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Simulation, a valuable tool in the estimation of helicopter flight dynamic characteristics

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Abstract: Estimating helicopter flight dynamic characteristics is a challenge. Manufacturers of the aircraft generally establish these characteristics by flight testing over a range of operational conditions. However, it is not always possible to test the aircraft in certain conditions. Simulation can play an important role in filling the gaps between the flight test data sets and extending the operating limits beyond the boundaries of the test envelope. A helicopter flight dynamic simulation requires a representation of the aerodynamics, dynamics and control systems. In this paper we model an important component of aerodynamics, that is, the rotor wake flow field. This very complex flow condition is often unsteady and dominated by vorticity. Important elements of the rotor wake vorticity are identified, then simplified (using a vortex sheet to represent the near wake of the rotor blade, and vortex rings to represent the intermediate and far wake) and then applied to mathematically simulate helicopter vertical flight conditions. Using this simple flow model, helicopter induced velocity and blade loadings have been calculated for hovering flight and compared with published data, including test data, to establish the validity of the model. The model has been extended to capture unusual blade loading associated with vertical flight including vertical gust effects and vortex ring states. It is difficult to safely and repeatably replicate such flight situations during flight tests. By hypothesizing helicopter flight as the flow represented by the generation and interaction of two jets of varying strength the unsteady flow can be better understood. The rotor can be seen to be producing one jet; the other is produced by the motion of the helicopter through the air. These two jets will interact producing a region of unstable flow. As the descent rate of the helicopter increases the location of the interface moves closer to the rotor disc and influences its lift generating capacity. Using the simple flow model we are able to simulate flight conditions, often in unsteady flow states, and extract meaningful data. Numerical simulations and results are presented in this paper for a range of operating conditions associated with helicopter vertical flight.

Keywords: *Helicopter Wake, Vortex Ring Method*

1. INTRODUCTION

Highly sophisticated models are needed to precisely predict helicopter flight dynamics and performance factors. However, satisfactory estimates can be obtained using a variety of simple methods previously developed **[Miller, 1981; Reddy, 1979**; **Kocurek *et al.*, 1976; Landgrebe, 1969].** They range from the complex and computationally demanding free wake analysis **[Miller**, **1981],** to the simpler prescribed wake methods **[Reddy, 1979**; **Kocurek *et al.*, 1976].** The free wake methods allow the vorticity to move and over many iterations the final location of the aerodynamic elements is obtained. The prescribed wake explicitly defines the location of the wake elements; for this reason it relies on access to experimental data for accurate placement.

The initial task was to investigate the methods available and select an appropriate model to develop and a means of testing the model. When selecting a method one must ensure its validity, the application under which is must perform, its accuracy and computational complexity. Thus a balance between complexity and versatility must be struck. The use of the highly sophisticated and complex free wake methods do not always guarantee convergence for marginally stable flow conditions associated with some flights including the hover case **[Crimi, 1965].** The simple models are more reliable and easier to implement but at the cost of accuracy. The required precision and ease of implementation led to the selection of the prescribed wake method **[Kocurek *et al.*, 1976]**. The code was written in C and was an implementation of a simple prescribed wake model, with no fuselage interaction or ground effects considered. The model selected includes a simple wake geometry; a vortex sheet to represent the vorticity immediately behind the blade, and ring vortex elements to represent the vorticity in the intermediate and far wake regions. A prescribed wake model is selected here because it provides greater flexibility to conduct parametric studies in order to gain some insight into complex flow conditions associated with helicopter vertical flight. It was important to compare results generated during vertical flight conditions with other models. By selecting a simpler model **[Reddy, 1986]** and results generated using Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD) **[Toffoletto *et al.*, 1989]** for comparison, the precision of the model could be ascertained. The model was then compared with recorded flight data **[Scheiman, 1964]** to establish overall confidence in results. The software was extended to simulate unsteady and unstable vertical flight conditions. While in hover the flow is in the downward direction through the rotor disc, however, during rapid vertical descent or with large vertical gusts the powerful tip vortices are no longer swept away, instead they recirculate in the plane of the rotor and the vortices from previous blades merge together. This can result in a large decrease in thrust, loss of pilot control authority and an increase in vibrations due to the unsteady nature of the flow. It is these characteristics that are to be investigated in the final stages of the paper. In section 3 the physics of the flow associated with helicopter vertical flight has been explained by comparing this to two interactive jet flows.

The work presented here will form a part of the flight dynamic models of a helicopter. Flight dynamics include aerodynamics, dynamics and control systems. To run these models in support of helicopter operations the model must be simple and provide good first order approximations. The use of CFD in rotor wake analysis **[Wakefield *et al.*, 2002; Reddy *et al.*, 2000; Brown 2005; Toffoletto *et al.*, 2002]** could most likely provide more accurate and detailed results, however, the resources to use these tools as part of flight dynamic modeling may be restrictive because of time constraints and the computational resources required.

In this paper, Section 2 presents a broad review of vorticity in a rotor wake, development of a simple wake model (SWM) and validation of the model. Section 3 presents simulation of vertical flight using the SWM developed in Section 2 and results of a parametric study and proposals for further work are made. In Section 4 some concluding remarks are drawn.

2. ROTOR WAKE MODELS

2.1. Rotor wakes

The wake formed by a helicopter in flight is dominated by vorticity. Generally the wake is divided into three distinct regions; the near wake, which is attached to the blade, an intermediate wake and a far wake. Consider a single blade rotating in hover with no ground effects present. Near to the trailing edge of the rotating blade a vortex sheet is formed. This sheet rapidly rolls up into two concentrated vortices located at the root and tip of

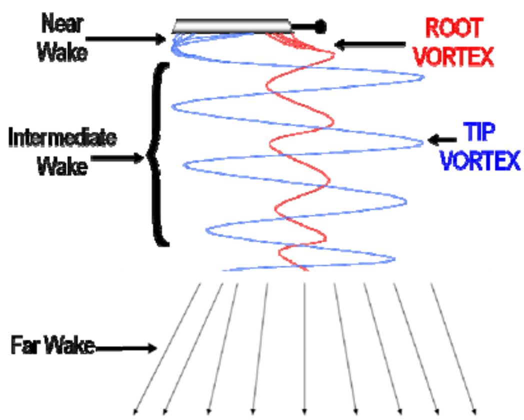

Figure 1. Vortex Wake Representation in Hover

the blade. As the blade rotates around, it forces the vortices downward. Radial contraction also occurs in the intermediate wake and finally expansion and vortex dissipation in the far wake. The complete representation is a near vortex sheet that quickly forms a contracting helical structure that eventually breaks down and expands shown in **figure 1**. This complex representation poses a difficult mathematical and physical modeling challenge. However, it is important to establish an accurate physical representation of the rotor wake as it has a significant effect on induced velocity at the rotor, blade loading, angle of attack and circulation thus affecting rotor performance. In forward flight the wake is stretched and blown away from the rotor and its effects are diminished.

2.2. Simple Models

In this section the helical vortex model described above is simplified for mathematical simulation of vertical flight. The curved vortex sheet behind the trailing edge (i.e. the vorticity in the near wake) of the blade is replaced with a series of straight semi infinite vortex lines in the plane of the rotor perpendicular to the trailing edge and the helical root and tip vortex structure (i.e. the vorticity in the intermediate wake) is replaced by a series of rings. The root vortices are neglected as their contribution is minimal. Beyond this well defined vortex structure the wake expands and dissipates. Vorticity in the far wake region can be modeled in several ways, however, in this paper it is represented as another vortex ring of equal radius to the blade and of the same axial displacement as the last intermediate vortex ring **[Kocurek *et al.*, 1976]. Figure 2** shows the simplified wake structure. In developing the model consideration has been limited to a single rotor. The fuselage and all other interactions have been neglected. The model can be further simplified by representing the vortex rings as infinite vortex lines, a method which was developed and implemented by **[Reddy, 1979]** at Aeronautical Research Laboratory independently of very similar work by **[Miller, 1981]** at Massachusetts Institute of Technology**.** However it has been shown **[Toffoletto *et al.*, 1989]** that maximum loading given by the vortex line, prescribed wake model with concentrated far wake is about 10% less than that given by other models**.** After careful consideration of all contributing factors the ring vortex wake, with concentrated far wake and semi infinite vortex lines representing the near wake, has been selected as the most suitable model for current research and it will be referred to as a simple wake model (SWM) in this paper.

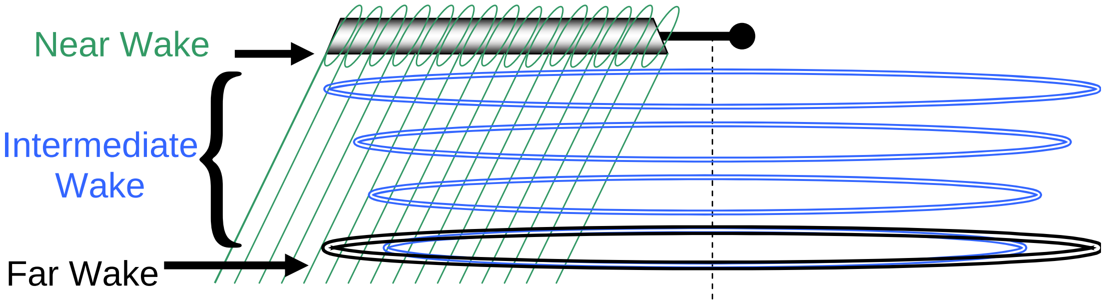

Figure 2. Simple Wake Model for Hover

2.3. Validation for Hover Case

The current results are compared **(figure 3)** with a free wake analysis computed for the Sikorsky S-58 **[Toffoletto et al., 1989]** and with flight data **[Scheiman, 1964]**. Current calculated results fell within the 0.125-0.8725 flight data percentile range for all results with the exception of the very outer edge of the blade where the predicted values were greater than the measured flight data. The current model predictions are also compared **(figure 4)** with the simple vortex line method for the UH-1H Iroquois **[Reddy, 1986]** and show comparable results for blade circulation and blade loading performance factors during hover. These comparisons show the current model could produce valuable engineering estimates.

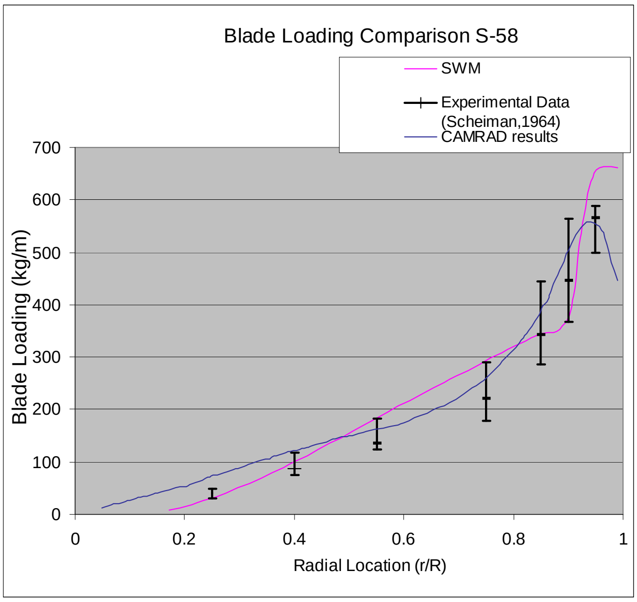

Figure 3. Sikorsky S-58 Comparison

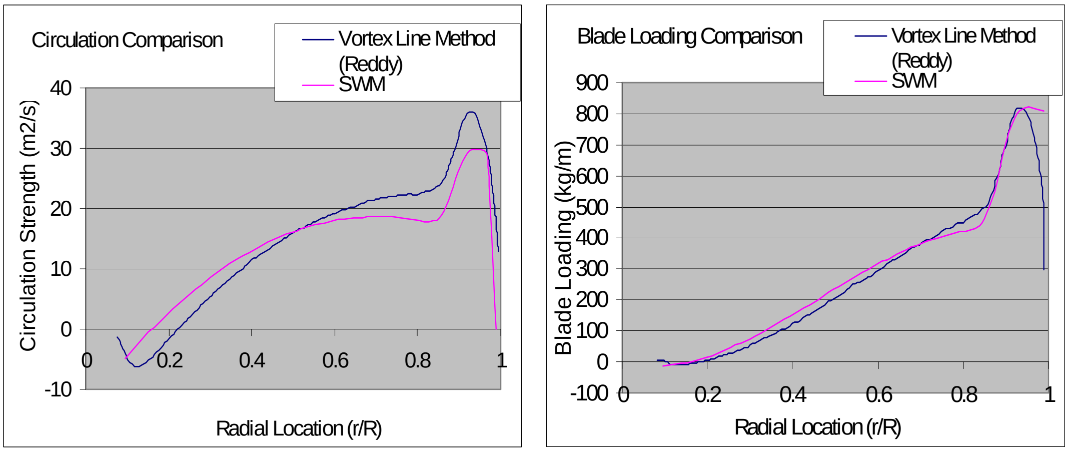

Figure 4. UH-1H Iroquois Comparison

3. APPLICATION OF SIMPLE WAKE MODEL TO VERTICAL FLIGHT

In this section flow fields associated with helicopter vertical flight are discussed and these are compared with the interaction of two jets. Using the SWM developed in Section 2 helicopter vertical flight is simulated and a parametric study is conducted and some results are presented.

3.1. Details of the Flow Field

Three basic flow states exist for the rotor in vertical flight; the normal working state, the vortex-ring state, and the windmill-brake state **[Gessow, 1983].** The normal working state encompasses climb and hovering flight, the windmill-brake state exists after rapid descent has commenced, and the vortex ring state is the transient state between the normal and windmill-brake states. The physics of helicopter vertical flight can also be explained as an interaction of two jets; one due to lift generation of the rotor (the rotor downwash) and the other due to the motion of the aircraft. The strengths of these jets vary according to the rotor thrust and the descent/ ascent rates of the helicopter. These two jets will interact and produce a flow domain that is highly unsteady and unstable. The position of the unstable flow domain (UFD) or jet interface depends on the relative strengths of the jets. For example in hover there is only a rotor generated jet, and during ascent both jets are in the same direction and during these states the UFD is infinitely far from the rotor plane **(figures 5 and 6).** As the helicopter begins to descend the UFD comes closer to the rotor plane and it affects the strength of the rotor jet (hence rotor performance) **(figure 7)**. Eventually as the UFD gets very close to the to the rotor plane it could create a flow field that would diminish the thrust generation capability of the rotor and the ability of the pilot to control the aircraft **(figure 8).** In this paper using the SWM that has been described in the previous section a parametric study is conducted to understand this complex flow/flight condition.

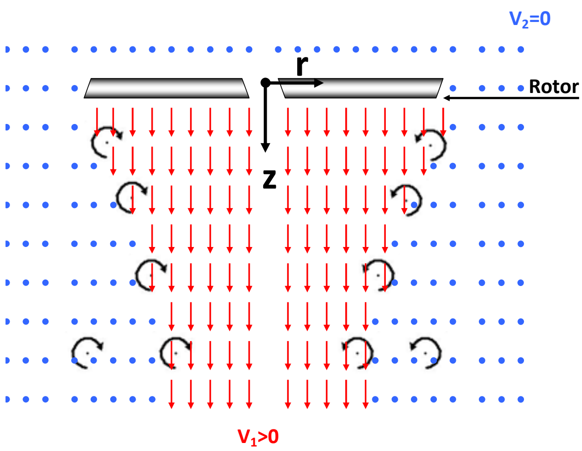

Figure 5. Flow Field During Hover

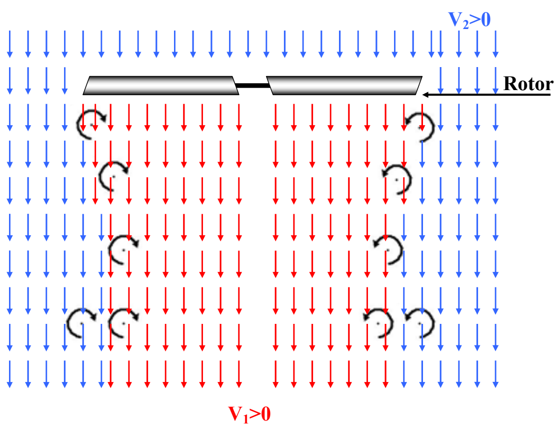

Figure 6. Flow Field During Ascent

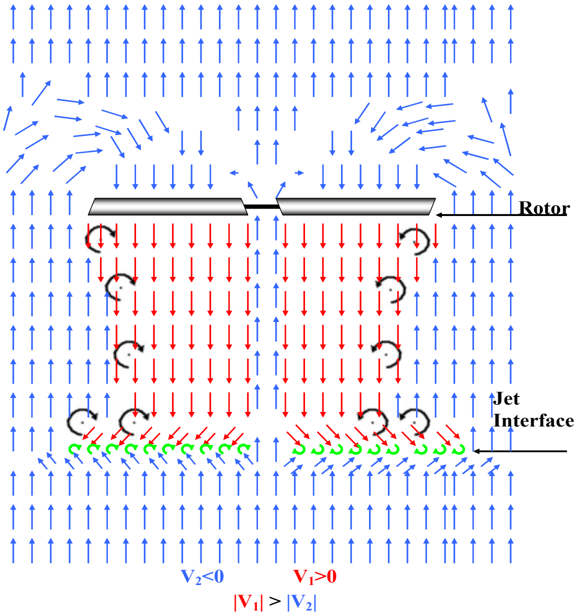

Figure 7. Flow Field During Slow Descent

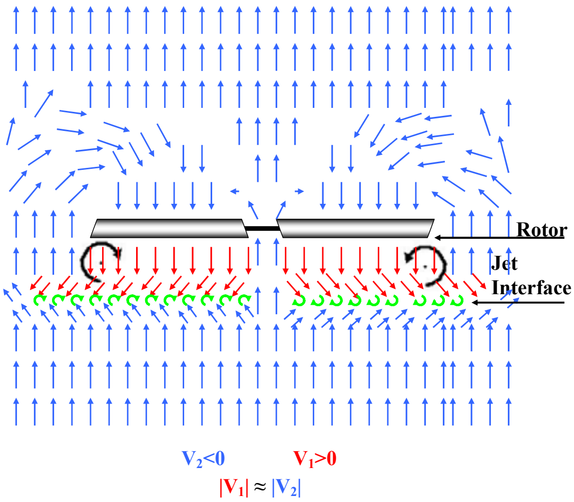

Figure 8. Flow Field During Rapid Descent

3.2. Numerical Results for Hover and Vertical Descent

To examine the sensitivity of various performance factors a parametric study was carried out. **Table 1** shows the input data provided to the SWM. The UH-1H was chosen for the parametric study. Vortex location was varied from the wake experimental data **[Kocurek *et al.*, 1976]**. The parametric study in this paper started with hover as a baseline flight condition. The wake geometry has been varied incrementally to capture various descent rates of the helicopter. During this parametric study first the axial location of the rings was varied (**figure 9),** then radial variation (**figure 10),** followed by equal adjustment of both radial and axial position (**figure 11).** The percentages represent the scaling of the vortex ring locations where 100% represents hover. The plots clearly show the significant co-dependence of wake geometry and helicopter performance factors. Axial proximity affects the magnitude of the results; as the wake moves closer to the rotor plane the effect on the various performance factors is amplified (**figure 9**). Whereas radial contraction and expansion of the wake results in a shift in the peak values of the performance factors radially (**figure 10).** The results in **figures 9 and 10** clearly illustrate the effects contraction and compression of the vorticity have on the blade performance. However in the real world these two effects will occur simultaneously and **figure 11** shows the results. As descent begins the vortex rings are pushed closer to the blade and radially outward and results presented here indicate that this results in a decrease in lift. As descent rates increase the wake is pushed even closer resulting in lift being generated only at the outer tip of the blade. As the wake approaches the blade, loading decreases and might even become negative. It is this kind of loading that may lead to loss of control, decrease in lift and increase in vibration. The effects are amplified as the wake continues to contract. The final result is when the UFD is close to the rotor disc showing the result of the wake elements bunch up together creating a single powerful ring **(Figure 11)** and producing a flight condition commonly known as vortex ring state. Results presented in this paper should be considered as preliminary and the next major step in this research would be to develop a procedure to estimate the location of vortex elements in the rotor wake for a range of helicopter descent/climb rates. It is here where CFD tools, wind/water tunnel models and full scale flight testing data will be required to couple the helicopter descent/climb rates with wake geometry.

Table 1. Input Data For Aircraft

INPUT DATA	**Iroquois UH-1H**	**Sikorsky S-58**
Lift-Curve Slope (/rad)	5.73	5.73
Number Of Blades	2	4
Blade Chord (m)	0.533	0.417
Number Of Span wide Stations	40	40
Radial Location Of Blade Root (m)	0.610	1.370
Rotor Radius (m)	7.315	8.534
Vortex Circulation Strength (m^2/s)	20	15
Blade Linear Twist (deg)	-10	-8
Blade Root Pitch Angle (deg)	14.00	14.67
Air Density (kg/ $m^{3)}$)	1.188	1.188
Rotor Angular Velocity (rad/s)	39.99	22.20
Thrust Coefficient	0.002868	0.005000

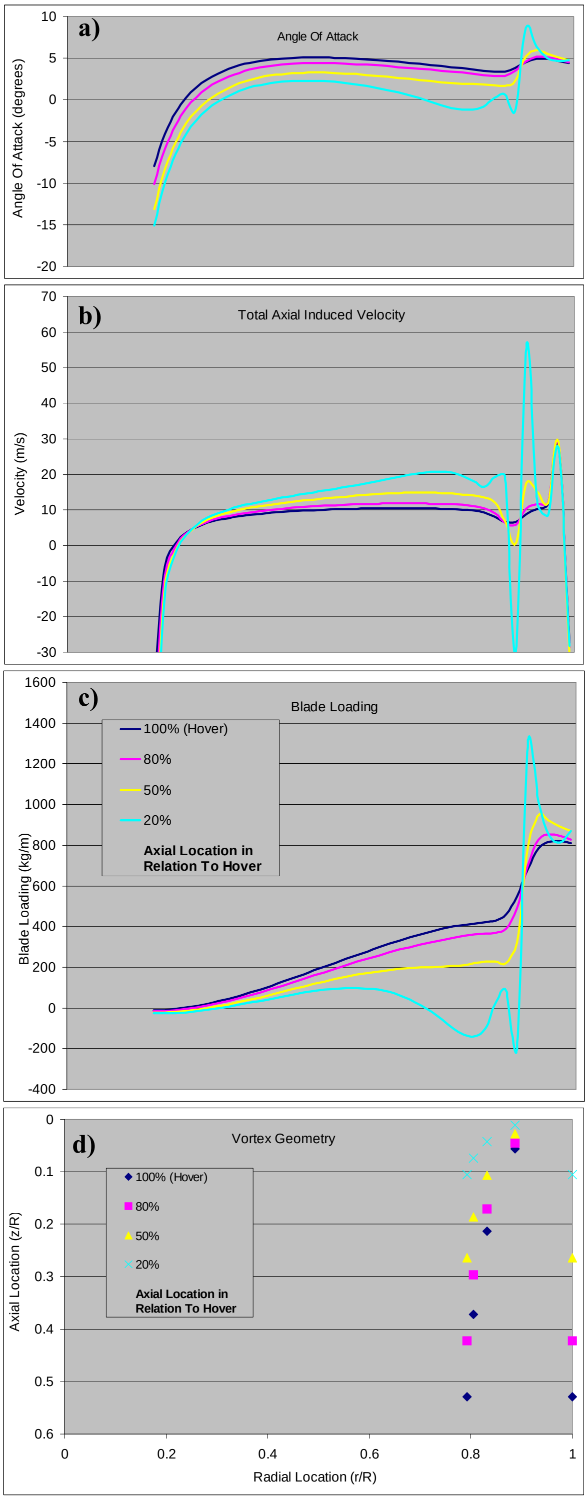

Figure 9.
Variation of (a) angle of attack, (b) induced velocity and (c) loading along the rotor blade as the axial location of the vorticity in the wake is varied from hover condition (d)

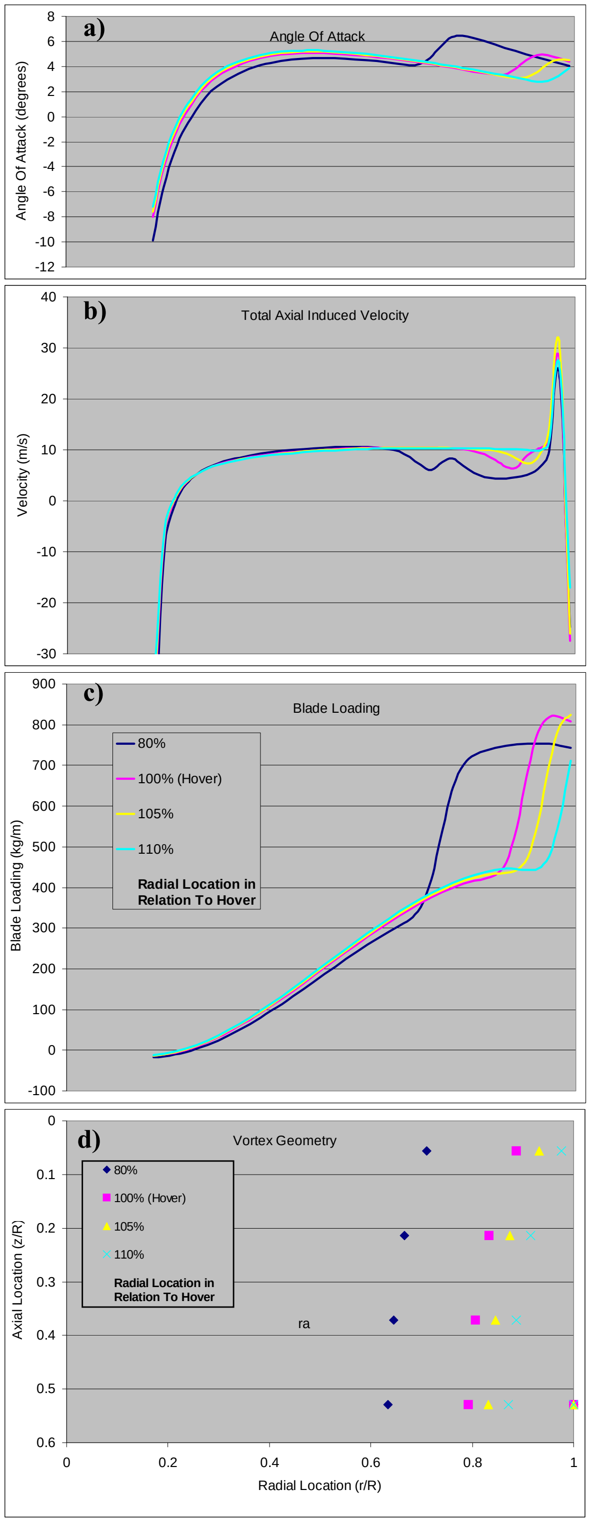

Figure 10.
Variation of (a) angle of attack, (b) induced velocity and (c) loading along the rotor blade as the radial location of the vorticity in the wake is varied from hover condition (d)

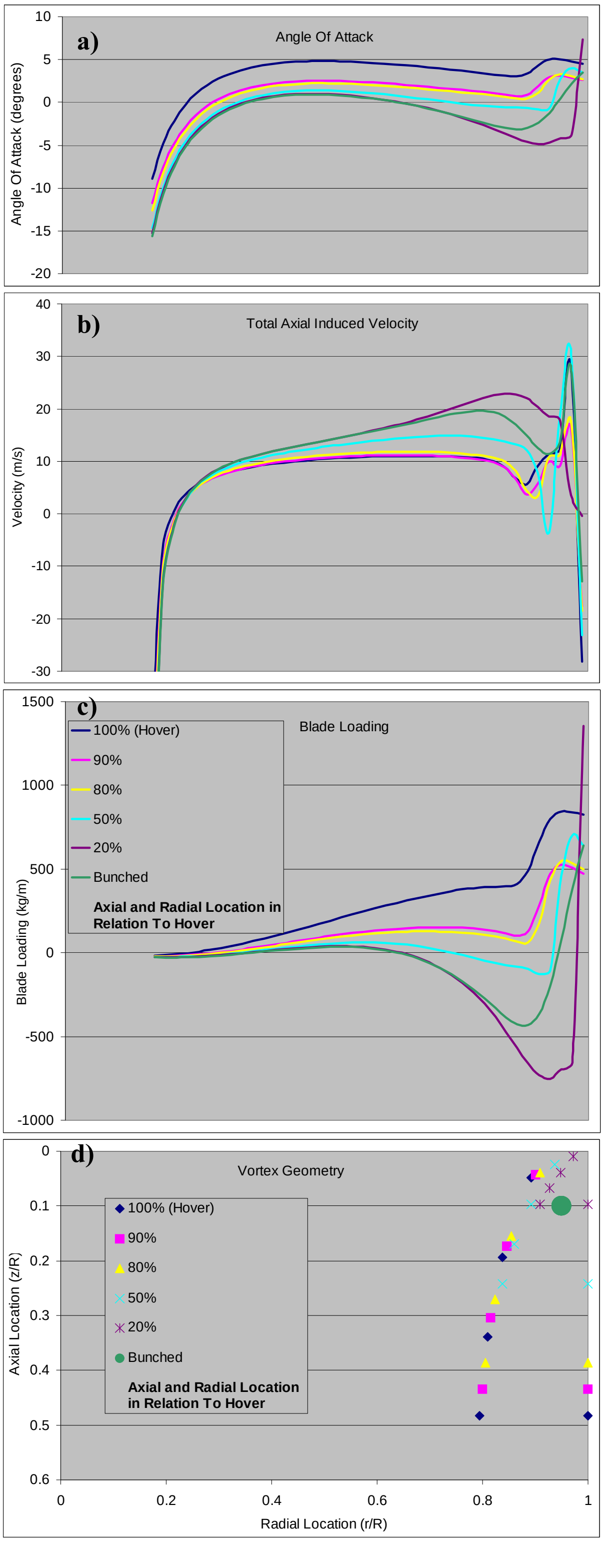

Figure 11.
Variation of (a) angle of attack, (b) induced velocity and (c) loading along the rotor blade as the combined radial and axial location of the vorticity in the wake is varied from hover condition (d).

4. CONCLUDING REMARKS

A simple vortex wake model suitable for helicopter vertical flight study has been developed. Validity of the model has been established by comparing current model predictions with previous published results including flight test data. The validated simple model is extended to simulate helicopter vertical flight conditions. Results obtained using a systematic parametric study provide an insight into blade loading variations that may be responsible for loss of pilot control and increased vibrations associated with helicopter vertical descent. Further study could be carried out to investigate the relationship between the vortex element locations and descent/climb rates during vortex ring state as an input to the SWM.

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REFERENCES

Brown R.E., Line A.J. (2005), Efficient High-Resolution Wake Modeling Using the Vorticity Transport Equation, AIAA, Vol. 43, No. 7, pp. 1434-1443

Gessow, A. and Myers, G.C. Jr. (1983), Aerodynamics of the Helicopter, Seventh Printing, Fredrick Ungar Publishing Co., New York, pp. 126.

Kocurek, J.D. and Tangler, J.L. (1976), A Prescribed Wake Lifting Surface Hover Performance Analysis, paper presented at the 32nd Annual National V/STOL Forum of the AHS, Washington, D.C., Paper No. 1001.

Landgrebe, A.J. (1969), An Analytical Method for Predicting Rotor Wake Geometry, JAHS, Vol. 14, No 4, October 1969.

Miller, R. H. (1981), A Simplified Approach To The Free Wake Analysis Of A Hovering Rotor, Proceedings of the Seventh European Rotorcraft and Powered Lift Aircraft Forum, Garmisch-Partenkirchen, W. Germany, September 1981, Paper No. 2; also, Vertica, Vol.6, 1982, pp.89-95.

Reddy, K.R. (1979), Prediction of Helicopter Rotor Downwash in Hover and Vertical Flight, ARL-Aero-Report-150.

Reddy, K.R. (1986), The Effect of Rotor Wake Geometry Variation on Hover Induced Power Estimation for a UH-1H Iroquois Helicopter, Aeronautical Research Laboratories, ARL-AERO-TM-384.

Scheiman, J. (1964), A Tabulation of Helicopter Rotor-Blade Differential Pressures, Stresses, and Motions as Measured in Flight, NASA TM X-952.

Toffoletto, R., Gilbert N.E., Hill S., Reddy, K.R. (1989), Incorporation Of Vortex Line And Vortex Ring Hover Wake Models Into A Comprehensive Rotorcraft Analysis Code, DSTO Flight Mechanics Technical Memorandum 408.

Toffoletto, R., Reddy, K.R (2002), Steady Rotor Flow Interaction with Ship Airwake, Proceedings of the ninth Asian Congresses of Fluid Mechanics

Wakefield, N. H., Newman, S. J., Wilson, P. A. (2002), Helicopter flight around a ship's superstructure, Proceedings of the Institution of Mechanical Engineers -- Part G -- Journal of Aerospace Engineering, Feb2002, Vol. 216 Issue 1, p13-28.