MODELLING A HELICOPTER ROTOR'S RESPONSE TO ENCOUNTERS WITH AIRCRAFT WAKES

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Abstract

In recent years, various strategies for the concurrent operation of fixed and rotary wing aircraft have been proposed as means of increasing airport capacity. In response, the research community has focused attention on assessing the impact of encounters with the wakes of nearby large transport aircraft on the safety of helicopter operations. This paper reviews the current literature and proposes an objective and general way of assessing the severity of such encounters. The sensitivity of the predicted interaction severity to some traditional modelling assumptions is then examined by presenting calculations, using various techniques, of the response of an isolated helicopter rotor to an interaction with an isolated vortex. Traditionally two different approaches to modelling the rotor wake have been used: inflow-type models, where the flow through the rotor is represented as a velocity distribution defined only on the rotor disc, and flow-type models where the dynamics of the entire rotor wake is captured in the simulation. In most previous studies the interacting vortex has been modelled as a distribution of vorticity in space which is time invariant in the frame of reference attached to the vortex. This frozen-vortex assumption is essential for consistency with inflow-type formulations but neglects the mutually-induced distortion of the interacting vortex and the rotor wake. We show that calculated interaction severities can be impacted significantly by these assumptions when they are embedded within current simulation techniques. Rotor responses calculated using both inflow-type and flow-type models are compared, and, for flow-type models, predictions obtained using the frozen-vortex assumption are contrasted with calculations where this assumption has been relaxed.

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Nomenclature

A : rotor disc area πR^2
a : aerofoil lift-curve slope
C_L : blade section lift coefficient
C_T : rotor thrust, scaled by $\rho A(\Omega R)^2$
c : blade chord scaled by R
I_β : blade flapping inertia, scaled by ρAR^3
L : distance from the vortex core to the rotor hub
N : number of rotor blades
R : rotor radius
r : radial coordinate scaled by R
v_i : velocity normal to rotor disc, scaled by ΩR
X^* : value of X under trimmed conditions
α : blade section angle of attack
β : blade flapping angle
β_0 : rotor coning angle
β_{1s} : rotor lateral tilt angle
β_{1c} : rotor longitudinal tilt angle
γ_β : rotor Lock number $ac/\pi I_\beta$
θ_0 : collective pitch control angle
θ_{1s} : longitudinal cyclic pitch control angle
θ_{1c} : lateral cyclic pitch control angle
μ : rotor forward speed scaled by ΩR
σ : rotor solidity Nc/π
ψ : blade azimuth
ω : blade flapping frequency scaled by Ω
Ω : rotor rotational speed $d\psi/dt$

Introduction

The placement of helicopter final approach and takeoff areas for the simultaneous operation of rotary and fixed-wing aircraft is a topic of current concern. By decreasing the separation distance between successive fixed-wing arrivals or departures, and by promoting the use of helicopters to increase airport capacity, transport planners are potentially able to maximize the use of ground- and air-space at airfields (Ref. 1). Thus, attention has focused on the understanding of the structure and dynamics of the wakes generated by fixed wing aircraft, the effects of interaction with such wakes on the dynamics and control of helicopters, and hence of the effect of wake encounters on the safety of rotorcraft operations in the near-airfield environment.

Growing from a relatively small body of experimental data and somewhat contradictory anecdotal pilot reports, a substantial literature has emerged in the last few years on the numerical simulation of the response of a helicopter to an encounter with the trailed vortices associated with large transport aircraft. Unfortunately, the wide variation in modelling techniques employed in the various published studies and an inconvenient tendency to present isolated cases rather than to focus on a few standard scenarios, has made it very difficult to organise the literature into a mutually-consistent body of evidence from which the safety implications of helicopter encounters with aircraft wakes can be inferred.

The aims of this paper, therefore, are threefold. Firstly, to provide a quantitative measure of the severity of helicopter-wake interactions, which can be used to contrast, compare and unify the results of studies such as these. Secondly, to provide a systematic and hierarchical investigation into the effects of various traditional modelling assumptions regarding the treatment of the interacting vortex and the helicopter's own wake on the predicted severity of helicopter-wake interactions, for a limited class of all possible interaction scenarios. Thirdly, to provide evidence from which it may be possible to reach an objective assessment of the level of physical realism that must be embodied in any practically pertinent computational simulation of a helicopter-wake interaction.

Previous Work

Mantay *et al.* (Refs. 2–4), in their 1976 experimental studies flying a Bell UH-1H parallel to the wake of a Douglas C-54 Skymaster, provided the first objective, and only experimental, assessment of the severity of an encounter between a helicopter and the wake trailed behind a large aircraft. They determined that the maximum blade loading while flying along the aircraft wake at separation distances greater than 0.42 nmi would not exceed the blade loading experienced during a steady 1.8g turn, and thus that such encounters would not pose a significant hazard to safe operation.

In 1977, inspired by Mantay's observation that the most severe upset to the helicopter should ensue from an encounter with a vortex lying parallel to the helicopter's flightpath, Dreier (Ref. 5) modelled the effect of such an interaction on the dynamics of an isolated rotor. Simple blade-element theory predicts both the flapping and the thrust-response of an isolated rotor to an encounter with a vortex lying parallel to the rotor's flightpath to increase linearly with increasing helicopter forward speed. By perturbing the inflow through his rotor disc using McCormick *et al.*'s (Ref. 6) vortex model, Dreier obtained predictions of the resultant rotor thrust and flapping response that were in general agreement with the predictions of the simple theory.

Saito (Refs. 7–9) and co-authors, using 'local momentum theory' (Ref. 10) coupled to a six degree of freedom fuselage dynamic model, have simulated the helicopter response to interactions with a gust-field representing the wake trailed behind a Boeing 747. Somewhat contrarily to Mantay's observation, though, the maximum vertical acceleration experienced by the simulated helicopter increased when its initial flightpath changed from being parallel to being perpendicular to the aircraft's wake. Nevertheless, for interactions where the helicopter trajectory initially ran perpendicular to the aircraft's flight path, vertical accelerations of less than $2g$ were obtained at separation distances greater than 2km for model parameters representative of UH-1 and OH-6 type helicopters.

In similar vein, Chopra, Kim and Bir (Ref. 11) have presented results, using a similar dynamic model to Saito's (but with suppressed fuselage yaw degree of freedom and elastic blades) for a series of scenarios representing a helicopter encountering the vortices trailed behind a Boeing 747. The aircraft's wake was modelled using Burnham's (Ref. 12) 1982 experimental data, but the dynamics of the helicopter's wake was modelled using Peters' (Ref. 13) Dynamic Inflow Model. Chopra's conclusions regarding the influence of the flight path relative to the vortex axis on the dynamic response of a four-bladed hingeless helicopter broadly appeared to support Mantay's experimental observations and to contradict the predictions of Saito's simulations.

Similar findings to Mantay were reported by Curtiss and Zhou (Ref. 14). They raised an important issue, however, by questioning the validity of Mantay's experimental findings. Acknowledging the complexity of the helicopter during a vortex encounter, they pointed out a pilot's subconscious ability to suppress certain effects associated with the incursion of a helicopter into an aircraft's wake. In this vein it is worth mentioning Padfield and Turner's (Refs. 15, 16) recent attempts to construct an alternative quantification of the severity of helicopter vortex interactions in terms of the ADS-33 handling qualities standard.

The principal impediment to interpreting all studies based on models which are complex enough to simulate the full helicopter system is, of course, that it is very difficult to differentiate those elements of the helicopter's behaviour which are inherent in the rotary-winged nature of the vehicle from the more aircraft-like effects which arise from the aerodynamic response of the fuselage to the vortex, and from coupling between the rotor and fuselage behaviour.

Discounting parametric differences between the various studies, published results suggest that the specific approach taken to modelling the helicopter vortex interaction might have significant impact on the outcome of simulations.

Reference Interactions

The wide range of very different interaction scenarios considered by these various authors, and the diffuse scatter of parameters used to define the helicopter and the strength and shape of the interacting aircraft's wake are a hindrance to the unification of these results into a clear and unambiguous understanding of helicopter-vortex interactions. The first question that must be addressed in reconciling these studies is whether interactions with comparable severity are being represented in each case.

An appropriate analytic measure of the impact a given vortex might have on the dynamics of any helicopter with which it might interact can be obtained by imagining a vortex of known axisymmetric core structure lying somewhere in space as a result of the nearby passage of a large aircraft. The effect of this vortex on nearby helicopter operations might then be characterised via its influence on the dynamic response of an 'idealised helicopter' during an idealised 'reference interaction' with the vortex. Let the idealised helicopter consist of a fully articulated, isolated rotor moving with constant velocity through the air.

Define two reference interactions: a parallel interaction, such that the vortex-induced flow-field at the rotor is time invariant, has zero in-plane component on the rotor disc, and is antisymmetric with respect to the longitudinal axis of the rotor. Secondly, define a reference perpendicular interaction such that the vortex-induced flow-field is symmetric with respect to the longitudinal axis of the rotor.

Linearised blade-element theory gives the thrust generated by a radial element on one of the blades of the idealised helicopter's rotor, located at distance r from the rotor hub to be

$$dC_T = \frac{ca}{2\pi}(\theta v_{\|}^2 - v_{\|}v_{\perp})dr \tag{1}$$

where the velocity components (as a fraction of the rotor tip speed) parallel and normal to the blade section are, to first order in blade flapping and the induced velocity normal to the rotor disc v_i,

$$v_{\|} = r + \mu \sin\psi \tag{2}$$

and

$$v_{\perp} = v_i + \beta\mu\cos\psi + r\frac{d\beta}{d\psi} \tag{3}$$

The overall thrust of the rotor is then

$$C_T = N\int_0^1 dC_T \tag{4}$$

and, if the rotor hub is not free to accelerate, the small-amplitude flapping response of the blade is a solution to

$$\frac{d^2\beta}{d\psi^2} + \omega^2\beta = \frac{1}{I_\beta}\int_0^1 r\,dC_T \tag{5}$$

The induced flow through the rotor can be broken down into a wake-induced component and vortex-induced component which, by definition of the reference interactions, is

$$v_i = v_{wake} + v_{vortex}(r,\psi) \tag{6}$$

For a helicopter with conventional swashplate-type control,

$$\theta = \theta_0(r) + \theta_{1s}\sin\psi + \theta_{1c}\cos\psi \tag{7}$$

where the control angles θ_0, θ_{1s} and θ_{1c} are essentially quasistatic when compared to the rotor timescale, $1/\Omega$. If the blade flapping is defined in terms of a Fourier series in blade azimuth,

$$\beta = \beta_0 + \beta_{1s}\sin\psi + \beta_{1c}\cos\psi + \cdots \tag{8}$$

where β_0 is the rotor coning and β_{1s} and β_{1c} respectively define the lateral and longitudinal tilt of the rotor disc, then, to first order accuracy, C_T, β_0, β_{1s} and β_{1c} during the interaction all have the form

$$\begin{aligned} X(\theta, v_i) - X^*(\theta^*, v^*_{wake}) \\ = \quad & (\Delta X)_{controls}(\theta) + (\Delta X)_{wake}(v_{wake}) \\ & + (\Delta X)_{vortex}(v_{vortex}) \end{aligned} \tag{9}$$

In other words, the interaction-induced perturbation to the thrust or flapping is the sum of three terms: a term due to any accompanying perturbations to the controls, a term involving any perturbations which might arise in the structure of the wake during the interaction, and a term due to the vortex-induced flow alone.

Representative values for the vortex-induced contributions to rotor thrust and flapping for a wide range of helicopters can be obtained by considering a rotor with zero hinge offset (so $\omega = 1$) comprised of blades with zero twist and constant chord and aerofoil section along their span. Define the disc-weighted moments of the vortex-induced velocity

$$\begin{aligned} & N(i,j,k) \\ & = \tfrac{1}{2\pi}\int_0^{2\pi}\int_0^1 v_{vortex}(r,\psi) r^i \sin^j\psi \cos^k\psi \, dr\, d\psi \end{aligned} \tag{10}$$

then, for a vortex aligned parallel (||) to the flightpath of the rotor,

$$(\Delta C_T)_{vortex\|} = \frac{-\sigma a}{2}\,\mu\, N(0,1,0) \tag{11}$$

$$(\Delta\beta_0)_{vortex\|} = \frac{-\gamma_\beta}{2}\,\mu\, N(1,1,0) \tag{12}$$

$$(\Delta\beta_{1s})_{vortex\|} = \frac{4\gamma_\beta}{3}\,\frac{\mu^2}{\mu^2+2}\, N(1,1,0) \tag{13}$$

$$(\Delta\beta_{1c})_{vortex\|} = \frac{16}{2-\mu^2}\, N(2,1,0) \tag{14}$$

If the vortex is aligned perpendicular ($\perp$) to the flightpath, then

$$(\Delta C_T)_{vortex\perp} = \frac{-\sigma a}{2}\, N(1,0,0) \tag{15}$$

$$(\Delta\beta_0)_{vortex\perp} = \frac{-\gamma_\beta}{2}\, N(2,0,0) \tag{16}$$

$$\begin{aligned} & (\Delta\beta_{1s})_{vortex\perp} \\ & = \tfrac{4}{3(2+\mu^2)}[\gamma_\beta\mu\, N(1,1,0) - 12\, N(2,0,1)] \end{aligned} \tag{17}$$

$$(\Delta\beta_{1c})_{vortex\perp} = \frac{16}{2-\mu^2}\, N(1,2,0) \tag{18}$$

These results illustrate that certain vortices may induce stronger flapping upsets than loading perturbations, and vice versa. Both types of upset are relevant, since excessive thrust response will lead to large accelerations of the fuselage and could induce damaging loads in the helicopter's transmission and structure, while excessive flapping response might induce mast-bumping or impacts with the rotor's flap-stops, or, in extreme cases, lead to collisions between the rotor blades and the helicopter's fuselage.

If the potential risk posed to helicopter operations by a given vortex is defined, therefore, in terms of both flapping and thrust perturbations during a reference interaction with the vortex (with the controls held fixed), then two characteristics of the vortex velocity profile are relevant and must be matched in simulations which are to be directly comparable. A set of interaction parameters, quantifying the potential severity of interaction with a given vortex, can thus be defined.

The simple theory derived earlier suggests that a suitable scaling for the potential thrust perturbation (per unit increment in forward speed) experienced by a helicopter encountering a parallel vortex is

$$n^{\mu}_{T\parallel} = \frac{a}{2(C^*_T/\sigma)} |N(0,1,0)| \tag{19}$$

The same theory suggests that, for practical values of the rotor Lock number, the scaling factor

$$n_{\beta\parallel} = 8|N(2,1,0)| \tag{20}$$

should provide a measure of the flapping that will be induced by the vortex.

Similarly, the theory suggests that the maximum potential thrust perturbation experienced by a helicopter encountering a perpendicular vortex should not be a function of helicopter forward speed, and should scale by

$$n^0_T\perp = \frac{a}{2(C^*_T/\sigma)} \max \left(|N(1,0,0)| , L \right) \tag{21}$$

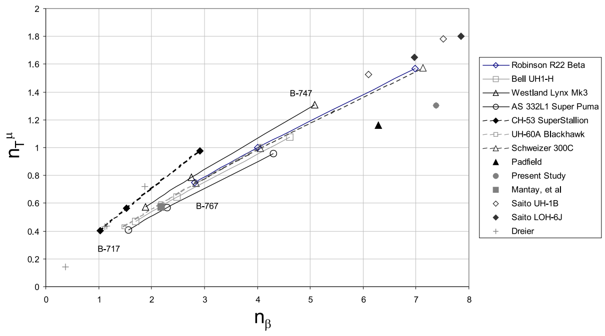
(where $\max(X,x)$ denotes the maximum value of X subject to variation of the parameter x). Finally, the scaling factor

$$n_\beta\perp = 8 \max \left(|N(2,0,1)| , L \right) \tag{22}$$

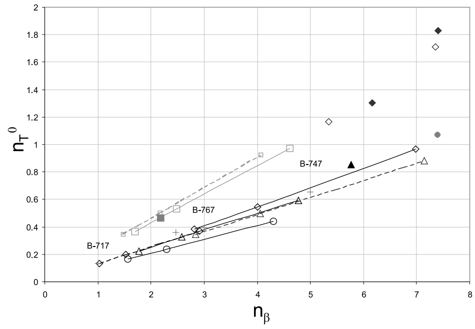
should provide a measure of the maximum flapping that will be experienced by the rotor.

Severity of Interactions

Figure 1 shows the interaction parameters defined in the previous section as evaluated for various published studies. To provide an assessment of the plausibility of the helicopter/vortex combinations selected in these studies, estimates of the interaction parameters for encounters of an assortment of helicopters with the wakes trailed from large aircraft are also plotted. Parameters representative of interactions with the wake trailed 2000 metres behind Boeing 717, 747 and 767 aircraft at cruise speed and maximum takeoff weight are portrayed using the Lamb vortex model employed by Saito (Refs. 7–9). The diffuse scatter of experimental studies exposed by these diagrams is consistent with the somewhat contradictory nature of previous studies and certainly strengthens the case for a more systematic approach to the problem. It is important to note that the single experimental point, (Refs. 2–4), represents a very much weaker interaction than might be experienced by current helicopter types, and indicates a pressing need for more relevant experimental data.



(a)



(b)

Figure 1: *Measures of Helicopter - Vortex Interaction Severity for Existing Studies: (a) Parallel Interaction (b) Perpendicular Interaction.*

Effect of Modelling Assumptions

An important additional element to successful reconciliation of past predictions would be the exposure of any numerical model-dependency in the calculations. The remainder of this paper demonstrates the very real possibility that, under certain conditions, over-simplified physical modelling of the rotor-vortex system may indeed lead to strongly model-dependent results.

To quantify the effect of some common modelling assumptions, we focus on the two reference interactions defined earlier, and compare the predictions of a hierarchy of computational models in which the aerodynamics of the rotor wake and the interacting vortex are modelled with increasing physical realism.

Rotor Model

In the work presented here, the rotor is modelled as a set of dynamically-independent rigid blades connected to a fully articulated rotor hub, and the motions of the blades are calculated via the Lagrangian of the system. Once the blade mass distribution has been established, the displacement and velocity of any point on the rotor, and hence the kinetic and potential energies and the rate of energy dissipation in the system, can be expressed in terms of a set of generalised coordinates and their time derivatives. The Euler equations relating the rate of change of the generalized coordinates to the derivatives of these energy terms and the forcing provided by the aerodynamic loading on the rotor are then integrated numerically to obtain the rotor's response.

The aerodynamic loading on each blade is determined using a discrete implementation of unsteady lifting-line theory at a series of collocation points along the length of the blade. Quasistatic lift generation on the blades is modelled using an arbitrarily-prescribed variation of sectional lift coefficient with angle of attack, while unsteady effects are modelled by appropriate feedback of the influence of the shed and trailed vorticity distribution behind each blade.

The rotor model, described above, embodies significant aerodynamic enhancements over the idealised helicopter rotor defined earlier: blade element theory fails to predict spanwise interactions along the blades, and nonlinear aerodynamic effects can be incorporated by using a suitable definition of $C_L(\alpha)$. By suppressing any acceleration of the rotor hub, we can focus purely on the response of the rotor itself to the interaction with the vortex and prevent any obscuring of the response by the contributions of the rotor fuselage and any of the other degrees of freedom of the full helicopter system.

Wake and Vortex Models

Two fundamentally different approaches to modelling the vortex-induced velocity field experienced by the rotor during interactions have traditionally been used. The first approach represents the effect of the rotor wake and interacting vortex by a velocity distribution normal to the rotor disc following the form of Equation 6. This inflow-based approach is fundamentally incapable of representing details of the vortex interaction which arise in the flow surrounding the helicopter. The second, more realistic, approach is to determine the dynamics of the entire flow in which the rotor is immersed using a suitable set of evolution equations for the fluid. Such a flow-based approach is capable of resolving the effects on the rotor's behaviour of any flow structures which might arise from the coupled dynamics of both the interacting vortex and the rotor wake itself.

In all cases presented here, the vortex is represented as a three-dimensional distribution of vorticity or velocity in space. The approach used almost exclusively in previous studies is to adopt a 'frozen vortex' assumption where the interacting vortex is represented as a spatial distribution of vorticity or velocity which is time invariant in the frame of reference attached to the vortex. The flow-based approach allows the implications of this assumption to be explored, and, in this paper, results obtained using the frozen vortex assumption are compared with calculations where the vortex has been allowed to deform in response to interaction with the helicopter-induced flowfield.

Inflow-Type Models

Results for two variants of our computational model using inflow-type representations of the rotor wake will be presented. Variant Glauert explores the consequences of adopting a simple time-invariant Glauert representation of the inflow through the rotor (Ref. 17). Apart from the enhancements induced by its more sophisticated rotor model, Glauert should thus be expected to provide results for the rotor thrust and flapping response closest to the expressions derived earlier using blade-element theory.

Variant DI, on the other hand, explores the consequences of allowing the inflow distribution on the rotor to respond to any changes in its loading that might be induced by interactions with a vortex. This is performed by adopting the commonly-used Pitt and Peters three-mode Dynamic Inflow Model (Ref. 18).

Flow-Type Model

A straightforward way to construct a flow-based model for the rotor aerodynamic environment is to represent the rotor wake as a time-dependent vorticity distribution in the region of space surrounding the rotor. If v is the flow velocity then the associated vorticity distribution $\omega = \nabla \times v$ evolves according to the unsteady vorticity transport equation

$$\frac{\partial}{\partial t}\omega + v \cdot \nabla\omega - \omega \cdot \nabla v = S \qquad (23)$$

This equation, derived from the incompressible Navier-Stokes equation in the limit of zero viscosity, shows the rotor wake to arise as a vorticity source S associated with the generation of aerodynamic loads on the rotor blades. The differential form

$$\nabla^2 v = -\nabla \times \omega \qquad (24)$$

of the Biot-Savart relationship relates the velocity at any point near the rotor to the vorticity distribution in the flow and hence permits the rotor wake to feed back into the aerodynamic loading, and thus the dynamics, of the rotor.

The Vorticity Transport Model (VTM) developed by Brown (Refs. 19, 20) employs a direct computational solution of Equation 23 to simulate the evolution of the wake of the helicopter. The model faithfully represents blade-wake interactions and the wake-wake interactions that lead to the growth, coalescence and rupture of vortical structures in the rotor wake. The VTM is coupled into the dynamic simulation of the rotor by using the loads generated by the rotor's aerodynamic model to construct S in terms of the shed and trailed vorticity from the rotor blades. After casting the equations on a structured grid surrounding the rotor, Equation 24 is solved by cyclic reduction (Ref. 21), while Equation 23 is marched through time using Toro's Weighted Average Flux algorithm (Ref. 22).

Results for two versions of our computational model using the VTM will be presented. In variant VTM (Frozen Vortex), the vortex-induced velocity distribution throughout the fluid surrounding the rotor is used to drive the evolution of the rotor wake though the velocity field v of the flow surrounding the rotor. This model, therefore, has greater fidelity than the inflow models and provides the most complete representation of the vortex-induced evolution of the rotor wake which is still compatible with the frozen vortex assumption.

Variant VTM (Free Vortex) is the most physically-representative model of the helicopter-vortex interaction. The frozen vortex assumption is eliminated and the interacting vortex is allowed to convect under the action of both its self-induced velocity field and the rotor wake-induced contributions to the velocity field v. It should be noted, however, that although of great practical interest, any relaxation of the frozen vortex assumption must result in a significant deviation of the calculation from the reference interaction scenarios used to underpin all the other cases presented in this paper.

Comparative Computations

The rotor and vortex used throughout this study are geometrically and dynamically similar to those used by Dreier in his 1977 numerical study (Ref. 5). Dreier's sectional aerodynamic model, however, is replaced with an empirical correlation which gives a closer match to published NACA 0012 data over the full 360^0 angle of attack regime (Ref. 23). The interacting vortex has the following radially-symmetric velocity distribution (Refs. 5, 6):

$$v_{vortex}/v_c = 1.359\, r/r_c \quad \text{if} \quad 0.0 \le \frac{r}{r_c} \le 0.60653$$

$$v_{vortex}/v_c = \frac{1+\ln(r/r_c)}{r/r_c} \quad \text{if} \quad \frac{r}{r_c} > 0.60653 \qquad (25)$$

All results are presented for a vortex with $r_c = 0.4484$ and $v_c = 0.0857$. As shown in Figure 1, the calculated severity of an encounter with this vortex is relatively high, but still realistic, when compared to the vortices used in previously-published numerical studies.

For each test case a set of rotor control angles is first obtained by trimming the rotor (in the absence of the vortex) to a thrust coefficient $C_T^* = 0.00449$ with zero cyclic flapping with respect to the hub axis. With the control angles locked at their trim settings, the rotor is then exposed to the vortex and its flapping and thrust response are measured. Comparative results are presented for advance ratios between zero and 0.35, and for vortices rotating in both positive (producing a down-flow on the advancing side of the rotor during a parallel interaction, or, initially, a down-wash on the rotor during a perpendicular interaction) and negative senses.

Parallel Interaction

The perturbations to the rotor thrust and disc-tilt predicted by the various numerical approaches are presented in Figure 2. The coning response of the rotor has not been plotted, as its features are virtually identical to those exhibited by the thrust response of the rotor. The thrust and longitudinal tilt-responses of the rotor, generated by the inflow models, differ little from the predictions of blade element theory, and, indeed, the predicted data are relatively insensitive to the approach used to generate them. Two details of the predicted thrust response are noteworthy, though. The vertical offset in the thrust perturbation relative to the

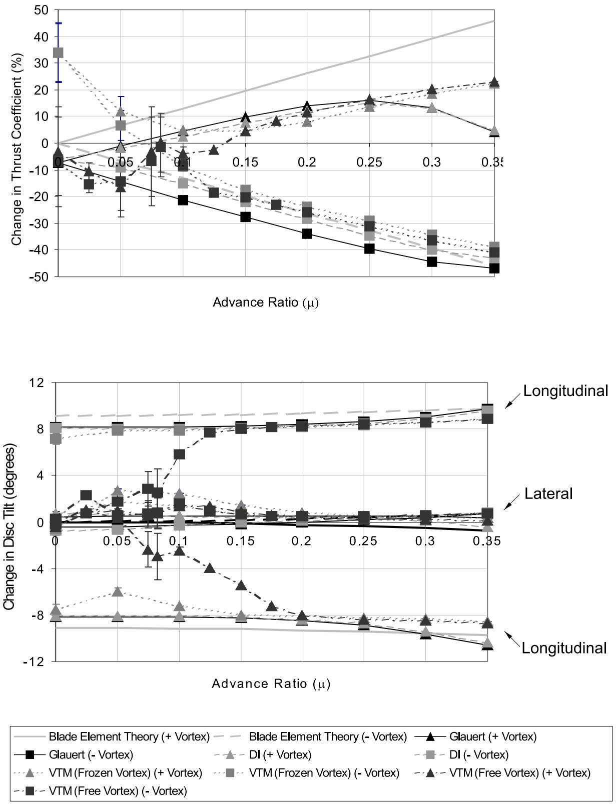


Figure 2: *Perturbations to Rotor Trim States in Response to a Parallel Vortex Interaction.*

predictions of blade element theory is a consequence of negative curvature of the $C_L(\alpha)$ variation in the attached flow regime while the softening of the gradient at high advance ratio, peculiar to interaction with a positive vortex, can be traced to a increasing loss of lift on the most outboard part of the advancing side of the rotor. Since this effect does not carry through to the predictions of the VTM-based models, it appears that this feature is a consequence of the overconstrained lateral inflow variation associated with the inflow type models used in this study. The same effect is present in the longitudinal flapping, but deviations from theory are reduced because the influence of the wake-induced velocity on the longitudinal flapping is much less significant than the relatively strong lateral distribution of normal velocity created by a vortex aligned parallel to the rotor flightpath.

An interesting feature of the predictions of both VTM (Frozen Vortex) and VTM (Free Vortex) is that, at low forward speed, the rotor no longer settles to a steady state following the encounter with the vortex. The emergence of this additional dynamic in the more complete physical models marks a significant departure from the static response predicted by the inflow-type approaches. The long-period fluctuations in the response of the rotor, particularly as seen in the predictions of VTM (Frozen Vortex) at low forward speed, can be traced back to re-ingestion of the rotor wake as it is cyclically convected by the velocity field of the interacting vortex (see the left part of Figure 3b, representing a snapshot of a blob of wake vorticity about

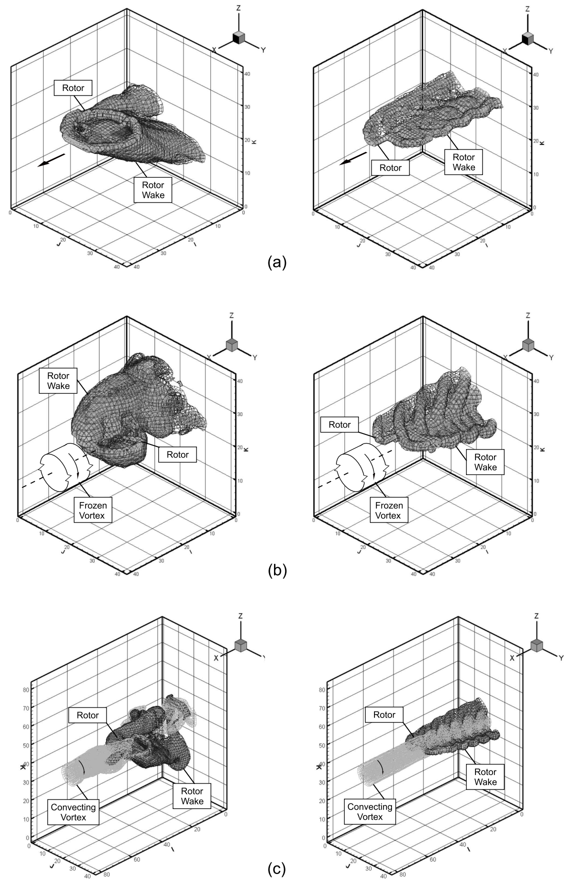


Figure 3: *Wake Morphology at μ=0.05 (left) and μ=0.35 (right) (a) In Trimmed Flight. (b) Frozen Vortex (c) Free Vortex. Vortex has positive sense of rotation.*

to be re-ingested by the rotor). This time-dependency cannot be captured by inflow-type approaches as it is crucially dependent on the details of the off-rotor flow. To show how these fluctuations depend on the advance ratio of the rotor, bars have been attached to the data of Figure 2 to represent the amplitude of any fluctuations which persist after filtering out variations at greater than blade-passing frequency.

The VTM (Frozen Vortex) model predicts the unsteadiness in the rotor response to persist for all advance ratios below about 0.10, while the VTM (Free Vortex) variant predicts unsteadiness to exist only between advance ratios of about 0.02 to 0.10. The existence of unsteadiness in the thrust perturbations predicted by variant VTM (Frozen Vortex) turns out to be a consequence of overconstraining the interacting vortex by imposing the frozen vortex assumption. If this assumption is relaxed and the vortex is allowed to convect freely then, as the advance ratio of the rotor is reduced, the vortex is increasingly intertwined with the rotor wake and then displaced as the rotor passes by. The middle and lower plots of Figure 3 illustrate the impact of the frozen vortex assumption on the predicted morphology of the rotor wake and the interacting vortex when compared to the trimmed rotor wakes in the top two plots. The validity of the frozen vortex assumption is preserved at high advance ratios because the rotor wake-induced deformation is a less significant contributor to the dynamics of the interacting vortex than convection by the free-stream velocity component. Since at higher advance ratios the wake-induced velocity also becomes a less significant contributor to the blade aerodynamics than the free-stream velocity, Figure 2 shows the expected result that, at high forward speeds, both VTM (Frozen Vortex) and VTM (Free Vortex) provide predictions which vary only slightly from those of the simpler inflow-type models.

At advance ratios less than about 0.02 the free-vortex approach shows the interacting vortex to be displaced so far from the rotor plane that the mixing of vorticity from the rotor wake and interacting vortex takes place downstream of the rotor where its effects on the dynamics of the system are relatively weak. The crucial importance of including the rotor wake-induced displacement of the interacting vortex in any simulation of the dynamics of the rotor system following a low-speed vortex interaction should be particularly apparent from the response, predicted by variant VTM (Free Vortex), of the longitudinal flapping of the rotor to interaction with the vortex. The important inference from this particular figure is that, at low speed, use of the frozen vortex assumption may lead to significant overprediction of the rotor response, particularly in terms of rotor flapping, to a vortex interaction.

Perpendicular Interaction

The perturbations to the rotor thrust and disc-tilt induced during a perpendicular interaction are presented in Figure 4. The open symbols represent the maximum perturbation associated with the downwash side of the vortex, whereas the solid symbols represent the maximum upwash-induced perturbation. Similarly to the parallel case, the coning has not been plotted, as its features are very similar to those exhibited by the thrust response.

The magnitudes of the perturbations, except for the longitudinal tilt, are noticeably larger than those for the parallel interactions. The predicted response of the rotor to the induced downwash of the vortices differs little from the predictions of quasi-steady blade element theory, and is fairly insensitive to the approach used to generate it. The upwash-related responses are, however, sensitive to the modelling approach used, and the large differences between the theoretical perturbations and the numerical ones can be traced to a loss of lift on the region of the rotor exposed to the vortex induced upwash. Time delay effects are also prevalent in the rotor response, and are particularly evident in the lateral disc tilt. As the forward speed of the rotor is increased and hence the total interaction time with the vortex is reduced, the flapping response of the rotor falls well below the values predicted by the quasi-static theory derived earlier.

Like with the parallel interaction, the frozen vortex assumption and the modelling techniques used have a large effect on the nature of the response. Figure 5 shows the evolution of the thrust and lateral tilt perturbations, filtered to remove harmonics at higher than 1/rev, as a function of

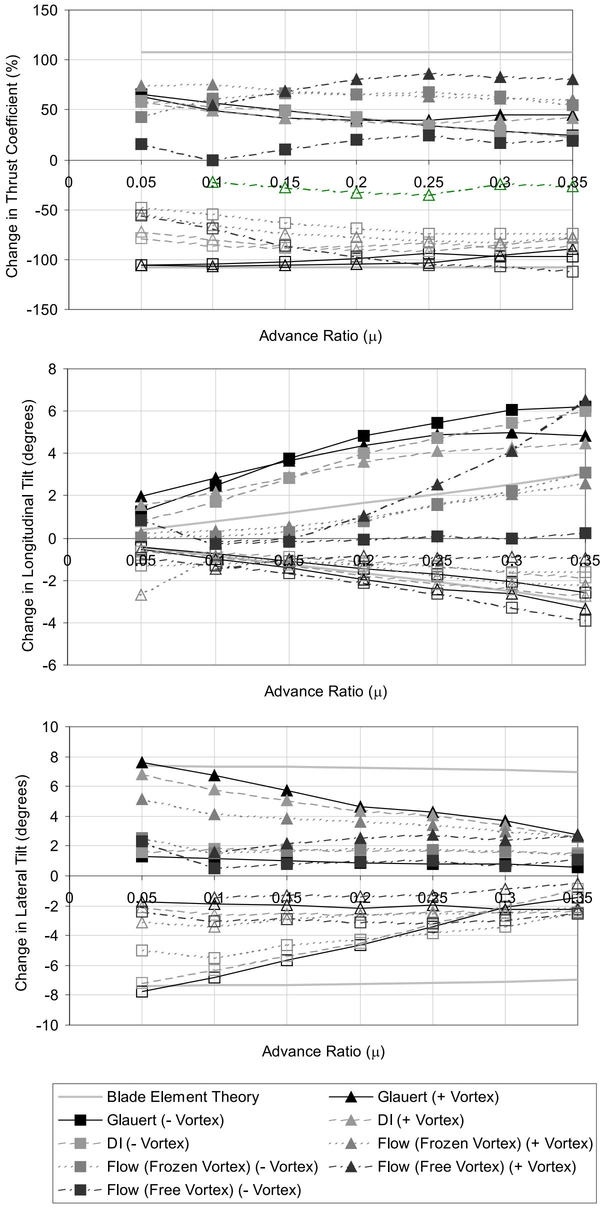


Figure 4: *Perturbations to Rotor Trim States in Response to a Perpendicular Vortex Interaction.*

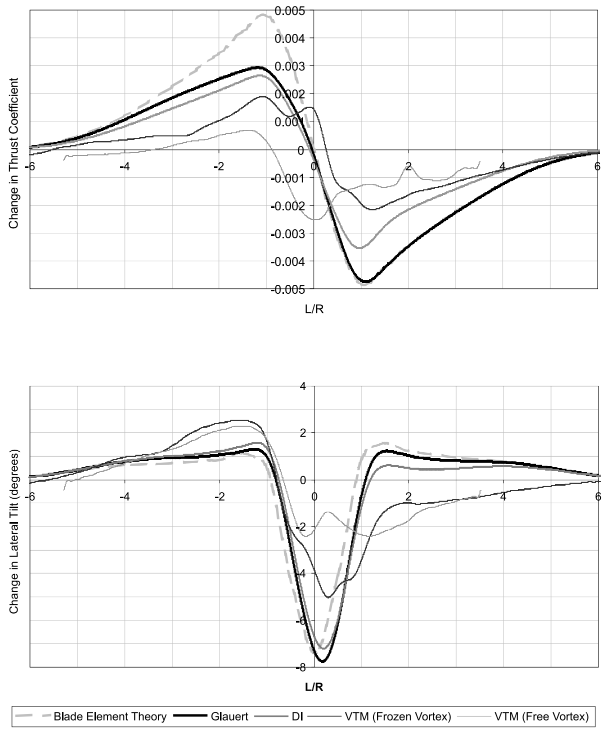


Figure 5: *Thrust and Lateral Tilt Response to a Perpendicular Vortex for* $\mu = 0.05$.

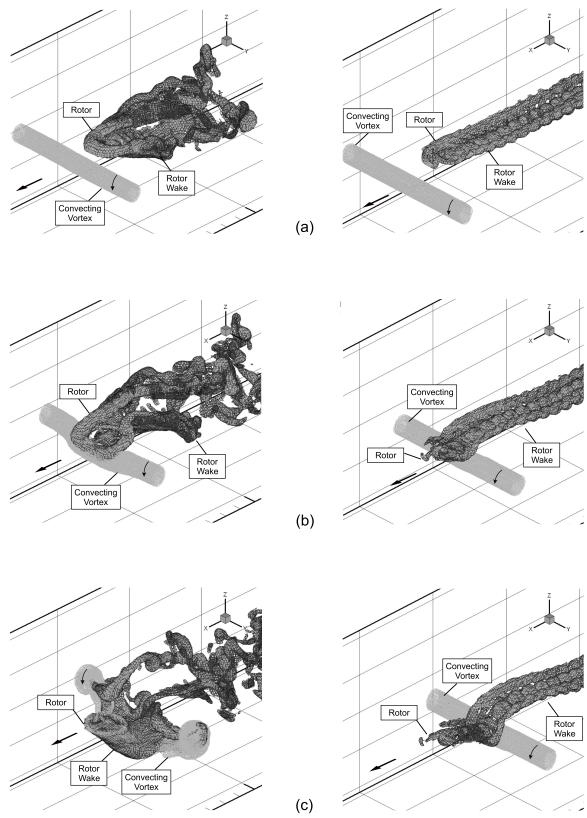


Figure 6: *Wake Morphology at μ=0.05 (left) and μ=0.35 (right) (a) Before Interaction (b) During Interaction (c) After Interaction. Vortex has negative sense of rotation.*

the distance from the vortex centre to the rotor hub, predicted by the various models for an advance ratio of 0.05. The dramatic differences in the shape of the response predicted by the VTM-based models should be noted: the large reduction in the predicted strength of the interaction compared to the simpler models is associated, once again, with the changes in wake structure and the distortion and displacement of the vortex that these models predict to take place during the interaction between the rotor and the vortex. Figure 6 shows the evolution of the rotor wake and the freely-convecting vortex during perpendicular interactions at two forward speeds. As in the case of the parallel interaction, if the frozen vortex assumption is relaxed and the forward speed is reduced, the VTM-based method shows the vortex to be increasingly intertwined in the wake and displaced by the rotor as it passes by.

These results, like those for the parallel response, suggest that helicopters may possess an obvious advantage over conventional aircraft by being able to limit the severity of their encounters with aircraft wakes simply by reducing forward speed while traversing a volume of space (e.g. an airfield's Terminal Control Area) which is known to be contaminated by aircraft trailing vortices.

Conclusions

The principal aim of this paper has been to provide a systematic and hierarchical investigation into the effects of various traditional modelling assumptions regarding the treatment of the interacting vortex and the helicopter's own wake on the predicted severity of helicopter-wake interactions, at least for a limited class of all possible interaction scenarios, and hence to provide evidence from which it may be possible to reach an objective assessment of the level of physical realism that must be embodied in any practically pertinent computational simulation of a helicopter-wake interaction.

The results presented here suggest that at high forward speeds, a relatively simplistic approach to the modelling of the wake and vortex dynamics is largely adequate for describing the rotor response during the simple vortex interactions analysed in this paper. It is unlikely that this conclusion extends to more general interactions, however, since, even for these simple interactions, at low forward speeds, oversimplified modelling of the rotor wake and the dynamics of the interacting vortex (in particular the adoption of the frozen vortex assumption) misrepresents the dynamic character of the interaction.

Most importantly from an operational point of view, oversimplification of the rotor wake and vortex dynamics in simulations of a helicopter encountering an aircraft's wake, particularly at the low advance ratios most relevant to operations near airports, may lead to significant overprediction of the helicopter's response to encounters with the wakes of any aircraft which might be operating nearby.

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