Modelling the interaction of helicopter main rotor and tail rotor wakes

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ABSTRACT

The mutual interaction between the main rotor and tail rotor wakes is central to some of the most problematic dynamic phenomena experienced by helicopters. Yet achieving the ability to model the growth and propagation of helicopter rotor wakes with sufficient realism to capture the details of this interaction has been a significant challenge to rotorcraft aerodynamicists for many decades. A novel computational fluid dynamics code tailored specifically for rotorcraft applications, the vorticity transport model, has been used to simulate the interaction of the rotors of a helicopter with a single main rotor and tail rotor in both hover and low-speed quartering flight, and with the tail rotor rotating both top-forward and top-aft. The simulations indicate a significant level of unsteadiness in the performance of both main and tail rotors, especially in quartering flight, and a sensitivity to the direction of rotation of the tail rotor. Although the model thus captures behaviour that is similar to that observed in practice, the challenge still remains to integrate the information from high fidelity simulations such as these into routine calculations of the flight dynamics of helicopters.

NOMENCLATURE

A	main rotor disc area, πR^2
N_{mr}	main rotor contribution to yaw moment, scaled by $1/\rho A(\Omega R)^2 R$
N_{tr}	tail rotor contribution to yaw moment, scaled by $1/\rho A(\Omega R)^2 R$
R	main rotor radius
R_{tr}	tail rotor radius
S	vorticity source
u	flow velocity
u_b	flow velocity relative to blade
$\theta_{0_{tr}}$	tail rotor collective pitch
μ	overall advance ratio, $(\mu_x^2 + \mu_y^2)^{1/2}$
μ_x	advance ratio in longitudinal direction
μ_y	advance ratio in lateral direction; positive to right
ν	viscosity
ρ	density
ω	vorticity
ω_b	bound vorticity
Ω	main rotor speed

Notation

$\bar{x}$	time-averaged value of $x(t)$
x'	perturbation of $x(t)$ from time-average
$\hat{x}$	RMS value of $x(t)$

1.0 INTRODUCTION

The methodology used to model the wakes that are induced by the rotors of a helicopter has developed considerably during the many decades in which these flying machines have been in widespread use. Progress in finding more flexible and accurate methods to

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calculate the induced velocity at the rotor blades, and hence the loading on the system, has accelerated in recent times due to advancements in computer performance and in the numerical algorithms that can be used to solve the equations of motion that govern the dynamics of the airflow surrounding the vehicle. Furthermore, a recognition that accurate prediction of the wake many rotor radii downstream of the vehicle, known informally as wake capturing, is essential to enable high-fidelity aerodynamic and acoustic prediction, has led to advanced computational fluid dynamics (CFD) codes that are tailored specifically to modelling rotorcraft flows.

Yet in many flight mechanics applications, especially those involving control law design and handling qualities assessment, very much simpler approaches to the modelling of the rotor aerodynamic environment are still routinely adopted. The most sophisticated approach in common use is founded upon the 'dynamic inflow' formalism of Peters and co-workers[1]. This formulation has achieved an impressive degree of sophistication in recent years, with the ability to account for the interaction between the multiple blades of multiple rotors and also to accommodate the gross effects of manoeuvres on the distortion of the flow field around the helicopter. Yet in none of the various incarnations of this approach is the detailed local dynamics of the wake of the helicopter represented in any great detail. Many subtle and not-so-subtle features of the helicopter aerodynamic field, such as the roll-up of the helicoidal wake to form distinct 'tip vortices', similar to those of a fixed-wing aircraft, in forward flight, and the inherent instability of the helicoidal wake structure in all flight conditions, are simply not captured by the approach. These simpler models are attractive to flight dynamicists, however, because their computational burden is relatively light, and their rendition in the state space form that is most amenable to dynamical simulation and analysis is usually relatively straightforward.

Throughout their short history, however, helicopters have been beset by flight dynamic and handling problems that have been induced by the very strong and highly unsteady aerodynamic interactions between the various load-producing components of the vehicle – for instance between the main rotor and the fuselage, tailplane or tail rotor. New helicopter designs continue to produce surprises in this respect, and when dynamic problems are encountered they can require expensive post-design modification to alleviate them. This paper will show that at least some of the characteristics of the aerodynamic interactions that lie at the heart of at least one of these flight dynamic problems, specifically the unsteadiness that can result under certain flight conditions because of the aerodynamic interaction between the main and tail rotor, are governed by the detailed and relatively local dynamics of the vorticity field that is created in the wake of the helicopter. A complete analysis of this and many other, similar problems is thus inaccessible to the flight mechanicist or handling qualities engineer using his or her standard set of tools.

There seems little way to progress in the integration of local wake effects into simulations of helicopter dynamics other than through the use of high-fidelity computational techniques that are based directly on numerical solution of the underlying equations for the dynamics of the flow around the helicopter. This springs simply from the fact that analysis of the wake in sufficient detail to allow the local structure of the wake to manifest itself in the dynamics of the vehicle naturally requires a model that represents the local fluid dynamics of the wake. Although computational models based on direct solution of the Euler or Navier-Stokes equation are becoming more widely used by helicopter aerodynamicists, many of these techniques suffer greatly from numerical dissipation and diffusion of the vorticity in the wake, meaning that their ability to preserve the wake geometry far downstream of the rotors, as well as to capture accurately the strength of localised events such as the blade-vortex interactions that influence strongly the response of the vehicle to the detailed structure of the wake, is very limited.

Helicopter interactional aerodynamics poses an extreme challenge to such methods since the various interacting components that are usually implicated in the dynamic problems experienced by the helicopter are generally relatively distant when seen on the length-scales of importance in the dynamics of the wake. Methods based on the solution of higher moments of the Navier-Stokes equation, especially the vorticity transport equation, show somewhat more promise in maintaining the wake structure for the long times and relatively great distances that are required to resolve accurately the aerodynamic interactions between the major components of the helicopter. Yet, although these methods might offer the only practicable direct approach to resolving the physical effects that govern many of the helicopter's dynamic problems, they are all far too computationally intensive, and, at least at present, an order or two in magnitude too slow, for use in routine flight dynamic calculations or for control system design. This does not mean that these models are without utility to the flight dynamicist; indeed this paper will hint at how calculations using such models can be used indirectly to construct and inform simpler phenomenological models that can be incorporated into standard flight mechanics analyses. This approach may enable the inherent deficiencies of the two types of modern analysis to be counterbalanced to some extent until computers become fast enough or some major breakthrough in numerical methods is made that will allow routine calculations to be made using high-fidelity computational models. In the mean time, an excellent opportunity exists for the rotorcraft CFD community in adopting this indirect approach by placing the emphasis on achieving a good understanding of the physics inherent in their data, and embracing the challenge of capturing the physics that is not. The definite benefit for the flight dynamics community should be that some representation of wake-related dynamical effects can be built into their analyses. In this way perhaps we may not be bound to repeat some of the expensive design mistakes of the past.

More specifically, the current paper shows some results from an investigation of the complex nonlinear aerodynamic interaction between the main and tail rotors in a conventional single main rotor helicopter. This interaction has been investigated using a CFD code which solves the incompressible vorticity transport equation in vorticity conservation form. A conventional helicopter has a large main rotor which provides lift and thrust for translational flight, and a smaller tail rotor that is mounted perpendicular to the main rotor to counter its torque reaction on the fuselage. Interaction between the wakes that are induced by the main and tail rotors is believed to be a primary contributor to unsteady aerodynamic forcing of the vehicle under certain flight conditions[2-3]. Any unsteadiness in the dynamics of the vehicle will, at best, be an annoyance to the pilot. More severe manifestations of the interaction might result in significant degradation of the handling qualities of the vehicle and, at worst, might even present a serious control problem to the pilot. In a simple two-rotor system, particularly one in which the rotors are configured conventionally, the degree of unsteadiness experienced by the vehicle has been found to be surprisingly sensitive to the direction of rotation of the tail rotor, as highlighted by Lynn *et al*[4] and others. The tail rotor of the helicopter may be designed to rotate in either direction. If the blades travel rearward at the top of the disc then the rotor is termed to have 'top-aft' rotation; the opposite direction of rotation is termed 'top-forward'. The direction of tail rotor rotation has emerged as an important issue during the design of several helicopters, including the AH-56A Cheyenne[2] and the YAH-64 Apache[3]. In some designs, such as the Mil Mi-24 and the Westland Lynx[5], the direction of rotation of the tail rotor has even been changed during the life-cycle of the vehicle in an attempt to improve their dynamic characteristics; certainly modern rule-of-thumb holds top-aft rotation of the tail rotor to be preferable to top-forward rotation. It should be emphasised though that the interaction between the main and tail rotor is just one of a range of aerodynamic effects that has engendered great interest within the helicopter community because of the need to optimise the performance of vehicles whilst simultaneously taking great pains to

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Table 1
Main rotor data

No. of blades	3
Rotor radius	R
Chord	$0.055R$
Twist	–8°(linear)
Aerofoil	NACA 0012
Root cut-out	$0{\cdot}19R$
Flap hinge offset	$0{\cdot}0875R$
Rotational speed	Ω
Direction of rotation	counterclockwise
Thrust coefficient, C_T	0·005

Table 2
Tail rotor data

No. of blades	3
Rotor radius	$R_{tr} = 0{\cdot}193R$
Chord	$0{\cdot}186R_{tr}$
Twist	0°
Aerofoil	NACA 0012
Root cut-out	$0{\cdot}21R_{tr}$
Flap hinge offset	0·0
Rotational speed	$5{\cdot}25\Omega$
δ_3	45°

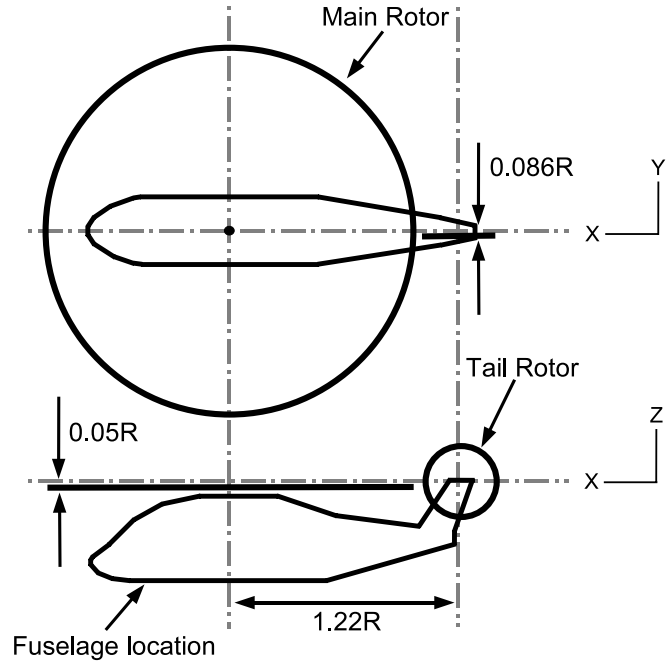


Figure 1. Rotor configuration (fuselage represented solely for clarity).

avoid the pathologies in their dynamic behaviour that might result from injudicious design. A comprehensive and very readable summary of the wide range of dynamic problems that might be encountered in a helicopter as a result of aerodynamic interactions between its various components is given by Sheridan and Smith[6].

2.0 HELICOPTER MODEL

To illustrate the capability of modern computational methods to reproduce the detailed dynamic features that result from the aerodynamic interaction between various components of the helicopter, a generic single main rotor and tail rotor helicopter configuration has been simulated using the vorticity transport model (VTM) developed by Brown[7], and extended by Brown and Line[8]. The VTM is a finite-volume computational fluid dynamics code which solves the incompressible vorticity transport equation

$$\frac{\partial}{\partial t}\omega + u\cdot\nabla\omega - \omega\cdot\nabla u = S + \upsilon\nabla^2\omega \qquad \ldots (1)$$

in vorticity conservation form across a fixed Cartesian grid centred on the main rotor hub. The source term

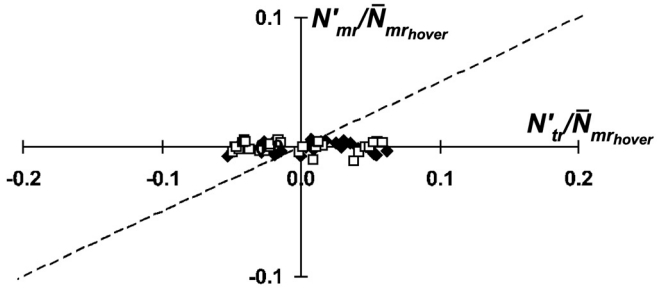
$$S = -\frac{\mathrm{d}}{\mathrm{d}t}\omega_b + u_b\nabla\cdot\omega_b \qquad \ldots (2)$$

is used to represent the source of the wake of the helicopter in terms of the trailed and shed components of the vorticity, ω_b, on the blades of the rotors.

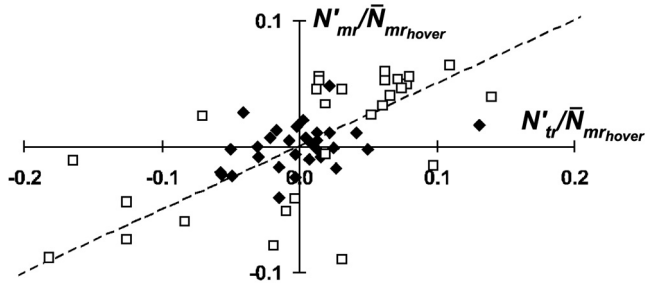
Importantly, the vorticity-velocity formulation of the VTM allows very strict control to be maintained over the compactness of the vortical structures in the flow, and by suitable algorithmic construction the wake of the helicopter can be made to persist indefinitely within the computational grid. This behaviour is in strong contrast to the performance of more conventional CFD algorithms based on the velocity-pressure formulation of the fluid dynamic equations, where vortical structures are generally diffused and dissipated very quickly. The VTM is thus admirably suited to the modelling of long-range aerodynamic interactions, and its retention of the wake structure allows both the low (1/rev and lower) frequency components of the loading on the system that influence the body dynamics, and the high frequency (1/rev and higher) components which are important if the dynamic response of the rotors is to be studied. The VTM has been validated successfully against several sets of highly regarded experimental data, including that of Harris, and Caradonna and Tung[8], and has been used extensively in the study of helicopter flight mechanics by Brown and Houston[9], and Houston and Brown[10], and rotor-fuselage aerodynamic interaction by Kenyon and Brown[11].

Results of simulations of a conventional helicopter configuration are presented for the tail rotor operating with both directions of rotation, both with the system in hover and also in level, low-speed left-quartering flight at an advance ratio $\mu = 0{\cdot}04$. In left-quartering flight, the system translates on a bearing of 135° from nose-forward. During each simulation the main rotor pitch was controlled using a simple, first-order model in order to maintain a constant main rotor thrust. The tail rotor collective pitch was similarly controlled to ensure a zero net yaw moment on the system. Additionally, both the longitudinal and lateral cyclic pitch of the main rotor were controlled to ensure zero tilt of the main rotor disc. This approach is not entirely appropriate to full-scale practice but endows some degree of generality to the computations. The time-constants of the control model can be set to represent various levels of aggressiveness on the part of the pilot or control system. In generating the results presented here they were set to prevent significant control activity at frequencies much greater than 0·2-0·4 per main rotor revolution, and thus to be roughly representative of the capabilities of a human pilot. The relative geometries and aerodynamic properties of the two rotors were chosen to be representative of a typical helicopter with separate main and tail rotors. The principal parameters for the main and tail rotors are given in Tables 1 and 2 respectively, and the relative locations of the main and tail rotors are shown in Fig. 1.

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(a) Hover



(b) Quartering, μ_x = -0.0283; μ_y = -0.0283

◆ Tail Rotor Top-Aft □ Tail Rotor Top-Forward

Figure 2. Perturbations to main and tail rotor aerodynamic yaw moments in hover and in quartering flight.

3.0 ROTOR PERFORMANCE

The controller allows the simulated helicopter to be flown to a state in which the net loading on the system is zero in the time-averaged sense; in other words to a state in which the system may be considered to be in nominal trim. The simpler helicopter flight mechanics models are often dynamically deficient in the sense that they predict zero instantaneous loading on the vehicle when in trim. In sharp contrast, high-resolution methods such as the VTM are able to capture the continuous and sometimes erratic excursions from nominal trim conditions that result from the aerodynamic interaction between the main and tail rotors.

Figures 2(a) and 2(b) show the VTM-predicted deviations from their nominal trim values of the yaw moment on the vehicle that are produced independently by the two rotors during hover and in quartering flight. Data for both directions of tail rotor rotation are presented. To produce these figures, the unsteady loading on the system was sampled at a frequency of once per main rotor revolution to allow a clearer appreciation of the variability in the aerodynamic forcing of the system over the range of frequencies that stimulates most directly the dynamics of the vehicle. A comparison of the extent to which the sampled data is scattered in the two figures reveals, firstly, that there is a much greater level of unsteadiness in the loading produced by both rotors in quartering flight than in hover – the computational model is thus demonstrably sensitive to the flight condition in which the helicopter finds itself. Secondly, and perhaps most importantly, the model is sensitive to the subtle influences on the form of the aerodynamic interactions within the system that arise from the detailed design of the helicopter – in this case, specifically, to the influence of the direction of rotation of the tail rotor. Consistently with flight test experience, the model predicts greater fluctuation in the loading on the system when the tail rotor rotates top-forward than when it rotates top-aft.

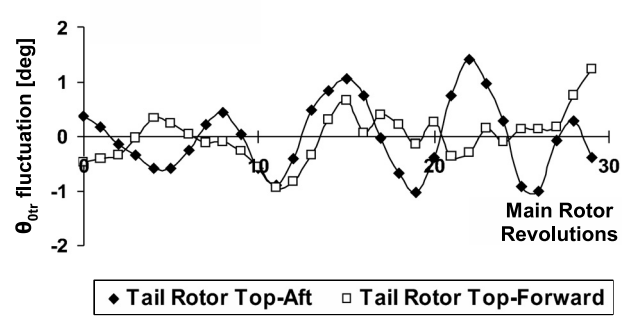


Figure 3. Fluctuations in tail rotor collective pitch in quartering flight.

The diagonal line in both Figs 2(a) and 2(b) represents nominal yaw equilibrium within the system – that is, the condition in which the torque generated by the main rotor is balanced exactly by the yaw moment that is produced by the tail rotor. The numerical 'pilot' described earlier attempts to adjust the state of the system to lie on this line by suitable inputs, through his pedals in the real aircraft, to the tail rotor collective pitch. The variation in tail rotor collective pitch with time that results from the activity of the model pilot in trying to establish yaw equilibrium is shown in Fig. 3 for the quartering flight case. When dimensionalised to be representative of a typical mid-sized helicopter, the data shows that the pilot responds to the fluctuating conditions at the tail rotor by varying the collective pitch over a range of about 2-3° with a frequency that is in the range of 0·5-1Hz. Again, these observations are consistent with full-scale experience. Given that one degree of tail rotor collective pitch usually represents about five to ten percent of total available pedal travel, this combination of amplitude and frequency of pedal input would arguably be manageable, but nevertheless extremely distracting and tiresome for the pilot under even the most benign operational conditions.

While the predicted control response is quite sensitive to the choice of time constants in the control model, the observations made above are all qualitatively consistent with flight dynamic experience, and show the power of the approach as a simulation tool in its own right. At present, using techniques such as the VTM to map out the aircraft response for more than a few values of the time constants is prohibitively expensive. The principal value, though, of a simulation that has been shown to embody the relevant characteristics of the problem at hand lies in the potential to exploit one's knowledge of its structure to understand the generic, underlying mechanisms that are responsible for the predicted behaviour. Provided that the simulation is sufficiently well-grounded in fundamental principles, so that the behaviour of interest is emergent rather than modelled directly, this understanding should, at least in principle, be achievable by dissecting out the particular interaction between the various effects that are embodied within the simulation that is responsible for the observed behaviour.

4.0 WAKE ANALYSIS

Since the dynamics of the wake is implicit in the aerodynamic interaction between the main and tail rotors, it should be possible to identify the origins of the unsteadiness in the loading on the individual rotors in the behaviour of the wake of the system. Figures 4(a) and 4(b) show the VTM-predicted geometries of the wakes that are generated by the main and tail rotors when operated in isolation from each other. Both rotors generate very similar wake structures that consist of an initially well-developed, cylindrical wake tube that eventually succumbs to its natural instability to perturbations to the helicoidal geometry of its constituent vortex filaments. In contrast, Fig. 5 shows the combined wakes of the main rotor and tail rotor

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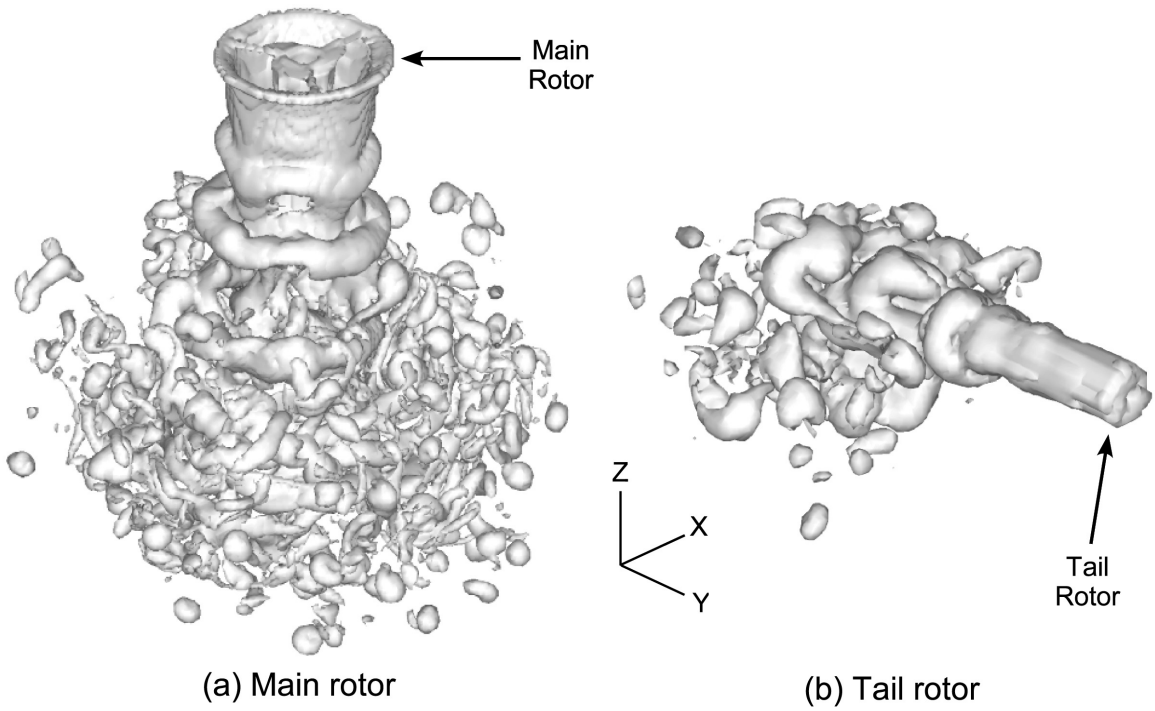


Figure 4. Wakes of isolated rotors in hover (individual rotors not to scale).

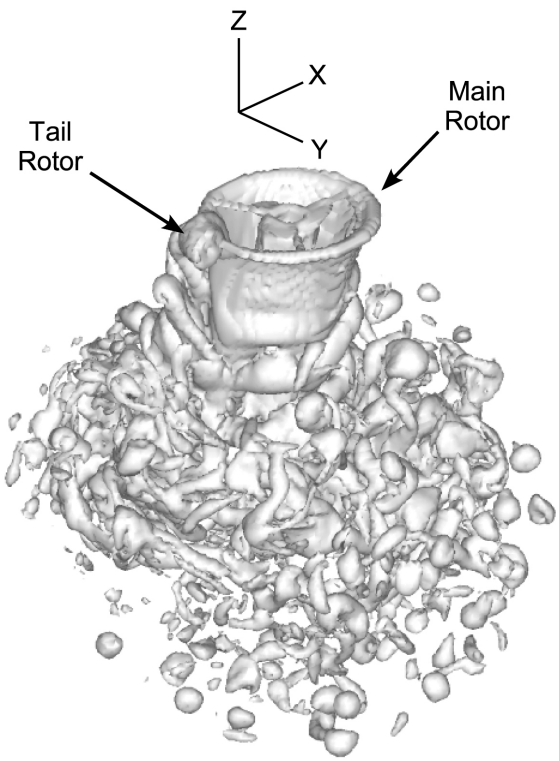


Figure 5. Wake of combined system in hover.

when operated together in hover, for the case where the tail rotor has top-aft direction of rotation. When influenced by the flow field of the main rotor wake, the tail rotor wake undergoes a radical change in its geometry. Instead of streaming out to the left of the helicopter as might be expected from the earlier images, after a very short distance it becomes entrained into the wake structure of the main rotor. A similar 'snap-shot' image of the combined wakes of the main and tail rotor when in left-quartering flight is shown in Fig. 6(a). In this flight condition a significant proportion of the tail rotor wake is drawn directly through the main rotor; shortly afterwards the wakes of the two rotors merge into a single structure.

This format does little, though, to reveal the origins of the unsteadiness in the loading on the two rotors. In this vein, however, the completeness of the physical description of the system that is provided by the high-fidelity model becomes a distinct advantage over the simpler simulation tool in terms of the possibilities for diagnosis of the behaviour of the system. In particular, the VTM provides a full description of the vorticity field that is induced by the rotors at each instant in time. Consequently, a variety of statistical analyses in the time domain may be performed in order to yield insight into the influence of the wake on the loading on the rotors. Decomposition of the wake into its mean structure together with a superimposed fluctuation yields considerable insight into the origin of the variability in the loading on the rotors, for instance. The mean component of the wake, $\bar{\omega}(x,t)$, can be approximated simply as the ensemble average

$$\bar{\omega}(x,t) = \frac{1}{2n+1}\sum_{i=-n}^{n} \omega(x, t+i\Delta t) \qquad \ldots (3)$$

over $2n + 1$ snapshots of the wake structure, $\omega(x,t)$, spaced apart by equal time intervals Δt. The associated RMS field representing the local fluctuations in the wake structure may then be calculated as

$$\hat{\omega}(x,t) = \left[\frac{1}{2n+1}\sum_{i=-n}^{n} (\omega(x, t+i\Delta t) - \bar{\omega}(x,t))^2\right]^{1/2} \qquad \ldots (4)$$

Such a decomposition of the structure of the wake, with the system in quartering flight, is shown in Fig. 6(b). In this figure, the geometry of the mean wake is represented by the lighter, translucent

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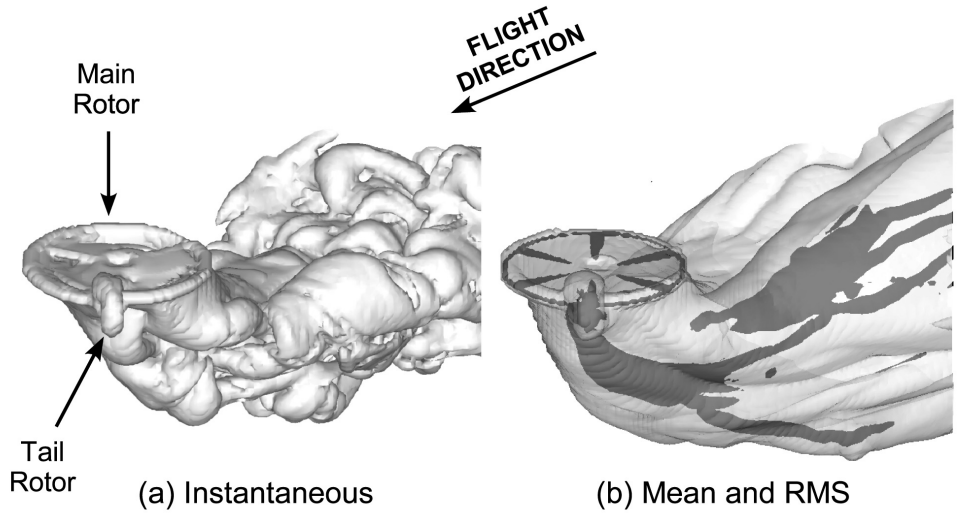


Figure 6. Wake of combined system in quartering flight, μ_x = –0·0283; μ_y = –0·0283.

surface, while the regions of greatest fluctuation within the structure of the wake are encapsulated by the darker surface. The mean wake can be used to gain some appreciation of the effects of the interaction between the two rotors on the gross geometry of the wake of the system at the particular flight condition of interest. The RMS field provides more detailed information. For instance, from Fig. 6(b) it can be seen that, although the region of greatest unsteadiness in the vorticity field includes the volume encapsulating the tail rotor, a region of significant unsteadiness also extends a considerable distance downstream into the wake of the combined system. The extent and location of this portion of the RMS field is associated with the extremely unsteady process whereby the wakes of the two rotor systems merge into a combined structure. It is almost certain that the long-range effect of this unsteadiness in the wake on the velocity distribution near the rotor is responsible for the unsteadiness in the performance of both the main and tail rotor in quartering flight[12]. Yet, governed as it is by local interactions between individual vortices within the wake, it is precisely this fundamental physical component of the interaction between the two rotors that is missed by simpler flight dynamics models that contain only a gross rendition of the dynamics of the wake. Even with full access to the physical content of the high fidelity model it can still be difficult to pin down the precise fluid dynamic mechanisms that lie at the heart of the observed behaviour of the system. In particular, the reason why the calculations should be sensitive to the direction of rotation of the tail rotor is still obscure, as is, in any meaningful sense, the reason why the merging of the two wakes should necessarily be associated with such unsteadiness in certain flight conditions but not in others. These issues are all subject to further study using very high resolution simulations that are able to resolve in detail the trajectories of the individual vortex cores and sheets that constitute the wakes of the two rotors.

5.0 A SIMPLE FLIGHT MECHANICS MODEL

The fact that calculations of this magnitude might be required to resolve the aerodynamic origins of some of the interaction-related dynamics of the two rotors does not bode entirely well for the idea that the essence of the high-fidelity simulations might be encapsulated in some way and incorporated into the types of model that might be exploited on a routine engineering basis. The question then remains how some representation of these effects can be incorporated into simpler flight mechanics models to allow them to reproduce, at least, some aspects of the behaviour of more complete models for the dynamics of the system.

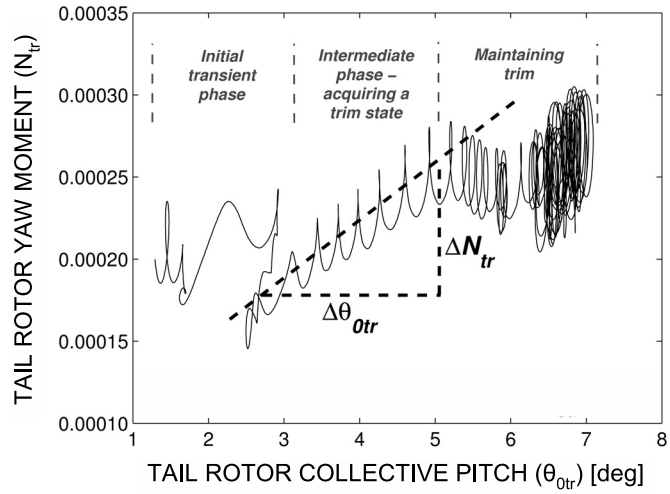


Figure 7. Tail rotor yaw moment *vs* collective pitch in quartering flight.

An example of how this might be achieved is illustrated using the data presented in Fig. 7. The simplest technique for helicopter flight dynamic analysis is borrowed from the fixed-wing community. The equations of motion for the vehicle are linearised about the trim state of interest; the linearised equations of motion are then used to analyse the small-perturbation dynamics of the vehicle about the trim state. In this way the stability of the system, the characteristic modes and frequencies of the dynamics and so on can be determined. The linearised equations are expressed in terms of a number of so-called stability derivatives – essentially the derivatives of the loads on the vehicle with respect to the various states that describe the dynamics of the system. The stability derivatives that are applicable to the trim state of interest are not inherent in the formalism, though, but need to be estimated using some external process. The figure shows the tail rotor contribution to the yaw moment on the vehicle as a function of tail rotor collective pitch, as

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predicted by the VTM for the entire duration of the simulation of the conventional helicopter configuration in quartering flight. The curve illustrated in this figure is essentially parameterised by time, and consists of three distinct phases. The leftmost portion of the curve is generated during the initial, transient dynamic of the system during which the wake of the helicopter is established. The rightmost portion of the curve is generated while the controller attempts to maintain the system in a state of trim. The intermediate segment of the curve, though, is generated once the wake of the system is relatively well established. In this phase of the simulation, the controller is attempting to match the yaw moment developed by the tail rotor to the torque generated by the main rotor by finding an appropriate setting for the tail rotor collective pitch. If one is prepared to ignore the pitfalls in using a linearised approach to helicopter flight mechanics based on stationary stability derivatives that are revealed in this figure, then the slope of the straight line obtained by regression on the data in this intermediate segment of the curve can be used as an estimate for the primary tail rotor control derivative $\partial N_r/\partial\theta_{0_{tr}} = N_{\theta 0_{tr}}$. The data presented in Fig. 7 yields $N_{\theta 0_{tr}} \approx \Delta N_r/\Delta\theta_{0_{tr}} = 0{\cdot}000036\rho A(\Omega R)^2 R$ which compares realistically to data obtained experimentally under more benign flight conditions. The important point to take on board is that this estimation technique takes into account the influence on the derivative of the interaction between the main rotor and the tail rotor as relevant to the particular flight condition under analysis - something that is very difficult to do using more conventional estimation techniques. Suitable simulations can also be devised to estimate various of the other stability derivatives that enter into the linearised equations of motion for the system.

As a second example, consider the influence of the time constants in the 'pilot' model used to drive the system towards trim. By varying the time constants a spectrum of behaviours can, in principle, be recovered, most having some relevance to the behaviour of the real aircraft. If the time constants are set somewhat smaller than was the case earlier, then the control system takes on the characteristics of a vibration suppression system where even the high-frequency components of the fluctuating loading on the helicopter can be ameliorated. Setting the time constants considerably larger than was the case earlier corresponds perhaps to the situation where the pilot remains passive rather than actively applying the requisite control inputs to trim the aircraft. In this case a smaller proportion of the loads on the system may be ameliorated by control input and the yaw dynamics of the airframe might be stimulated. The simplest models ignore the low-frequency forcing of the system that results from the aerodynamics of the interaction between the main and tail rotors, since this does not arise naturally from within the formalism itself. The results of the simulations presented earlier should serve to remind the analyst, especially when using these simple models, of the possibility of interaction between the low-frequency forcing from the wake and the dynamics of the pilot or the low-frequency structural or rotor modes that might, under unfavourable conditions, result in extremely objectional dynamical behaviour of the vehicle.

6.0 CONCLUSION

The two applications described in the previous section may be considered as constituting a relatively weak interaction between high-fidelity simulation and modelling on the level that is suitable for routine flight dynamic analyses. The ultimate goal should be to use the high-fidelity model to inform the construction of a simple but comprehensive phenomenological model for the dynamic effects of the aerodynamic interaction between a main and tail rotor that encapsulates the effects of flight condition and direction of tail rotor rotation, perhaps in a small set of relatively simple ordinary differential equations. This model could then be incorporated wholesale into simpler analysis techniques to allow them to reproduce the requisite effects within their predictions. Progress towards such a goal might be encouraged by considerable success in the construction of phenomenological models for dynamic stall, rotor wake and tailplane interaction, and, to a somewhat more limited extent, the vortex ring state. Yet the results presented here caution against overt optimism in this regard, suggesting as they do that the physical mechanisms that drive the aerodynamic interaction between the main rotor and the tail rotor operate at length-scales which are at least two orders of magnitude smaller than the separation between the rotors themselves, and are buried in the mutual interactions between elements of the detailed vortical structure of the wake far from their source on the rotor discs. These mechanisms are difficult to resolve and understand using even the most powerful computational techniques that are currently available, let alone simpler aerodynamics tools. For the moment helicopter interactional aerodynamics remains poorly understood and an area ripe for further research for both practical and academic reasons, and computations continue to reveal to us the extent of our lack of detailed understanding of the dynamics of this exceedingly complex class of flying machines. Yet, as computers have advanced in power by the year, some of the most advanced computational models, as demonstrated here, have begun to show tantalising glimpses of what may be possible given just a few more gigabytes of accessible RAM or megahertz of clock speed.

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