AFRL-VA-WP-TP-2004-300

UAV AERIAL REFUELING – WIND TUNNEL RESULTS AND COMPARISON WITH ANALYTICAL PREDICTIONS

William B. Blake
Edward G. Dickes

JANUARY 2004

AIR VEHICLES DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YY)*** January 2004	**2. REPORT TYPE** Conference Paper Preprint	**3. DATES COVERED** ***(From - To)***

4. TITLE AND SUBTITLE UAV AERIAL REFUELING – WIND TUNNEL RESULTS AND COMPARISON WITH ANALYTICAL PREDICTIONS	**5a. CONTRACT NUMBER** In-house **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** N/A
6. AUTHOR(S) William B. Blake (AFRL/VACA) Edward G. Dickes (Bihrle)	**5d. PROJECT NUMBER** N/A **5e. TASK NUMBER** N/A **5f. WORK UNIT NUMBER** N/A
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Control Theory Optimization Branch (AFRL/VACA) Control Sciences Division Air Vehicles Directorate Air Force Research Laboratory, Air Force Materiel Command Wright-Patterson AFB, OH 45433-7542 Bihrle Applied Research Hampton, VA 23666	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFRL-VA-WP-TP-2004-300
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Vehicles Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson Air Force Base, OH 45433-7542	**10. SPONSORING/MONITORING AGENCY ACRONYM(S)** AFRL/VACA **11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)** AFRL-VA-WP-TP-2004-300

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Conference paper to be presented at the AIAA Atmospheric Flight Mechanics Conference, Providence, RI, August 2004. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

Results from a wind tunnel test of a delta wing UAV behind a KC-135R are presented and compared with predictions from a planar vortex lattice code. Both the predictions and data show wake interference effects on the UAV that vary significantly with relative lateral and vertical position, and weakly with relative longitudinal position. Predicted trends are excellent for all force and moments except for drag, and magnitudes are reasonably well predicted. The distribution of lift between the tanker wing and tail is shown to have a strong effect on the receiver aerodynamics.

15. SUBJECT TERMS

Aerial refueling, wind tunnel testing

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			William B. Blake
Unclassified	Unclassified	Unclassified	SAR	14	**19b. TELEPHONE NUMBER** *(Include Area Code)* (937) 255-6764

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

AIAA 2004-xxxx

UAV AERIAL REFUELING – WIND TUNNEL RESULTS AND COMPARISON WITH ANALYTICAL PREDICTIONS

William B. Blake [*]
Air Force Research Laboratory
Wright Patterson AFB OH 45433-7531

Edward G. Dickes [**]
Bihrle Applied Research
Hampton VA 23666

ABSTRACT

Results from a wind tunnel test of a delta wing UAV behind a KC-135R are presented and compared with predictions from a planar vortex lattice code. Both the predictions and data show wake interference effects on the UAV that vary significantly with relative lateral and vertical position, and weakly with relative longitudinal position. Predicted trends are excellent for all force and moments except for drag, and magnitudes are reasonably well predicted. The distribution of lift between the tanker wing and tail is shown to have a strong effect on the receiver aerodynamics.

NOMENCLATURE

A	Aspect ratio
b	Wing span
C_L	Lift coefficient
C_D	Drag coefficient
C_l	Rolling moment coefficient
C_m	Pitching moment coefficient
C_m	Yawing moment coefficient
C_Y	Side force coefficient
x	Longitudinal distance from UAV c.g. to UAV c.g., positive forward
y	Lateral distance from UAV c.g. to tanker c.g., positive right
z	Vertical distance from UAV c.g. to tanker c.g., positive down
α	Angle of attack

INTRODUCTION

For over 50 years, the USAF has employed aerial refueling to increase the range of its aircraft. Aerial refueling also reduces forward basing requirements, decreases response times for critical targets, and increases loiter times for surveillance aircraft. The Air Force Research Laboratory, in partnership with DARPA, NASA and Boeing, is currently pursuing a program to demonstrate autonomous refueling of a UCAV class UAV[1]. UCAVs under current development by the Air Force and Navy are survivable designs capable of delivering bomb loads in excess of 1000 lb. Prototype aircraft have been flown by both Boeing (X-45) and Northrop (X-47). Although comparable in size to fighter aircraft, UCAVs are generally lighter with smaller moments of inertia. This aggravates the effects of turbulence behind the tanker that the UCAV will encounter before, during and after refueling.

The flow survey rig within the Langley 30x60 Full Scale Wind Tunnel was modified several years ago to allow testing of multiple aircraft in formation[2]. Several wind tunnel tests of receiver aircraft behind a KC-135R tanker have since been completed in this facility. The primary objectives of the refueling tests was to assess the stability and control characteristics of the UAV in the tanker wake and to develop a database for simulation and control law development. This paper will discuss results from one of these tests, and compare the test results with predictions generated by a vortex lattice code.

Previous studies have shown good agreement between vortex lattice predictions and wake interference effects on downstream aircraft. Rossow[3]

---

[*] Aerospace Engineer, Associate Fellow AIAA

[**] Aerospace Engineer, Senior Member AIAA

ASC - 03 - 3283

measured wake- induced effects on several sets of isolated wings that were separated longitudinally by many wing spans. He showed that the vortex lattice method is extremely accurate for predicting wake induced lift and rolling moment when the span of the downstream wing is substantially less than that of the wake generating wing. Bloy et al[4] investigated formations typical of aerial refueling with the receiver less than one wing span downstream of the tanker. Their tests were conducted in a small wind tunnel with a wingspan to tunnel width ratio of 0.7. Significant wall interference effects were uncovered by taking measurements in both open and closed test sections. They found good agreement with vortex lattice predictions when compared to their open test section results.

DISCUSSION

WIND TUNNEL SET-UP

The wind tunnel tests were conducted in the Langley Full Scale Wind Tunnel (30x60), operated by Old Dominion University. The tanker was a 1/13 scale KC-135R (Figure 1). Four electric fans were used to simulate the engine thrust. The tanker was attached at the top of its fuselage to the flow survey carriage used in the Langley tunnel (Figure 1). The top mount arrangement minimizes rig interference effects when the receiver is in the nominal refueling position below the tanker. Relative position between the tanker and receiver was achieved by moving the survey carriage. The receiver was a 1/13 scale Lockheed tailless aircraft[4] consisting of a 65 degree delta wing with a sawtooth trailing edge with sweep angles of 25 degrees (Figure 1). It is a single engine design with a two narrow inlets on the lower surface. The inlets were blocked for the present test. It was mounted from the bottom to a post that was fixed to the tunnel floor (Figure 2).

Both aircraft were equipped with internal 6 component strain gauge balances. By moving the tanker and keeping the received fixed, all changes to the receiver aerodynamics were due to the tanker wake and not to small variations in flow angularity present in the Full Scale tunnel.

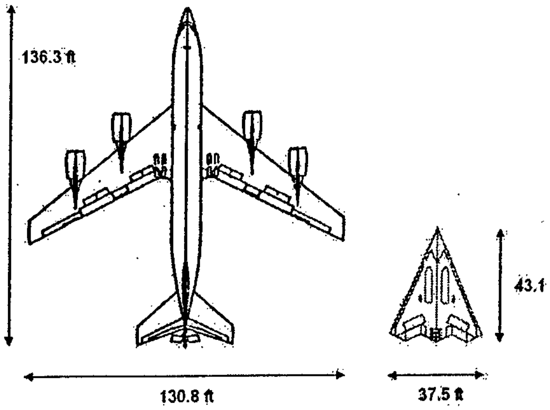

Figure 1. KC-135R/UAV Geometry (full scale)

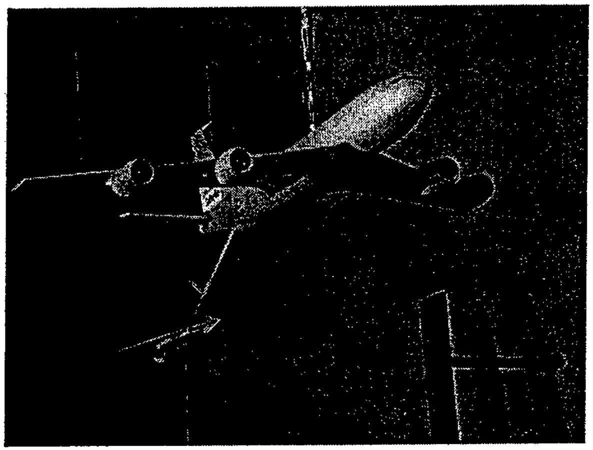

Figure 2. Wind Tunnel Models on Apparatus

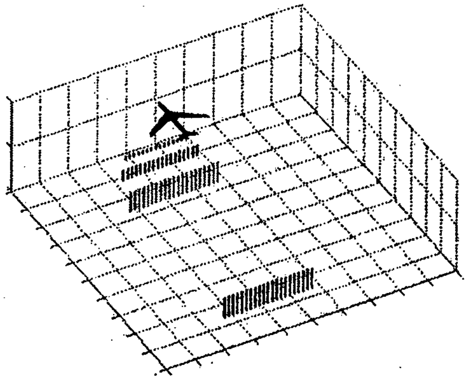

Figure 3. Schematic of Test Matrix

Data were taken with the tanker in four vertical planes upstream of the receiver (Figure 3). Each plane consisted of approximately 200 points in the lateral and vertical direction. Data were only taken with the tanker to the right of the receiver, when looking upstream, thus, symmetry of the results was assumed. The tanker was set at an angle of attack of 2 degrees with a horizontal stabilizer setting of –8 degrees. This results in a trimmed lift coefficient of 0.36, corresponding to a reference refueling condition of 250,000 lb at 29,000 ft. The receiver was tested at two angles of attack (4 and 7 deg) at each position. This paper will only show results from the 4 deg angle of attack runs. All runs were conducted at a tunnel dynamic pressure of 5 psf, which corresponds to a speed of approximately 65 ft/sec.

COMPUTATIONAL METHOD

A modified version of the planar vortex lattice code HASC95[8] was used to predict the wake induced effects on the trail aircraft. The number of permissible vortex elements was increased from 2000 to allow for better definition of multiple aircraft. A program was also written that automatically generates input files for a user defined set of tanker/receiver positions, runs the code for each position, and saves the results. Total computation time for a run of 130 relative positions was about 4 hours on an SGI Indigo II workstation.

The tanker was modeled with 2100 elements, the receiver with 450 elements. Cosine spacing of the elements was used in the chordwise direction. Even spacing of the elements was used in the spanwise direction. This is necessary in order to ensure correct alignment of vortex filaments and control points when the aircraft overlap in the lateral direction. An element width of 15 inches (full scale) was chosen for both vehicles. This results in some slight approximations to the actual geometry. A comparison of the actual and modeled spans is shown in Table 1. The HASC95 representation of the vehicles is shown in Figure 4.

	Modeled Span (in)	Actual span (in)
KC-135 wing	1560	1570
KC-135 tail	510	520
UAV	450	450

TABLE 1. HASC Geometry Approximation

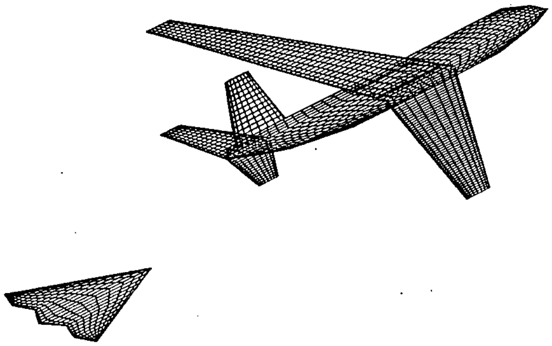

Figure 4 HASC95 lattice model

Wake induced effects are a function of the lift of the wake generating aircraft, hence it is very important to match the measured lift of the tanker with the HASC95 model. HASC95 uses a single angle of attack for both aircraft, which requires adjustments to wing incidence angles in order to match the test conditions. Two methods were studied for modeling the vehicles, as shown in Table 2.

	Wind tunnel	HASC A	HASC B
KC-135 CL	0.36	0.36	0.36
KC-135 AOA	2	2	4
KC-135 wing camber	yes	no	No
KC-135 wing incidence	2	4.6	2.6
KC-135 tail incidence	-8	-8	-10
UAV AOA	4	2	4
UAV wing incidence	0	2	0

TABLE 2 – HASC95 Modeling Options

Methods A and B were found to give identical results, so Method A was used for all subsequent calculations.

RESULTS - LONGITUDINAL

Figure 5 shows the variation in wake induced lift on the receiver as a function of lateral spacing for two longitudinal spacings. Longitudinal spacing is measured from the c.g. of the tanker to the c.g. of the receiver. The closest spacing shown (x/b=0.85) represents the “pre-contact” position, with the nose of the receiver approximately 20 ft (full scale) from the aft end of the tanker. At the farthest spacing (x/b=3), the receiver is 300 ft (full scale) behind of the tanker. Vertical spacing is also measured from c.g. to c.g., a vertical spacing of zero indicates that the receiver is about 2 ft (full scale) above the wing root and 5 ft (full scale) below the wing tip and horizontal tail. Lateral spacing (x-axis) represents the relative lateral position between the vehicles, non-dimensionalized by the span of the tanker. A value of 0 means that the centerlines of the vehicles are aligned. A value of 0.5 means that the nose of the receiver is aligned with the left wing tip of the tanker. The wing tips are aligned at a value of 0.64, beyond that, there is no overlap between the configurations in the lateral direction. Both the prediction and data show almost no effect of longitudinal spacing, while lateral spacing has a very large effect. With the vehicles aligned, a small lift increase is predicted and measured, as the lateral spacing increases, increasing downwash is evident that peaks at a spacing of 0.3 spans. The downwash decreases and upwash is encountered outboard of the tip. The increase in lift with the vehicles aligned results from the large download on the horizontal tail of the tanker required for trim. This causes upwash directly beneath the tail and adds to the wing downwash outboard of the tail. This is depicted in Figure 6. The KC-135 design dates to the early 1950's and has a high degree of static stability.

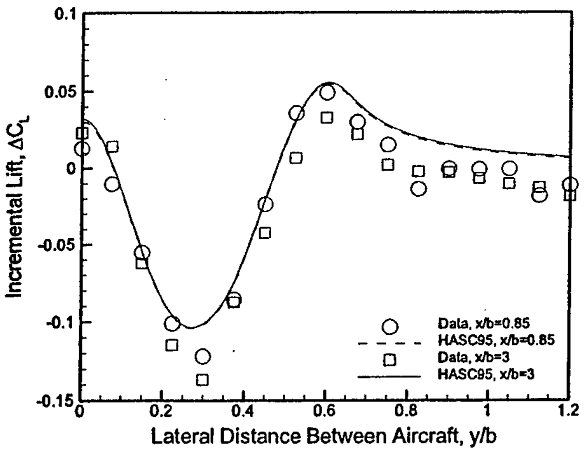

Figure 5. Comparison of predicted and measured wake induced lift, z/b=0.

The effect of trim tail deflection was assessed computationally and the result is shown in Figure 7. To match the overall total tanker lift with different tail deflections, the tanker wing incidence was modified. Figure 7 shows that with no tail deflection, a large lift loss is present until the receiver approaches the tanker wing tip. It also shows that the peak lift loss is larger for the downloaded tail when the receiver is just outboard of the tail and the tail downwash is added to the wing downwash.

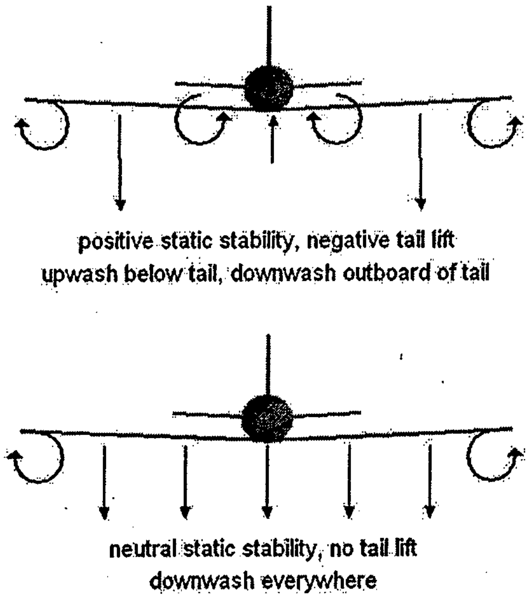

Figure 6. Effect of tail lift on tanker wake, rear view.

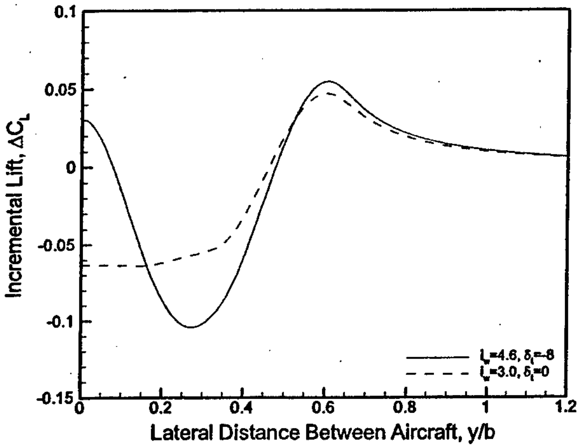

Figure 7. Effect of tanker tail deflection on wake induced lift, x/b=0.85, z/b=0.

Figure 8 shows the induced lift for two vertical spacings as a function of lateral spacing. The additional vertical spacing shown (z/b=-0.225) corresponds to the refueling position (for boom type refueling). The magnitude of the lift change is reduced at all spanwise locations and the small lift increase for the in-plane (z=0) case is now a small lift decrease.

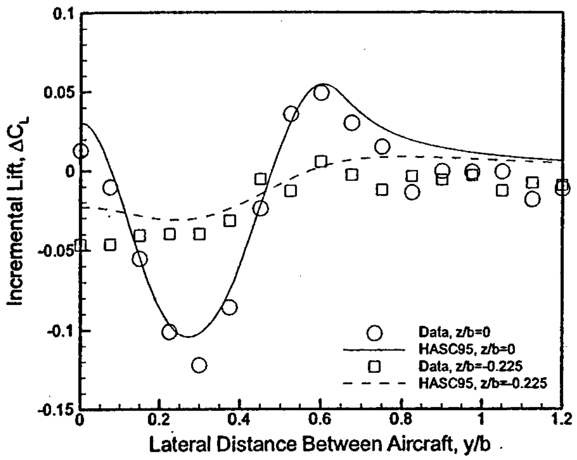

Figure 8. Comparison of predicted and measured wake induced lift, x/b=0.85.

Figure 9 shows the effect of vertical spacing at a lateral spacing of y/b=0 (vehicle centerlines aligned). The effect of the tail download can be clearly seen in this figure. The receiver is directly behind the horizontal tail at a vertical spacing of z/b=0.04, which is the location of the peak increase in lift. As the receiver moves away from this position on either direction, the tail induced lift decreases. As is moves significantly downward, the lift loss decreases and asymptotically approaches zero. At the boom refueling position, the lift loss is underpredicted by about a factor of two. The reason for this discrepancy is not known at this time. Some of it may be due to the effect of the refueling boom, which was not included in the HASC95 model.

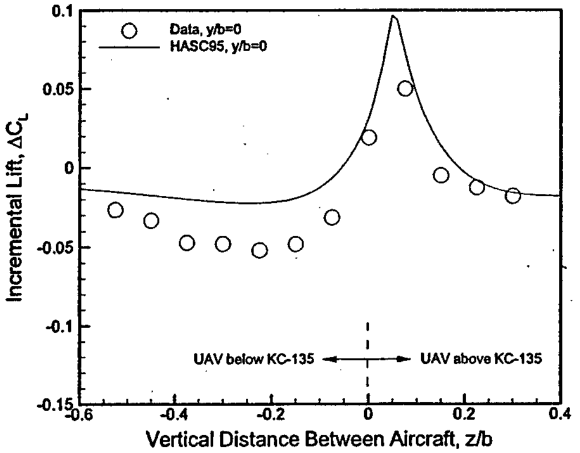

Figure 9. Comparison of predicted and measured wake induced lift, y/b=0, x/b=1.5.

Figure 10 compares the measured and predicted drag increments as a function of lateral spacing for two vertical spacings. Figure 11 shows the effect of vertical spacing on drag. Both figures show poor agreement between the measured and predicted values, and in many cases the sign is incorrectly predicted. Much of this is undoubtedly due to viscous effects, which HASC95 ignores.

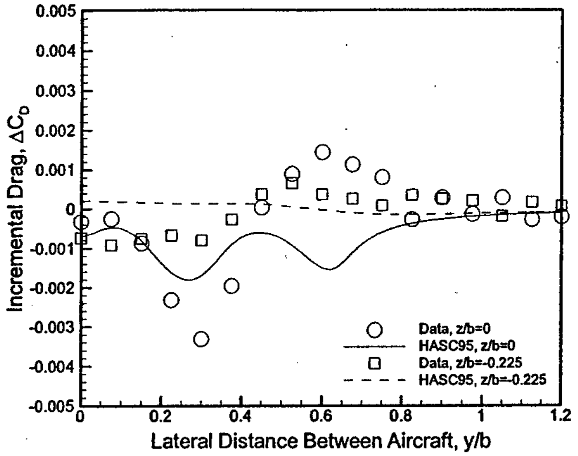

Figure 10. Comparison of predicted and measured wake induced drag, x/b=0.85.

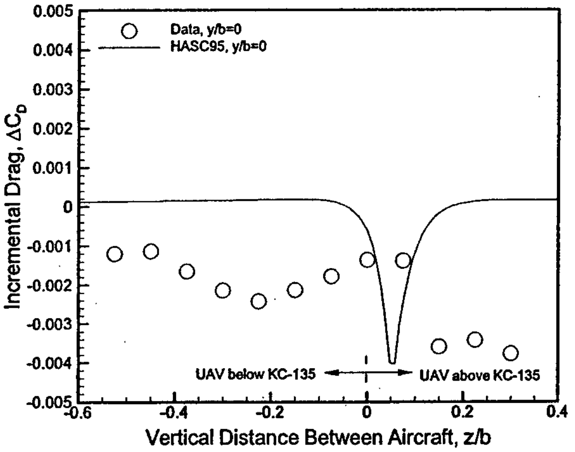

Figure 11. Comparison of predicted and measured wake induced drag, y/b=0, x/b=1.5.

Predicted and measured pitching moment increments are compared in Figure 12 as a function of lateral spacing and Figure 13 as a function of vertical spacing. Both the prediction and data show five distinct peaks as lateral spacing is increased for the in-plane case. The magnitudes of the peaks, however, are underpredicted in every case. The peaks appear to correspond to where the wing tips of the receiver are in regions of either maximum upwash or downwash. At the refueling position beneath the aircraft (z/b=-0.225), the moments are very small but well predicted. As vertical spacing is varied (Figure

13), two peaks due to the tanker tail are evident, which are both reasonably well predicted.

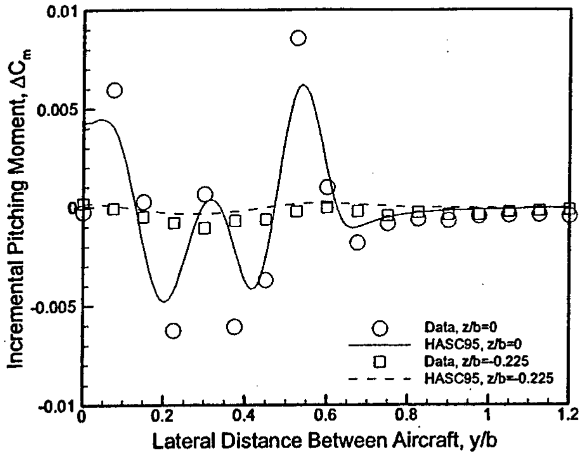

Figure 12. Comparison of predicted and measured wake induced pitching moment, x/b=0.85.

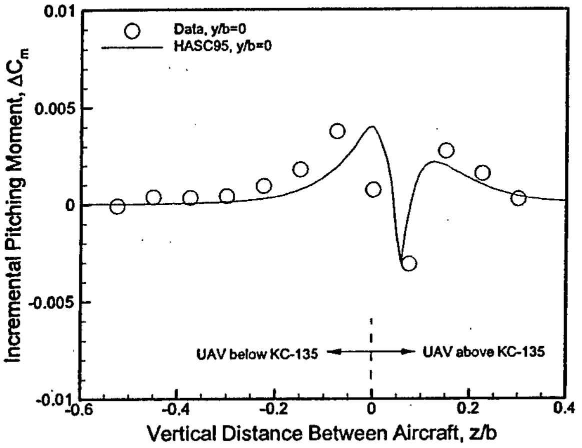

Figure 13. Comparison of predicted and measured wake induced pitching moment, y/b=0.

RESULTS – LATERAL-DIRECTIONAL

The effect of lateral spacing on induced rolling moment at the two extreme longitudinal spacings is shown in Figure 14. As with the induced lift, there is virtually no effect of downstream spacing but a large effect of lateral spacing. Both the trend and magnitude of the induced rolling moment are very well predicted. The peaks correspond to the centerline of the UAV being positioned directly behind the tip vortices of the tanker tail and wing respectively. The slight inflection point with the UAV at about y/b=0.3 corresponds to the UAV crossing from above to below the plane of the tanker wing, resulting from the wing dihedral. There is insufficient data to determine whether this inflection point is real.

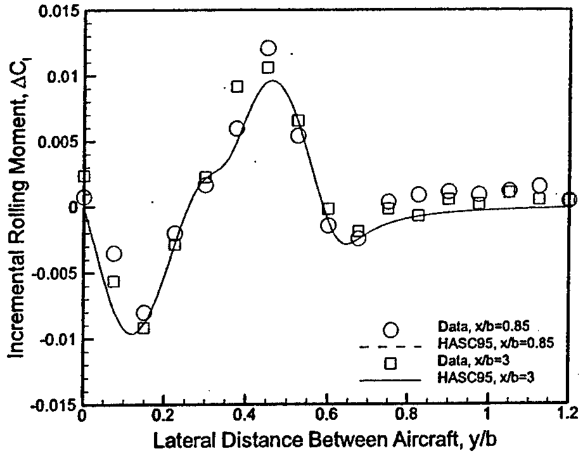

Figure 14. Comparison of predicted and measured wake induced rolling moment, z/b=0.

The predicted effect of the tanker tail setting is given in Figure 15. With no tail deflection, there is only one rolling moment peak, which arises from the tanker wing tip vortex. The peak value is lower due to the reduced lift from the tanker wing, since there is no large tail download to overcome.

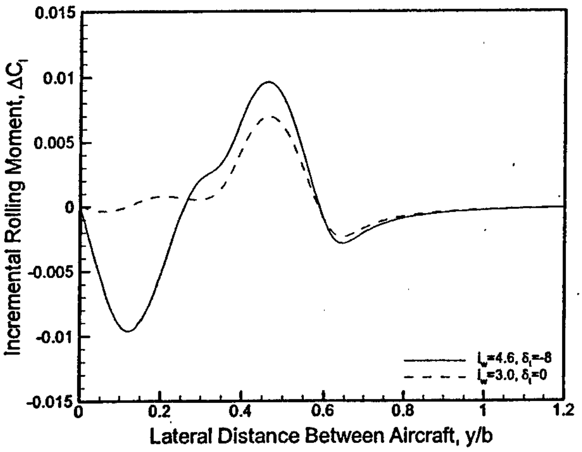

Figure 15. Effect of tanker tail deflection on wake induced rolling moment, x/b=0.85, z/b=0.

Figure 16 shows the effect of lateral spacing for two vertical spacings. The rolling moments at the lower spacing (refueling position) are much lower than the in-plane case and are well predicted. Figure 17 shows the effect of vertical spacing with the UAV positioned just inboard of the wing-tip. The peak moment is above the c.g. of the tanker due to the dihedral of the wing. The prediction is excellent.

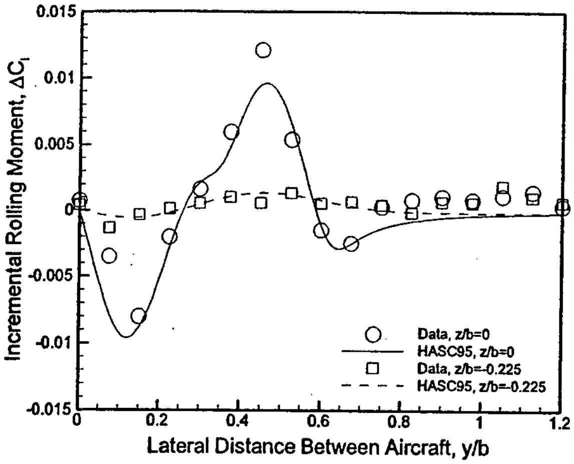

Figure 16. Comparison of predicted and measured wake induced rolling moment, x/b=0.85.

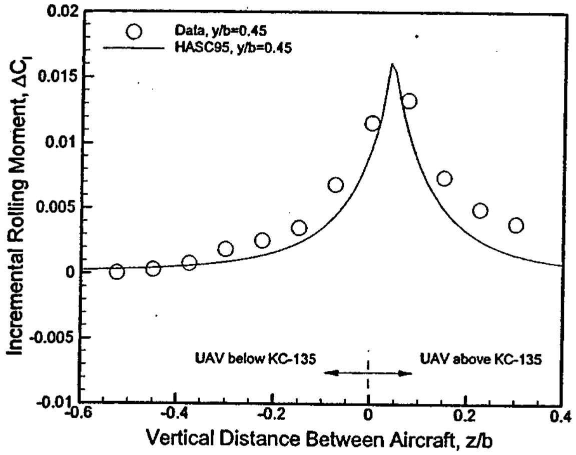

Figure 17. Comparison of predicted and measured wake induced rolling moment, y/b=0.45.

The effect of lateral spacing on induced yawing moment is shown in Figure 18. To provide a fair comparison, the vertical axis on this plot is identical to the rolling moment results shown on Figs 14-16. Very small yawing moments are found for the in-plane case and no yawing moment is found for the refueling position. This is presumably due to the lack of a vertical tail on the receiver. Although small, the in-plane results show a different sign than the prediction when the receiver is behind the tanker wing (y/b<0.5). This indicates that the source of the yawing moment may be differential drag from the two halves of the wing, since the drag predictions were also poor for the in-plance case.

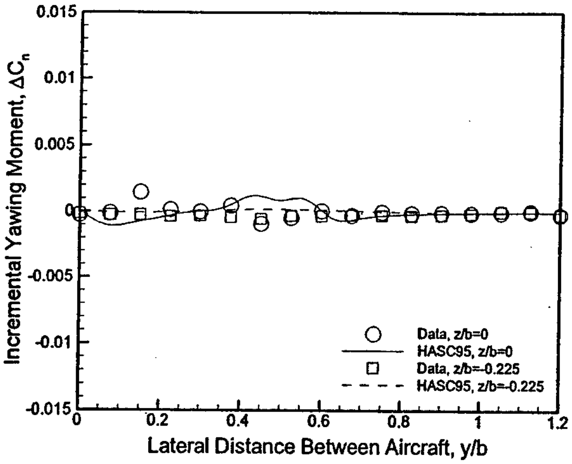

Figure 18. Comparison of predicted and measured wake induced yawing moment, x/b=0.85

The effect of lateral spacing on induced side force is shown in Figure 19. The trend is well predicted for both heights, although the overall magnitudes are small (smaller than the induced lift results by a factor of 20). This is probably due to the lack of a vertical tail on the configuration.

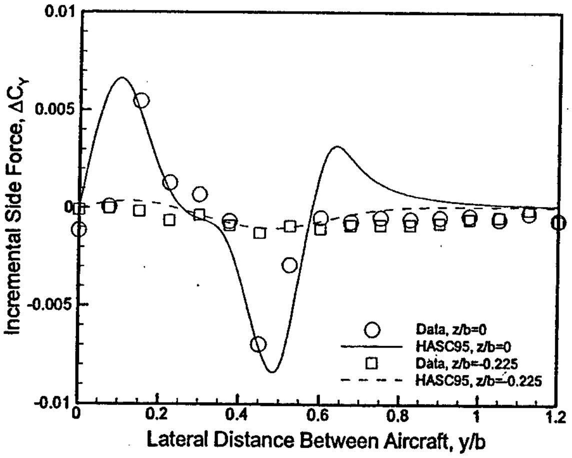

Figure 19. Comparison of predicted and measured wake induced side force, x/b=0.85

CONCLUSION

Resuls from a wind tunnel test of UAV aerial refueling in a large-scale wind tunnel have been presented and compared with predictions from a planar vortex lattice code. In the longitudinal axis, wake induced effects were well predicted for lift and pitching moment and poorly predicted for drag. Lift and moment trends were extremely well predicted while peak magnitudes were typically under-predicted. In the lateral-directional axes, wake induced effects on rolling moment were very well predicted. Wake effects on yawing moment and side force were found to be small, due to the lack of a vertical tail on the receiver configuration. The computational analysis indicates that the distribution of tanker lift between the tanker wing and tail is found to have a significant effect.

REFERENCES

1. Sirak, Michael, "USA Studies Ways to Refuel Drones in Flight," Jane's Defence Weekly, January 22, 2003.

2. Gingras, D.R., Player, J.L., and Blake, W.B., "Static and Dynamic Wind Tunnel Testing of Air Vehicles in Close Proximity," AIAA paper 2001-4137, presented at the AIAA Atmospheric Flight Mechanics Conference, August 2001.

3. Rossow, V.J., "Validation of Vortex-Lattice Method for Loads on Wings in Lift-Generated Wakes," Journal of Aircraft, Vol. 32, No. 6, November-December 1995, pp. 1254-1262.

4. Bloy, A.W., West, M.G., Lea, K.A., Jouma'a, M., "Lateral Aerodynamic Interference Between Tanker and Receiver in Air-to-Air Refueling," Journal of Aircraft, Vol. 30, No. 5, pp. 705-710, September-October 1993.

5. Dickes, E.G., and Blake, W.B., "Wind Tunnel Measurements of UAV Aerial Refueling Wake Interference Effects," AIAA Paper 2004-xxxx, presented at the AIAA Atmospheric Flight Mechanics Conference, August 2004.

6. Gillard, W.J, and Dorsett, K.M., "Directional Control for Tailless Aircraft Using All Moving Wing Tips," AIAA paper 97-3487, presented at the AIAA Atmospheric Flight Mechanics Conference, August 1997.

7. Albright, A.E., Dixon, C.J., and Hegedus, M.C., "Modification and Validation of Conceptual Design Aerodynamic Prediction Methods HASC95 With VTXCHN, NASA CR-4712, March 1996.