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Conditioning of unsteady cross-flow instability modes using dielectric barrier discharge plasma actuators

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ABSTRACT

In this study, experiments are performed towards the identification and measurement of unsteady modes occurring in a transitional swept wing boundary layer. These modes are generated by the interaction between the primary stationary and travelling cross-flow instabilities or by secondary instability mechanisms of the stationary cross-flow vortices and have a crucial role in the laminar-to-turbulent breakdown process. Detailed hot-wire measurements were performed at the location of stationary instability amplitude-saturation. In order to deterministically capture the spatio-temporal evolution of the unsteady modes, measurements were phase- and frequency-conditioned using concurrent forcing by means of a dielectric barrier discharge plasma actuator mounted upstream of the measurement domain. The actuator effect, when positioned sufficiently upstream the secondary modes onset, was tuned such to successfully condition the high-frequency *type-I* and the low-frequency *type-III* modes without modifying the transition evolution. Two primary stationary cross-flow vortices of different amplitude were measured, revealing the effect of base-flow variations on the growth of travelling instabilities. The response of these two stationary waves to the naturally occurring and forced fluctuations was captured at different chordwise positions. Additionally, the deterministic conditioning of the instability phase to the phase of the actuation allowed phase-averaged reconstruction of the spatio-temporal evolution of the unsteady structures providing valuable insight on their topology. Finally, the effect of locating the actuator at a more downstream position, closer to the *type-I* mode branch-I, resulted in laminar-to turbulent breakdown for the high-frequency actuation while the low-frequency forcing showed milder effects on the transition evolution.

1. Introduction

1.1. Background

Swept wings and axisymmetric bodies at incidence or rotating about their axis feature three-dimensional streamlines. Within the boundary layer, the flow experiences an imbalance between pressure and inertial forces and tends to be torn by the pressure gradient. This phenomenon causes a secondary flow called *cross-flow* (CF), which leads to inviscidly unstable boundary layers. In low free-stream turbulence environments, this instability manifests in stationary co-rotating vortices (the so-called cross-flow vortices (CFVs)), approximately aligned with the flow [2,29]. These cross-flow vortices, although weak disturbances of the wall-normal and spanwise velocity components, deeply modify the base-flow boundary layer by displacing low-momentum air upwards towards the outer edges of the boundary layer and vice versa, thus causing a strong modification of the spatial arrangement of the streamwise velocity [1,2]. Strong velocity gradients along the wall normal and spanwise directions appear in the transitional boundary layer, giving rise to the development and amplification of Kelvin-Helmholtz (KH) type instability modes [3]. Two different travelling modes (*type-I* and *type-II*) have been individuated and named after their locations with respect to the streamwise velocity gradients as *z-mode* and *y-mode*, respectively [22]. These two modes feature very high frequencies and explosive spatial amplifications. Malik et al. [21] and White and Saric [38] reported a third region of strong fluctuations related to the interaction between the primary travelling cross-flow waves and the stationary CF vortices. Fischer and Dallmann [10], Högberg and Henningson [13], Wassermann and Kloker [35] and Bonfigli and Kloker [3] interpreted these fluctuations as a secondary instability mechanism. This mode is defined in literature as *type-III*. The frequency of the *type-III* mode has been identified to be one order of magnitude lower than the *type-I-type-II* modes. In addition, the spatial growth rates are significantly lower for this low-frequency mode.

High-frequency fluctuations were experimentally observed by Poll [26] and Kohama et al. [16]. Later, dedicated measurements were

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Nomenclature

Symbols

A	amplitude
b	wing span in the Z direction
c	wing chord in the x direction
c_X	wing chord in the X direction
C_μ	actuator momentum coefficient
C_p	pressure coefficient
d	roughness elements diameter
E	voltage amplitude
f	frequency
k	roughness elements height
M	optical magnification
Re	free-stream Reynolds number
t	time
T	actuator thrust in the wall-parallel direction
Tu	turbulence intensity
u,v,w	velocity component along the x,y,z directions
U,V,W	velocity along the X,Y,Z directions
x,y,z	wing coordinates
x_t,y_t,z_t	wing surface coordinates
X,Y,Z	wind-tunnel coordinates
α	angle of attack, wavenumber
γ	angle of the inviscid streamline w.r.t x
δ_f	spectral frequency resolution
ϑ	momentum-loss thickness
λ	wavelength
Λ	sweep angle
ν	kinematic viscosity
ϱ	air density
Φ	phase
ω	angular frequency
$\overline{...}$	time-average
$\{...\}$	standard deviation w.r.t. the subscript quantity
$...'$	fluctuations
$\lvert...\rvert$	magnitude

Sub/super-scripts

co	cut-off
e	at the boundary layer edge
DBD	related to the actuator
s	sampling
m	at the maximum extent
I	related to stationary modes
II	related to unsteady modes
∞	free-stream quantity
Φ	related to phases
0	reference value

Abbreviations

AC-DBD	Alternating Current Dielectric Barrier Discharge
CE	Covered Electrode
CF	Cross-Flow
CFV	Cross-Flow Vortices
CTA	Constant Temperature Anemometer
DNS	Direct Numerical Simulation
DRE	Distributed Roughness Element
EE	Exposed Electrode
EMI	Electromagnetic Interference
HF	High Frequency
HWA	Hot-Wire Anemometry
KH	Kelvin-Helmholtz
LF	Low Frequency
POD	Proper Orthogonal Decomposition
PR	Phase Reconstructed
PSD	Power Spectral Density
TS	Tollmien-Schlichting

performed by Kawakami et al. [14], White and Saric [38], Glauser et al. [11] and Serpieri and Kotsonis [32]. Theoretical studies using secondary linear instability theory were carried out by Koch et al. [15], Malik et al. [21,22], Bonfigli and Kloker [3] and Groot et al. [12] while direct numerical simulations were performed by Högberg and Henningson [13] and Wassermann and Kloker [35,36]. The overall consensus of the aforementioned studies indicates that the convective secondary instability vortices abruptly grow over the strong shear regions caused by the primary waves and eventually lead to laminar-turbulent breakdown within a relatively confined streamwise region. Following this observation, transition prediction approaches, based on the evolution of the secondary instability modes, have been proposed through the years [22,11].

In comparison to experimental investigations, DNS simulations and theoretical analyses could describe in greater detail these secondary vortices, by inferring their topology and spatio-temporal evolution. The advantage of theoretical/numerical studies over experimental approaches stems from the use of hot-wire anemometry (HWA) and hot-film wall shear measurements as the most used flow diagnostic techniques. These techniques, despite their high spatial and temporal resolution, are limited to single-point and in most cases velocity magnitude and wall shear stresses measurements, thus leading to data which are not correlated in space. Unsteady modes developing in swept wing boundary layers present a multitude of frequencies and wavelengths, pertaining to the aforementioned instabilities. As such, their observation by point measurements like HWA can only be performed in a statistical manner. Full spatio-temporal information can be attained by rigorous knowledge of the phase of the incoming instability.

To overcome this limit of hot-wire based investigations, Kawakami et al. [14] and Chernoray et al. [4] forced the secondary instability (of CFVs in the work of Kawakami et al. and of streamwise roughness-induced vortices in the work of Chernoray et al.) with localized periodic blowing/suction thus locking the phase of the flow structures with the signal of the forcing jet. This approach allowed illuminating measurements, capable of inspecting the spatio-temporal evolution of the travelling modes. Recently, Serpieri and Kotsonis [31] and van Bokhorst and Atkin [34] followed a similar approach as the two aforementioned studies. The work of van Bokhorst and Atkin focussed on the effect of changing the forcing amplitude on the development of the secondary modes, whereas Serpieri and Kotsonis presented preliminary results of the current study. A different approach was followed by Glauser et al. [11], making use of multiple sensors (multiple hot-wire probes and multiple hot-films sheets), thus allowing multi-point correlations.

The current study is part of an ongoing effort by the authors to provide experimental description of the complex phenomena describing the evolution and breakdown of laminar swept wing boundary layers. The wind-tunnel facility and model described in this study have been used in a previous study [32], aimed at elucidating the spatial organization of these structures. This was made possible with the deployment of advanced tomographic - PIV [32], yielding spatially resolved measurements of the naturally occurring secondary modes. Nevertheless, due to technical constraints, temporal description of the unsteady flow field was limited. The flow structures were only indirectly related to their pertinent frequencies, measured with HWA, by application of