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Modeling of the Receiver Aircraft in Air-To-Air Refueling

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Nomenclature

b	=	wing span, m
C_l	=	rolling moment coefficient, $L/q_\infty Sb$
L	=	rolling moment, Nm
L_{RT}	=	matrix of direction cosines
$Oxyz$	=	axes fixed in aircraft
P, Q, R	=	angular velocity components about Ox, Oy, and Oz, rad s^{-1}
q	=	dynamic pressure, Nm^{-2}
S	=	wing area, m^2
U, V, W	=	velocity components along Ox, Oy, and Oz, ms^{-1}
v	=	resultant velocity, $[U \quad V \quad W]^T$, ms^{-1}
y	=	sideways displacement from the plane of symmetry of the tanker wing, positive to starboard, m
z	=	vertical position below tanker wing apex, m
θ	=	pitch angle, rad
ϕ	=	bank angle, rad
ψ	=	yaw angle, rad
∇	=	gradient operator, $[\partial/\partial x \quad \partial/\partial y \quad \partial/\partial z]^T$

Subscripts

R	=	receiver aircraft
T	=	tanker aircraft
w	=	(tanker) wake
∞	=	free-flight condition

Superscript

T	=	transpose of matrix

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Introduction

THERE is active interest in the United Kingdom in setting up a real-time air-to-air refueling flight simulation for training purposes with work carried out by the flight management and control group at the Defence Evaluation Research Agency (DERA), Bedford. The work has initially been aimed at the simulation of the Tornado combat aircraft making contact with the VC10 tanker aircraft and with aerodynamic modeling provided by the present authors. The purpose of this Note is (1) to outline the approximate model of the receiver used in the real-time simulation to reduce computing time and (2) to justify its use by estimating the accuracy of prediction of one of the main aerodynamic effects, namely, the rolling moment induced on the receiver by the tanker wake.

The approximate receiver model adopted is the single-point model as applied by Etkin[1] in the case of wind effects on aircraft. This model is based on the tanker wake conditions at the receiver center of gravity and determines the effect of the tanker wake-induced velocity on the receiver air speed. All six of the translational and rotational air speed components are considered. An advantage of this simple model is that it applies to any receiver aircraft using the aircraft aerodynamic data stored in the flight simulation. To validate the approximate model, the tanker wake and receiver aircraft model developed previously by Bloy and West[2] is used. This model incorporates a line vortex model of the tanker wake rollup with the vortex lattice method applied to all lifting surfaces and with the effect of the tanker wake on the receiver represented by equivalent twist distributions of the lifting surfaces. Linear distributions of downwash and sidewash are assumed in the single-point model compared with variable downwash and sidewash in the exact model.

Tanker Wake Results

The DERA flight simulation required wake velocity data for the VC10 tanker at typical flight conditions corresponding to a flight Mach number of 0.544 and an aircraft lift coefficient of 0.335. As in previous work,[3] the VC10 is represented by its wing planform with the vortex wake rollup calculated to a distance of five wing spans downstream. Over the tanker wing with a downstream step size equal to one-eighth of the wing mean chord, 60 equally spaced spanwise with two chordwise line vortices are taken. To avoid chaotic motion where vortex lines intersect each other, the smoothing factor proposed by Krasny[4] is used with the value of this factor taken as 1% of the wing span.

In the DERA simulation, the wake conditions are specified by a three-dimensional data array giving the downwash and sidewash velocities together with three velocity gradients required in the single-point model described in the following section. Figure 1 shows typical spanwise distributions of downwash velocity at a position one wing span downstream. At this downstream location, which corresponds approximately to the point at which the receiver makes contact with the center hose and drogue, the wake rollup is only partly complete. Figure 1 shows the large gradients of downwash near the tip vortex with the induced flow changing to an upwash outboard of the wing tip.

Single-Point Model of Receiver Aircraft

Etkin[2] considers the aircraft as planar with simple expressions given for the wake-induced roll, pitch, and yaw rates in terms of the velocity gradients over the lifting surfaces. When receiver aircraft axes are used as the frame of reference, the equivalent rotational velocity components of the tanker airwake P_w, Q_w, and R_w are given from Etkin[2] by

$$P_w = \frac{\partial W_w}{\partial y}, \qquad Q_w = \frac{-\partial W_w}{\partial x}$$

$$R_{1w} = \frac{-\partial U_w}{\partial y}, \qquad R_{2w} = \frac{\partial V_w}{\partial x} \tag{1}$$

as shown in Fig. 2. The effective roll, pitch, and yaw rates of the receiver aircraft relative to the air are $(P - P_w)$, $(Q - Q_w)$, and

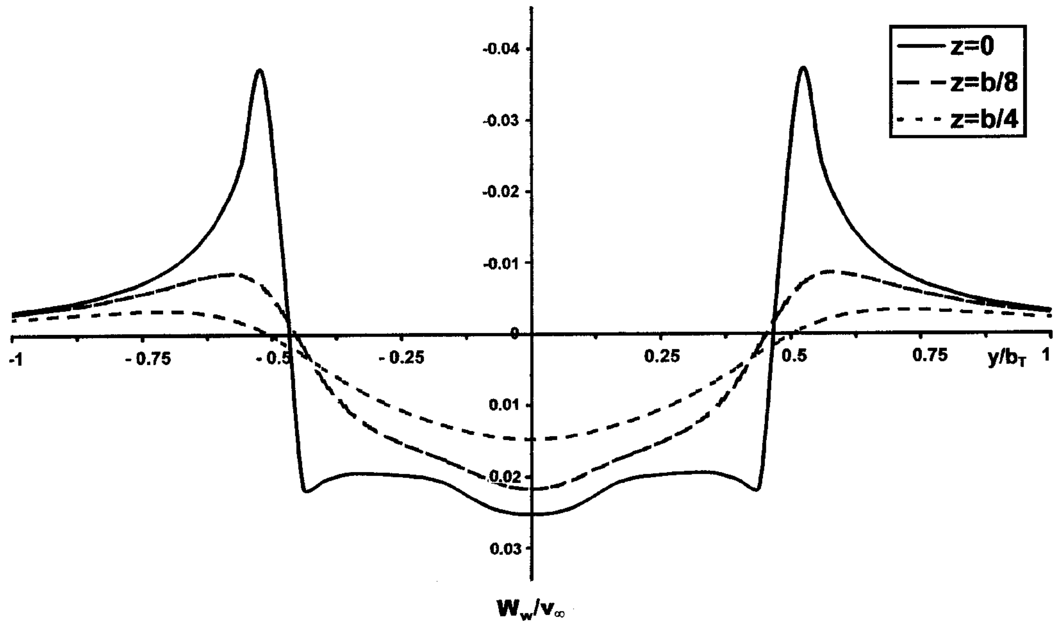

Fig. 1 Spanwise distribution of downwash behind VC10 tanker at one wing span downstream.

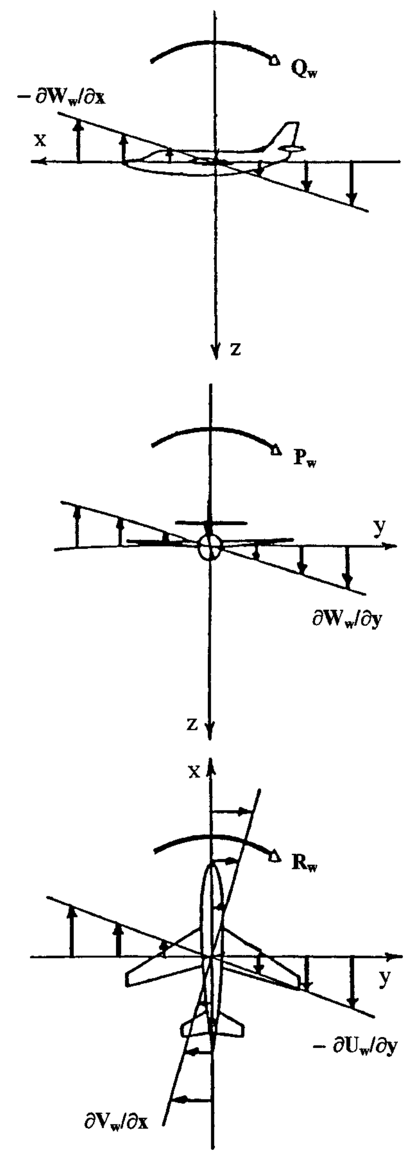

Fig. 2 Relation between wake rotational velocity and wake velocity gradients.

$(R - R_w)$, respectively, whereas the translational velocity components are approximately $(U - U_w)$, $(V - V_w)$, and $(W - W_w)$ along the Ox, Oy, and Oz axes respectively.

In Etkin's model,[2] the effective rate of roll applies to the planar lifting surfaces, namely, wing and tailplane/foreplane, and excludes the fin. Application of this rate of roll to the complete aircraft, therefore, implies some error in the predicted rolling moment, although calculations indicate that the error is relatively small. The effective rate of yaw considered by Etkin includes two terms. The first term $-(\partial U_w/\partial Y)$ relates to the variation in air speed across the wing and tailplane producing the main component of the rolling moment due to rate of yaw. The second term relates to the variation in sidewash along the receiver fin and fuselage producing the main component of the side force and yawing moment due to rate of yaw. Ideally the first component of the rate of yaw should be used in the estimation of the rolling moment, and the second component used in the estimation of the side force and yawing moment.

Etkin's relations[2] are given with respect to receiver aircraft body axes, and to complete the rotational model of the wake effect on the receiver, it is necessary to transform the wake velocity gradients from tanker to receiver aircraft axes. Etkin and Etkin[5] give the appropriate transformation. There are nine velocity gradients in the tanker aircraft axes, namely, $\partial U_w/\partial x$, $\partial U_w/\partial y$, $\partial U_w/\partial z$, $\partial V_w/\partial x$, $\partial V_w/\partial y$, $\partial V_w/\partial z$, $\partial W_w/\partial x$, $\partial W_w/\partial y$, and $\partial W_w/\partial z$, although these can be reduced as follows. At the typical separation distances between tanker and receiver used in refueling the induced wake velocity components are essentially downwash and sidewash, that is, the induced velocity component in the freestream direction U_w together with the velocity gradients $\partial U_w/\partial x$, $\partial U_w/\partial y$, and $\partial U_w/\partial z$ are considered to be negligible. The condition of zero vorticity components in the wake gives

$$\frac{\partial W_w}{\partial y} = \frac{\partial V_w}{\partial z}, \qquad \frac{\partial W_w}{\partial x} = \frac{\partial U_w}{\partial z} \cong 0, \qquad \frac{\partial V_w}{\partial x} = \frac{\partial U_w}{\partial y} \cong 0 \tag{2}$$

Three nonzero derivatives remain, and these are

$$\frac{\partial V_w}{\partial y}, \qquad \frac{\partial W_w}{\partial y}\left(=\frac{\partial V_w}{\partial z}\right), \qquad \frac{\partial W_w}{\partial z}$$

Etkin and Etkin[5] gives expressions for the transformation of the tanker airwake translational velocity and velocity gradient components from tanker aircraft axes to receiver aircraft axes. The translational velocity vector in receiver axes $v_{w,R}$ in terms of the corresponding velocity vector in tanker axes $v_{w,T}$ is given by

$$v_{w,R} = L_{\mathrm{RT}} v_{w,T}$$

where

$$L_{\mathrm{RT}} = \begin{bmatrix} (\cos\theta\cos\psi) & (\cos\theta\sin\psi) & (-\sin\theta) \\ (\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi) & (\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi) & (\sin\phi\cos\theta) \\ (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) & (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) & (\cos\phi\cos\theta) \end{bmatrix} \tag{3}$$

The transformation of the wake velocity gradients ∇v_w is given as

$$\nabla_R v_{w,R}^T = L_{\mathrm{RT}}\left(\nabla_T v_{w,T}^T\right) L_{\mathrm{RT}}^T \tag{4}$$

where ∇ is the gradient operator and L_{RT}^T is the transpose of the matrix L_{RT}. This appears to be a complex transformation, although it is simplified by neglecting the wake U-velocity component in tanker axes, and in any case, only four of the nine elements of $\nabla_R v_{w,R}$ are required, namely, $\partial U_w/\partial y$, $\partial V_w/\partial x$, $\partial W_w/\partial x$, and $\partial W_w/\partial y$.

Accuracy of Single-Point Method

An estimate of the accuracy of the single-point method applied to the Tornado aircraft was made as follows. The procedure involved application of the vortex lattice method computer program developed by Lea[6] to a wing–fin–tailplane representation of the Tornado in its air-to-air refueling configuration as shown in Fig. 3. The lifting surfaces are divided into panels as follows: 32 spanwise × 2 chordwise on the wing, 18 spanwise × 2 chordwise on the tailplane, and 10 spanwise × 1 chordwise on the fin.

Downwash and sidewash velocity distributions determined previously from the tanker wake rollup calculations are then superimposed on the receiver. In the vortex lattice method, the spanwise variation of downwash on the wing and tailplane and the spanwise variation of sidewash on the fin are represented by appropriate twist distributions. The method does not allow a spanwise variation in sidewash on the wing or tailplane, but instead assumes a constant value equal to that at the centerline of the wing or tailplane with a similar condition applying to the spanwise variation in downwash on the fin. A set of equations in matrix form are then solved to obtain the resulting circulation distribution and, hence, the six aerodynamic force and moment components acting on the receiver, namely, lift, drag, and side forces and pitching, rolling, and yawing moments. These arise from the position and attitude of the receiver within the tanker wake.

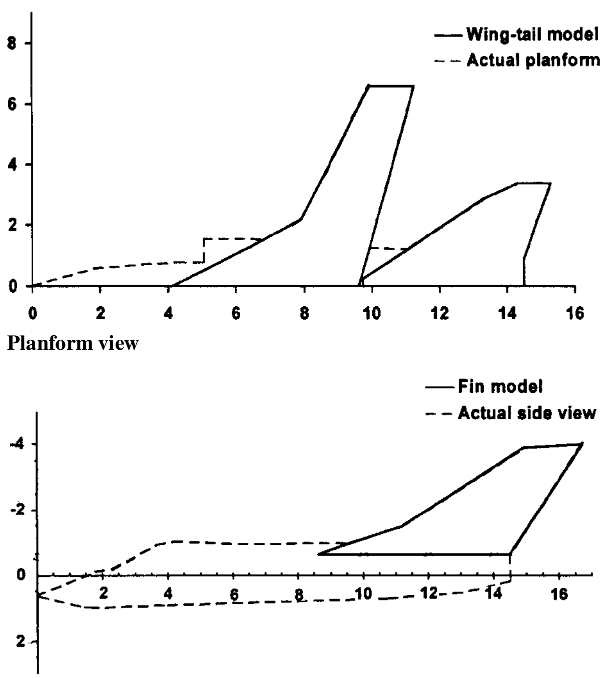

Fig. 3 Actual and modeled Tornado aircraft in its air-to-air refueling configuration; all scales are in meters.

The accuracy of the single-point method is determined by comparing results from 1) the vortex lattice model with variable downwash and sidewash from the tanker wake rollup calculations and 2) the vortex lattice model with linear variation of downwash and sidewash on the receiver lifting surfaces.

The latter model is the single-point model utilizing the tanker wake velocity and velocity gradient components taken at the position of the receiver center of gravity.

The following typical cases are considered. The receiver is positioned with zero yaw and bank at a distance one wing span downstream of the tanker and at various points in the vertical *Oyz* plane. The vortex lattice method requires the receiver pitch angle to be input and then proceeds to calculate the receiver lift coefficient. The receiver pitch angle is adjusted to maintain its lift equal to its weight with the controls fixed in the neutral position. Several iterations of the time-consuming calculations are required to achieve convergence to the steady flight lift coefficient within an acceptable tolerance.

Figure 4 shows the induced rolling moment. As the receiver is displaced sideways from the wake centerline, one wing experiences more downwash than the other with the induced rolling moment increasing to a maximum as the receiver approaches the tanker wing tip. At this point, the inboard wing experiences downwash, whereas the outboard wing experiences upwash. To give an indication of

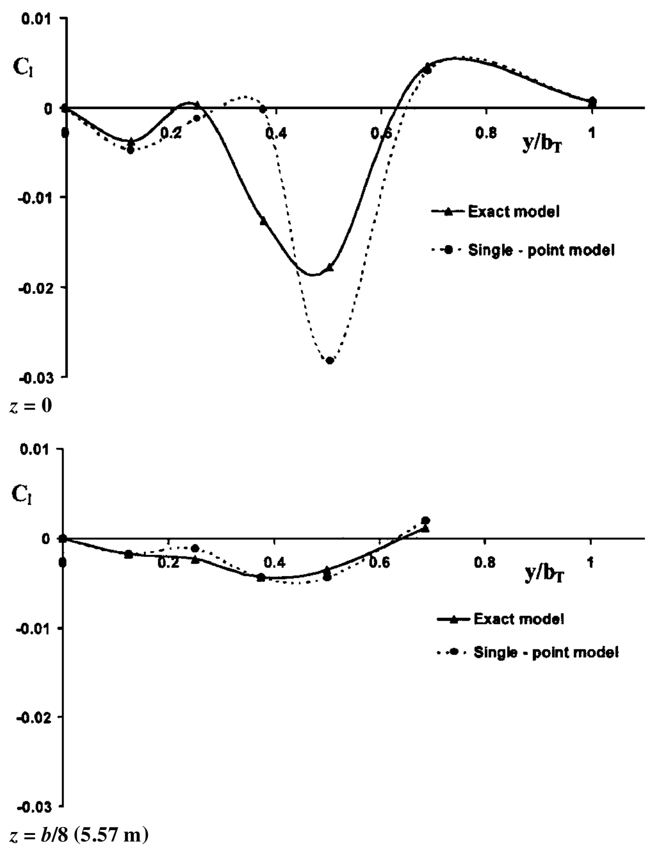

Fig. 4 Predictions of induced rolling moment on receiver.

the magnitude of the rolling moment, it is estimated that a rolling moment coefficient of 0.001 produces a steady rate of roll of about 3 deg/s. Taking this value as the acceptable error, the results show satisfactory agreement between the exact and single-point method predictions except close to the tanker wake downstream of its wing tip vortex, where the velocity gradient is high, and downstream of the wing trailing-edge kink, where a significant change in the spanwise gradient of the wing loading and downwash occur.

A similar conclusion applies to the prediction of the other aerodynamic parameters, namely, the induced drag, pitching moment, side force, yawing moment, and pitch angle. In the case of the side force and yawing moment, the present single-point analysis extends the planar expressions of Etkin[2] to include two components of the wake rate of roll. These are

$$P_{1w} = \frac{\partial W_w}{\partial y}, \qquad P_{2w} = \frac{\partial V_w}{\partial z} \tag{5}$$

The additional term P_{2w} relates to the variation in sidewash across the fin. Applying P_{1w} to all of the lifting surfaces, namely, wing, fin and tailplane, results in errors in the side force and yawing moment of up to 30% in the present case.

Further calculations, not presented in this Note, have shown that the single-point model of the receiver is essentially restricted to cases where the ratio of the receiver wing span to the tanker wing span is much less than one. An alternative multipoint model is, therefore, required for other practical cases of interest such as the refueling of a tanker aircraft in flight from another tanker aircraft. Span ratios vary from 0.91 in the case of a Hercules tanker refueling from a VC10 tanker to 1.12 in the case of a Tristar tanker refueling from a VC10 tanker. The single-point model, however, is considered adequate in simulating typical approaches of the Tornado combat aircraft to the hose and drogue trailing either from the centerline hose drum unit or the wing-mounted pod of the VC10 tanker. Although the single-point model is less accurate near the tanker wing tip vortex, this is of little concern because the combat aircraft would not be expected to fly in this region, and in any case, the combat aircraft would roll quickly on entering the tip vortex with the lift force displacing the aircraft sideways away from the tip vortex. For training purposes it may be useful to demonstrate this effect.

The validity of the exact vortex lattice method that equates the rotation of the leading aircraft vortex wake to variable downwash and sidewash over the following aircraft lifting surfaces has been investigated by Rossow.[7] Lift and rolling moment measurements were taken on a series of models of varying wing span located downstream of a B-747 aircraft model and traversed through the tip vortices. The data were then compared with results from the vortex lattice method using measured downwash distributions in the wake of the B-747 aircraft model as input to the vortex lattice code. Three following wings of span 0.19, 0.51, and 1.02 times the span of the wake-generating model were tested, and Rossow[7] found that the predicted loads on the following wings are reliable as long as the span of the following wing is less than 0.2 times the generator span. As the span of the following wing increases above 0.2, the vortex lattice method continues to predict correctly the trends and nature of the induced loads, but it overpredicts the magnitude of the loads by increasing amounts. Rossow[7] concludes that the wake of the generating wing is sufficiently altered by the large following wing to account for the discrepancy between theory and experiment. For the case considered in this Note, the wing span ratio is 0.30, although the wake interaction effect is less severe than that of Rossow[7] with the receiver located below the tanker tip vortex.

Conclusions

An approximate single-point model of the receiver aircraft in air-to-air refueling has been adapted from the planar aircraft model of Etkin[2] for flight in non-unform wind. The model is simple and easy to apply and has been validated in the case of the Tornado combat aircraft refueling from a VC10 tanker aircraft. Acceptable accuracy is achieved using the single-point model in all regions of the tanker wake except close to the tanker wake downstream of the wing tip vortex although this limitation is of little practical concern.

The single-point model becomes less accurate as the span of the receiver aircraft is increased and is unsuitable for cases involving large receiver aircraft such as a tanker refueling from another tanker.

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Studies on Vortex Flaps Having Different Flap Hinge-Line Positions

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Introduction

THE leading-edge vortex flap is a deflectable surface at the leading edge of a delta wing. A leading-edge separation vortex is formed over the flap surface, which helps to reduce the drag and to improve the lift/drag (L/D) ratio of the delta wing.[1] Many studies have confirmed the benefit of the vortex flap.

There are several factors that affect the vortex flap characteristics: first, sweepback angle of the delta wing; second, leading-edge shape, i.e., sharp or rounded leading edge; and third flap hinge-line position. The first author has carried out experimental studies using delta-wing models that have different sweepback angles fitted with tapered vortex flaps.[2] The benefit of the vortex flap was confirmed, and the effect of the sweepback angle was revealed. The first author also conducted wind-tunnel studies to determine the effect of the second factor, i.e., the difference between sharp and rounded leading-edge vortex flaps.[3] It was shown that deflecting the rounded leading-edge vortex flaps improves the L/D at relatively higher lift coefficients when compared with the sharp-edged vortex flaps.

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