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A Rational Approach to Comparing the Performance of Coaxial and Conventional Rotors

Hyo Won Kim[1]
Postgraduate Research Student
Department of Aeronautics
Imperial College London
London, UK

Richard E. Brown*
Mechan Chair of Engineering
Department of Aerospace Engineering
University of Glasgow
Glasgow, UK

The merit, in terms of its efficiency and performance, of the twin, contrarotating coaxial rotor configuration over the more conventional single rotor system has long been a point of contention. Previously published comparisons yield seemingly inconsistent and conflicting conclusions. In this paper, the basis for a fair, like-for-like comparison of the performance of coaxial and single rotor systems is discussed. A comparison between experimentally measured data and numerical predictions of rotor performance obtained using the vorticity transport model shows that a computational approach can be used reliably to decompose the power consumption into induced and profile constituents. These comparisons show that a somewhat stronger similarity in geometry needs to be enforced between the two types of rotor system than previously suggested in order that the systems be directly comparable. If the equivalent single rotor system is constructed to have the same disk area, blade geometry, and total number of blades as that of the coaxial rotor, then the geometric differences between the two systems are confined to the defining characteristics of the two types of rotor system, in other words to the vertical separation between the rotor blades and their relative direction of rotation. The differences in aerodynamic performance between a coaxial rotor and an equivalent single rotor defined in this way then arise solely as a result of the differences in the detailed interaction between the blades and their wakes that arise within the two types of system. Using this form of comparison, the articulated coaxial system is shown to consume marginally less induced power than the equivalent single rotor system. The difference is small enough, however, to be obscured if the profile drag of the blades is overtly sensitive to operating condition, as for instance might be the case at low Reynolds number.

Nomenclature

C_D sectional profile drag coefficient
C_P rotor power coefficient
C_T rotor thrust coefficient
K coefficients of airfoil drag model
α angle of attack
θ_0 collective pitch
θ_{1s} longitudinal cyclic pitch
θ_{1c} lateral cyclic pitch
μ rotor advance ratio
σ rotor solidity

Subscripts

i induced component
l lower rotor of coaxial system
p profile component
u upper rotor of coaxial system

*Corresponding author; email: r.brown@aero.gla.ac.uk.
Manuscript received June 2007; accepted July 2009.
[1]Currently Postdoctoral Research Assistant, Department of Aerospace Engineering, University of Glasgow, Glasgow, UK.

Introduction

Recent developments in the rotorcraft world, led by Sikorsky Aircraft Corporation's announcement of their X2 demonstrator and the development of several unmanned aerial vehicle (UAV) prototypes, indicate a resurgence of interest in the coaxial rotor configuration as a technological solution to operational requirements for increased helicopter forward speed, maneuverability, and load-carrying ability.

The coaxial concept is not new, of course. Although Russia has historically been the world's largest developer and user of coaxial rotor helicopters, and an extensive body of research has been produced in that country, the United States, United Kingdom, Germany, and Japan have also pursued research into the coaxial rotor configuration (Ref. 1). Some highly innovative designs, such as Sikorsky's S-69 advancing blade concept (ABC) (also known as the XH-59A), and Kamov's Ka-50 attack

Note: Throughout this paper, the lower rotor of the coaxial system should be taken to rotate anticlockwise, and the upper rotor to rotate clockwise, when viewed from above. In single rotor simulations, the rotor should be taken to rotate anticlockwise when viewed from above.

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helicopter, have attempted to exploit the coaxial configuration to obtain improved performance in parts of the flight envelope.

In several cases, however, the performance of practical coaxial configurations fell short of expectations, and this led to a temporary hiatus in the development of the concept. In many such cases the shortcomings in the practical implementation of the coaxial concept could be traced back to deficiencies in modeling or understanding the specific details of the interaction between the rotors and the effect of the wake on the behavior of the system—especially under unsteady flight conditions. In recent years, though, computational tools have developed to the extent where the highly interactive and nonlinear wake flows generated by the two rotors of the coaxial configuration can be modeled with a much greater degree of confidence than has been possible in the past.

Despite this, the actual merit of the coaxial rotor system relative to the more conventional, single rotor system in terms of performance and efficiency still remains as a point of contention in some quarters. Some previously published comparisons of the performance of the coaxial system relative to its conventional counterpart run the risk of being misinterpreted, however. This is because of the inconsistent basis upon which the comparisons are founded (Ref. 1). For instance, it is tempting to reconcile the thrust and power of two disparate rotor systems simply by normalizing by rotor solidity. This discounts the fact though that a rotor with relatively low solidity has limited thrust-producing capacity as a result of the onset of blade stall at higher thrust coefficients, and thus compares poorly with a high-solidity rotor when compared on this basis. In fact, blade element theory can be used to demonstrate that a unique relationship between normalized power and normalized thrust can be obtained only for rotors of identical disk area *and* solidity.

The principal aim of this paper is thus to show that a rational basis for the comparison of coaxial and conventional rotor systems can be defined in which differences in the efficiency and performance of the two types of rotor emerge solely as a result of the fundamental differences in the configuration of the two systems. To do this, a comprehensive rotor code, known as the vorticity transport model (VTM), is first shown to capture accurately the performance of coaxial rotor systems as well as conventional single rotor systems. This is done by comparing numerical predictions against a set of measured data from full-scale experiments. Having established the ability of the VTM to resolve the differences in the performance of the two types of rotor, the model is then used to explore the sensitivity of the overall performance of coaxial and conventional rotor systems to the method that is used to trim the rotor. An equivalent conventional single rotor system is then defined that differs geometrically from the coaxial rotor only in terms of those features that differentiate the two types of rotor configuration from each other—in other words, the vertical separation between the rotor blades and their relative direction of rotation. The differences in aerodynamic performance between a coaxial rotor and its equivalent single rotor defined in this way should then arise solely as a result of the differences in the detailed interaction between the blades and their wakes that arise within the two types of system, and hence this definition of equivalence should yield the fairest comparison between the performance of the two types of rotor.

Computational Model

The VTM, developed by Brown (Ref. 2) and extended by Brown and Line (Ref. 3), is used in this paper to calculate the performance of both conventional and coaxial rotor systems. The VTM has shown considerable success in both capturing and preserving the complex vortex structures contained within the wakes of conventional helicopter rotors (Refs. 2 and 3) and has been used previously to study rotor response to wake encounters (Refs. 4 and 5), the vortex ring state (Refs. 6 and 7), and the influence of ground effect (Refs. 8 and 9) on the performance of helicopter rotors.

The VTM is based on a time-dependent computational solution of the vorticity–velocity form of the Navier–Stokes equations on a Cartesian grid surrounding the rotorcraft. The problem of preserving the vortical structures in the flow from the effects of numerical dissipation is addressed very effectively by the convection algorithm that is used in the VTM, resulting in a wake structure that remains intact for very large distances downstream of the rotor system. Hence long-range aerodynamic interactions that are produced by wake effects generally tend to be well represented.

The VTM uses an adaptive grid system to follow the evolution of the wake. This is done by generating computational cells where vorticity is present and destroying the cells once the vorticity moves elsewhere. The computational domain is thus effectively boundary-free, and significant memory savings are achieved using this approach. Computational efficiency is further enhanced by using a series of nested computational grids to capture the wake. The cells within the outer grids are arranged to be coarser than those closer to the rotor. This helps to reduce the overall cell count during a computation whereas still maintaining a highly resolved flow field near the rotor.

In the present work, the rotor blades are assumed to be structurally rigid but the coupled flap–lag–feather dynamics that are endowed by an articulated rotor hub are fully represented. This is done through numerical differentiation of the nonlinear Lagrangian of the system to obtain the equations of motion of the blades. In the version of the VTM used to generate the results presented in this paper, the blade aerodynamics are modeled using an extension of the Weissinger-L version of lifting line theory. Local blade stall is modeled using a variation on Kirchoff's trailing edge separation model, where the length of the stall cell is given as a prescribed function of local angle of attack based on known airfoil characteristics. Since this aerodynamic model is still essentially inviscid, the profile drag of the blade is calculated as a separate function of local angle of attack and then added to the local aerodynamic force that is calculated from the lifting line model. Configurations with multiple rotors, such as coaxial systems, can be dealt with very easily since each blade of each rotor, through its production of trailed and shed vorticity in response to its aerodynamic loading, can be treated simply as a source of vorticity into the computational domain.

Throughout the simulations presented in this paper, the computational domain is discretized such that one rotor radius is resolved over 40 grid cells. The computational time step used to evolve the simulations is chosen to be equivalent to 3 deg of the rotor azimuth.

Model Verification

A very useful benchmark, against which the performance of computational models for interacting rotors can be evaluated, exists in the form of Harrington's experimental study of coaxial rotor performance in hover (Ref. 10). An interesting feature of Harrington's work was that he compared the performance of his coaxial rotor against the performance of a conventional single rotor—actually one of the two rotors from his coaxial configuration—allowing the data to be used to assess the ability of computational methods, particularly those that have proved adequate for conventional rotors, to represent the more highly interactive aerodynamic environment of the coaxial rotor.

Two different coaxial rotor configurations were tested in Harrington's original study; in this paper, the ability of the VTM to predict the performance of coaxial systems is assessed by comparing numerical results against the experimental data for the system referred to as "rotor 1" in Ref. 10. This coaxial system consisted of two, contrarotating, two-bladed teetering rotors, separated by $0.19R$ along their shared rotational axis.

Table 1. Summary of rotor properties

Rotor radius	R
Number of rotors	2
Blades per rotor	2
Rotor separation	$0.190R$
Root cutout	$0.133R$
Solidity	0.054
Twist	None
Flap hinge offset	0 (teetering)
Chord (tapered)	$0.076R$-$0.029R$ (linear)
Thickness (tapered)	$0.023R$-$0.003R$ (nonlinear)
Airfoil sections	NACA-00xx series
Lock number	4.3 (estimated)

The rotors were operated at a tip Reynolds number of approximately 1×10^6. The blades were untwisted and had linear taper. A significant complication, from a modeling perspective, was introduced by allowing the blades to change thickness in a nonlinear way along the span of the blade. Although the blade sections were based on the symmetric NACA four-digit profile, this feature resulted in nonstandard airfoil sections, for which measured aerodynamic information is unavailable, on most parts of the blade. The geometry of the rotor is summarized in Table 1.

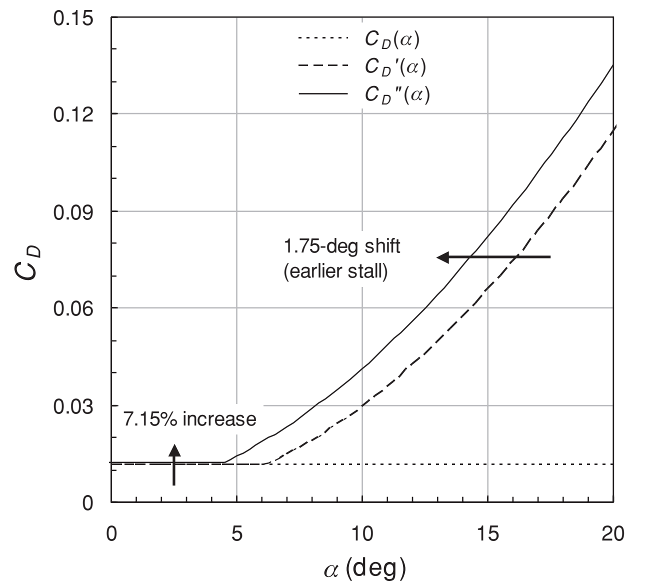


Fig. 2. Variation of sectional profile drag coefficient with angle of attack as used in the VTM simulations.

Calibration of the drag model

In the absence of drag data for the airfoil sections, Harrington's experiment was replicated using a number of rather simple profile drag models within the VTM. Initially the profile drag was simply assumed to be independent of angle of attack so that

$$C_D(\alpha) = K_0 \tag{1}$$

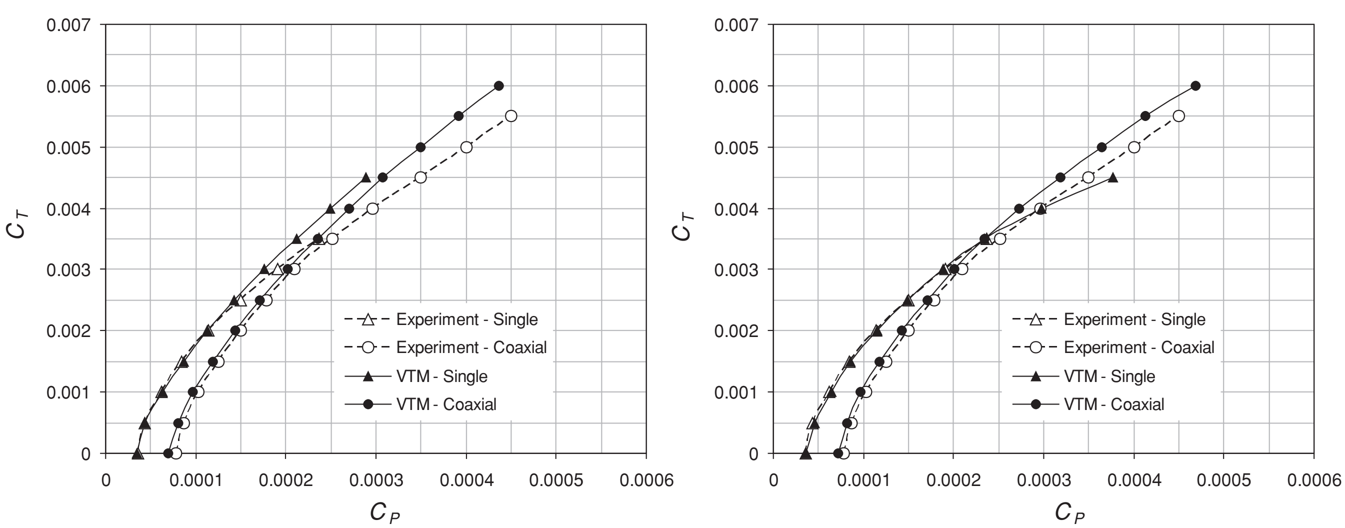
The same drag model was used everywhere along the blade regardless of its sectional profile; the value $K_0 = 0.0115$ was selected to reproduce the experimentally measured torque on Harrington's isolated single rotor at zero thrust.

Figure 1(a) shows a comparison between Harrington's experimental data and VTM calculations of power vs. thrust using this profile drag model. As is to be expected, there is a significant discrepancy in the predicted power consumption of both the coaxial and single isolated rotors, especially at high C_T where airfoil stall and the associated increase in drag becomes significant.

Figure 1(b) shows a comparison between experiment and the VTM-calculated power vs. thrust using a somewhat more sophisticated profile drag model that represents the drag rise due to blade stall at high angle of attack in a more realistic fashion. Compared to the earlier model, this second profile drag model simply modifies the poststall behavior of the airfoil sections by switching to a nonlinear variation of drag at high angle of attack, as shown in Fig. 2. More specifically,

$$C_D'(\alpha) = \max\left[K_0,\ K_1(1 - \cos 2\alpha)\right] \tag{2}$$

where α is the local angle of attack of the blade section. Setting $K_1 = 0.49$ gave the best fit between VTM predictions and the measured performance of Harrington's isolated single rotor.



(a) Using $C_D(\alpha)$ profile drag model

(b) Using $C_D'(\alpha)$ profile drag model

Fig. 1. Power vs. thrust: VTM simulations compared to Harrington's experimental data.

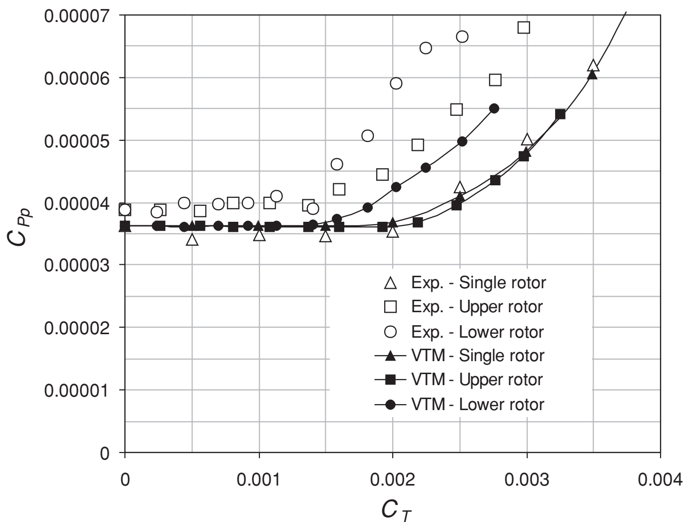


Fig. 3. Comparison of VTM computed profile power (using C'_D drag model throughout) against experimental estimates.

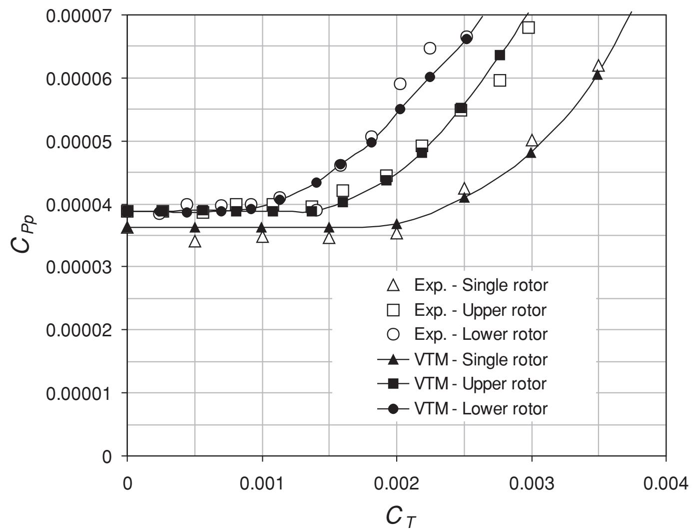


Fig. 4. Comparison of VTM computed profile power (using C''_D drag model for coaxial and C'_D drag model for single rotor) against experimental estimates.

As shown in Fig. 1(b), very good agreement between experiment and numerics is indeed obtained for the isolated rotor using this drag model, but the power consumed by the coaxial rotor is still significantly underpredicted at high C_T. In addition, it might have been expected that, at zero thrust, the power consumed by the coaxial system would have been exactly twice that of the isolated single rotor, given that the blades of the rotors were not twisted. The VTM suggests that this is indeed the case, but the experimental data reveal Harrington's coaxial system to have had a slightly higher power consumption at zero C_T.

These discrepancies are revealed more clearly in Fig. 3, where the profile component of power consumed by the isolated rotor, and each constituent rotor of the coaxial system, is plotted against its own thrust, rather than against the overall thrust produced by the rotor system. In this figure, predicted values are compared against experimental estimates that were obtained by subtracting the computed induced component from the measured total power of the system, and, in the case of the coaxial rotor, enforcing the condition that at trim each rotor should consume the same overall power. As can be seen, the calculated VTM results obtained for the isolated single rotor using the more sophisticated drag model agree very closely with the experimental estimates of the profile power for this system. The calculations suggest, however, that the upper rotor of the coaxial system should have a nearly identical variation of profile power with thrust to that of the isolated single rotor, whereas the experimental data reveal that the upper rotor of Harrington's coaxial system to have had a significantly higher profile power consumption than his isolated rotor. In both cases, the profile power consumption of both upper and lower rotors is very similar at low thrust, but, as thrust is increased, the profile power consumption of the lower rotor becomes significantly greater than that of the upper rotor.

The simulations thus suggest, as far as profile power is concerned, that the upper rotor of the coaxial system operates effectively as if it were in isolation while only the performance of the lower rotor is affected significantly by the presence of a second rotor. If the interaction between the two rotors is dominated by the behavior of the wake of the system, then this behavior is to be expected. It is shown in Ref. 11 that a significant proportion of the lower rotor is immersed in the wake of the upper rotor, whereas the upper rotor is affected most directly by its own wake and only indirectly by the presence of the wake of the lower rotor. Any wake-induced interactional effects (on profile power as well as more obviously on induced power) should thus be far more pronounced on the lower rotor than on the upper and, indeed, should become more obvious as the thrust of the system is increased.

The observed discrepancy between the experimental data for the profile power consumption of the isolated rotor and the coaxial rotor can be reconciled fairly easily with this notion of the effect of aerodynamic interactions within the system, though, if a slight difference between the profile drag characteristics of the two rotor systems is allowed for. By rewriting the sectional profile drag model for the coaxial system in slightly more general form as

$$C''_D(\alpha) = \max\,[K''_0,\ K_1\{1 - \cos 2(\alpha + \alpha_{\text{mod}})\}] \tag{3}$$

to allow the zero-lift drag coefficient (i.e., K''_0) to be increased by 7.15% and the stall angle of the airfoil to be reduced by $\alpha_{\text{mod}} = 1.75$ deg (see Fig. 2) then a significantly better match between calculations and the experimentally determined profile power of the coaxial system is achieved, as is shown in Fig. 4. This small change in the drag model translates into a very much improved agreement between the VTM predictions and Harrington's experimental data for the overall power consumption of the coaxial system, as shown in Fig. 5. Even bearing in mind the relatively low tip Reynolds number of the experimental system, and the likelihood thus that the sectional drag would be sensitive to the precise conditions on the rotor blade (Ref. 12), it seems a little glib to attribute the modification to the drag polar that is required to achieve a good match with the experimental data for the coaxial rotor simply to some small discrepancy in Reynolds number between the experiments conducted on the isolated single rotor and on the coaxial rotor (such as might arise from imperfect control of the rotor speed, for instance). This many years after Harrington's experiments were conducted, the exact reason for this rather curious discrepancy can only be guessed at, but a purely viscous, or noncirculatory interaction between the two rotors of the coaxial system that is beyond the present capabilities of the VTM to resolve cannot be discounted (see Refs. 13 and 14, for instance).

Power Comparisons

A major advantage of a computational analysis compared to an experimentally based study is that the numerically calculated power

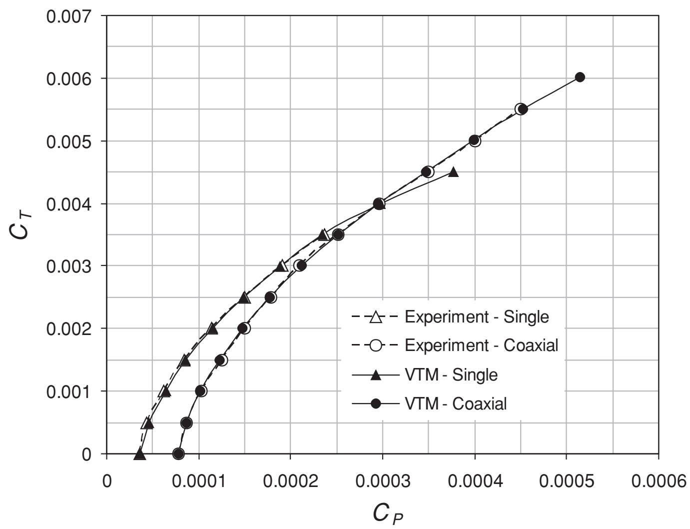


Fig. 5. Power vs. thrust: VTM simulations compared to Harrington's experimental data.

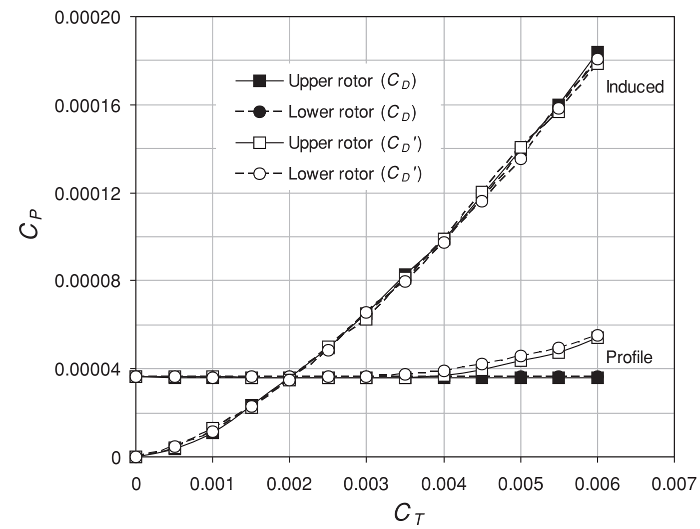


Fig. 6. Power constituents for the coaxial system in hover, as a function of overall thrust coefficient.

consumption of a rotor can easily be separated into its parasite, profile, and induced constituents. With a conventional rotor, any uncertainty in performance that might arise from uncertainty in the profile drag characteristics of the rotor blades can thus be confined to the resultant uncertainty in the profile power consumption of the system without influencing the argument regarding the other constituents of the rotor power. This is because the torque produced by the rotor for any given thrust is canceled by independent, external means (e.g., by the tail rotor). For a coaxial rotor, the situation is slightly more complicated: Any uncertainty in the profile power consumed by the rotor stands the risk of translating directly into a similar uncertainty in the induced power because of the additional requirement that, for trim at any given overall thrust, both rotors must generate the same net torque. Thus, in reaching any generally valid conclusions regarding the relative performance of coaxial and conventional rotor systems, as is attempted in this paper, extreme care must be taken to ensure the robustness of any results to the particular profile drag characteristics of the systems being compared. This is despite the fact that in both types of rotor system the primary effect of the wake is on the induced power.

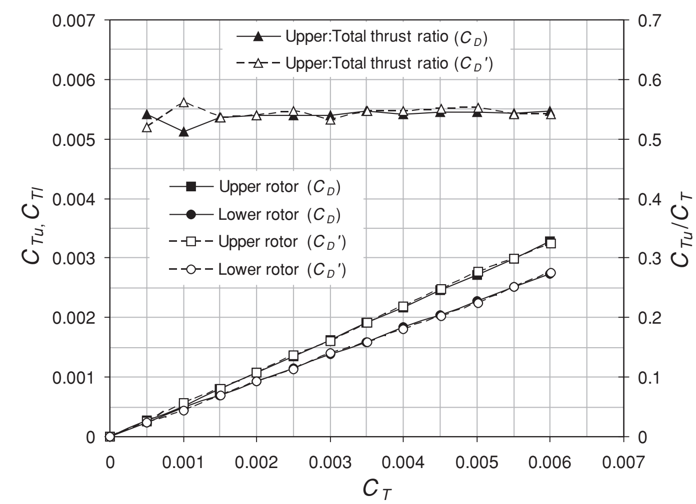


Fig. 7. Thrust sharing between the upper and lower rotors of the coaxial system in hover, as a function of overall thrust coefficient.

Hover

Figure 6 shows the VTM-predicted partition of power between the upper and lower rotors, separated into profile and induced constituents as a function of overall thrust coefficient, that results from satisfying the trim condition of zero net torque on Harrington's coaxial rotor. Figure 7 shows the associated partition of thrust between the upper and lower rotors that is required to generate overall torque balance within the system. The sensitivity of the trim state to the profile drag characteristics of the blades can be judged by contrasting the results of the calculations presented in these figures using the simple, constant C_D model and the more representative C'_D profile drag model. Even though the two models produce distinctly different predictions of the profile power consumption of the rotor, particularly at high thrust coefficient, the figures show that, no matter what the profile drag characteristics of the blades, the profile power differential between the upper and lower rotors that results from trimming the system amounts to a very small percentage of the overall power consumed by each individual rotor and has almost negligible effect on the partition of thrust between the upper and lower rotors. It is hopefully not too great an extrapolation from the limited results presented here to suggest, thus, that a comparison between coaxial and conventional rotors, at least in terms of induced power consumption, can indeed be conducted without undue obscuration by the link between induced and profile power that results from the method that is used to trim the coaxial system.

Forward flight

Turning next to the ability of the VTM to capture the performance of coaxial rotors in forward flight: This aspect of the performance of the model can be assessed rather neatly by comparing predictions against wind-tunnel data from Dingeldein's 1954 investigation of the performance of various coaxial rotor configurations (Ref. 15). The advantage of using this data set is that one of the rotors used in Dingeldein's study was geometrically identical to Harrington's "rotor 1," and hence comparison with these data provides a logical extension to the assessment of the predictive capability of the VTM in hover that was presented above.

VTM simulations of Dingeldein's coaxial rotor were conducted over a range of forward flight speeds. To represent the effects of fuselage

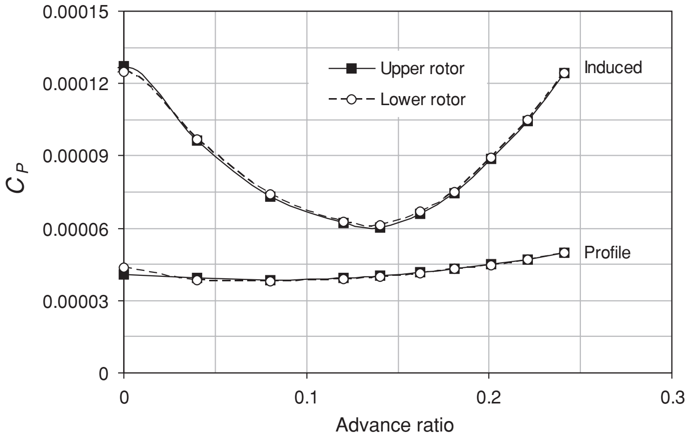


Fig. 8. Power constituents for the coaxial system in forward flight, as a function of advance ratio (overall $C_T = 0.0048$).

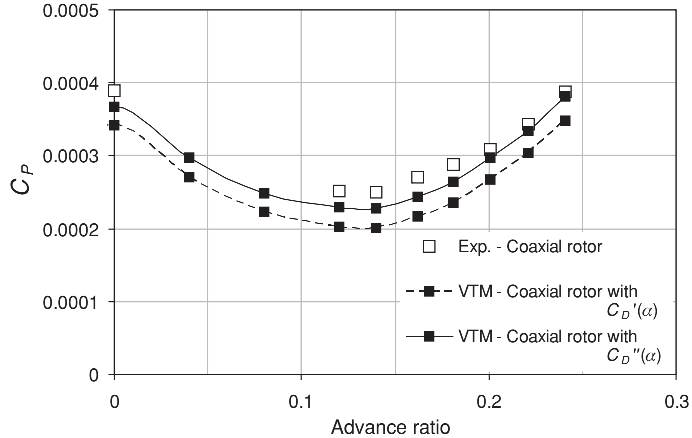


Fig. 10. Overall power consumption for the coaxial system in steady level flight ($C_T = 0.0048$).

parasite drag on the trim state of the experimental system, the forward tilt of the rotor was adjusted to produce sufficient forward force to overcome the drag corresponding to a fuselage equivalent flat plate area of 0.02 times the rotor disk area. This effect was replicated in the simulations by trimming the rotor to the required force using collective pitch, aligning the shaft with the required thrust vector and trimming out residual lateral and longitudinal forces using suitable cyclic pitch input. The simple, mechanical linkages between the upper and lower rotors of Dingeldein's coaxial system were reproduced in the simulation by applying equal cyclic pitch inputs to both upper and lower rotors. As in the experiment, differential collective pitch was used in the simulations to trim the rotor to zero net yawing moment.

Figure 8 shows the VTM-predicted partition of power between the upper and lower rotors (as was shown in Fig. 6 for hover), separated into profile and induced constituents as a function of advance ratio, that results from satisfying the trim condition of zero net torque. Figure 9, showing the associated partition of thrust between the upper and lower rotors, reveals that the unequal partition of thrust initially seen at hover (in Fig. 7) converges to an equal partition between the two rotors as the forward speed is increased. This is consistent with the interaction between the upper and lower rotors diminishing gradually as the freestream velocity increasingly dominates over the vorticity-induced velocity within the wake in governing the rate of convection of the vorticity in the wake. Figure 10 shows a comparison between VTM simulations and Dingeldein's measurements of power consumption against advance ratio with his rotor trimmed to a thrust coefficient of 0.0048 throughout. Calculations using the C_D' and the C_D'' profile drag models both underestimate slightly the experimental measurements of power, but the trend of the data is well matched by the VTM predictions over the entire speed range that was simulated. It is worth noting though that Dingeldein's and Harrington's measurements on ostensibly the same rotor system of the power required to hover at $C_T = 0.0048$ are not consistent—Dingeldein's measurement of hover power was greater than Harrington's by approximately 5%. It is thus plausible that another small adjustment to the profile drag model, along lines similar to that which was required in the hover simulations described earlier, would be all that would be required to yield very close agreement between experimental and simulated results. However, the apparent variability in the profile drag characteristics of the blades within Harrington and Dingeldein's series of tests is a distinct frustration to comprehensive validation of numerical predictions using their otherwise very valuable data.

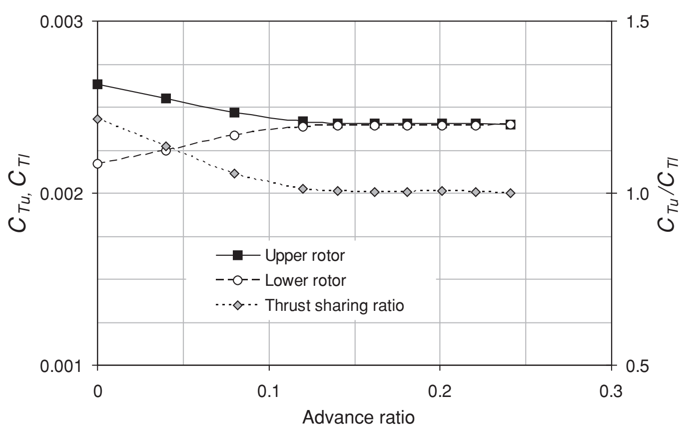


Fig. 9. Thrust sharing between the upper and lower rotors of the coaxial system in forward flight, as a function of advance ratio (overall $C_T = 0.0048$).

Coaxial and Conventional Rotors Compared

The power required by a rotorcraft for a given lifting capacity is usually determined by the hover performance of its rotor system. For a coaxial rotor, trim of the yawing moment is achieved by matching the torque of the upper and lower rotors via differential collective pitch input so that the net torque about the shared rotor axis is zero. It has long been a point of contention whether or not this arrangement is more efficient than the more conventional main rotor—tail rotor configuration, bearing in mind that the tail rotor typically consumes an additional 10% of the main rotor power to maintain overall yaw moment equilibrium in steady hover, and about 5% in forward flight (Ref. 12).

When comparing the performance of a coaxial rotor configuration to that of a conventional rotor system, care must be taken to ensure appropriate equivalence between the two systems. Various aspects of the relative performance of the two systems can be made more (or less) apparent depending on whether the comparison is performed at equal disk loading or equal thrust coefficient, for instance. Figure 5 may be interpreted, at face value, to suggest that Harrington's single rotor is more efficient than his coaxial rotor at low thrust but less efficient at

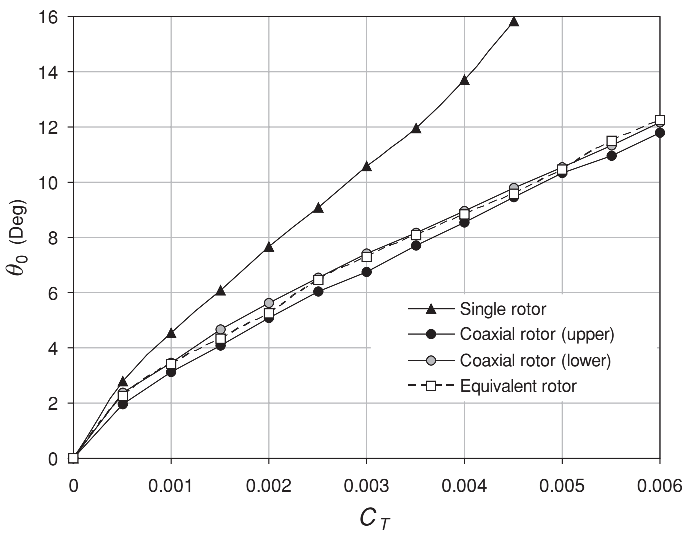


Fig. 11. Collective pitch required to trim to given thrust coefficient (using C_D' profile drag model throughout).

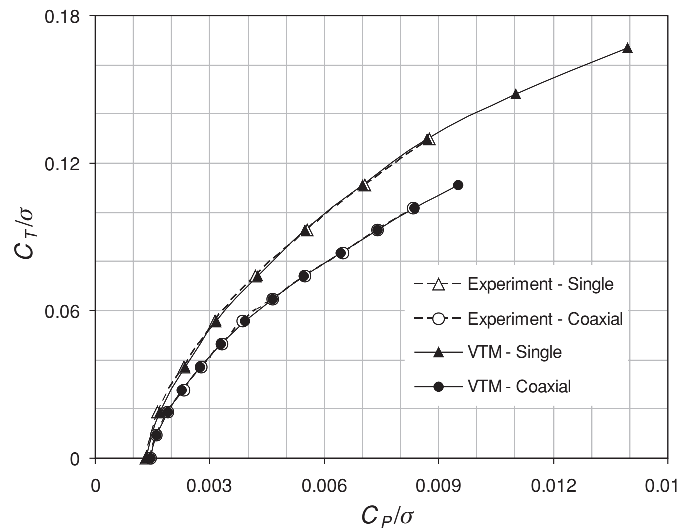


Fig. 12. Power vs. thrust: comparison after normalizing by rotor solidity.

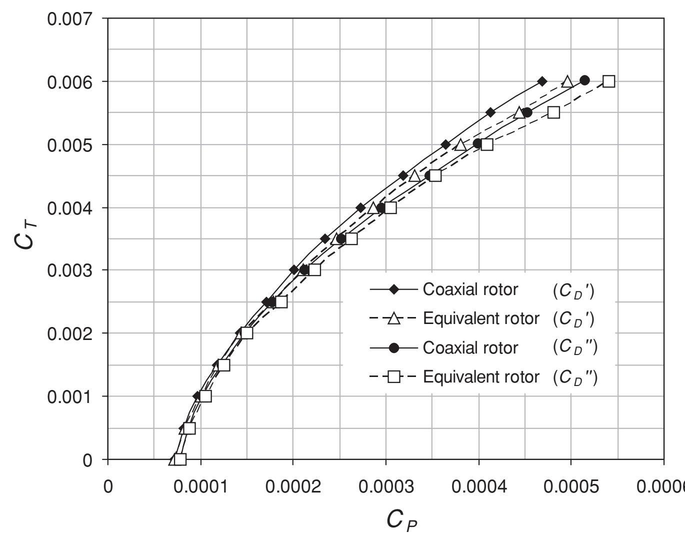


Fig. 13. Power vs. thrust: comparison between rotors with identical solidity and blade properties.

higher thrust. This is obviously the case, but somewhat obscures the point that Harrington's single rotor is relatively limited in lifting capability by rotor stall compared to the coaxial rotor simply because it has half the blade area of the coaxial system. This is shown more clearly in Fig. 11 where, compared to the coaxial rotor, the rapid divergence in the collective pitch required to trim the single rotor is indicative of a sharp decline in the VTM-predicted lifting capability of the rotor beyond a thrust coefficient of approximately 0.003. The pitfalls of this form of comparison lie essentially in the unmatched solidities of the two systems (Ref. 16). It is tempting to try to avoid this problem simply by normalizing C_T and C_P by the rotor solidity. Figure 12 shows the data from Fig. 5 rescaled in this manner and appears to reveal that, per blade, the single rotor is more efficient than the coaxial rotor throughout the tested range of thrust coefficients. For the comparison between the two configurations to be wholly consistent, though, it seems most reasonable to compare the performance of the coaxial rotor against a conventional system that has as similar geometry to the coaxial rotor as possible so that differences in performance can be attributed properly to the fundamental differences in configuration between the two types of rotor system. Such a comparison is presented in Fig. 13. In this figure, VTM predictions of the performance of Harrington's two-bladed coaxial rotor are compared against predictions of the performance of a four-bladed, conventional (i.e., planar, corotating) rotor configuration with blades that do have the same geometry and aerodynamic properties as the blades of the coaxial rotor. This approach yields a comparison between rotors that have the same solidity and hence very similar lifting performance, as indicated in Fig. 11 by the similarity in the collective pitch required by the two rotors to trim to a given thrust coefficient. This form of comparison exposes most clearly the effects on performance that are induced solely by the fundamental differences in the configuration of the two types of rotor system, in other words, the relative sense of rotation of the blades and their vertical separation.

Presentation of the data in the form of Fig. 13 shows the equivalent conventional rotor to consume slightly more power than the coaxial rotor as thrust coefficient is increased, but also that the difference in performance between the two rotor systems is of similar order to the uncertainty in their profile power consumption, as indicated by the two drag models. The data thus raise significant doubt as to whether an absolute and general quantification of the merits of conventional rotors relative to coaxial systems in terms of *overall* power consumption is possible. This is because the rather small differences in performance that are seen between the two systems implies that the blade aerodynamic properties under the precise operating conditions of the systems being compared may have significant impact on their relative merits. A similar comparison of overall power consumption between the coaxial rotor and the equivalent conventional rotor over a range of advance ratios in forward flight is shown in Fig. 14. The variability in the predicted power arising from the uncertainty in the profile drag model is seen to be a feature of forward flight as well as of hover. The relative difference between the performance of the two rotor systems, however, is seen to diminish as forward speed is increased and, indeed, at the highest advance ratios that were simulated, the two systems are shown to consume nearly identical power. This observation is entirely consistent with the reduction in interaction between the upper and the lower rotors of the coaxial system alluded to earlier that results in their reaching a near-equal partition of thrust as the advance ratio is increased.

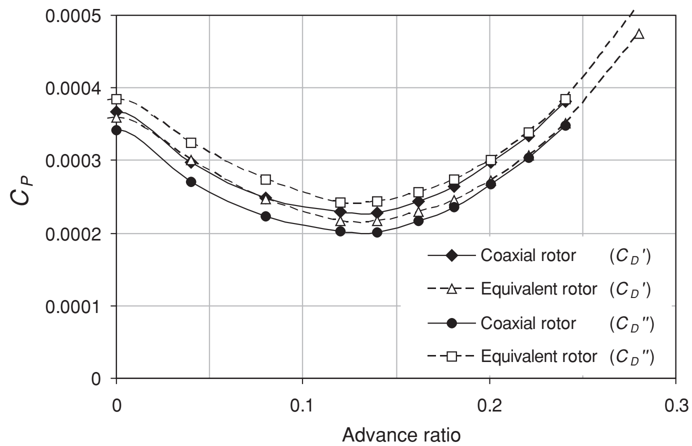


Fig. 14. Power vs. advance ratio: comparison between rotors with identical solidity and blade properties ($C_T = 0.0048$).

If the variability in the results presented here can indeed be attributed to Reynolds number related effects on the blades, then it is worth bearing in mind that this variability would, in all likelihood, become less marked the greater the Reynolds number of the system, since it is known that the sensitivity of sectional drag to Reynolds number is most marked at lower values of this parameter. This should have interesting consequences for the relative merit of the two types of rotor system when one considers the range of Reynolds numbers that current vehicles (from UAVs to full-scale aircraft) might be designed to operate.

Conclusions

The VTM is used to model the aerodynamic performance of a coaxial rotor and a conventional single rotor. This is done to establish a rational approach to comparing the performance of the two rotor systems despite their distinct configurational differences. The reliability of the numerical prediction is assessed by comparing the power consumption of Harrington's coaxial rotor as predicted by the VTM to that experimentally measured by Harrington and Dingeldein, in hover and forward flight, respectively. Validation of numerical predictions against the experimental data shows that the overall power consumption is sensitive to the particular drag polar that is used to represent the profile drag of the airfoil sections, and hence, by inference, to any variability in the precise operating conditions of the rotor blades. Some degree of absolute quantification does appear to be justified when this variability in profile drag, hence, profile power, is removed to reveal the induced component of the power consumption, however.

The numerical results obtained by replicating Harrington's experiment are used to highlight the potential misrepresentation of the merit of the coaxial system relative to the conventional single rotor configuration that might arise if a very strong geometric similarity between the two systems is not enforced. It is shown that if the rotors being compared have different solidities, then simply normalizing the thrust and power by solidity, as has been done on occasion in the past to support arguments for and against the two types of rotor, yields a very misleading interpretation of the relative performance of the two systems. This is because the thrust-generating capability of the low-solidity rotor is compromised by its disproportionately higher profile power as a result of the onset of blade stall at high thrust coefficient. Given these observations, an equivalent, conventional single rotor consisting of an equal number of geometrically identical blades to those used in the coaxial system is constructed. The geometric differences between the coaxial rotor and the proposed equivalent rotor are thus confined to the defining characteristics of the two types of rotor systems—in other words to the direction of rotation and the vertical separation of the rotor blades. This forces any difference in performance between the two systems to arise solely as a result of the differences in the detailed interaction between the blades and their wakes that arise within the two types of system. The resulting approach thus allows a fair like-for-like comparison between the performance of coaxial and conventional rotor systems.

On this basis, the simple coaxial system studied in this paper is shown to consume somewhat less power than the equivalent conventional system, though the variability in the total power consumption due to the uncertainly in the given drag model is of comparable magnitude to the relative difference in the power consumed by the two types of rotor. The results presented here caution thus that the merits of the coaxial system relative to the equivalent, conventional rotor in terms of overall power consumption may be obscured if the profile drag characteristics of the blades are overtly sensitive to operating condition, as for instance might possibly be the case at low Reynolds number.

Similar conclusions apply to steady forward flight at moderate advance ratios. Although the analysis presented here is suggestive, it should be cautioned that further work is required to determine whether the conclusions presented here extend to forward flight in the case where significant flapwise stiffness is introduced to the rotor system, for example, as in the ABC-type coaxial rotor system.

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