Modelling a helicopter rotor's response to wake encounters

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ABSTRACT

In recent years, various strategies for the concurrent operation of fixed- and rotary-wing aircraft have been proposed as a means of increasing airport capacity. Some of these strategies will increase the likelihood of encounters with the wakes of aircraft operating nearby. Several studies now exist where numerical simulations have been used to assess the impact of encounters with the wakes of large transport aircraft on the safety of helicopter operations under such conditions. This paper contrasts the predictions of several commonly-used numerical simulation techniques when each is used to model the dynamics of a helicopter rotor during the same idealised wake encounter. In most previous studies the mutually-induced distortion of the wakes of the rotor and the interacting aircraft has been neglected, yielding the so-called 'frozen vortex' assumption. This assumption is shown to be valid only when the helicopter encounters the aircraft wake at high forward speed. At the low forward speeds most relevant to near-airfield operations, however, injudicious use of the frozen vortex assumption may lead to significant errors in predicting the severity of a helicopter's response to a wake encounter.

NOMENCLATURE

a	aerofoil lift-curve slope
A	rotor disc area πR^2
c	blade chord scaled by R
C_L	blade section lift coefficient
C_T	rotor thrust, scaled by $\rho A(\Omega R)^2$
I_β	blade flapping inertia, scaled by $\rho A R^3$
L	distance from the vortex core to the rotor hub
N	number of rotor blades
r	radial coordinate, scaled by R
r_c	vortex core radius, scaled by R
R	rotor radius
S	vorticity source, scaled by $\Omega^2 R^2$
t	time, scaled by $1/\Omega$
v	velocity of flow surrounding rotor, scaled by ΩR
v_c	velocity at periphery of vortex core, scaled by ΩR
v_i	velocity normal to rotor disc, scaled by ΩR
v_P	velocity parallel to blade section, scaled by ΩR
v_T	velocity normal to blade section, scaled by ΩR
v_{vortex}	vortex-induced velocity field, scaled by ΩR
v_{wake}	wake-induced velocity field, scaled by ΩR
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	blade feathering angle
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	vorticity of flow surrounding rotor, scaled by ΩR^2
ω	blade flapping frequency, scaled by Ω
Ω	rotor rotational speed

1.0 INTRODUCTION

Innovative exploitation of the runway-independent nature of helicopter operations has been proposed as a means of maximizing the use of ground- and air-space at airfields[1] and thus of increasing

Paper No. 2818. Manuscript received 4 December 2002, revised version received 1 March 2003, accepted 21 May 2003.

https://doi.org/10.1017/S0001924000004954 Published online by Cambridge University Press

airport capacity. Placement of helicopter final approach and takeoff areas close to active runways increases the likelihood, though, that helicopter operations might be disrupted by encounters with the wakes of other aircraft operating nearby.

A fair degree of effort has been devoted to understanding the dynamic behaviour of a helicopter during an interaction with the wake generated by a large fixed-wing aircraft. The aim of most previous studies has been to quantify the effect of wake encounters on the safety of rotorcraft operations, but not all of these studies have yielded results that are directly relevant to the near-airfield operational environment. In their 1976 experimental studies flying a Bell UH-1H parallel to the wake of a Douglas C-54 Skymaster, Mantay *et al*[2-4] provided the first objective assessment of the severity of an encounter between a helicopter and the wake of a large transport aircraft. They concluded that the maximum load factor of 1·8g experienced during an interaction with the C-54 wake (at least for following distances greater than 0·42nm) was well within the helicopter's safe operating limits. This single set of experiments precipitated a series of numerical studies that broadly supported its conclusions. The resulting perception of wake encounters as having a benign effect on the safety of helicopter operations led to a decline in interest in the field in the late 1980s. These early studies were largely concerned, however, with the response of the helicopter to wake encounters in free air. It was not until the more recent studies by Padfield and Turner[5-8], where the severity of a wake encounter was judged in terms of its impact on aircraft handling qualities, that the effect of the operating environment of the helicopter could be acknowledged in any objective manner. Their observation that loading perturbations of the magnitude observed in the earlier experimental and computational works might pose significant piloting problems under terminal flight conditions, together with the increasing urgency of the airfield capacity problem, has sparked a resurgence of interest in the field.

The earliest numerical study appears to have been conducted by Dreier[9] in 1977. He modelled the helicopter as an isolated, articulated rotor with linear blade aerodynamics (up to the stall) and rigid blades. A uniform inflow distribution on the rotor was determined from trim conditions then held constant throughout the simulation. Interaction with another aircraft's wake was modelled by superimposing on the rotor a velocity field designed to represent a vortex with McCormick *et al*'s[10] logarithmic velocity distribution lying parallel to the rotor's flightpath. This velocity field was also held invariant throughout the simulated interaction. Dreier's study succeeded in reproducing, both in magnitude and trend, the fundamental flapping and loading response of the helicopter rotor expected from a simple blade-element based theory. This was despite some anomalies which he attributed to the post-stall behaviour of his blade aerodynamic model.

Saito and co-authors[11-13] provided a significant advance in modelling fidelity by using Azuma's[14] local momentum theory to allow quasistatic coupling between the local rotor aerodynamic loading and the induced flow through the rotor. The wake of the interacting aircraft was modelled by a time-invariant two-dimensional velocity field, through which the helicopter could be flown. The resultant loads on the rotor hub were coupled into a six degree of freedom dynamic model for the helicopter fuselage, allowing the effects of a wake encounter on the helicopter's flightpath and rigid-body rotation rates to be modelled. In general, a fixed-wing aircraft responds to a vortex encounter by rotating about an axis which is parallel to the vortex, while a helicopter's rotational response takes place primarily about an axis which is oriented at 90° to the incident vortex. Saito's works illustrated these major differences in the behaviour of fixed-wing aircraft and helicopters in response to a wake encounter, and also investigated the variations in pitch-roll cross-coupling found between helicopters with articulated or hingeless rotor hub designs.

A further advance in aerodynamic modelling fidelity was provided by Kim, Bir and Chopra[15] who used Peters' three-state Dynamic Inflow Model[16] to incorporate the effects of time lags in the development of the induced flow in response to the rotor aerodynamic loading. The yaw mode was suppressed in their fuselage dynamic model but blade aeroelastic effects were incorporated in fuller form than in previous works using elastic beam theory. Modelling of the interacting wake, using Burnham's[17] 1982 experimental data for a Boeing 747, followed a similar strategy to that adopted by Saito. The resultant model was used to refine the distinction between the behaviour of helicopters with teetering, articulated and hingeless rotors exposed by Saito's earlier work.

Using a similar simulation technique, Curtiss and Zhou[18] obtained results which generally supported Mantay's experimental conclusions regarding the loading induced on a helicopter during a vortex interaction. They pointed out, however, that any pilot has a tendency to suppress, subconsciously, certain dynamics of the airframe. Their suggestion that a flight simulator be coupled to their code to study the pilot-induced damping of the helicopter's response underpins the recent resurgence of interest in the subject led by Padfield and Turner[5-8]. Their approach of assessing the helicopter's response to a vortex interaction by analogy with the ADS-33 standard for rotorcraft handling qualities has made significant progress towards defining a practical method for evaluating the operational significance of wake encounters.

Unfortunately, the wide variation in modelling techniques employed in the various published studies and the absence, in most cases, of any systematic variation in model parameters has made it difficult to organise the literature into a mutually-consistent body of evidence from which any general conclusions regarding the safety implications of helicopter encounters with aircraft wakes can be inferred. The situation is compounded by a singular lack of data against which these computations can be validated, and thus the possibility of model-dependence in some of the published results cannot be excluded. In particular, in most previous studies the mutually-induced distortion of the wakes of the rotor and the interacting aircraft has been neglected, yielding the so-called 'frozen vortex' assumption. This assumption has generally been adopted as a matter of computational expediency, but where the wakes interact over relatively long timescales, its validity must be called into question. Such is the case when the helicopter is operating at the low forward speeds that are characteristic of terminal flight operations.

In this paper, the properties of several of the key aerodynamic modelling techniques used in previous studies are contrasted. This is done by using each technique in turn to simulate the helicopter's dynamic response during the same idealised wake interaction scenario.

The results of this comparison suggest that a certain amount of faith can indeed be placed in the results of previous studies of wake interactions, if care is taken not to extrapolate these results too far from the high-speed, free-flight conditions under which the simulations were originally conducted. In the context of near-airfield operations where the helicopter is generally operating at much lower forward speed than in free air, the results presented here suggest, however, that these same techniques may be too simple to capture the full range of physics inherent in the interaction.

2.0 IDEALISED WAKE ENCOUNTER

Results for two simple, idealised interactions will be presented. In both cases the wake of the interacting aircraft is represented as an isolated vortex of known axisymmetric core structure lying in the flightpath of the helicopter. The helicopter is idealised as an isolated rotor, composed of rigid blades which are free to flap and lag about an articulated hub. The hub itself is constrained, though, to follow a prescribed, non-accelerating trajectory through space. Similarly, the controls of the rotor are held fixed throughout the interaction. This paper will concentrate on the numerical issues involved in simulating wake encounters by using this highly idealised interaction to isolate the influence of the rotor and its aerodynamics on the behaviour of the helicopter.

https://doi.org/10.1017/S0001924000004954 Published online by Cambridge University Press

The constraints imposed on the form of the interaction by these simplifications should not pose too much of an impediment to broader, and more operationally-relevant, interpretation of these simulations, however. During a wake interaction, the pilot of the helicopter can behave in a variety of ways. At one extreme, the controls can be held fixed, allowing the thrust and flapping response of the rotor to translate directly into acceleration of the vehicle - and thus, possibly, into uncommanded deviations from its intended flightpath. At the other extreme, the controls can be moved in some fashion to compensate for the perturbations to the thrust and flapping induced on the rotor during the interaction — with clear bearing on the handling qualities attributed to the vehicle. A broad characterisation of the implications of a vortex encounter expressed in operational terms such as these can usually be inferred from an understanding of the isolated behaviour of the helicopter's rotor.

In the first idealised interaction, called here the 'parallel interaction', the vortex axis is coincident (at least initially, in the more complete simulations) with the trajectory of the rotor hub. The most interesting feature of this type of interaction is that the simpler aerodynamic models predict the rotor response to be quasistatic. The dynamic features of this type of interaction are only exposed by those aerodynamic models in which the frozen vortex assumption has been relaxed. In the second example used in this paper (the 'perpendicular interaction') the vortex axis initially lies in the plane of the rotor but is oriented to be perpendicular to the hub's trajectory. Since the flowfield induced by the vortex on the rotor is time-varying in this situation, this type of interaction excites more directly any time dependencies inherent in the aerodynamic model for the rotor.

2.1 Analytic results

This highly-constrained idealisation of the wake encounter allows a set of simple analytic results for the rotor's response to be derived. The advantage of this approach is that, in the absence of independent validation data, these analytic results can be used to underpin the predictions of the more sophisticated numerical methods presented in this paper.

Linearised blade element theory[19] gives the thrust generated by a radial element on one of the blades of the rotor, located at distance r from the rotor hub, as

$$\mathrm{d}C_T = \frac{ca}{2\pi}(\theta v_P^2 - \mathrm{v}_P \mathrm{v}_T)\mathrm{d}r \qquad \ldots (1)$$

If the induced velocity parallel to the plane of the rotor is neglected, then 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,

$$\mathrm{v}_P = r + \mu \mathrm{Sin}\,\psi \qquad \ldots (2)$$

and

$$\mathrm{v}_T = \mathrm{v}_i + \beta\mu \mathrm{Cos}\,\psi + r\frac{\mathrm{d}\beta}{\mathrm{d}\psi} \qquad \ldots (3)$$

The induced flow through the rotor can, of course, be decomposed into a component induced by the rotor wake and a component induced by the interacting vortex:

$$\mathrm{v}_i = \mathrm{v}_{wake} + \mathrm{v}_{vortex} \qquad \ldots (4)$$

The overall thrust generated by the rotor is

$$C_T = N\int_0^1 \mathrm{d}C_T \qquad \ldots (5)$$

and, if the rotor hub is not free to accelerate, the small-amplitude flapping response of the blade is a solution to[19]

$$\frac{\mathrm{d}^2\beta}{\mathrm{d}\psi^2} + \omega^2\beta = \frac{1}{I_\beta}\int_0^1 r\mathrm{d}C_T \qquad \ldots (6)$$

If the blade feathering angle θ is kept constant throughout the interaction by holding the controls fixed, and the blade flapping is defined in terms of a Fourier series in blade azimuth,

$$\beta = \beta_0 + \beta_{1s}\mathrm{Sin}\psi + \beta_{1c}\mathrm{Cos}\psi + \ldots \qquad \ldots (7)$$

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 analytic results for the rotor's response during both the parallel and perpendicular interactions follow very simply from simultaneous solution of Equations (5) and (6). The following results apply to the simplified situation of a rotor with zero hinge offset (so ω = 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

$$M^i_{j,k} = \frac{1}{2\pi}\int_0^{2\pi}\int_0^1 v_{vortex}(r,\psi) r^i \mathrm{Sin}^j\psi \mathrm{Cos}^k\psi \mathrm{d}r\mathrm{d}\psi \qquad \ldots (8)$$

Then, for the parallel interaction, the perturbations to the thrust and flapping induced by the velocity field v_{vortex} during the encounter are

$$\Delta C_T = \frac{-\sigma a}{2}\mu M^0_{1,0} \qquad \ldots (9)$$

$$\Delta\beta_0 = \frac{-\gamma_\beta}{2}\mu M^1_{1,0} \qquad \ldots (10)$$

$$\Delta\beta_{1s} = \frac{4\gamma_\beta}{3}\frac{\mu^2}{\mu^2+2}M^1_{1,0} \qquad \ldots (11)$$

$$\Delta\beta_{1c} = \frac{16}{2-\mu^2}M^2_{1,0} \qquad \ldots (12)$$

An additional perturbation to the thrust and flapping arises, of course, from changes in v_{wake} during the course of the interaction.

Similarly, for the perpendicular interaction, the vortex-induced perturbations to the rotor's thrust and flapping are

$$\Delta C_T = \frac{-\sigma a}{2}M^1_{0,0} \qquad \ldots (13)$$

$$\Delta\beta_0 = \frac{-\gamma_\beta}{2}M^2_{0,0} \qquad \ldots (14)$$

$$\Delta\beta_{1s} = \frac{4}{3(2+\mu^2)}\left[\gamma_\beta\mu M^2_{0,0} - 12M^2_{0,1}\right] \qquad \ldots (15)$$

$$\Delta\beta_{1c} = \frac{16\mu}{2-\mu^2}M^1_{2,0} \qquad \ldots (16)$$

This final set of results assumes that the rotor flapping response is rapid compared to the speed with which the rotor traverses across the vortex.

3.0 NUMERICAL ROTOR MODEL

The same rotor aeromechanical model is used in each of the numerical simulations presented in this paper. This model differs, however, from the analytic model of the previous section by virtue of its nonlinear sectional aerodynamics and by its representation of the

https://doi.org/10.1017/S0001924000004954 Published online by Cambridge University Press

coupled flap-lag motion of the blades. These enhancements are necessary for stability of the numerical rotor model, but their introduction does have an observeable effect on the outcome of simulations. These effects must be accounted for in comparisons of the outputs of the analytic and computational models. All calculations presented here are for an anticlockwise-rotating rotor with three blades, a solidity of 0·05, and a Lock number of approximately 4·8. The blades are assumed to be rigid, and to be connected to a fully-articulated (but non-accelerating) rotor hub with a collocated flap/lag hinge offset by 0·056R from the rotor axis. The motions of the blades are calculated by numerical reconstruction of the non-linear Lagrangian of the system, but, for small flapping angles, the approach reproduces very closely the solutions of Equation (6). 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. A variation of sectional lift coefficient with angle of attack given by the empirical correlation

$$C_L(\alpha) = (1 + 0\cdot9325(1+\mathrm{Cos}\alpha)e^{-1108\cdot8|\mathrm{Tan}(\alpha/2)|^{4\cdot9222}})\mathrm{Sin}2\alpha \qquad \ldots (17)$$

is used throughout, giving a close match to published NACA 0012 data[20] in both attached and separated flow regimes.

4.0 NUMERICAL VORTEX MODEL

In all calculations presented here the interacting vortex has the following radially-symmetric velocity distribution[9,10]:

$$v_{vortex}/v_c = 1\cdot359 r/r_c \quad \text{if} \quad 0\cdot0 \le \frac{r}{r_c} \le 0\cdot60653$$
$$v_{vortex}/v_c = \frac{1+\ln(r/r_c)}{r/r_c} \quad \text{if} \quad 0\cdot60653 < \frac{r}{r_c} \qquad \ldots (18)$$

All results are presented for a vortex with r_c = 0·4484 and v_c = 0·0857. This yields a relatively strong interaction — of roughly the same strength, for instance, as would be felt by a Sikorsky S-76 or similar medium transport helicopter flying directly through the core of a tip vortex in the wake 2,000m behind a Boeing 747 aircraft [21].

The interacting vortex is represented in the numerical models as a three-dimensional distribution of vorticity or velocity in space.

The approach used almost exclusively in previous studies is to adopt the '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. A primary component of this work is to compare results obtained using the frozen vortex assumption with calculations where the vortex has been allowed to deform in response to interaction with the rotor-induced flowfield.

5.0 NUMERICAL WAKE MODELS

Two fundamentally different approaches to modelling the rotor-induced flow-field are possible. The first approach represents the induced flow as a velocity distribution defined only on the rotor disc, for example following the form of Equation (4). Variants of this approach have been used in all the previous works cited in the introduction to this paper. This inflow-based approach is, by definition, fundamentally incapable of representing any details of the vortex interaction which arise in the dynamics of the flow field away from the rotor disc and thus mandates implementation of the frozen vortex assumption. If the frozen vortex assumption is to be eliminated, then the dynamics of the entire flow in which the rotor is immersed must be modelled. Such a flow-based approach would then, at least in principle, be capable of resolving the effects on the rotor's behaviour of any flow structures which might arise from the coupled dynamics of the interacting vortex and the rotor-induced flow-field.

5.1 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, uniform inflow distribution on the rotor disc. The variation of the inflow with rotor forward speed is calculated in this model using Glauert's well-known result[22] that

$$v_{wake}^4 + \mu^2 v_{wake}^2 - (C_T/2)^2 = 0 \qquad \ldots (19)$$

Apart from the enhancements induced by its more sophisticated rotor model, GLAUERT should be expected to provide results for the rotor thrust and flapping response that are closest to the analytic 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 the rotor loading that might be induced by interactions with the vortex. This is done by adopting the commonly-used Pitt and Peters three-mode dynamic inflow model[16] used in several of the papers cited in the introduction. This model represents the inflow distribution as the sum of three inflow modes, one corresponding to a uniform inflow distribution on the rotor disc and the other two corresponding to longitudinal and lateral gradients of the inflow across the rotor disc. These modes are coupled by a set of first-order ordinary differential equations to the thrust and aerodynamic pitching and rolling moments generated by the rotor. As such the model provides a simple representation of the experimentally-observed time-lags in the response of the inflow to changes in the rotor's aerodynamic loading.

5.2 FLOW-TYPE MODELS

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

$$\frac{\partial}{\partial t}\omega + v\cdot\nabla\omega - \omega\cdot\nabla v = S \qquad \ldots (20)$$

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

$$\nabla^2 v = -\nabla\times\omega \qquad \ldots (21)$$

of the Biot-Savart relationship relates the velocity at any point near the rotor to the vorticity distribution in the flow. Using this formalism, the strength and geometry of the rotor wake, as it evolves in time, can be fed back into the aerodynamic loading, and thus the dynamics, of the rotor. This formalism is related to the better-known Lagrangian free-vortex (or, more simply, 'free-wake') approach by a simple shift in reference frame, and the results obtained using a model constructed using the approach described here would be expected to show broadly similar characteristics to those generated by a suitably-constructed free-wake simulation.

The vorticity transport model (VTM) developed by Brown[23,24], on the other hand, employs a direct computational solution of Equation (20) 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

https://doi.org/10.1017/S0001924000004954 Published online by Cambridge University Press

trailed vorticity from the rotor blades. After casting the equations on a structured grid surrounding the rotor, Equation (21) is solved by cyclic reduction[25], while Equation (20) is marched through time using Toro's weighted average flux algorithm[26].

Results for two numerical models constructed using the VTM will be presented. In both models, the velocity field of the interacting vortex is used to generate the inflow distribution at the rotor as well as to convect and deform the rotor's wake according to Equation (20). In variant VTM(Frozen Vortex), the frozen vortex assumption is invoked and the interacting vortex is forced to retain its shape throughout the interaction with the helicopter rotor. In variant VTM(Free Vortex), however, the frozen vortex assumption is eliminated and the interacting vortex is allowed to convect and deform under the action of both its self-induced velocity field and the velocity field induced by the rotor and its wake.

6.0 COMPARATIVE COMPUTATIONS

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 $C_T = 0{\cdot}0045$ 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 0.00 (hover) and 0·35, and for vortices rotating in both clockwise and anticlockwise senses. Here, a 'positive' vortex is defined as producing an up-flow on the advancing side of the rotor during a parallel interaction, or, initially, an upwash on the rotor during a perpendicular interaction.

6.1 Parallel interaction

The perturbations to the rotor thrust and disc-tilt predicted by the various numerical approaches in response to a parallel vortex interaction are shown in Fig. 1. The coning response of the rotor has not been plotted, as its features are virtually identical to those of the thrust response of the rotor. The simple blade element theory presented earlier predicts an antisymmetric response of the rotor to vortices with positive or negative sense. To aid interpretation of the predictions of the various approaches in the light of this theory, half the difference between the perturbations induced by positive and negative vortices, and thus the symmetric component of the predicted rotor response, is plotted as a function of advance ratio on the left-hand side of Fig. 1. On the other hand, the plots at right illustrate the deviations from antisymmetry in the predictions of the various approaches by portraying the sum of the perturbations induced by positive and negative vortices as a function of the advance ratio of the rotor.

The principal feature of Fig. 1 is that very little difference is apparent between the results predicted by the inflow-type numerical models and the analytic results derived earlier — at least as far as the rotor's longitudinal tilt and the gradient with advance ratio of the rotor's thrust response is concerned. Discrepancies between the numerical and analytic predictions can be traced back to the slightly different treatments of the blade sectional aerodynamics in the two approaches. The $C_L(\alpha)$ variation used in the numerical simulations has negative curvature in the attached flow regime whereas the theory presented earlier assumes linear blade aerodynamics. This causes the vertical offset between the thrust perturbation predicted by the numerical models and by blade element theory. Similarly, the softening of the thrust gradient at high advance ratio, peculiar to interaction with a positive vortex, can be traced to the ability of the numerical simulations to predict the onset of stall on parts of the rotor disc as the rotor forward speed is increased. The more comprehensive flow-based models do not predict this feature of the rotor's response, suggesting that it is, in fact, an artifact of the limited number of degrees of freedom available to the (admittedly rather simple) inflow type models used in this study in representing the lateral inflow variation on the rotor disc. This same effect is present in the numerical predictions of the rotor's longitudinal flapping response, but deviations from blade element theory are small in this case. This is 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 induced by the interacting vortex when it is aligned parallel to the rotor's flightpath.

For the parallel interaction, the response of the lateral disc tilt is relatively small compared to the longitudinal tilt. Nevertheless there is a rather large discrepancy between the numerically-predicted response of the lateral disc tilt and the results from blade element theory. This is because the three-dimensional representation of the vortex used in the numerical simulations allows the coupling between the rotor coning and the vortex induced cossflow on the rotor disc plane, that was ignored in the derivation presented earlier, to be accounted for.

Turning to the flow-type numerical models, an interesting feature of their predictions 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. In Fig. 2, the amplitude of any fluctuations that persist in the rotor response after filtering out variations that occur at frequencies greater than blade-passing frequency is plotted against the advance ratio of the rotor. As can be seen, 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 primarily between advance ratios of about 0·02 to 0·10.

These long-period fluctuations in the response of the rotor can be traced back to unsteadiness in the development of the rotor wake. This time-dependency in the rotor loads thus cannot, by definition, be captured by any inflow-type approach as it is crucially dependent on the details of the off-rotor flow. Figure 3 shows a sequence of diagrams using iso-contours of vorticity to illustrate the numerically-predicted morphology of the rotor wake during the parallel interaction. The top two diagrams show the wake structures generated by the trimmed rotor, the left diagram when at relatively low forward speed, the right when at high. The centre diagrams show snapshots of the wake structure predicted by variant VTM(Frozen Vortex) during the vortex interaction. The left diagram shows how, at low forward speed, a significant proportion of the near-wake is predicted to be re-ingested by the rotor as it is cyclically convected by the velocity field of the interacting vortex. The lower left diagram shows the corresponding wake structure predicted by the VTM(Free Vortex) model in which the frozen vortex assumption has been relaxed. The unsteadiness in the rotor response at very low forward speed predicted by variant VTM(Frozen Vortex) turns out to be an artifact of overconstraining the geometry of 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 forward speed of the rotor is reduced, the vortex becomes increasingly intertwined with the rotor wake and is displaced vertically below the rotor as the rotor passes by. At advance ratios less than about 0·02 the interacting vortex is 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, as shown in the middle diagram of Fig. 1. The important inference from this diagram is that, particularly at low forward

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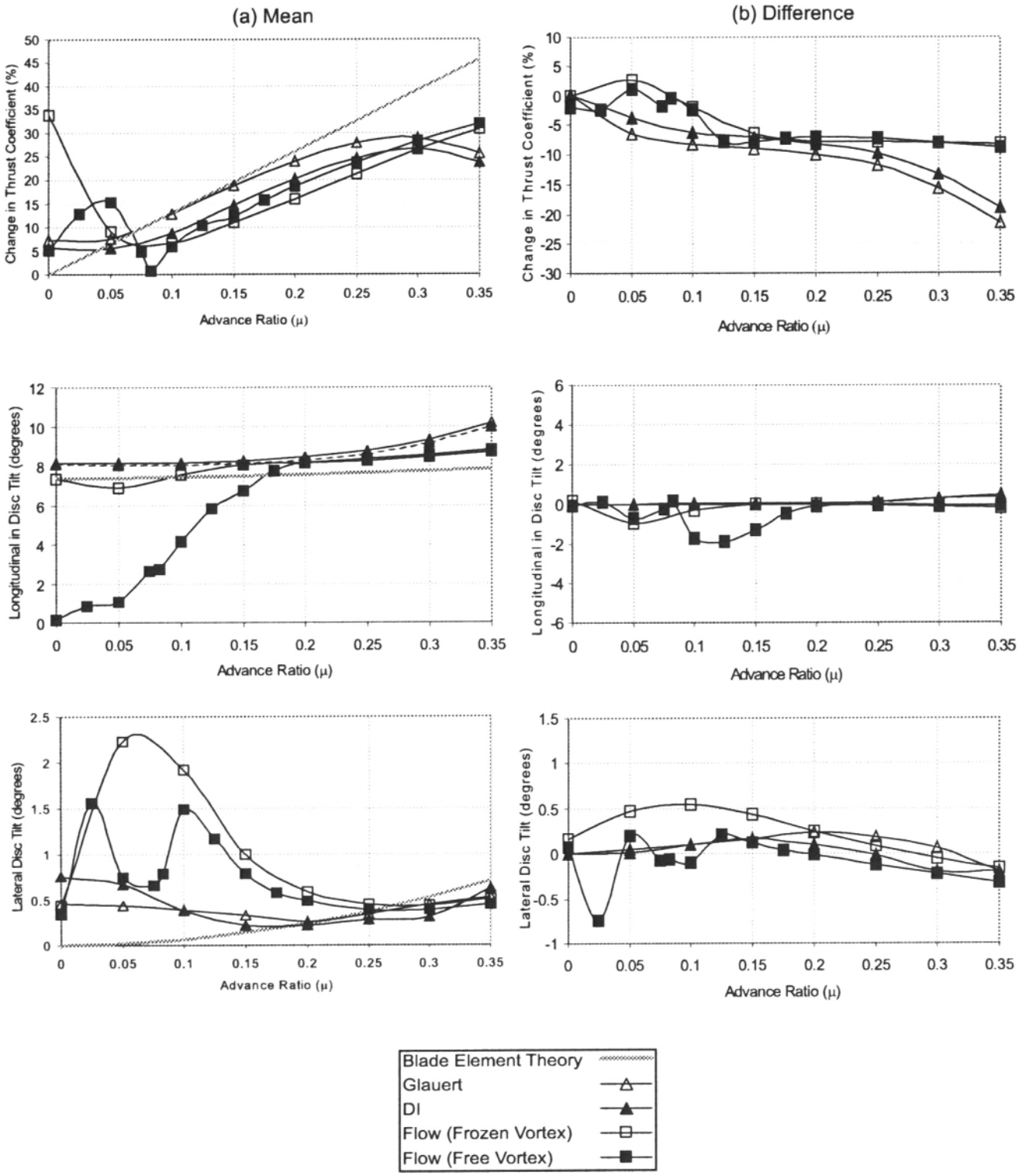


Figure 1. Perturbations to rotor trim states in response to a parallel vortex interaction.

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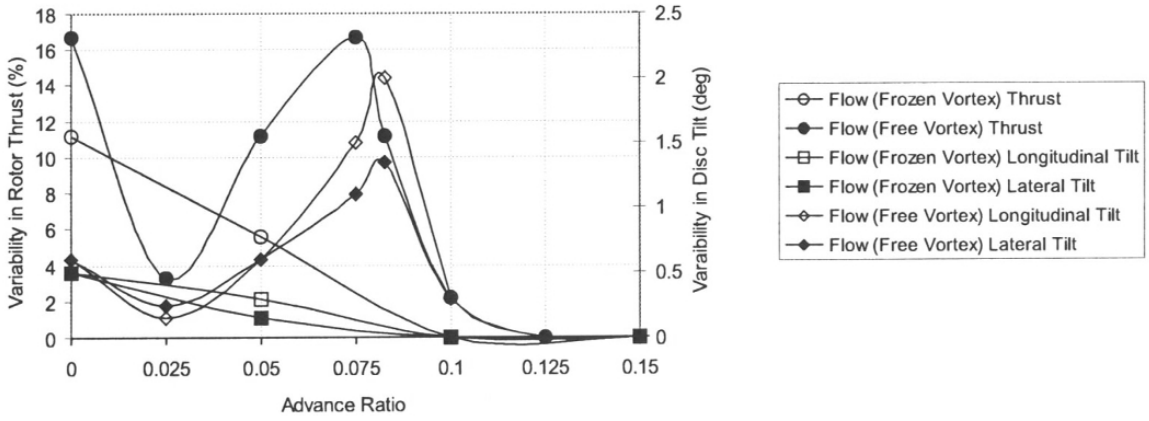


Figure 2. Variability in rotor thrust and flapping response to a parallel vortex interaction.

speed, use of the frozen vortex assumption may lead to significant overprediction of the rotor response, especially in terms of rotor flapping, to a parallel vortex interaction.

On the other hand, Fig. 1 shows that, at high forward speeds, both VTM(Frozen Vortex) and VTM(Free Vortex) provide predictions of the rotor response which vary only slightly from those of the simpler inflow-type models. This is partly because at higher advance ratios the wake-induced velocity becomes a less significant contributor to the blade aerodynamics than the free-stream velocity. Also, 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 is convection by the free-stream velocity. This can be seen by comparing the middle and lower right hand diagrams in Fig. 3 where it is evident that the wake and vortex structures predicted by VTM(Frozen Vortex) and VTM(Free Vortex) are very similar at high forward speed.

6.2 Perpendicular interaction

Illustrative time-histories of the perturbations to the rotor thrust and disc-tilt induced during a low-speed perpendicular interaction are shown in Fig. 4. The coning has not been plotted, since, as in the parallel case, its features are very similar to those of the thrust response of the rotor. The horizontal time-axis in these diagrams has been parameterised both in terms of the distance L from the rotor hub to the centre of the core of the interacting vortex, and in terms of the elapsed number of rotor revolutions, to allow easier analysis of the rotor's response during the interaction. The thrust, coning and longitudinal tilt of the rotor all exhibit a characteristic doublet type response as first the upwash, and then the downwash, induced by the vortex passes across the rotor disc. The lateral tilt, on the other hand, exhibits a triplet (differentiated doublet) type response with the maximum perturbation occurring as the vortex core passes the rotor hub. The rotor response predicted by the inflow type models GLAUERT and DI are quite similar in character to the analytic results, but the predictions of the flow type models VTM(Frozen Vortex) and VTM(Free Vortex) differ considerably from the predictions of the simpler models. These differences are principally a result of the rather gross deformations of the rotor wake (in the case of both models) and the interacting vortex (in the case of VTM(Free Vortex)) that the flow type models predict to accompany a vortex interaction at this forward speed. Figure 5 shows the evolution of the rotor wake and the interacting vortex predicted by VTM(Free Vortex) at two different forward speeds. The diagram at left shows the same interaction represented in Fig. 4, and illustrates the intense intertwining of the vortex and rotor wake, and the displacement of the interacting vortex away from the plane of the rotor, that takes place as the interaction progresses. The diagram at right represents a higher speed interaction where wake deformation by the interacting vortex is still significant, but where the deformation and displacement of the interacting vortex is very much more subtle.

The response of the rotor to a perpendicular interaction is governed by the interplay between three separate time-lags within the system. If the time-lags in the rotor response are small compared to the duration of the interaction with the vortex then the rotor will respond quasistatically to the vortex-induced flow field. The response of the rotor to upwash or downwash should then be independent of the temporal order in which the velocity peaks are encountered. On the other hand, if the time-lags are comparable to the duration of the interaction, then the resultant retardation in the rotor response should appear as a dependence on the order in which the vortex-induced velocity peaks are encountered.

The behaviour of the various numerical methods can thus be better understood by careful analysis of the symmetries in the rotor's response portrayed in the results of Fig. 6. In this figure the peak thrust and longitudinal flapping response of the rotor is shown as a function of forward speed. The diagrams at left represent the mean of the upwash-induced response and the mean of the downwash-induced response for interactions with positive and negative vortices, and thus can be used to expose asymmetries in the rotor response associated with the direction of the rotor-induced flow on the rotor disc. The diagrams at right represent the mean of the difference in the upwash-induced response and the difference in the downwash-induced response for interactions with positive and negative vortices. Significant deviation from zero in the data plotted in these diagrams indicates an asymmetry in the rotor response associated with the order in which the vortex-induced velocity peaks are encountered. Finally, Fig. 7 shows how the peak lateral flapping response of the rotor varies with the rotor's forward speed.

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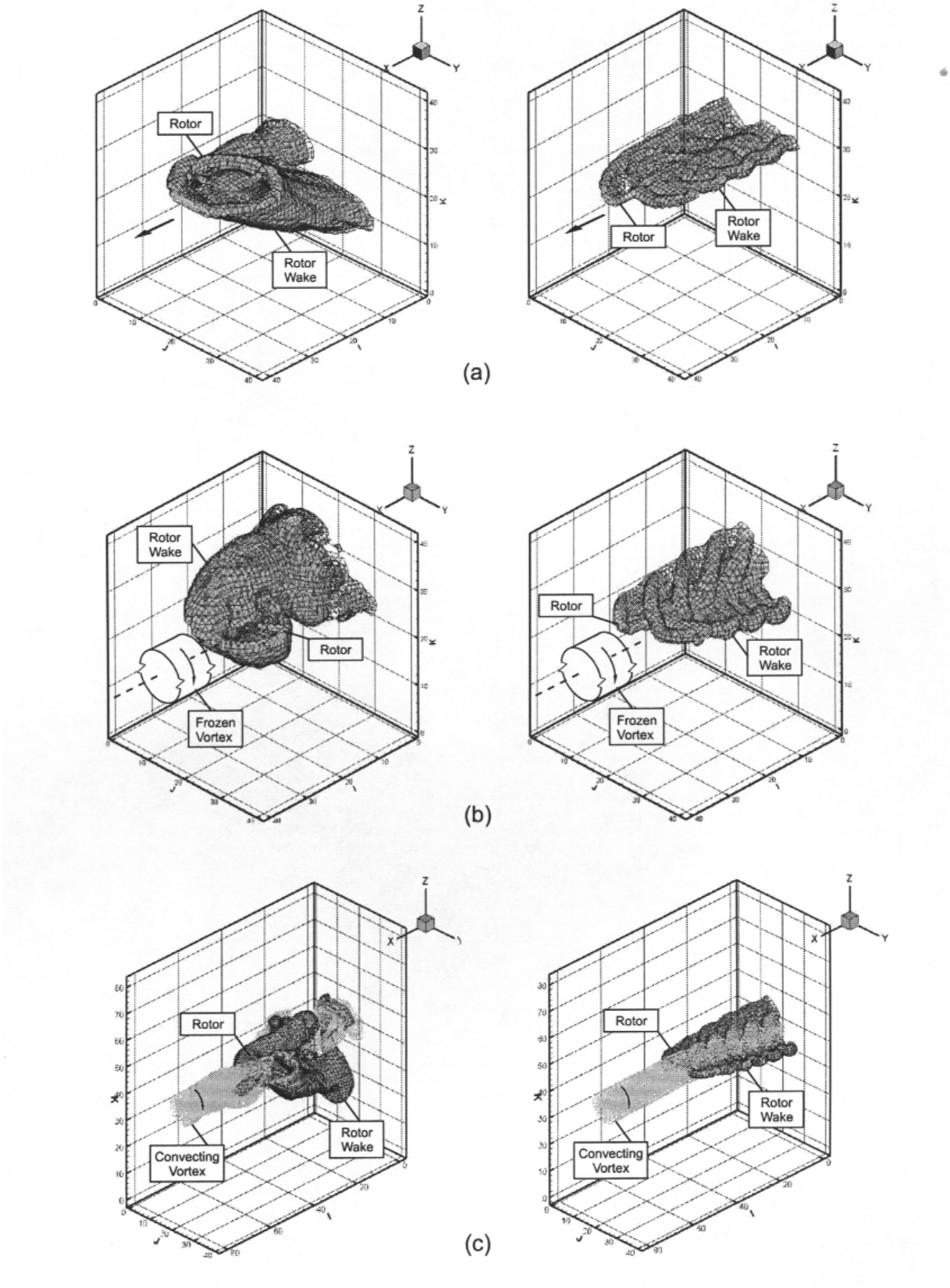


Figure 3. Wake morphology during a parallel interaction at $\mu = 0{\cdot}05$ (left) and $\mu = 0{\cdot}35$ (right) (a) in trimmed flight. (b) frozen vortex (c) free vortex. The interacting vortex has a positive sense of rotation.

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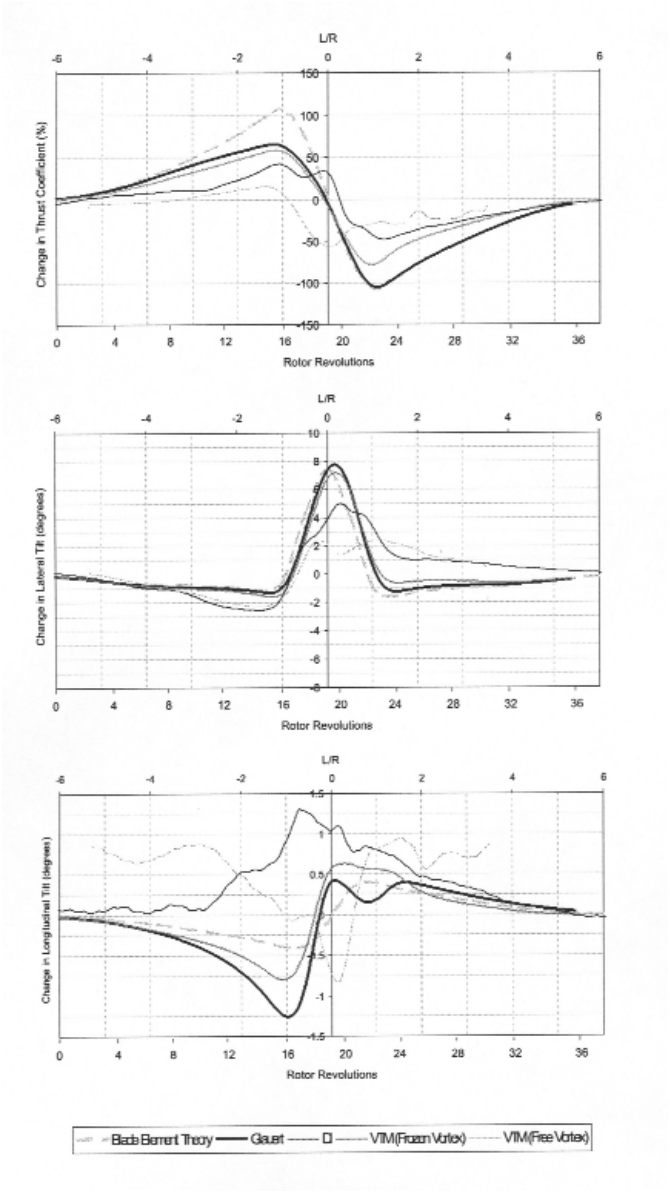


Figure 4. Thrust and tilt in response to a perpendicular interaction at $\mu = 0{\cdot}05$. The interacting vortex has a positive sense of rotation.

The first time-lag in the rotor system is associated with the inertial term in the flapping response of the rotor - this effect is contained in all the numerical simulations but, as described earlier, the analytic results assume that the rotor response is fast compared to the speed at which the rotor traverses across the vortex. For a rotor with the Lock number used here, linearised blade dynamic theory estimates that the ratio of the time constant of the flapping response to the interaction time is of order 10^{-1} at the slowest forward speed for which results are provided, and of order 1 at the fastest. Thus at low forward speed the rotor response should be essentially quasistatic while at high forward speeds the effects of the time-lag should be significant. The influence of the time-lag in the rotor dynamics on the response of the rotor should be most easily discerned from GLAUERT's predictions, since this is the only time-lag that this model contains. The lateral flapping response predicted using this model shows this effect most clearly. At low forward speed, the agreement between the analytic results and GLAUERT's predictions is very close, but, as the forward speed of the helicopter is increased, the predicted perturbation to the lateral flapping falls increasingly below the corresponding analytical value. This trend is also clearly apparent in the predictions of all the other numerical models, but agreement with the analytical results is obscured by the additional features of these more advanced models. The effects of the time-lag in the rotor dynamic response are weaker in the longitudinal flapping, but the right-hand diagram indicates an increasing lack of temporal symmetry in the interaction, as would be expected to accompany the convergence in timescales as the forward speed of the rotor is increased.

The second time-lag in the rotor system is associated with the response of the wake-induced inflow distribution on the rotor to loading changes caused by interaction with the vortex. All the numerical models except for GLAUERT are sophisticated enough to represent this effect, but it is not represented at all in the analytic model. For the interaction presented here, this time-lag is small compared to the time for which the rotor interacts with the vortex. The theory behind the dynamic inflow formalism[16] provides an estimate of the ratio of the inflow time constant to the interaction time of order 10^{-1} throughout the speed range tested here. The inflow dynamics should thus act in an essentially quasistatic manner to reduce the thrust and flapping response of the rotor. This effect is clearly seen in Fig. 6 if the predictions of the two flow type models GLAUERT (in which the effect is absent) and DI (which contains the effect) are contrasted. As in the parallel interaction, the strong asymmetry between the upwash- and downwash-induced thrust response predicted by the flow type models is induced by the nonlinearity in the blade aerodynamic model. In particular, the presence of blade stall on parts of the rotor during interaction with an upwash from the interacting vortex caps the thrust response of the rotor at a broadly similar, and forward speed-independent, value in all inflow-type simulations. It also produces very much larger values for the longitudinal disc tilt than are predicted by the flow-type models or by blade element theory. The flow type models, in comparison, exhibit far greater symmetry in their response to vortex-induced upwash or downwash on the rotor disc than do the inflow type models. It appears that in these models, as in the parallel interaction, the additional degrees of freedom available to the inflow distribution reduces the extent of blade stall on the rotor disc, with a resultant reduction in the asymmetry of the rotor response.

A third time-lag appears in the numerical simulation of the rotor system if the frozen vortex assumption is eliminated. Simplistically, if the vortex is encountered at high forward speed then it has insufficient time to distort as the rotor passed by. The rotor thus responds in a manner consistent with the frozen vortex assumption. On the other hand, if the vortex is encountered at low forward speed then there is sufficient time during the interaction for it to be distorted and displaced by the rotor-induced velocity field. Although the dynamics of the interacting vortex are complicated by local stretching and rotation of lines of vorticity, the net effect on predictions should be that the two flow type models VTM(Frozen Vortex) and VTM(Free Vortex) should yield similar results at high advance ratio, although not necessarily at low. The results for the averaged rotor response shown on the left-hand side of Fig. 6 suggest that this is broadly the situation, except that convergence between the predictions of the two methods as the forward speed of the rotor is increased is slower than in the case of the parallel interaction. As for the parallel interaction, VTM(Free Vortex) predicts a significantly smaller primary flapping response at low forward speed than does VTM(Frozen Vortex). A similar, but somewhat weaker, effect is evident in the thrust response of the rotor. Again, the importance of including the mutually-induced distortion of the helicopter wake and interacting vortex when simulating wake encounters at low forward speed is clearly demonstrated.

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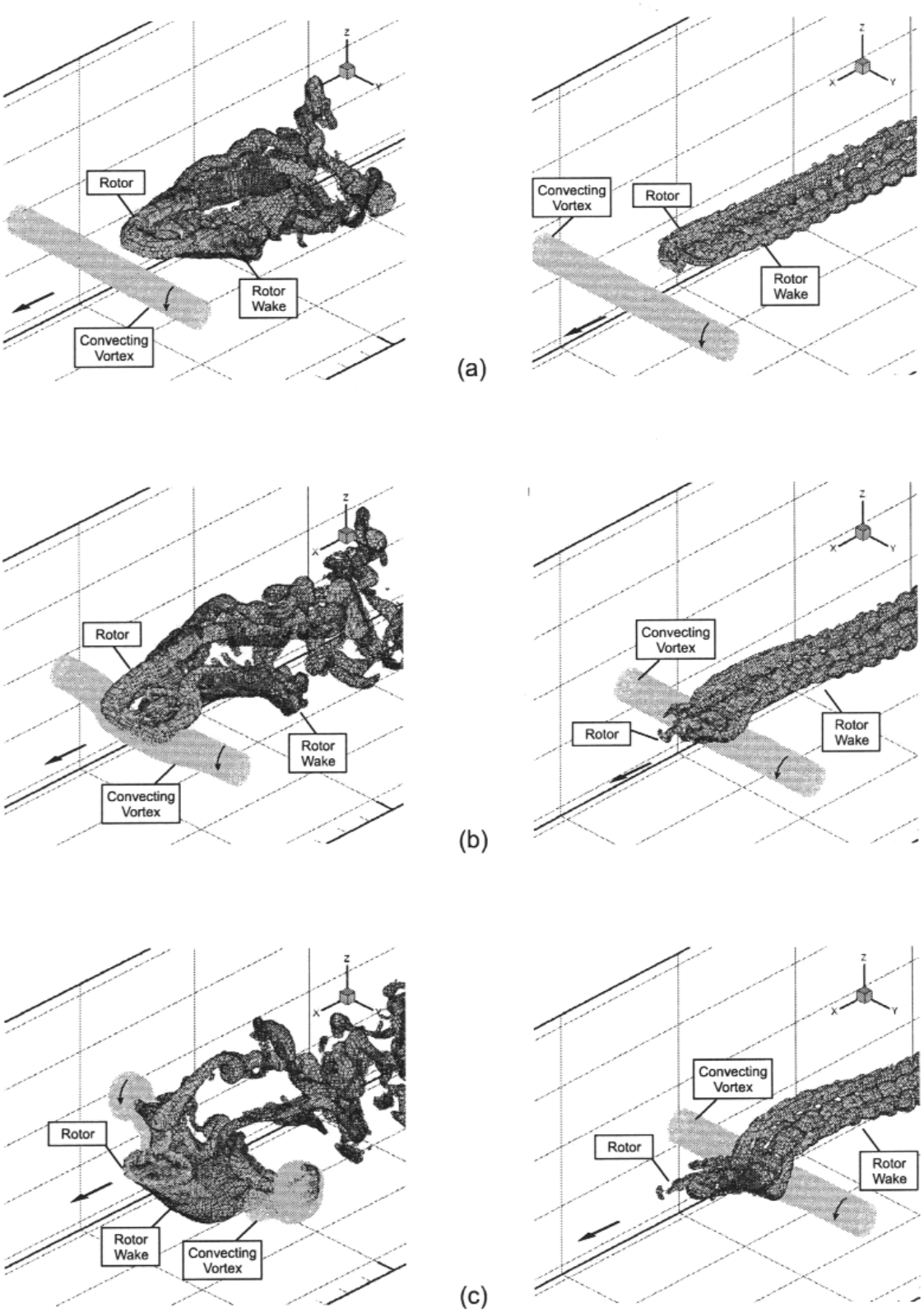


Figure 5. Wake morphology at $\mu = 0{\cdot}05$ (left) and $\mu = 0{\cdot}35$ (right)
(a) before (b) during (c) after a parallel interaction. The interacting vortex has a positive sense of rotation.

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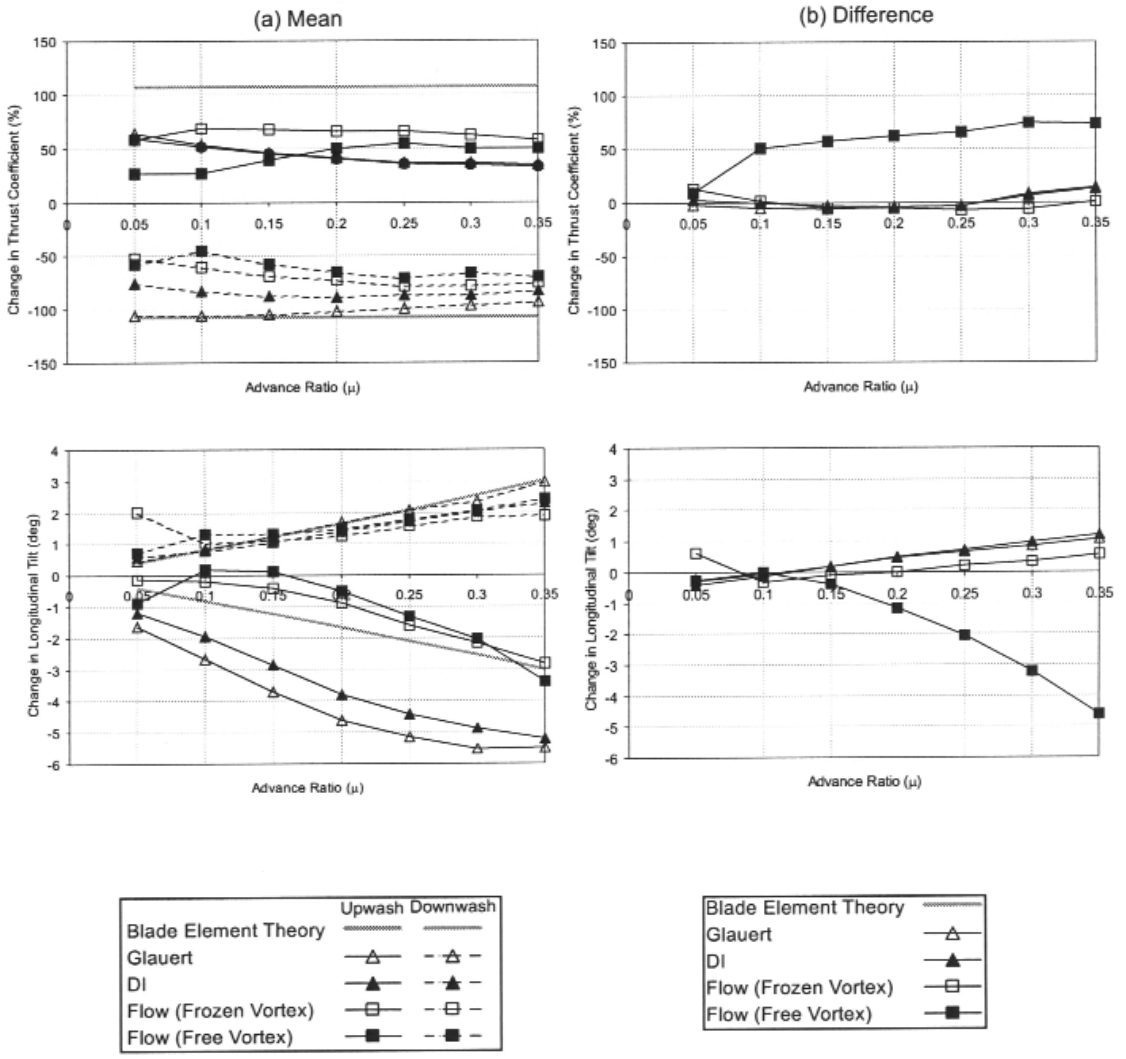


Figure 6. Perturbations to thrust and longitudinal flapping in response to a perpendicular vortex interaction. (a) mean (b) difference between upwash- and downwash-induced response.

The right-hand diagrams of Fig. 6 contain a slight complication to this interpretation of the data, however. All the inflow type models, and also VTM(Frozen Vortex), predict the strength of the interaction to be strongly governed by whether the rotor is experiencing upwash or downwash, but to be only weakly dependent on the sequencing of the velocity peaks. This indicates the absence of any particularly strong dynamics, on timescales comparable to the duration of the vortex interaction, in these models. Interestingly, though, this symmetry is broken in the predictions of the VTM(Free Vortex) model. In particular, the rapid divergence away from zero in the differential measure of the longitudinal flapping response of the rotor indicates an emerging directionality in the rotor flapping response as its forward speed is increased. This directionality must be a direct consequence of the time-lag associated with the deformation of the interacting vortex, since it is the presence of a numerical representation of this physical process which differentiates the predictions of VTM(Free Vortex) from the predictions of VTM(Frozen Vortex) where the directionality is not observed. The results presented here illustrate that even the subtle deformations of the interacting vortex that take place during interactions at high forward speed must be properly accounted for if detailed predictions of the time-history of the rotor response are required (for instance during handling qualities or trajectory simulations) rather than just simple estimates of the magnitude of the rotor response.

7.0 CONCLUSIONS

The aim of this paper has been to provide a systematic comparison of some of the properties of several of the key aerodynamic modelling techniques used in previous numerical simulations of helicopters encountering wake vortices. In particular, this paper examines the validity of the so-called 'frozen vortex' assumption. This assumption holds that the mutually induced distortion of the helicopter's own

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wake and the interacting vortex has limited effect on the predicted severity of helicopter-wake interactions and thus can be ignored.

Most previous simulations have adopted the frozen vortex assumption. The results of this paper suggest that a certain amount of faith can indeed be placed in the results of these studies, if care is taken not to extrapolate their results too far from the high-speed, free-flight conditions under which the simulations were originally conducted.

At low advance ratio, however, 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, and, in the context of the interactions examined here, generally leads to over-prediction of the rotor's response to a vortex encounter. This observation has particularly important implications for the extrapolation of the results of previous studies into the context of near-airfield operations, particularly since under these conditions the helicopter is usually operating at low flight speed. The danger is that overt reliance on previous results, without corroborating data from studies that are more fully representative of actual operational conditions, may lead to a significant misrepresentation of the dangers posed to helicopter operations by encounters with the wakes of other aircraft which might be operating nearby.

ACKNOWLEDGEMENTS

The work described in this paper is sponsored by the ongoing Engineering and Physical Sciences Research Council Grant GR/L/013136 *Helicopter Response to Vortex Encounters in the Near-Airfield Environment* and an ORS student scholarship.

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