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A Study Of Roll Attractor And Wing Rock of Delta Wings at High Angles Of Attack

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Wing Rock

• What is Wing Rock?

Wing rock is a high angle of attack dynamic phenomenon of limit cycle motion predominantly in roll. One of the earliest observation of wing rock was made by Mckinney and Drake (NACA RM No. L7k07 (1948)) in free flight model tests. The wing rock is one of the limitations to combat effectiveness of the fighter aircrafts. Interest in wing rock has picked up considerably following the study of Nguyen et.al (AIAA Paper No.81-1883 (1981)).

• Causes of Wing Rock

- Nonlinearities in static rolling and yawing moments at high alpha.
- Static hysterisis of rolling moment with roll/sideslip angles.
- Dependence of roll damping on roll/sideslip angle such that negative damping occurs at small angles and positive damping at high angles.
- Nonlinear variation in roll damping with roll rate.

Roll Attractor

- What is Roll Attractor?

The steady state or equillibrium trim angle (ϕ_{trim}) attained by the free-to-roll model, held at some angle of attack, and released from rest at a given initial roll (bank) angle (ϕ_0).

- Multiple Roll Attractors.

Model attains different trim angles (ϕ_{trim}) depending on initial roll angle (ϕ_0)

Previous Studies of Roll Attractor Phenomenon

- Hanff and Ericson, Paper 31, AGARD CP-494, 1990
- Jenkins, Myatt and Hanff (AIAA 93-0621)

- Model Tested: 65deg Delta Wing.

$\alpha \leq 20deg,\ \phi_{trim} = 0$
$\alpha = 20deg,\ \phi_{trim} = \pm 1.5deg$
$\alpha = 30deg,\ \phi_{trim} = 0, \pm 21.0deg$
$\alpha = 35deg,\ \phi_{trim} = \pm 11.0deg$
$\alpha \geq 40deg,\ \phi_{trim} = 0$

Hanff and Ericson (1990)

$\alpha = 30deg$

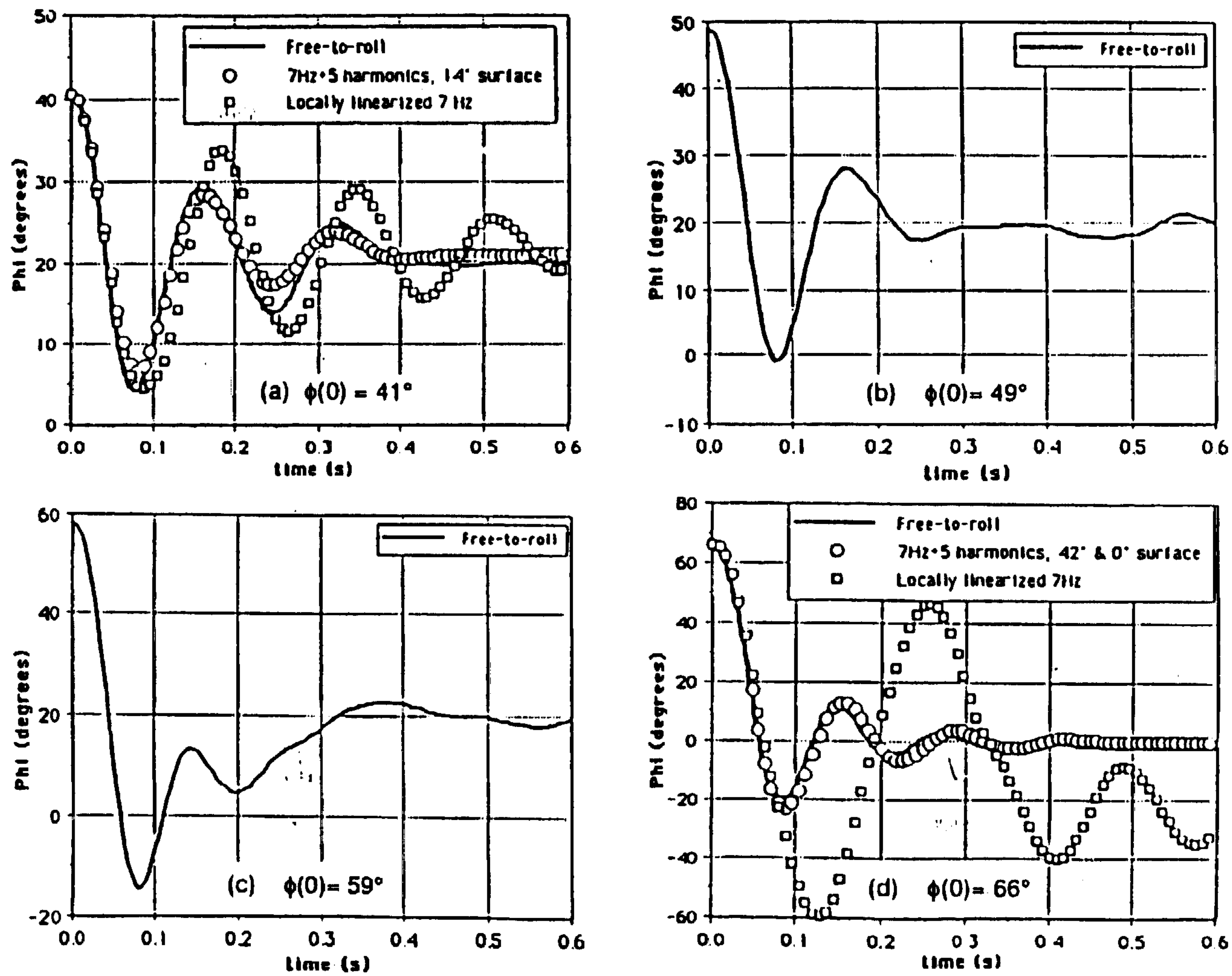


Fig.5 Free-to-roll motion histories.

Outline Of Presentation

- Test Facility and Experimental Work.
- Mathematical Modelling Of Roll Attractor Phenomenon.
- Analysis And Comparison Of Predictions With Experimental Data.
- Concluding Remarks.

Experimental Work

• Test Models:

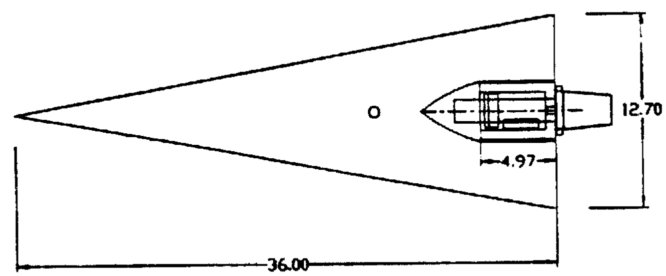
(1) 80 Deg. Delta Wing (Wing Rock Studies and Effect of Fences on Wing Rock)
(2) 60 Deg. Delta Wing (Roll Attractor Studies)
(3) Aircraft Model With 60 Deg. Delta Wing (Wing Rock And Roll Attractor Studies)

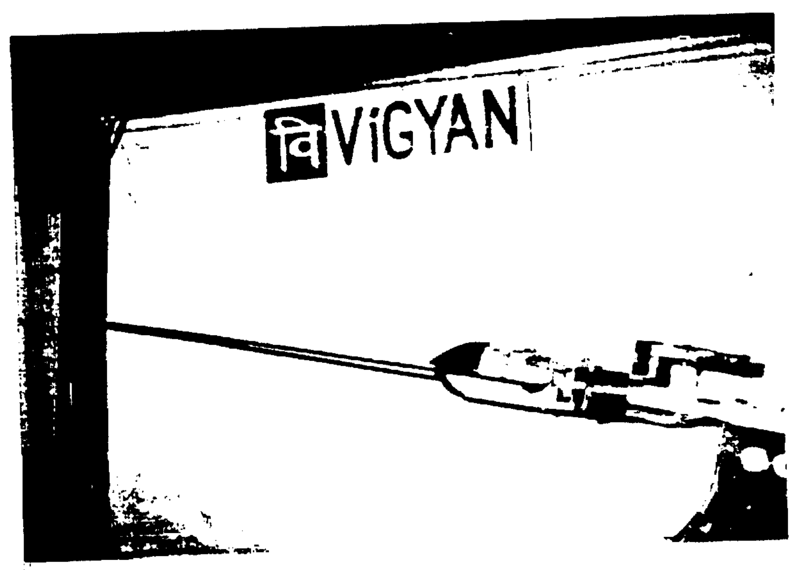
• Test Facility:
Vigyan's Low Speed Wind Tunnel, 3ft x 4ft, Maximum speed = 175 ft/sec

• Sensors:
Rate Gyro for Roll Rate and Accelerometer for Roll Angle

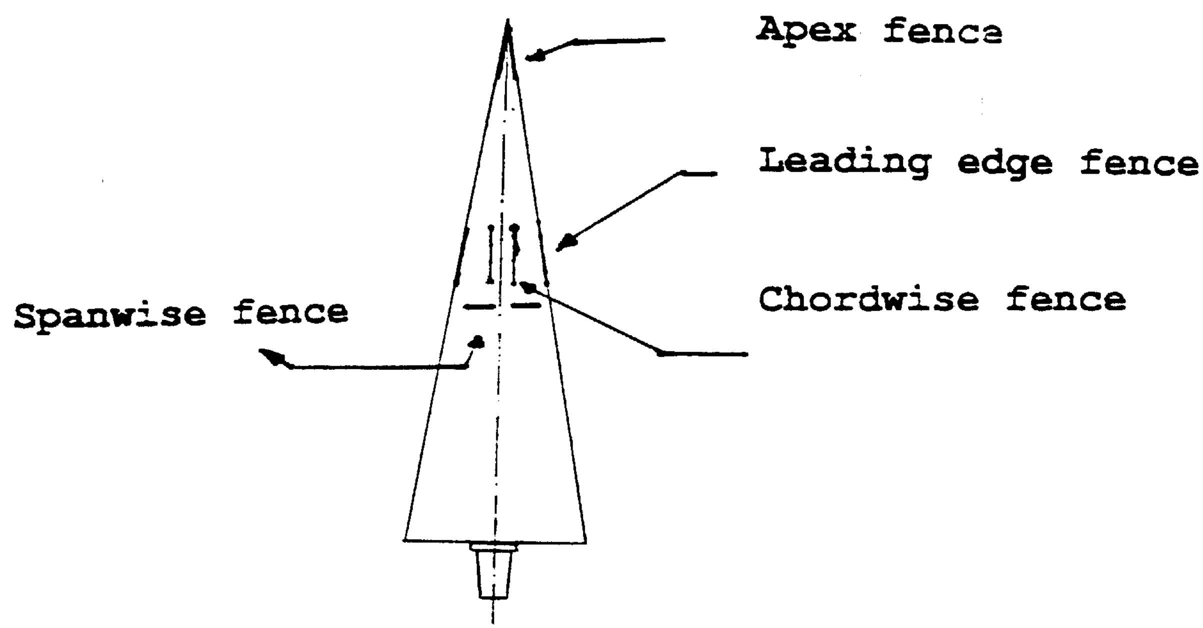
80 Deg Delta Wing

Model Geometry
View of The Model Mounted in Wind Tunnel



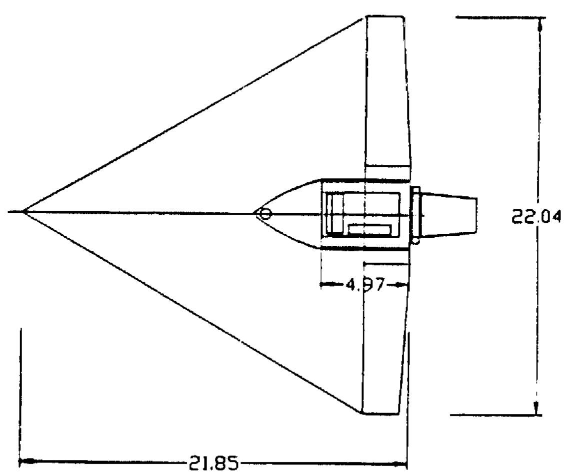


Geometry of Various Fences Employed For 80 Deg Delta Wing



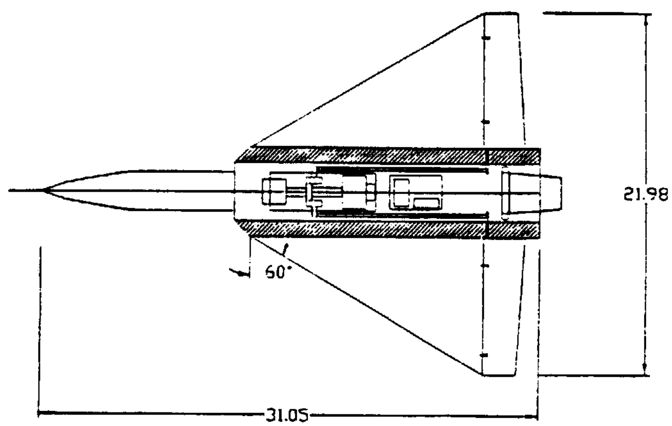
60 Deg Delta Wing Model

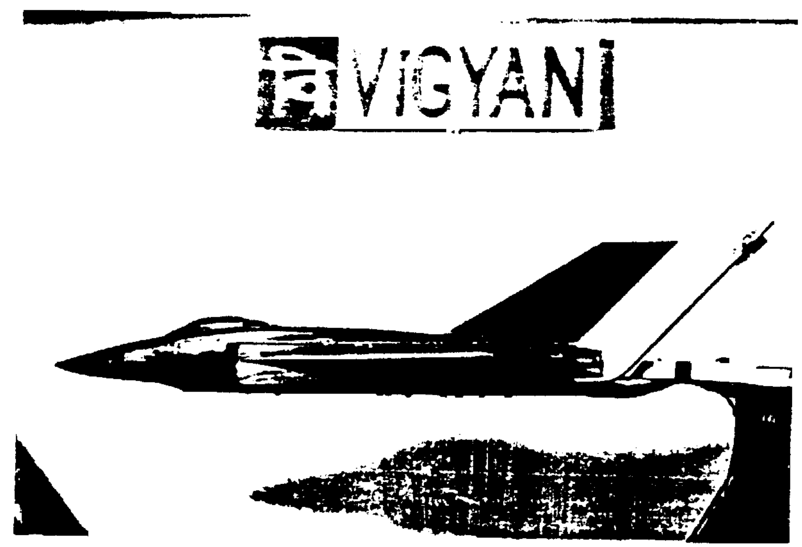
Model Geometry
View of The Model Mounted in Wind Tunnel



Aircraft Model With 60 Deg Delta Wing

Model Geometry
View of The Model Mounted in Wind Tunnel

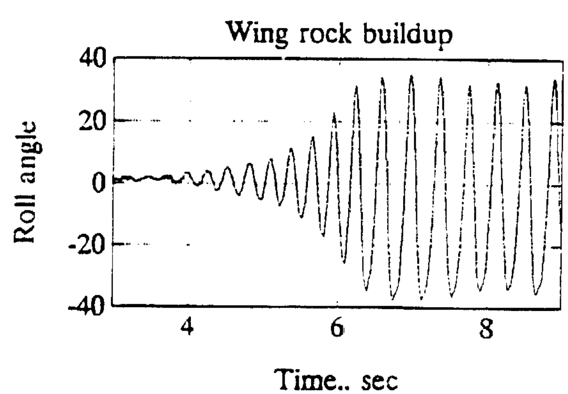


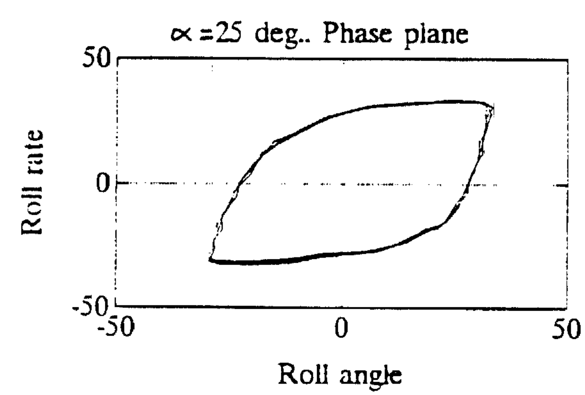


Wing Rock Buildup of 80 Deg Delta Wing

$\alpha = 25$ Deg

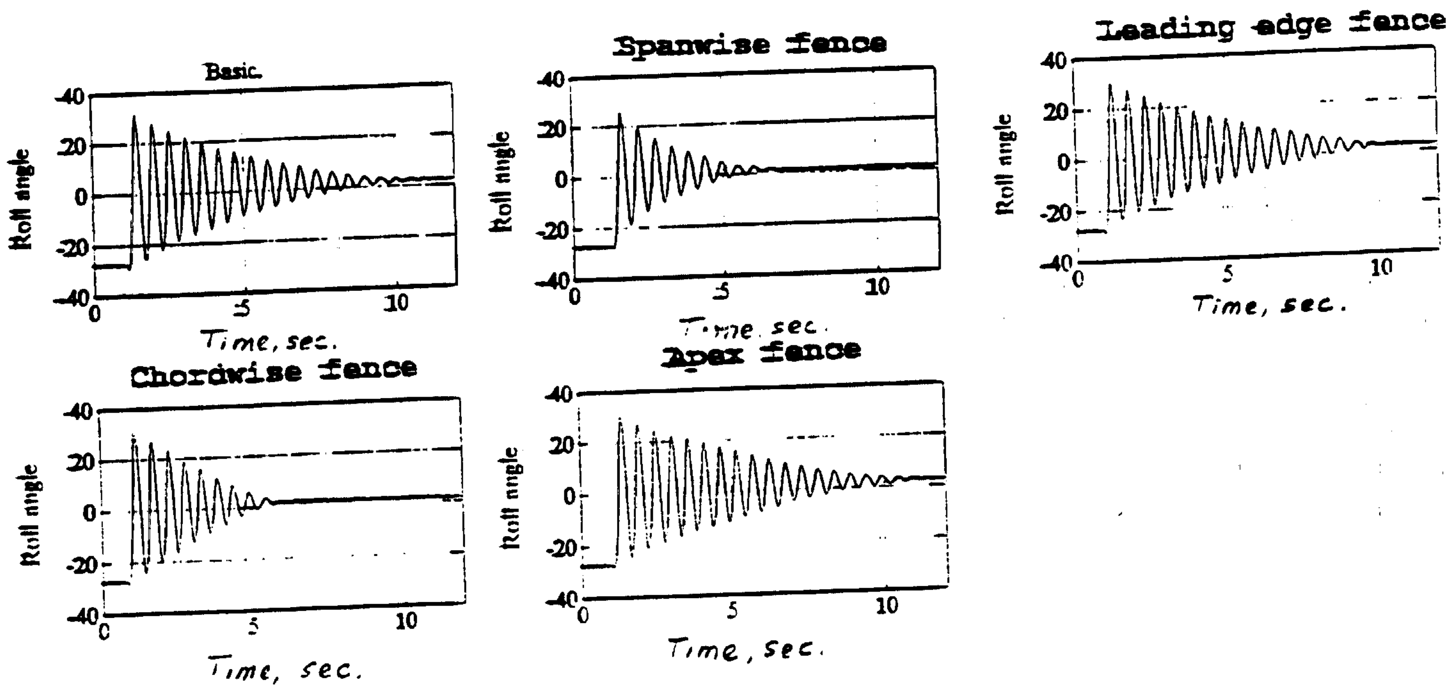
We observed that the value of α for the onset of wing rock was around 25 Deg, which is consistent with previous studies.





Effect of Various Fences on Wing Rock of 80 Deg Delta Wing

For $\alpha \leq 25$ Deg, we observed that the fences donot have any major effect on the roll damping. Typical results obtained at $\alpha = 20 Deg$ are presented below.

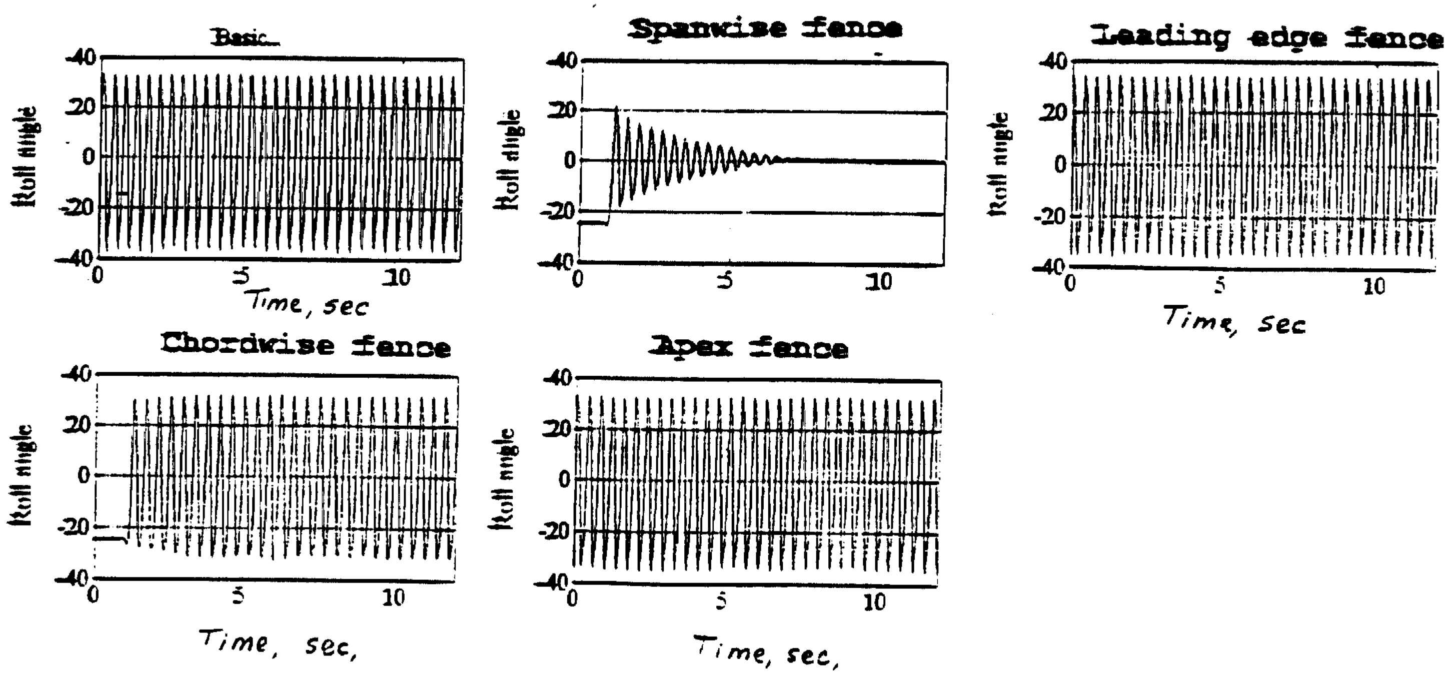


Effect of Various Fences on Wing Rock of 80 Deg Delta Wing

(Continued...)

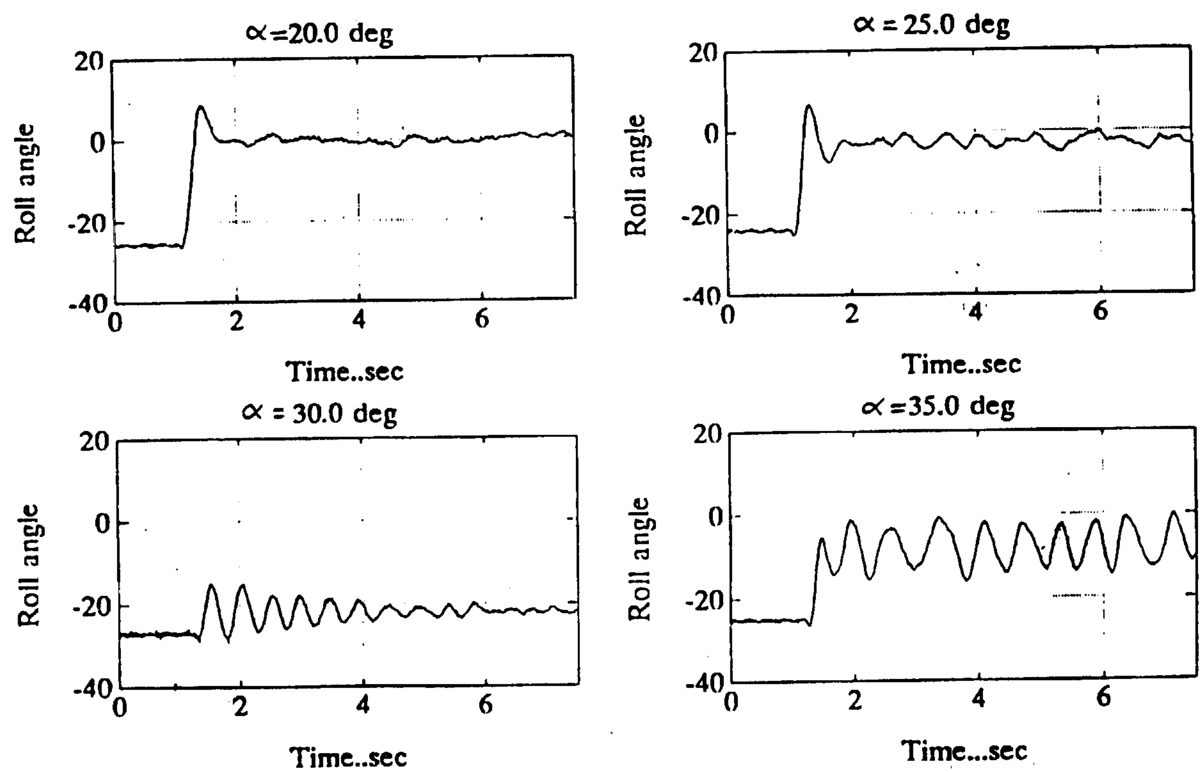
Spanwise fences are found to be effective in suppressing the wing rock motion.

$$\alpha = 30deg$$



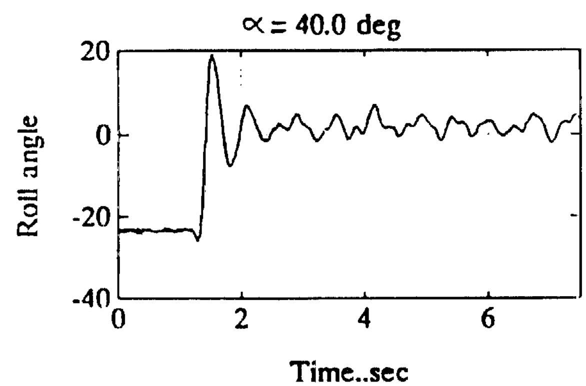
Present Roll Attractor Experimental Results

60 deg Delta Wing Model



Present Roll Attractor Experimental Results (Continued..)

60 deg Delta Wing



Summary of Roll Trim Angles

$\alpha \leq 20deg,\ \phi(trim) = 0$

$\alpha = 25deg,\ \phi(trim) = \pm 3.5deg$

$\alpha = 30deg,\ \phi(trim) = 0, \pm 21.0deg$

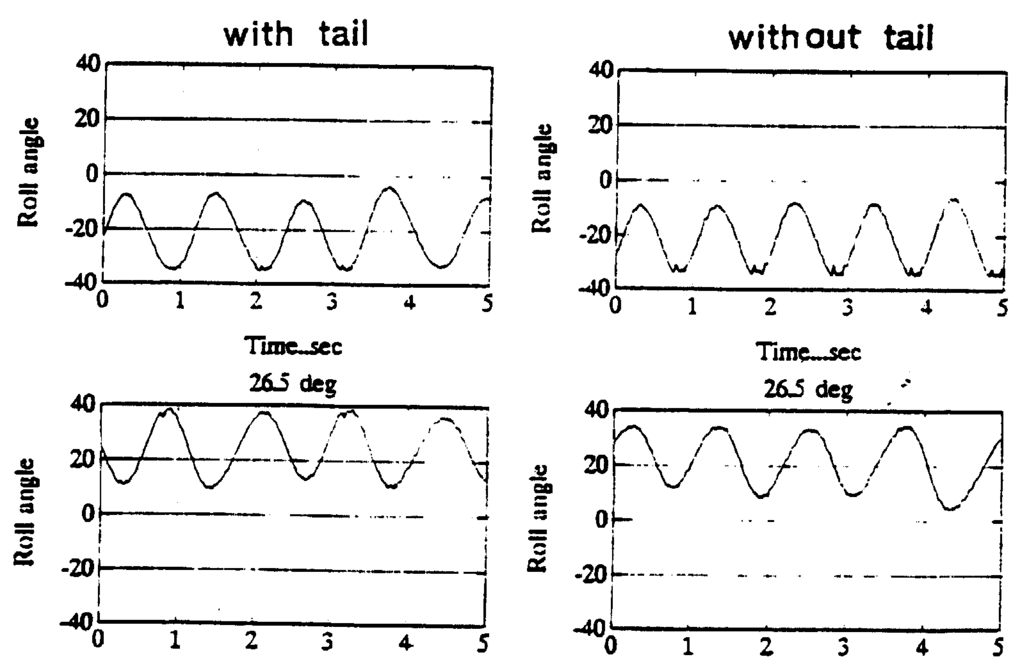
$\alpha = 35deg,\ \phi(trim) = \pm 11.0deg$

$\alpha \geq 40deg,\ \phi(trim) = 0$

Experimental Results of Aircraft Model With 60 Deg Delta Wing

This generic aircraft model with 60 deg delta wing exhibits "one sided" wing rock. It may be noted that the 60 deg delta wing alone does not exhibit wing rock but has non zero roll trim angles as noted earlier. Hence it is evident that the forebody must be responsible for creating wing rock since tail apparently has no effect.

α=26.5 deg



Simulation Of Model Motion In Roll Attractor Studies

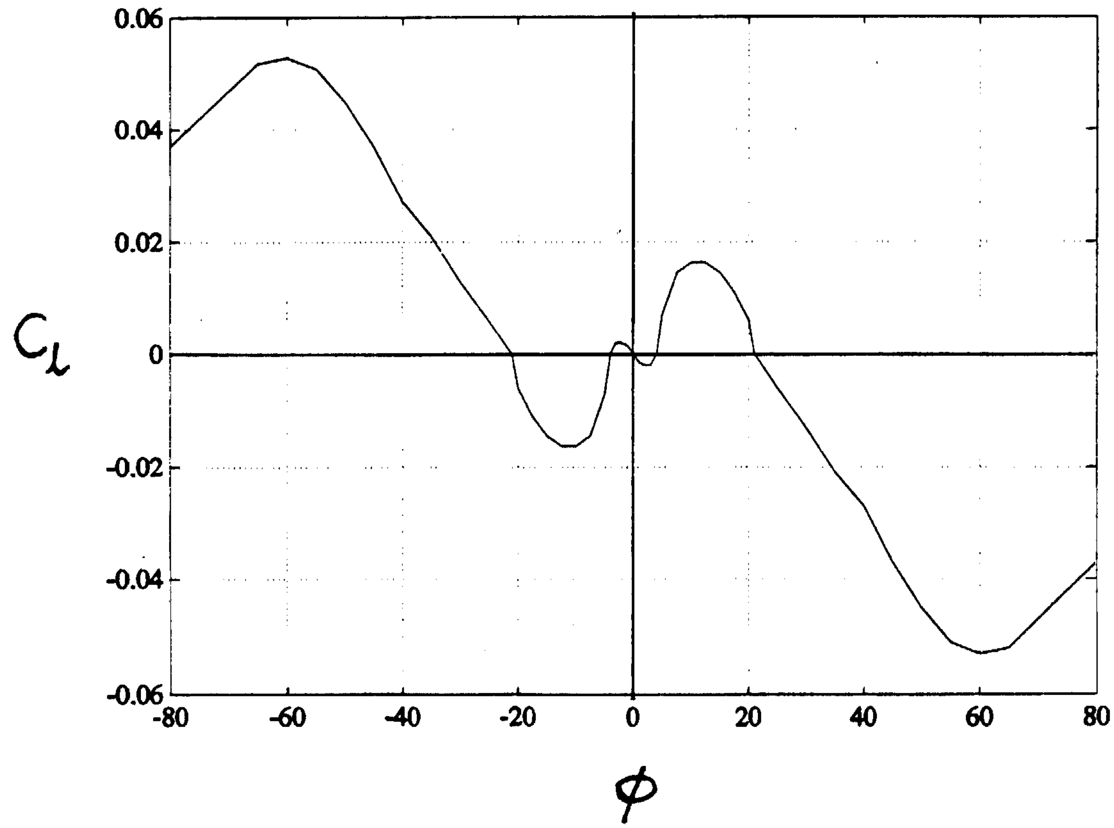
- Single DOF Free-To-Roll Motion

$$
\begin{aligned}
I_x\ddot{\phi} &= L_{\dot{\phi}}\dot{\phi} + L(\phi) \\
\ddot{\phi} &= \frac{L_{\dot{\phi}}\dot{\phi}}{I_x} + \frac{L(\phi)}{I_x} \\
\ddot{\phi} &= C_{lp}\dot{\phi} + C_l(\phi)
\end{aligned}
$$

- Method of Solution:

(i) Use $C_l(\phi)$ from experimental data of Hanff (1993).
(ii) Use C^2 cubic splines to interpolate data
(iii) Assume C_{lp} constant
(iv) Do Numerical integration using Matlab

Experimental Static Rolling Moment Coefficient, Hanff et.al (1993)



Solution Structure

- Represent the plant model in state-space form

$$\dot{x} = F(x)$$

where $x \varepsilon R^2$, $x_1 = \phi$ and $x_2 = \dot{\phi}$.

$$F(x) = \begin{bmatrix} x_2 \\ -C_{lp}x_2 + C_l(x_1) \end{bmatrix}$$

- Attractor:

The set of all trajectories starting from different initial conditions but ending in the same subspace of the given state-space as $t \rightarrow \infty$

- Fixed points/Equillibrium solutions can form elements of attractor set.

Fixed Points/Equillibrium Solutions

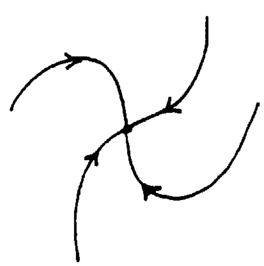
For Fixed Points, $F(x) = 0$.
i.e, $x_2 = 0$ and $C_l(x_1) = 0$
From Experimental C_l vs $\phi(x_1)$ graph,
$x_{10} = 0, \pm 4deg, \pm 21deg$. (3 Attractors)

- Stability Of Fixed Points

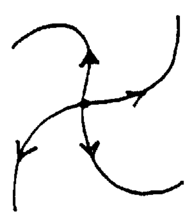
Let $x(t) = x_0 + y(t)$. Assume $F(x) \varepsilon C^2$.
Ignoring second and higher order terms, we get,
$\dot{y} = Ay$
A is the Jacobian matrix of first partials of $F(x)$.

Stability of Fixed Points

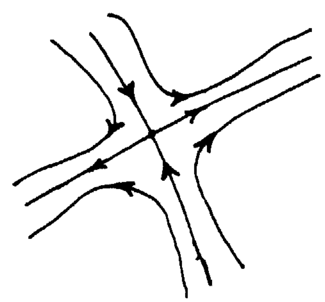
- Stable Node - If Eigen Values Of A are real and negative.
- Unstable Node - If Eigen Values Of A are real and positive.
- Saddle Point - If Eigen Values Of A are real, some and positive and others negative.



Stable Node



Unstable Node



Saddle Point

Fixed Points

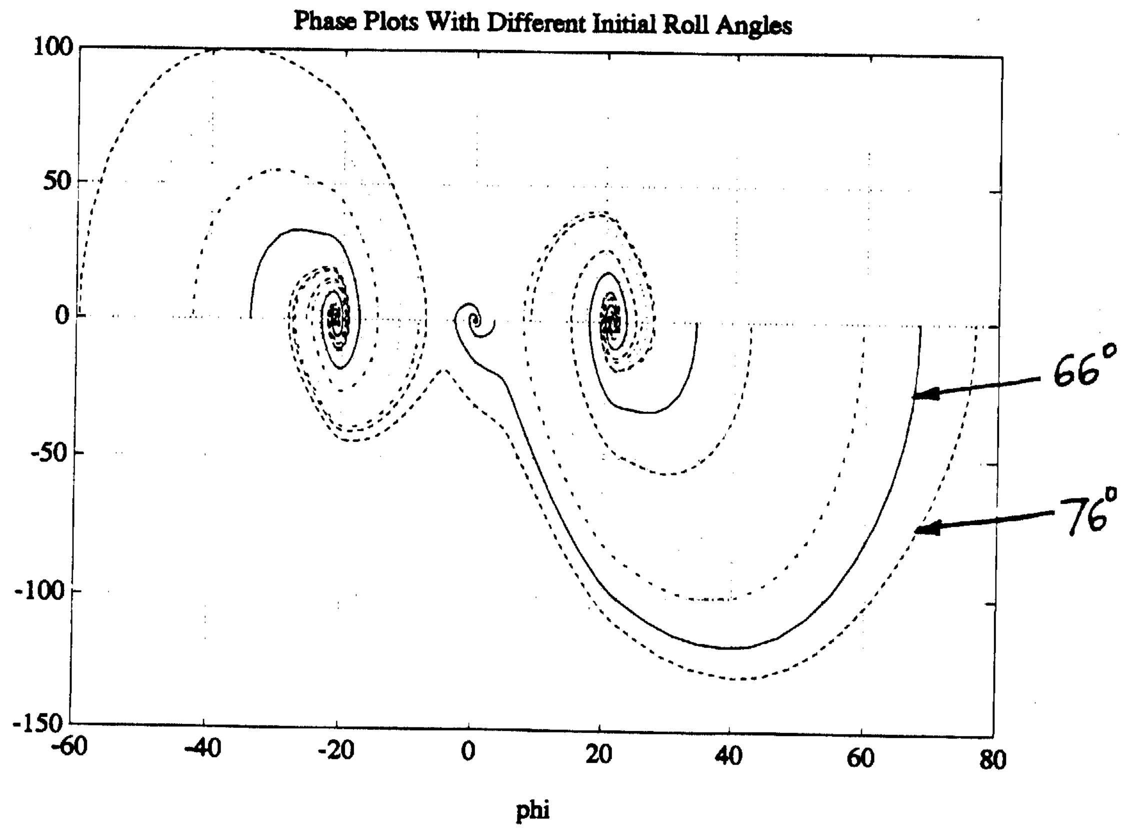
We have three fixed points. The associated eigen values and the nature of the fixed point (node) are as follows,

(a) $x_{10} = 0, x_{20} = 0, \lambda_1 = -0.009166, \lambda_2 = -0.1908338$; (Stable Node)

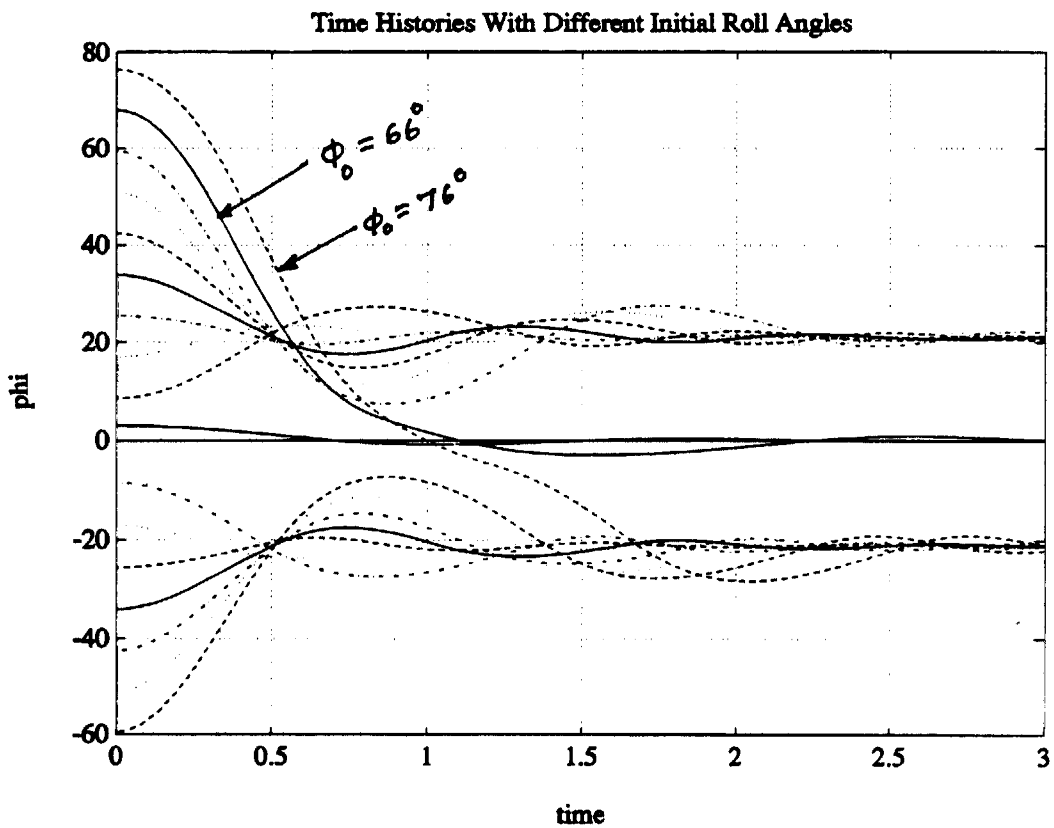
(b) $x_{10} = \pm 4, x_{20} = 0, \lambda_1 = 0.021854, \lambda_2 = -0.221854$; (Saddle Point)

(c) $x_{10} = \pm 21, x_{20} = 0, \lambda_1 = -0.03558369, \lambda_2 = -0.1645416$; (Stable Node)

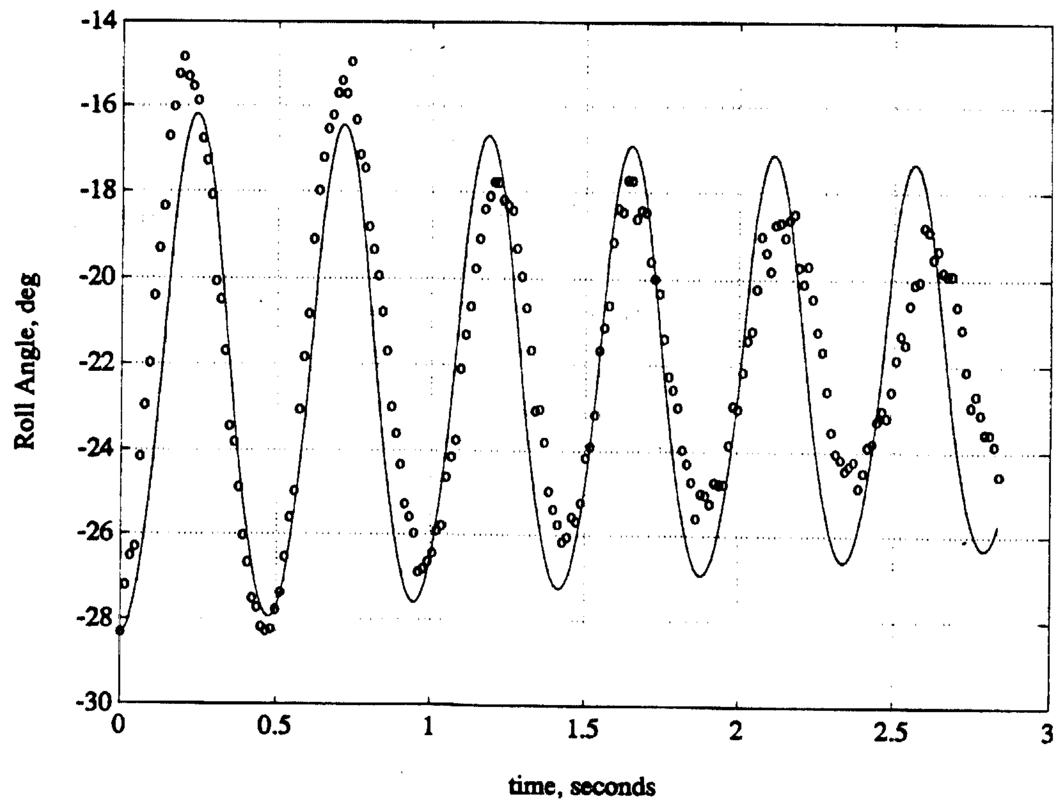
Results Of Simulation
(Phase Plane Trajectories)



Results Of Simulation (Time Histories)

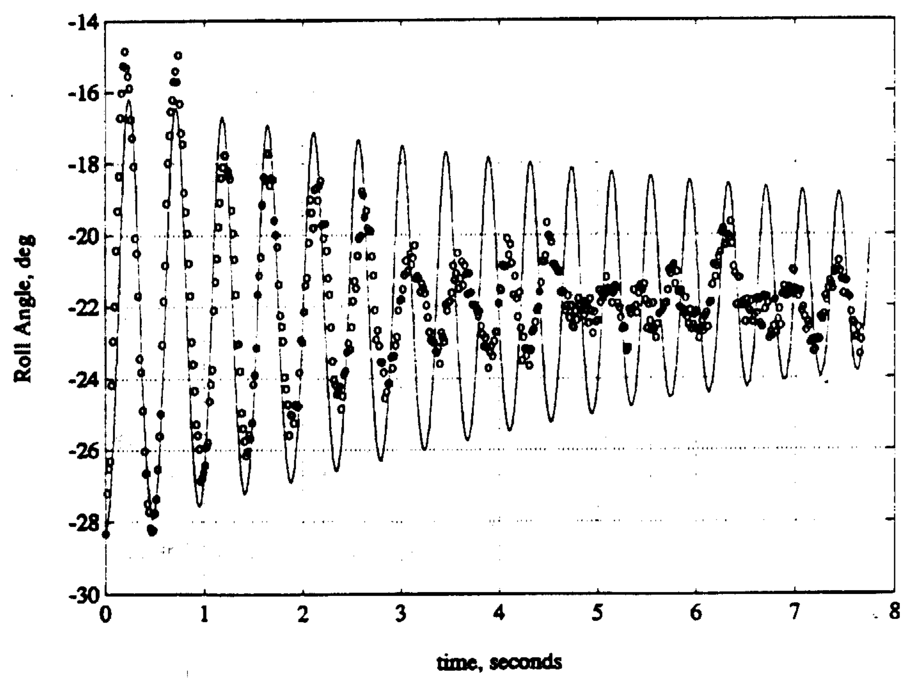


Predicted And Measured Time Histories (First 3 Seconds)



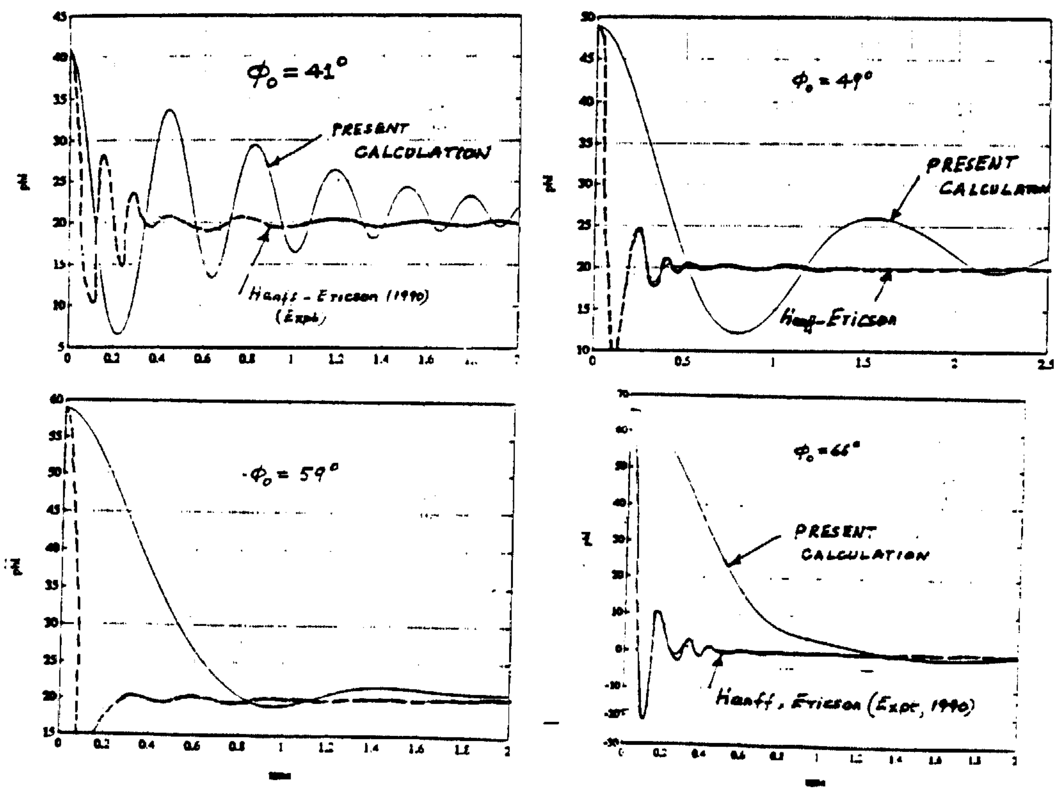
Comparison Of Predicted And Measured Time Histories (Present Experiments)

It may be noted that the present simulation based on assuming constant roll damping and nonlinear experimental data on rolling moment coefficient predicts the multiple roll trim angles of 60 deg delta wing correctly. The difference in the transients especially at lower roll angles could be due to nonlinearity in roll damping which is ignored here.



Comparison Of Predicted And Measured Time Histories (Hanff and Ericson)

From this figure we observe that the present simulation predicts all the roll trim angles of Hanff and Ericson. As mentioned previously, the locally linearized simulation of Hanff and Ericson fails to predict the roll trim angle for $\phi(0) = 66deg$.



Concluding Remarks

- Experimental Test Facility For Dynamic Semi-Free Flying Models Developed.
- Single DOF, Free-To-Roll Tests Conducted on 80 and 60 deg Delta Wings and Aircraft Model.
- Wing Rock Observed For 80 deg Delta Wings.
- Wing Rock Not Observed For 60 deg Delta Wing, Multiple Roll Attractor Observed.
- Aircraft Model (60 deg Delta Wing) Exhibits One Sided Wing Rock.
- The Simple Math Model Successfully Predicts Multiple Roll Attractors Recorded by Hanff and Ericson. However, The Transients Donot Match.
- Hanff and Ericson Failed To Predict The Roll Attractor For $\phi_0 = 66deg$.
- Predicted Transient Is In Better Agreement With Present Experimental Data.

Further Work

- Conduct Free-To-Roll Roll Attractor Tests For 60 deg Delta Wing For All the Initial Values Of Hanff and Ericson.
- Consider Nonlinear Damping in Math Model.
- Use Parameter Identification Techniques For Better Matching Of Math Model And Experimental Data.