Fluidic Control of Steering Aerodynamic Forces on Axisymmetric Bodies using a Mid-Body Cavity

Philip Abramson^{*}, Bojan Vukasinovic[†] and Ari Glezer[‡] Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405

The aerodynamic steering forces and moments on an axisymmetric bluff body are fluidically controlled by segmented vectoring of the outer flow through a mid-body axisymmetric cavity. Control is effected by an array of four individually-addressable, aft-facing synthetic jet actuators that emanate from the upstream end of the cavity over an integrated Coanda surface. The model is wire-mounted in the wind tunnel such that each support wire is instrumented with a miniature inline strain gage sensor for direct dynamic force measurements. The cavity flow field associated with quasi-steady and transitory actuation that results in asymmetric forces and moments is also characterized using high-resolution PIV measurements. It is shown that single jet actuation generates a quasi-steady, nearlymatched force couple at the upstream and downstream ends of the cavity. Transitory activation of multiple jets can be used to control the onset and sequencing of the couple forces and therefore the time history of the resultant force and moment.

Nomenclature

A_{i}	actuator orifice cross-sectional area
\dot{C}_{μ}	jet momentum coefficient
$D^{'}$	axisymmetric body diameter
E	actuator voltage
E_s	strain gage readout
f	actuation frequency
F_D	drag force
F_L	lift force
F_S	side force
M_P	pitch moment
M_Y	yaw moment
R	axisymmetric body radius
Re_D	Reynolds number
Т	actuation period
t	temperature
U_0	free stream velocity
U_j	average jet velocity
ρ	air density
τ	time

I. Background

Flow control research in recent years has demonstrated that stalled or separated flow over external aerodynamic surfaces can be partially or fully attached by fluidic manipulation upstream of separation. In aerodynamic applications, post stall performance enhancement has been typically accomplished either at actuation frequencies

^{*} Graduate Research Assistant, AIAA Member.

[†] Research Engineer, AIAA Member.

[‡] Professor, Associate Fellow AIAA.

that are within the receptivity range of the separating shear layer (e.g., Hsiao et al.¹, Williams et al.², Chang et al.³, and Seifert et al.⁴) or at frequencies that are substantially higher than the characteristic frequency of the airfoil (e.g., Erk^5 , Smith et al.⁶, Amitay et al.^{7,8}, and Honohan et al.⁹). Even more aggressive flow control can be achieved by fluidic actuation over a Coanda surface as shown in a substantial body of work since the 1940s. The global flow characteristics are typically modified by blowing a conventional, high aspect ratio jet along the surface. As shown by Newman¹⁰, 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 surface. The attachment (Coanda effect) of a separated plane jet to an adjacent solid convex surface that extends to the edge of the nozzle is effected by the formation of a low-pressure region between the jet and the surface owing to entrainment.

Earlier investigations of separated flow downstream from a backward facing step (e.g., Riesenthal et al.¹¹) have demonstrated that the flow can be significantly modified using time-periodic excitation that is applied either upstream or at the base of the step. Sigurdson¹² considered the effect of azimuthally uniform time-periodic actuation on the separated flow on the surface of an axisymmetric blunt body downstream from its sharp leading edge (where the actuation was applied through a slot at the upstream edge). These effects were exploited by Rinehart et al.¹³ who investigated the generation of a normal force on a body of revolution using the interaction of a single synthetic jet with an axisymmetric Coanda surface around the base of the model. They found that the induced change in the aerodynamic force on the body that was found to be associated with the vortex shedding of the jet activation. More recently, McMichael et al.¹⁴ exploited flow control of the separated base flow of an axisymmetric 40 mm spin-stabilized projectile to effect aerodynamic steering forces and moments. The generated forces and moments were sufficient to control the trajectory of the projectile in flight.

In the earlier work of Abramson et al.¹⁵, they investigated the effects of asymmetric flow actuation on an axisymmetric body of revolution with four, equally-spaced azimuthal synthetic jets issuing from within a backward facing step in the tail. The authors reported saturation of the induced aerodynamic forces with actuation input which depends on the model's tail geometry. Before this limit is reached, the lift coefficient, ΔC_L increases with the model Reynolds number for a fixed jet momentum coefficient. In addition, transient dynamics were also investigated in regard to the full-force effect during transient onset and stop during continuous actuation. It was found that the transient onset of the quasi-steady flow was about 5 ms, while it took about 7 ms for the flow to relax back to its baseline state, once the actuation is terminated. The accompanying work of Abramson et al.¹⁶ focused on both continuous and transitory generation of aerodynamic steering forces and moments on the axisymmetric bluff body. They also proposed that time-periodic (spinning) sequential actuation of adjacent azimuthally-distributed jets could be coupled to the baseline spin of the body and therefore used for trajectory stabilization.

In the current work, the application of fluidic flow control over a mid-body cavity of an axisymmetric body is explored as a source for generation of both quasi-steady and transitory aerodynamic forces and moments that can be utilized for airborne steering. The flows over axisymmetric cavities have been investigated in numerous investigations, predominantly motivated by their application to the drag reduction and enhanced flow stability. Gharib and Roshko¹⁷ investigated such effects and studied the flow oscillation patterns and changes to the overall drag on an axisymmetric body. It was found that there was a critical value of cavity width to depth ratio which results in a drag increase of $C_D=0.4$. However, they observed that small cavity widths produce minimal drag which is of smaller value than the friction drag which would be associated with a solid surface were the cavity absent, therefore, these cavities have a favorable effect. In addition, they observed three distinct modes of flow oscillation for ranges of cavity geometry. In other work, Howard and Goodman¹⁸, used a series of shallow cavities to investigate their ability to reduce drag. They determined that the amount of drag reduction provided by the cavities was a function of their location and the flow Reynolds number. With cavities placed in series towards the back of the body and a Re_D greater than 10⁵, a 35% drag reduction was evident. Furthermore, Powers¹⁹ investigated drag reduction in near sonic flows. The work demonstrated that the presence of a cavity can cause a slight reduction on the base drag, with the reduction varying monotonically with increasing Mach Number. A drag reduction of $C_D=0.05$ and 0.08 were shown for Mach number 0.3 and 0.93 respectively.

The present investigation focuses on the mid-body cavity of an axisymmetric model with an objective of the generation of steady or transitory asymmetric forces and moments that can be applied for the body steering, rather than for the drag reduction. Furthermore, typical generation of the lift/side force utilizing Coanda-assisted flow vectoring is associated with the drag increase. The present approach builds on the control approach that was

developed for the flow control at the body's tail^{15,16} and involves both active and passive control elements. The controlled flow is characterized using direct force and PIV measurements.

II. Experimental Setup and Procedures

II.1 The Wind Tunnel Model

The present investigation is conducted in an open-return wind tunnel at Georgia Tech having a test section that measures 91 cm on the side with a test section speed up to 40 m/s. The aerodynamic control forces (and associated moments) on the axisymmetric model are generated using an azimuthal array of four synthetic jet actuators that are equally distributed along the perimeter of the mid-body cavity at the cavity upstream edge (Figure 1). Each jet is embedded into the surface with a 0.38×28.9 mm backward facing orifice such that it is issued over an azimuthal

segment of an axisymmetric constant radius Coanda surface of 25 mm, that turns through ninety degrees. Each jet was driven by a nominal sinusoidal signal at f = 2,000 Hz, which is an order of magnitude higher than the natural shedding frequency of the model¹⁶. The jet actuation leads to the vectoring of the outer flow into the cavity. When carrying sufficient momentum, the vectored flow can interact with the outer flow at the opposite cavity side, thus creating another source for the flow asymmetry, which then induces a net radial force.



Figure 1. Side view of the axisymmetric wind tunnel model. Arrows mark the jet centerlines.

The axisymmetric model is built using stereo-lithographed and aluminum components and it measures 80mm in diameter and 220mm in overall length. Adjacent to the nose, there is the mid-body cavity section which measures 40mm in length and 32 mm in depth. The upstream end of this cavity houses four independently-driven, piezoelectric actuators that generate synthetic jets. The adjoining backward-facing step to the circumference of the body is 1.5 mm in height. The step height is shallow enough to enable local flow attachment when the control jet is activated, but high enough to prevent attachment of the free stream flow in the absence of the jet. The Coanda surface downstream of the orifice, has cut-in grooves along the orifice edges that guide the jet flow and prevent its sudden diffusion.

The model is supported in the center of the wind tunnel test section by eight wires, 0.63mm in diameter, that are tied into a cylindrical (hoop) frame that is secured to the tunnel wall, as shown in Figure 2. The mounting of wind tunnel models by wires is not new. In an earlier study Bennett¹⁹ used wire-mounted models to determine the oscillatory modes of the system for stability testing. In more recent work, Magill et al.²⁰ used a wire suspension model for virtual flight testing of missile dynamics coupled with load cells to measure the tension. As shown in Figure 2, the wires are connected to a frame that consists of two steel circular hoops that are each 3 mm thick and 48cm in diameter, placed 70cm apart using four aluminum rods (2cm in diameter) that run along the tunnel length. Modified violin string keys that are attached to the outside surface of the frame are used to control the wire tension. The physical connection to the wind tunnel wall is facilitated through two $120 \times 10 \times 1$ cm steel beams connected horizontally along the left and right sides of the hoop frame. The wall connection is accomplished with four L-

shape brackets each in line with vertical dampers, used to isolate the model from the tunnel vibration. Once the hoop frame is mounted in the wind tunnel, the tension in each of the mounting wires is set to 50N.

Vibration analysis of the suspended axisymmetric model using an equivalent spring-mass system was carried out to increase the natural frequencies and reduce the amplitudes of the model vibrations. The



Figure 2. Side view of the model mounted into the hoop frame and wire-support.



Figure 3. Custom-made force-measurement transducer (a) and its detached circuitry (b).

transverse and longitudinal vibration frequencies of each of the mounting wires, which depend on the tension, are an order of magnitude higher than the natural frequencies of the model and therefore the wire tension does not significantly affect the model's natural frequencies. In the wire mounting system, the natural frequency is proportional to the cross sectional area of the wire and inversely proportional to the model's mass and the wire length. The natural frequencies of the model were adjusted by varying these parameters.

In the present investigation, the changes in the aerodynamic forces induced by flow control actuation are measured relative to the corresponding aerodynamic forces of the baseline (unforced) flow. Each data record is 4.5 seconds long. The actuation is turned on at $\tau = 0.5$ sec and terminated at $\tau = 2.5$ sec (4,000 cycles of nominal continuous actuation) thereby allowing for measurement of the transitory aerodynamic force response to the onset and termination of the actuation as well as the "quasi-steady" response once the actuation transients die out. As all of the force measurements are done relative to the baseline, the baseline measurements clearly result in all three forces $(F_{\rm D}, F_{\rm L}, \text{ and } F_{\rm S})$ and two moments $(M_{\rm P}, \text{ and } M_{\rm Y})$ to be zero in the absence of actuation. Nonetheless, spectral analysis of the baseline time traces for the individual forces and moments yields the dominant peaks of the corresponding vibration modes. Thus, 110, 85, and 86 Hz are measured natural frequencies for the drag, lift, and side force respectively, reflecting the model vibrations in longitudinal and side directions. Also, resonance frequency for the pitch and yaw moments are measured at 25 and 21 Hz.

II.2 Force Measurements

Custom-designed and built hardware are used for the measurement of the time-dependent tension in the mounting wires which is used for extraction of the aerodynamic forces and moments on the model. These measurements are enabled by the redesign of the previously developed force transducers¹⁶. The transducer, shown in Figure 3a, incorporates a Wheatstone Bridge amplifier circuit with four strain gages forming the bridge and placed on opposite sides of a FR4 circuit board of dimensions $15 \times 8 \times 1$ mm,. The board is placed in series with the mounting wires using an adaptor plate and set screws and it has a nominal strain of 6µstrains per Newton force. Each transducer is incorporated into the test model at the anchoring point of the support wires, as schematically shown in Figure 2. Only the strain gages were placed on the FR4 circuit board, with the rest of the circuitry placed on the frame (Figure 3b). Previous tests in Abramson et. al.¹⁶ indicated a relatively high temperature sensitivity of the sensor module of about 0.18 V/°C, and that prompted a temperature-compensation adjustment of the transducer readings. The sensors temperature compensation requirement is further considered in the current design where the strain gages were incorporated as all four of the arms in the Wheatstone bridge, using two Tee-Rosette strain gages

placed on opposite sides of the FR4 board. Each Tee-Rosette incorporates two strain gages, with the traces of each running perpendicular to each other. The Rosettes were connected such that each pair of parallel lined strain gages was connected to form the opposite arms of the Wheatstone bridge. A potentiometer and balance limiting resistor are connected in parallel with one of the strain gage legs to provide an offset to zero the voltage on each of the transducers. With this setup, all four arms of the bridge experience the same change in resistance change due to temperature, and therefore it is expected that their temperature sensitivity is greatly reduced. Figure 4 illustrates the temperature sensitivity of the redesigned sensor module for a given flow condition in the wind tunnel. The sensors' readings are nearly flat, having a typical sensitivity of about $0.03 - 0.04 \text{ V/}^{\circ}\text{C}$, which indicates that a nearly five-fold improvement in temperature



Temperature sensitivity of the transducers' Figure 4. response Es for a given flow condition.



Figure 5. Static validation of the transducers' force measurement F_s split into the tension (•) and compression (•) responses to static weight W (a), and as a function of the applied force F_g to the front (•) and back (•) (b).

changes in the aerodynamic forces and moments.

sensitivity is achieved. Nonetheless, the temperature compensation algorithm, much like a default temperature compensation procedure for hotwire anemometry, is still incorporated into the raw signal processing routine, as outlined in the previous work¹⁶. The temperature sensitivity dE_s/dt is measured at the beginning of each test following the initial tunnel warm-up. The sensor module also has sufficiently high signal-to-noise ratio to enable good resolution of the

Each of the force measurements of the individual transducers is decomposed into three coordinate axis and the three orthogonal forces, drag F_D , lift F_L , and side force F_S are obtained by the directional sum of the eight decomposed forces along the wires. The moments were calculated by taking sum of the cross products between the position vector r between the center of gravity (cg) of the model to the connection point of each wire, and the force along each wire. Due to the axisymmetric nature of the model, the calculated roll moment is zero as expected, and the pitch moment M_P and the yaw moment M_Y are extracted.

II.3 Calibration Procedures

Each of the force transducers is calibrated *a priori* independently with precision masses, obtaining a linear load versus voltage curve for each. These experiments were conducted by suspending the transducers in a miniature wind tunnel to limit large changes in temperature drift. These tests verified that all the transducers were within 3% precision of each other. Once the transducers were incorporated into the suspended model support frame, a separate set of calibration procedures are conducted. First, precision masses were hung on the model for additional *in situ* sensor calibration. These tests demonstrated a linear scale of about 170 mV/N for all the transducers, which was very similar to the *a priori* calibration. Furthermore, each of the individual measurements is split into two groups of responses: those that are under compression (i.e., reduced tension, lower four transducers) and those that are under tension (upper four transducers). Figure 5*a* shows the applied static weight *W* and the resulting force measurements by the transducers under compression and tension, showing that the applied force is equally split between the two groups of sensors, i.e., that the transducer responds to both tension and compression in the same way. Second set of

in situ calibration procedure involved testing of the transducers responses to the static force applied along the body's main axis, at the front (nose) and at the back (tail) of the model. A precision force gauge, Dillon 10 Newton capacity $\pm 0.005 N$, is used to apply forces acting at the nose and tail on the model and the transducers response to the forcing is shown in Figure 5*b*. Again, the force measurement algorithm is validated in these tests as well. These calibration curves are used not only for data reduction but also during the mounting, alignment, and balancing of the wind tunnel model within the hoop frame.

Each of the four synthetic jet actuators was calibrated in a hot-wire calibration stand outside of the wind tunnel. The actuation frequency in the present experiments is 2 kHz and during calibration the actuation voltage is varied between 10 and 100 Vrms while the jet velocity is measured at the center of the orifice exit plane (the mean jet velocity is defined as averaged velocity during the expulsion half of the actuation



Figure 6. Calibration of the jet exit velocities for four synthetic jet actuators with applied voltage. Jet operating parameters are marked by arrows.

cycle). Figure 6 shows the jet calibration data within the operating range of the present tests, having the jet operating conditions marked by the arrows, where the default operating condition of the jet is $U_j/U_{j,max} = 0.7$. For a nominal wind tunnel speed of 40 m/s, and the corresponding $Re_D = 2.13 \cdot 10^5$, the momentum coefficient of each actuator in the default operating condition is $C_{\mu} = \rho U_j^2 A_j/(\rho U_0^2 D^2 \pi/4) = 0.0013$, where A_j is the actuator exit orifice area.

III. Fluidic Control using the Mid-Body Cavity

III.1 Continuous Control

To illustrate the resulting flow field through the cavity upon actuation of a single jet, composite views of the baseline and actuated flows along the cavity (and the jet) plane of symmetry are shown in Figure 7 for the top jet actuation at $C_{\mu} = 1.3 \cdot 10^{-3}$. The mean velocity and vorticity fields of the baseline flow (Figure 7*a*) indicate slight asymmetry between the top and bottom cavity sides. It is also seen that the shear layer that forms off the upstream edge of the cavity impinges the downstream edge, and the outer streamlines become slightly displaced outboard. When the flow is actuated by the top jet (Figure 7b), several important features are observed. First, a significant vectoring of the outer flow into the upper cavity is forced over the Coanda surface, and throughout this cavity side in general. Such a strong flow vectoring into the cavity also displaces the stagnation point towards the model axis at the downstream cavity edge. Furthermore, the outboard flow from the stagnation point gains momentum and penetrates further into the outer flow around the model. Thereby, the outer flow streamlines become further displaced downstream from the cavity. Although the flow vectored downward from the upper cavity section passes around the cylindrical shaft as an obstacle, the altered flow dynamics in the bottom section of the cavity is rather dramatic: for most of the cavity's plane of symmetry, the flow direction is reversed and the baseline's recirculating flow pattern is broken such that it results in the net momentum efflux through the boundary (shown dashed in Figure 7b). This net flux out of the cavity also breaks the outer flow symmetry by displacing the shear layer over the cavity into the outer flow, and creating a bubble of trapped vorticity over the bottom of the model surface. Only the upstream portion of this bubble is captured in the measured plane shown in Figure 7b. Analysis of the resulting flow field from the standpoint of the induced asymmetric forces points to the conclusion that the considered actuation by a single jet actually generates one minor and two major sources of the overall flow asymmetry, and therefore induces three sources of the asymmetric force generation. The first source is the flow momentum change over the Coanda surface, which generates a predominantly upward lift force. The second source is the relatively weak recirculating bubble off the top cavity edge, which adds to the force generated by the flow turning over the Coanda

surface, but the first source is the dominant one. It should be also noted that both of these lift-generating dynamics contribute to the drag force. The third and presumably the most interesting source of the generated force is a rather large bubble along the bottom model surface, starting downstream from the cavity. This flow alteration generates a predominantly downward lift force that opposes the other two lift sources. Clearly, utilization of Coanda-assisted flow vectoring through the mid-body cavity results in more complex flow dynamics than similar vectoring of the flow at the body's tail, where only one source of the flow asymmetry is generated by the segmented flow turning over the Coanda surface^{15,16}.

Figure 8 further illustrates the flow momentum change under the control shown in Figure 7*b*. Although considering only the central vertical plane, it is still illustrative to examine the net momentum flux through the cavitie's upper and lower boundaries, which are marked in Figure 7*b*. Distribution of the momentum flux components indicate a broad influx of momentum along the upper boundary up to $x/R \approx 0.85$, where the vicinity of the downstream cavity edge and stagnation point below turns the flow upward and the momentum influx reverses into the efflux. The fluid



Figure 7. Raster plots of the mean vorticity component ζ^* with overlaid equidistant mean velocity profiles measured in the symmetry plane for the flow ($Re_D = 2.13 \cdot 10^5$) actuated by the top jet at $C_{\mu} = 0.0013$ (b), and the corresponding baseline flow (a). The cavity boundary is drawn dashed in (b). ζ^* : -10



Figure 8. Cross-stream momentum flux components through the upper (•) *and lower* (•) *cavity boundary (as marked in Figure 7b) for actuation by the top jet at* $C_u = 0.0013$.

flowing out of the cavity near the rear cavity wall can only weakly penetrate the outer flow and therefore only a weak recirculating bubble is formed which results in a weak symmetry breaking downstream from the cavity edge. Contrary to the upper boundary, there is virtually no momentum flux through the lower boundary from the upstream edge up to $x/R \approx 0.45$. However, past the cavity midpoint, momentum efflux steadily increases and reaches about a threefold larger magnitude than the peak influx on the opposite side. In addition to the fact that the efflux peak magnitude at the lower boundary is significantly higher than the influx along the upper boundary, the outflow region is very broad and comprises half the cavity length. Such a broad and high-momentum penetration of the outer flow generates a much stronger alteration of the outer flow symmetry around the body as a relatively large zone of trapped vorticity is formed downstream from the back cavity edge. Therefore, it is expected that the two dominating effects on the generation

of the asymmetric forces on the body are the Coanda-assisted vectoring in the upper cavity section and the generation of the recirculating bubble along the bottom surface of the body.

Asymmetric forces and moments that are induced by above-discussed cavity flow dynamics are directly

measured by the custom-made force transducers described in Section 2. Figure 9 shows the time traces of the phaseaveraged force and moment increments that are induced by the top actuator $(C_{\mu} = 1.3 \cdot 10^{-3}, Re_D = 2.13 \cdot 10^{5})$. These data show that the segmented vectoring of the flow over the top Coanda surface and induced trapped vorticity over the bottom body surface yield a resultant vertical (lift) force that is nominally about -0.2 N. In concert with the change in the vertical force, there is also an increase in the pitching moment which is clockwise with respect to the model's cg and therefore corresponds to a nose-up moment. It is noteworthy that along with the change in the lift force, there is also an increase in the drag force of about 0.1N. In addition, a slight increase in the side force upon the top jet activation indicates that the resulting cavity dynamics breaks the sideways symmetry and generates a small but detectable net side force. However, presumably the two most interesting outcomes of the aerodynamic force (and moment) control within the midbody cavity are the two sharp transients of the lift force at the onset (t = 0.5 s) and termination (t = 2.5 s) of the actuation, as well as the generation of a much higher quasisteady pitching moment than in the aerodynamic control at the tail¹⁶. A sharp increase of the upward lift is measured immediately after the onset of actuation, with the peak magnitude of $F_L = 0.5$ N after $\Delta t = 10$ ms. After its local peak, the lift force not only decreases, but also changes its sign, settling at $F_L = -0.2$ after about $\Delta t = 30$ ms from the onset of actuation. Immediately after the termination of actuation, the quasi-steady downward lift force increases up to $F_L = -0.6$ N after approximately $\Delta t = 16$ ms. After reaching the local peak, the force magnitude progressively decreases until the flow relaxes back to its baseline state at about $\Delta t = 40$ ms. The lift force transient response to both



Figure 9. Time traces of the relative measured drag (a), lift (b), and side (c) forces, and the pitch (d) and yaw (e) moments for the flow actuated by the top jet only at $C_{\mu} = 0.0013$. Transient lift-force response to onset and termination of the actuation are shown in (f) and (g).



Figure 10. Time traces of the relative pitch moment calculated about the point along the body axis at the downstream (a) and upstream (c) edge, and at the cavity centerpoint (b). The actuation case is the same as in Figure 9.

recalculated about three points along the model axis: at the upstream cavity edge, at the cavity midpoint, and at the downstream cavity edge. The resulting time traces of these three pitching moments are shown in Figure 10. There is a slight bias towards a lower pitching moment when the anchoring point is shifted towards the downstream cavity edge, which is in accord with the previous assessment that the overall stronger effect on the lift force comes from the

trapped vorticity, which is closer to the downstream edge of the cavity. Moving the anchoring point closer to the upstream cavity edge increases the contribution of the trapped vorticity to the overall pitching moment, and decreases the contribution of the Coanda surface region. If there were only a single lift force, the pitching moment magnitude would linearly change with the shift in the anchoring point.

It was shown previously that the azimuthal distribution of the four actuators around the tail, analogous to the present one, induced practically additive effects from the individual jets, i.e., there was practically no interference among singular effects of each of the jets^{15,16}. Here, it is expected that the operation of more than one of the jets would induce a joint rather than additive effect, as they are all issued into the common cavity rather than into the wake. Figure 11 shows all force and moment responses to the simultaneous actuation by the top and right jets along the upstream cavity edge. As a result, the side force (Figure 11c) becomes altered in a same fashion as the lift force when exclusively the top jet is active. Analogous to the top jet actuation, there are characteristic transient responses at the onset and termination of the actuation, with the change of the sign and sharp increase in the force magnitude at the onset of actuation and before reverting to the baseline level at termination. Furthermore, the quasi-steady force response indicates that the overall effect is in the direction opposite to that induced by the flow turning over the Coanda surface. In accord with the

the onset and the termination of actuation are shown closely in Figures 9f and g, respectively. It is noteworthy that the sharp transients associated with the onset and the termination of the jet are not seen in the pitching moment trace, which is attributed to the strong natural oscillations of the model about its lateral axis with the period of 40 ms (Section 2), which presumably dampen the observed force transients that have characteristic time of 10 to 16 ms.

The analysis of the mean flow field of Figure 7b suggested the formation of two major sources of the lift force upon the top jet activation, and moreover, two dominant forces of the opposing signs. Furthermore, the corresponding lift force measurement shown in Figure 9b indicates that the net downward lift force generated by the trapped vorticity is stronger than the upward lift force off the Coanda surface. To further assess the existence of presumably two induced lift forces, the pitching moment is



Figure 11. Time traces of the relative measured drag(a), *lift*(b), *and side*(c) *forces, and the pitch*(d) *and yaw*(e) *moments for the flow actuated by both the top and side jet at* Cm = 0.0013.

AIAA-2009-4276



Figure 12. Raster plots of the mean vorticity component ζ^* with overlaid equidistant mean velocity profiles measured at the symmetry plane for the flow $(Re_D = 2.13 \cdot 10^5)$ actuated by the top jet at $C_{\mu} = 0$ (a), 7.1E-5 (b), 2.4E-4 (c), 7.7E-4 (d), 1.3E-3 (e), and 1.9E-3 (f). Vorticity levels are the same as in Fig. 7.

change in the side force, there is the corresponding change in the yaw moment, and the transients observed in the side force are dampened in the yaw trace due to the moment body oscillation natural reflected in the vaw moment measurements, which oscillates frequency substantially at lower than the transients.

Figure 12 shows the timeaveraged distributions of the velocity and vorticity for the baseline and controlled flows at $Re_D = 2.13 \cdot 10^5$. Actuation is applied by the top actuator with increasing jet momentum coefficients, ranging from $C_{\mu\nu} = 7.1 \cdot 10^{-5}$ (Figure 12*b*) to 1.9 \cdot 10^{-3} (Figure 12*f*). The corresponding baseline flow is shown in Figure 12a. The baseline flow field indicates a typical weak recirculating

bubble being formed inside the cavity, and the shear layer formed off the upstream cavity edge impinging at the downstream edge of the cavity. It is remarkable that even the weakest actuation (Figure 12*b*) significantly alters the flow dynamics within the cavity. Upon the actuation, the outer flow becomes vectored into the cavity, reducing the recirculating domain. Furthermore, most of the flow near the downstream end-wall of the cavity accelerates downward. Lastly, the stagnation point at the rear wall of the cavity becomes displaced downward, and the upward flow from the stagnation point also gains momentum, slightly penetrating the outer flow at the downstream edge. A clear trend in the further alteration in the flow dynamics with the increase in jet momentum coefficient is seen in

Figures 12b-f: the downward motion along the rear wall gains progressively momentum; the recirculating bubble moves closer to the upstream Coanda-shaped wall and becomes displaced further downward; and penetration of the stream off the stagnation point becomes weakly stronger with an increase in C_{μ} . Note also that "compression" of the recirculating bubble in the non-vented enclosure would increase its circulation. In the case of the axisymmetric the "compressed" cavity, bubble along a segmented azimuthal domain is free to redistribute vorticity over the non-compressed domain, and hence the vorticity levels in the central symmetry plane do not change significantly.



Figure 13. Raster plots of the mean vorticity component ζ^* with overlaid equidistant mean velocity profiles measured at the symmetry plane for the flow $(Re_D = 2.13 \cdot 10^5)$ actuated by the bottom jet at $C_{\mu} = 0$ (a), 7.1E-5 (b), 2.4E-4 (c), 7.7E-4 (d), 1.3E-3 (e), and 1.9E-3 (f). Vorticity levels are the same as in Fig. 7.





Figure 14. Raster plots of the mean vorticity component ζ^* with overlaid equidistant mean velocity profiles measured at the symmetry plane for the flow at $Re_D = 1.07 \cdot 10^5$ (a, b) and $1.6 \cdot 10^5$ (c, d) actuated by the top jet at $C_{\mu} = 0$ (a, c), 5.2E-3 (b), and 2.3E-3 (c). Vorticity levels are the same as in Fig. 7.

Figure 15. Raster plots of the mean vorticity component ζ^* with overlaid equidistant mean velocity profiles measured at z/R = 0.5 (a, b) and -0.5 (c, d) for the flow at $Re_D = 2.13 \cdot 10^5$ actuated by the top jet at C_{μ} = 0 (a, c) and 1.3E-3 (b, d). Vorticity levels are the same as in Fig. 7.

A complementary view of the effect that the active jet has on the cavity dynamics at the opposite side along the azimuth is deduced by the activation of the bottom jet, while the measurements are taken again over the top side of the cavity in the vertical symmetry plane. The resulting time-averaged distributions of the velocity and vorticity for the baseline and controlled flows at $Re_D = 2.13 \cdot 10^5$ are shown in Figure 13. Similar to the analysis of the cavity dynamics on the side of the active jet (Figure 12), it is remarkable that even the weakest actuation (Figure 13*b*) is sufficient for enabling the global flow asymmetry: the flow vectored from the active side of the cavity carries a strong momentum through the upper cavity boundary and is able to penetrate the outer flow much stronger than the flow on the opposite side. As a result, the shear layer forming off the cavity leading edge becomes vectored upward, and the cavity flow penetrates the outer flow and forms the recirculating bubble downstream from the cavity. Such a flow dynamic becomes a significant source of the asymmetry of the flow over the axisymmetric body. The effect of the increasing jet momentum coefficient on the flow dynamics within the non-actuated side of the cavity is expressed through the gradual amplification of the base effect seen for the lowest C_{μ} . This effect is the increased magnitude of the reversed flow within the cavity and increased penetration of the outer flow.

The effect of a given actuation level of a single control jet on the flow dynamics is shown in Figure 14, where the control effect that was already tested at $Re_D = 2.13 \cdot 10^5$ (Figure 12e) is tested for lower tunnel speeds that correspond to $Re_D = 1.07 \cdot 10^5$ and $1.6 \cdot 10^5$. With the actuation magnitude constant, lowering the tunnel speed effectively increases the jet momentum coefficient. Therefore, the effect on the baseline flow is expected to be in accord with the increasing C_{μ} , much like the outcome of direct variations of C_{μ} (Figure 12). The strongest vectoring of the outer flow is measured for the highest C_{μ} (Figure 14b), i.e., for the lowest tunnel speed. The weakest vectoring (but still exceptionally strong) is measured for the lowest C_{μ} (highest tunnel speed, Figure 12e).

Figure 15 shows a comparison between the cavity flow at two vertical planes that are equidistant, but on the opposite sides, from the symmetry plane. It should be noted that the distance $z/R = \pm 0.5$ is further outward from the central plane than the active jet edge, so that no jet is issued directly within the field of view. Both the baseline flow cuts (Figures 15*a* and *c*), and controlled flows (Figures 15*b* and *d*) imply certain asymmetry, which can be partially attributed to the possible slight misalignment of the model. This finding is also in concert with the outcome of the direct force measurements for this case (Figure 9), which showed that the top jet actuation also induces a slight side force. However, the most interesting point is that the jet actuation of this baseline flow induces a notable vectoring of the outer flow even outside the span of the segmented jet orifice. In other words, the jet's effect spreads quickly outward from the jet axis. Figure 16 shows three cut views of the flow dynamics, the central vertical plane, the

AIAA-2009-4276



Figure 16. Raster plots of the mean vorticity component ζ^* with overlaid equidistant mean velocity profiles for the baseline ($Re_D = 2.13 \cdot 10^5$, a - c) and actuated flow by the top jet at $C_{\mu} = 1.3E$ -3 measured at z/R = 0 (a, d), 0.2 (b, e) and 0.36 (c, f).

vertical plane tangential to the connecting shaft that forms the cavity bottom, and the vertical plane that is adjacent to the jet edge. It is interesting to note that the outer flow vectoring and downwash through the to be cavity appears the strongest along the plane that is tangential to the shaft. It seems to even surpass the effect along the symmetry plane, which is attributed to the shaft being an obstacle for the flow oncoming directly at the shaft. The weakest effect is clearly measured at the jet's edge, although significant vectoring of the outer flow into the cavity is still seen. Figure 15 already illustrated that the vectoring effect persists even past the jet orifice edge.

III.2 Transient Dynamics

It was previously stated during the analysis of the direct force measurements for the top jet actuation (Figure 9),



Figure 17. Raster plots of the phase-locked vorticity component ζ^* with overlaid equidistant mean velocity profiles ($Re_D = 2.13 \cdot 10^5$) for the onset of actuation by the top jet ($C_\mu = 1.3E-3$) at $\tau/T = 0$ (a), 2 (b), 4 (c), 6 (d), 8 (e), 10 (f), 12 (g), 15 (h), 20 (i), 30 (j), and 40 (k) and 50 (l). Vorticity levels are the same as in Fig. 7.

¹¹ American Institute of Aeronautics and Astronautics



Figure 18. Same as Fig. 17 for the termination of actuation by the top jet.

that the coupled transient dynamics yield momentary forces that are of substantially higher magnitude and opposite sign than the quasi-steady force. Further insight into the transient dynamics is sought via phase-referenced PIV measurements that can isolate the instantaneous flow structures at given times (phases) of the actuation signal. Therefore, sets of PIV measurements are obtained at specific phases of the harmonic actuation, enabling an insight into the time-resolved spatial dynamics of the flow.

Figure 17 shows phase-locked PIV measurements, i.e., averaged flow fields at particular phases of the actuation signal, taken at the onset of actuation by the top jet ($\tau/T = 0$) and after 2, 4, 6, 8, 10, 12, 15, 20, 30, 40, and 50 actuation cycles. After two actuation cycles are completed (Figure 17*b*), the second vortex issued is observed next to the jet orifice, while the first vortex (both remaining with the same sense of vorticity as in the global flow) is convected to about x/R = 0.3. In addition, also visible is a large start-up vortex that is displaced outside of the cavity and into the outer flow, almost reaching the downstream edge of the cavity. After four actuation cycles (Figure 17*c*), the three preceding vortical structures remain coherent in the flow field, while the first structure issued is diffused. A notable difference relative to the flow field as compared to $\tau/T=2$, is that the flow immediately downstream from the third issued vortex (x/R = 0.3) is now attached to the surface, and is preceded by the second issued vortex which is displaced downward at about x/R = 0.7. It is remarkable that all the other flow fields at later times (Figure 17*d*–*l*) remain virtually unchanged, which indicates that a time-invariant effect of the actuation is reached after four actuation cycles, which is only 2ms.

The transient flow response to the termination of actuation is assessed from the corresponding PIV measurements taken relative to the stop of actuation at $\tau = 0$ (Figure 18). After the last vortices are issued into the flow, the last coherent vortex is seen after $\tau/T = 2$ (Figure 18*b*). After that, the flow remains mostly attached to Coanda surface due to inertia, but slowly relaxes up to $\tau/T = 8$ (Figure 18*e*) when a notable reversed flow becomes visible in the counter-clockwise vorticity along the surface. This zone of reversed flow continues to creep upstream with time, up until $\tau/T = 30$ (Figure 18*j*), when the flow relaxes back to its baseline state.

Further insight into the flow dynamics over the side of the cavity opposite to actuation is obtained by the actuation of the bottom jet and phase locked PIV measurements taken over the upper side of the cavity. The resulting flow fields for the actuation onset are shown in Figure 19. After several actuation cycles (up to $\tau/T = 6$, Figure 19*d*), the flow practically does not respond to actuation. After eight actuation cycles (Figure 19*e*), the flow slowly begins to "open" near the trailing edge of the cavity, and the flow starts to become issued from the cavity into



Figure 19. Same as Fig. 17 for the onset of actuation by the bottom jet.

the outer flow at about $\tau/T = 20$ (Figure 19*i*). This outflow intensifies with time, and at about $\tau/T = 50$ (Figure 19*l*), the flow becomes nearly time-invariant.

Finally, a transient response after the stop of actuation over the cavity side opposite to the actuated side is shown in Figure 20. The flow remains almost unaffected by the actuation termination up to fifteen actuation periods (Figure 20*h*). After this time, it slowly relaxes back to its baseline state, although it does not appear to be fully relaxed even after 50T (Figure 20*l*).



Figure 20. Same as Fig. 17 for the termination of actuation by the bottom jet.

13 American Institute of Aeronautics and Astronautics



Figure 21. Measured lift force (a, b) and net cross-stream momentum flux components through the upper (•) and lower (•) cavity boundary (c, d) during the transient onset (a, c) and termination (b, d) of actuation by the top jet at $C_{\mu} = 0.0013$.

Similar to the illustration of the mean influx and efflux of the momentum through the cavities lower upper and boundaries in the central measured plane (Figure 8), analogous calculations are done for each of the transient sets of data shown in Figures 17-20. After integration across the cavity length, the net momentum flux across each cavity side is plotted as a function of time in Figures 21c-The corresponding time d. traces of the transient lift force upon the onset and termination of actuation are shown in Figures 21a-b. There is a clear relationship between the directly-measured force response and the extracted

momentum flux from the PIV measurements. It is observed that the beginning of a detectable change in the lift force upon the actuation onset coincides with the first notable influx of momentum through the upper cavity side (marked as A). As the influx increases with time, and the efflux through the lower boundary remains around zero, the overall lift force increases in magnitude up to the point where a start of a notable efflux is detected, and influx starts to level off (marked as B). From this point onward, the efflux increases faster than the influx, and as a consequence the overall force decreases and eventually changes its sign as the recirculating bubble effect on the efflux side becomes dominant over the Coanda surface on the upper side (also seen in Figure 9). In addition, upon actuation termination, the analysis of the time-traces of the lift force and net momentum flux show that the initial sharp decline of the momentum influx induces an imbalance in the quasi-steady lift force. Consequently, the lift force initially starts to increase in magnitude in the negative direction, as the overall effect becomes biased towards the recirculating bubble, as the influx decreases faster than the efflux (marked as C). After the influx nearly-vanishes (marked as D), the overall force is predominantly downward and from that point it decreases in magnitude with the decrease of efflux, and the force approaches zero towards the end of the measurement domain.

IV. Conclusions

Aerodynamic forces and moments are affected on an axisymmetric bluff body over an axisymmetric mid-body cavity. The forces and moments are induced by the azimuthally-segmented vectoring of the outer flow using continuous flow actuation. The actuation is induced by an array of four synthetic jet actuators that emanate from azimuthally-segmented slots built into the upstream edge of the cavity which are equally distributed around its perimeter, and with the bottom orifice surface extending into a Coanda surface. The effects of the actuation are characterized using direct, time-resolved force and moment measurements as well as time and phase-averaged PIV measurements of the flow within the cavity and over the immediate outer flow. In the present experiments, the wind tunnel model is suspended in the test section by eight wires that are each integrated with an in-line miniature force sensor that provides direct measurements of the time-varying changes in the wire tension and thereby of the global aerodynamic forces and moments with minimal wake interference.

Contrary to the similar actuation approach of the wake control by Abramson et. al¹⁶, where the only source of asymmetry was the flow over the Coanda surface, the control of the flow over the mid-body cavity induces two major sources of asymmetry: the directly vectored flow over the Coanda surface at the side of the cavity actuation, and the recirculating bubble formed at the opposite side of the model, downstream from the cavity. These two sources induce coupling forces that are opposite in sign. Therefore, the resultant force that is generated is the net difference between these two opposing forces. However, a significant transient variation in the generated force is

measured at the onset and termination of actuation. These transient dynamics are attributed to the different transient responses of the cavity flow dynamics on the side directly actuated by the jet, and on the opposite non-actuated cavity side. A full flow response on the side opposite to actuation takes a longer time to establish compared to the actuated side. As a consequence, the resulting force is initially generated by the flow response within the actuated cavity side, which is progressively offset by the flow evolvement on the opposite side. Furthermore, since the opposite-side effect by the recirculating bubble is stronger than the effect from the Coanda surface on the controlled side, the net force for the fully-established flow changes its magnitude and its direction before settling at the quasisteady level. Similarly, when the fully-established actuation is terminated, the flow relaxes faster in the controlled side of the cavity and this induces a force initially increases in magnitude, peaks, and than asymptotically approaches zero as the cavity flow fully relaxes to its baseline state. It is noteworthy that at any point during the transient or steady effect, the resultant force is not at its maximum potential, as the dominant force effect is always offset by its opposing pair. In addition, the overall force magnitude between the transient onset and termination spans about 1 N.

In conclusion, the present work indicates that the selective transitory manipulation of the control sources over a mid-body cavity can lead to the momentary generation of a *single-sign* force (off the Coanda surface) without allowing enough time for the opposing effect to develop on the opposite side. This approach can be used for the control effect sequencing and tailoring of the time-history of the resultant force and moment. Alternatively, transitory activation of multiple jets can be used to control the onset and sequencing of the *couple* forces and thereby the time history of the resultant force and moment.

Acknowledgment

This work has been supported by the Army Research Office monitored by Dr. T. Doligalski.

References

¹Hsiao, F. B., Liu, C. F., and Shyu, J. Y., "Control of Wall-separated Flow by Internal Acoustic Excitation", *AIAA J.*, Vol. 28, 1990, pp. 1440-1446.

²Williams, D., Acharya, M., Bernhardt, K. & Yang, L., "The Mechanism of Flow Control on a Cylinder with the Unsteady Bleed Technique", *AIAA Paper*, 29 th Aerospace Sciences meeting, Reno, NV, 1991.

³Chang, R. C., Hsiao, F. B., and Shyu, R. N., "Forcing Level Effects of Internal Acoustic Excitation on the Improvement of Airfoil Performance", *J. Aircraft*, Vol. 29, 1992, pp. 823-829.

⁴Seifert, A., Bachar, T., Koss, D., Shepshelovich, M. and Wygnanski, I., "Oscillatory blowing: A tool to delay boundary layer separation". *AIAA J*.Vol. 31, 1993, pp. 2052-2060.

⁵Erk, P. P., "Separation Control on a Post-stall Airfoil using Acoustically Generated Perturbations", PhD Thesis, Tech. Univ. Berlin, Germany, 1997.

⁶Smith, D. R., Amitay, M., Kibens, V., Parekh, D. E., and Glezer, A., "Modification of Lifting Body Aerodynamics using Synthetic Jet Actuators", *AIAA Paper* 98-0209, 1998.

⁷Amitay, M., Kibens, V., Parekh, D. E., and Glezer, A., "Flow Reattachment Dynamics over a Thick Airfoil Controlled by Synthetic Jet Actuators", *AIAA Paper* 99-1001, 1999.

⁸Amitay, M., Smith, D. R., Kibens, V., Parekh, D. E., and Glezer, A., "Aerodynamic Flow Control over an Unconventional Airfoil using Synthetic Jet Actuators", *AIAA J.*, Vol. 39, 2001, pp. 361-370.

⁹Honohan, A.M., Amitay, M., and Glezer, A., "Aerodynamic Control using Synthetic Jets", *AIAA Paper* 2000-2401 2000, 2000.

¹⁰Newman, B.G., "The Deflexion of Plane Jets by Adjacent Boundaries-Coanda Effect", *Boundary Layer and Flow Control*

¹¹Riesenthal, P.H, H.M. Nagib, and D.J. Koga, "Control of Separated Flows using Forced Unsteadiness", *AIAA Paper* 85-0556, 1985.

¹²Sigurdson. L. W., "The Structure and Control of a Turbulent Reattaching Flow", *J. Fluid Mech.*, Vol. 298, 1995, pp. 139-165.

¹³Rinehart, C., McMichael, J. M., and Glezer, A., "Transitory Flow and Force Development on a Body of Revolution using Synthetic Jet Actuation", *AIAA Paper* 2003-0618, 2003.

¹⁴McMichael, J. M., Lovas, J. A., Plostins, P., Sahu J., Brown, G., and Glezer, A., "Micro adaptive Flow Control Applied to a Spinning Projectile," *AIAA Paper* 2004-2512, 2004.

¹⁵Abramson, P., Rinehart, C., Vukasinovic, B., and Glezer, A., "Fluidic Control of Asymmetric Forces on a Body of Revolution", *AIAA Paper* 2007-4505, 2007.

¹⁶Abramson, P., Culp, J., Vukasinovic, B., and Glezer, A., "Fluidic Control of Aerodynamic Forces on a Body of Revolution", *AIAA Paper* 2009-1078, 2009.

¹⁷Gharib, M. and Roshko, A., "The Effect of Flow Oscillations on Cavity Drag", J. Fluid Mechanics, Vol. 117, 1987, pp.501-530.

¹⁸Howard, G., and Goodman, W., "Axisymmetric Bluff-Body Drag Reduction Through Geometrical Modification", J. Aircraft, Vol. 22, No. 6, 1985, pp. 516-522.

¹⁹Powers, S., "Flight Tests of External Modifications Used to Reduce Blunt Base Drag", *J. Aircraft*, Vol. 28, No.8, 1991, pp. 517-525.

²⁰Bennett, R., and Farmer, M., "Wind-Tunnel Technique for Determining Stability Derivatives from Cable-Mounted Models", *J. Aircraft*, Vol. 15, No. 5, 1978, pp. 304-310.

²¹Magill, C., Cataldi, P., and Morency, J., "Demonstration of Wire Suspension System for Dynamic Wind Tunnel Testing", *AIAA Paper* 2004-1296, 2004.