

SPATIO-TEMPORAL COHERENT FLOW STRUCTURE EVOLUTION OF ZNMF JET CONTROLLED NACA 0015 AIRFOIL FLOW

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ABSTRACT

One of the primary aims of flow separation control is to prevent boundary layer separation and as such extend the effective operational range of engineering devices such as diffusers, compressors, turbines and airfoils. Separation flow control can be implemented by either the addition of fixed geometric features such as vortex generators or flaps, (referred to as passive control), or via the addition of kinetic energy in the form of small-scale or large-scale perturbations in order to modify the flow (*i.e.* active control [2]). Active control can take various forms, such as steady or oscillatory blowing and/or suction, vibrating surfaces or acoustic excitation (see [3]) and unlike passive methods can be deactivated or adjusted to cater to a wider range of operating conditions.

For the case of flow over airfoils, active flow control via periodic excitation has been shown to delay separation and hence, increase lift at angles of attack (AoA) beyond the natural stall angle [11]. Time-dependent forcing, such as that produced by pulsating jets, has been shown to require of the order of 80% less momentum than steady blowing or suction for the same lift coefficient [10]. This difference is thought to be associated with the excitation of frequency (*i.e.* temporal) characteristics, which are related to characteristic time-scales of the flow and hence depend on the AoA. For most airfoils at low AoA the flow will be completely attached such that the dominant frequency f_{wake} is associated with the time-scale of the wake of the airfoil and is proportional to the free-stream velocity U_∞ and the length-scale of the wake L_{wake} [9], which can be

expressed as:

$$f_{wake} \propto \frac{U_\infty}{L_{wake}}. \quad (1)$$

As the AoA increases, flow separation occurs, introducing frequencies associated with the separated shear layer whose frequency f_{SL} is proportional to the shear layer advection velocity U_{SL} and its momentum thickness θ_{SL} [4], such that:

$$f_{SL} \propto \frac{U_{SL}}{\theta_{SL}}. \quad (2)$$

For some airfoils at moderate AoA this separation may occur near the leading edge, allowing the flow to reattach to the airfoil further downstream and thereby forming a transient separation bubble with an associated frequency f_{sep} , proportional to the time-average separation length L_{sep} [8], such that:

$$f_{sep} \propto \frac{U_\infty}{L_{sep}}. \quad (3)$$

At high AoA, where separation control is of most interest, the flow usually will not reattach and the dominant or natural frequencies will be f_{wake} and f_{SL} .

The results presented in this paper are concerned with the flow configuration used by [11], in which ZNMF jet forcing was applied at the leading edge of a NACA-0015 airfoil at $Re = 3 \times 10^4$. In this case laminar separation occurs in the vicinity of the leading edge for the unforced case. From a series of lift force measurements over a range of AoA, forcing frequencies and momentum blowing coefficients, [11] observed a maximum lift enhancement of 45% at AoA $\alpha = 18^\circ$ when

excitation was applied at optimal frequencies of $f^+ = 0.65$ and 1.3. Dye flow visualisations and planar PIV measurements were performed which show the dramatic reduction of the separated flow region when this forcing was applied (Figure 1). However these measurements were unable to capture the dynamics and frequencies associated with these flow structures in either the excited or natural case.

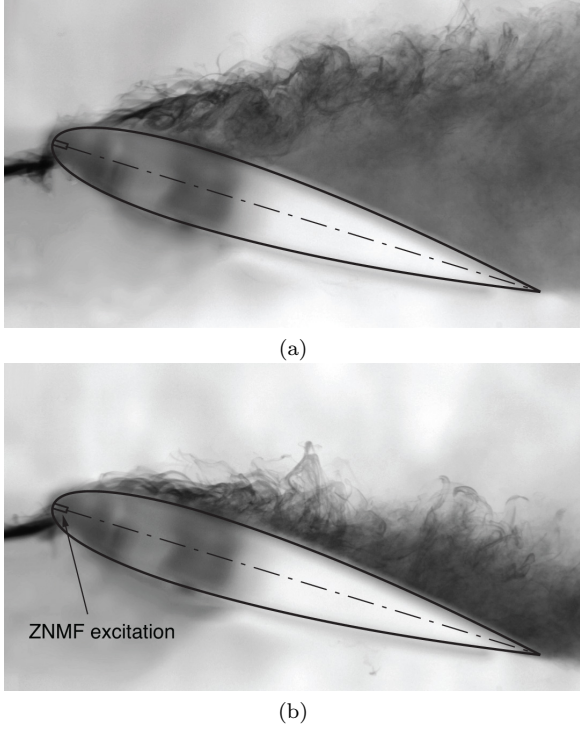


Figure 1: Dye flow visualisation adapted from [11] of a NACA-0015 airfoil, $Re = 3 \times 10^4$, $\alpha = 18^\circ$: (a) unforced case; (b) ZNMF jet forcing at the leading edge, $f^+ = 1.3$, $c_\mu = 0.0014$.

Recently [6] studied the same configuration using large-eddy simulation (LES) to investigate the frequencies and stability modes present in the unforced base flow and to improve understanding of the separated flow and the reason for the optimal forcing frequency. Results identified both a shear layer instability at the leading edge and bluff body shedding with the most unstable mode corresponding to a frequency on the order of the first sub-harmonic of the leading edge shear layer frequency $f_{SL}/2$.

This paper presents fully time-resolved measurements of the flow acquired using HR-PIV to provide the spatio-temporal 2C-2D velocity vector field over the NACA-0015 airfoil [1] in the same experimental configuration and facility as [11]. The experiments are conducted in a horizontal recirculating water tunnel, which consists of 5 working sections of 1.1 m length and 500 mm \times 500 mm cross-section. An extensive characterisation of this facility is given in [7]. A Perspex NACA-0015 airfoil with a chord length $c = 100$ and a span of 510 mm is mounted vertically in the second working section such that the top of the airfoil protrudes above the free-surface at all times. A gap of approximately 2 mm is left between the airfoil and the floor to enable adjustment of the AoA without damaging the tunnel floor. The free-stream turbulence intensity, assessed by PIV is less than 0.75%. The tunnel is operated at a freestream velocity of $U_\infty = 260$ mm/s at 25.5 $^\circ$ C, corresponding to a chord-based Reynolds number

of $Re = 3 \times 10^4$, defined as:

$$Re = \frac{U_\infty c}{\nu} \quad (4)$$

The ZNMF jet forcing is applied along the entire span of the airfoil and normal to the leading edge, via a rectangular slot of height $h = 0.15 \pm 0.05$ mm and length $l = 460$ mm. The jet is driven by pressure oscillations that are supplied to a cylindrical cavity with a diameter of 5 mm, located behind the slot. Unlike experiments in air, the high viscosity and incompressible behaviour of water means that the optimal forcing frequency ($f = 3.3$ Hz) can be achieved using a stepper motor driven piston of diameter $D_p = 20$ mm coupled with a Scotch-Yoke mechanism, as shown in Figure 2. This external mechanism allows the use of a relatively thin airfoil with a low blockage ratio, while also enabling easy adjustment of the forcing frequency f and amplitude \hat{a} by varying the motor speed and Scotch-Yoke crank length, respectively.

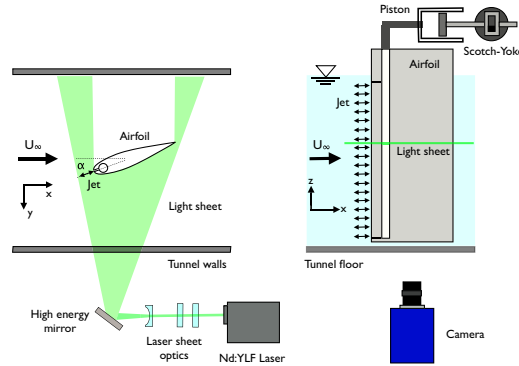


Figure 2: Schematic of the experimental setup in the horizontal water tunnel.

The flow features and frequencies associated with both the uncontrolled baseline case and the open-loop leading edge ZNMF control case at the optimum frequency of [11] are studied based on the HR-PIV measurements. This data also allowed the recovery of the Koopman modes associated with the separated airfoil flow [5] which are also discussed.

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