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

T. Niranjana, D.M. Rao and Bandu N. Pamadi
Vigyan Research Associates Inc.,

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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 hysteresis 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 equilibrium trim angle ($\phi_{trim}$) attained by the free-to-roll model, held at some angle of attack, and released from rest at a given initial roll (bank) angle ($\phi_0$).

• Multiple Roll Attractors.

Model attains different trim angles ($\phi_{trim}$) depending on initial roll angle ($\phi_0$)
Previous Studies of Roll Attractor
Phenomenon

- Jenkins, Myatt and Hanff (AIAA 93-0621)

- Model Tested: 65\text{deg} Delta Wing.

\[ \alpha \leq 20\text{deg}, \phi_{trim} = 0 \]
\[ \alpha = 20\text{deg}, \phi_{trim} = \pm 1.5\text{deg} \]
\[ \alpha = 30\text{deg}, \phi_{trim} = 0, \pm 21.0\text{deg} \]
\[ \alpha = 35\text{deg}, \phi_{trim} = \pm 11.0\text{deg} \]
\[ \alpha \geq 40\text{deg}, \phi_{trim} = 0 \]
Hanff and Ericson (1990)

$\alpha = 30^\circ$deg

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

Apex fence
Leading edge fence
Chordwise fence
Spanwise fence
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 $\alpha$ 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 do not 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.

\[ \alpha = 30 \text{deg} \]
Present Roll Attractor Experimental Results

60 deg Delta Wing Model

\[
\begin{align*}
\text{Roll angle} & \quad \alpha = 20.0 \text{ deg} \\
\text{Roll angle} & \quad \alpha = 25.0 \text{ deg} \\
\text{Roll angle} & \quad \alpha = 30.0 \text{ deg} \\
\text{Roll angle} & \quad \alpha = 35.0 \text{ deg}
\end{align*}
\]
Present Roll Attractor Experimental
Results (Continued..)
60 deg Delta Wing

Summary of Roll Trim Angles
\[ \alpha \leq 20\text{deg}, \phi(\text{trim}) = 0 \]
\[ \alpha = 25\text{deg}, \phi(\text{trim}) = \pm 3.5\text{deg} \]
\[ \alpha = 30\text{deg}, \phi(\text{trim}) = 0, \pm 21.0\text{deg} \]
\[ \alpha = 35\text{deg}, \phi(\text{trim}) = \pm 11.0\text{deg} \]
\[ \alpha \geq 40\text{deg}, \phi(\text{trim}) = 0 \]
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.

\[ \alpha = 26.5 \text{ deg} \]
Simulation Of Model Motion In Roll
Attractor Studies

- Single DOF Free-To-Roll Motion

\[ I_x \ddot{\phi} = L_x \dot{\phi} + L(\phi) \]
\[ \ddot{\phi} = \frac{L_x \dot{\phi}}{I_x} + \frac{L(\phi)}{I_x} \]
\[ \ddot{\phi} = C_{lp} \dot{\phi} + C_l(\phi) \]

- 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 \( x \in \mathbb{R}^2 \), \( x_1 = \phi \) and \( x_2 = \dot{\phi} \).

\[ F(x) = \begin{bmatrix} x_2 \\ -C_l p x_2 + C_l(x_1) \end{bmatrix} \]

- Attractor:
The set of all trajectories starting from different initial conditions but ending in the same subspace of the given state-space as \( t \to \infty \)
- Fixed points/Equilibrium solutions can form elements of attractor set.
Fixed Points/Equilibrium 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,
\( x_{10} = 0, \pm 4\, \text{deg}, \pm 21\, \text{deg} \). (3 Attractors)

- Stability Of Fixed Points
Let \( x(t) = x_0 + y(t) \). Assume \( F(x) \in C^2 \).
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 positive.
- Unstable Node - If Eigen Values Of \( A \) are real and negative.
- Saddle Point - If Eigen Values Of \( A \) are real, some and positive and others negative.
Fixed Points

We have three fixed points. The associated eigenvalues and the nature of the fixed point (node) are as follows:

(a) \( x_{10} = 0, x_{20} = 0, \lambda_1 = -0.009166, \lambda_2 = -0.190838 \); (Stable Node)

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

(c) \( x_{10} = \pm 21, x_{20} = 0, \lambda_1 = -0.0358369, \lambda_2 = -0.1645416 \); (Stable Node)
Results Of Simulation
(Phase Plane Trajectories)

Phase Plots With Different Initial Roll Angles

66°
76°
Results Of Simulation (Time Histories)

Time Histories With Different Initial Roll Angles

\( \Phi_0 = 66^\circ \)
\( \Phi_0 = 76^\circ \)

phi

0 0.5 1 1.5 2 2.5 3

time
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 $\phi(0) = 66\text{deg}$.
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 $\phi_0 = 66\text{deg}$.
- 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.