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Effect of aspect ratio on wing rock at low Reynolds number

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ABSTRACT

Wing rock phenomenon has been studied extensively on slender delta wings but a little is understood about wing rock occurring on rectangular wing planforms, which is the focus of this paper. Specifically, a systematic procedure is discussed for experimental studies of single degree-of-freedom wing rock on rectangular wings. The characterization of limit cycle oscillations in terms of amplitude and frequency is based on the free-to-roll tests in wind tunnel. Rectangular wings with aspect ratio from 2 to 4.5 (with increment of 0.25) are studied at low Reynolds numbers (less than 0.1 million) and low Strouhal numbers (10^{-2}) that are typical for the flight of micro air vehicles in urban environment. The changing trend in oscillation amplitude and frequency of the resulting sustained limit cycle oscillations is analyzed. The results indicate that wing rock occurs in post-stall regime (14–16° of angle of attack) and its amplitude tends to increase from aspect ratio 2 to 3.25 and decrease thereafter. The wing-rock frequency shows a decrease from aspect ratio of 2 to 3.75 and increase thereafter.

1. Introduction

Wing rock is a rotational oscillation phenomenon that is usually undesirable. The wing rock phenomena involves complex multiple degree of freedom non-linear dynamics, which results in the aircraft undergoing self-excited Limit Cycle Oscillations (LCO) primarily in the roll axis. It usually occurs at relatively low flight speeds when the aircraft is flying at high angle of attack.

The wing rock phenomenon has been most intensively studied on delta wings, because the leading edge vortices that are thought to cause the rotary motion are most easily detectable on delta wings. Many highly-maneuverable modern fighter aircrafts possess the delta wing configuration and need to operate at high angles of attack during landing and other flight situations. Therefore, it is of interest to study these wing rock motions so as to improve the safety and handling qualities of these aircrafts. Ross [30] studied the nonlinear motion affecting the delta wing aircraft having a sweep angle of 75° and aspect ratio of 0.925. These physical dimensions unintentionally make the research aircraft vulnerable to wing rock motions. The aircraft underwent huge amplitude of roll oscillation, and the amplitude continues to increase when the angle of attack is further increased. Activating the ailerons or decreasing the angle of attack was shown to be effective in controlling the wing rock motion. The study concluded that the wing rock motion is due to the reduction of the roll damping at high angle of attack.

More wing rock studies by Ross and Nguyen [31] found that wing rock tends to occur at two distinct flight conditions. The first is at transonic speeds when the shock-induced stall/unstall phenomenon causes the aircraft to undergo roll oscillations at low angles of attack; the second region is when the aircraft is observed to be flying at high angles of attack at low subsonic speeds.

Polhamus [28] captured the steady-state features of leading edge vortex flows on delta wings. The dimension of any delta wing can be characterized by the aspect ratio, which is a direct function of the sweep angle. Depending on the angle of attack, the two strong leading edge vortices show different patterns during flow visualization. It was concluded that wing rock will occur from momentary asymmetric vortices. Hence wing rock phenomenon is observed most of the time on slender delta wings. As the aspect ratio increases, the roll damping also increases resulting in the aircraft being much less susceptible to wing rock. A study done by Prudnikov [29] concluded that a delta wing with sweepback angle of less than 72° will not likely experience wing rock.

The reason for the asymmetric vortices, which are thought to induce the wing rock oscillations on delta wings, are speculated to be either due to periodic asymmetry in position, strength or its breakdown [26,7,8,22,16]. As such, much effort is put into elucidating the leading edge vortex and breakdown position during the wing rock cycle, including smoke visualization studies [18,19,1,2] and water tunnel experiments [24,25].

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Nomenclature

AR	Aspect Ratio	p	Roll rate
LCO	Limit Cycle Oscillations	q	Pitch rate
UAV	Unmanned Air Vehicle	r	Yaw rate
MAV	Micro Air Vehicle	Amp	Amplitude
ϕ	Roll angle	ω	Angular frequency
θ	Pitch angle	Re	Reynolds number
ψ	Yaw angle	St	Strouhal number

Jun and Nelson [18] studied the asymmetry in vortex core positions during one cycle of wing rock oscillation. It is observed that even at zero initial roll angles there is an apparent asymmetry in vortex core position that provides a disturbance to initiate wing rock. The difference in suction lift on both sides of the wing span drives it into rotary motion.

Besides simple delta wings, the LCO of wing rock have also been observed on various other configurations. Studies have been done to investigate the effect of forebody-wing interaction on the static and dynamic roll stability on aircrafts at high angles of attack [3]. In X-31 aircraft, canards are placed in front of highly swept wings. Without the canard, such a wing configuration will not undergo wing rock oscillations. However, the canard introduces forebody vortices which induce wing rock condition [21,6]. Another separate investigation by Katz and Levin also demonstrates that a delta wing which is unlikely to undergo wing rock, exhibits LCO once a small canard is installed [20]. The small canard and the wing itself produce four leading edge vortices which are asymmetric, resulting in complex dynamic vortex interactions between the motion of the wings and those vortices.

There are also other cases when the wing itself has a smaller sweepback than required to naturally exhibit wing rock. However Ericsson [9,12,10,11] reveals that fore-bodies are able to induce wing rock on the wings with aspect ratio larger than unity. The F-18 High Alpha research Vehicle (HARV) is one such vehicle where the wing rock is induced by the interaction between the wing and the forebody vortices [10]. Another aircraft exhibiting a similar effect is the X-29 research aircraft. This aircraft is special because the wings are swept forward unlike the usual sweptback configurations. The closely coupled canard and forward swept wing combination however is found to create a set of side body/canard and main-wing root vortices that induce strong wing rock oscillations on the main wing when the angle of attack exceeds 30°. Ross and Nguyen [31,12,13] further investigates the problem by removing the canard and main wings of the X-29 model, leaving only the fuselage and tail [31]. However the X-29 model still shows LCO, hence it can be concluded that the forebody vortices are indeed the primary cause of the sustained rotary oscillation.

Besides swept wings, Levin and Katz [23] report in seminal findings that the wing rock phenomena could be observed on rectangular wings of aspect ratio less than 0.5. Continuous oscillations are observed when the angle of attack for the rectangular planforms exceeds 20° and the AR is 0.47 or smaller. They also observe autorotation when the AR 0.25 wing was subjected to a higher alpha. The wing rock phenomena on low aspect ratio rectangular wings at high angles of attack are later verified by Williams and Nelson [32–34]. The wing rock phenomena study of rectangular wings is extended up to aspect ratio of 0.55 [32].

Levin and Katz [23] developed a postulate that the self-sustained oscillations are caused not only by the periodic changes in strength and location of leading edge vortices, but in this case also driven by the shedding of side edge vortices. A flow visualization of the leading and side edge vortices with helium/soap bubbles, laser sheet and smoke depicted the complexity of the flow field as compared to a delta wing. Particle Image Velocimetry (PIV) tests conducted by Gresham et al. [14,17] predict that dynamic cases show time lag in the development of vortices. Furthermore it was also discovered that there is significant variation in the positions of the side-edge vortices in the normal direction, but not in the span-wise direction.

Levin and Katz [23] concluded that, similar to the case of delta wings, the two longitudinal vortices provide the driving force for the oscillations. When the aspect ratio is reduced below 0.5, the decrease in roll damping is sufficient to allow the vortex-induced instabilities to develop into LCO. Moreover the loss of the average lift is less than in the case for delta wings during roll oscillations. Williams and Nelson [34] further investigate the fluid dynamic mechanisms which cause wing rock in low aspect ratio rectangular wings. They find such wings to be statically stable, but dynamically unstable. As a result, when the wing is set at high angle of attack, a small disturbance due to free-stream or wing surface can trigger self-induced oscillations. It is conjectured that the loss of leading-edge vortex seem to be responsible for the dynamically unstable roll motion.

Wing rock observed on rectangular wings of low aspect ratio has been attributed to be driven by the side-edge vortices. Besides low aspect ratio rectangular wings, Gresham et al. [15] report the observation of wing rock phenomena on rectangular wings of aspect ratios of 2 and 4. It was previously believed that wings with aspect ratio greater than 2 are unlikely to exhibit wing rock motion because the side-edge vortices develop far from each other or from the fuselage, therefore vortex–structure interaction is not likely to occur. Furthermore it has been established that wings of such aspect ratios have higher roll damping [29], hence reducing the probability of occurrence of wing rock phenomena on rectangular wings. However Gresham's observed that rectangular wings of aspect ratios of 2 and 4 exhibited wing rock, with standard deviation of roll angle of almost 50°. It is noted that the wing rock motion on high aspect ratio wings occur only in the post-stall regime, and that the amplitude of roll oscillations increases as the angle of attack is increased. The PIV experiments suggested that the rotational motion is likely driven by the vortex dynamics and vortex–wing interaction. Variation of the strength of the vortices due to variation in the position and time lag during the rolling motion are also observed.

Studies of wing rock on rectangular wings are relevant to small Unmanned Air Vehicles (UAVs) and Micro Air vehicles (MAVs) because such wing planform is relatively common for these aircrafts. In this paper, rectangular wings with aspect ratios in between 2 and 4.5 are considered as these are typical aspect ratios found in small UAVs and MAVs.

At present, the main purpose of MAVs is for surveillance and reconnaissance; hence the important performance measures include the capability to perform slow, sustained forward-speed flight with good maneuverability. To complete the flight missions, the MAVs are often required to fly at high angle of attack for prolonged duration. Due to their small mass, MAVs are highly affected by atmospheric gust conditions, which could expose them to further