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Measurements of the flow due to a rapidly pitching plate using time resolved high resolution PIV

A-J. Buchner [a,*,1], J. Soria [a,b]

[a] *Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC), Department of Mechanical and Aerospace Engineering, Monash University, Melbourne, Australia*
[b] *Department of Aeronautical Engineering, King Abdulaziz University, Jeddah, Saudi Arabia*

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ABSTRACT

The flow topology arising from unsteady airfoil motion is complex, but the benefits of understanding such flows extend to a wide variety of applications. Natural flows such as those induced by birds or insects during flapping flight, or by the rapidly moving fins of swimming fish, as well as flows over the manoeuvring wings of micro air vehicles (MAVs) or the rotors of helicopters or wind turbines exhibit behaviours typical of rapidly manoeuvring airfoils. This paper presents measurements and discussion on a set of recent experiments performed on a rapidly pitching plate in low Reynolds number flow. Time resolved particle image velocimetry (PIV) data with a high spatio-temporal resolution are presented, and the main features of the flow are identified. Measurements are taken at six Reynolds numbers ranging between 1500 and 10 000 and an analysis is given of the temporal evolution of the massively separated flow at the leading edge as well as at the trailing edge and in the wake. Individual coherent structures are located and tracked, and the variation of their strength and fluctuation are quantified as a function of time. Several key observations are made regarding the effect of Reynolds number on the topology of the wake structure of a pitching flat plate.

1. Introduction

Rapidly pitching airfoils are known to produce highly complex wakes consisting of multiple coherent structures which interact both mutually and with the airfoil [14,6,9,19]. The wakes produced by rapidly pitching airfoils can, depending on the kinematics of the airfoil, contribute to thrust or lift production but the practical use of the high instantaneous forces produced by pitching airfoils remains dependent on building a more comprehensive, rigorous, and detailed understanding of the physics governing the production, stability, interaction dynamics, and turbulent decay of the coherent structures shed from the airfoil. These processes are complex and highly nonlinear. Recent years have seen a rapid expansion of investigations in this area [23,6,19,18,8,3,2] but the large parameter space affecting such flows, and the difficulties in performing accurate measurements on flows in the vicinity of rapidly moving objects or surfaces has constrained progress.

Flows separating from rapidly moving airfoils are observed in a variety of contexts. The motivation behind the present study was originally with a view to application in the field of bio-inspired flight vehicles, however helicopter rotors, wind turbines, rapidly manoeuvring air and sea craft, unsteady gust-driven aerodynamics, and biological propulsion utilising oscillating propulsors such as fins or wings all exhibit complex behaviours related to dynamically separating flows. Of primary importance to the fundamental understanding of such flows is a complete knowledge of the production, evolution, and interaction of coherent structures such as vortices and shear layers shed by the pitching foil, a daunting task for such a complex flow and made even harder by the variability of the flow from experiment to experiment [25]. For this reason it is imperative to very carefully choose the conditions of the investigation so that the parameter space within which the problem resides is manageable.

When considering the dynamics of rapidly pitching airfoils, the problem can be divided into two main categories; periodic, and non-periodic. Periodic motion relates to those applications such as steady cruising insect or bird flight, whilst the less studied non-periodic problem is more applicable to manoeuvring such as the perching or acceleration of birds, or gust response of an aircraft wing. The non-periodic problem is perhaps the more fundamental

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[*] Corresponding author.
E-mail address: abel-john.buchner@monash.edu (A-J. Buchner).
[1] *Current address:* Department of Mechanical and Aerospace Engineering, D225 Engineering Quadrangle, Princeton University, Princeton, NJ 08540, USA.

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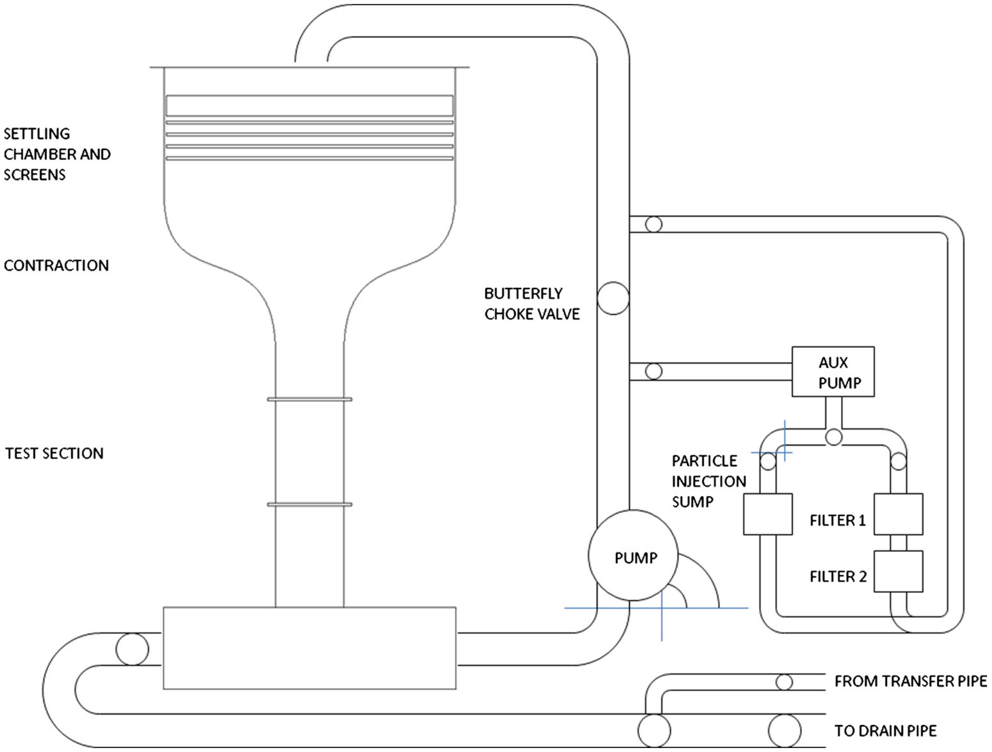

Fig. 1. Schematic of the experimental facility.

of the two, as the flow separation characteristics depend only on the airfoil kinematics and freestream conditions. It is a richer case, which presents a more significant challenge to the experimentalist who cannot make the common assumption of statistically stationary flow, or assume temporal periodicity, in analysing the experimental data. This article details an experimental measurement campaign focusing on providing much needed time resolved measurements of the flow around an airfoil, pitched rapidly to a high angle of attack and subsequently returned to a position aligned with the freestream. The kinematics chosen for this investigation are identical with the motion presented in Ol [19] and Buchner et al. [2], and represent a single, non-periodic pitch motion. In this way it is possible to study the growth and separation of coherent structures, as well as the downstream evolution of the same, in isolation from their preceding counterparts.

Non-periodic motions such as this have received significant attention recently. It is considered that there exists now a substantial repository of knowledge regarding the flowfield produced by such a pitching plate, allowing solid benchmarking of the current results, but that insufficient attention has previously been paid to quantitatively enunciating the effects of Reynolds number on the massively separated vortical flowfield. This paper addresses this shortcoming in the context of previous experimental and numerical investigations using similar kinematics [16,8,3,2]. Some previous investigations have considered the development of three-dimensionality in massively separated dynamic stall flows [3,8,2], an effect which has been shown to be somewhat Reynolds number dependent, but the present study remains focused on the Reynolds number dependency of the two-dimensional structures associated with dynamic stall. [13] outlines some two-dimensional Reynolds number dependency of vortex shedding from a pitching airfoil, but only at small pitch amplitudes. The present study provides experimental velocity data for large scale pitch amplitudes acquired at a sufficiently faster rate than the timescales of plate motion to be considered temporally resolved. This significant advantage has only in the past few years become feasible.

The review presented by Ol [17] claims that there exists little dependency on Reynolds number in the range 10^3 to 10^4, but this is based on a very brief qualitative comparison of several experimental and computational studies and due to the unavailability of temporally resolved experimental data at the time, this is understandable. The current investigation, in providing such temporally resolved data gives a clearer and more quantitative view of the Reynolds dependency in this range. It is found that significant dependency on Reynolds number exists, but that it is confined primarily to the smaller scale arrangement and dynamics of the massively separated vortical structures whilst the larger scale features are largely Reynolds invariant.

2. Details of experiment

2.1. Description of experimental facility

Experiments are performed in a vertical water tunnel facility at the Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC) at Monash University. The tunnel has a perspex test section of 250 × 250 mm cross-section and upstream development length of 550 mm. A large, symmetric contraction with a ratio of $16:1$ preceded by a settling chamber with multiple settling screens lead to a relatively low freestream turbulence intensity at the freestream speeds relevant to this experiment, with no measurable long-period freestream velocity variation. A schematic layout of the LTRAC vertical tunnel facility is shown in Fig. 1.

Pre-mixed seeding particles are introduced into the system via an exchange sump on an auxiliary circuit attached to the return path of the facility, and filtration between experiments is also performed via this circuit. Freestream velocity calibrations and turbulence level at both the testing position and a position 275 mm upstream are provided in Fig. 2.

The airfoil used in these experiments is a flat plate with hemicylindrical rounded leading and trailing edges, constructed of carbon fibre, with a chord length of 50 mm and thickness of 1.6 mm. The plate spans the full width of the 250 mm wide test section,