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Near wake development of a wing tip vortex under the effect of synthetic jet actuation

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ABSTRACT

An experimental investigation on the effectiveness of synthetic jet actuation in controlling a wingtip vortex of a rectangular, square-tipped NACA 0012 wing at a chord Reynolds number $Re_c = 8 \times 10^4$ is reported. Spanwise pressure measurements on the suction surface of the wing showed that forcing the wingtip vortex at a frequency in the range of frequencies of the long and short-wave instabilities resulted in decreased pressure coefficients as compared to natural vortex measurements. Two control configurations were then considered for hotwire wake measurements, namely, a "least effective" configuration with momentum coefficient $C_\mu = 0.004$ and actuation frequency $F^+ = 0.71$, and a "most effective" configuration with $C_\mu = 0.04$ and $F^+ = 0.213$. Measurements at $x/c = 1$ showed that, under the latter case, the vortex was stretched into an ellipsoid shape with a 50% average decrease in the peak tangential velocity, and 30% broadening of the effective vortex core radius. Further downstream, the vortex seemed to regain its universal shape but with reduced strength. The results suggested that the lower frequency control configuration allowed the synthetic jet to travel larger distances into the vortex bringing turbulent structures within its core resulting in increased mixing and subsequently decreased vortex strength.

1. Introduction

Wingtip vortices are of great importance in aerodynamics because of their impact on many practical applications such as airplane drag, wake encounters in congested airports, vortex blade interaction, noise and vibration, and more. For example, induced drag caused by wingtip vortices plays a significant role in its performance as it can amount to up to 40% of the overall aircraft drag [1]. Similarly, the region of strong coherent rotational flow induced by wingtip vortices typically persists for several nautical miles which may pose a potential hazard to the following aircraft both in ground proximity and en-route [2,3]. Imposed roll (up to 45 degrees has been reported [4]), loss of altitude and stable flight conditions and strong structural dynamic loads are some of the dangers that the following airplane may encounter [5]. Control devices capable of mitigating or weakening the effect of wake vortices to safe levels could enable operational improvements through the reduction in the minimum separation distance between airplanes.

Despite the numerous studies on wingtip vortex flows, the state of knowledge is yet to provide a firm base for the design of effective wingtip geometry or control devices. The idea behind developing wingtip devices is to mainly introduce instabilities to initiate wake destruction [6] and therefore improve the aerodynamic characteristic of the corresponding lifting surface [7,8]. Methods of wingtip vortex control can be divided into either passive or active, airborne or ground-based. In the past decade, several methods have been proposed to modify the structure of wingtip vortices on airplane wings they include wing endplates, wingtip sails [9], winglets [10,11], spiroid winglets [12], wingtip mounted slender half-delta wing [13,14], oscillating flaps [15], oscillating winglet flaps [16], plasma actuator [17], continuous blowing [18,19] and pulsed jets [20–22].

Despite the overall decrease in total drag, winglets have been shown to increase parasitic drag [23]. They may also pose a structural challenge and an inherent limitation to aircraft design as they are generally optimized for part of the flight envelope. Nevertheless, these wingtip devices have been traditionally adopted by aircraft manufacturers.

More recently, a patent entitled "Surface Structure on a Ground Surface for Accelerating Decay of Wake Turbulence in the Short Final of an Approach to a Runway" has been suggested in [24], and

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Nomenclature

A_j	Synthetic jet slot area	m^2
A_w	Half-wing planform area	m^2
C_μ	Synthetic jet momentum coefficient	
C_p	Pressure coefficient	
$C_{p_{nv}}$	Pressure coefficient of the natural flow	
F^+	Non-dimensionalized actuation frequency	
L_j	Synthetic jet slot length	m
R_{uu}	Normalized streamwise Reynolds stress	
R_{vv}	Normalized spanwise Reynolds stress	
R_{ww}	Normalized transverse Reynolds stress	
Re	Reynolds number, $\bar{U}_\infty c/\nu$	
S_{xx}	Frequency spectra of $\bar{U}_x$	m^2/s
S_{yy}	Frequency spectra of $\bar{U}_y$	m^2/s
S_{zz}	Frequency spectra of $\bar{U}_z$	m^2/s
T	Actuation period	s
$\bar{U}_0$	Local freestream velocity	m/s
$\bar{U}_\infty$	Wind tunnel freestream velocity	m/s
$\bar{U}_\theta$	Circumferential velocity	m/s
$\bar{U}_x$	Mean axial velocity	m/s
$\bar{U}_y$	Mean spanwise velocity	m/s
$\bar{U}_z$	Mean transverse velocity	m/s
$\bar{V}_j$	Synthetic jet space time-averaged velocity scale	m/s
$\bar{\Gamma}$	Circulation	m^2/s
$\bar{\Gamma}_c$	Vortex core circulation	m^2/s
$\bar{\xi}_x$	Streamwise vorticity	s^{-1}
$u\bar{u}$	Streamwise Reynolds stress	m^2/s^2
$v\bar{v}$	Spanwise Reynolds stress	m^2/s^2
$w\bar{w}$	Transverse Reynolds stress	m^2/s^2
δ	Wing dihedral	deg
λ	Synthetic jet stroke length	m
λ_L	Wavelength of the Crow's instability	m
λ_S	Wavelength of the Widnall's instability	m
(x, y, z)	Streamwise direction from wingtip quarter-chord reference location	m
ρ_∞	Freestream air density	kg/m^3
ρ_j	Synthetic jet air density	kg/m^3
$\vec{v}_j$	Synthetic jet exit velocity field	m/s
c	Wing chord	m
f	Frequency	Hz
f^*	Non-dimensionalized frequency	
f_λ	Frequency of the corresponding instability	Hz
f_a	Synthetic jet actuation frequency	Hz
f_{cut}	High-pass filter cut-off frequency	Hz
k	Turbulent kinetic energy	m^2/s^2
r	Radial distance from mean vortex axiscenter	m
r_c	Vortex core radius	m
r_{NV}	Vortex core radius of the natural vortex	m
r_{C1}	Vortex core radius of case C1	m
r_{C2}	Vortex core radius of case C2	m
$b/2$	Wing half span	m
${f^*}_{cut}$	Non-dimensionalized high-pass filter cut-off frequency	

later tested by the German Aerospace Center (DLR) [25] to reduce the vortex effects encountered in airport runways. The method consisted of placing parallel ground plates near the runway threshold. They found that the introduction of plate lines generate secondary vortices which were drawn and looped around the wing tip vortex. The highly intense interaction of the wingtip vortex and the secondary vortices resulted in a rapid spreading and propagation of disturbances along the wake-vortex direction leading to a fast approaching and early vortex decay in ground proximity [25]. The suggested ground-based method requires relatively little technical effort to be tested and to be installed in airports. However, this method remains passive. The difficulties in parametrically describing all these designs and computationally testing them are continuously driving designers of modern aircraft towards more known, corroborated and simple choices that can be adapted to all flight configurations, specifically landing and take-off. For these reasons, the attention has been recently shifted towards active flow control techniques.

As opposed to passive devices, the former can be optimized for a given flight segment of the flight envelope, leading to improved control efficiency of the wingtip vortex. Heyes et al. [20] used pulsed span-wise air jets at the wingtip to perturb a vortex evolving in the near field. They demonstrated that wingtip jets caused a displacement of the vortex with a magnitude proportional to the blowing rate. They also showed that with actuation, a remarkable increase in core radius accompanied with a decrease in peak circumferential velocity and an increase in the core axial velocity deficit were directly related to the added mass of fluid ejected from the wingtip slot. A more elaborate active flow control technique, which uses zero net mass flux fluidic perturbation namely, synthetic jets (SJ) is believed to outperform steady blowing and steady suction as it exhibits less structural challenges and provides more effective forcing in that no air bleed from the engine is required to operate SJs as they add momentum, turbulence and vorticity to the flow. In addition, SJs introduce variable frequency disturbances that can be tuned to the inherent instabilities of the wingtip vortex. Margaris and Gursul [26] conducted a PIV study on the effect of synthetic jet actuation (SJA) on a wingtip vortex using a wing equipped with several blowing slot geometries placed at different positions at the wingtip proximity. They found that the rate of reduction in the tangential velocity was comparable to that obtained with a continuous blowing. However, no conclusions were drawn on the choice of actuation parameters. Duraisamy and Baeder [27] numerically reproduced the experimental study reported in [20] on the effect of spanwise steady and oscillatory blowing on the wing tip vortex. They achieved a reliable validation of the mean flow field by using a high order accurate scheme with appropriately refined meshes. They concluded that the interaction of the pair of counter-rotating vortices with the vorticity sheet feeding the wing tip vortex resulted in an increased turbulence level in the vortex core; however, no appreciable control effect was achieved by means of SJA as compared to continuous blowing. In a recent study, Greenblatt [28] used a different technique to control the wingtip vortex consisting of deflecting an outboard flap mounted on a wing semi-span and then, modifying the shear layer above the flap by means of SJ perturbations. He showed that a relatively small control momentum coefficient can produce large changes in the shear layer deflection and the flap pressure distribution with relatively small changes in the local aerodynamic loads. However, the deflection of the shear layer was found to move the wing tip vortex outboard considerably, and change the axial velocity in the vortex core from a wake-like to a jet-like flow. A substantial increase in the core axial vorticity and an associated overshoot in circulation were both reported when the actuation was applied. In a more recent study, Dghim et al. [29] used a high aspect ratio curved slot SJ mounted at the tip to control a wing tip vortex at a relatively low Reynolds number. They reported nearly 30% decrease in the core axial vorticity and an increase in the lateral diffusion of the vortex due to turbulence addition. However, the selection of the SJ control parameters was left inconclusive. In