JOURNAL OF AIRCRAFT
Vol. 32, No. 6, November–December 1995

Trailing Vortex Effects on Large Receiver Aircraft

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The aerodynamic forces and moments on the Hercules receiver aircraft, due to its horizontal and vertical position and bank, yaw, and pitch attitudes in the wake of the KC10 tanker aircraft, are assessed relative to the receiver's aerodynamic characteristics in free air. Large changes in lift, drag, and pitching moment are predicted near the tanker wake centerline. As the receiver is displaced sideways towards the tanker wingtip vortices it experiences large side force and yawing moment and particularly high rolling moment. The most significant term due to the receiver attitude is the rolling moment due to bank.

Nomenclature

b = wingspan, m
C_{D_i} = induced drag coefficient, $D_i/q_\infty S$
C_L = lift coefficient, $L/q_\infty S$
C_l = rolling moment coefficient, $L/q_\infty Sb$
$C_{l\theta,\phi,\psi,\beta,\delta_a}$ = rolling moment derivatives, in nondimensional form, $\partial C_l/\partial\theta$, $\partial C_l/\partial\phi$, $\partial C_l/\partial\psi$, $\partial C_l/\partial\beta$, $\partial C_l/\partial\delta_a$
C_m = pitching moment coefficient, $M/q_\infty S\bar{c}$
$C_{m\theta,\phi,\psi,\alpha,\delta_e}$ = pitching moment derivatives, in nondimensional form, $\partial C_m/\partial\theta$, $\partial C_m/\partial\phi$, $\partial C_m/\partial\psi$, $\partial C_m/\partial\alpha$, $\partial C_m/\partial\delta_e$
C_n = yawing moment coefficient, $N/q_\infty Sb$
$C_{n\theta,\phi,\psi,\beta,\delta_r}$ = yawing moment derivatives, in nondimensional form, $\partial C_n/\partial\theta$, $\partial C_n/\partial\phi$, $\partial C_n/\partial\psi$, $\partial C_n/\partial\beta$, $\partial C_n/\partial\delta_r$
C_X = force coefficient, $X/q_\infty S$
$C_{X\theta,\phi,\psi,\alpha}$ = force derivatives, in nondimensional form, $\partial C_X/\partial\theta$, $\partial C_X/\partial\phi$, $\partial C_X/\partial\psi$, $\partial C_X/\partial\alpha$
C_Y = side force coefficient, $Y/q_\infty S$
$C_{Y\theta,\phi,\psi,\beta}$ = side force derivatives, in nondimensional form, $\partial C_Y/\partial\theta$, $\partial C_Y/\partial\phi$, $\partial C_Y/\partial\psi$, $\partial C_Y/\partial\beta$
C_Z = force coefficient, $Z/q_\infty S$
$C_{Z\theta,\phi,\psi,\alpha}$ = force derivatives, in nondimensional form, $\partial C_Z/\partial\theta$, $\partial C_Z/\partial\phi$, $\partial C_Z/\partial\psi$, $\partial C_Z/\partial\alpha$
$\bar{c}$ = wing mean chord, m
D_i = induced drag, N
h = perpendicular distance to vortex line, m
L = lift, N
L = rolling moment about Ox, Nm
M = pitching moment about Oy, Nm
N = yawing moment about Oz, Nm
$Oxyz$ = axes fixed in aircraft
q = dynamic pressure, Pa
S = wing area, m^2
v_i = induced velocity, m/s
X = force component along Ox, N
Y = side force, N
y = sideways displacement from the plane of symmetry of the tanker wing, positive to starboard, m
Z = force component along Oz, N
z = vertical separation between datum points of tanker and receiver aircraft, m
α = angle of attack, rad
β = sideslip angle, rad
Γ = circulation, m^2/s
δ = smoothing factor
δ_a = aileron deflection angle, rad
δ_e = elevator deflection angle, rad
δ_r = rudder deflection angle, rad
θ = pitch angle, rad
ϕ = bank angle, rad
ψ = yaw angle, rad

Subscripts
T = tanker aircraft
∞ = free air conditions

Introduction

THE operation of large aircraft in close proximity as in aerial refueling can produce large effects on the receiver aircraft. For example, Bradley[1] has described an exploratory test in which a Hercules aircraft approached a typical refueling position on the starboard wing of a Tristar tanker aircraft. As the receiver approached the refueling position it was necessary to apply progressively more right aileron and rudder. Eventually at a point behind the tanker and well short of a typical drogue position, full aileron travel was required to hold the wings level and the approach was terminated. Other handling problems described by Bradley[1,2] include the tendency of the receiver to enter a short period pitching oscillation when making contact or in the refueling position. Both the VC10 and Victor aircraft exhibited this tendency. In the case of the Hercules aircraft receiving from jet tanker aircraft the Hercules was found to be susceptible to a "directional wandering" or lateral oscillation that required considerable rudder activity to maintain a low amplitude of the oscillation. The directional wandering was judged to be unacceptable in flight behind heavy Tristar or KC10 tanker aircraft at low speed.

The tanker trailing vortex wake also has a large effect on the performance of the receiver aircraft. Due to the tanker downwash the receiver lift vector is inclined backwards, effectively increasing the induced drag. As an example, Bradley[2] has given data that indicate that the effective drag of the Hercules aircraft is nearly doubled when in contact with a Tristar tanker. In some cases the receiver is power limited so that refueling takes place in descending flight.

In previous work, Bloy et al.[3,4] have modeled the aerodynamic interference between the tanker trailing vortex wake and the receiver aircraft, obtaining predictions that agree with flight test observations.[2] These include longitudinal trim changes made in the approach to the tanker and correlation of the receiver aircraft induced drag increment due to the tanker wake. The most recent work considers the lateral and direc-

Received Feb. 4, 1995; revision received April 24, 1995; accepted for publication April 24, 1995.
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tional stability and control of the Hercules aircraft in flight behind a KC10 tanker. The tanker wing wake is modeled using a three-dimensional line vortex method[5] with the aerodynamic loads on the receiver determined using the vortex lattice method coupled with approximate expressions for the receiver fuselage effect. This work predicts the large decrease in the directional stability of the receiver as quantified by the gradient of the rudder angle vs sideslip and the associated aileron angle that is up to two to three times the value obtained in free air.

In the United Kingdom there has been interest in the flight simulation of air-to-air refueling, both as a training aid and as a development tool. Bradley[2] has described the problem of the unacceptable lateral handling of the Nimrod aircraft refueling from a heavy Tristar tanker. This problem was investigated on a simulator by assessing changes made to the yaw damper control laws, although Bradley[2] reports that the simulation was not considered realistic enough to be useful in resolving the problem. The use of simulators in training offers major savings in direct operating costs and aircraft fatigue life. Prothero[6] has described the simulation requirements for air-to-air refueling and states that the process in achieving a successful contact between tanker and receiver and holding for long enough to achieve the necessary fuel transfer is the area in which a great deal of training time is spent. Simulation of this flight phase therefore requires good modeling of the aerodynamic interference between tanker and receiver.

The purpose of the present work is to provide typical data from an improved model of the aerodynamic interference between tanker and receiver aircraft. This uses the three-dimensional wake roll-up method described by Bloy and West[5] and applied in previous work[4] to the KC10 tanker/Hercules receiver combination. The same combination of tanker and receiver is considered over an envelope of the receiver positions and attitudes that covers that required for flight simulation. From the results the most important aerodynamic terms are identified.

Other work relevant to the simulation of trailing vortex effects on aircraft in close formation is that of Iversen and Bernstein[7,8] using a fully rolled up trailing vortex model to simulate the effect on a C-130 aircraft. In this work only the induced lift and rolling moment increments were calculated. These loads varied with the position of the following aircraft in the trailing vortex wake and were dependent on the downwash distribution due to the lead aircraft. Hoganson[9] determined the longitudinal aerodynamic interference between the KC10 tanker and B52 receiver using a semi-infinite vortex sheet model of the tanker wake. A typical approach path was considered and results given for the induced downwash distribution and the corresponding lift force and pitching moment. The upstream influence of the receiver on the tanker was shown to be small.

Flight Conditions and Aircraft Data

Figure 1 shows the KC10 tanker and Hercules receiver aircraft at a horizontal separation of 1.04 times the tanker wingspan as measured between the datum positions taken at the wing apex of each aircraft. As in the previous work[4] the tanker is considered at a lift coefficient of 0.8 and flight Mach number of 0.35. The receiver is considered at a pitch angle of 6 deg to the horizontal that at the typical refueling position gives a lift coefficient of 0.5, similar to that used previously. Other relevant tanker and receiver aircraft data are listed in Table 1.

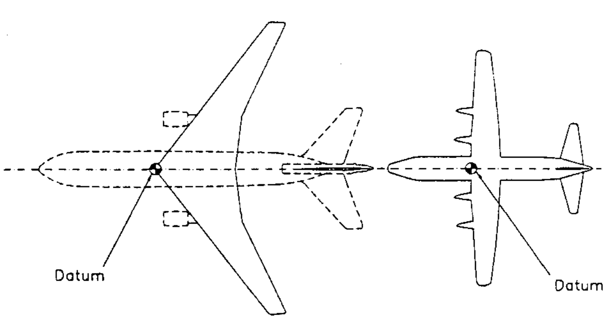

Fig. 1 KC10 tanker/Hercules receiver aircraft model.

Table 1 Tanker and receiver aircraft data

	KC10 tanker aircraft	Hercules receiver aircraft
Wing area	367.7 m^2	161.8 m^2
Wingspan	50.4 m	40.4 m
Wing twist	3 deg	3 deg
Wing dihedral	4 deg	2.5 deg

Estimated aerodynamic data relevant to the Hercules aircraft in free air conditions are given in Table 2.

Aerodynamic Model

A three-dimensional line vortex method[5] is used to model the tanker wing trailing vortex wake roll-up. The method includes the effect of the bound vortex and proceeds stepwise downstream from the tanker wing trailing edge aligning the trailing vortices in the local stream direction. One hundred twenty equally spaced spanwise line vortices are taken with a downstream step size equal to one-eighth of the wing mean chord. The roll-up is calculated to a distance four wingspans downstream and, to avoid the problem of chaotic motion where vortex lines intersect each other, the smoothing factor proposed by Krasny[10] is used. This factor limits the high velocities induced on line vortices in close proximity. For a doubly infinite line vortex, the modified v_i is given by

$$v_i = \frac{\Gamma}{2\pi h}\left(\frac{h^2}{h^2 + \delta^2 b^2}\right)$$

with the choice of δ dependent on the step size, number of trailing vortex lines, and length of wake over which the roll-up calculations are performed. Krasny[10] gives examples of the chaotic motion that can occur in the tip vortex if the step size is too large or the number of trailing vortex lines is too small. Krasny[10] also shows that the method converges as the step size is refined. Reducing the value of the smoothing factor gives a more detailed model of the tip vortex with more turns of the tip vortex spiral represented. For the present calculations a value of δ of 0.025 produced satisfactory solutions, although there is evidence of the instability problem described by Krasny.[10] This can be seen in Fig. 2 in the downstream region of the vortex sheet between the two tip spirals. However, its effect on the induced downwash and sidewash at the receiver is negligible. The calculated aerodynamic loads are also relatively insensitive to the value of δ.

The tanker aircraft induces downwash and sidewash over the receiver aircraft with the induced loads dependent on the position and attitude of the receiver. As in previous work[4] the vortex lattice method is used to determine the aerodynamic loads on the wing, tailplane, and fin with the downwash and sidewash effects represented by an appropriate twist angle. The distributed load along the fuselage is modeled by forces and moments about the c.g. due to the induced downwash and sidewash at the c.g. Engineering Sciences Data Unit data sheets[11-13] are used to estimate the loads due to the receiver fuselage and engine nacelles.

The previous work[4] considered the case of small lateral displacements of the receiver from a position on the centerline of the tanker wake with no bank or sideslip and the nine lateral aerodynamic derivatives due to side, bank, and yaw displacements were estimated. In the present work the in-

Table 2 Hercules aerodynamic data in free air

C_{L_∞}	C_{Di_∞}	$C_{l\beta}$	$C_{l\delta_a}$	$C_{m\alpha}$	$C_{m\delta_e}$	$C_{n\beta}$	$C_{n\delta_r}$
0.783	0.0196	−0.103	−0.229	−2.47	−3.5	0.079	−0.104

All derivatives are per radian and the c.g. is at the wing quarter-chord position.

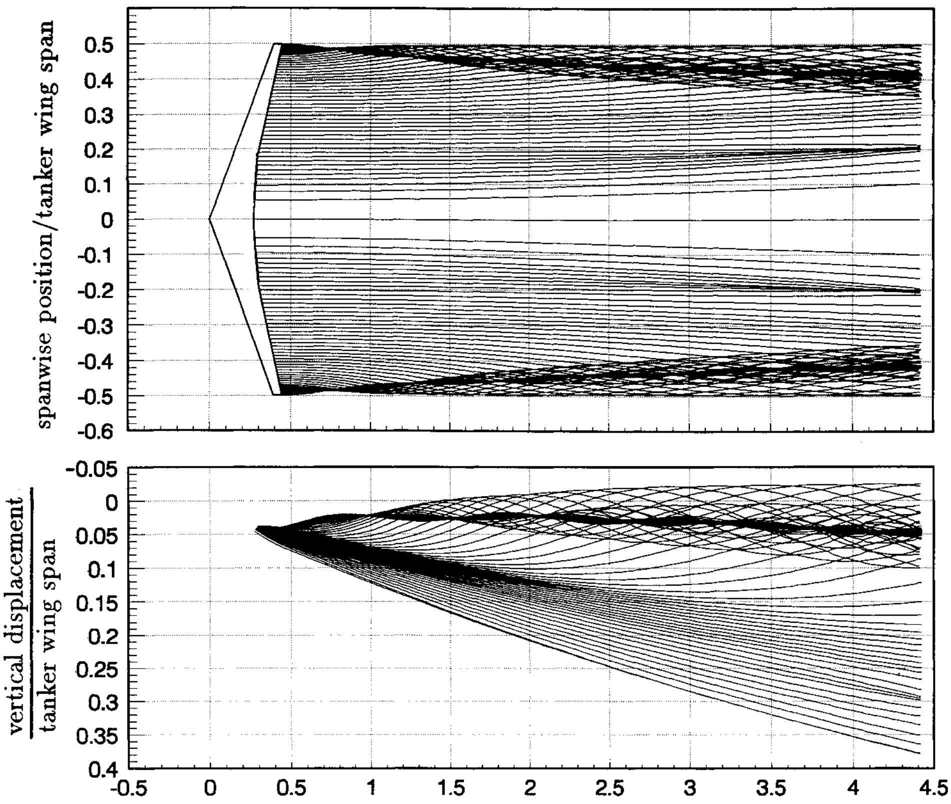

Fig. 2 Roll-up of tanker wing wake.

duced aerodynamic forces and moments on the receiver vary nonlinearly with the position coordinates x, y, and z of the receiver relative to the tanker. These forces and moments are usually illustrated by contour plots in the y, z plane at various downstream positions. Bank, yaw, and pitch displacements also produce forces and moments, and for the most significant aerodynamic terms it has been found that the forces and moments vary almost linearly with displacement angles in the range ±10 deg. This allows the induced forces and moments due to the receiver attitude to be represented by aerodynamic derivatives. These are also shown by contour plots. All 18 of the aerodynamic terms, viz., X, Y, Z, L, M, and N due to ϕ, θ, and ψ are considered.

Aerodynamic Results

Figure 2 illustrates the roll-up of the tanker wing wake modeled by trailing-line vortices. Normally, in air-to-air refueling, the receiver is positioned below the tanker wing wake, although the fin may experience buffeting as it penetrates the tanker wake. All of the present results correspond to the receiver located downstream at a distance between the tanker and receiver datum points, which are located at the wing apex points, of 1.04 times the tanker wingspan. The minimum vertical separation between the datum points is 0.15 times the tanker wingspan, which positions the receiver datum point just below the tanker wing wake. Figure 3 shows the downwash and sidewash induced by the tanker wing at the position of the receiver wing.

Firstly, consider the forces and moments due to the position of the receiver within the tanker wake. In the lateral case the rolling moment coefficient shown in Fig. 4 is essentially due to the spanwise variation of downwash with the peak amplitudes occurring in the region $0.25 < y/b_T < 0.5$, where the highest spanwise downwash gradients occur. In order to indicate the scale of this term the rolling moment coefficient is compared with the rolling moment coefficient due to aileron deflection. For a linear behavior of the ailerons, this ratio gives the amplitude of the aileron deflection, in radians, required to balance the induced rolling moment. Figure 4 then shows the high rolling moment produced as the receiver is displaced outboard with the rolling moment acting to direct the lift vector towards the centerline of the tanker wake. As the receiver is displaced outboard of the tanker wingtip it experiences an upwash over the inner wing, which reverses the direction of the rolling moment.

Side force and yawing moment coefficient contours, which are similar in form, depend mainly on the sidewash over the fin and fuselage. Peak amplitudes then occur close to the center of the tip vortex. Figure 5 shows the corresponding high value of the yawing moment coefficient compared with the yawing moment coefficient due to rudder deflection. This ratio gives the rudder deflection required to balance the induced yawing moment, which tends to yaw the nose of the receiver towards the centerline of the tanker wake. Figure 6 shows the variation of the ratio of C_Y to C_{L_∞}. This ratio is equivalent to the bank angle required to prevent sideways drift of the receiver.

For this tanker/receiver aircraft configuration the longitudinal force and pitching moment coefficient contours (shown in Figs. 7–9) exhibit a similarity. $(-C_X)$ is equal to the ef-

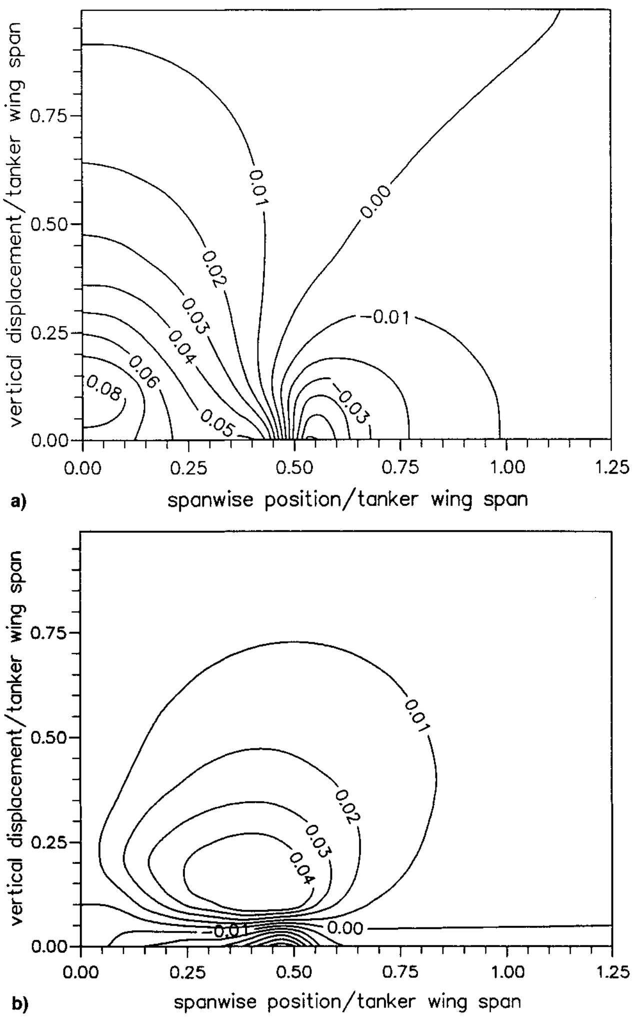

Fig. 3 Contours of a) downwash angle (rad) and b) sidewash angle (rad) induced by tanker wing at position of receiver wing.

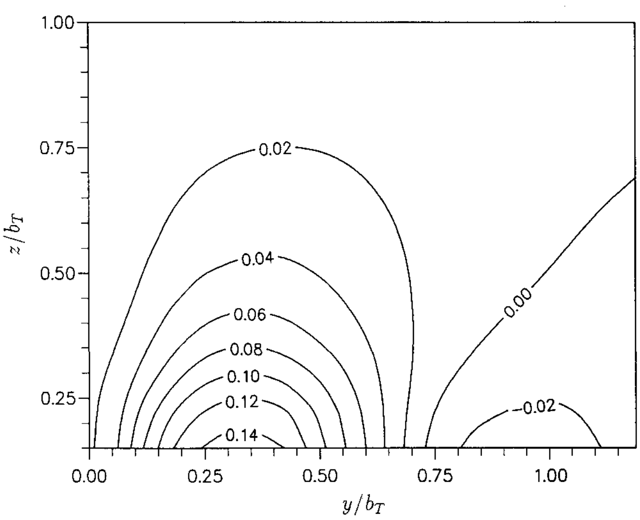

Fig. 4 Contours of rolling moment parameter $C_l/C_{l\delta_a}$ (rad).

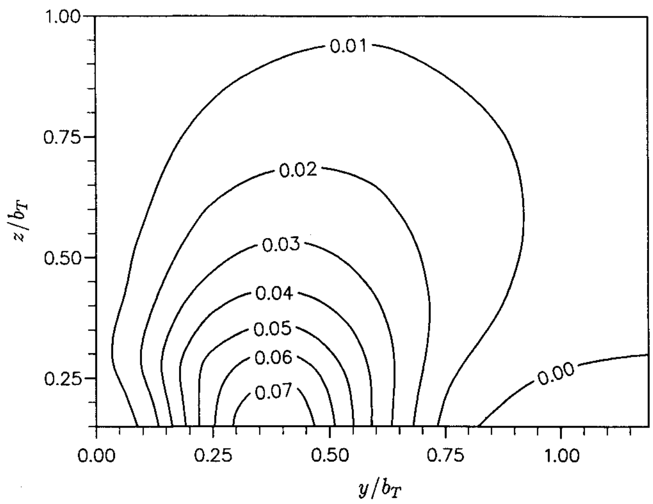

Fig. 5 Contours of yawing moment parameter $C_n/C_{n\delta_r}$ (rad).

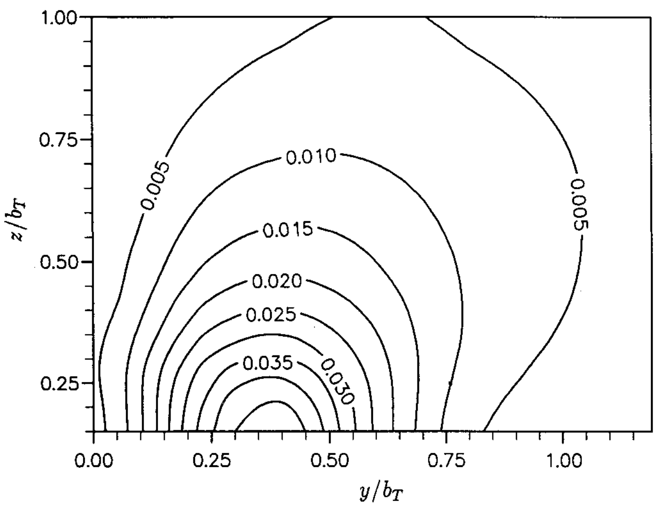

Fig. 6 Contours of side force parameter C_Y/C_{L_∞}.

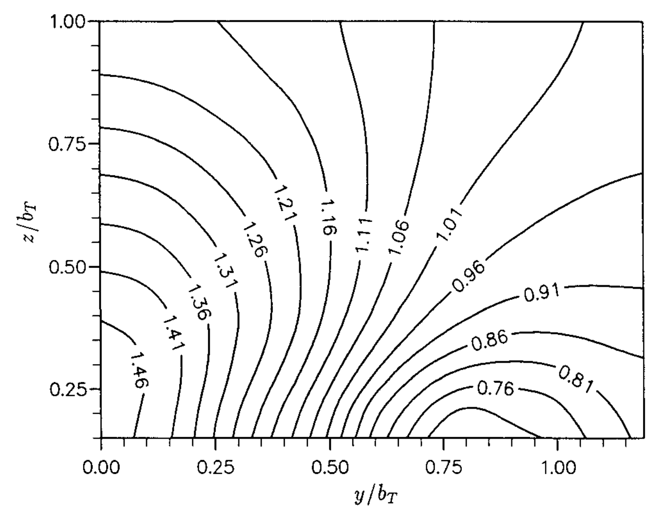

Fig. 7 Contours of induced drag parameter $C_{D_i}/C_{D_{i\infty}}$.

fective drag of the receiver, which is dependent on the downwash angle. Downwash reduces the receiver angle of attack, and consequently, the lift and induced drag. Since the relative airflow is directed slightly downwards, the lift is inclined rearwards, and it is this component that leads to the overall increase in drag. The predicted lift-dependent drag contours are shown in Fig. 7 in comparison with the free air value. The highest changes occur near the tanker wake centerline where the downwash is highest and reverse in sign in the upwash region outboard of the tanker wingtip. These comments also apply to the lift coefficient contours shown in Fig. 8 in comparison with the free air value. The lift coefficient C_L is equal to $(-C_Z)$.

Pitching moment coefficients on the receiver are associated with three effects. The main effect is the tanker downwash

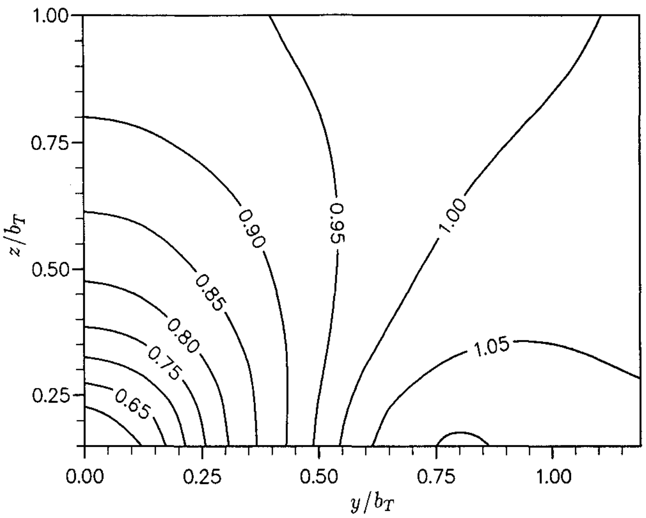

Fig. 8 Contours of lift force parameter C_L/C_{L_∞}.

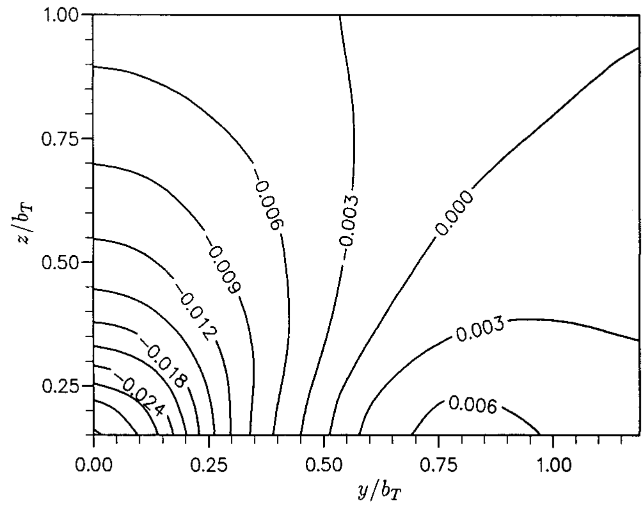

Fig. 9 Contours of pitching moment parameter $C_m/C_{m_{\delta_e}}$ (rad).

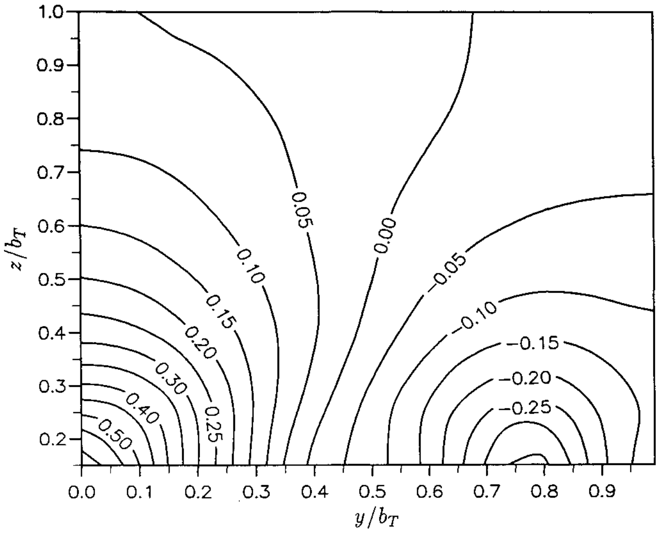

Fig. 10 Contours of rolling moment due to bank angle parameter C_{l_ϕ}/C_{l_β}.

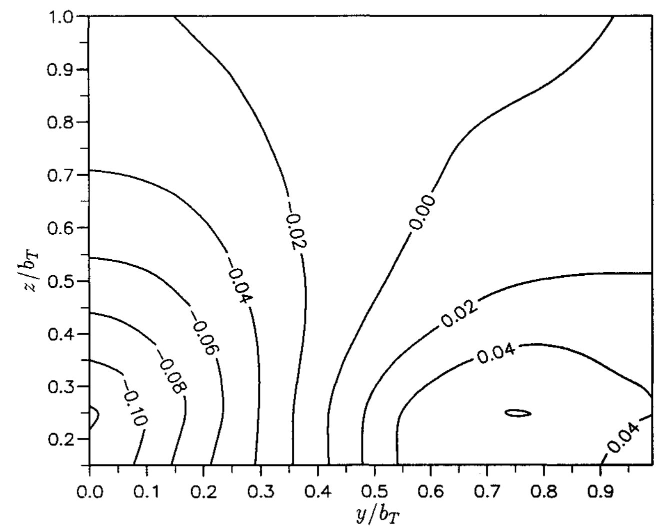

Fig. 11 Contours of yawing moment due to bank angle parameter C_{n_ϕ}/C_{n_β}.

that reduces the receiver incidence and the inherent static stability of the aircraft gives a nose-up pitching moment. Secondly, the mean tanker downwash over the tailplane is higher than that over the wing, producing a nose-up moment. Thirdly, the tanker downwash alters the lift distribution over the receiver wing, and consequently, the downwash over the receiver tailplane. Figure 9 shows the resulting contours in terms of the pitching moment coefficient due to elevator.

The remaining aerodynamic interference terms are those associated with the bank, pitch, and yaw attitudes of the receiver relative to the tanker wake. These terms are presented in derivative form. To assess their significance each derivative is compared with the corresponding static stability derivative due to angle of attack or sideslip. For example, the derivative C_{l_ϕ} is compared with C_{l_β}. This approach is valid if all of the angles involved in any simulation, viz., α, β, ϕ, θ, or ψ are comparable in magnitude.

Consider the effect of banking the receiver. Near the centerline of the tanker wake this produces a stabilizing effect with the downgoing wing experiencing less downwash and the upgoing wing experiencing more downwash. The resulting rolling moment tends to maintain the wings being level. Figure 10 shows the relative significance of the derivative C_{l_ϕ} compared with the corresponding C_{l_β}. The highest values occur on the centerline with the rolling moment reversing in direction as the receiver moves outboard of the tanker wingtip.

Banking the receiver results in a component of the tanker downwash acting normal to the fin. This is the main term in the sideforce and yawing derivatives. Figure 11 shows C_{n_ϕ} compared with the corresponding directional static stability derivative C_{n_β}. Peak amplitudes occur on the tanker wake centerline where the downwash is highest. Although the values of C_{n_ϕ} are relatively small, the term ϕC_{n_ϕ} was considered significant by Bloy and Jouma'a[4] when analyzing trim in steady sideslip in air-to-air refueling. The plot of C_{Y_ϕ}/C_{Y_β} is similar in form although the peak amplitude of about 5% is considered to be small.

The remaining derivatives due to bank C_{X_ϕ}, C_{Z_ϕ}, and C_{m_ϕ} are considered to be small. Compared with the corresponding derivatives due to incidence, the ratios C_{X_ϕ}/C_{X_α}, C_{Z_ϕ}/C_{Z_α}, and C_{m_ϕ}/C_{m_α}, which are zero on the centerline of the wake, increase to peak amplitudes less than 7% outboard of the wingtip.

Yawing the receiver changes the sidewash over the fin, producing a side force and yawing moment with negligible rolling moment. Peak amplitudes occur on the centerline and outboard of the tanker wingtip where the spanwise gradients of sidewash are highest. Compared with the corresponding static stability derivatives, only the ratio C_{n_ψ}/C_{n_β} (shown in Fig. 12) is considered to be significant.

None of the remaining three derivatives due to yaw, C_{X_ψ}, C_{Z_ψ}, and C_{m_ψ}, is significant when compared with the corre-

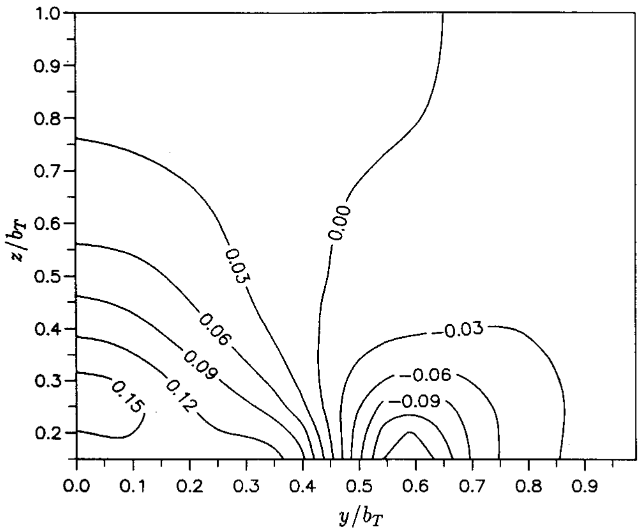

Fig. 12 Contours of yawing moment due to yaw angle parameter C_{n_ψ}/C_{n_β}.

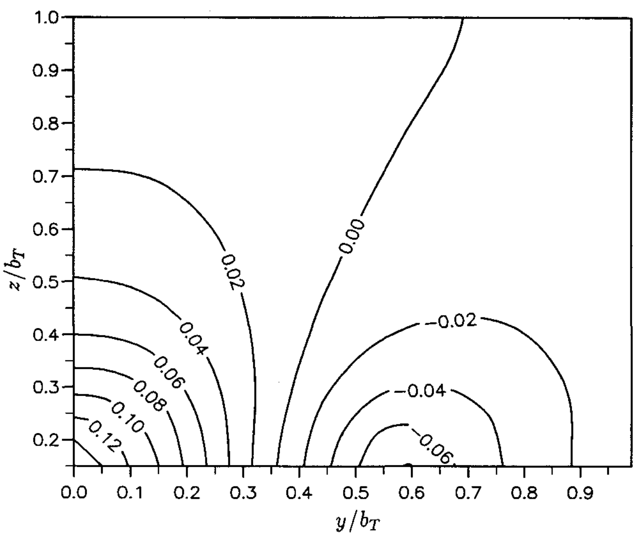

Fig. 13 Contours of pitching moment due to pitch angle parameter $C_{m_\theta}/C_{m_\alpha}$.

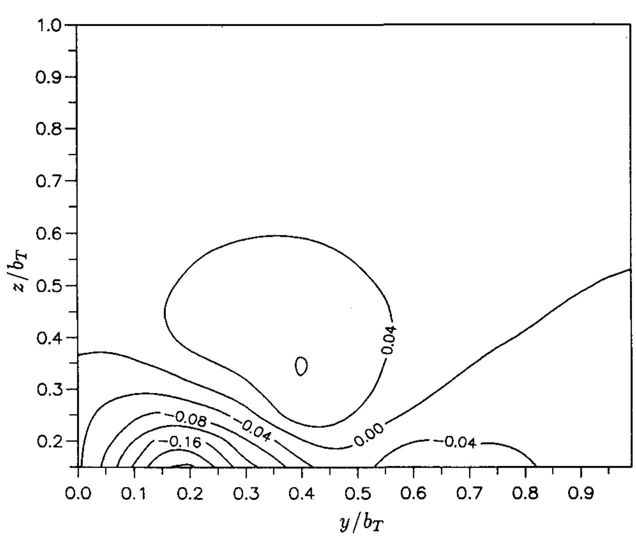

Fig. 14 Contours of yawing moment due to pitch angle parameter C_{n_θ}/C_{n_β}.

sponding static stability derivatives due to the angle of attack. These small terms are associated with the change in downwash over the tailplane as the receiver aircraft yaws.

Pitching the receiver aircraft moves the tailplane into a region of lower or higher downwash and results in a significant pitching moment, as shown in Fig. 13, where the ratio $C_{m_\theta}/C_{m_\alpha}$ is plotted. Peak amplitudes are produced at the centerline where the downwash is highest with the pitching moment changing sign as the receiver aircraft moves into the region of upwash outboard of the tanker wingtip. The derivatives C_{X_θ} and C_{Z_θ} associated with the tailplane drag and lift increments, respectively, can be neglected.

Coupled with the change in downwash over the tailplane due to pitch is a change in sidewash over the receiver fin. This produces a significant yawing moment as shown by the contour plot of the ratio C_{n_θ}/C_{n_β} given in Fig. 14. The associated C_{Y_θ} is relatively small.

Conclusions

Application of an aerodynamic interference model to a Hercules aircraft flying in the wake of a KC10 tanker has given the forces and moments on the receiver due to its position and attitude. These forces and moments have been assessed by comparison with the aerodynamic characteristics of the receiver aircraft in free air.

In the lateral case, high side force, yawing, and rolling moments are produced as the receiver is displaced sideways from the centerline of the tanker wake towards the tanker wingtip vortices. The most important of these aerodynamic terms is the rolling moment due to sideways displacement, which can exceed the available roll control moment. This term is associated with the spanwise variation of downwash due to the tanker. Within the region between the tanker wingtip vortices the induced yawing and rolling moments are stabilizing, tending to return the receiver aircraft towards the centerline of the tanker wake.

In the longitudinal case large changes in the receiver lift, drag, and pitching moment near the tanker wake centerline are due to the effect of the tanker downwash. Lift is reduced and lift-dependent or induced drag is increased. For the Hercules receiver aircraft there may be insufficient power to overcome drag, making it necessary to refuel in descending flight. The receiver experiences a nose-up pitching moment due essentially to its static stability with respect to angle of attack.

Aerodynamic derivatives due to the receiver attitude are assessed by comparing with the corresponding aircraft derivatives due to the angles of attack and sideslip. The most significant of these terms is the rolling moment due to bank angle derivative, which has a peak value approximately equal to one-half the rolling moment due to sideslip angle derivative. Terms of lesser significance are the yawing moments due to bank, pitch, and yaw angles and the pitching moment due to pitch angle.

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