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MODEL VALIDATION FOR WAKE-VORTEX/AIRCRAFT ENCOUNTERS

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Wake-vortex effects on an 10% scale model of the B737-100 aircraft are calculated using both strip theory and vortex-lattice methods. The results are then compared to data taken in the 30' x 60' wind tunnel at NASA Langley Research Center (LaRC). The accuracy of the models for a reduced geometry, such with the horizontal stabilizer and the vertical tail removed, is also investigated. Using a 10% error in the circulation strength and comparing the model's results with the experiment illustrates the sensitivity of the models to the vortex circulation strength. It was determined that both strip theory and the vortex lattice method give accurate results when all the geometrical information is used. When the horizontal stabilizer and vertical tail were removed there were difficulties modeling the sideforce coefficient and pitching moment. With the removal of only the vertical tail unacceptable errors occurred when modeling the sideforce coefficient and yawing moment. Lift could not be accurately modeled with either the full geometry or the reduced geometry.

1. INTRODUCTION

There are more people passing through the world's airports today than at any other time in history and with this increase in civil transport, airports are becoming capacity limited. In order to increase capacity and thus meet the demands of the flying public the number of runways and the number of flights per runway must be increased.

During Visual Meteorological Conditions (VMC), it is the pilot's responsibility to maintain safe separation. Under these conditions the separation distance between aircraft during landing and takeoff are significantly lower than the distances used under Instrument Meteorological Conditions (IMC). When the aviation weather service indicates IMC there is low visibility, and it is the controller's responsibility to maintain safe separation distances. One way to increase production per runway is to decrease the separation distances during IMC, and research programs are underway to determine how this can be implemented safely. It has been predicted that with new, shorter separation distances during IMC, airport capacity could be increased by 10-15 percent.

The Federal Aviation Administration (FAA), airline operators, and the National Aeronautics and Space Administration (NASA) joined together in an effort to determine new separation distances. Dunham et. al. [1] suggests that this can be accomplished during IMC only if a metric that defines an acceptable wake-vortex encounter is developed for use in automated air-traffic-control systems. This metric would be derived from a matrix of safe distances for several leader/follower-aircraft pairs and meteorological conditions. The behavior of wing-tip vortices directly affects the metric definition. This is due to the hazardous upset that an aircraft can experience when encountering a trailing wake of a preceding larger aircraft. This wake - vortex encounter can redistribute the aerodynamic load of the smaller aircraft and often results in loss of control.

In response to these factors NASA has launched the Terminal Area Productivity (TAP) program. This program consists of four areas: Air Traffic Management, Aircraft/Air Traffic Control Systems Integration, Low-Visibility Landing and Surface Operations, and Reduced Spacing Operations [2]. The Reduced Spacing Operations (RSO) component of TAP used wind tunnel testing, piloted and unpiloted simulations, flight testing, and computational analysis [1] to develop the metric for

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an acceptable wake-vortex/aircraft encounter. Development of an Aircraft Vortex Spacing System (AVOSS) was also a part of the RSO. When complete, this system will use information provided by vortex sensors and operational definitions of acceptable strengths for wake-vortex/aircraft encounters from models to account for atmospheric effects on the transport and decay of the wake and give smaller but safe separation distances between aircraft.[3]. The work described in this paper can provide guidelines for using the models to predict wake-induced aerodynamic effects.

2. METHODOLOGY

The methods proposed to predict the wake-vortex effects in an automated air-traffic control system are based on strip theory and vortex lattice methods. These modeling techniques are not new and over the years several versions have been developed that incorporate more dynamical effects; such as turbulent wind fields. However, unfortunately the two methods have never been validated against experimental data although this is essential if they are to be used to determine a metric for an acceptable wake encounter and thereby safe separation distances.

For validation, the methods are compared to data from static tests performed in NASA Langley's 30' x 60' wind tunnel. The static tests measured the forces and moments of an aircraft encountering a trailing vortex. Data sets were taken for the B737-100 model with full geometry (wing, horizontal stabilizer, and vertical tail), and with two reduced geometry configurations; vertical tail removed and both the horizontal stabilizer and the vertical tail removed. Again, the objective of this part of the study is to determine the least amount of geometrical information required for accurate results from the models. This information will also be useful to determine the least amount of geometry information required for fleet wide analysis. Finally a sensitivity study of the models was performed.

2.1 Wind Tunnel Tests

A ten-percent scaled down model of Boeing's B737-100 aircraft was used for the static in NASA LaRC's 30'x 60' wind tunnel. The wind-tunnel model was constructed of fiberglass and aluminum was placed on a static mount that was used to measure the forces and moments induced by the wake of the generating wing. The Kruger flaps were set to zero degrees. Figure 1 shows the experimental setup used inside the wind tunnel. Smoke generators were used to visualize the wake-vortex. Measurements were taken with both the wing and the following aircraft inverted to negate a bounce back effect that occurred when the generating wing was lower than the model. Pressure was measured with a 1/8" diameter 5-hole pressure probe. The model was removed and replaced by the probe for the pressure measurements.

Data was collected at the locations analyzed shown in Figure 2 for an alpha-sweep, where the angle of attack is varied, and a beta-sweep, where the sideforce coefficient is varied. Angles for the alpha-sweep were –6, -4, -2, 0, 2, 4, 6, 8, 10, and 15 degrees 10, -4, -2, 0, 2, 4, and 10 degrees for the beta-sweep. These angles were measured with an accelerometer that was mounted on the model. Only alpha-sweep data was collected when the horizontal stabilizer and vertical tail were removed, and for the removal of the vertical tail, only the beta sweep data was taken. Force and moment measurements included the sideforce coefficient, lift coefficient, drag coefficient, rolling moment, yawing moment, and pitching moment.

2.3.1 Generating Wing

Two separate NACA 4412 airfoil sections were used for the generating wings in the experiment. These were simple wings without flaps to enable large variations in vortex strengths. The first wing had a span of 9.3 ft. and lift coefficient of 0.56. The second wing had a span of 18.6 ft and lift coefficient of 0.28. The angle of attack of the wing determines the circulation strength of the induced vortex and the lift coefficient is directly proportional to the vortex circulation strength. Hence, for the large wing the circulation strength was set to 0.28 and for the small wing it was set to 0.56 in the model calculations. Each generating wing was placed at a constant distance of 300 in. from the following model aircraft and was mounted on a movable tunnel survey carriage. Smoke generators were placed on the sides of the wing to mark the wing-tip vortices. The carriage was then positioned at the locations shown in Figure 2 with respect to the following aircraft. The center of the vortex was location (0,0).

2.4 Strip Theory

Strip theory requires each wing to be separated into chordwise strips, and each strip is modeled as a two dimensional airfoil. The strips are defined by their area, dihedral angle, angle of incidence, lift curve slope, quarter chord and three quarter chord points at the midspan of each strip.

Reimer and Vicroy [5] describe the method used in strip theory to calculate the forces and moments. They begin by finding the freestream velocity and local wind velocity at the three-quarter-chord point of each strip. They use the following transformation to translate the inertial velocities to velocities relative to the body axis.

$$\begin{pmatrix} u_b \\ v_b \\ w_b \end{pmatrix} = \begin{pmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\phi\sin\theta\cos\psi - \sin\psi\cos\phi & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\phi\cos\theta \\ \cos\psi\cos\phi\sin\theta + \sin\psi\sin\phi & \sin\psi\cos\phi\sin\theta + \cos\psi\sin\phi & \cos\phi\cos\theta \end{pmatrix} \begin{pmatrix} u_i \\ v_i \\ w_i \end{pmatrix} \tag{1}$$

where θ is the pitch angle, ψ is the yaw angle, and ϕ is the roll angle. The local velocity is found by summing the freestream velocities and the wake induced velocities of each strip.

The local angle of attack normal to the planform is then computed for the right half of the planforms, which lie in the horizontal direction,

$$\alpha_{N_i} = \alpha_{s_i} + \tan^{-1}\left(\frac{w_i \cos\delta_i - v_i \sin\delta_i}{u_i}\right) \tag{2}$$

and for the left half of the planforms which lie in the horizontal direction.

$$\alpha_{N_i} = \alpha_{s_i} + \tan^{-1}\left(\frac{w_i \cos\delta_i + v_i \sin\delta_i}{u_i}\right) \tag{3}$$

For the planforms which lie in the vertical direction, the dihedral, δ, is set to 90°, and the angle of attack is the negative of the sideslip angle. Incremental lift and sideforce coefficients are then computed by:

$$C_{L_i} = \frac{S_i}{S} c_{l_i} \alpha_{N_i} \cos\delta_i \tag{4}$$

$$C_{Y_i} = \frac{S_i}{S} c_{l_i} \alpha_{N_i} \sin\delta_i \tag{5}$$

where S is the planform reference area, S_i is the reference area of strip i, and c_{l_i} is the two-dimensional lift curve slope of the ith strip. Finally, the incremental forces and moments can be summed as follows:

$$C_L = \sum_{i=1}^{N_{strips}} C_{L_i} \tag{6}$$

$$C_Y = \sum_{i=1}^{N_{strips}} C_{Y_i} \tag{7}$$

$$C_l = \frac{1}{b} \sum_{i=1}^{N_{strips}} \left(C_{L_i} y_{c/4_i} + C_{Y_i} z_{c/4_i} \right) \tag{8}$$

$$C_m = \frac{1}{c} \sum_{i=1}^{N_{strips}} C_{L_i} x_{c/4_i} \tag{9}$$

$$C_n = \frac{1}{b} \sum_{i=1}^{N_{strips}} C_{Y_i} x_{c/4_i} . \tag{10}$$

where $x_{c/4_i}$, $y_{c/4_i}$, and $z_{c/4_i}$ are the coordinates of the quarter-cord point. Drag is neglected in this model.

The objective is to determine the forces and moments that act on each incremental panel then to sum all the contributions to determine the reaction over the entire aircraft. To determine the effect the wake has on the aircraft, the change in the forces and moments are computed using the difference in results from two calculations: one that includes an encountering wake model and one calculation without the wake model.

2.5 Vortex-Lattice Model

The vortex-lattice method developed by Margason and Lamar [20] was modified to account for nonuniform flow and an increased number of planforms. A detailed description of the calculations and approach can be found in Vicroy[7]. This method is similar to strip theory since only wing sections are utilized for the geometry and thickness is neglected. The difference is that the vortex lattice method separates the sections of each wing in both the chordwise and spanwise directions to form many elemental panels. A no-flow boundary condition at the ¾-chord point. This means that at the ¾-chord of each panel the flow can not be perpendicular to the plane of the panel and must match the angle of attack of the ¾-chord point.

A horseshoe vortex is also associated with each panel. A vortex filament is located in the spanwise direction at the ¼-chord point and a vortex filament extends from the ¼-chord point on both sides of the panel and extends in the chordwise direction to infinity. The Kutta-Joukowski theorem is then used to determine the lift associated with each panel. A summation of the lift across the entire planform is performed and the information is used to determine the aerodynamic characteristics of the encountering aircraft. The effect of the wake encounter is again determined by the difference in calculations with and without a wake model.

2.6 Wake-Vortex Model

The circulation of the wake- vortex is defined by

$$\Gamma = \frac{2C_L U_\infty^2 S}{\pi b}. \qquad (11)$$

where C_L is the lift coefficient, U_∞ is the freestream velocity, S is the planform area, and b is the wing span. The model also uses information about the core radius and location (y,z) of the two counter-rotating vortices. The wake model is described by Greene [4] and is used to match actual measured velocity data of airplane wakes. In this case the model will match the velocity measurements that were taken during the wind tunnel experiment. The velocity measured at numerous points during the experiment will be used as input for the wake model, which gives the vortex location and strength. The vortex model also defines the tangential velocity in a single vortex, and provides the downwash and sidewash velocity components. Figure 3 shows the experimental, model, and error in the sidewash velocity distribution for the large generating wing. Similar results were found for the other velocity components for the large and small generating wings. In each case the experimental velocity and model velocity are in good agreement as can be seen by the error.

3. RESULTS

There were three objectives to this research a) to assess the accuracy of strip theory and the vortex-lattice method in predicting wake-vortex induced forces and moments; b) to assess the accuracy of the methods when reduced geometry is used, and c) to assess the accuracy of the methods when a sensitivity study is performed. The results that follow are for the large generating wing with full and reduced geometry. Results for the small wing and the results from the sensitivity analysis can be found in Pete [8].

3.1 Large Wing

Figure 4 shows the alpha sweep for the sideforce coefficient. Location (0,0), which is at the center of the vortex, shows a disturbance in the sideforce coefficient. Disturbances can also be seen at (0,-30) and (30,-30). These areas are dominated by the crossflow (sidewash) which could be the cause of the disturbance. Location (0,30) would also have a large amount of cross flow. When comparing the models to the experiment it can be seen that at (0,0) strip theory model deviates from the experiment while the vortex-lattice model appears to give results that more resemble the data from the experiment. Locations (0,-30) and (30,-30) show both methods deviate from the experimental results. The models show virtually no change in the sideforce coefficient whereas the experiment shows that there is a difference. At all other locations, results from both models are fairly accurate when compared to the experimental data. Most disturbances seen in the sideforce coefficient are along the y-axis, and both models appear to be less accurate in this direction.

Very little change was detected in pitching moment, lift, drag coefficient, rolling moment, and yawing moment by the experimental data or the models.

Figure 5 shows the effect of varying the sideforce coefficient has on the accuracy of strip theory and the vortex-lattice method. The change in sideforce coefficient at location (0,0) shows that both models deviate from the experimental data. Also, neither model replicates the experimental data at (0,30). This is an area dominated by the cross flow but models show no change in the sideforce coefficient, which is not the case in the experiment. The same applies to locations (30,-30) and (-30,30) as for (0,-30). For the remaining locations both models prove to have a high amount of accuracy.

Figure 6 shows the deviation in the change in rolling moment between the models and experiment at (0,30) and (-30,30). All other locations show that the models and experiment are in agreement although strip theory model seems less accurate than the vortex-lattice method. Changes in yawing moment, given by both models were in good agreement with the experimental data. There was consistency in the results from the experiment and the models at all locations for the change in drag.

To determine the minimum geometrical information needed for the models to still produce accurate results comparisons are made between experiment and model results with full and reduced geometry. The first tests were those in which the horizontal stabilizer and vertical tails were removed. A representative example is shown in Figure 7. Model results for the pitching moment, which is controlled by the horizontal stabilizer that has now been removed, show major inaccuracies when compared to the experimental data. The models show a linear relation to the angle of attack that is not reflected by the experiment. When alpha equals four degrees, both models accurately represent the experimental data.; however as the angle increases and decreases from four degrees the error in the modeling shows the same behavior. These results are consistent at all locations. Changes in lift have similar inaccuracies in the models.

4. CONCLUSIONS

Model calculations of the sideforce coefficient and rolling moment showed inaccuracies for locations along the y-axis. The lift coefficient showed poor results. In the beta-sweep with full geometry for the rolling moment, yawing moment, and drag coefficient could be accurately modeled. Pitching moment, lift coefficient, and sideforce coefficient showed discrepancies.

With the removal of the horizontal stabilizer and the vertical tail sideforce coefficient, pitching moment, and lift coefficient could not be modeled accurately, while drag coefficient, rolling moment, and yawing moment could. Separation at high angles of attack was viewed for drag and rolling moment. When removing only the vertical tail sideforce coefficient, lift coefficient, pitching moment, and yawing moment could not be modeled. Drag coefficient and rolling moment remained in good agreement with the experimental data, even though rolling moment showed separation at high angles of attack. It appears that the alpha sweep with full geometry will be able to accurately model the reactions encountered by a following aircraft. Lift could not be modeled for any of the four cases. The remaining three cases jointly had problems modeling the pitching moment, lift coefficient, and sideforce coefficient.

A number of the reactions appeared to show problems along the y-axis, locations directly above and below the vortex which are dominated by cross flow created by the counter clockwise rotation of the vortex. Directly above the vortex center the flow is moving to the right in the positive y-direction and below the vortex the flow is moving to the left in the negative y-direction. The two corner locations (-30,30) and (30,-30) have the influence of crossflow and vertical flow. These areas were the most troublesome when trying to model the experimental data. In comparing the results of the strip theory and vortex-lattice models it appears that the vortex-lattice model is generally more accurate than the strip theory model. The only case were strip theory was more accurate was when calculating the change in pitching moment. Regardless of which model appears to be more accurate, either model can be used because the inaccuracies between the two models themselves are insignificant.

Plans to continue this research involve comparing the strip theory and vortex-lattice models to a free flight wind tunnel experiment in which a pilot flies the 10 % scale model of the B737-100 aircraft inside the wind tunnel by remote control. In this experiment the pilot will be able to make an approach to the vortex which is a more realistic encounter of a wake-vortex. A cable will be attached to the model that will serve as the guide for the aircraft. The model will then be flown at different locations with respect to the vortex and the forces and moments that the aircraft encounter will be recorded. The last step will be to compare the strip theory and vortex-lattice models to actual flight test data..

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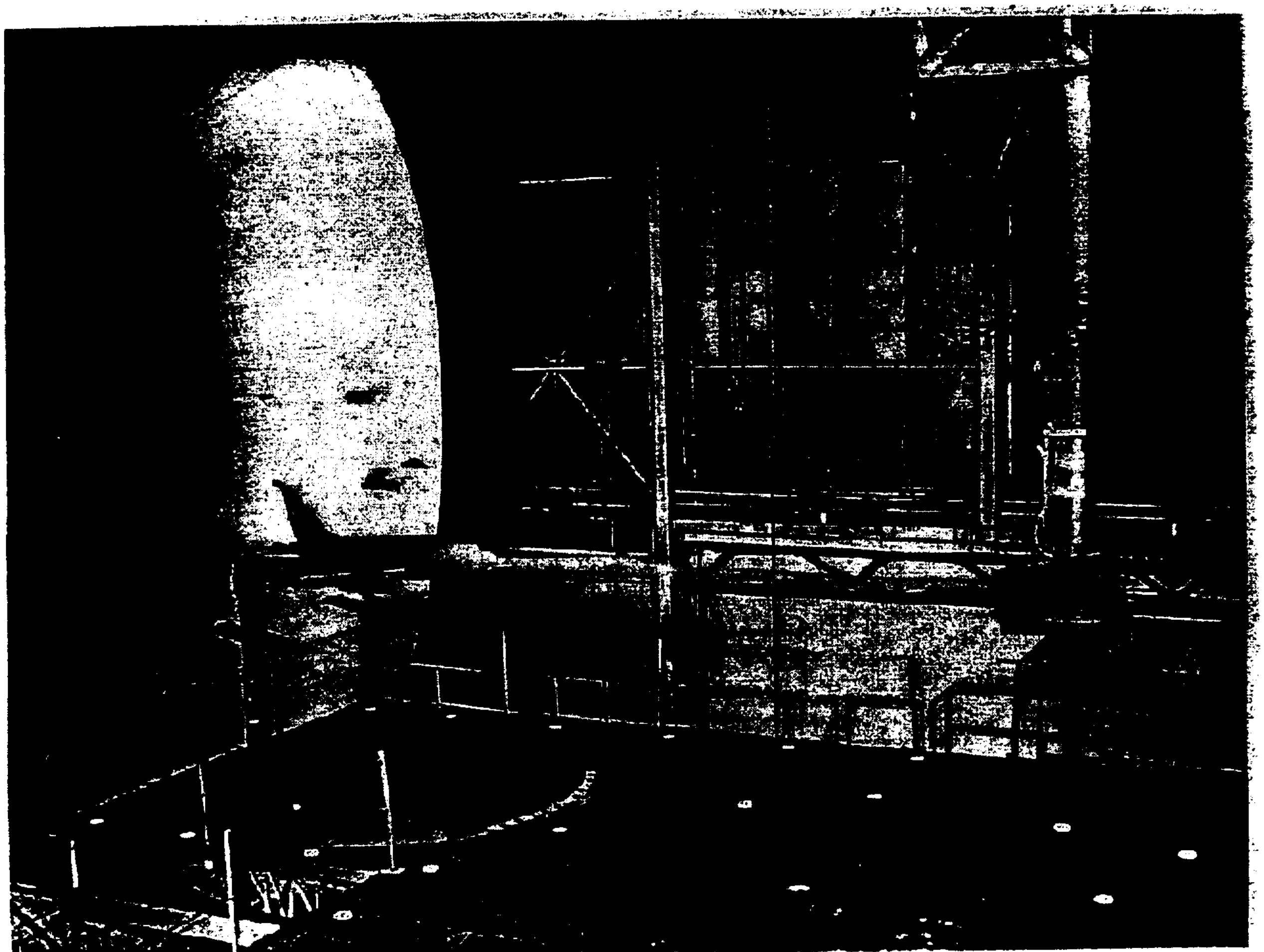


Figure 1: Photo of 30' x 60' wind tunnel static test

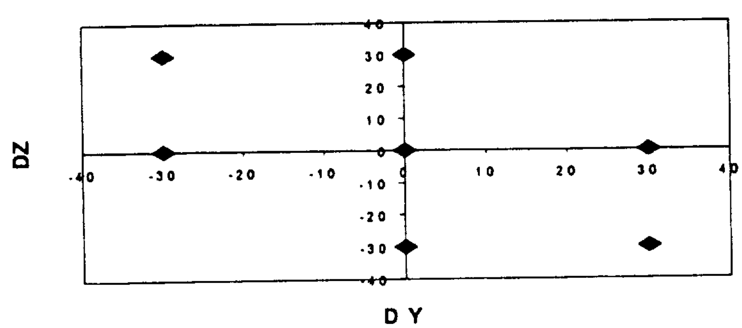
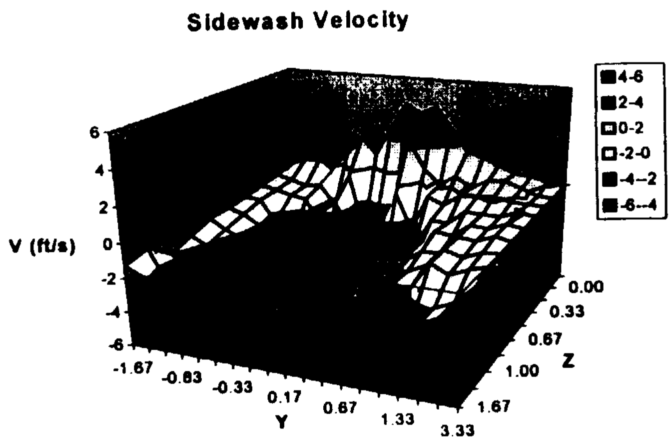
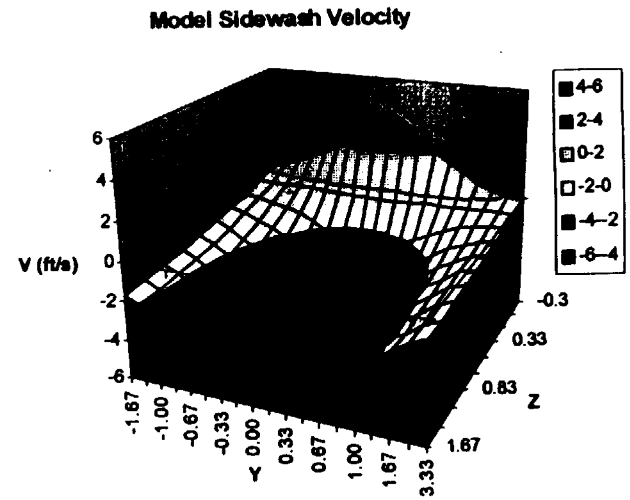


Figure 2: Locations analyzed throughout experiment



(a)



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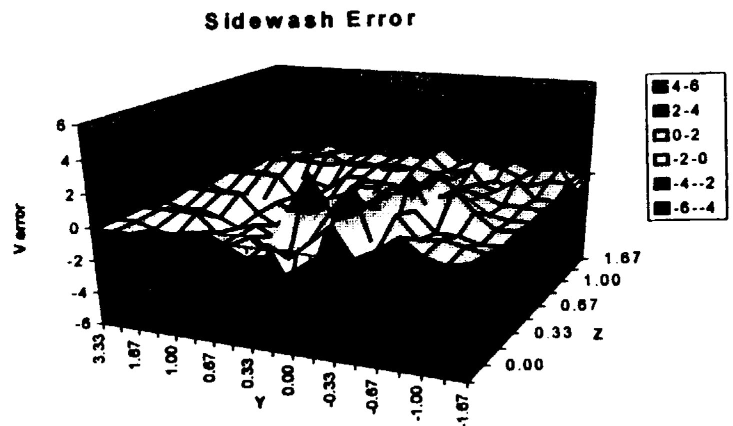
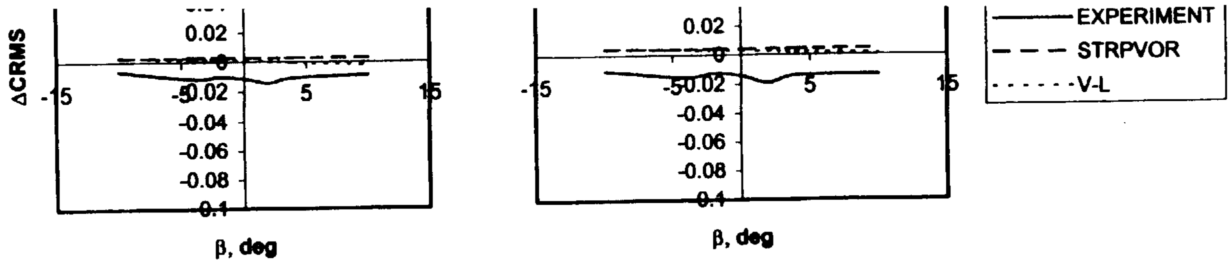


(c)

Figure 3: Large Generating Wing Lift Coefficient (CL) = 0.56. (a) Experimental Sidewash Velocity Data (b) Model Sidewash Velocity (c) Model Sidewash Velocity Error Data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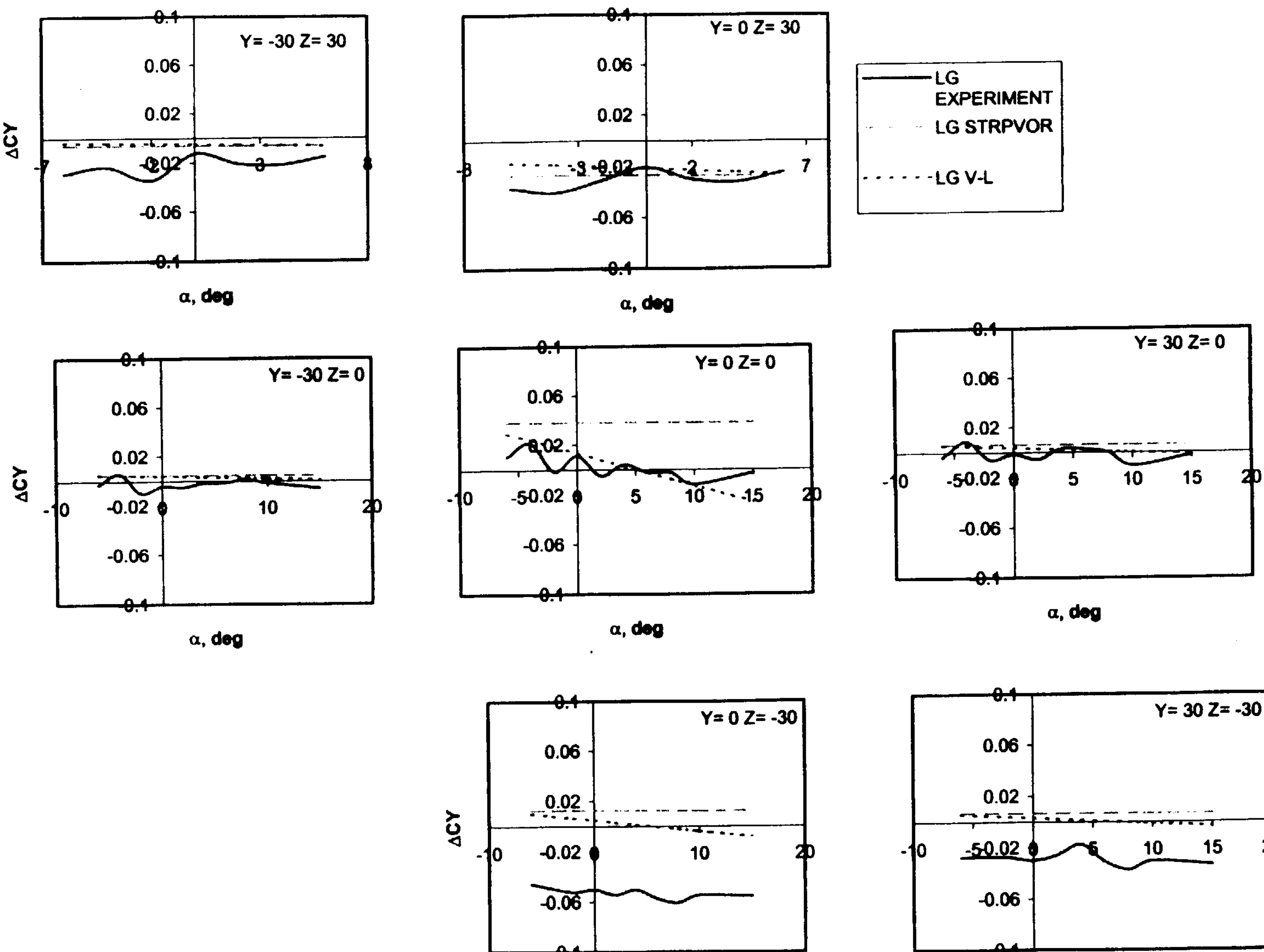
β, deg
β, deg
EXPERIMENT
STRPVOR
V-L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Y= 0 Z= 30
LG EXPERIMENT
LG STRPVOR
LG V-L
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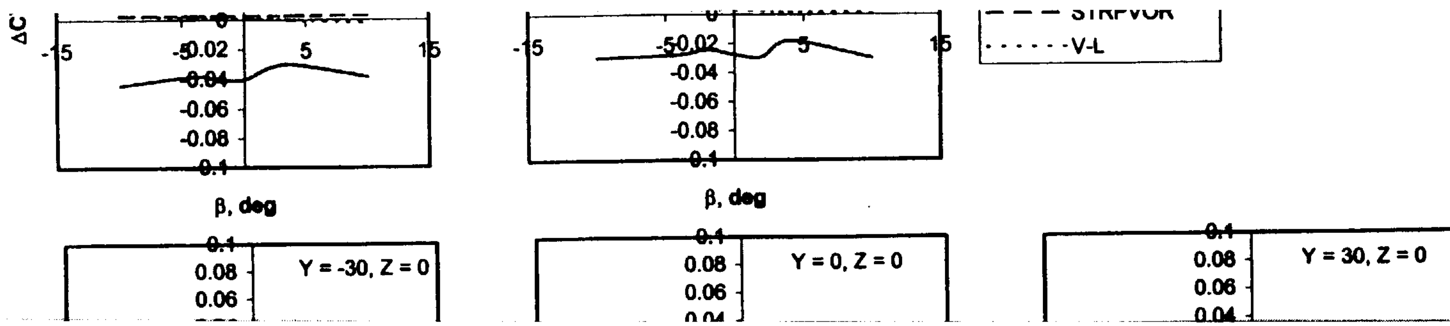
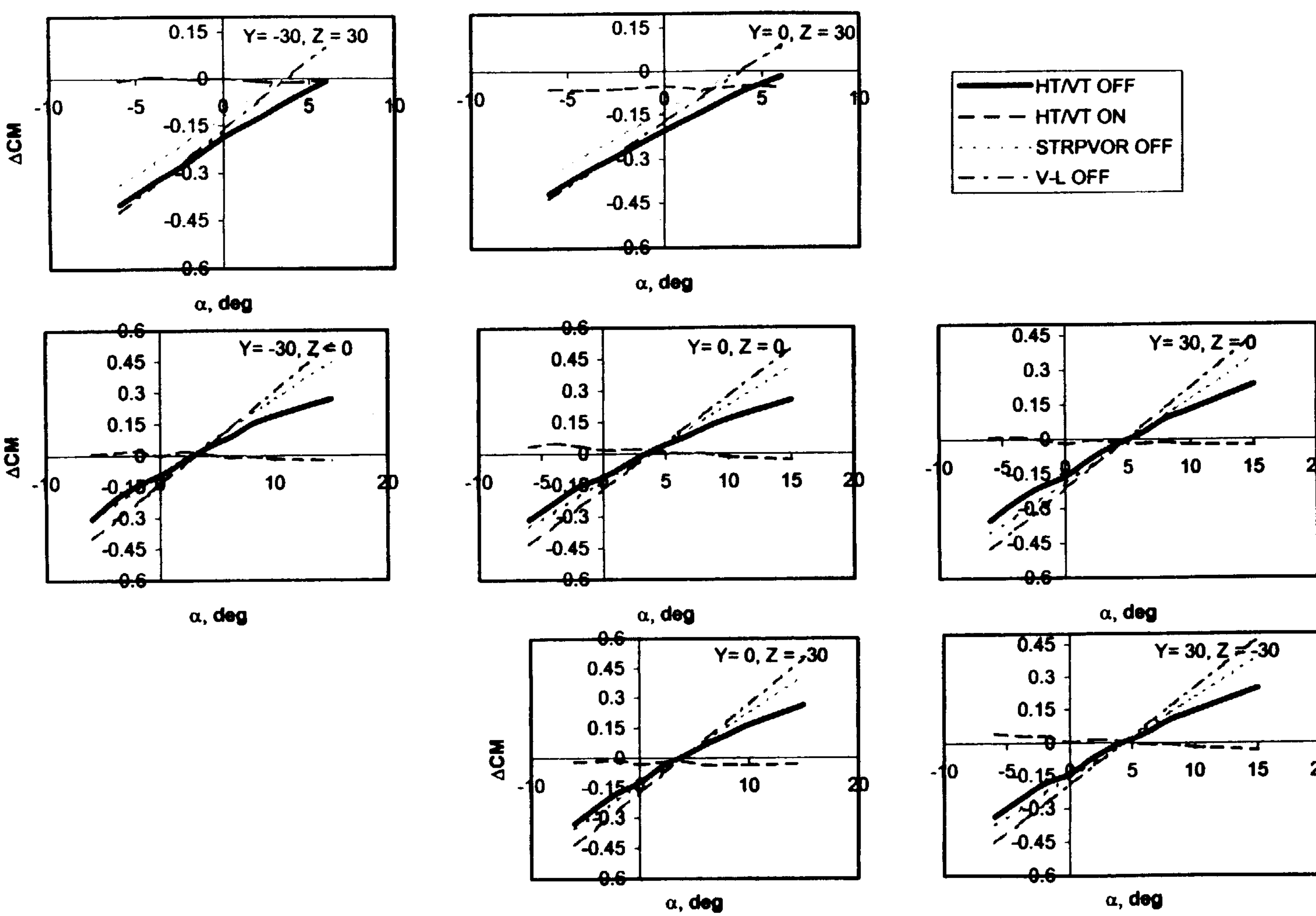
ΔCY
α, deg





HT/VT OFF
HT/VT ON
STRPVOR OFF
V-L OFF
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Y= 0, Z = 30
Y= -30, Z = 0
Y= 0, Z = 0
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Y= 0, Z = -30
Y= 30, Z = -30
ΔCM
α, deg