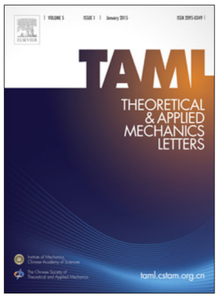
Accepted Manuscript



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PII: S2095-0349(17)30120-4
DOI: https://doi.org/10.1016/j.taml.2017.11.004
Reference: TAML 192

To appear in: *Theoretical & Applied Mechanics Letters*

Received date : 17 September 2017
Accepted date : 18 September 2017

Please cite this article as: S. Zou, A. Gao, Y. Shi, J. Wu, Causal mechanism behind the stall delay by airfoil's pitching-up motion, *Theoretical & Applied Mechanics Letters* (2017), https://doi.org/10.1016/j.taml.2017.11.004

Causal Mechanism Behind the Stall Delay by Airfoil's Pitching-Up Motion

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Abstract

Why the stall of an airfoil can be significantly delayed by its pitching-up motion? Various attempts have been proposed to answer this question over the past half century, but none is satisfactory. In this Letter we prove that a chain of vorticity-dynamics processes at accelerating boundary is fully responsible for the causal mechanism underlying this peculiar phenomenon. The local flow behavior is well be explained by a simple potential-flow model.

Keywords: dynamic stall, boundary vorticity flux, unsteady aerodynamics

Dynamic stall involves incredibly rich complex-flow phenomena that typically occur on a pitching foil. An airfoil oscillating sinusoidally through high angles of attack can produce high lift peaks while keep flow attached well beyond static stall angle of attack, and then suddenly falls off at a much larger dynamic stall angle ([1, 2]). Dynamic stall is a central subject of unsteady aerodynamics, playing an important and inevitable role in many manmade and natural flyers including helicopter rotors and insect flight. However, despite of the great efforts of a few generations of researchers in the past half century, one's current physical understanding of the hysteresis loops of lift, drag and moment during a dynamic stall cycle is still incomplete.

Ironically, compared with later stages of the dynamic-stall cycle after the lift falls off, for which the basic physics can at least be qualitatively inferred from the observed data by the motion and interaction of separated vortices, for the first stage, i.e., the stall delay as the foil pitches up, no satisfactory theoretical explanation has been available although the flow is still attached [3]. Therefore, in this letter we focus on a thorough exploration of the physical mechanism in this stage. It is evident that the phenomenon is related to the delay of boundary-layer separation during the pitching up; but no consensus has been reached on more detailed interpretation. According to Ericsson [4] and Ericsson and Reding [3], force on a pitching foil will deviate from the static forces realized at the instantaneous angle of attack due to the superposition of two effects based on von Kármán's theory [5]: the frequency-induced normal velocity distribution over the airfoil (the so-called q effect) that can be visualized as a frequency-induced camber; and the effect of rate of change of angle of attack (the so-called $\dot{\alpha}$ effect). During the upstroke, a pitching foil will appear as having a positive camber. But this explanation cannot explain the reason of the delay of boundary-layer separation. Due to dissatisfaction with the above explanation, Ericsson [6] further proposed that the motion of the leading edge produces the so-called "leading-edge jet" effect: During the "up stroke", the boundary layer is strengthened due to the large difference in tangential wall velocity at the stagnation point and the flow separation point. It is similar to the "rolling leading edge" that generates the Magnus lift, which enhances the boundary layer and delays stall. But this superficial analogy is irrational and can not hit the right physics either.

On the other hand, as summarized in Ref. [7], Carta [8] used a quasi-steady theory to show analytically that pitching airfoil reduces the adverse pressure gradient over the suction side than that of a steady airfoil, and further weaken as the pitching rate increases. Walker et al. [9] points out that a stronger static pressure suction peak is produced with the pitching rate increases, which ultimately lead to a more energetic dynamic stall vortex. While these interpretations were on the right track, unfortunately they are not thorough enough for obtaining quantitative links between the up-stoke motion, change of pressure distribution, and stall delay.

Actually, the desired links can be found in the well-developed boundary vorticity dynamics as reviewed by Lighthill [10], Wu and Wu [11, 12], and improved by Chen [13]. A complete rational theory on the stall delay by foil's pitching up can then be constructed as presented below.

It is well known that, by a very simple but elegant reasoning, Lighthill [14] laid down the basis on the vorticity generation at a stationary solid wall in two-dimensional (2D) viscous and incompressible flow. In wall tangent-normal coordinate (s, n), with $\boldsymbol{n}$ being the unit normal at the wall pointing out of the fluid, by applying the Navier-Stokes equation to the wall and using adherence condition, there is

$$\frac{1}{\rho}\frac{\partial p}{\partial s} = \nu\frac{\partial \omega}{\partial n}, \quad \frac{1}{\rho}\frac{\partial p}{\partial n} = -\nu\frac{\partial \omega}{\partial s}, \tag{1}$$

where ρ, p, ν, ω are density, pressure, kinematic viscosity, and vorticity, respectively. The first equation in Eq. (1) shows the balance between the on-wall tangent pressure gradient and

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