of the V-22 under the upwind CH-46 at different WHODs (cases 4-9, offset=2($b_v/2$))

3.3 Unsteady airloads of the V-22 under interaction of the CH-46 and the ship at different lateral offsets

Figure 13 shows the variation of the referred rolling moment of the V-22 with the LHA ship and the upwind CH-46 for different lateral offsets (WHOD=25ft). As the lateral offset increases from $-1(b_v/2)$ to $5(b_v/2)$, the average of the referred rolling moment first decreases and undergoes a rapid change of sign before returning to its initial values. The average of the referred rolling moment of the V-22 is negative as the offset increases from $-1(b_v/2)$ to 0, while it is positive as the lateral offset increases from 0 to $2(b_v/2)$. The average of the referred rolling moments reach the minimum ($RM_{ref}=0.92$) and maximum ($RM_{ref}=1.02$) when the lateral offsets are $-1(b_v/2)$ and $1(b_v/2)$, respectively. This suggests that the main landing gear of the V-22 is lifted since the referred rolling moment approaches 1. This is because, at a lateral offset of $-1(b_v/2)$, the rolled-up tip vortex of the upwind CH-46 impinges on the right rotor of the V-22 resulting in a decrease of its rolling moment. Nevertheless, at the lateral offset of $1(b_v/2)$, the rolled-up tip vortex of the upwind CH-46 impinges onto the left rotor of the V-22 resulting in an increase of its rolling moment, as shown in Fig. 13.

The average of the referred rolling moment is dominated by the right rotor as the lateral offset increases from $-1(b_v/2)$ to $0(b_v/2)$. However, it is dominated by the left rotor with further increase of the lateral offset from $0(b_v/2)$ to $1(b_v/2)$.

$5(b_v/2)$. When the lateral offset is smaller than zero, the peak-to-peak value of the right rotor is greater than that of the left rotor, as shown in Fig. 13, while the opposite happens when the lateral offset is positive. This is because the upwind CH-46 is hovering above the deck of the ship and when the lateral offset is smaller than zero, the rolled-up tip vortex of the CH-46 passes near the right rotor of the V-22 influencing its airloads. It then convects far away from the left rotor of the V-22 resulting in a slight effect on the left rotor. Nevertheless, the rolled-up tip vortex of the CH-46 convects further down near the left rotor of the V-22 as shown in Fig. 5 and plays a significant role in the airloads of the left rotor when the lateral offset is greater than zero.

Fig. 13 Variation of the referred rolling moment of the V-22 under the upwind CH-46 at different lateral offsets (cases 10-16, WHOD=25ft)

4 Conclusion

A vortex-based approach is used here to predict the flow field and the airloads of a tilt rotor under the interaction of an upwind tandem rotor during shipboard operations. The aerodynamics of the rotors is modelled by an unsteady panel method, and the unsteady behaviour of the rotor wake is taken into account through the vortex particle method. The effects of sea surfaces and ship structure are modelled by a viscous boundary model. The present approach is applied to the 1/48th-scaled models of the CH-46 and V-22, running on the deck of a model of LHA amphibious assault ship. The predicted flow field is compared with experiments performed at the NASA Ames Research Center, and some conclusions can be drawn as follows:

- (1) The predicted vertical velocity at the location where the downstream V-22 rotor would be induced by the upwind CH-46 during shipboard operations compare reasonably well with experiments and published CFD results.
- (2) The left rotor of a V-22 placed at the scan plane, experiences an upwash and downwash induced by the rolled-up tip vortex of the upwind CH-46, and the fluctuation of the vertical velocity is reduced with increasing the

WHOD of the upwind CH-46.

- (3) Contrary to the isolated V-22 during shipboard operation, the referred rolling moment of the V-22 is obviously strengthened, and the interaction of the wake from the upwind CH-46 plays a significant role in the unsteady airloads of the V-22. The rolled-up tip vortex of the upwind CH-46 impinges upon the left rotor of the V-22 resulting in a variation of the V-22 rolling moment dominated by the left rotor.
- (4) As the WHOD of the CH-46 increases, the average and the fluctuations of the rolling moment of the V-22 decrease. However, with increasing the lateral offset of the upwind CH-46 the average of the rolling moment rapidly changes sign from negative to positive and back.

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