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EFFECT OF MAIN ROTOR WAKE INTERFERENCE ON TAIL ROTOR AERODYNAMIC CHARACTERISTICS

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ABSTRACT Using a vortex wake analysis method, the interference velocity field downstream (in the hub plane of a tail rotor) of a helicopter main rotor has been calculated for different tail rotor hub locations with respect to the main rotor and for a range of speeds. This interference velocity field has been included in a study of aerodynamic loads and performance estimation for a helicopter tail rotor. For the steady forward flight case considered in this paper, the results show that the main rotor wake interference could influence considerably the tail rotor power requirement (from a reduction of about 20% to an increase of about 35%) depending on the location of the tail rotor with respect to the main rotor.

1. INTRODUCTION

The helicopter aerodynamic environment is made up of a flow field generated by a number of separate, but related, components. The air disturbed by one aerodynamic component of the helicopter creates a complex and often adverse aerodynamic environment at another component. A descriptive term for this is interactional aerodynamics. Modern helicopters show an increasing susceptibility to interactional aerodynamic problems because of design trends to higher disc loadings and compactness.

The complexity in modelling the helicopter aerodynamic environment has, within the international rotorcraft community, led to modelling of specific components with limited or no account taken of interference effects from other components. A general interactional formulation is not available, and effects are usually included through empirical corrections. These limitations have been perceived as one of the main impediments to good correlation between theory and tests.

Because of the number of components and the nature of the flow field generated by each component, a comprehensive mathematical analysis of the interactional phenomena is extremely difficult. To solve this interactive fluid problem, various simplifying assumptions are necessary. In particular, these relate to the number and the geometry of components, as well as to the flow field produced by each component.

Recent research at ARL (Aeronautical Research Laboratory) has focused on the interaction of the main rotor and tail rotor components. The main aim is to develop mathematical models of this interaction using vortex flow analysis. This will reduce the reliance on empirical corrections and advance the aerodynamic models a step closer to a more accurate representation of the physics of the problem, thereby increasing confidence in performance and rotor loads predictions.

Ideally, analytical models should include main rotor induced effects at the tail rotor, as well as tail rotor induced effects at the main rotor. Because of the complex nature of the rotor wake, modelling such a combination would require an excessive amount of computer time. For most forward flight conditions, the tail rotor wake will be blown away from the main rotor, thus reducing its interference effect on the main rotor.

Using a free wake analysis, the interference effect of the induced velocity downstream of a Bell 412 main rotor and in the hub plane of a Lynx tail rotor has been calculated for different tail rotor hub locations with respect to the main rotor and for a range of speeds. This interference velocity field has then been included in the estimation of the aerodynamic characteristics of a Lynx helicopter tail rotor.

2. DESCRIPTION OF THE MODELS

The aerodynamic interaction between the main rotor and the tail rotor is not always strongly mutually coupled. For example, in hover it is the effect of the tail rotor wake on main rotor inflow and loads which is more significant in helicopter aerodynamic analysis (Reddy and Riseborough, 1991) than the main rotor wake effect on the tail rotor. In forward flight the main rotor wake comes very close to the tail rotor, and in some instances the tail rotor might even be completely immersed in the main rotor wake. In this case the effect of the main rotor wake on the tail rotor is more important than the tail rotor effect on the main rotor. Thus in the analysis of main rotor and tail rotor aerodynamic interaction in forward flight (mainly considered here), inclusion of the main rotor wake influence in the tail rotor aerodynamic analysis will provide a good engineering estimate for this problem.

The aerodynamic interaction problem may be split into a two stage analysis. Firstly, the interference flow field in the hub plane of a tail rotor due to the main rotor wake is calculated. Secondly, this interference flow field is included in the tail rotor analysis. For the mathematical analysis, detailed knowledge of the rotor systems and their vortex wake structure is required. These details are discussed in the following two subsections.

2.1 Wake Models

The wake induced flow is an important, and often crucial, element in all helicopter aerodynamic problems. Most current helicopter aerodynamic analyses use a helical wake structure consisting of finite core filaments for the tip vortex and a vortex sheet for the inboard vorticity. The vortex sheet is often represented by a vortex lattice or, for mathematical simplicity, by a single blade root vortex (Johnson, 1980). The CAMRAD/JA (Comprehensive Analysis Model for Rotorcraft Aerodynamics and Dynamics - Johnson Aeronautics version) computer program (Johnson, 1988), which employs a vortex lattice model for the inboard vortex sheet, is used in this paper to calculate rotor generated flow. If the wake geometry, i.e. strength and position of the vortex elements in the wake, is known, then the velocity at any given point can be calculated using the Biot-Savart law. The two wake geometry calculation methods used in CAMRAD/JA are a prescribed wake analysis and a free wake analysis.

In the prescribed wake method, the wake geometry is specified, having been determined from an empirical data base generated from flow visualization studies. Blade loads obtained

*Part of this research was conducted at NASA Ames Research Center while K.R. Reddy was on an overseas attachment.

using this method agree quite well with experiments (when used for rotors with similar blade profiles), but there are severe disadvantages when new or different blade geometries are used (Reddy, 1992). The free wake analysis starts from some initial specification of an approximate vortex geometry and inflow, and then iterates until a converged geometry is found. The iterative numerical process is computer intensive. In this paper, as a compromise between modelling accuracy, computer time, and engineering application of this analysis, the free wake model available in CAMRAD/JA is used in the estimation of main rotor interference velocity, while the prescribed wake model is used in the tail rotor aerodynamic analysis.

2.2 Rotor Models

Several experimental investigations were conducted at NASA Ames Research Center in the US to provide quantitative information on the aerodynamic and acoustic interactions that occur between various helicopter components (Homes et al., 1990; Felker, 1991). A major full-scale test program in which the rotor/fuselage interactions for a Bell 412 helicopter rotor and a body of revolution has only recently been completed (Norman and Yamauchi, 1991). This test has provided the first complete quantitative data base detailing the effects of a rotor on a fuselage. A Lynx tail rotor will be added to this test set-up for future main rotor and tail rotor full-scale interactional aerodynamic testing (Homes et al., 1990). Fig. 1 is a schematic of the model showing the relative positioning of the fuselage and the rotors in the NFAC (National Full-Scale Aerodynamic Complex) 40 by 80 foot wind tunnel test section. The main rotor is mounted on a three-strut support system and the tail rotor is mounted on the TRTR (Tail Rotor Test Rig).

The Bell 412 rotor system is a four-bladed rotor with elastomeric bearings and dampers and has a radius (R) of 7.01 m with a 0.35 m blade chord. The blades are made of composite material and have two advanced aerofoils along the blade span; inboard of 0.66 R, the blades have a 12% thick aerofoil and outboard blade sections have an 8% thick aerofoil. The blades have a nonlinear twist of 15 degrees and the rotor speed is 33.929 rad/s.

The Lynx tail rotor consists of four blades with an asymmetric NPL 9615 blade profile (Gregory and Wilby, 1968), which is a derivative of a NACA 0012 section having a 6.2% extension to the chord and a drooped leading edge with larger radius of curvature. The principal parameters and dimensions of the Lynx tail rotor are: rotor radius = 1.15 m, blade chord = 0.18 m, blade root cut-out = 0.425 m, rotor speed = 157.622 rad/s.

The fuselage is essentially a body of revolution. The forward 69.87% of the fuselage is made up of a 30.74% thick NACA four-digit aerofoil (based on a chord of 6.61 m). The aft 30.13% consists of a right circular cone with a spherical cap at the base. The maximum diameter is 2.03 m and the length is 6.93 m. This well-streamlined body should have a small effect on the main rotor and tail rotor aerodynamic interactional study in forward flight. The fuselage effects are not modelled in the current study.

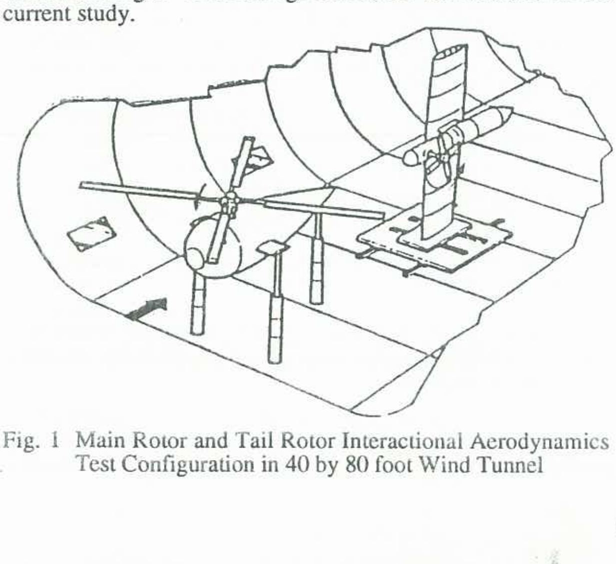

Fig. 1 Main Rotor and Tail Rotor Interactional Aerodynamics Test Configuration in 40 by 80 foot Wind Tunnel

3. NUMERICAL RESULTS AND DISCUSSION

The capability of the program CAMRAD/JA to calculate the velocity field away from a rotor disc is exploited here. As a first step, using the free wake model available, the interference flow field downstream of a Bell 412 main rotor wake is calculated for different configurations (various locations of tail rotor with respect to main rotor) and for various flight conditions (different speed and thrust). In the second step, the resulting interference flow is included in the tail rotor analysis.

In forward flight, the vorticity in the wake of a rotor takes a much more complex form. It is more chaotic, and tends to concentrate towards the edges of the wake. The resulting interference velocity is also more complex and varies considerably across the rotor wake.

To establish and check the analysis procedure, the tail rotor was initially rotated 90 degrees (so that its axis of rotation was parallel to that of the main rotor) and located underneath the hovering main rotor. Fig. 2 shows an elevation of the two rotors and their wake geometries. In hover, the rotor wake is axisymmetric, regular, and produces strong downwash. The calculated interference velocity in the hubplane of the tail rotor due to the main rotor is shown in Fig. 3. The figure shows that the interference velocity varies as a function of tail rotor radius and azimuthal angle. For the flight condition (hovering rotor developing maximum thrust of 54795 N), momentum theory gives a rough estimate for the induced velocity in the rotor plane of 12 m/s. Under the main rotor, where the tail rotor is located,

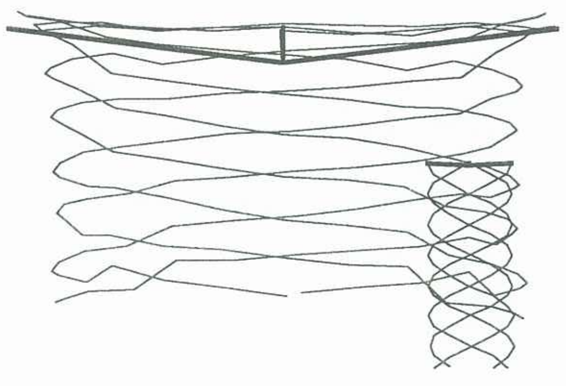

Fig. 2 Wake Geometries of two Rotors when Tail Rotor is Below Main Rotor in Hover

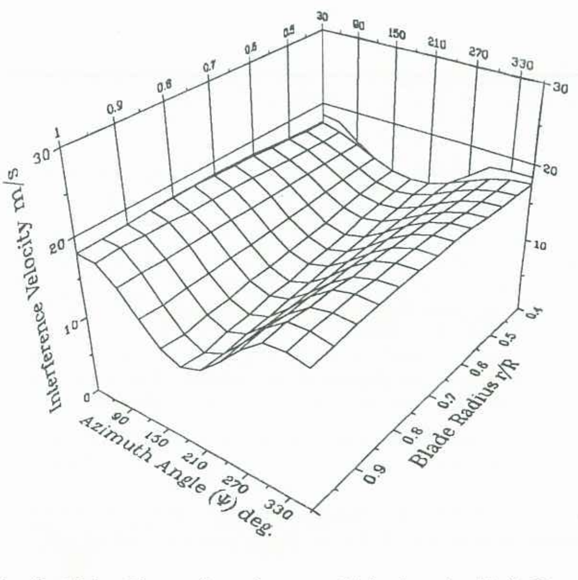

Fig. 3 Main Rotor Interference Velocity in Tail Rotor Hubplane when Tail Rotor is Below Main Rotor in Hover

the velocity will be slightly higher than this value because of wake contraction. The velocity field in Fig. 3 is of similar magnitude (ranging from 10 to 18 m/s) compared to the momentum results, thus establishing confidence in the detailed estimation of interference velocity. The velocity variation across the tail rotor hubplane is because the velocity field in the main rotor wake varies as a function of rotor radius, being maximum near the blade tip and reducing towards the centre of the rotor. The effect of this interference velocity on tail rotor performance is considerable, and this will be discussed later.

Having checked the analysis procedure, the aerodynamic interaction in forward flight is now considered for a conventional tail rotor configuration. In forward flight, the wake is skewed back and most of the vorticity moves towards the edges of the wake forming two large vortices. These vortices are very powerful and are of the same type as those that extend from the wing tips of a fixed-wing aircraft. Formation of these vortices is evident in a 10 m/s (~20 knots) wind and the vortices are fully developed at 18 m/s (~35 knots). Such vortices have been observed trailing from a helicopter flying through smoke or agricultural dust. It has been noted that the greatest effect on tail rotor performance is caused by the interaction of the tail rotor with these 'wing tip' vortices (Wiesner and Kohler, 1974).

To estimate this interference, CAMRAD/JA was run for a number of speeds and with the tail rotor placed in different locations downstream of the main rotor. The results are presented in this paper for a 30.9 m/s (60 kn) forward speed. For this case, the tail rotor hub was located at the same height as the main rotor (i.e. same water line, WL = 0) and it was 8.23 m downstream of the main rotor hub (i.e. fuselage station, FS = 1.17 R where R = 7.01 m is radius of main rotor). With these values for fuselage station and waterline fixed, the buttline value was varied to cover the width of the main rotor wake. It was initially located in the centre of the main rotor wake (i.e. zero buttline, BL = 0). The relative positions of the two rotors and their wake geometries are shown in Fig. 4. The interference velocity seen by the tail rotor is presented in Fig. 5.

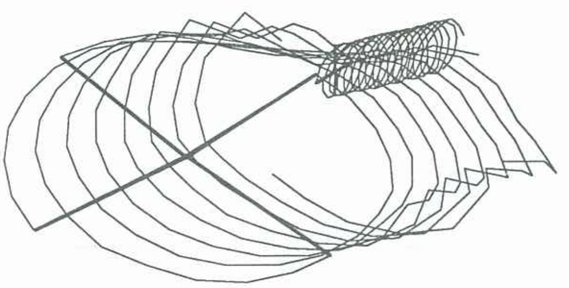

Fig. 4 Wake Geometries of Rotors when Tail Rotor is in the Centre of Main Rotor Wake for 30.9 m/s (60 kn) Forward Speed

If the rotor was a symmetrical circular wing, the vorticity on the two sides of the wake would be equal and opposite and the resulting interference velocity in the tail rotor hubplane would be zero. However, in the case of a helicopter rotor, the wake is asymmetric because vorticity shed by the blade on the advancing side of the rotor is different from the blade on the retreating side. Because of this asymmetry, the main rotor wake produces small interference velocities (shown in Fig. 5) in the tail rotor hub plane.

To capture the strong 'wing tip' vortex interactional effect, often encountered during helicopter sideslip, the tail rotor was moved close to the edges (BL = 0.75 R) of the main rotor wake. Fig. 6 shows the wake geometries when the tail rotor is on the starboard side of the main rotor wake. Fig. 7 shows the interference velocity for this case. As can be seen in this figure, the interference velocity is quite strong and nonuniform in nature.

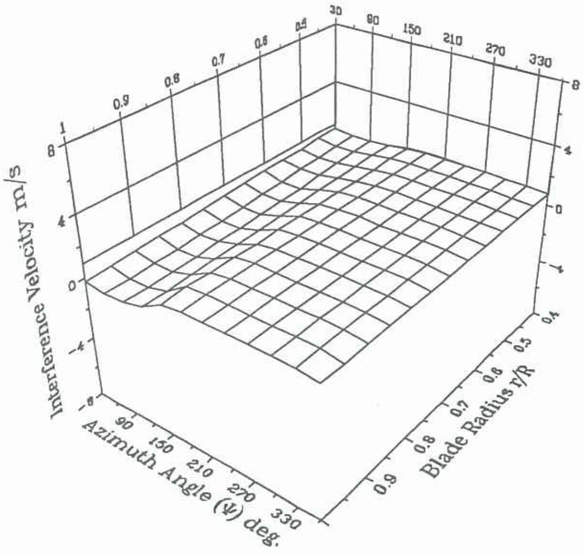

Fig. 5 Main Rotor Wake Interference Velocity in Tail Rotor Hubplane when Tail Rotor is in the Centre of Main Rotor Wake for 30.9 m/s (60 kn) Forward Speed

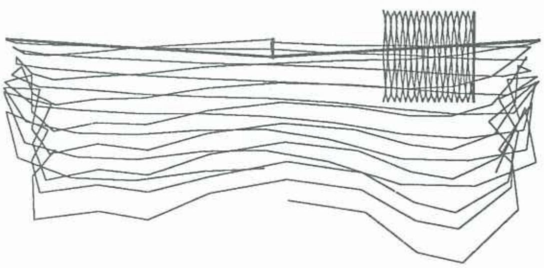

Fig. 6 Wake Geometries of Rotors when Tail Rotor is on the Starboard Side of the Main Rotor Wake for 30.9 m/s (60 kn) Forward Speed (Rear View)

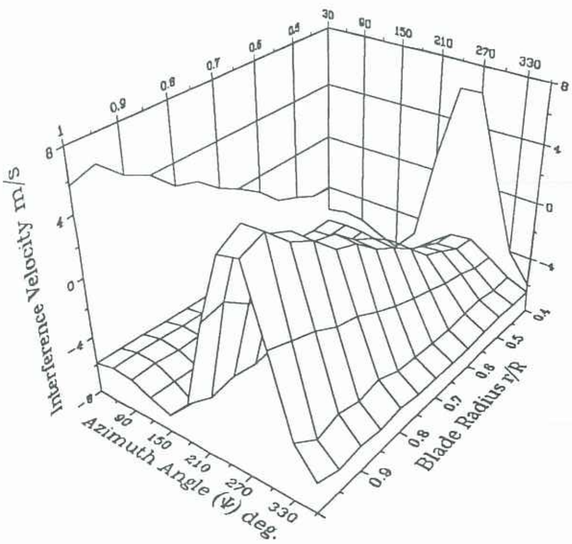

Fig. 7 Main Rotor Interference Velocity in Tail Rotor Hubplane when Tail Rotor is on the Starboard Side of the Main Rotor Wake for 30.9 m/s (60 kn) Forward Speed

Figs 8 and 9 show the wake geometries and the corresponding interference velocity when the tail rotor is on the port side (BL = -0.75 R) of the main rotor wake.

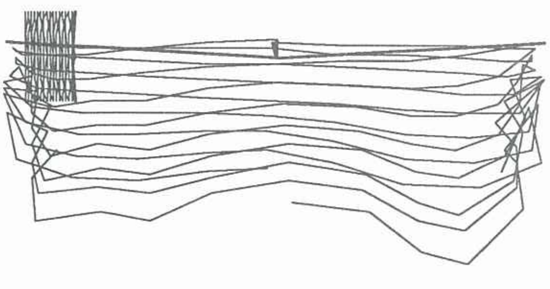

Fig. 8 Wake Geometries of Rotors when Tail Rotor is on the Port Side of Main Rotor Wake for 30.9 m/s (60 kn) Forward Speed (Rear View)

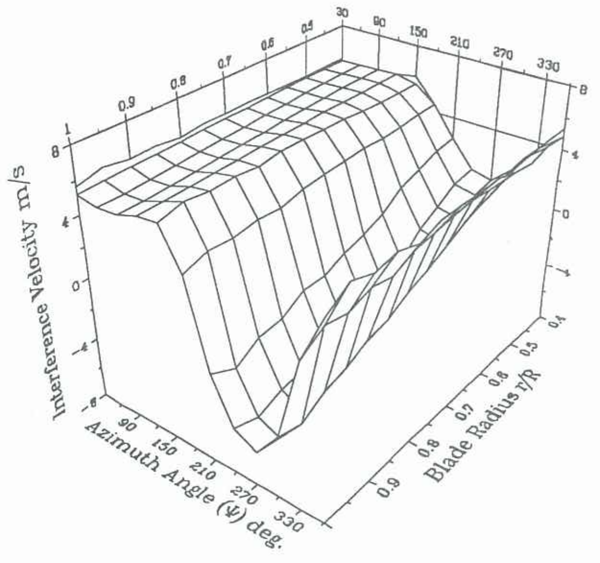

Fig. 9 Main Rotor Wake Interference Velocity in Tail Rotor Hubplane when Tail Rotor is on the Port Side of Main Rotor Wake for 30.9 m/s (60 kn) Forward Speed

The effect of these main rotor wake interference velocities (shown in Figs 3, 5, 7, and 9) on tail rotor performance is presented in Table 1.

For the hover case considered when the tail rotor is rotated 90 degrees and far from the main rotor (FS = 10 R), 51.8 kW of power is required to develop 2118 N (close to maximum for this rotor) of thrust. When the tail rotor is placed in the main rotor wake (Fig. 2) its power requirement increases to 76.1 kW, a 47% increase.

Table 1. Tail Rotor Power

	TAIL ROTOR LOCATION				POWER (kW)				
SPEED (m/s)	FS/R_{Main}	BL/R_{Main}	WL/R_{Tail}	ATTITUDE	Induced	Interference	Profile	Parasite+ Climb	Total
0	10.00	0.00	-1.00	HOR	35.6	0.0	16.1	0.0	51.7
0	0.68	0.00	-1.00	HOR	26.0	31.9	18.4	0.0	76.3
30.9	10.00	0.00	0.00	VER	27.8	0.0	13.7	-3.5	38.0
30.9	1.17	0.00	0.00	VER	28.1	-1.2	12.8	-3.4	36.3
30.9	1.17	0.75	0.00	VER	27.9	9.5	17.1	-3.4	51.1
30.9	1.17	-0.75	0.00	VER	29.3	-7.6	12.5	-3.8	30.4

For the case of 30.9 m/s (60 kn) forward speed, the tail rotor power requirement varies considerably, depending on its location. In the absence of any interference, the tail rotor requires 38.0 kW of power to develop 2118 N of thrust. When the rotor is in the centre of the wake (Fig. 4), its power requirement is slightly reduced (by about 4 %). When the rotor is close to the starboard edge of the main rotor wake (Fig. 6), the interference velocity is directed into the tail rotor disc and it adds to the rotor induced velocity. The tail rotor power requirement increases by about 35% to accommodate this extra inflow. When the tail rotor is close to the port edge of the main rotor wake (Fig. 8), the interference velocity opposes the tail rotor wake induced flow. This in effect reduces the tail rotor power consumption by about 20%.

4. CONCLUDING REMARKS

A general interactional aerodynamic model of a helicopter is not available. The helicopter aerodynamic interactional effects are usually either omitted or included through empirical factors. The corrections used do not allow the intermediate results, such as rotor inflow and blade loading distribution, to be estimated adequately. Because such effects can influence helicopter trim, power, noise, vibration, and fatigue loads, it is important that attempts are made to more accurately model them to increase confidence in the predictions.

The results presented in this paper indicate that the main rotor produces a strong nonuniform interference velocity field in the tail rotor hubplane. This is particularly true when the tail rotor is close to the 'wing tip' vortices (edges) of the main rotor wake. Inclusion of this interference velocity in the tail rotor analysis influences the tail rotor power requirement from a reduction of about 20% to an increase of about 35%, depending on the position of the tail rotor behind the main rotor.

REFERENCES

FELKER, F.F. (1991) Results From a Test of a 2/3-Scale V-22 Rotor and Wing in the 40 by 80 Foot Wind Tunnel, *Proc. of the 47th Annual Forum of the American Helicopter Society*, Phoenix, Arizona, 89-99.

GREGORY, N. and WILBY, P.G. (1968) NPL 9615 and NACA 0012 - A Comparison of Aerodynamic Data, *ARC CP No. 1261.*

HOMES, H., SCHAIRER, E., HICKS, G., WANDER, S., BLANKSON, I., ROSE, R., OLSDON, L., and UNGER, G. (1990) NASA Aerodynamics Program Annual Report 1989, *NASA TM 4175.*

JOHNSON, W. (1980) *Helicopter Theory*, Princeton University, New Jersey, 713-718.

JOHNSON, W. (1988) *A Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics Volume I: Theory Manual*, Johnson Aeronautics, Palo Alto, California.

NORMAN, T.R. and YAMAUCHI, G.K. (1976) Full-Scale Investigation of Aerodynamic Interactions Between a Rotor and Fuselage, *Proc. of the 47th Annual Forum of the American Helicopter Society*, Phoenix, Arizona, 461-486.

REDDY, K.R., and RISEBOROUGH, P. (1991) Effect in Hover of Tail Rotor Wake Interference on Main Rotor Velocity Field, Loads, and Power, *Proc. of the International Aerospace Congress*, Melbourne, 521-529.

REDDY, K.R. (1992) Comparison of Calculated and Measured Aerodynamic Characteristics of a Lynx Tail Rotor in Hover, *Proc. of the Fifth Asian Congress of Fluid Mechanics*, Taejon, Korea.

WIESNER, W. and KOHLER, G. (1974) Tail Rotor Performance in Presence of Main Rotor, Ground, and Winds, *J. of the American Helicopter Society*, 19, 2-9.