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3C10　Investigation of Aerodynamic Characteristics for Pitching Airfoil

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Abstract

This study investigates the unsteady aerodynamic behavior of a pitching airfoil at a low Reynolds number (Re = 5×10^4) across a range of reduced frequencies (k = 0.01 to 0.10), focusing on dynamic stall characteristics of lift and boundary layer transition point (BLTP). Aerodynamic forces were measured using a six-component force sensor, while BLTP was measured with Carbon Nanotube Temperature-Sensitive Paint (cntTSP). Results show that increasing reduced frequency leads to greater hysteresis in both lift and BLTP curves. Moreover, patterns of delayed stall onset, increased maximum lift coefficient, and shift in BLTP disappearance indicative of full flow separation and subsequent recovery point are noted in this study. Above quasi-steady frequency, the lift curve transitions to an elliptical hysteresis loop.

1. Introduction

Oscillating airfoils serve as a fundamental tool for investigating dynamic stall phenomena induced by unsteady flow conditions. Beyond their role in replicating flow oscillations, they provide a simplified yet representative model for studying the underlying principles governing dynamic stall. Since the early development of rotorcraft, dynamic stall under unsteady conditions has been a subject of extensive research. More recently, interest in this phenomenon has expanded due to its relevance in emerging unsteady aerodynamic applications, including flapping wing flight, axial and crossflow wind and tidal turbines, and wake interactions [1]. The complex nature of unsteady aerodynamics arises from the interaction of multiple time-dependent parameters, often exhibiting nonlinear and coupled effects. To gain a comprehensive understanding of such flows, it is essential to isolate and investigate the influence of individual governing parameters.

In rotorcraft forward maneuvers, which constitute a significant portion of the flight, the advancing and retreating blade phases of the rotor blades create highly unsteady, oscillatory conditions. This unsteadiness is characterized by the advance ratio, defined as the ratio of aircraft forward speed to rotor rotation speed. It can be experimentally reproduced using a pitching airfoil at varying reduced frequencies. Fundamental studies on this aspect of dynamic stall can be traced back to several decades, such as [2].

Recent advancements in micro-aerial vehicles (MAVs) and planetary exploration aircraft, particularly for Mars, have intensified interest in low Reynolds number aerodynamics (Re = 10^4 – 10^5).

The present study focuses on unsteady aerodynamic behavior at Re of 5 × 10^4, examining lift performance and boundary layer transition point (BLTP) dynamics across a range of reduced frequencies from quasi-steady to unsteady (k = 0.03 to 0.10). The boundary layer plays a critical role in the overall flow field around the airfoil. It influences flow states, such as laminar and turbulent flow, as well as flow separation and reattachment. These factors significantly impact pressure distribution, pitching moment characteristics, and lift generation.

2. Method

The experimental parameters are summarized in Table 1. The airfoil with an aspect ratio of 4 has wingtip plates installed on both ends with a gap within 1 mm to reduce 3D airfoil effects such as wingtip vortices. The Angle of Attack (AoA) was tested from 3° to 13° for both oscillating and static conditions to cover the regions of highest lift-drag ratio (L/D) and stall angle measured at AoA of 5° and 10.5° respectively on the static airfoil for the corresponding Re. During oscillations, the AoA of the airfoil was tracked by a potentiometer (RV30YN20S B102, Tokyo Cosmos Electric Co., Ltd) with standard deviation in terms of AoA measured at 0.004°, installed at the rotational axis and set to a sampling frequency of 5,000 Hz with the oscillating waveform following the same as used in [3].

Carbon Nanotube Temperature-Sensitive Paint (cntTSP) was used to visualize the convective heat transfer coefficient property of the chord-wise flow over the airfoil, which is then used to identify the boundary layer transition point (BLTP). Details and validation of this method have been demonstrated and are outlined in Ikami et al., 2021 [3]. cntTSP has the advantage of minimal flow interference and enables full-surface visualization of the airfoil over other methods, such as pressure taps, which are limited to discrete point measurements. The cntTSP experimental setup, instrumentation, and methodology follow that of the reference study. During testing, reference and run image sets are taken sequentially to maintain the same conditions. Images were captured using a high-speed camera (FASTCAM SA-X2 Photron) equipped with a 50 mm focus lens and a 575 ± 50 nm optical bandpass filter appropriate for the cntTSP formulation with an emission peak at 580 nm [4]. The cntTSP is illuminated by two blue LEDs (IL-106B, HARDsoft) of wavelength 462 nm. For the run images, the cntTSP coating was heated for 30 seconds at 300W/m^2 before immediately starting image capturing to induce a sufficient temperature differential for accurate measurements. Each image set was captured for 13.31 seconds. At least 5 minutes interval was given between each pair of reference and run sets for the airfoil to reach steady room temperature.

Table 1 Experimental Parameters.

Parameter		Value
Airfoil		NACA-0012
Airfoil Size (mm)		Span, 300 Chord, 75
Flow Speed (m/s)		10
Chord-based *Re*		5×10^4
Oscillation Range (°)		3 – 13
Oscillation Frequency, *k*		0.03, 0.05, 0.10
BLTP	Tool	cntTSP
	cnt pre-heat (s)	30
	Frames total	Static : 6,665 Oscillating : 66,568
	Exposure time (µs)	197.2
	Frame/second (Hz)	5,000
Lift	Tool	6-Component force gauge
	Meas. Time (s)	300
	Meas. freq (Hz)	5,000

For aerodynamic force measurements, the setup is depicted in Fig. 1. The aerodynamic force measurement setup uses the same setup as the cntTSP tests, with the addition of a six-component force sensor (Nano 2.5/2A, BL Force Torque Sensor) positioned between the oscillating mechanism and the airfoil. This placement ensures that the sensor captures only the aerodynamic forces and the airfoil's rotational inertia, with minimal influence from the oscillating mechanism. The rotational inertia is then removed by subtracting the results from wind-on against wind-off conditions while maintaining all other conditions. Both cntTSP and force measurement data had phase averaging performed to reduce noise further.

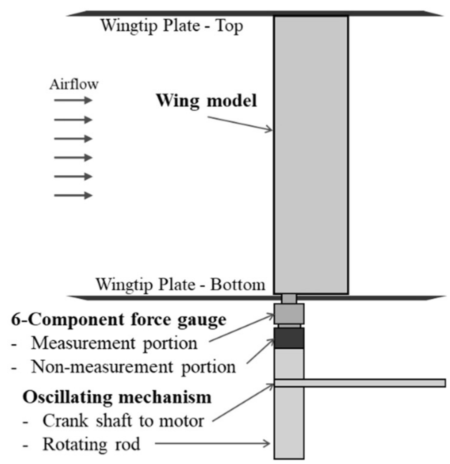

Fig. 1 Force Measurement Setup.

3. Results and Discussion

The lift coefficients (C_l) for varying reduced frequencies are presented in Fig. 2. A clear hysteresis loop is observed across all tested frequencies, indicative of dynamic stall effects. As the reduced frequency increases, the onset of stall is delayed, and the maximum C_l attained before stall increases correspondingly. Specifically, the stall angle shifts from 10.5° under static conditions to 11.1°, 11.5°, and 12.6° for reduced frequencies k = 0.03, 0.05, and 0.10, respectively. These results exhibit a consistent trend with previous studies reported in the literature [5], [6].

At lower frequencies (k = 0.03 and 0.05), the lift curves retain a shape similar to the static lift slope. However, as the frequency increases, this resemblance diminishes. The hysteresis loop widens, and the lift coefficient experiences a more pronounced drop during the downstroke corresponding to the onset of dynamic stall. This results in a larger reduced lift during the downstroke and a larger recovery period over a broader AoA range. At the highest frequency tested (k = 0.10), the lift response becomes predominantly governed by the oscillatory motion, forming an elliptical hysteresis loop.

Fig. 3 illustrates the variation of the BLTP with oscillation frequency. Similar to the lift data, the BLTP exhibits increasing hysteresis with frequency. As the AoA increases, the BLTP shifts progressively toward the leading edge and becomes indistinct near the stall onset, indicating full boundary layer separation. Upon pitch-down, the BLTP reappears and gradually moves rearward toward the trailing edge. The BLTP for these AoA points are left as gaps in the plots in Fig. 3. These disappearance and reattachment points are further illustrated in Fig. 4, showing a forward shift with increasing frequency. While higher frequencies delay the initial separation (i.e., increase the AoA at which the BLTP vanishes), they also delay reattachment during downstroke.

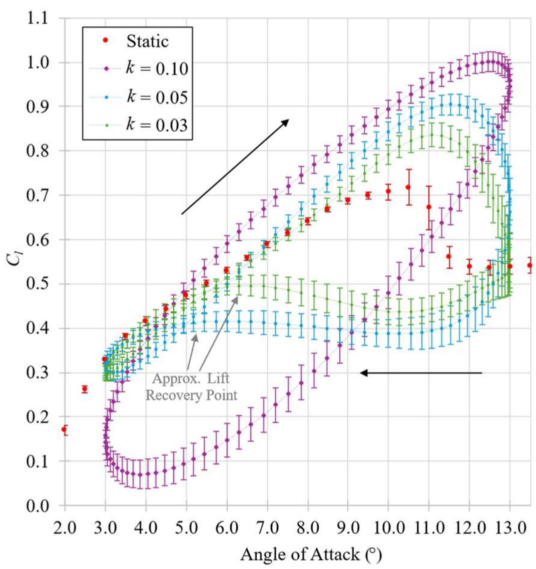

Fig. 2 C_l against Oscillating Frequency.

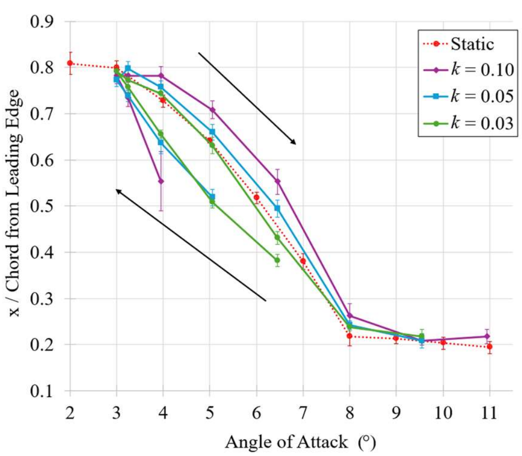

Fig. 3 BLTP against Oscillating Frequency.

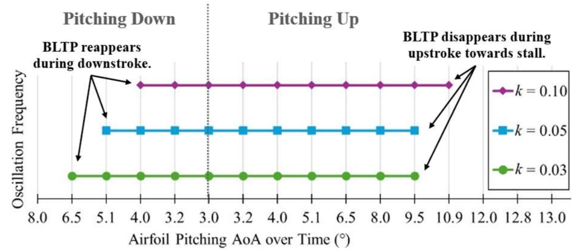

Fig. 4 BLTP Recovery and Stall against Oscillation Frequency.

4. Conclusion

This study investigated the unsteady aerodynamic characteristics of dynamic stall on a pitching airfoil at a low Reynolds number ($Re = 5 \times 10^4$) over a range of reduced frequencies from quasi-steady to unsteady (k = 0.01 to 0.10), focusing on lift performance and BLTP behavior. Results demonstrated that dynamic stall phenomena become increasingly pronounced with increasing oscillation frequency, as evidenced by increasing hysteresis, delayed stall onset, increased maximum lift coefficient, and shift in BLTP disappearance and recovery point.

At the highest frequency, the lift response deviated significantly from quasi-steady behavior, transitioning to an elliptical hysteresis loop. BLTP measurements obtained using cntTSP further revealed the frequency-dependency of transition location. The BLTP advanced toward the leading edge with increasing AoA and disappeared near the stall, indicating flow separation. During pitching down, the BLTP reemerged and moved downstream. This BLTP disappearance point and recovery point both shift forward at higher frequencies, resulting in higher AoA before disappearance but also lower AoA before recovery.

Acknowledgements

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