The Lateral Stability problem and Numerical Simulation of a Slender Delta Wing during Self-excited Wing Rock

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Abstract

The Lateral stability problem of modern combat aircraft in high angle of attack is an important issue ralated to flying safety. This investigation foucus on the sideslip behaviors of a slender delta wing during self-excited wing rock. The nonlinear double degree of freedoms aerodynamics model is established for governing the coupling movement in combined free-roll and free-sideslip motion. Then, a numerical investigation is conducted on the dynamic characteristics of an 80ff delta wing in combined free-roll and free-sideslip by solving flow governing equations and Euler rigid-body dynamics equations simultaneously. Implicit, upwind, flux-difference splitting, finite volume scheme and the second-order-accurate finite difference scheme are employed to discrete and solve these governing equations. The governing equations of fluid and movements are solved alternately with a coupling method, either loosely coupling or tightly coupling, both coupling methods are discussed. Well-regulated sideslip oscillation is observed as expected. The sideslip behaviors are mostly affected by the roll oscillatory properties, i.e., the frequencies and phases. The loosely coupling method achieved considerably efficiency and accuracy. The behaviors of double DOFs motion are more complicate than that of single DOF wing rock.

1 Introduction

One of the most common dynamic phenomena experienced by slender wing aircraft flying at high angles of attack is the one known as wing rock. Wing rock is a complicated motion that typically affects several degrees of freedom (DOF) simultaneously[1]. As the name implies, the primary motion is an oscillation in roll, however, the roll characteristics are significant influenced by other coupling motion DOFs. During data analysis, ref[2] and [3] found that some aircrafts proved stable in wind tunnel are unstable in flying test, they think that the dissimilarity of DOFs should account for the phenomenon. Double DOFs motion in combined free-roll and free-sideslip is a common form of coupling wing rock, as Figure 1 depicted.

This is something like Dutch roll, but they are essentially different. Dutch roll is a concept come from disturbance flow and can be described by linear aerodynamic model, however, couping wing rock in combined free-roll and free-sideslip is essentially nonlinear aerodynamic problem under high angle of attack. The concept of vortical lift force has made delta wing the most popular configuration incorporated in modern combat aircraft. With the help of advance control systems, moreover, it becomes more and more feasible for combat aircraft to maneuver in high angle of attack. As the delta wing is the main function plate of lift force and actual configuration of modern combat aircraft, the delta wings oscillating in roll at low speed and high attack angle regime have received a substantial volume of experimental [4]-[6] and computational [7]-[10] research work. However, asymmetrical leading edge vortexes and its fiercely interactions dominant the flowfield, nonlinear aeroforce and moment vary complicately. Owing to the difficulties lying in experiment designing and measuring, these work mainly focus on single DOF wing rock. To the authorrss knowledge, compared with the researches of single DOF wing rock, the numerical investigation about delta wing in this kind of double DOF motion is seldom addressed in published literature. In this paper, we study the double DOFs motion characteristics of the 80ꜰꜰ swept sharp-edged delta wing in combined free-roll and free-sideslip numerically, compare roll characteristics with that of single DOF wing rock, discuss the coupling regime between free-roll and free-sideslip and the flow mechanism sustaining double DOFs wing rock.

2 Model and Methods

2.1 Delta wing model and mesh

An 80° swept-back, sharp-edged delta wing model is incorporated in this investigation. In Figure 2, an O-H topology is employed to mesh the delta wing. The computational domain extends 2.5 chord lengths forward from the wing apex and 5 chord lengths backward from the wing tailing edge. The radius of the computational domain is 4 chord lengths. The minimum grid size in the normal direction to the wing surface is 1.0×10^{-4} chord length on the whole solid surface.

2.2 Flow governing equations

The unsteady, three-dimensional, compressible, full Navier-Stokes equations in strongly conservative form have been used. The equations have been written in a fixed inertial frame of reference and transformed to the computational domain using a generalized time-dependent transformation(ξ, η, ζ, t). The dimensionless form is given as:

$$\frac{\partial Q}{\partial t} + \sum_k \frac{\partial E_k}{\partial k} = \sum_k \frac{\partial E_{vk}}{\partial k} \qquad k = ¸, \jmath, \imath \tag{1}$$

$$Q = J^{-1}(æ, æu, æv, æw, æe)^T \tag{2}$$

Where Q is conservation variables, t means time, E and Ev are the inviscid and viscid fluxes in the ξ, η, and ζdirections, respectively. The detail definitions of the inviscid and viscid fluxes are in ref [11].

2.3 Rigid body dynamics equations

The relevant DOFs in this study are roll and sideslip. Both of roll and sideslip equations are second order autonomous ordinary differential equations in time. The rolling equation is written in the body-axes frame of reference to keep the roll-axis moment of inertia constant throughout the entire motion. While the sideslip motion equation is written in the inertial frame of reference. They are given as follow:

$$\begin{cases} I_{xx}\,\ddot{;} = C_l \\ m\,\ddot{z}_o = C_z \end{cases} \tag{3}$$

The rolling angle Œ is defined positive when the left-hand side (pilot view) of the wing moving down-wards, the variable z_0 represent the z-component of mass center in the inertial frame of reference and its positive direction coincide with the coordinate.C_l and C_z are coefficients of roll moment and transverse force respectively. The parameters I_{xx} and m represent dimensionless roll moment of inertial and mass of the delta wing respectively, written as:

$$I_{xx} = \frac{2\tilde{I}_{xx}}{\tilde{\text{æ}}_\infty \tilde{S}\,\tilde{c}^3} \quad , \quad m = \frac{2\tilde{m}}{\tilde{\text{æ}}_\infty \tilde{S}\,\tilde{c}} \tag{4}$$

The superscript '∼' represents variables with dimension. None of the structural damping is considered in this paper.

2.4 Solution algorithm

The implicit, finite volume scheme is used to solve the unsteady, three dimensional, compressible, full Navier-Stokes equations. The Nonoscillation, contains No free parameters and Dissipative (NND) flux-difference splitting scheme[12] is employed to discretize the inviscid fluxes, while the second-order accurate central difference scheme is applied to the discretization of the viscous fluxes which are linearized in time, eliminated in the implicit operator and retained in the explicit terms. The Spalart-Allmaras (SA) model is employed to evaluate the turbulence influences of leeward vortical flow.

The Lower-Upper Symmetric Gauss-Seidel (LU-SGS) scheme is employed to enhance the efficiency of time integration, besides a dual-time-step method [13] which is a Newton-like sub-iteration process is employed to reduce the effect of the inherent time lag in applying the boundary conditions and reduce the factorization error for unsteady-state calculations.

A second-order-accurate finite difference scheme [14] is applied to discretize the rigid-body dynamics equations (3), including roll equation and sideslip equation.

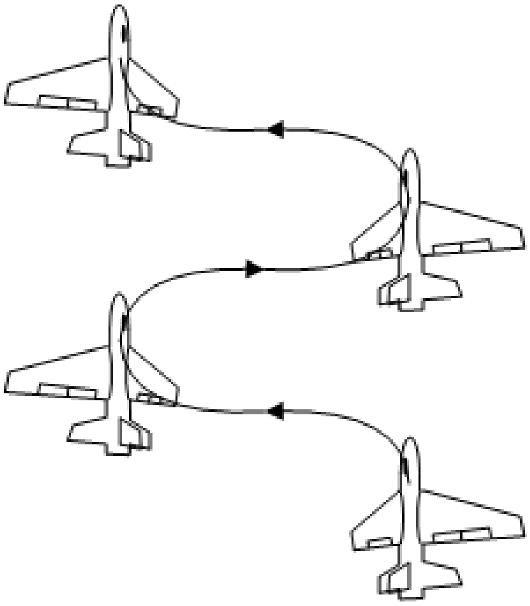

Figure 1: Schematic of aerocraft in combined free roll and free sideslip motion

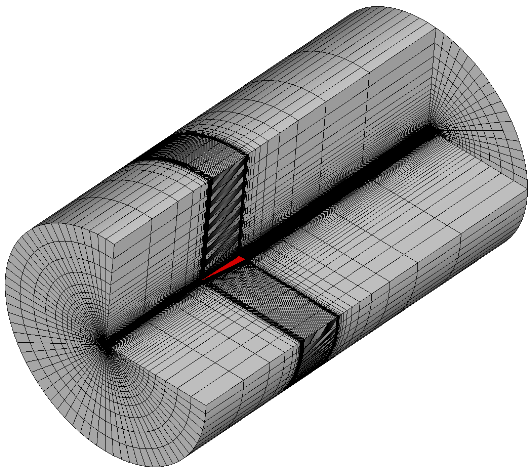

Figure 2: The 80° swept delta wing model and space computational grid distribution

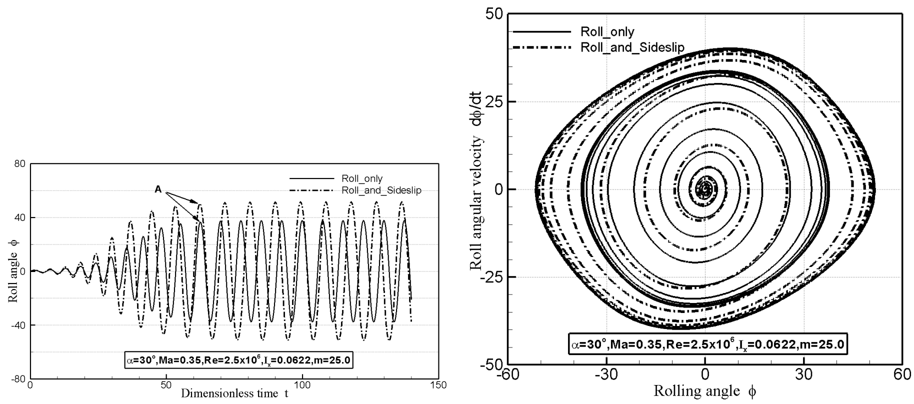

Figure 3: the comparison between roll only and combined roll and sideslip wing rock

3 Results and Disscussions

The nonzero lateral force of rocking delta wing indicates deterioration of lateral stability, accordingly, a sideslip motion is expected to observed as a result. The lateral motion of delta wing during wing rock is evaluated simultaneously.

3.1 Dynamic behaviors of multi-DOFs oscillation

With the nonlinear aerodynamic model established in section 2, the double DOFs motion simulation of the 80ғг delta wing in combined free-roll and free-sideslip is conducted. For manifesting the characteristics of combined free-roll and free-sideslip motion, the roll history curve and phase curve of the double DOFs motion are compared with that of single DOF wing rock. As Figure 3(a) depicted, double DOFs motion built limit cycle oscillation and its roll amplitudes significantly greater than that of single DOF wing rock, indicates that sideslip motion has an influence on the amplitudes characteristics of wing rock. Figure 3(b) draws the phase curves, both single DOF wing rock and double DOFs wing rock in combined roll and sideslip exhibit limit cycle amplitudes in roll, but the later motion built a larger area with limit cycle phase curve, uncover the fact that sideslip has substantially influence on roll amplitudes.

Focus on the frequency characteristics of the roll oscillation history curve, it can be found that the period time are slightly expanded with the influence of sideslip motion, it indicates that double DOFs wing rock in combined free-roll and free-sideslip has larger limit cycle amplitudes and lower frequencies than that of single DOF wing rock. Form startup at the balance angle to limit cycle amplitude achieved a time span is needed. It is interesting that the time spans of the two motions with different DOFs are almost equivalent in spite of different amplitudes and frequencies, as the symbol ғөАгç in Figure 3(a) depicted.

In order to study the rock mechanism of the double DOFs motion in combined free-roll and free-sideslip, nine typical positions in the positive rolling procession ($\omega_x > 0$) are extracted to demonstrate the interaction between the leeward vortical structures and delta wing. As Figure 4 depicted (pilot view), it describes the unsymmetrical evolution of leeward vortexes in the sectional plane (x/c=0.57), wo

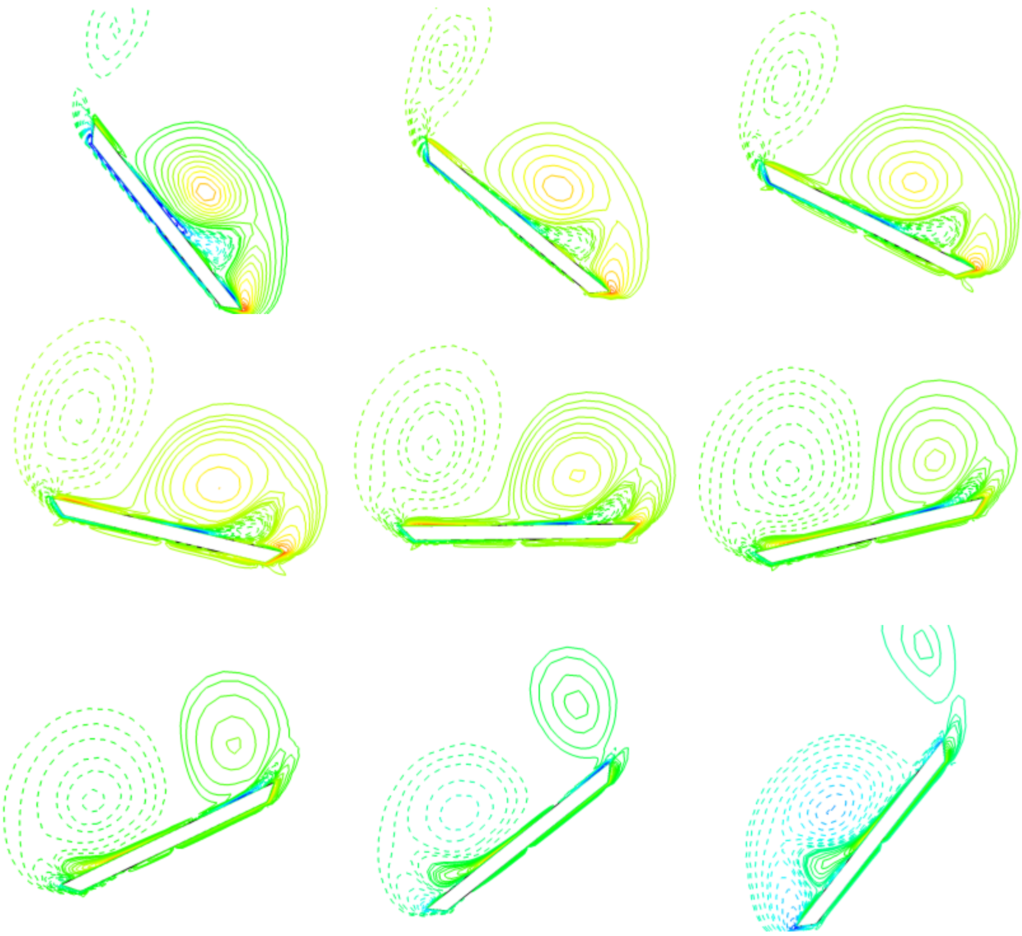

Figure 4: The evolution of sectional (x/c=0.67) streamwise vorticity in positive rolling procession

represent dimensionless sideslip velocity. In the picture, streamwise vorticity are drawn by ISO lines, color represents its magnitude and dash line represnts minus value.

The evolution procession can be mainly divided into three stages. First stage, Figure 4(a) (d), delta wing preserves minus roll angle, left leading edge moves upward and right leading edge moves downward (pilot view), it indicates that the washing effect leads effective attack angle increase at right side and an decrease at left side, as a result, the right leading edge vortexes dominate the leeward flow field of delta wing. As the delta wing rolling right, leading edge vortexes strength increase unsymmetrically on both side across the body symmetry, left side increase rapidly and right side increase slowly. The asymmetrical increase reduced the unsymmetry distribution of pressure, consequently, asymmetrical moment decrease, although roll angular velocity keep increase, the accelerate become more and more smaller. Figure 4(e) is the second stage, the delta wing located about 0° roll angle. As the vortexes movement lag behind the delta wing roll, vortexes preserve unsymmetrical distribution at a symmetrical location. It is critical that turns the delta wing roll unstable at large attack angles. The third stage, Figure 4(f) (i), delta wing preserves positive roll angle, leeward vortexes experience a reverse procession of first stage, leading edge

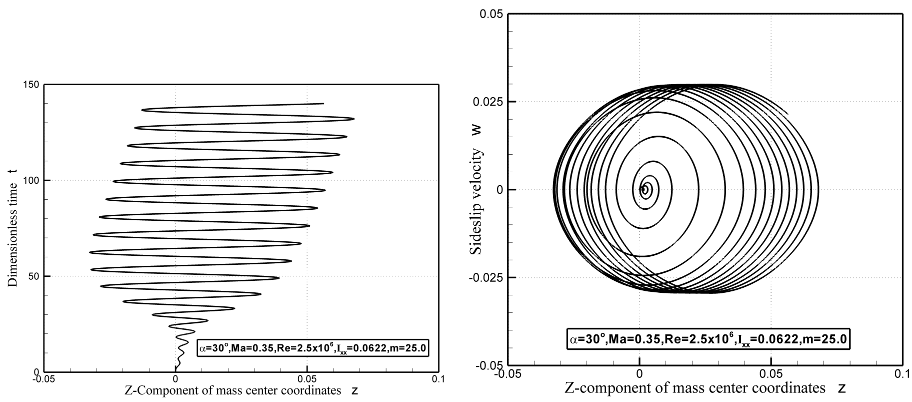

Figure 5: The lateral behaviors of delta wing in double DOFs motion

vortexes strength decrease asymmetrically as the delta wing rolling right on both side across the body symmetry plane, dominant vortexes structure shift from right side to left side. Down washing effect essentially eliminate attack angle decrease with roll angle increase, which makes the left leading edge vortexes almost preserve its strength during the third stage. On the other hand, at the right side, up washing effect collaborate with right roll effectively diminished the right leading edge vortexes strength, whatrss more, the right leading edge vortexes move away from the leeward surface of delta wing. All of these cause an opposite moment and preserve a increase trend, which makes right roll of delta wing slow down till stop.
For evaluting the behaviors of couple method, the results of loose couple method and tight couple method are compared. In fact, the time history curve almost coincide, no significant discrepancy is observed, including ampliudes and frequencies. Considering the efficiency, the loose couple method is employed to conduct the following massive simulation

3.2 Lateral oscillation

The lateral motion is focused. A typical oscillation is observed. Along with the oscillation in rolling, the sideslip motion is excited. After several periods, approximately invariant amplitudes are built with a fixed frequency, as Figure 5(a) depicted. Compared with the wing span, the amplitude of sidesliping displacement is about 0.1 chord length which is not significant. Dissimilarly, the lateral motion is not oscillating around a fixed balance position. The average position of sideslip shift right slightly. Consequently, the phase curve could not form a limit cycle, as Figure 5(b) depicted.

3.3 Coupling regime

Considering the significant influence of sideslip on roll oscillation, the coupling regime of the double DOFs motion in combined free-roll and free-sideslip is discussed also.Figure 6 draws the time history curves of roll angular velocity and sideslip velocity, the conclusion can be drew that sideslip velocity and roll angular velocity of double DOFs wing rock are almost in same frequencies and opposite phase, which indicates that the couple regime of double DOFs motion is right sideslip during left rolling and left sideslip during right rolling. In Figure 4, we find that when roll motion achieve its amplitudes, sideslip velocity almost equal to zero. In the first stage, leeward leading edge vortexes induced suction region on the right side of delta wing and generated right side-force that makes delta wing sideslip right. In third stage, the suction region shift from right side to left side, the right sideslip velocity decelerates till zero along with the right roll stop. A similar procession can be inferred in the negative procession ($\omega_x < 0$) of roll oscillatory. So the complete story of coupling procession during a period time is drew in Figure 7 and the coupling regime can be conclude as right sideslip during left rolling and left sideslip during right rolling.

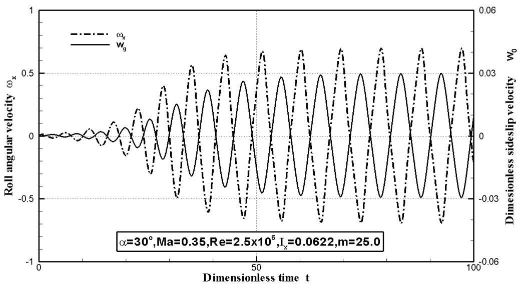

Figure 6: the time history curves of sideslip velocity and roll angular velocity

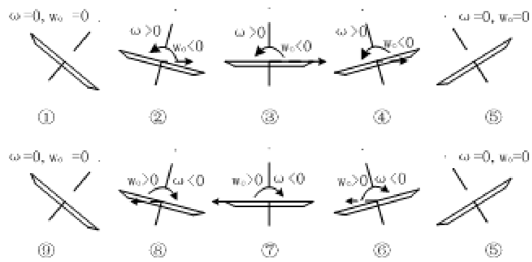

Figure 7: Schematic of the coupling regime of free-roll and free-sideslip

In single DOF wing rock, with definitely incidence angle, sideslip angle and attack angle fully depend on roll angle. With the influence of sideslip, extra hysteresis phenomena induced. As Figure 8(a) depicted, sideslip angle loops hysteretically with roll angle that is different from single DOF wing rock. The sideslip angle definitely increases during positive roll procession and decreases during negative roll procession, the increment versus roll angle achieve limit cycle oscillation eventually, as Figure 8(b). The situation of attack angle is similar to sideslip angle, hysteresis effect is induced by sideslip motion, nevertheless it has a more complicate hysteresis curve which looks like a beautify butterfly as Figure 9 depicted.

4 Summary

Dynamic characteristics of an 80° delta wing in double DOFs wing rock are investigated numerically and the lateral behavior is focused. Results show that sideslip

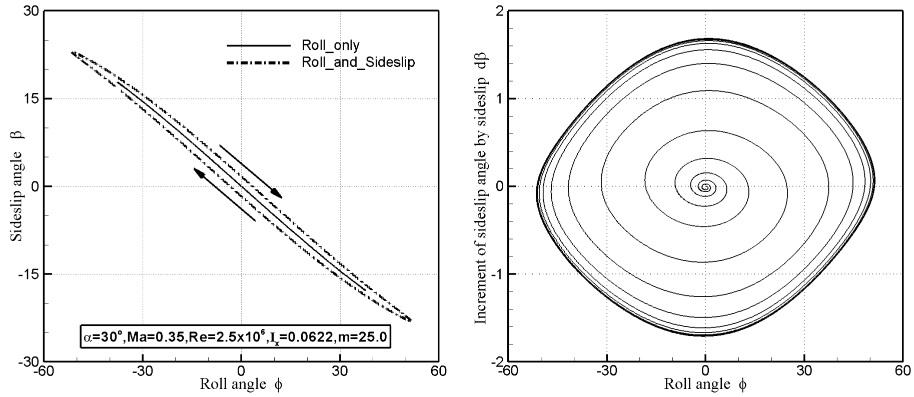

Figure 8: Influence of the coupling effects in combined roll and sideslip motion on sideslip angle

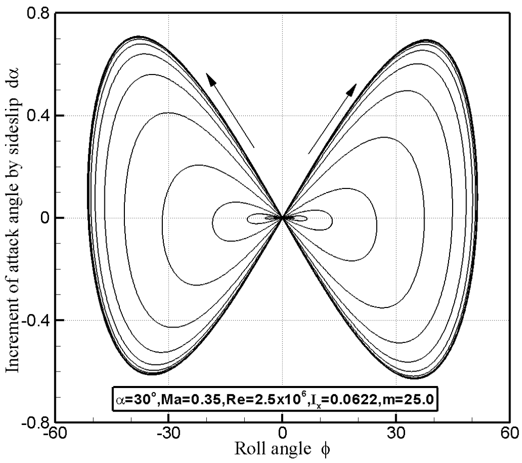

Figure 9: increment of attck angle VS roll angle

motion has an influence on the rolling amplitudes; Asymmetric oscillation of vortices is the flow mechanism sustaining wing rock of slender delta wing in combined free-roll and free-sideslip; Right sideslip during left rolling and left sideslip during right rolling are the coupling regime of slender delta wing in combined free-roll and free-sideslip motion; with the influence of sideslip, attack angle and sideslip angle lag behind the roll angle is observed, the asymmetrical characteristics of flow structures and hysteresis effects are enforced during coupling wing rock; the loose couple method can achieve the same accuracy as that of tight couple method and can achieve high efficiency.

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