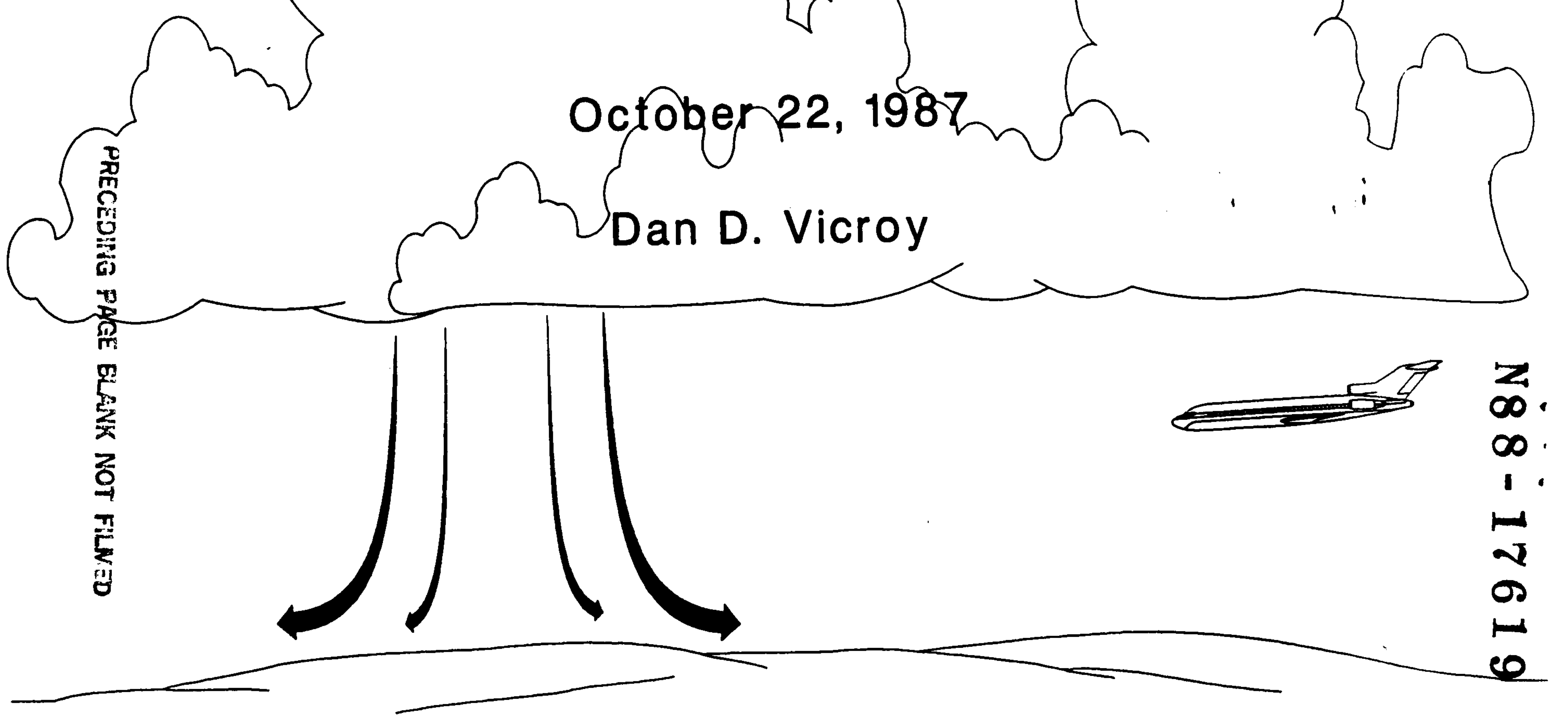
Investigation of the Influence of Wind Shear on the Aerodynamic Characteristics of Aircraft Using a Vortex-Lattice Method

October 22, 1987

Dan D. Vicroy



N88-17619

Abstract

Wind shear is considered by many in the aviation community to be one of the major safety issues facing their industry. The Federal Aviation Administration has addressed this problem through an Integrated Wind Shear Program Plan which incorporates the expertise of industry, universities, and various government agencies such as the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration and the Department of Defense. The plan is aimed at reducing the hazard of low-level wind shear through improved training and operating procedures, wind shear detection systems and flight guidance systems.

The flight simulator is a important tool used to address the airborne aspects of the wind shear program. The fidelity of the analytical models which represent the airplane and the atmosphere within the flight simulators is therefore of critical importance. The bulk of the simulation and analytical studies conducted to date have concentrated on determining the effect of the changing free-stream velocity vector on the airplane performance, and on developing higher fidelity wind shear models. Very little work has been done to determine the effect of the spatial variation of the wind field about the airplane on the airplane's aerodynamic characteristics. It is important that these aerodynamic effects are characterized and presented in a form which can be incorporated into research and training simulators. The research presented in this paper is a preliminary effort to address this need.

The objective of this study was to investigate and characterize the aerodynamic effect of shear flow through a series of sensitivity studies of the wind velocity gradients and wing planform geometry parameters. The wind shear effect was computed using a modified vortex-lattice computer program and characterized through the formulation of wind shear aerodynamic coefficients. The magnitude of the aerodynamic effect was demonstrated by computing the resultant change in the aerodynamics of a conventional wing and tail combination on a fixed flight path through

a simulated microburst.

The results of this study indicate that a significant amount of the control authority of the airplane may be required to counteract the wind shear induced forces and moments in the microburst environment. It is important to note that the forces and moments presented in this report are only due to the spatial variation of the wind field, and are not currently accounted for in today's research and training simulators.

Outline

- [x] Introduction
- [ ] Modification of Vortex-Lattice Algorithm
  - Spatially Varying Wind Field
  - Boundary Condition
  - Force and Moment Equations
- [ ] Program Checkout and Validation
- [ ] Shear Coefficient Development
- [ ] Sensitivity Studies
  - Vortex-Lattice Distribution
  - Planform Geometry
  - Wing and Stabilizer Combination
- [ ] Concluding Remarks

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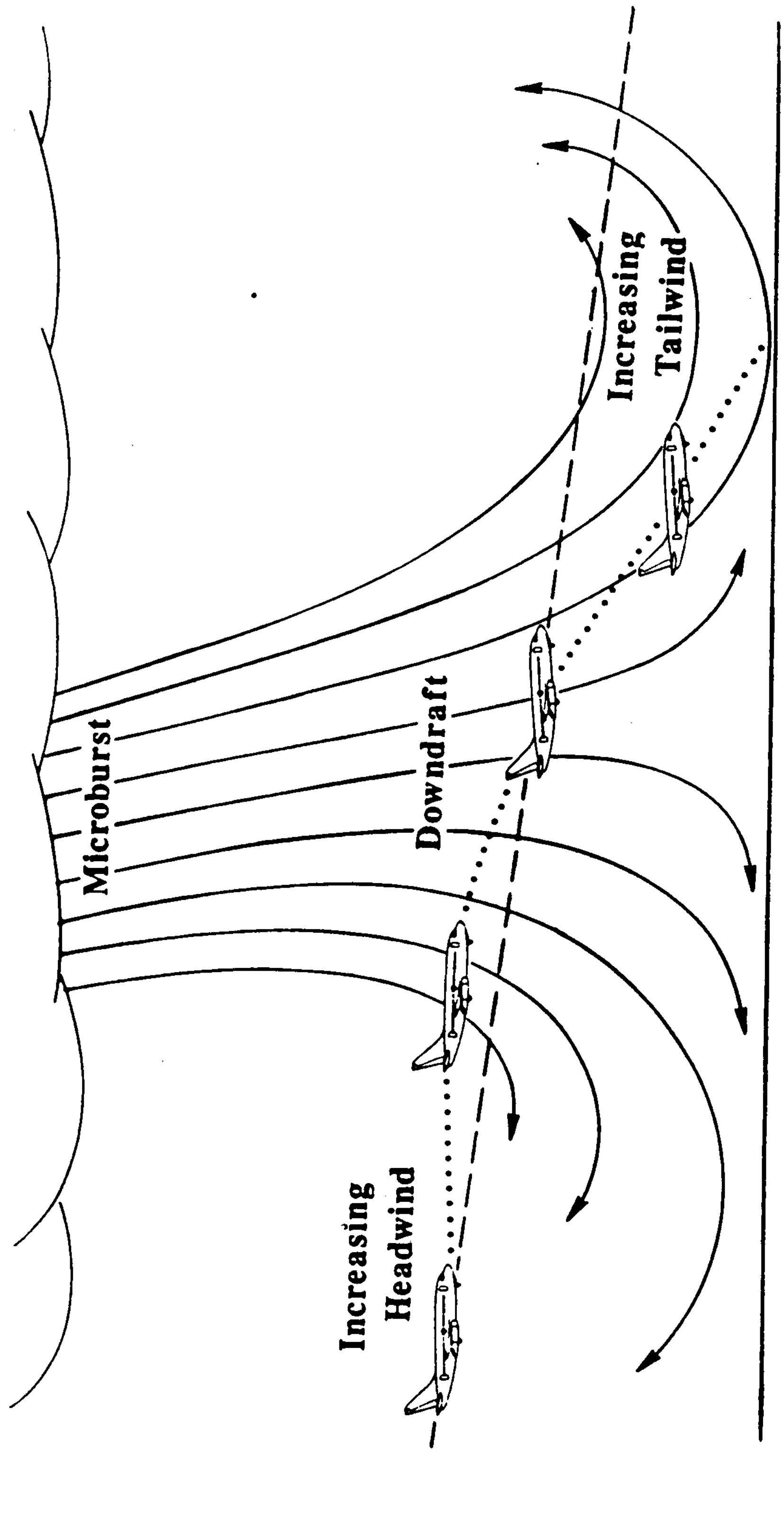
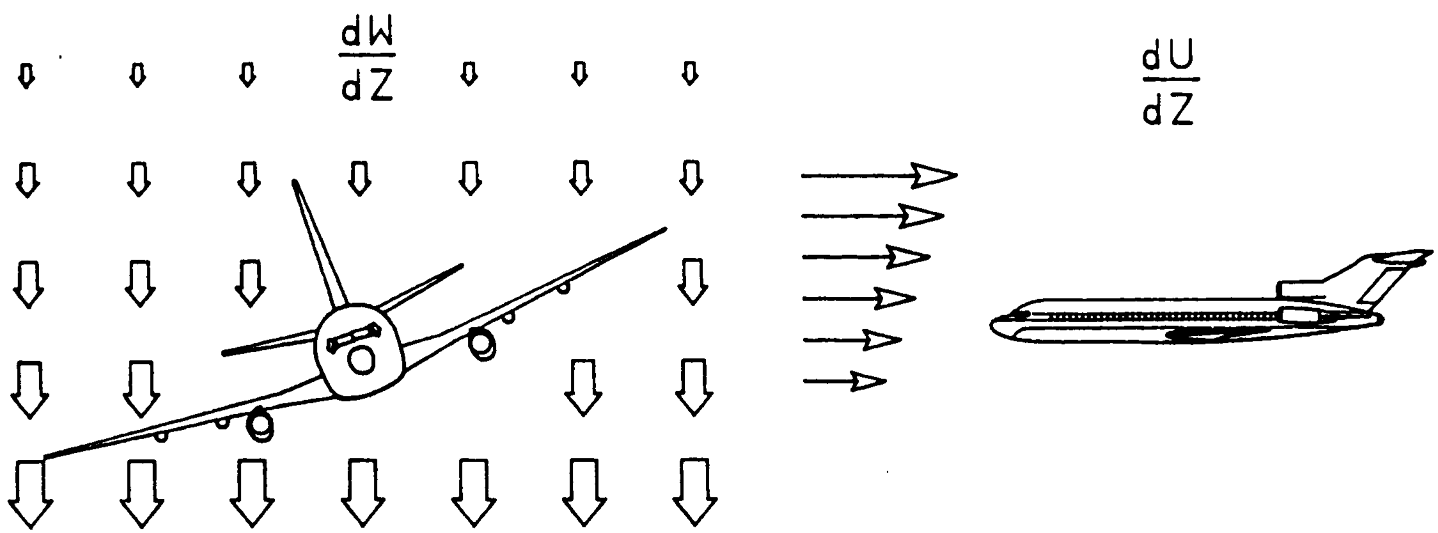

Microburst
Downdraft
Increasing Headwind
Increasing Tailwind

Research Objective

Investigate and characterize the aerodynamic effect of shear flow through a series of sensitivity studies of the spatial wind velocity gradients and wing planform geometry parameters



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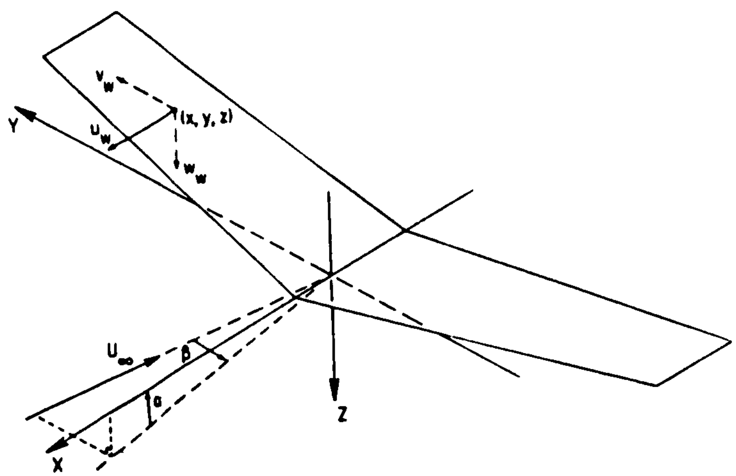
Defining Wind Field



Uniform Flow

$$\begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix} = -U_\infty \begin{pmatrix} \cos\alpha\cos\beta \\ \sin\beta \\ \sin\alpha\cos\beta \end{pmatrix}$$

Nonuniform Flow

$$\begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix} = \begin{pmatrix} u_s \\ v_s \\ w_s \end{pmatrix} - U_\infty \begin{pmatrix} \cos\alpha\cos\beta \\ \sin\beta \\ \sin\alpha\cos\beta \end{pmatrix}$$

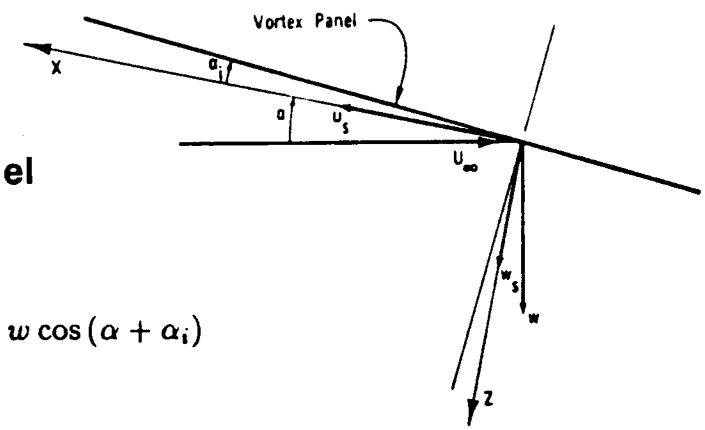
where:

$$\begin{pmatrix} u_s \\ v_s \\ w_s \end{pmatrix} \equiv \begin{pmatrix} \frac{\partial u_s}{\partial x} & \frac{\partial u_s}{\partial y} & \frac{\partial u_s}{\partial z} \\ \frac{\partial v_s}{\partial x} & \frac{\partial v_s}{\partial y} & \frac{\partial v_s}{\partial z} \\ \frac{\partial w_s}{\partial x} & \frac{\partial w_s}{\partial y} & \frac{\partial w_s}{\partial z} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Boundary Condition

Boundary Condition:

No flow through the panel

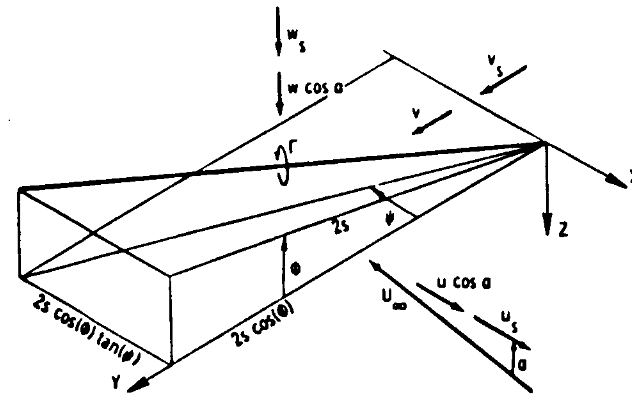


$$U_\infty \sin(\alpha+\alpha_i) - u_s \sin\alpha_i = w_s \cos\alpha_i + w\cos(\alpha+\alpha_i)$$

Force and Moment Equations

Lift of line vortex element per unit span

$$\tilde{\ell} = \rho V \Gamma$$



Spanwise bound vortex element

$$\ell_s = F_{x_s} \sin\alpha - F_{z_s} \cos\alpha$$

$$d_s = -F_{x_s} \cos\alpha - F_{z_s} \sin\alpha$$

where

$$F_{x_s} = \rho \Gamma 2s \cos\phi \, [U_\infty \sin\alpha - u \sin\alpha - w \cos\alpha - w_s - k(v + v_s) \tan\phi]$$

$$F_{y_s} = \rho \Gamma 2s \cos\phi \, [(U_\infty \cos\alpha - u \cos\alpha - u_s + w \sin\alpha) \tan\phi + k(v + v_s) \tan\psi]$$

and $k = +1$ (right side); -1 (left side)

Sideforce

$$F_{z_s} = \rho \Gamma 2s \cos\phi \, [-U_\infty \cos\alpha + u \cos\alpha - w \sin\alpha + u_s$$
$$+ (-U_\infty \sin\alpha + u \sin\alpha + w_s + w \cos\alpha) \tan\psi]$$

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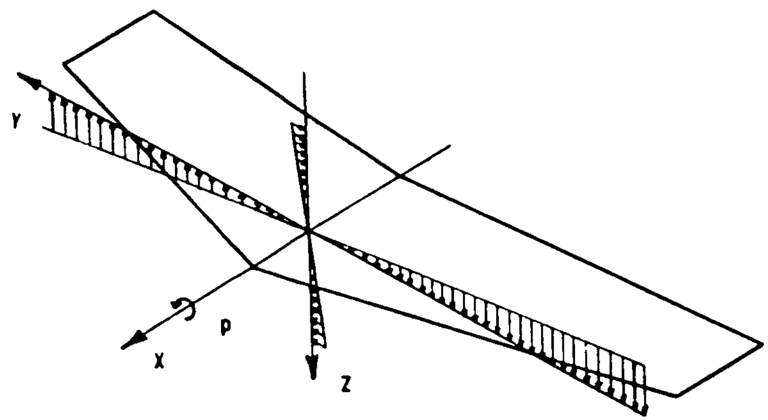
Rotary Motion

Rolling

$$p = \frac{1}{2}\left(\frac{\partial v_s}{\partial z} - \frac{\partial w_s}{\partial y}\right)$$



Pitching

$$q = \frac{1}{2}\left(\frac{\partial w_s}{\partial x} - \frac{\partial u_s}{\partial z}\right)$$

Yawing

$$r = \frac{1}{2}\left(\frac{\partial u_s}{\partial y} - \frac{\partial v_s}{\partial x}\right)$$

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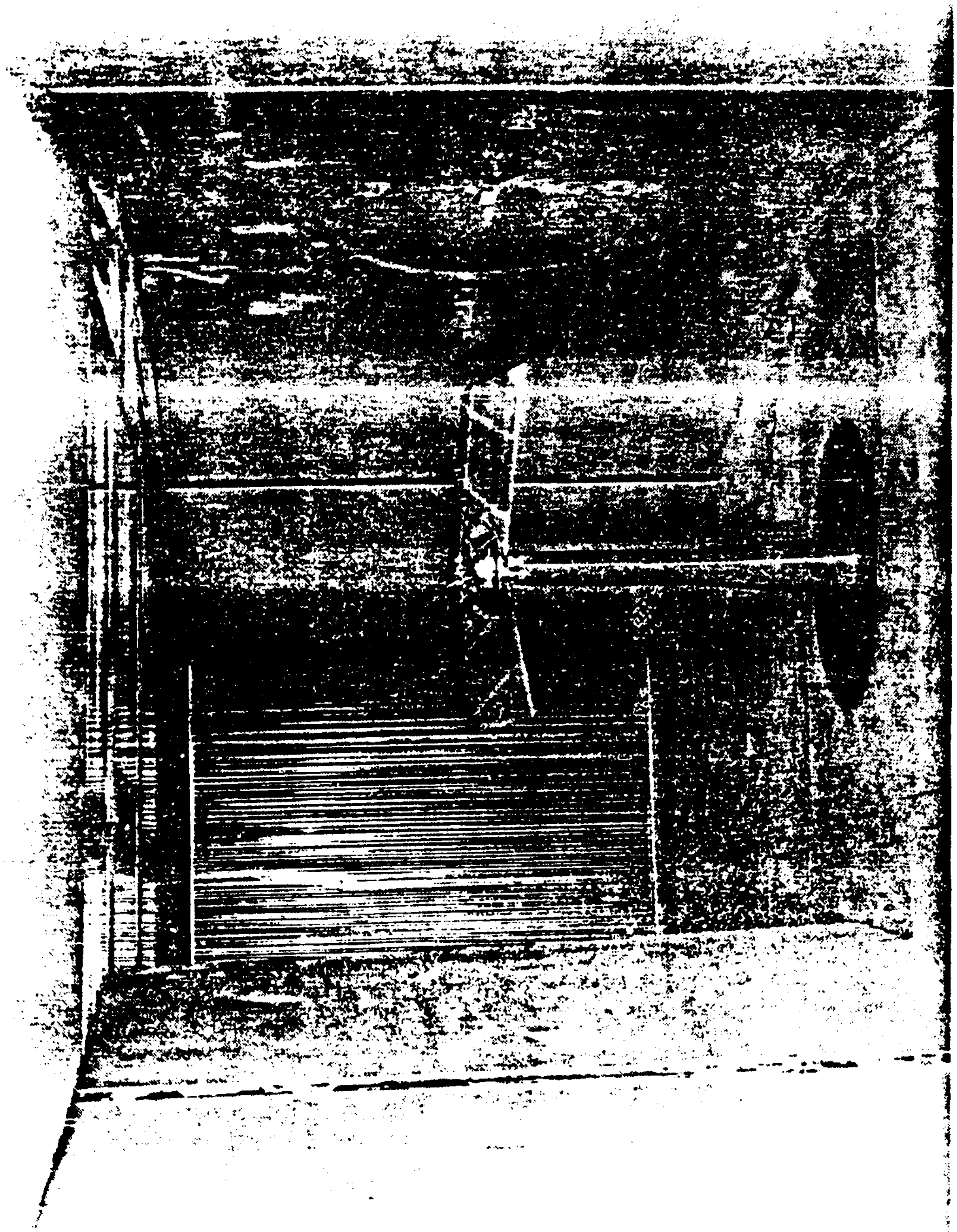

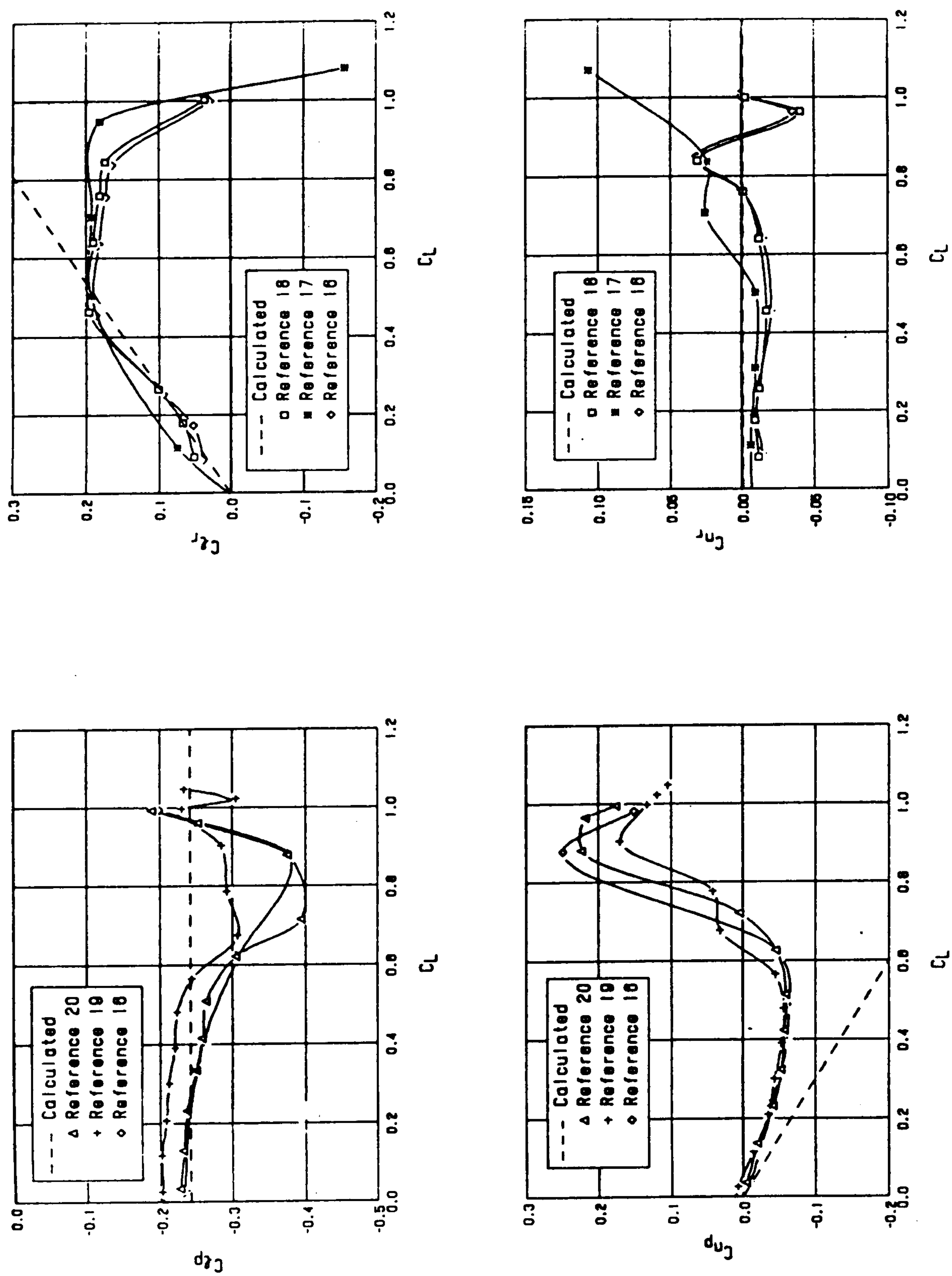

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Shear Coefficient Development

Shear lift coefficient as defined by Campos:

$$C_{L_S} = \frac{\partial C_L}{\partial\left(\frac{S\bar{c}}{2U_\infty}\right)}$$

Total lift coefficient now becomes:

$$C_L = C_{L_\alpha}\alpha + C_{L_o} + C_{L_S}\frac{S\bar{c}}{2U_\infty}$$

Change in force and moment coefficients due to shear

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$$\begin{bmatrix} \Delta C_L (2U_\infty/\bar{c}) \\ \Delta C_D (2U_\infty/\bar{c}) \\ \Delta C_Y (2U_\infty/b) \\ \Delta C_l (2U_\infty/b) \\ \Delta C_m (2U_\infty/\bar{c}) \\ \Delta C_n (2U_\infty/b) \end{bmatrix} = [\alpha \mathbf{A} + \mathbf{B}] \begin{bmatrix} \partial u_s/\partial x \\ \partial u_s/\partial y \\ \partial u_s/\partial z \\ \partial v_s/\partial x \\ \partial v_s/\partial y \\ \partial v_s/\partial z \\ \partial w_s/\partial x \\ \partial w_s/\partial y \\ \partial w_s/\partial z \end{bmatrix}$$

$$\mathbf{A} = \begin{pmatrix} C_{L_{\alpha u_x}} & C_{L_{\alpha u_y}} & C_{L_{\alpha u_z}} & C_{L_{\alpha v_x}} & \cdots & C_{L_{\alpha w_z}} \\ C_{D_{\alpha u_x}} & C_{D_{\alpha u_y}} & C_{D_{\alpha u_z}} & \cdot & \cdots & \cdot \\ C_{Y_{\alpha u_x}} & C_{Y_{\alpha u_y}} & \cdot & \cdot & \cdots & \cdot \\ C_{l_{\alpha u_x}} & \cdot & \cdot & \cdot & \cdots & \cdot \\ C_{m_{\alpha u_x}} & \cdot & \cdot & \cdot & \cdots & \cdot \\ C_{n_{\alpha u_x}} & \cdot & \cdot & \cdot & \cdots & C_{n_{\alpha w_z}} \end{pmatrix} \qquad \mathbf{B} = \begin{pmatrix} C_{L_{u_x}} & C_{L_{u_y}} & C_{L_{u_z}} & C_{L_{v_x}} & \cdots & C_{L_{w_z}} \\ C_{D_{u_x}} & C_{D_{u_y}} & C_{D_{u_z}} & \cdot & \cdots & \cdot \\ C_{Y_{u_x}} & C_{Y_{u_y}} & \cdot & \cdot & \cdots & \cdot \\ C_{l_{u_x}} & \cdot & \cdot & \cdot & \cdots & \cdot \\ C_{m_{u_x}} & \cdot & \cdot & \cdot & \cdots & \cdot \\ C_{n_{u_x}} & \cdot & \cdot & \cdot & \cdots & C_{n_{w_z}} \end{pmatrix}$$

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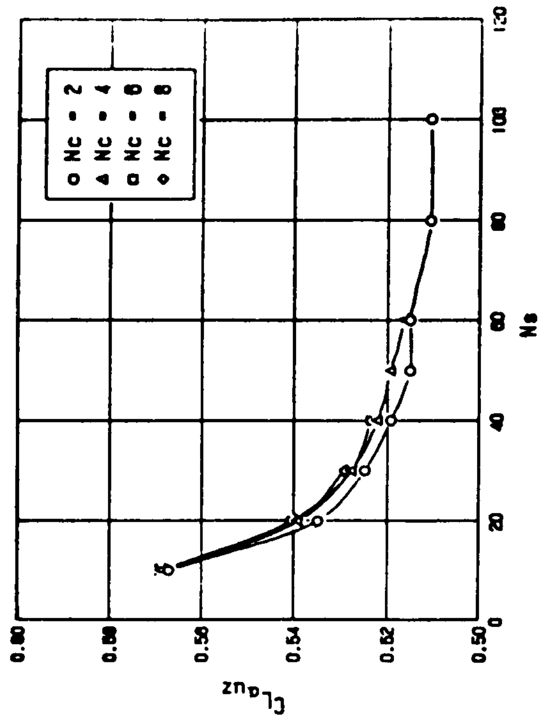

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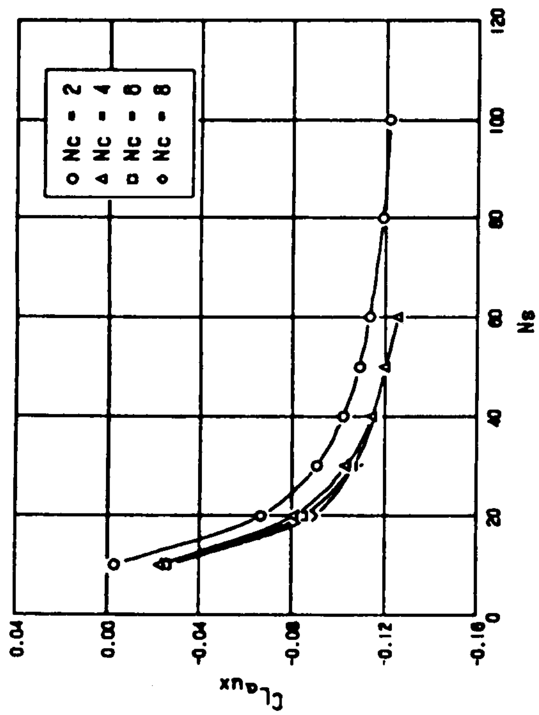
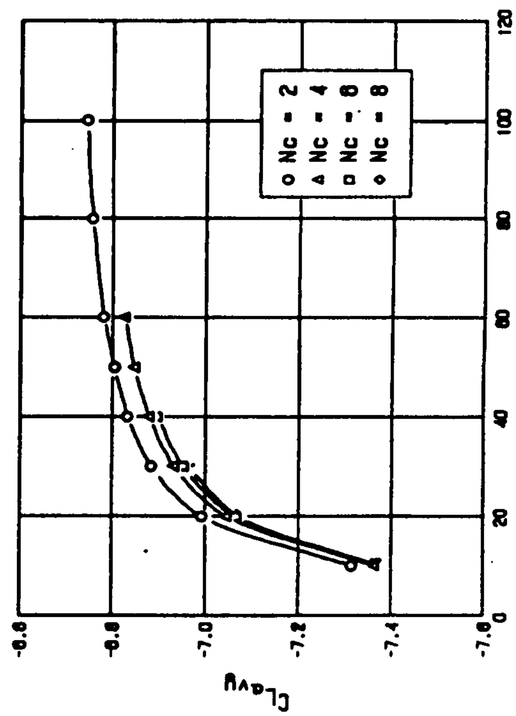
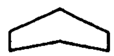
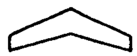
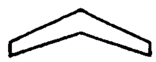
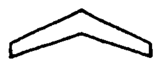
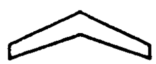
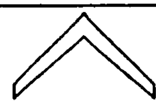
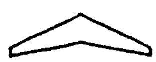
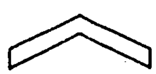


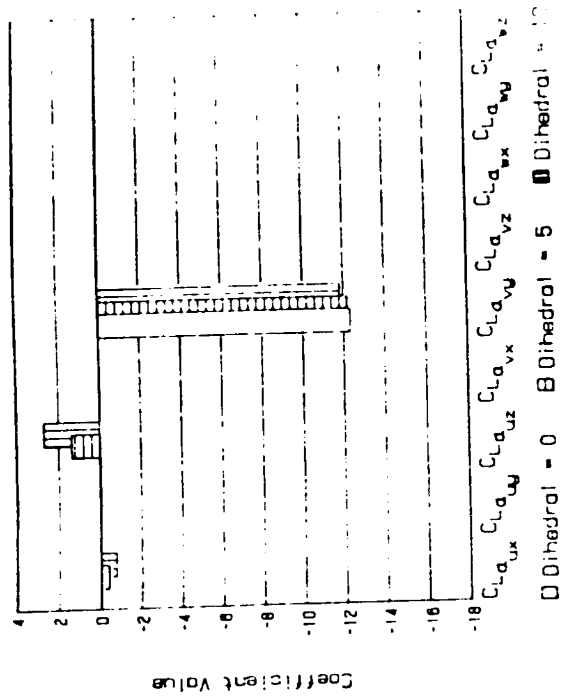


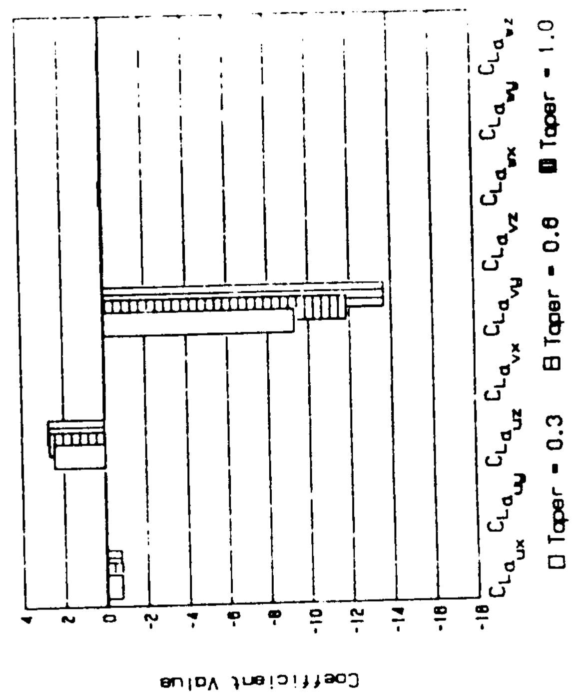
Sensitivity Study Results

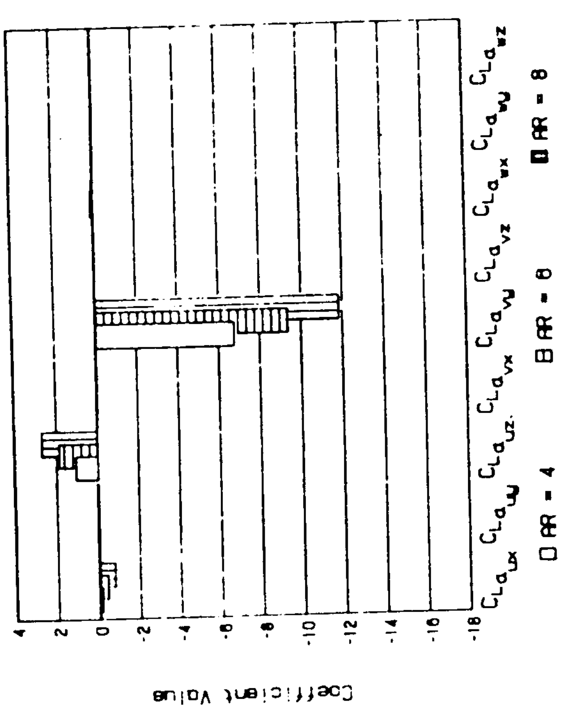
Vortex-Lattice Distribution

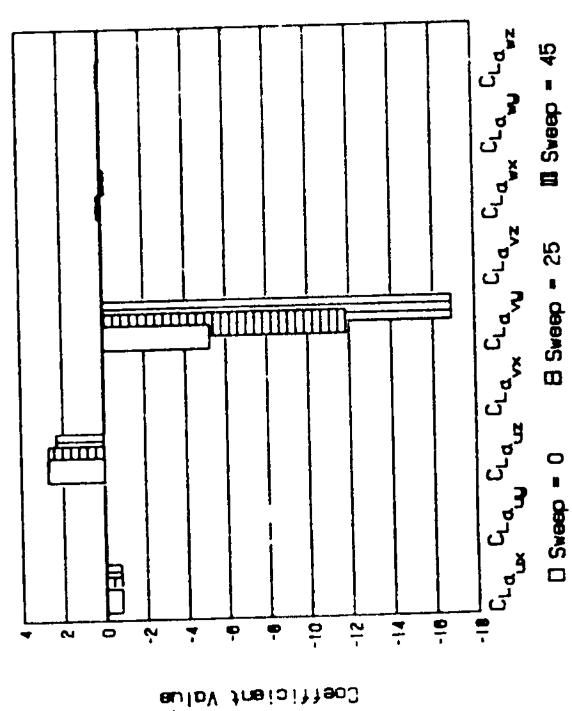
- Increasing Ns and Nc resulted in asymptotic convergence of shear coefficient values
- Ns<30 and Nc<4 resulted in significant variations in computed values
- Ns=40 and Nc=4 selected for remaining sensitivity studies

Configuration	Aspect Ratio	Sweep (deg)	Taper Ratio	Dihedral (deg)
1 	2.61	45	1.0	0
2 	2.61	45	1.0	10
3 	4.0	25	0.6	10
4 	6.0	25	0.6	10
5 	8.0	25	0.6	10
6 	8.0	25	0.6	0
7 	8.0	25	0.6	5
8 	8.0	0	0.6	10
9 	8.0	45	0.6	10
10 	8.0	25	0.3	10
11 	8.0	25	1.0	10









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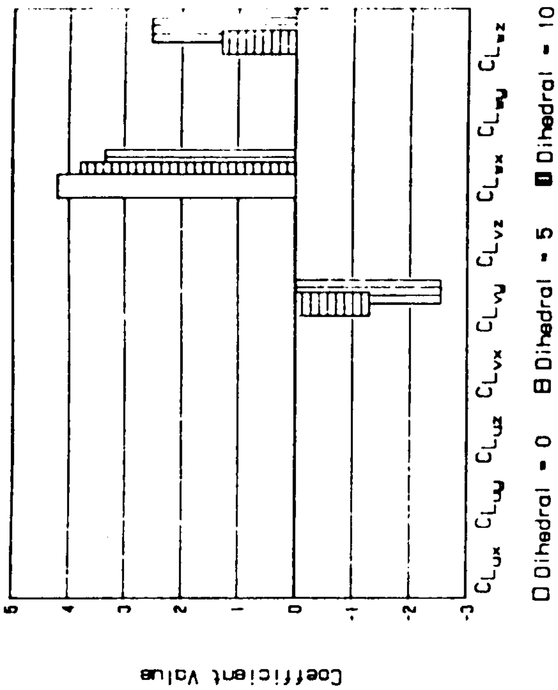

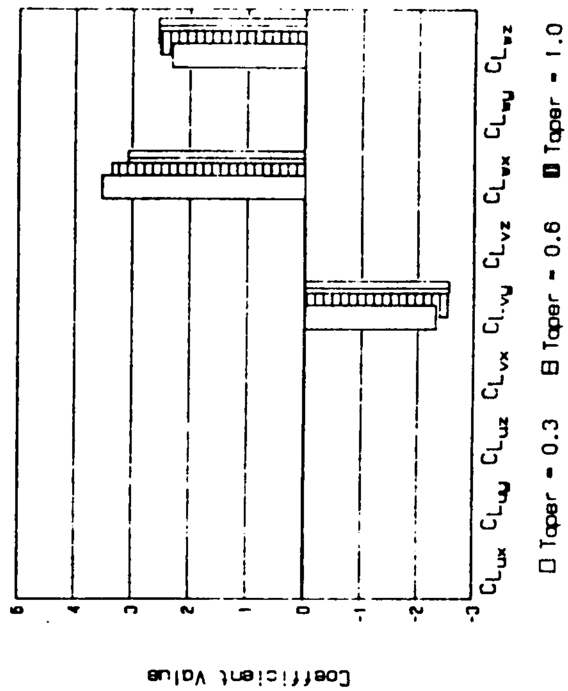

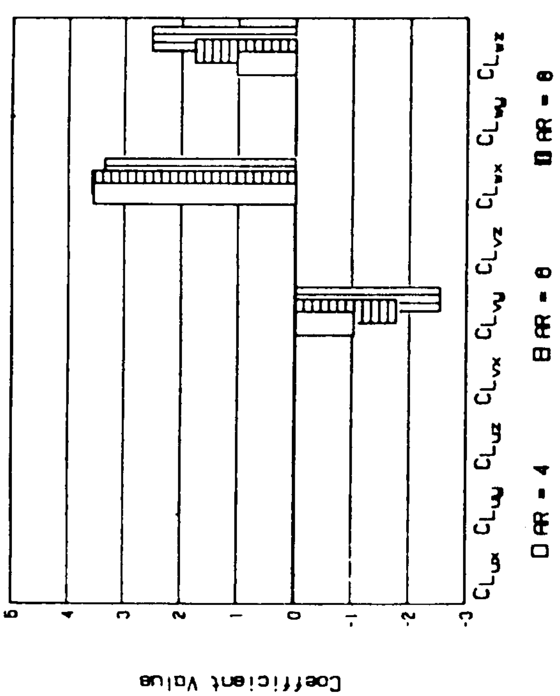

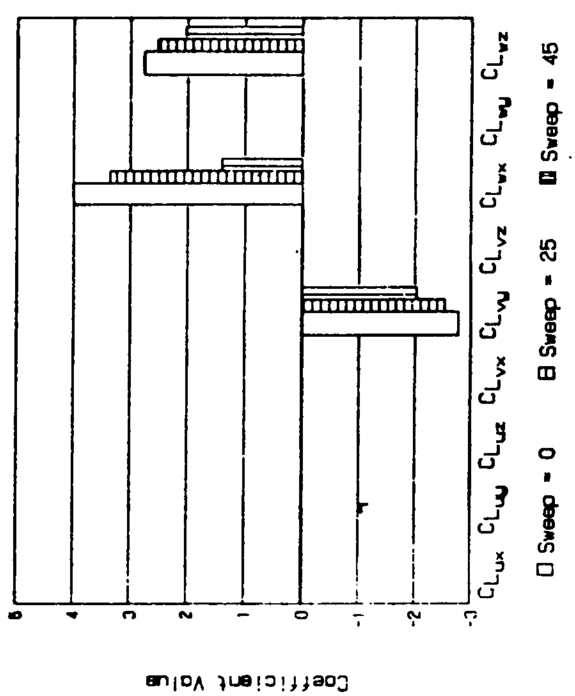

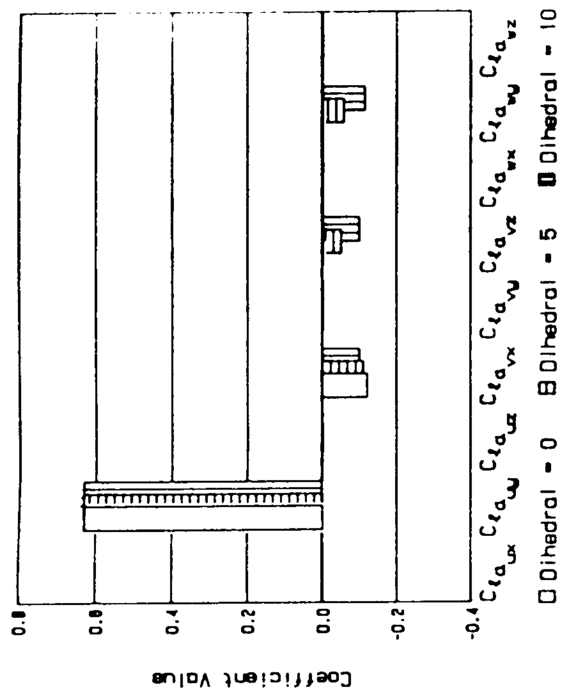

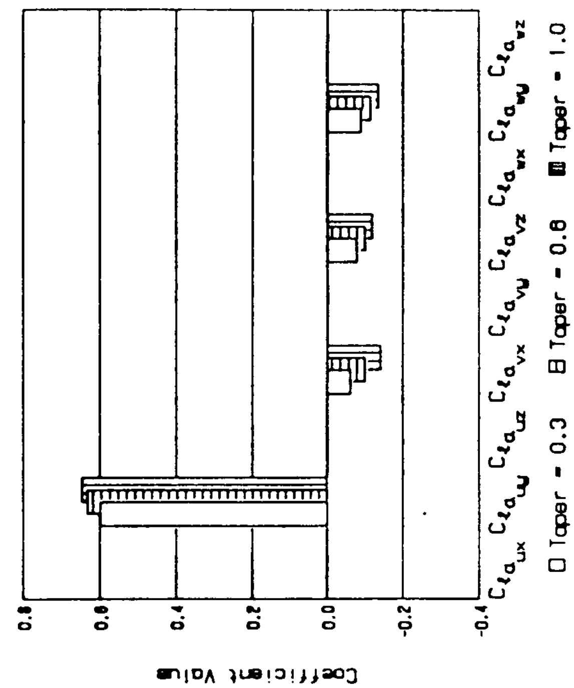

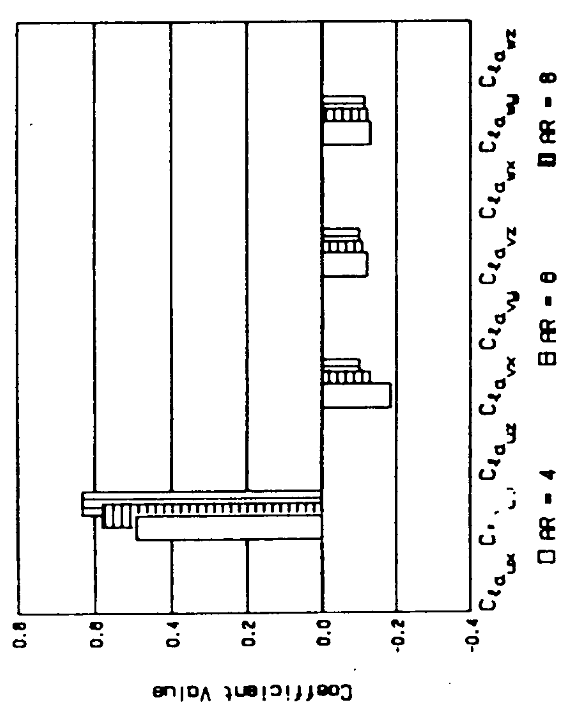

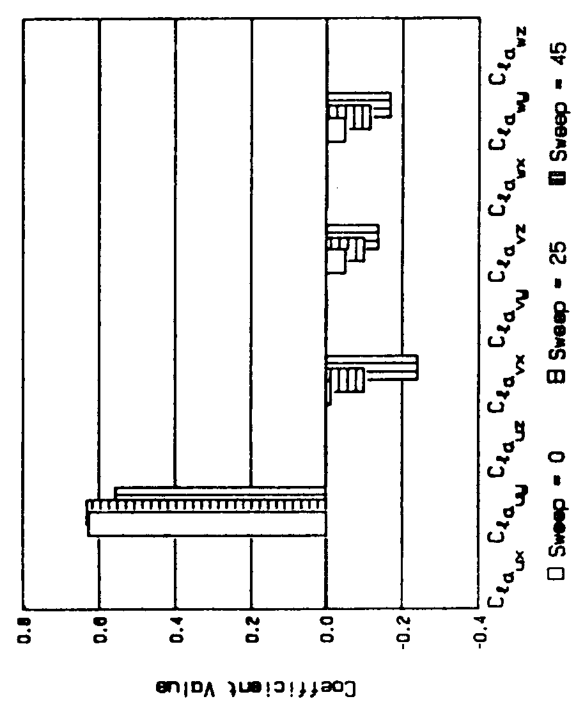

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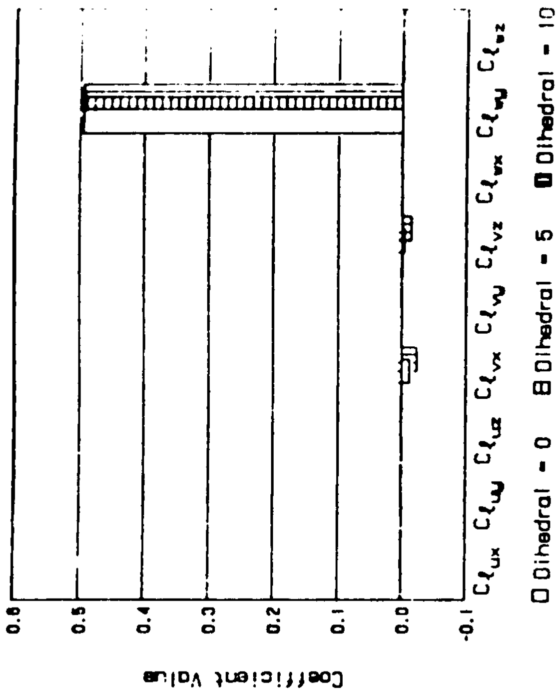

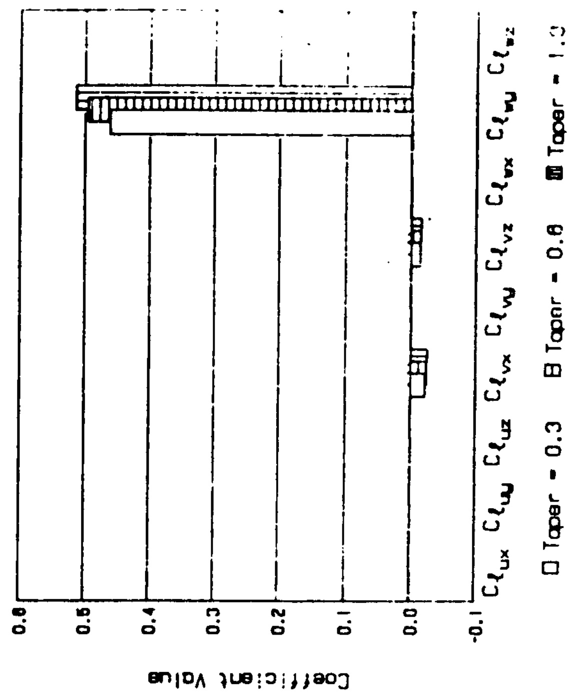

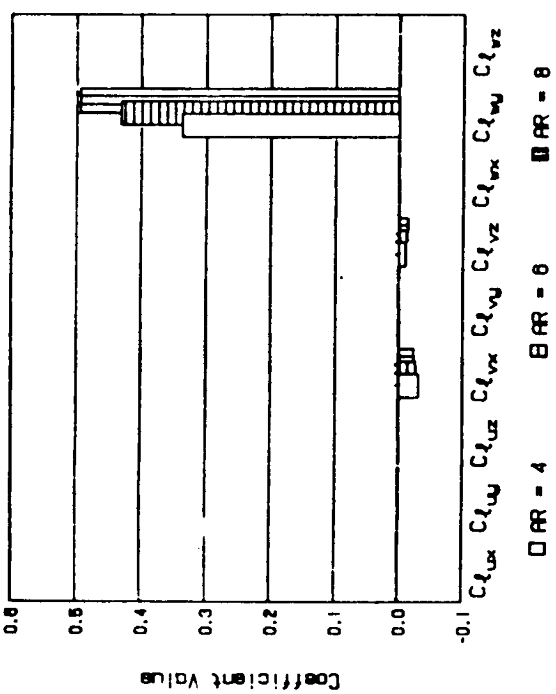

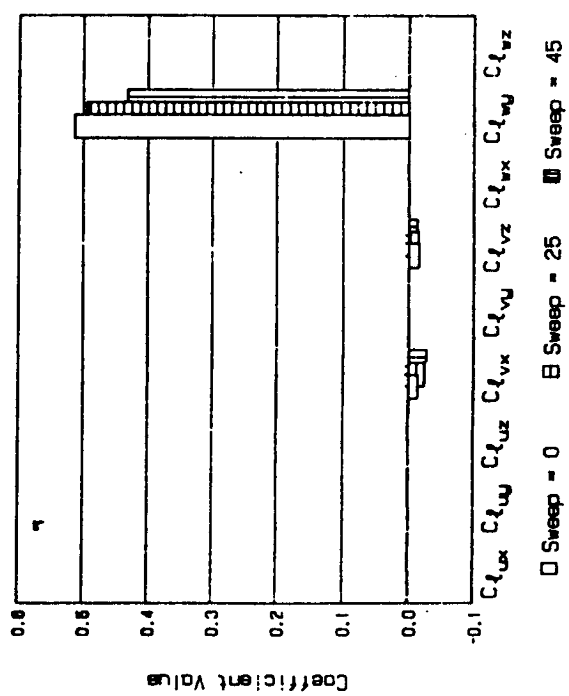

Sensitivity Study Results

Planform Geometry Effect

- Separation of gradient effects into longitudinal and lateral categories
- In general, sweep had the largest effect on the shear coefficients
- Taper ratio had the smallest effect

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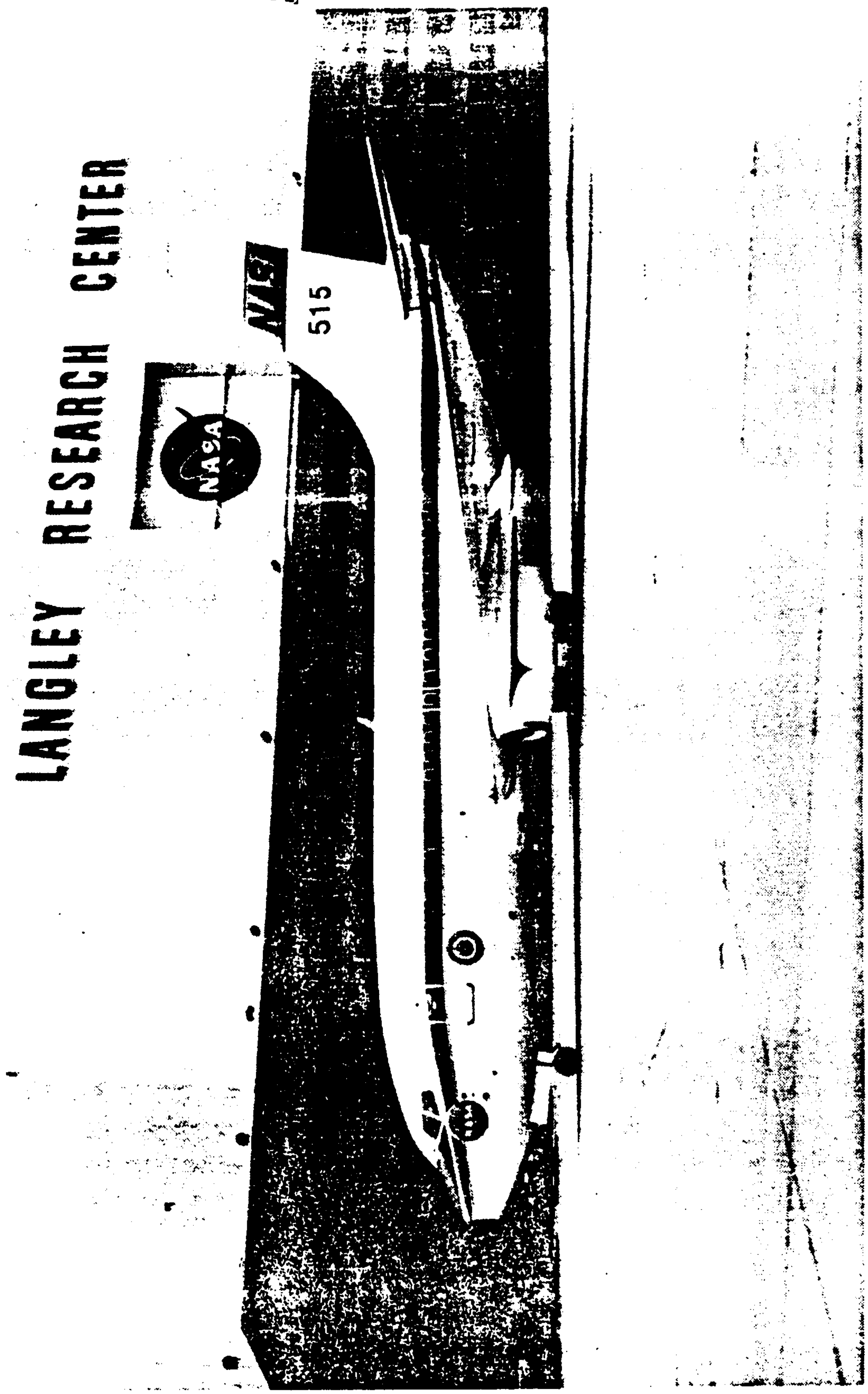
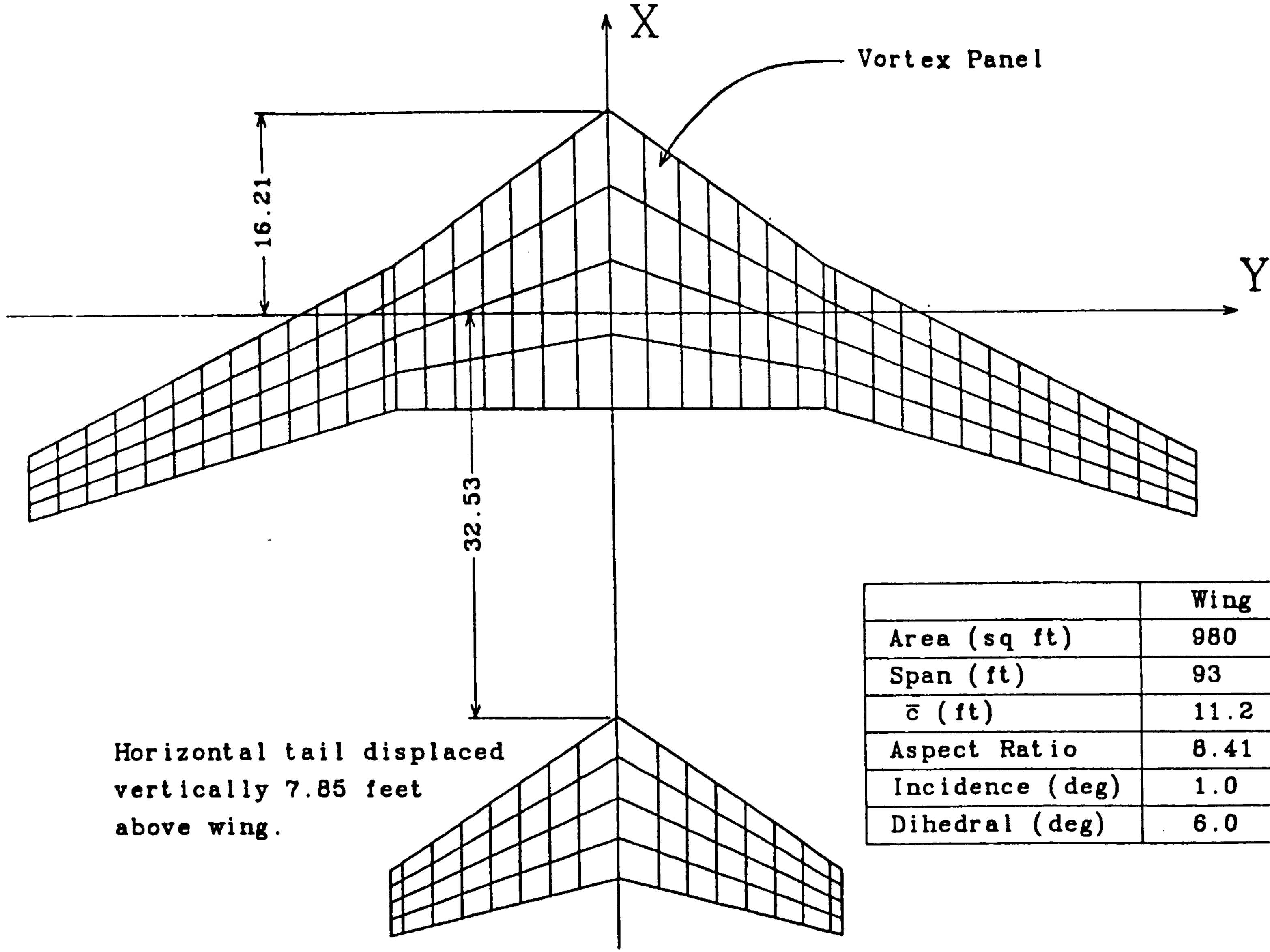
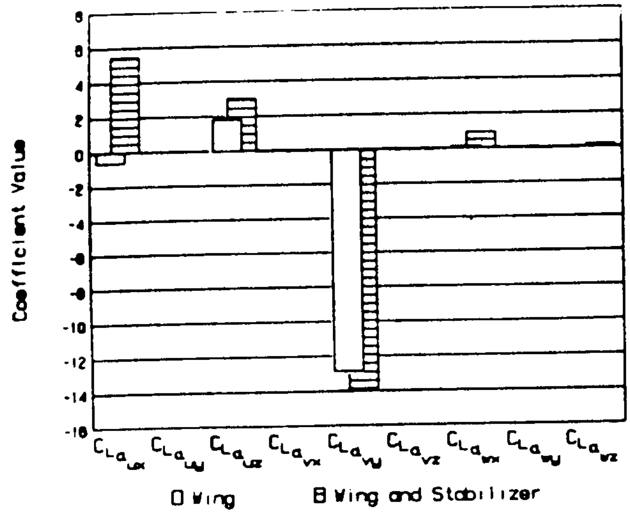
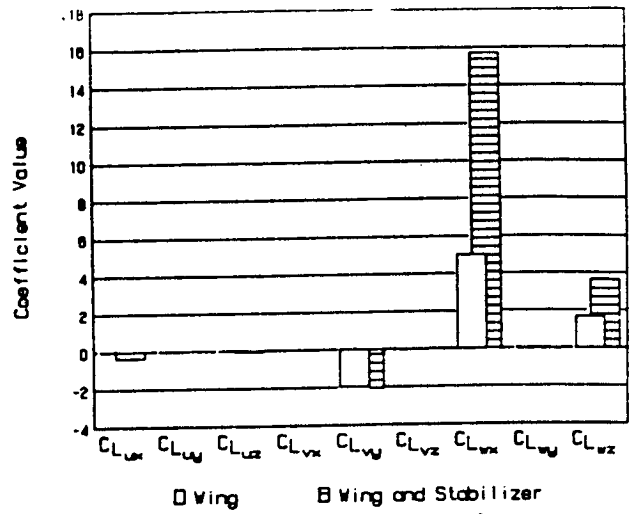




Horizontal tail displaced vertically 7.85 feet above wing.

	Wing	Tail
Area (sq ft)	980	312
Span (ft)	93	36
$\bar{c}$ (ft)	11.2	9.6
Aspect Ratio	8.41	4.0
Incidence (deg)	1.0	0
Dihedral (deg)	6.0	7.0


Coefficient Value
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
CLa_ux CLa_uy CLa_uz CLa_vx CLa_vy CLa_vz CLa_wx CLa_wy CLa_wz
Wing
Wing and Stabilizer


Coefficient Value
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16
14
12
10
8
6
4
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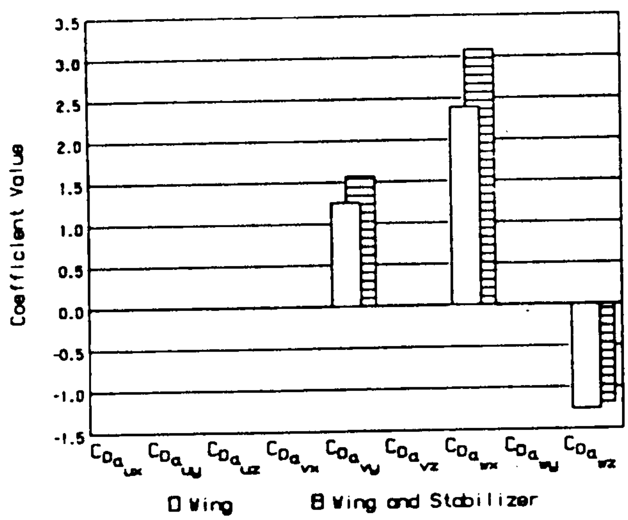
-4
CL_ux CL_uy CL_uz CL_vx CL_vy CL_vz CL_wx CL_wy CL_wz
Wing
Wing and Stabilizer


Coefficient Value
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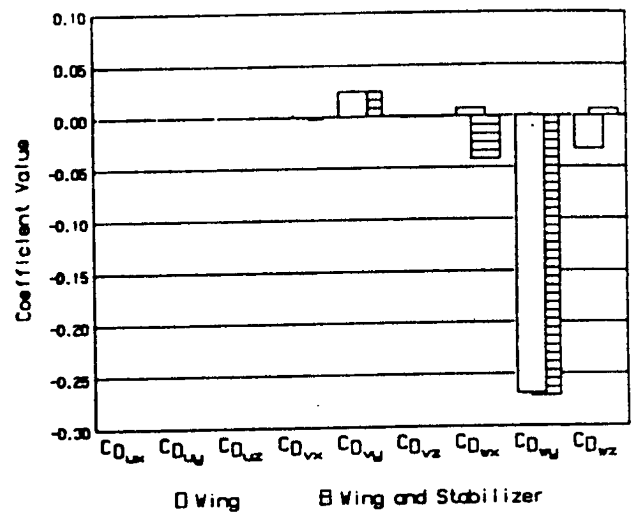
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
CDa_ux CDa_uy CDa_uz CDa_vx CDa_vy CDa_vz CDa_wx CDa_wy CDa_wz
Wing
Wing and Stabilizer


Coefficient Value
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0.05
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-0.05
-0.10
-0.15
-0.20
-0.25
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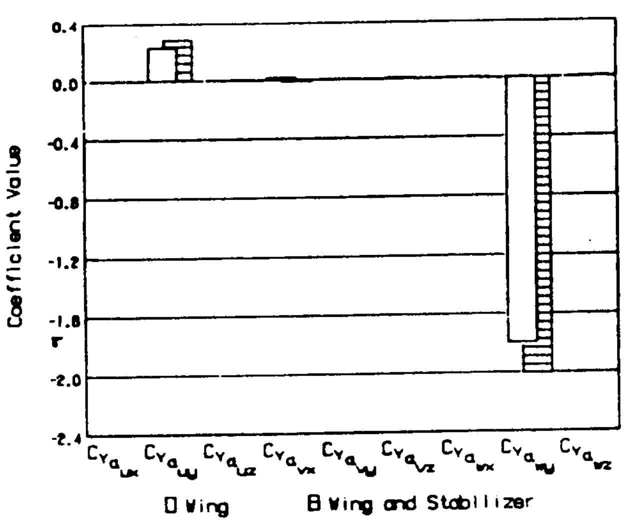
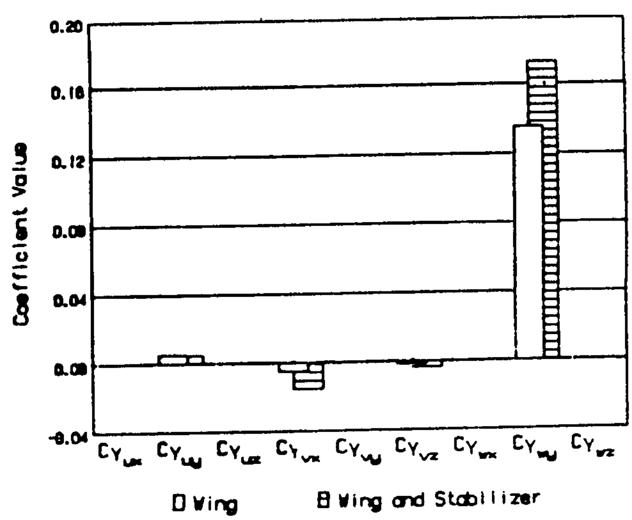
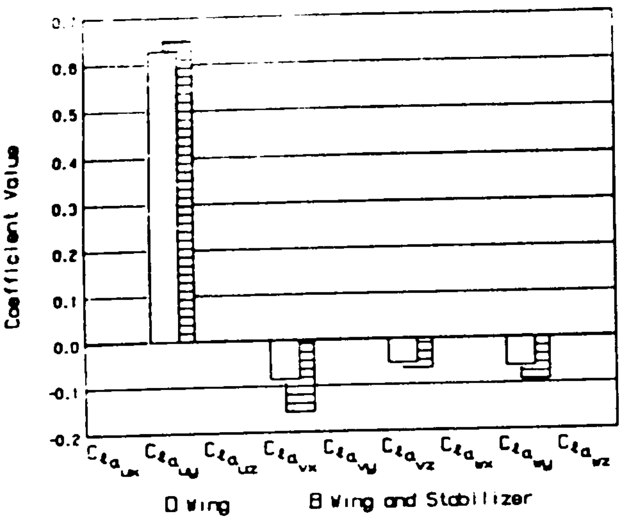
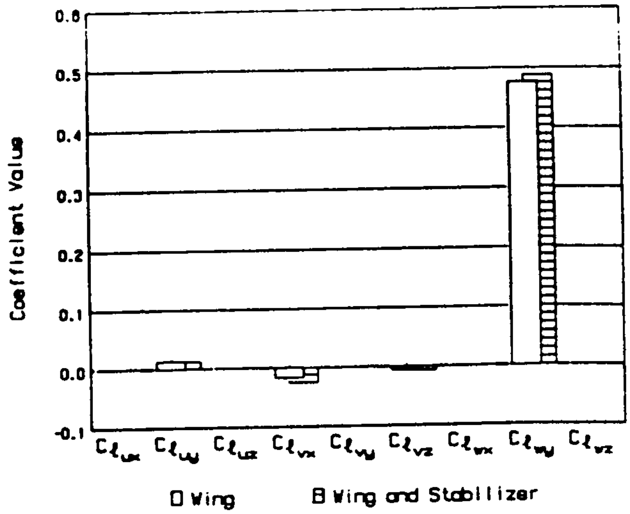
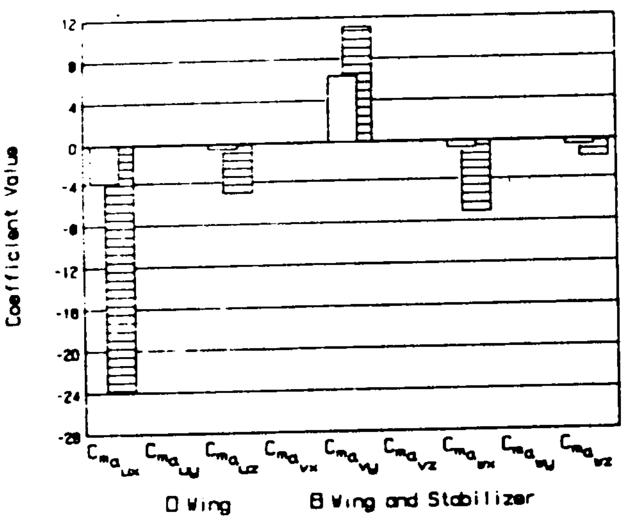
CD_ux CD_uy CD_uz CD_vx CD_vy CD_vz CD_wx CD_wy CD_wz
Wing
Wing and Stabilizer

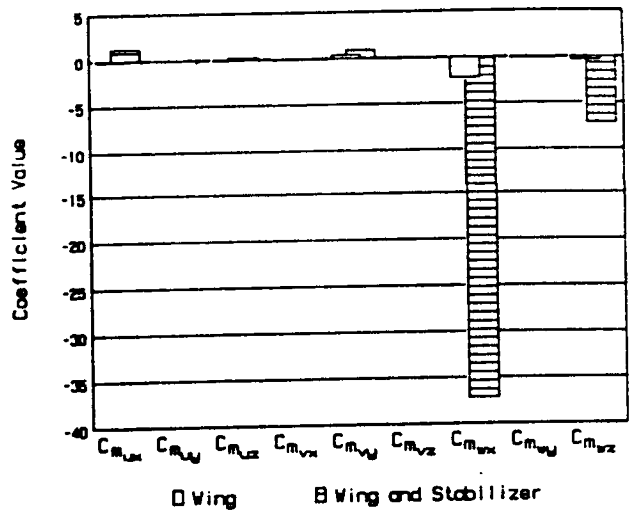

Coefficient Value
0.4
0.0
-0.4
-0.8
-1.2
-1.6
-2.0
-2.4
CYa_ux CYa_uy CYa_uz CYa_vx CYa_vy CYa_vz CYa_wx CYa_wy CYa_wz
Wing
Wing and Stabilizer

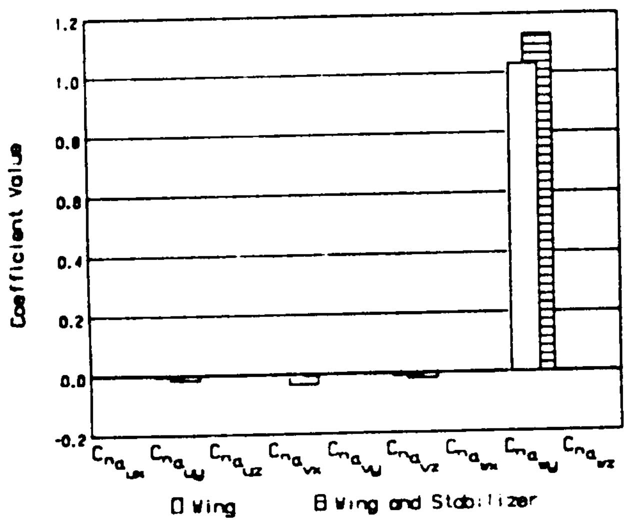

Coefficient Value
0.20
0.16
0.12
0.08
0.04
0.00
-0.04
CY_ux CY_uy CY_uz CY_vx CY_vy CY_vz CY_wx CY_wy CY_wz
Wing
Wing and Stabilizer

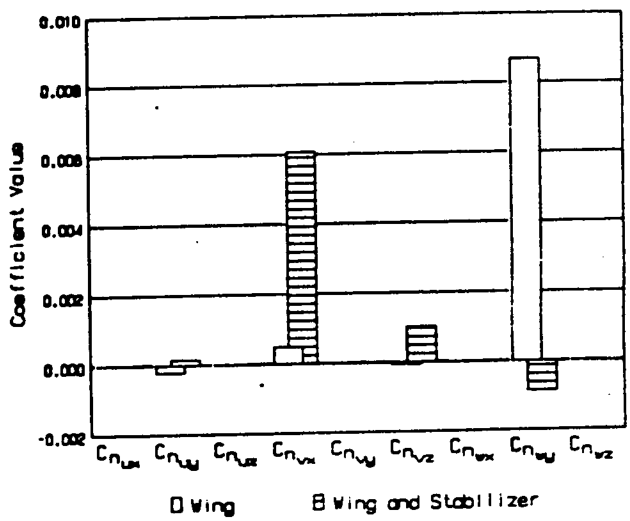












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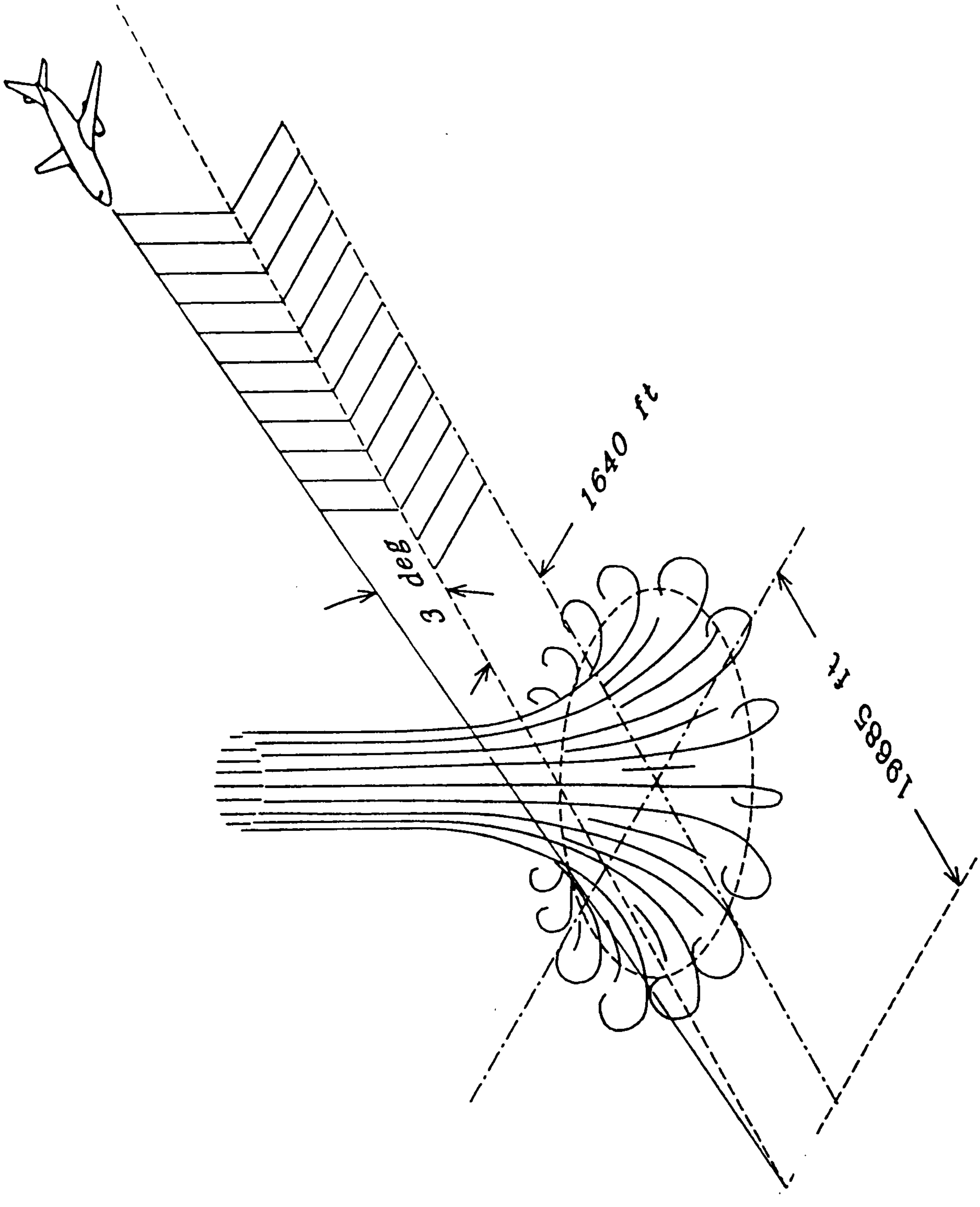
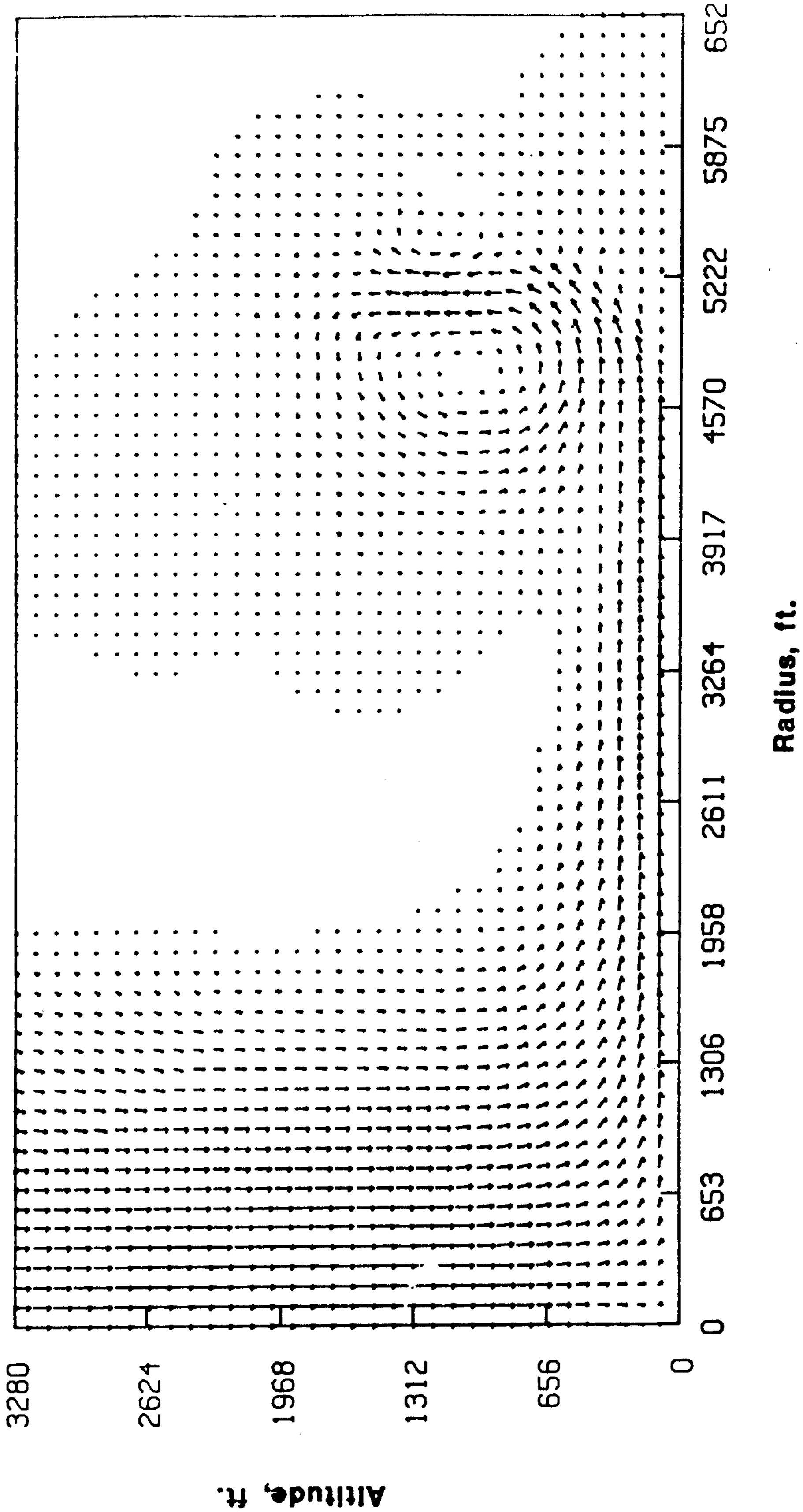
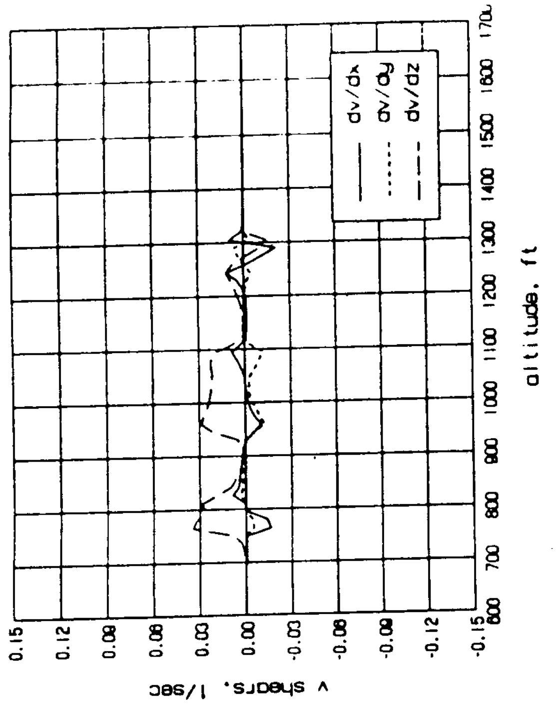
Sensitivity Study Results

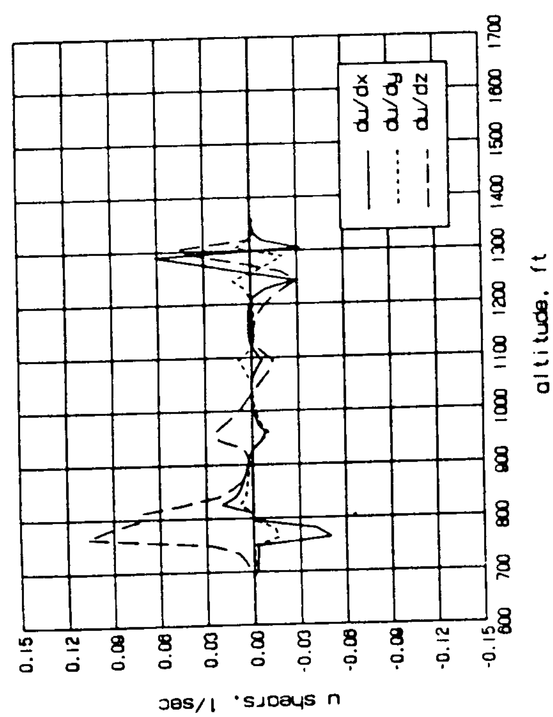
Wing and Stabilizer

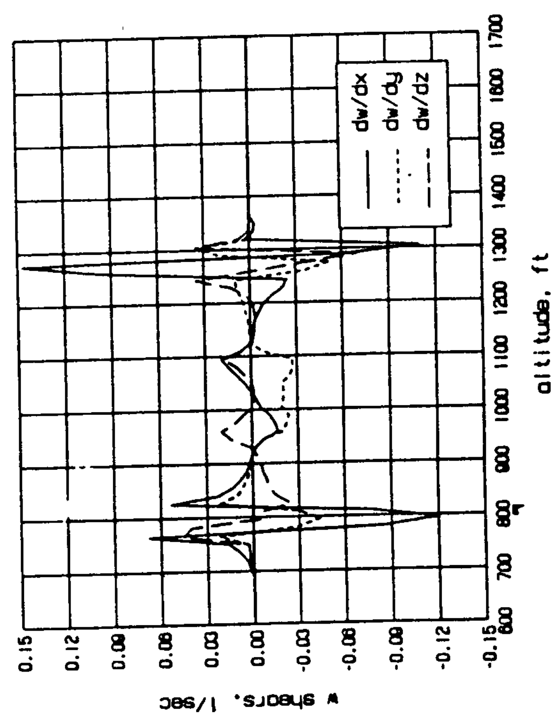
- Addition of stabilizer increased the magnitude of the shear coefficient in nearly every case
- Primarily a longitudinal effect
- Horizontal and vertical displacement of stabilizer led to large increases in x and z shear coefficients


1640 ft
3 deg
19685 ft


Altitude, ft.
3280
2624
1968
1312
656
0
Radius, ft.
0
653
1306
1958
2611
3264
3917
4570
5222
5875
6528







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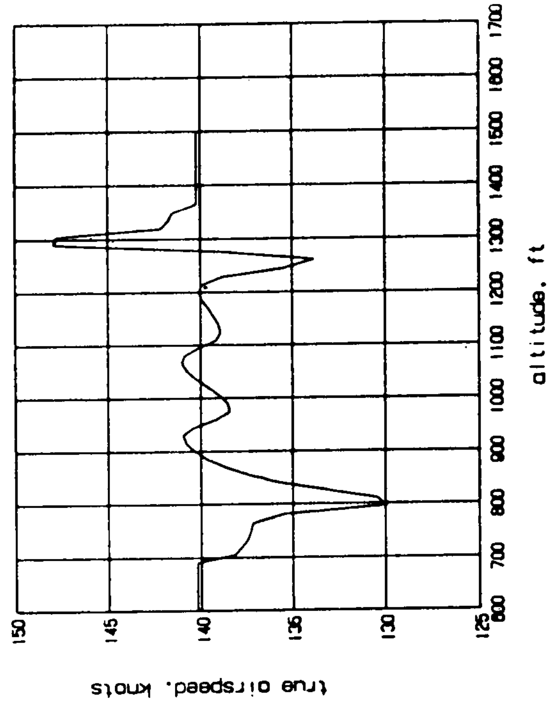
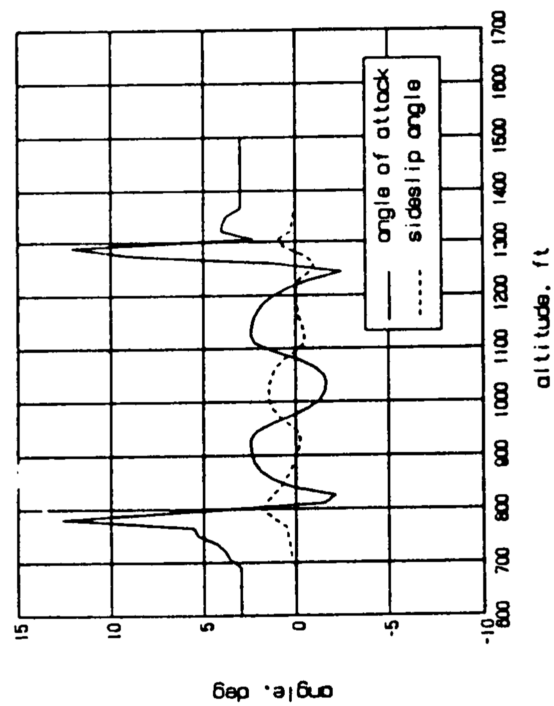
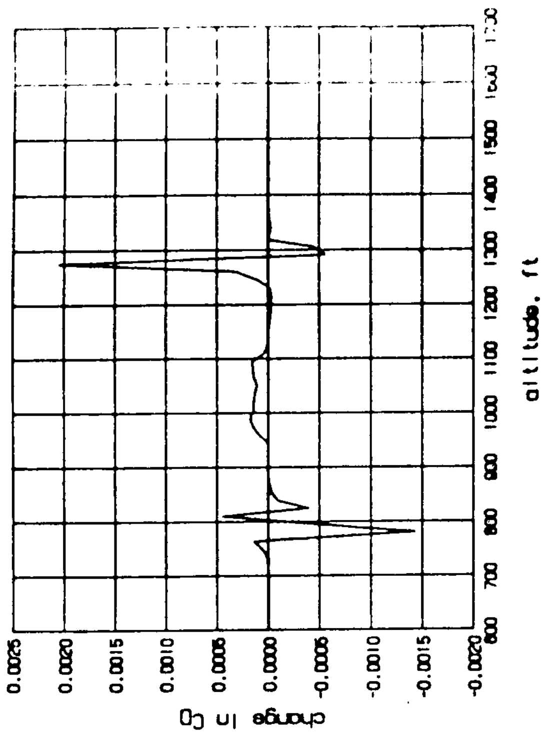
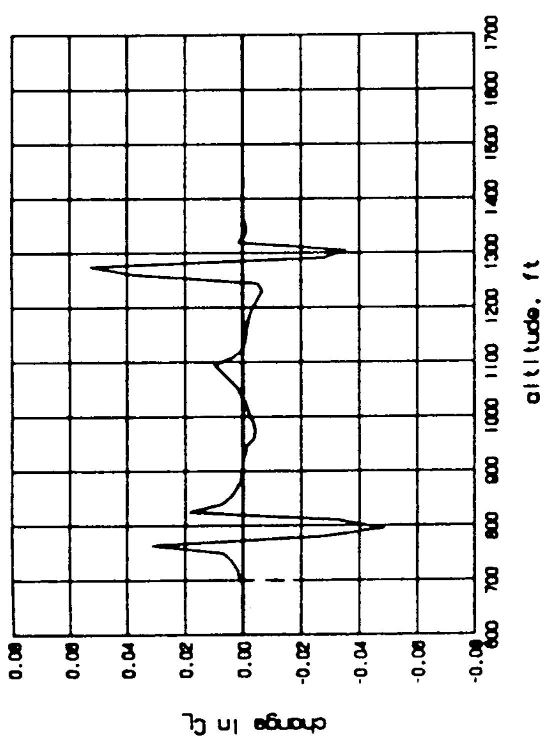
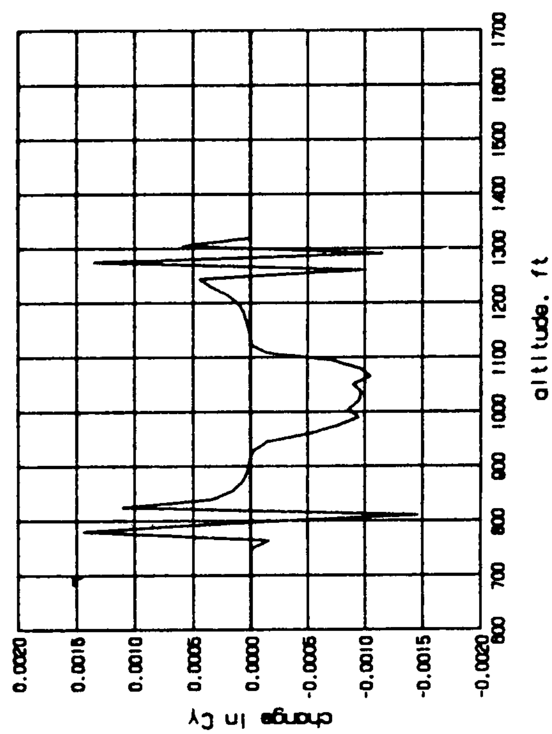

true airspeed, knots
altitude, ft
150
145
140
135
130
125
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700


angle, deg
altitude, ft
angle of attack
sideslip angle
15
10
5
0
-5
-10
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700







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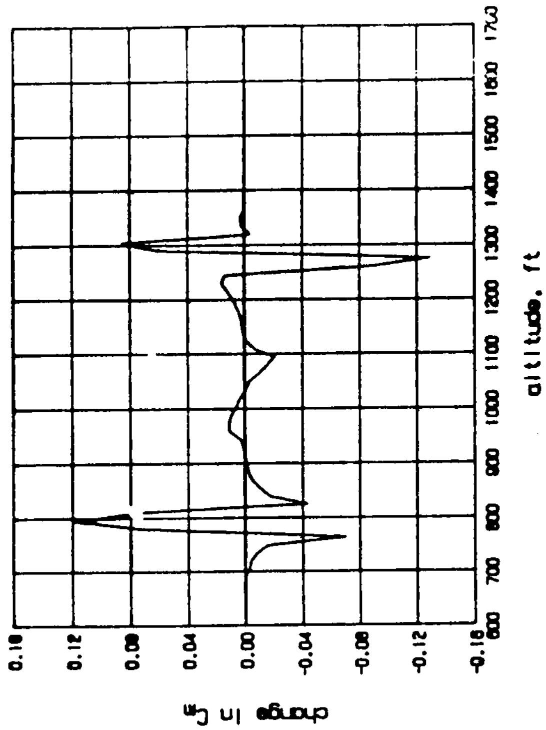
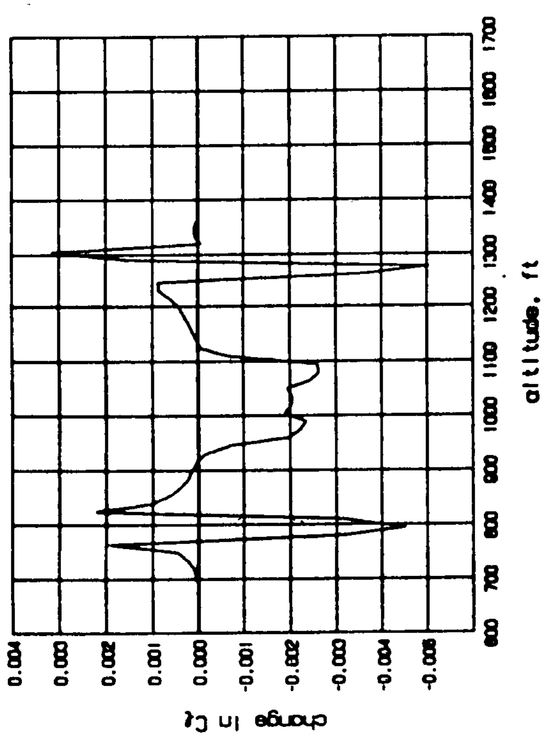
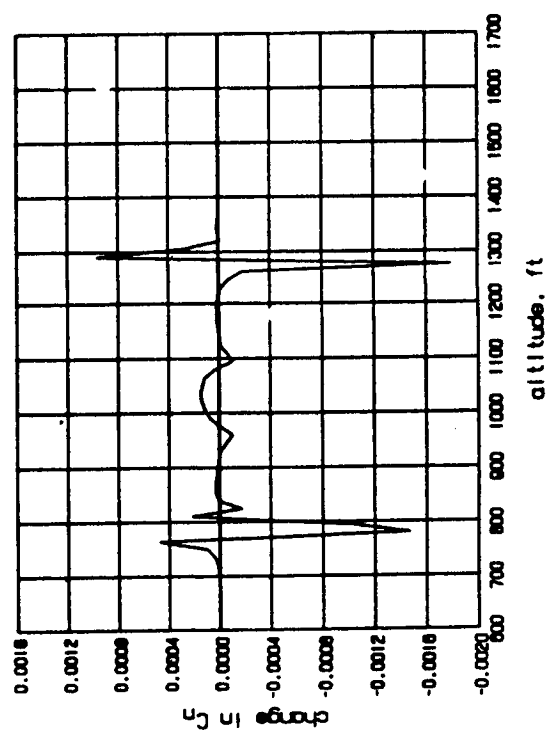
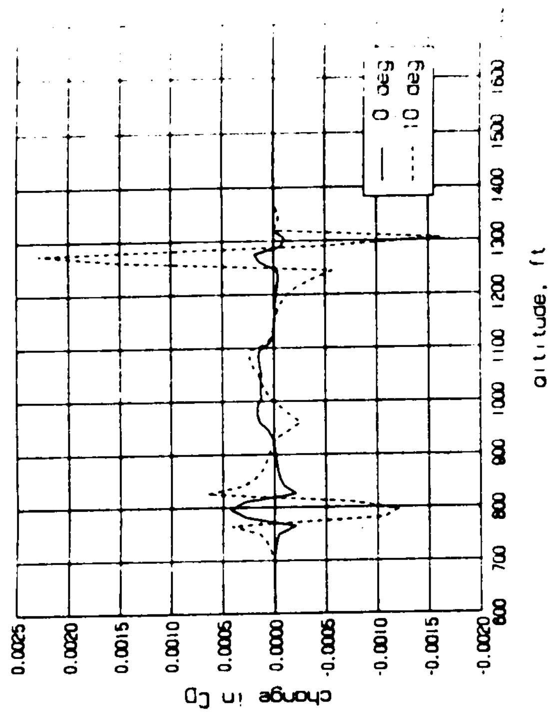
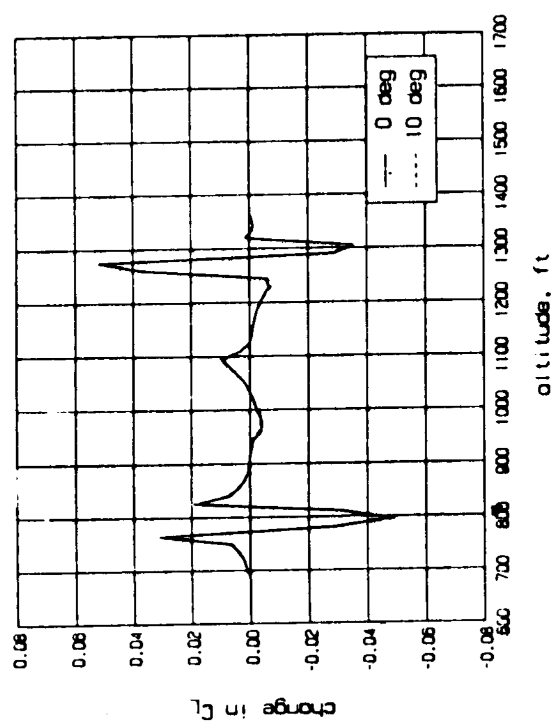
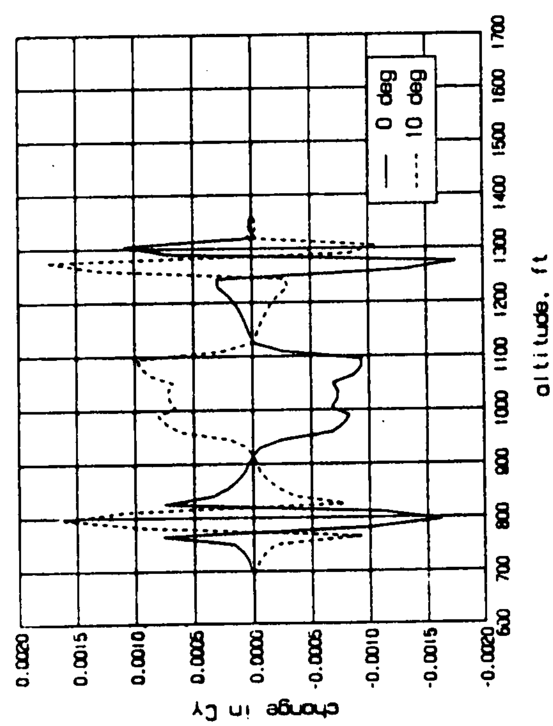

change in Cm
altitude, ft


change in Cℓ
altitude, ft


change in Cn
altitude, ft







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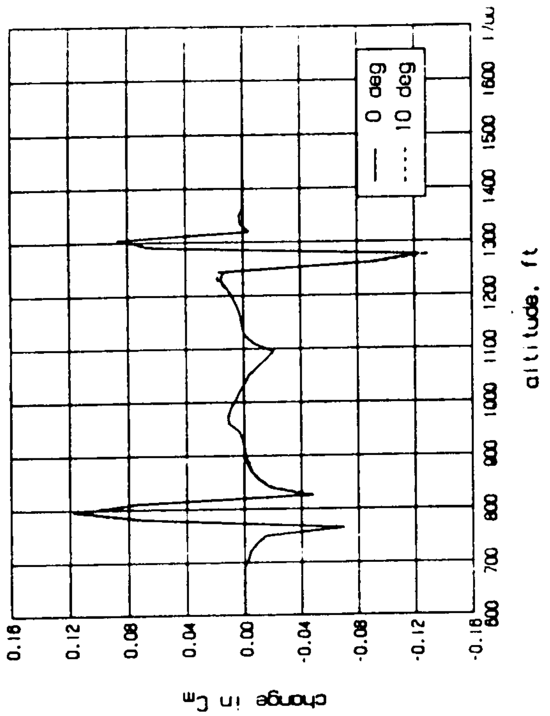
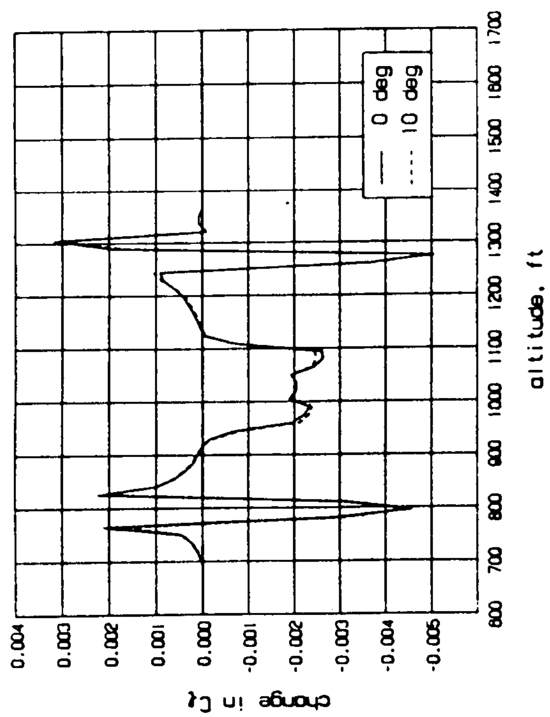
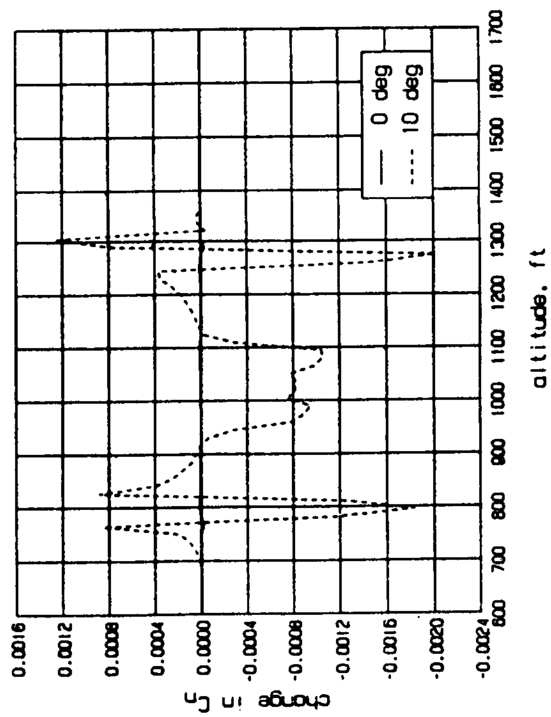
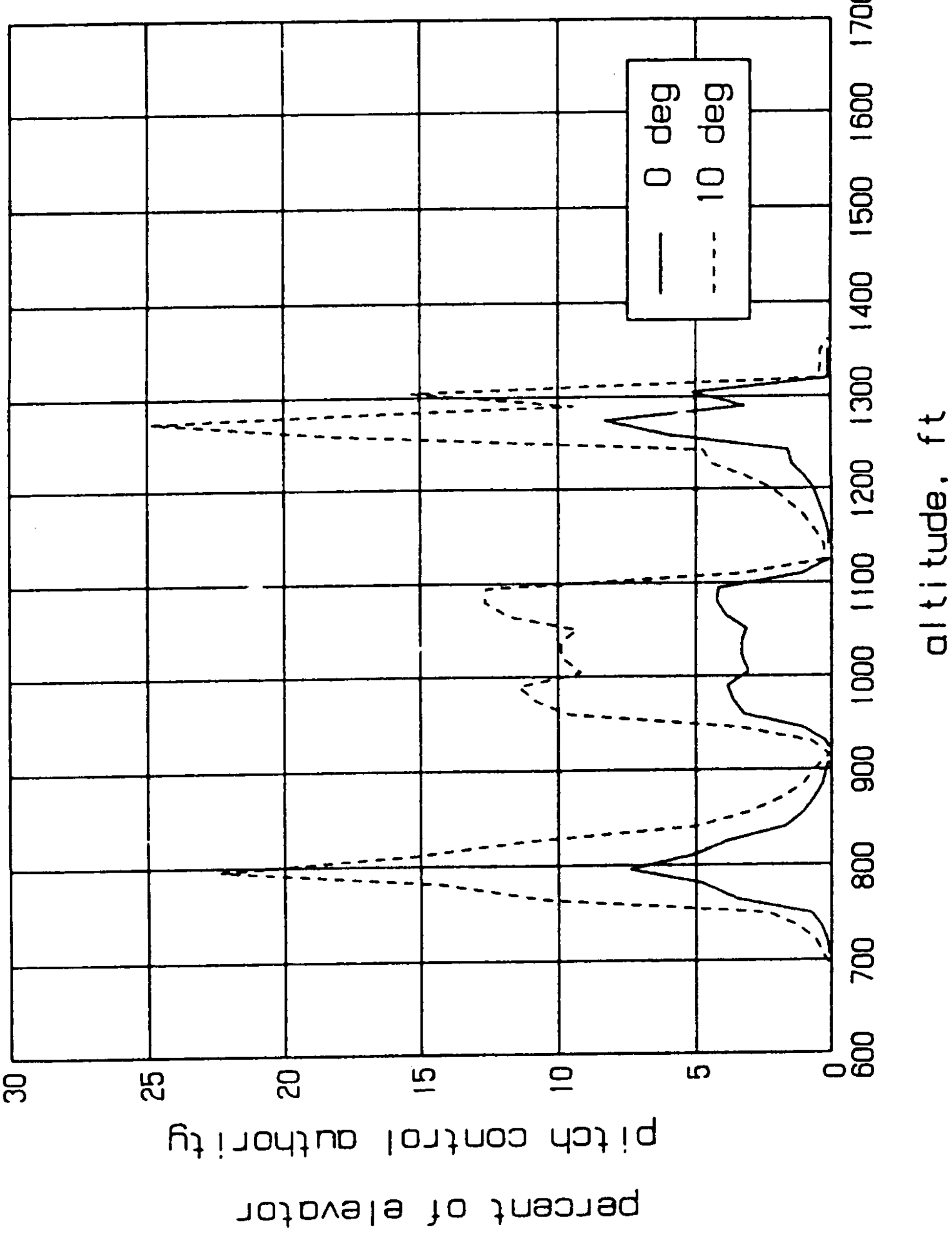
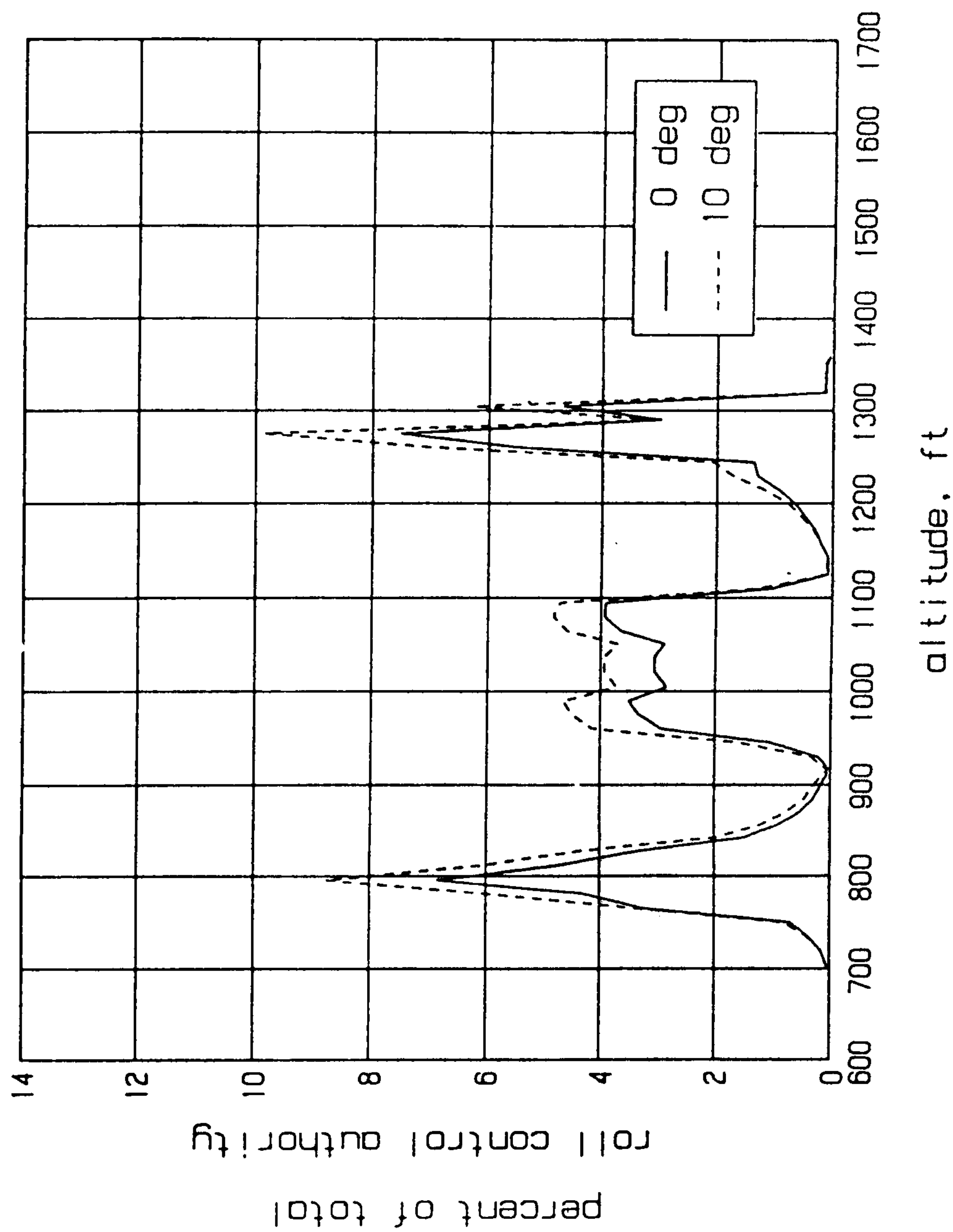

change in C_m
altitude, ft
0 deg
10 deg
0.16
0.12
0.08
0.04
0.00
-0.04
-0.08
-0.12
-0.16
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700


change in C_ℓ
altitude, ft
0 deg
10 deg
0.004
0.003
0.002
0.001
0.000
-0.001
-0.002
-0.003
-0.004
-0.005
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700


change in C_n
altitude, ft
0 deg
10 deg
0.0016
0.0012
0.0008
0.0004
0.0000
-0.0004
-0.0008
-0.0012
-0.0016
-0.0020
-0.0024
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700



0 deg
10 deg
altitude, ft
pitch control authority
percent of elevator
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
0
5
10
15
20
25
30


percent of total
roll control authority
0
2
4
6
8
10
12
14
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
altitude, ft
0 deg
10 deg

Outline

- ☑ Introduction
- ☑ Modification of Vortex-Lattice Algorithm
  - Spatially Varying Wind Field
  - Boundary Condition
  - Force and Moment Equations
- ☑ Program Checkout and Validation
- ☑ Shear Coefficient Development
- ☑ Sensitivity Studies
  - Vortex-Lattice Distribution
  - Planform Geometry
  - Wing and Stabilizer Combination
- ☑ Concluding Remarks

Concluding Remarks

Study Limitations

- Limited to small angle of attack range and thin airfoil approximation
- Effect of sideslip was not investigated
- Fuselage and vertical surface effects were not acconuted for

Concluding Remarks

Pertinent Results of Study

- A method of characterizing the aerodynamic effect of wind shear in the form of wind shear aerodynamic coefficients was formulated
- A method of modifying a vortex-lattice algorithm to compute the aerodynamic effect of wind shear was demonstrated
- An example of the magnitude of the wind shear aerodynamic effect was computed for a conventional wing and stabilizer configuration on a fixed flight path through a microburst

Concluding Remarks

Recommendations for Future Research

- Adaptation of more sophisticated aerodynamic codes to compute wind shear effect on complete configuration
- Simulation studies of pilots ability to manage the flight path witn the wind shear induced aerodynamic effects
- Wind tunnel studies to confirm analytical results and explore high angle of attack effects

QUESTIONS AND ANSWERS

RICK PAGE (FAA Technical Center) - Do you intend to do any research work into asymmetrical microbursts and also multiple glidepaths?

DAN VICROY (NASA LaRC) - We used a symmetrical microburst in this case but flew off to the side of it about 1500 ft. so that we would get asymmetrical effects. The shears are transformed into the body axes yielding asymmetrical shear gradients as we penetrated the microburst. So, we essentially did take into account that effect. Certainly this is just one example. I plan to look at more complex aerodynamic codes to compute the shear coefficients of complete airplane configurations. Another study that could be done is to do more of a statistical analysis of what kind of changes you are going to see with a variety of different kinds of microbursts. I don't plan to do that myself, but that work certainly could be done.