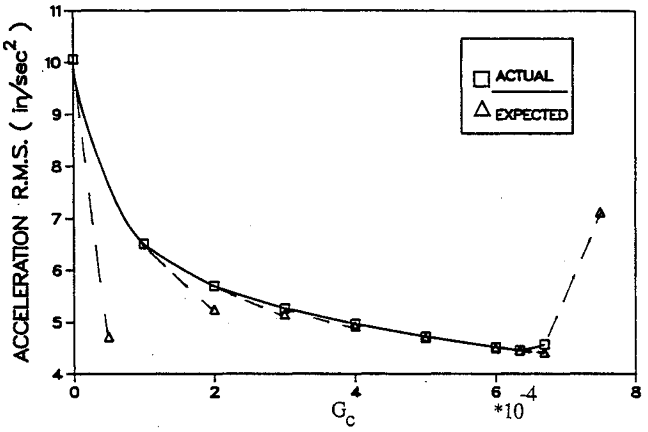

Fig. 1 Closed-loop wingtip rms acceleration vs control gain.

$\sigma_{w_g} = 1$ in./s, premultiplied by the low-pass filter of Eq. (8) with $a = 2640$ rad/s, which yields 3 gust states.

Fifteen doublet-lattice unsteady AFC matrices were calculated at Mach 0.62 for k values of 0 to 4.0. The MS aerodynamic approximation, Eq. (9), was performed with 4 aerodynamic lag terms that yield 4 aerodynamic states. The initial constraint set was data matched at $k = 0.0$ and $k = 4.0$, which is well above the frequencies of significant aeroelastic activity. To evaluate the accuracy of the aerodynamic approximation in gust-response analysis, PSD functions of the response were calculated in the frequency domain once with the "exact" quadratic interpolation of the tabulated AFC matrices via MSC/NASTRAN, and once with the MS approximated aerodynamics. While the PSD functions of wingtip acceleration—obtained by the two ways—were in excellent agreement, the MS wing-root bending-moment exhibited large errors in the range of 0–0.3 Hz. The errors are related to inaccuracies in approximating the quasisteady aerodynamics associated with rigid-body vertical velocity. The problem was fixed by constraining the approximation to match the imaginary data at the lowest nonzero tabulated $k = 0.005$ instead of the imaginary-part match at $k = 4$. The change had negligible effects of other results.

Parametric studies were performed at 90% of the open-loop flutter dynamic pressure to demonstrate gust response and sensitivity variations with structural and control design variables. An example is the effect of the preactuator control gain G_c on the wingtip acceleration response, shown in Fig. 1. The "expected" values in the figure, which are based on the sensitivity derivatives at the connected points, demonstrate the accuracy of the sensitivity computations. A separate analysis indicated 3.0-Hz flutter with $G_c = -0.4 \times 10^{-4}$. It can be observed in Fig. 1 that the control law is very effective at low positive gain values. When the gain increases, the system approaches a 30.4-Hz flutter at $G_c = 6.8 \times 10^{-4}$. The two flutter bounds are indicated in Fig. 1 by the large sensitivity derivatives at $G_c = 0.0$ and $G_c = 6.7 \times 10^{-4}$.

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Interference Between Tanker Wing Wake with Roll-Up and Receiver Aircraft

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Introduction

VORTEX wake roll-up is a problem of interest when one aircraft flies in formation behind another aircraft as in air-to-air refueling. In this case the following or receiver aircraft approaches the leading or tanker aircraft from below, and typically refuels at a position about one span downstream of the tanker aircraft. A more detailed description of the approach has been given by Bradley[1] for the hose and drogue method of refueling, and by Hoganson[2] for the flying boom method of refueling. During refueling, the main wing of the receiver lies below the tanker wake trailing vortices, although the fin may intersect the tanker wake.

In a previous work, Bloy et al.[3–5] investigated both theoretically and experimentally the effect of the tanker downwash and sidewash on the receiver. Relatively simple wake models were used and it is the purpose of this Note to present results for a more realistic roll-up model of the wake. There are numerous other references on vortex roll-up, although many of these are two-dimensional methods applicable far downstream of the wing. For the present case a method that allows for the effect of the wing bound vortices was required. Also, it was not considered necessary to correctly model the trailing vortex viscous core since the flow of interest is that well outside the core. The chosen method is similar to that used by Butter and Hancock[6] in which the trailing vortex sheet is represented by vortex lines shed from the wing trailing edge. The positions of these vortex lines are then determined by integrating downstream. Moore[7] found that the line vortex method can produce chaotic motion of the vortices associated with the very high velocities induced by vortices in close prox-

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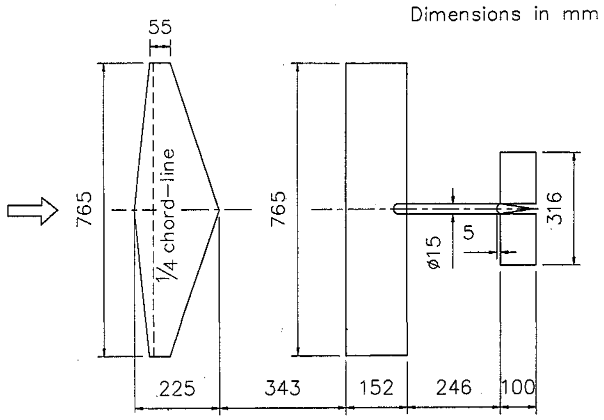

Fig. 1 Dimensions of tanker wing and receiver aircraft model.

imity. To prevent this chaotic motion the method of Krasny[8] is incorporated. This method modifies the induced velocity due to a line vortex so that high velocities near the vortex core are avoided.

In air-to-air refueling, the forces and moments acting on the receiver aircraft depend on its position and attitude within the tanker vortex field. Bloy et al.[3–5] have indicated the most significant aerodynamic terms. Since the effect of the trailing vortex roll-up is greatest in the region of the wingtip, two of the most affected aerodynamic terms are the rolling moments due to side and bank displacements of the receiver. These terms depend mainly on the variation of downwash across the receiver wing, and results are given both for the flat vortex sheet and vortex roll-up models of the wake applied to a tanker wing/receiver aircraft model tested previously by Bloy et al.[5] Relevant dimensions and positions of the models are given in Fig. 1.

Numerical Method

The method requires the distribution of circulation Γ over the tanker wing, which is that determined previously by Bloy et al.[5] using the linear vortex lattice method with 30 spanwise and 4 chordwise points across the wing. By curve-fitting the resulting spanwise circulation distribution, the position of the trailing line vortices chosen to be of equal strength were found. Eighty line vortices were used, each shed at the wing trailing edge initially in the freestream direction. The vortex wake roll-up is represented by straight line segments and is determined by stepping downstream. Since the trailing edge is swept forward, the starting point of the calculation is at the wingtip. A first step equal to a standard step length of $\frac{1}{16}$th of the mean chord is taken along the line vortex from the wingtip. Inboard of the wingtip a variable first step length is required to proceed to the same streamwise position as that along the line vortex from the wingtip. In each of the steps the velocity induced by all other trailing vortex elements and by the wing-bound vortices is calculated at the midpoint of the step. The wing-bound vortices are located at the quarterchord line of each wing panel and in the chordwise direction over the wing surface. The trailing-line vortex along the first step is then allowed to follow the local stream direction, and the downstream end position of the first step is calculated with the remaining part of the trailing-line vortex aligned with the freestream. A second step is made along the trailing-line vortices, repeating the calculation of the induced velocity due to the wing-bound vortices and the trailing vortex system obtained after the first step. The downstream end of the second step is calculated and the process repeated to the required distance downstream.

To prevent chaotic motion of the trailing vortices, a smoothing factor δ as defined by Krasny,[8] is used to remove the singularity in the Biot-Savart law. The smoothing factor is analogous to the introduction of artificial viscosity, and for the present calculations satisfactory solutions were obtained with a value of δ, which is a fraction of the wingspan b of 0.025. For a doubly-infinite line vortex, the modified induced velocity v is given by

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

Once the position of the tanker wing wake with roll-up has been determined, then the induced downwash and sidewash over the receiver can be determined by the Biot-Savart law with or without the smoothing factor. There is little difference between results obtained using either expression, and in the present work the Biot-Savart law was used. As stated in the introduction two aerodynamic derivatives are considered. These are the rolling moments due to side displacement y and bank displacement ϕ of the receiver from the zero sideslip, wings level position on the centerline of the tanker wake. The rolling moments are mainly due to the asymmetric distribution of downwash angle ε over the receiver wing, which is represented by a twist distribution in the vortex lattice method. Sixty spanwise and four chordwise points were used as described in the previous work by Bloy et al.[5] Contributions from the fin and low tailplane combination were also calculated using the vortex lattice method with 30 spanwise and 4 chordwise points on the fin and each half of the tailplane.

Results and Discussion

Theoretical results were obtained at the experimental test conditions used in previous work.[5] The tanker wing was considered at a lift coefficient of 0.544, whereas the receiver aircraft model was considered at a pitch angle of 6 deg to the horizontal. Although the roll-up model does not allow for the interaction between tanker and receiver wakes, this effect is much reduced at the test conditions where the receiver angle of attack (= pitch angle − tanker downwash angle) is relatively low. Calculations of the tanker wing wake roll-up were performed to a distance four wing-spans downstream. The resulting trailing vortex pattern is shown in Fig. 2. The tip vortices move slightly upwards initially and inboard increasing in strength downstream. The strength is estimated by counting trailing vortices within the tip vortex spiral. At the position of the receiver wing the tip vortex strength is 42.5% of the

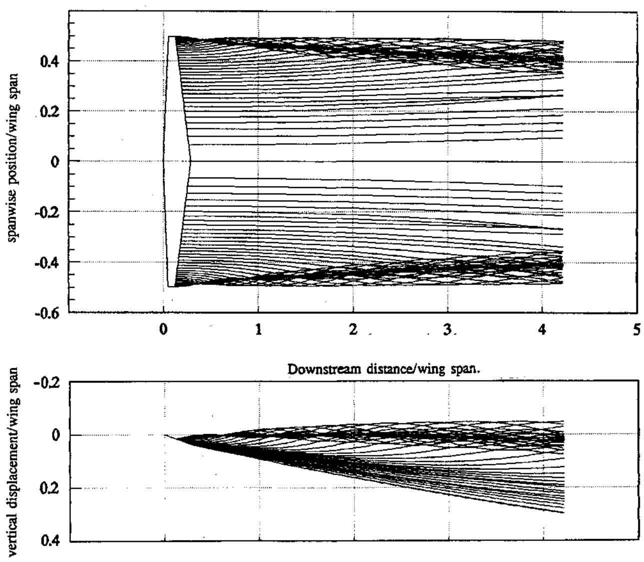

Fig. 2 Roll-up of the tanker wing trailing vortices.

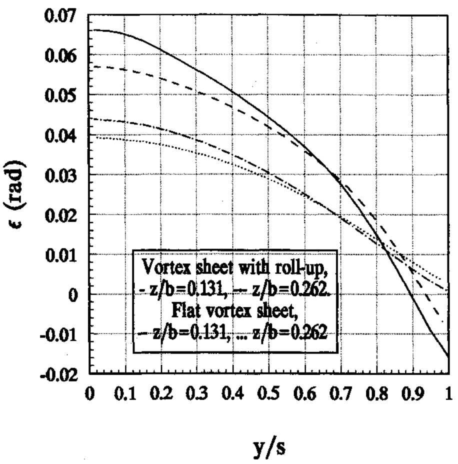

Fig. 3 Downwash induced by tanker wing at position of receiver wing.

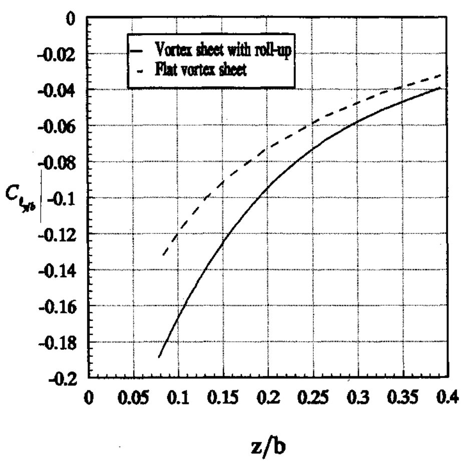

Fig. 4 Effect of wake roll-up on receiver rolling moment due to sideways displacement derivative.

tanker wing centerline circulation. At two wingspans downstream the strength increases to 55%.

For comparison, results were obtained for both the flat vortex sheet and the vortex sheet with roll-up models of the tanker wing wake. Typical downwash distributions over the receiver wing using both models are given in Fig. 3 at two values of the vertical separation z between tanker and receiver wings. Since the flat vortex sheet model assumes that the trailing vortices are all shed horizontally in the same plane, it effectively increases the vertical separation between the wake and receiver. Consequently, the corresponding downwash over the central part of the receiver wing is less than that obtained from the wake model with roll-up. Towards the tip the situation is reversed.

Consider the effect of the tanker downwash and sidewash on the receiver wing. As the receiver aircraft is displaced sideways to starboard, the port wing experiences higher downwash while the starboard wing experiences lower downwash or higher upwash. This produces a rolling moment on the receiver aircraft that would roll the aircraft with the starboard wing moving up. The lift vector would then be inclined to the port side and the receiver would tend to return to the centerline position. This is a stable response and the restoring rolling moment depends on the downwash gradient in the spanwise direction, i.e., $\partial\varepsilon/\partial y$. This gradient is predicted to be significantly higher in magnitude from the wake model with roll-up than from the flat vortex sheet model. The effect on the receiver rolling moment coefficient due to sideways displacement derivative $C_{l_{y/b}}$ [$=\partial C_l/\partial(y/b)$] is shown in Fig. 4. At a typical contact position during refueling in the region of $z/b = 0.1$, the improved wake model leads to a 40% increase in the magnitude of the derivative.

Banking the receiver in the tanker wake also produces a stable response. Consider the receiver banked with the right wing down. The downwash over this wing is reduced while that over the port wing is increased. This produces a rolling moment on the receiver aircraft that would tend to roll the aircraft with the starboard wing moving up towards the wings level position. Although the sidewash changes have some effect, the restoring rolling moment depends mainly on the downwash gradients in the vertical direction, i.e., $\partial\varepsilon/\partial z$. This gradient changes sign from the wake centerline to the wingtip. Although the wake model with roll-up predicts higher magnitudes of the gradient $\partial\varepsilon/\partial z$ compared with the flat vortex sheet model, the effect on the rolling moment due to bank derivative is negligible.

Conclusions

A model of wing wake roll-up has been developed and applied to the problem of the lateral aerodynamic interference between tanker and receiver aircraft during air-to-air refueling. For the configuration considered, the wake roll-up gives a tip vortex strength at the receiver wing position that is 42.5% of the circulation at the tanker wing centerline. From the downwash and sidewash distributions the receiver rolling moments due to sideways and bank displacements have been calculated. Compared with the predictions from a flat vortex sheet model of the wing wake, the predictions from the wake roll-up model indicate significantly higher values of the receiver rolling moment due to sideways displacement derivative. For the configuration considered, the effect of roll-up on the receiver rolling moment due to bank derivative is negligible.

Acknowledgment

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