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Active decoupling of the axisymmetric body wake response to a pitching motion

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ABSTRACT

Controlled interactions between fluidic actuators and the cross flow over the aft end of a wire-mounted axisymmetric wind tunnel bluff body model ($Re_D=2.3\cdot10^5$) are exploited for modification of the near wake dynamics, and the consequent global aerodynamic loads. Actuation is effected using an array of four aft-facing synthetic jet modules through narrow, azimuthally-segmented slots that are equally distributed around the perimeter of the tail end. The model is supported by eight wires, each including a miniature inline force transducer for measurements of the time-resolved tension. The model's position is varied in a prescribed trajectory by synchronous activation of shape memory alloy (SMA) segments in each of the mounting wires, and the aerodynamic forces and moments are manipulated over a range of pitch attitude. The effectiveness of the flow control approach is demonstrated by decoupling of the wake response from the body's pitch motion at a low pitch frequency ($k=0.013$). It is shown that, under the active control, the wake symmetry can be restored or its asymmetry can be amplified.

1. Technical background

Numerous earlier investigations have shown that stalled or separated flows over external aerodynamic platforms can be either fully or partially attached by fluidic manipulation at or upstream of flow separation. It has been shown that the separating shear layer over stalled 2- and 3-D aerodynamic surfaces is typically dominated by a strong coupling to the instability of the near wake (e.g., Wu et al., 1998). Traditional separation control strategy uses actuation coupling to the narrow-band receptivity of the separating flow at the unstable Strouhal numbers of the near wake (e.g., $St_D\sim O(1)$, Neuberger and Wygnanski, 1987; Hsiao et al., 1990; Williams et al., 1991; Chang et al., 1992; Seifert et al., 1993). An alternative approach uses actuation at substantially higher frequencies to decouple the global flow instabilities from fluidic modification of the "apparent" aerodynamic shape of the body (e.g., $St_D\gg O(1)$, Erk, 1997; Smith et al., 1998; Honohan et al., 2000; Amitay et al., 2001; Glezer et al., 2005). The global flow characteristics are typically modified with active flow control by issuing a jet through a high aspect ratio orifice along the body surface. More aggressive 'hybrid' (combined active and passive) flow control can be achieved by fluidic actuation over a Coanda surface, as shown in a substantial body of work since the 1940s. As shown by Newman (1961), the flow direction of a planar jet can be substantially altered near the exit plane either by the jet adherence to a curved surface that is a smooth extension of the nozzle, or by the reattachment of a separated jet to an adjacent solid 'Coanda' surface. The Coanda effect has been the basis of circulation control over lifting

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Nomenclature

A_J	actuator orifice cross-sectional area
$C_{D,S,L,M,Y}$	aerodynamic force and moment coefficients
C_{D0}	baseline aerodynamic drag on model with U0
C_{SMA}	force coefficient induced by SMA wire
$\dot{C}_{SMA}$	rate of force coefficient induced by SMA wire
C_μ	jet momentum coefficient
D	axisymmetric body diameter
D_{SMA}	diameter of SMA wire
f_A	synthetic jet actuation frequency
f_A^*	dimensionless synthetic jet actuation frequency
f_P	model pitching frequency
f_{PSD}	power spectra frequencies
f_{PSD}^*	dimensionless power spectra frequencies
$F_{D,S,L}$	aerodynamic drag, side, and lift forces
$F_{M,Y}$	aerodynamic pitch and yaw moments
F_{SMA}	force induced by SMA wire
$\dot{F}_{SMA}$	rate of force induced by SMA wire
h_J	jet orifice height
h_S	backward-facing step height
k	reduced frequency
L	model length
L_{SMA}	length of SMA wire
P_A	applied synthetic jet power
P_A^*	dimensionless applied synthetic jet power
P_{SMA}	applied SMA wire power
P_{SMA}^*	dimensionless applied SMA wire power
PSD	normalized power spectral density
R_C	Coanda surface radius
Re_D	Reynolds number
St_D	Strouhal number
t	elapsed time
t_C^*	time scaled by model convective time scale
t_{SMA}^*	time scaled by SMA convective time scale
u	streamwise velocity
U	variable free stream velocity
U_0	nominal free stream velocity
U_J	maximum jet expulsion velocity
v_C	cross-stream velocity from model center
x	downstream distance from model tail
x_C	model wire mounting center location
x_L	laser vibrometer location
z	side-stream distance from model center
$\Delta C_{D,S,L,M,Y}$	actuation force and moment coefficients
Δy	offset in image plane location
Δz	laser vibrometer measured displacement
θ	model pitching angle
θ_0	desired pitching angle amplitude
ρ	air density
ζ	wake vorticity

surfaces in aerodynamic systems (e.g., Englar, 2000). Hybrid flow control was also demonstrated by Nagib et al. (1985) who combined a short backward facing step with a jet to control local separation. This approach was also utilized for internal flows, such as controlling separation in adverse pressure gradients in a diffuser (Lo et al., 2012).

Aerodynamic flow control has also been applied to axisymmetric platforms with an objective to control their airborne flight dynamics. Freund and Mungal (1994) applied steady circumferentially-uniform blowing over Coanda surfaces at the aft corner of the body, leading to drag reduction up to 30%. Rinehart et al. (2003) and Rinehart (2011) investigated the generation of a normal force on an aerodynamic platform using the interaction of a single synthetic jet with an integrated axisymmetric Coanda surface. Their results suggested that the induced force by actuation was equivalent to the lift force on the body at an angle of attack of 3°. McMichael et al. (2004) were able to control the trajectory of a 40 mm axisymmetric spin stabilized projectile by exploiting separated base flow control which effected steering forces and moments. Corke et al. (2008) reported an altered drag and side force, generated with a tangential blowing plasma actuator placed upstream of a Coanda surface on an axisymmetric body. Abramson et al. (2011), investigated the effects of asymmetric flow actuation on an axisymmetric body of revolution with four, equally-spaced azimuthal synthetic jets issuing from within a rearward facing step in the tail, inducing aerodynamic forces and moments on the model with fluidic actuation. Abramson et al. (2012) further studied different active control actuation amplitude modulation schemes for possible utilization in controlling the wake behind an axisymmetric body.

Control of the aerodynamic forces on axisymmetric airborne platforms builds on numerous earlier investigations of the uncontrolled baseline flow and its natural instabilities. The basic motions of spinning projectiles, including linear and nonlinear natural nutation and precession instabilities, induced by the Magnus effect, along with damping, and normal forces and moments are discussed in detail in the classical work of Nicolaides (1970). The instabilities of axisymmetric bodies in the presence and absence of spin were discussed in detail by Murphy (1980). While the spin-stabilized ones are gyroscopically stable to axisymmetric moment instability, they are susceptible to roll resonance (Price, 1967), and spin-yaw lock in Murphy (1987), which add complicated non-linear effects to the body dynamics that are in general hard to correct for. In recent years considerable attention has been devoted to the development active control approaches for both fin- and spin-stabilized axisymmetric bodies. Examples include aerodynamic forces induced by a piezoelectric-articulated nose section (Barrett and Lee, 2004), synthetic jet actuation on a spinning projectile (Sahu, 2006), and the swerve response of finned and spin-stabilized airborne bodies to generic control forces (Ollerenshaw and Costello, 2008a, 2008b). In the present work, synthetic jet actuation is applied to investigate the potential for both steering and stabilization in a model that would not use spin or fins for stabilization.

An inherent problem with any experimental aerodynamic study of a nominally ‘free’ body is related to its mounting into a test section. Ideally, the model support should not cause aerodynamic interference (e.g., magnetic-force supports by Higuchi et al. (1996)), but the predominant supports involve sting mounts that are directly in the body’s wake. An alternative support, aimed at minimizing the wake–support interference, was utilized by Abramson et al. (2011, 2012), where a