Roll Attractor of Delta Wings At High Angles of Attack

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Abstract

The effects of sideslip and initial roll angles on the free-to-roll response of the 60 deg delta wing model at high angles of attack were investigated. Sideslip changed the location of multiple roll attractors as well as the response of the free-to-roll 60 deg delta wing model. As the sideslip increased, wing rock developed after reaching an attractor. Initial roll angle also influenced the response of the free-to-roll model. At large sideslip and for certain initial roll angles, wing rock developed initially about one attractor and then jumped to another attractor with continued wing rock motion.

1 Introduction

The roll attractor phenomenon, which is the steady state roll angle attained by a free-to-roll model, is displayed by highly swept sharp leading edge delta wings at high angles of attack [1, 2, 3, 4]. The leading edge sweep angles for which multiple roll attractors exist are quite high but still below the value which leads to wing rock. At zero sideslip, such highly swept delta wings do not exhibit wing rock by themselves but may do so in the presence of a long slender body [4, 5]. The underlying physical mechanism for wing rock of delta wings in zero sideslip is well understood [6, 7, 8, 9, 10], but the flow mechanism leading to the existence of multiple roll attractors is unclear. Ericsson [11] speculates multiple roll attractors are linked to the existence of so called 'critical states' for the 65 deg delta wing, which at $\alpha = 30$ deg and $\beta = 0$ has three roll attractors of 0, +21 deg and -21 deg [1].

Hanff et.al [1, 2] have generated a vast data base for the time varying rolling moment of a 65 deg delta wing at $\alpha = 30$ deg from forced oscillation tests. Using this data, they performed simulations for the model released from initial roll angles of 41 deg and 65.6 deg based on (a) full nonlinear and (b) locally linearized roll damping model [1, 2]. The fully nonlinear simulation for both the cases agreed well with the free-to-roll model time history. However, the simulation based on locally linearized roll damping model did not produce satisfactory results. It predicted that the trajectory initiating with the roll angle of 65.6 deg would terminate in the roll attractor of -21 deg where as the free-to-roll model ended in the roll attractor of 0 deg. The simple mathematical model [4] using experimental data of static rolling moment and a constant roll damping moment successfully predicted all the three attractors of the 65 deg delta wing model of [1] including the zero attractor with initial roll angle of 65.6 deg. However, the transient motion differed from that observed in the free-to-roll tests.

The purpose of this paper is to study the effects of sideslip and initial roll angles on the response of a free-to-roll delta wing model at high angles of attack. Experiments were conducted on a 60 deg delta wing model free-to-roll about its body axis. The angle of attack was fixed at 30 deg, sideslip was in the range of ±20 deg and the initial roll angle was varied up to ±90 deg. At low sideslip, the response of the free-to-roll model was one of damped oscillation towards an attractor. As the sideslip increased, the model gradually developed wing rock about the attractors. At certain initial roll angles, the model developed wing rock about one attractor and after few cycles of wing rock oscillations, it jumped to another attractor and continued to wing rock.

2 Experimental Work

Single degree-of-freedom, body axis free-to-roll, experiments were conducted in ViGYAN's 4 ft x 3 ft low speed wind tunnel having a maximum velocity of 175 ft/sec. The test model was a sharp leading edge 60 deg delta wing with a wing span of 22.04 in. The angle of attack was equal to 30 deg and the sideslip varied in the range ±20 deg. The roll angle was measured using a rotary potentiometer and the roll rate was measured using a rate gyro. However, the roll rate data was not used in the present analysis. The rotary potentiometer was calibrated using an accurate digital inclinometer. The calibration curve was linear for roll angles of ±90 deg. The amplified analogue output of these two sensors was recorded on a storage oscilloscope which also had the capability of A/D conversion. The sampling was done at a rate of 10ms. The digitized data was recorded on a desktop computer.

A solenoid operated device coupled to a gear motor was used to position the model to any desired pre-set roll angle (ϕ_0) in the range of ±90 deg, and release it remotely to initiate free-to-roll motion. The model motion was also recorded using a remotely controlled video camera.

The test dynamic pressure was around 5lb/ft^2 which corresponds to a velocity of 67 ft/sec and a Reynolds number of 3.57 x 10^5 per ft. The model was carefully balanced statically prior to the release in to the airflow by adjusting small weights along the rear part of the axle on which the free-to-roll model was mounted. However, with wind on, the free-to-roll model displayed a slight bias of about 3 deg to the port side. When released at $\alpha = 30$ deg and $0 < \phi_0 < 3$ deg, the model started rolling in the opposite (port) side. However, at $\phi_0 > 3$ deg, the model started rolling to the starboard side as expected. Thus, a slight aerodynamic asymmetry is indicated in the test model geometry or its mounting or both.

The delta wing model and test apparatus are shown in Fig.1.

3 Results and Discussion

3.1 Model At Zero Sideslip

The initial investigation [4] on the free-to-roll response of the 60 deg delta wing at $\alpha = 30$ deg and $\beta = 0$ had indicated that the model had three roll attractors of $0, +21$ deg and -21 deg in agreement with [1] for 65 delta wing model. However, in the present study consisting of extensive and detailed measurements of the free-to-roll response of the 60 deg delta wing model released from various initial roll angles in the range -90 deg to $+90$ deg at $\alpha = 30$ deg and $\beta = 0$, the zero attractor was not found. Further, the two attractors recorded in this study at $\alpha = 30$ deg and $\beta = 0$ are different and equal to $+34.5$ deg and -32 deg. The numerical difference between these two attractors is ascribed to the slight asymmetry in the model or its mounting as stated earlier.

Typical time histories of the model held at $\alpha = 30$ deg and $\beta = 0$ and released from various initial angles are presented in Fig 2. It is observed that the model motion is heavily damped and the model reaches the steady state within few cycles of oscillation. For low and moderate values of ϕ_0 on either side (except for the bias as stated earlier and observed in Fig.2(a)), the model motion usually terminated in the attractor on the same side [Fig.2(b) and Fig.2(c)]. However, when the model was released from $\phi_0 = 76$ deg [Fig.2(d)], the model crossed over to the other side and ended up in the attractor of -31 deg. In [4] the simple mathematical model for the 65 deg delta wing predicted that if the model were held at $\alpha = 30$ deg, $\beta = 0$ and released from an initial roll angle of 76 deg, it would cross over and a terminate in the attractor of −21 deg. The present experimental result eventhough obtained for a 60 deg delta wing model lends support to the simple mathematical model of [4] for the 65 deg delta wing model.

3.2 Model In Sideslip

For 10 deg $< \beta <$ 20 deg and certain values of ϕ_0, the model developed wing rock around a non zero mean roll angle. The term attractor usually refers to the steady state ($\dot{\phi} = 0$) roll angle attained by a free-to-roll model. However, for simplicity the term attractor is also used in this paper to refer to the mean roll angle of wing rock in the presence of wing rock. With this generalization, the data on roll attractors for the model released from various initial roll angles (ϕ_0) is summaraized in Figs.3 and 4. The test data obtained at negative sideslip is converted to positive sideslip by proper adjustment of signs of various parameters. A small aerodynamic asymmetry is evident in the data. As the sideslip increases, the two attractors of 34.5 deg and −32 deg of zero sideslip move toward each other and eventually at $\beta = 20$ deg appear to merge (Fig.3). In other words, at $\beta = 20$ deg, only one attractor around −45 deg is found to exist. Another interesting observation is the appearance of the zero attractor for $\beta = -10$ deg. The reasons for this are not clear at this time.

The data presented in Fig.4 is representative of attractor basin of the 60 deg delta wing model at $\alpha = 30$ deg and β in the range of ±20 deg.

Typical time histories at various sideslip are presented in Figs. 5 to 9.

For small sideslip ($\beta = \pm 5$ deg), the free-to-roll oscillatory response of the model is damped as observed for zero sideslip [Fig.5]. It is interesting to observe that for $\phi_0 = 70$ deg [Fig.5(b)], the model crosses over to the other side and ends up in the attractor of −45 deg in a manner similar to that observed at zero sideslip.

As sideslip increases the model start to slowly develop wing rock after reaching the attractor. At $\beta = \pm 10$ deg the wing rock tendency is low or moderate [Fig.6]. Whether the model experiences the wing rock or not also depends on the initial roll angle from which it is released. The model released from $\phi_0 = 45$ deg, 52 deg and −45 deg exhibits damped motion to the attractors of 12 deg, −50 deg and 0 respectively and remains stationary on reaching the attractor [Fig.6(a), Fig.6(b) and Fig.6(d)]. However, the model released at $\beta = -10$ deg and from $\phi_0 = 30$ deg exhibits mild wing rock about the attractor of 45 deg as shown in Figs. 6(c). The amplitude of the wing rock is small (< 5 deg).

With further increase in sideslip to $\beta = \pm 15$ deg, the wing rock tendency becomes stronger [Fig.7]. The amplitude increases to about 10 deg. Some interesting time histories were obtained for $\beta = -15$ deg when the model was released from initial roll angles of 72 deg and −52 deg as shown in Fig.8. In both cases, the model first reaches the attractor of 45 deg and develops wing rock within 2 or 3 cycles. The model released from $\phi_0 = 72$ deg performs developed wing rock for about 7 to 8 seconds during which it goes through about 10 cycles and then jumps to the attractor of 18 deg and continues the wing rock. The model released from $\phi_0 = -52$ deg moves to the same attractor initially and also develops wing rock about that attractor. However, it rocks around that attractor of 45 deg for a much longer time of (30 or 35 seconds) before jumping to the attractor of 18 deg and continue the wing rock. Since the time interval for one oscilloscope sweep was set equal to 20 seconds for data collection, this particular time history was captured in two successive oscilloscope sweeps. (Note that Fig.8(c) is a continuation of Fig.8(b)) Even then, only a small part of the wing rock after the jump was captured. Perhaps one more oscilloscope sweep was required. However, the video camera recording which was done for a much longer time showed that the wing rock continued and no further jumps occured.

With further increase in sideslip to $\beta = \pm 20$, the wing rock tendency of the model was noted to subside. For some values of ϕ_0, the model exhibits damped oscillatory motion towards the attractor. Typical time histories are shown in Fig. 9.

3.3 Flow Mechanism Causing Wing Rock

Majority of the past studies on wing rock of delta wings at high angle of attack were performed at zero sideslip [6, 7, 8, 9, 10]. It is generally accepted that in zero sideslip, the wing rock occurs for slender, sharp leading edge delta wings of leading edge sweep ≥ 75 deg. For the 80 deg delta wing, which perhaps has received maximum attention in wing rock research, the alternate lift-off of the lee side vortex is the key ingredient of wing rock mechanism. This alteranate lift-off of the lee side vortex leads to a statically stabilizing and dynamically destabilizing effect due to convective time lag. The statically stabilizing effect provides the aerodynamic spring necessary to maintain the oscillatory motion. The dynamically destabilizing effect leads to the amplitude build up that continues until the vortex breakdown occurs on the downgoing wing and which creates enough damping to limit the oscillation amplitude.

For wing of lower leading edge sweep, say 75 deg delta wing [9], vortex lift-off was not a factor in inducing wing rock. According to [9], a possible cause for wing rock of 75 deg delta was the dynamic response of the vortex strengths to the changes in effective apex angle as the wing oscillates in roll. For higher sweep angles, say 85 deg delta, spacing between vortices is very small and this vortex crowding leads to strong mutual interactions. The wing rock was noted [9] to occur when one vortex stayed attached to the wing surface through out the wing rock cycle and the other vortex went through the lift-off and reattachment cycles.

Against this existing scenario in published literature, in the present study the wing rock was observed for 60 deg delta wing in sideslip at $\alpha = 30$ deg and certain initial roll angles. Further, the wing rock occurred around non zero roll attractors, and was not of the typical limit cycle oscillation. In addition, the model jumped during the wing rock from one attractor to another and continued the wing rock.

The effective angles of attack, sideslip, sweep angle of right and left sides for a wing at an incidence α, sideslip β and roll angle ϕ are given by the following relations:

$$\begin{aligned} tan\alpha_{eff} &= tan\alpha cos\phi \\ tan\beta_{eff} &= tan^{-1}\left(\frac{sin\alpha cos\beta cos\phi - sin\beta sin\phi}{cos\beta cos\alpha}\right) \\ \Lambda_R &= \Lambda - \beta_{eff} \\ \Lambda_L &= \Lambda + \beta_{eff} \end{aligned}$$

Using these relations, it is evident that for those cases which led to wing rock, at $t \leq 0$ (prior to release of the free-to-roll delta wing model), $\alpha_{eff} \leq \alpha$, $\Lambda_R \neq \Lambda_L \neq \Lambda$. This scenario at $t \leq 0$ is different from the case of slender delta wings at high angles of attack, zero sideslip and $\Lambda_R = \Lambda_L = \Lambda$ investigated in the literature as discussed above. Therefore, at this stage it is not possible to speculate about the possible flow mechanism causing the wing rock observed in the present study. Additional information involving static and dynamic flow visualization may be necessary to shed some light on the flow mechanism causing the wing rock of 60 deg delta wing at combined high angle of attack, sideslip and initial roll angles.

4 Concluding Remarks

Single degree-of-freedom, free-to-roll experiments were conducted on a sharp edged 60 deg delta wing model at an angle of attack of 30 deg to study the effect of sideslip and initial roll angle on multiple roll attractors and the nature of the model response. At high angles of attack, the 60 deg delta does not exhibit wing rock at zero sideslip but has of multiple roll attractors. Sideslip was found to strongly influence the multiple roll attractors. At high sideslip, the model developed wing rock. For some initial roll angles, the model developed wing rock around one attractor initially and after few cycles of wing rock oscillation, it jumped to another attractor and continued the wing rock. Further studies are necessary to understand the complex physical flow mechanism leading to such interesting phenomenon.

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References

[1] Hanff E.S., and Ericsson L.E.; *Multiple Roll Attractors of a Delta Wing at High Incidence*, Paper No.31, AGARD CP-494,1990.

[2] Hanff, E.S., and Jenkins, S.B.; *Large Amplitude High- Rate Roll Experiments On A Delta And Double Delta Wing*, AIAA Paper 90-0224.

[3] Jenkins, J.E., Myatt, J.H., and Hanff E.S.; *Body Axis Rolling Motion Critical States of a 65deg Delta wing*, AIAA Paper No.93-0621, January 1993.

[4] Pamadi, B.N., Rao, D,M., and Niranjana, T.; *Wing Rock and Roll Attractor of Delta Wings at High Angles of Attack*, AIAA Paper No.94-0807, January 1994.

[5] Nguyen, Luat, T., Whipple, Raymond, D., and Brandon, Jay, M.; *Recent Experiments of Unsteady Aerodynamic Effects On Aircraft Flight Dynamics at High Angles of Attack* AGARD CP No. 386, Paper No, 28, 1985.

[6] Nguyen, Luat T, Yip, Long P, and Chambers Joseph R; *Self-Induced Wing Rock of Slender Delta Wings*, AIAA Paper No.81-1883, August 1981.

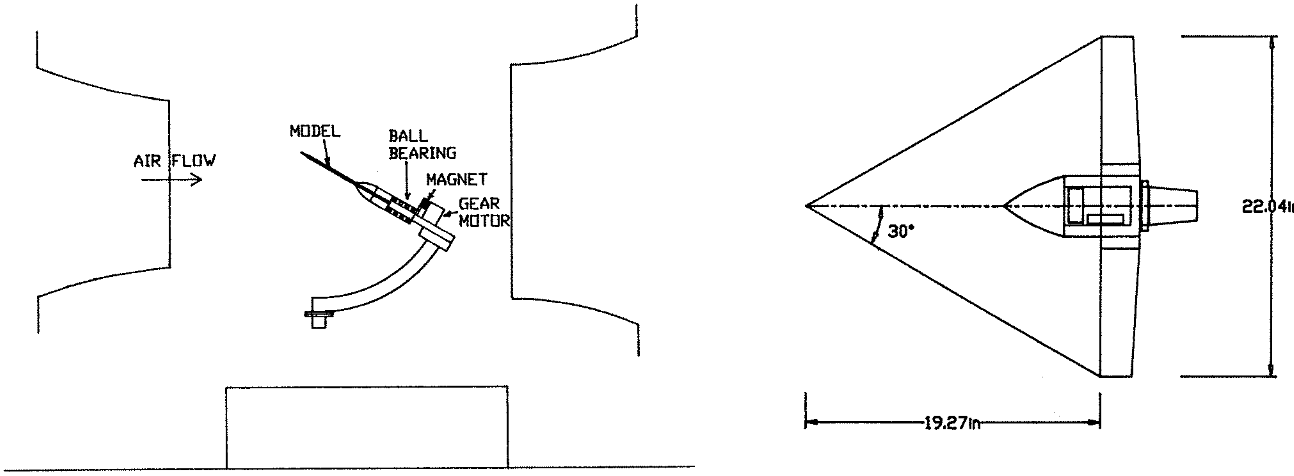
[7] Ericsson, Lars, E.; *Fluid Mechanics of Slender Wing Rock*, Journal of Aircraft, Vol. 21, No. 5, pp. 322-328, 1984.

[8] Ericsson, Lars, E.; *Slender Wing Rock Revisited*, Journal of Aircraft, Vol.30, No. 3, pp.352-356, May-June 1993.

[9] Ng, T. T., Malcolm, G, N., and Lewis, L. C,; *Experimental Study of Vortex Flows Over Delta Wings in Wing Rock Motion*, Journal of Aircraft, Vol. 29, No. 4, July-August 1992, pp. 598-603.

[10] Jun, Y.W., and Nelson, R.C.; *Leading Edge Vortex Dynamics On A Delta Wing Undergoing Wing Rock Motion*, AIAA Paper 87-0332.

[11] Ericsson, L.E.;*Flow Physics Of Critical States For Rolling Delta Wings*, AIAA Paper 93-3683 CP.



(a) Model in the wind tunnel (b) 60 deg delta wing model

Fig. 1 Schematic diagram of experimental setup

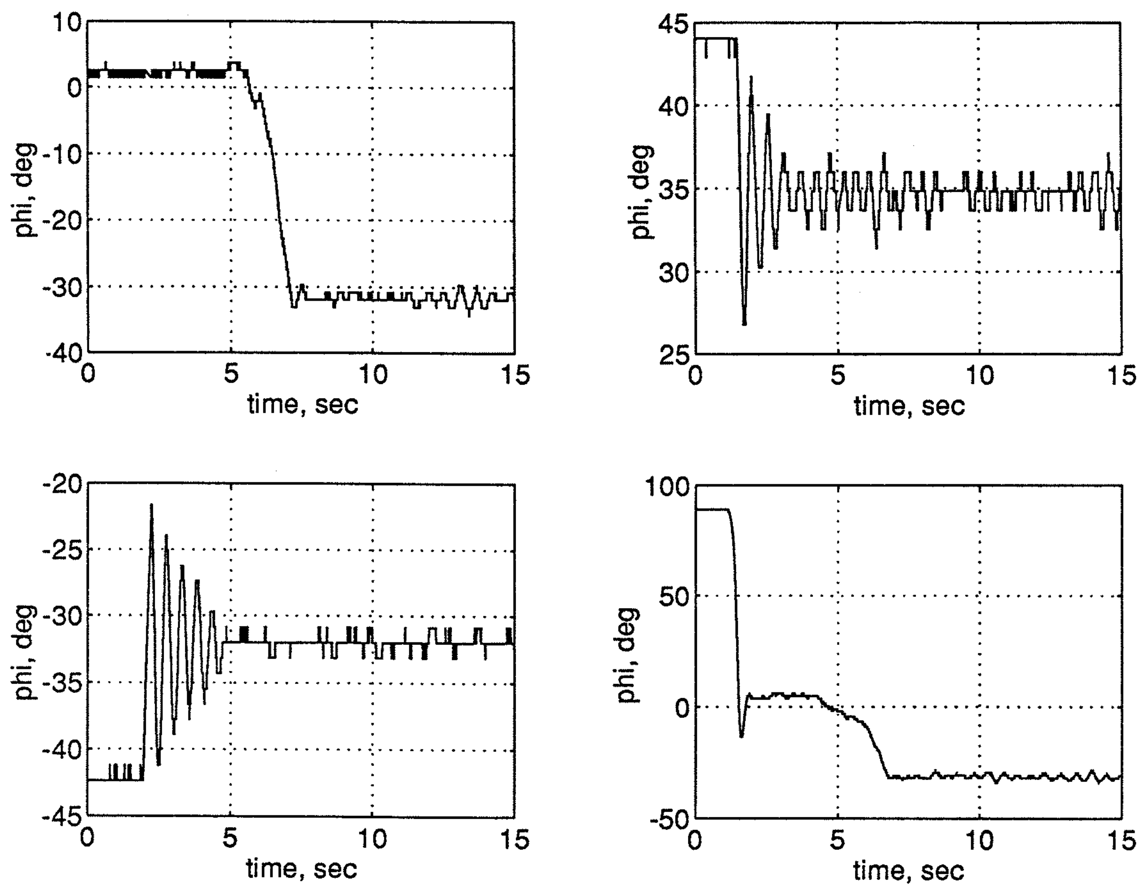


Fig. 2 Typical time histories (alpha=30 deg, beta=0)

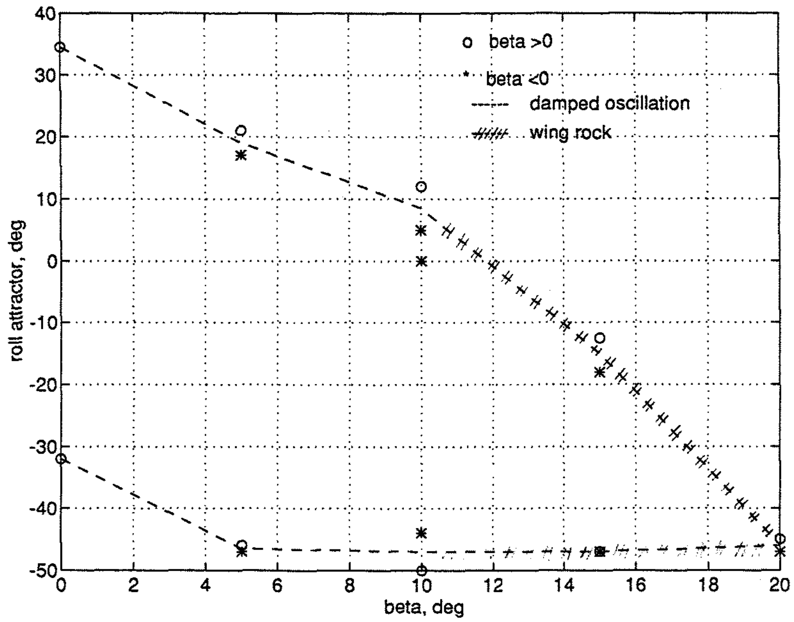


Fig. 3 Variation of roll attractors with sideslip

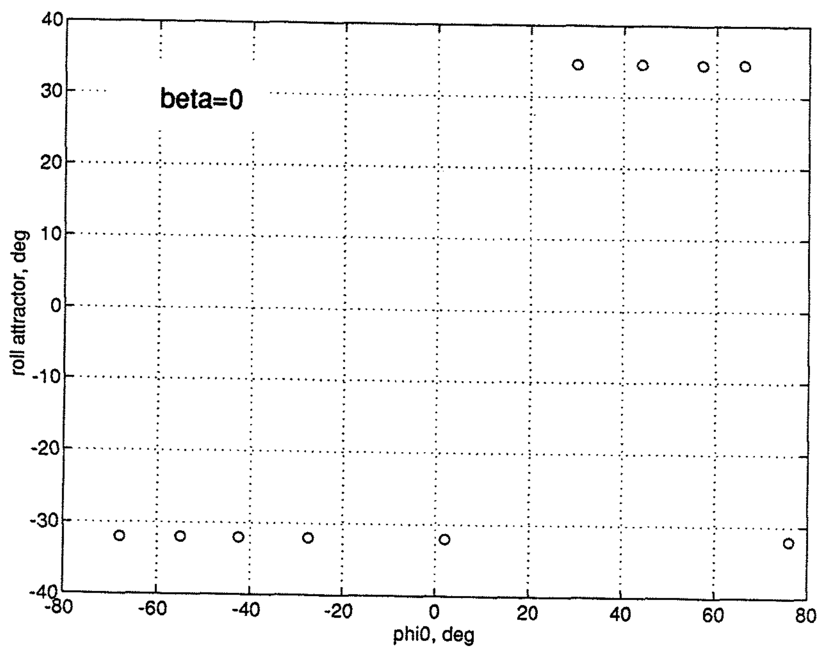


Fig. 4 Variation of roll attractors with initial roll angle
(continued)

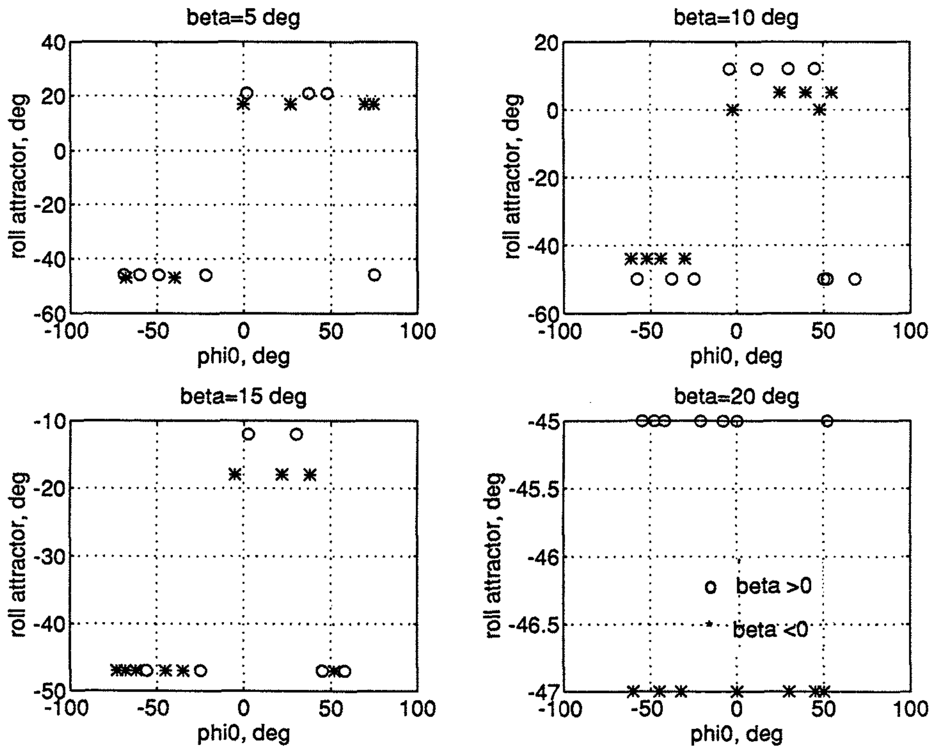


Fig. 4 Variation of roll attractors with initial roll angle (concluded)

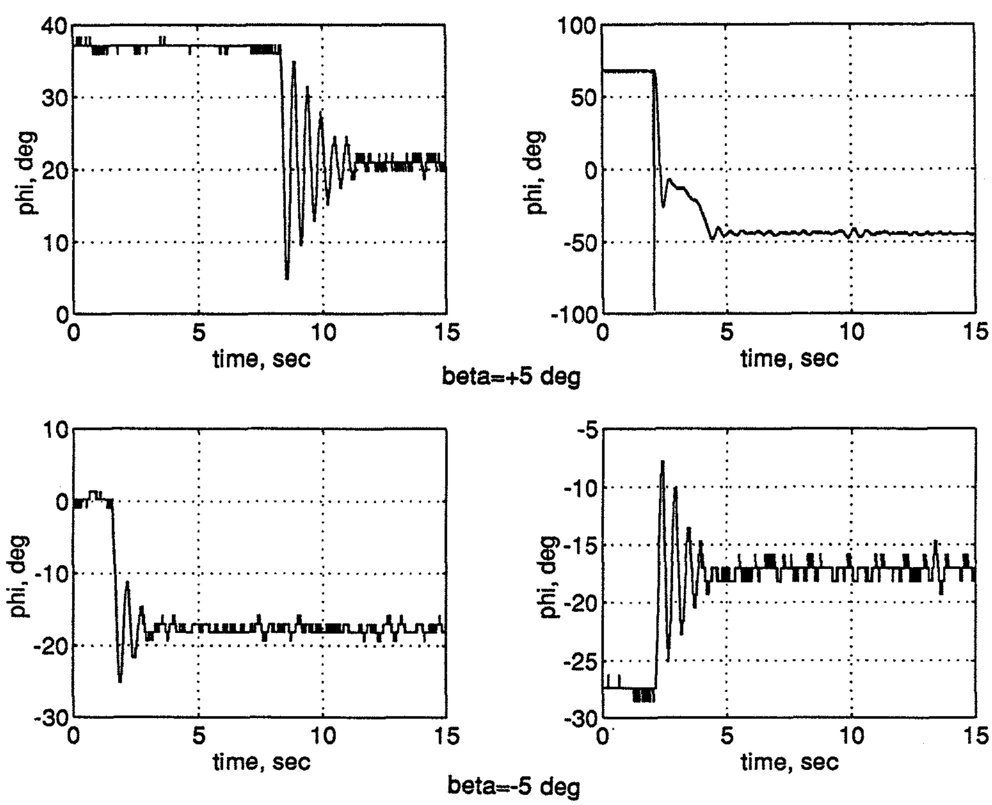


Fig. 5 Typical time histories (alpha=30 deg, beta= +5 deg and -5 deg)

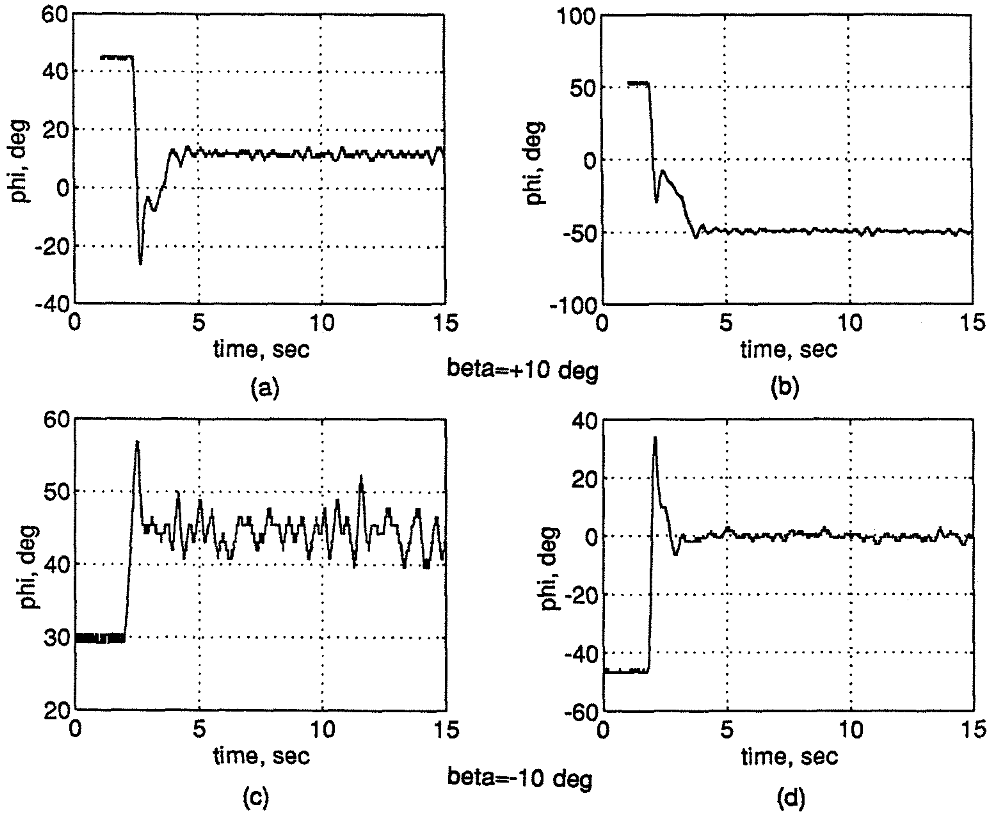


Fig. 6 Typical time histories (alpha=30 deg, beta=+10 deg and -10 deg)

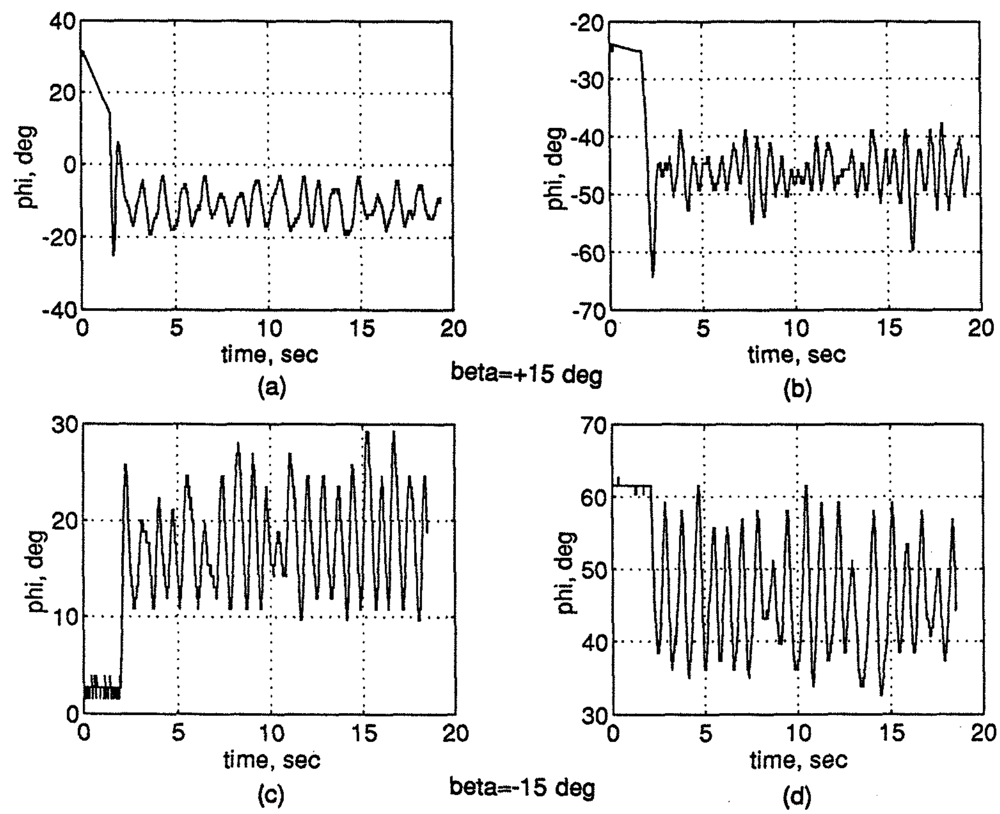


Fig. 7 Typical time histories (alpha=30 deg, beta= +15 deg and -15 deg)

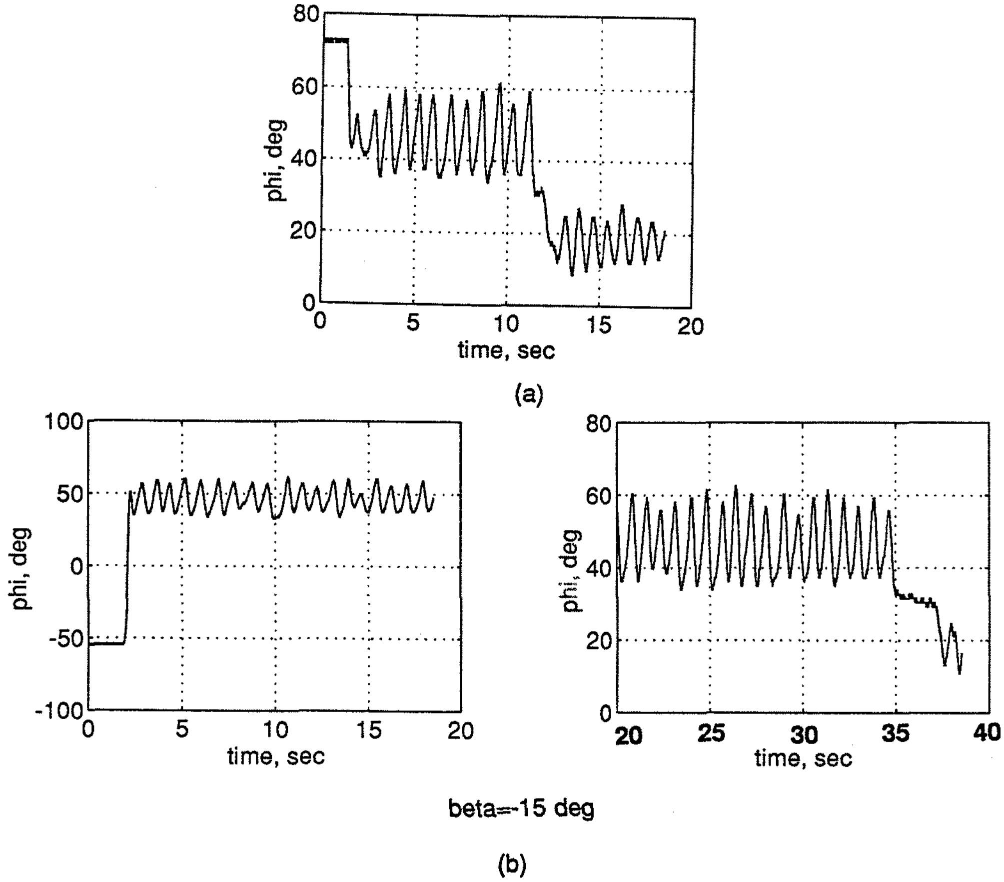


Fig. 8 Wing rock jump time histories (alpha=30 deg, beta=| -15 deg)

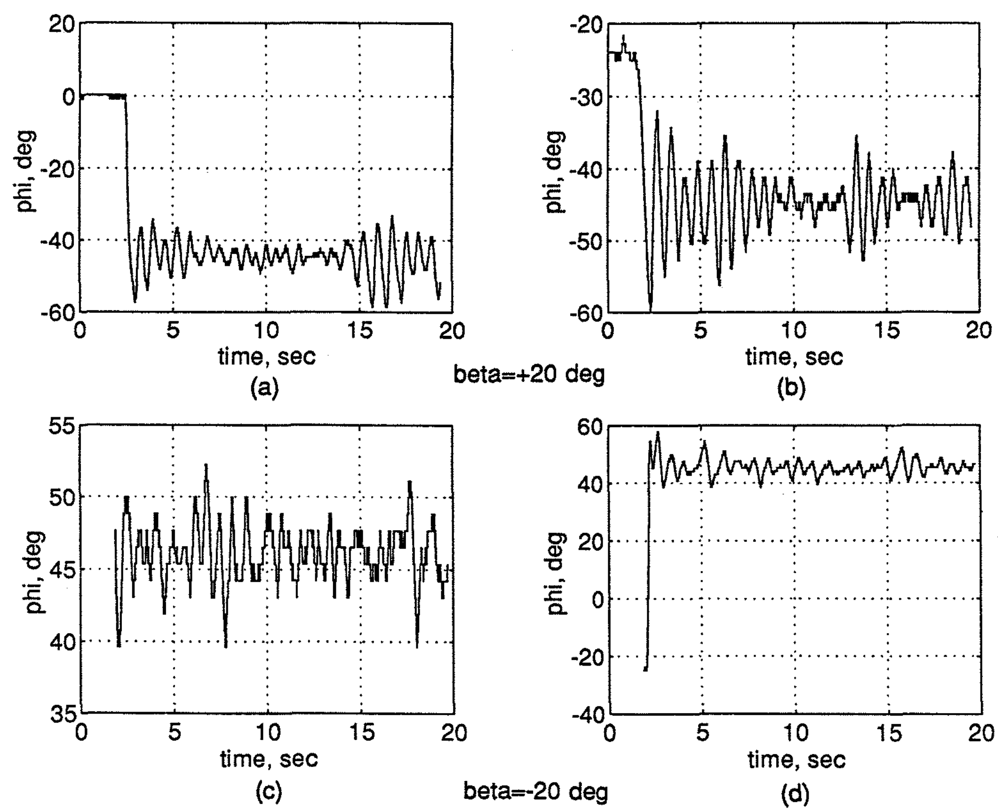


Fig. 9 Typical time histories (alpha=30 deg, beta= 20 deg and -20 deg)