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An insight into the dynamic stall lift characteristics

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ABSTRACT

The article presents an insight into the dynamic stall lift characteristics through experimental work and a detailed survey of the seminal articles related to the phenomenon. Of particular interest is the dynamic stall observed on lifting surfaces as they undergo high-rate pitching motions at constant speeds up to a predetermined maximum angle of attack. The effects of several contributing parameters, such as the reduced frequency, Mach and Reynolds numbers of operation and the airfoil geometry, have been investigated. In addition, the behavior of the lift curve slope for an airfoil undergoing constant pitch dynamic stall has been analyzed in detail to gain a better understanding of the mechanism for the unsteady case. The unsteady lift-curve has been broken down into stages and each stage has been analyzed separately. The aim is to obtain a deeper insight into the lift generation mechanism involved in unsteady motion of the airfoil in order to improve the design of flow control techniques to exploit the dynamic stall process for a large range of applications.

1. Introduction

Dynamic stall and its associated effects are one of the most critical factors that limit the design and operation of aerodynamics-related applications such as helicopters, flapping-wing micro-air-vehicles and wind turbines. Dynamic stall can be considered as the delay of conventional flow separation on wings and airfoils caused by rapid variations in the angle of attack beyond the critical static stall angle due to virtually any kind of unsteady motion [8]. The unsteady motion, including pitching, plunging, heaving or a combination of these, results in the generation of intense vorticity on the suction side of the airfoil which is accompanied by large excursions in lift, drag and pitching moments, well beyond those observed during steady-state operation [9,17].

The unsteady effects associated with the rapid variations of the angle of attack of an airfoil were first observed by Kramer [41]. However, after this initial study, due to its limited perceived applicability at the time, little attention was given to the problem till it was identified on retreating blades of helicopters in the 1960s [28,31]. Due to the abrupt pitching moment excursions, the phenomenon has posed severe restrictions on the flight envelopes and attainable performance of the vehicle as well as imposing high demands on the material selection for the blade. Dynamic stall has also been observed on wind turbine blades [13,21,75], where it limits the performance of the turbines and negatively affects the fatigue life of the blades [80], thereby increasing the operation and maintenance costs. In wind turbines, dynamic stall has been observed to be caused by unsteady inflow, gusts, rapid changes in wind direction and yawed operation [13,76,81]. Furthermore, for conventional fixed-winged aircraft, vertical convections of large-scale air-masses can also induce dynamic stall on the wings during operation in the lower atmosphere resulting in turbulence, large fatigue loads and passenger discomfort. One aspect of dynamic stall research has, therefore, been motivated to principally avoid or suppress, to some extent, the coupled unsteady effects of the phenomenon [8,17,40,42,46,55,58].

In contrast to the above, research is also being directed towards efficient control of dynamic stall to take advantage of the increased lift. This new-found interest primarily stems from the study of bird and insect flight. Flapping motion is the major mode of locomotion for the flying insects and birds, and the swimming of fish [50,93]. It has been observed that the wing area and aspect ratio of birds and insects is generally too small in comparison to their body mass to sustain any reasonable steady-state flight [82]. Therefore, it is believed that birds and insects take advantage of the dynamic stall effects such as the high magnitude of unsteady lift to sustain their flights [49]. The high manoeuvrability of flying animals has also piqued interest in improving the manoeuvrability of fighter jets through exploiting the unsteady aerodynamic effects of dynamic stall. However, unlike the previous cases where sinusoidal oscillations are commonly encountered and studied, focus on aircraft manoeuvrability enhancements [43,64] has directed the research attention towards airfoil pitching at constant rates to high angles

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of attack [89]. Furthermore, recent interest in the development of micro-air-vehicles, motivated by military needs of aerial reconnaissance in confined spaces, has also increased the need in understanding of the unsteady phenomenon to exploit the high magnitudes of the lift force produced.

However, regardless of the significant progress made towards the understanding of unsteady separation in recent years, dynamic stall still remains one of the major unsolved problems in aerodynamics. A detailed understanding of the complex flow phenomenon is required for its efficient control and possible application. Therefore, the primary focus of the current article is to decipher the trends in the lift curve of an airfoil pitching at constant rates to predetermined maximum angles of attack. The choice of constant pitch rates as the principal unsteady motion inducing dynamic stall, instead of the more conventionally studied sinusoidally-pitching motions, is primarily due to the limited insight available for the former type. Consequently, an attempt has been made to highlight the fundamental aspects of dynamic stall lift using literature, theories and supplementary experimental and flow visualization studies.

2. Experimental setup

2.1. Pressure measurements

Pressure measurements were carried out on a pitching airfoil in the closed-loop KC Wind Tunnel at the University of Adelaide. The working section of the tunnel has a cross section of 0.5 m × 0.5 m as shown in Fig. 1a. The turbulence intensity of the working section was measured to be approximately 0.6%. The test Reynolds number based on the airfoil chord length was varied between 50,000 and 150,000 for the experiment.

The model selected for the study was the thick, symmetric NACA 0021 airfoil, constructed from acrylic. The airfoil was manufactured in two parts, with a total of 17 pressure taps along the mid-span based on a similar distribution to that of Jumper et al. [39]. The pressure taps were concentrated near the leading edge of the airfoil, as shown in Fig. 1b, since the largest pressure variations were expected in this region. For both the suction and pressure sides, a total of nine pressure taps were drilled in the foil surface. The chord length of the airfoil was 100 mm and the span was 495 mm, leading to an aspect ratio of 4.95 and a maximum blockage of approximately 12% at an angle of attack of 40 deg. The aspect ratio of the airfoil was considered adequate since in previous experiments [6,32,54,59], aspect ratios of generally less than 4 have been used to determine the dynamic effects on pitching airfoils. Furthermore, as indicated by Leishman [47], dynamic stall characteristics of finite-span wings are qualitatively similar to those of two-dimensional airfoils. Therefore, no corrections were applied to the results presented in the article. On the other hand, as shown by Granlund et al. [26], dynamic blockage is more benign compared to static blockage and does not influence the results to a large extent. Moreover, since at present no viable methods are available to determine wall corrections for the dynamic case, the results presented here are as measured without any corrections applied.

The airfoil was mounted vertically in the center of the working section as indicated in Fig. 1a. The bottom of the foil was connected to a heavy steel pedestal and the top was pinned to the ceiling of the working section to mitigate vibrations. The gap between the ceiling of the working section of the tunnel and the airfoil top was less than 5 mm in order to minimize three-dimensional effects due to tip vortices. This is in accord with the prescribed standards for the gap in two-dimensional studies [7] and is similar to earlier experiments performed in the tunnel [30]. The airfoil was instrumented with *TruStability*® differential pressure sensors that were board-mounted, self-calibrated and placed inside the airfoil as shown in Fig. 1b. The maximum deviation of the sensors is 0.25% from the best-fit-straight-line fitted to the output measured over the pressure range of ±1 psi. The sensors provided analogue outputs and their frequency response was defined by the sampling rate of the data acquisition system. The positive port of the differential pressure sensors were connected to the pressure taps using copper tubing and flexible plastic hoses. The length of the hoses was kept as small as possible in order to minimize any damping and phase delays in the pressure response of the system following the recommendation of Irwin et al. [33]. Even then, a slight delay of 0.05 s in the pressure response of the system was observed during initial testing, which was corrected. On the other hand, as shown by Yoshida et al. [98], the bends in the hoses have a negligible effect on the pressure measurements and were, therefore, untreated. The negative ports were connected to a reference plenum that was in turn left open to the ambient conditions to provide the freestream static pressures. The differential measurements were recorded digitally at a rate of 5000 samples per second using the *National Instruments*® USB-6210 Data Acquisition System (NI-DAQ). The differential pressures were non-dimensionalized using the dynamic pressure of the freestream, which was measured using a Pitot-static tube and the Fluke 922 Airflow meter. The airfoil was rotated about its mid-chord using a 22 mm diameter *Maxon*® brushed DC electric motor coupled with a 157:1 reduction gearbox to provide the suitable moment for the experiment. The motor reached the set rotational speed in approximately 0.03 s which was considerably smaller than the run-time for experiment. The motor was placed inside a steel frame, shown in Fig. 1c, which in turn was mounted on the heavy steel pedestal to inhibit vibrations. An electronic position encoder was connected to the motor to monitor the position and velocity. The encoder was connected to a computer-based control system which was used to provide the position and velocity information for the experiment through an in-house code developed using *NI-LabVIEW*®.

The chord-normal (C_N) and chord-axial (C_A) aerodynamic force coefficients were obtained through integration of the area between the pressure distribution curves using the following expressions:

$$C_N = -\oint C_p d\left(\frac{x}{c}\right)$$

$$C_A = \oint C_p d\left(\frac{y}{c}\right)$$

The numerical integration was performed using the trapezoidal rule for non-uniform spacing between the pressure taps following Hansen [29] as follows:

$$\int_a^b f(x)dx \approx \frac{1}{2}\sum_{k=1}^{N}(x_{k+1} - x_k)(f(x_{k+1}) + f(x_k))$$

Here, $f(x)$ is the pressure coefficient as a function of chordwise position, N is the total number of pressure taps on both the suction and pressure sides, x is the chordwise position and a, b are the stagnation pressure taps. The numerical integration was carried out in the anticlockwise direction starting from the leading edge of the airfoil forming a closed loop around the foil. Finally, the lift (C_L) and pressure drag (C_D) coefficients were determined using the coordinates transformation.

Each test case was repeated ten times in order to obtain the averaged results that are presented in this article.

2.2. Hydrogen-bubble flow visualizations

Additional investigations were carried out in this series of experiments to understand the dominant flow features during