HIGH SPEED, LOW ANGLE-OF-ATTACK
PNEUMATIC VORTEX CONTROL

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Abstract
Forebody pneumatic vortex control has previously been demonstrated through full-scale flight test to be effective for directional control of aircraft at low Mach number and high angle-of-attack flight conditions. The objective of the present research was to investigate the suitability of two-axis (wing, and vertical tail) pneumatic vortex lateral/directional control of a current fighter-type aircraft at high Mach number and low angle-of-attack flight conditions. The pneumatic effectors were tested for first augmenting, and then replacing the conventional aileron and rudder on a generic F-16 XL configuration. Evaluations were conducted on a high fidelity, nonlinear, six degree-of-freedom, non real-time simulation of this aircraft. Results demonstrate that at low blowing coefficient levels and with conventional effector augmentation, aileron and rudder activity and maximum deflections can be reduced. At higher yet realistic and attainable levels of compressor bleed air, aileron and rudder can be completely replaced by pneumatic devices, yet still allow the aircraft to complete aggressive bank-to-bank maneuvers and simulated penetration strike missions.

Introduction
Pneumatic vortex control (PVC) using either tangential slot blowing or nozzle blowing to control the forebody vortices generated by aircraft at high angles-of-attack is a generally well understood and mature technology. The viability of the concept for generating controllable yawing moments has been extensively tested in wind tunnels for several years [1-5]. More recently, the promise of PVC was successfully demonstrated in full-scale flight test to reduce the loss of directional control power on fighter type aircraft at high angles-of-attack [6-8]. The X-29A aircraft was fitted with compressed nitrogen gas bottles to power PVC nozzles mounted on each side of the forebody, essentially providing yaw augmentation only. The PVC nozzles were controlled manually by the pilot, i.e. open-loop, and not as part of the X-29A digital flight control system. The tests demonstrated that PVC was a viable means of generating well behaved yawing moments at high angles-of-attack and low Mach numbers. The time delays experienced in initiating a PVC event were small, and the responses to PVC inputs were generally fast and acceptable to the pilot. Specific recommendations for extending the PVC research program included using engine compressor bleed air to power the PVC nozzles, and closing the loop on the nozzles within the flight control system.

All-PVC control, characterized by pneumatic devices completely replacing conventional aerodynamic effectors, provides the potential for significant reductions in radar detectability by eliminating control surface deflections altogether. To realize this potential in the operational context of low level strike/interdiction missions requires the use of pneumatics as multi-axis control effectors over the full subsonic/transonic flight envelope. Recent wind tunnel testing of PVC has expanded into the low angle-of-attack / high Mach number flight regime, and to other configurations such as the high speed civil transport [9-11]. Results indicated that with sufficient engine compressor bleed air, PVC devices are an attractive control effector for high speed / low angle-of-attack flight conditions. Other testing [12,13] successfully demonstrated wing-mounted PVC devices for generating multi-axis moments.

The remaining step prior to serious consideration of an all-pneumatic controlled aircraft is
six degree-of-freedom evaluation of closed-loop multi-PVC (forebody, wing, and tail mounted devices) evaluated at low angle-of-attack / high speed flight conditions. The impact of PVC on flight performance, mission performance, and auxiliary systems (specifically engine compressor bleed air requirements) was the focus of the present research.

**Research Objectives**

The goal of the present research was to accomplish the following objectives through the use of a six degree-of-freedom flight simulation computer program:

1. Evaluate the feasibility of using PVC as the only type of control effector, and PVC augmented with conventional surfaces.
2. Extend the PVC concept to high speed, low angle-of-attack flight conditions which are representative of low level strike/interdiction missions.
3. Investigate the effects of multi-axis PVC, i.e. a suite of PVC devices mounted on the forebody, wing, and vertical tail which are capable of simultaneous operation.
4. Quantify the effect of various levels of engine compressor bleed mass flow rate on PVC performance.
5. Determine the threshold of engine compressor bleed mass flow rate required to completely eliminate conventional surfaces without degrading closed-loop vehicle performance.

**PVC Research Flight Simulation Tool**

Realistic evaluation of six degree-of-freedom closed-loop PVC on a high performance combat aircraft requires the use of a high fidelity flight simulation tool. The Lockheed F-16XL was selected as the baseline aircraft configuration to be studied (Figure 1). This aircraft is currently on flying status at the NASA Dryden Flight Research Center (DFRC) and is suitable for modification into a flying testbed for PVC research. In addition, the DFRC maintains both real-time and non real-time high fidelity, nonlinear, six degree-of-freedom simulations of this aircraft.
system, labeled CAS in Figure 2. Instead, a control allocation/mixing scheme was devised to integrate the PVC devices into the existing F-16XL flight control system.

\[ \Delta C_{\text{n req}} = C_{\text{n req}} - C_{\text{n \delta_{PVC}}} \delta_{PVC} \]

\[ \delta_{r \text{ filtered}} = \frac{\Delta C_{\text{n req}}}{C_{\text{n \delta_{r}}}} \]

This filtered value of commanded rudder deflection is then sent to the rudder actuator. This allocation concept was also extended to controlling the wing mounted PVC device in lieu of using aileron as the primary lateral control effector. This allocation concept proved to be adequate for one-axis PVC control (either wing mounted or vertical tail mounted).

For multi-axis PVC control, additional allocation is required to effectively "mix" multiple PVC devices. For this research, simultaneous use of both the wing mounted and vertical tail mounted PVC devices was accomplished by directing aileron commands to the wing mounted PVC device and likewise directing rudder commands to the vertical tail mounted PVC device. The aileron command signal in fact commands non-symmetric aileron deflections since it is used to modulate both lateral and directional motions. The mixing scheme extracts the symmetric content of this signal and feeds it to the wing mounted PVC device according to the previously described allocation algorithm. Subsequent evaluation of the allocation/mixing scheme demonstrated that crossfeed signals like the aileron to rudder interconnect (ARI) must be disabled. This is because the original aircraft model attempts to couple the individual effectors in a proverse manner. Since the PVC devices have inherently different aerodynamic coupling properties than the conventional control effectors, the interconnect modeling is inappropriate and therefore must be deactivated. It will be shown in the results section that this action does not severely degrade control harmony. Although not a goal of the present research, complete redesign of the control laws to provide the correct crossfeed signals would realize the maximum performance and benefit of using the PVC devices.

**PVC Device Modeling**

Pneumatic control devices on the forebody, wing, and vertical tail were modeled in the simulation with existing PVC wind tunnel data supplied by Wright Laboratory [12,14]. The data consists of
increments to normal force, sideforce, pitching moment, rolling moment, and yawing moment. Data was available for either on/off operation of the devices (fixed magnitude of control power), or proportional control by varying the massflow through the nozzle. Both types of device operation were modeled. Consistent with experimentally determined data, the associated dynamics and time delays were modeled as first-order lags with a time constant of 0.1 seconds. Consistent with the concept of incorporating PVC devices alongside conventional types to form an overall control effector suite, the PVC devices were mechanized in the flight simulation in exactly the same fashion as the existing conventional effectors. Reduction of engine thrust due to bleed air usage was not modeled, since the low percentage of bleed used (less than 4 lbm/sec) made this a second order effect.

**Test Design**

The test case matrix was designed to highlight the parametric effect of PVC massflow on closed-loop maneuver performance of an aircraft equipped with PVC devices. The test case ensemble (Table 1) consisted of i) an aggressive 3/4 stick roll doublet performed at Mach 0.9 at 25,000 feet over a sweep of PVC massflow levels; ii) a test case to determine the threshold of PVC massflow at which pneumatics can completely replace conventional effectors with no change in closed-loop performance; and iii) a segment of a low-observable penetration strike mission using only pneumatics.

**Table 1 Test Case Matrix**

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<tr>
<th>case</th>
<th>$\dot{m}_{\text{wing}}$ (lbm/s)</th>
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The roll doublet evaluations were conducted for two lateral/directional control effector suites. The first suite used PVC wing and vertical tail mounted devices to completely replace all conventional lateral/directional control effectors, and the second suite used the same PVC devices as the primary control effectors with the conventional effectors as secondary or augmenting effectors, using the control allocation scheme previously described. Lack of suitable forebody PVC device data prevented its use for these tests. Bandwidth limitations of the PVC effectors precluded their use for pitch control effectors without extensive modification of the existing F-16XL DFCS, which was beyond the scope of this research. Data collection runs for the generic F-16XL were performed at an aircraft weight of 32,019 (lbf); inertias of $I_{xx} = 18,000$ (slug-ft$^2$), $I_{yy} = 101,000$ (slug-ft$^2$), $I_{zz} = 116,000$ (slug-ft$^2$), and $I_{xz} = .530$ (slug-ft$^2$); and center of gravity location 45.31% MAC.

**Test Results**

Figure 3 shows the responses for Case 0, the nominal F-16XL roll doublet case. The bank angle response is precise, and both angle-of-attack and normal load factor deviate only slightly from the trim values, represented by the first two seconds of data. The digital flight control system feeds-in three degrees of rudder to coordinate the roll. The maximum roll rate generated by the ailerons is 150 degrees per second.

Figure 4 displays the responses for Case 7, which is wing and vertical tail blowing at eight and six lbm/sec respectively, and augmentation provided by the aileron and rudder. For an identical lateral stick input, the body-axis roll rate and bank angle responses are identical to the nominal case. There is a slight difference in the pitch axis responses, as the PVC devices inherently generate pitching moments which the aileron and rudder do not. Since the control allocation scheme does not have a dedicated pitch axis capability, the induced pitching moments are seen as disturbances by the pitch control system, and are subsequently damped out. Compared to the nominal case, use of PVC reduces maximum aileron deflections overall by roughly two degrees. Maximum rudder deflections are reduced overall by up to three degrees when the required deflections are small. But for larger commanded rudder deflections, use of PVC resulted in larger actual deflections and increased rudder activity. This behavior is due to the exceptionally strong cross-axis effects inherent to PVC devices compared to conventional elevons, ailerons, and rudders. Additionally, whereas the nominal F-16XL digital flight control system has been
purposely designed to reduce cross-axis responses resulting from deflection of the elevon, aileron, and rudder, the control allocation scheme simply selects the particular PVC device which can generate the largest magnitude response for that particular commanded axis. The by-product PVC generated moments which show up in other axes, whether of beneficial sign or not, are not accounted for by the control allocation scheme and are therefore seen as disturbances by the nominal F-16XL digital flight control system. Note that implementation of a dedicated PVC flight control system would alleviate this problem. For this maneuver, adverse yawing moments were generated by the PVC devices and rudder was used to cancel them out. The plots of PVC device activity indicate that with conventional effector augmentation, the devices are capable of generating the steady-state forces and moments required to initiate and sustain the maneuver without using the maximum level of blowing coefficient available ($C_\mu = .0015$ wing, $C_{\mu} = .0011$ tail). However, the PVC devices appear to lack the bandwidth necessary to smoothly arrest the roll acceleration, thereby resulting in some excessive activity characterized by “waviness” near the end of the maneuver.

The results of the other augmentation test case (Case 8, not shown) demonstrated that halving the wing and tail nozzle massflow levels did not affect the bank angle and body axis roll rate responses, but did result in slightly degraded pitch responses. The most significant difference was in the directional axis, where reduced PVC control power required extra rudder deflection to satisfy the demands of the maneuver. Both the maximum rudder deflections and the rudder activity were significantly increased compared to the nominal test case. The conclusion to be drawn from these test cases is that even with conventional effector augmentation, PVC devices must possess adequate control power or else overall system performance (in terms of the deflections and activity of the conventional effectors) may in fact be worse compared to a purely conventional control effector suite. Of course, the quality of the control allocation scheme will have a strong effect on this result, but even the best control allocation scheme needs effectors with large, uncoupled control power, regardless of the type of effector used.

An important part of this investigation was to eliminate the augmentation provided by the aileron and rudder, and repeat the maneuver using only PVC devices. Figure 5 displays the results for Case 4, which used the same massflow levels as Case 7 above. Compared to the nominal Case 0, the system was unable to achieve the full commanded bank angle displacement because the PVC devices were able to generate less than half the required body axis roll rate. A noteworthy result was that the pitch axis was virtually unaffected during the maneuver, unlike the strong effects observed for the augmented system in Cases 7 and 8. Likewise, the low-observables benefit of zero aileron and rudder deflections was achieved at the cost of saturated PVC devices. PVC device bandwidth was not an issue for this test case since the PVC devices simply could not generate large roll accelerations. However, in some scenarios, trading roll performance for increased survivability is beneficial.

Another objective of this research was to determine the threshold level of PVC device massflow required to completely replace the conventional effectors. A parametric study showed that 15 lbm/sec ($C_{\mu} = .0028$) supplied to both the wing and tail PVC devices generated sufficient control power to successfully complete the roll doublet maneuver with no appreciable degradation in closed-loop performance. The bank angle response was virtually identical to the nominal Case 0. Naturally, the control allocation scheme could not completely eliminate the cross-axis effects, but overall closed-loop performance was very close to Case 0.

Figure 6 shows a sample penetration strike mission flown with an ingress consisting of a 90 degree evasive turn to the right, followed by a 90 degree evasive left turn onto the initial point, a short weapons release run, and an egress consisting of a 180 degree heading change. The entire 125 second mission segment was successfully flown using pneumatics only, with massflow levels of 4 lbm/sec for the wing ($C_{\mu} = .00074$) and 3 lbm/sec for the vertical tail ($C_{\mu} = .00056$). The mission performance in terms of time of exposure to hostile defenses can be improved by increasing the massflow to the PVC devices, thereby increasing the maximum turn rate.

**Summary and Conclusions**

A high fidelity batch-type computer simulation tool of the F-16XL aircraft incorporating forebody, wing, and vertical tail mounted pneumatic vortex control devices was built for evaluating lateral/directional closed-loop performance, required PVC massflow levels, and penetration strike mission performance. Eleven test cases, including a segment...
of a penetration strike mission were evaluated, and based upon the results it is concluded that:

1. Signature characteristics, as measured by peak aileron and rudder deflection, can be improved by using pneumatic devices operated at low blowing coefficient levels ($= 0.0012$) and minimal massflow levels (4 lbm/sec). The effector suite used to accomplish this reduction consists of pneumatic devices as the primary control effectors, with augmentation provided by conventional (elevon and aileron) effectors. For the particular test cases studied, maximum aileron and rudder deflections could be reduced up to three degrees compared to a conventional F-16XL for the same maneuver.

2. Significant and usually adverse cross-axis responses can be expected when using multiple-axis PVC devices. X-29A flight testing showed similar cross-axis coupling resulting from open-loop use of forebody PVC devices. This problem can be alleviated by use of a dedicated PVC integrated flight control system.

3. Conventional ailerons and rudder can be completely replaced by purely pneumatic devices operating at realistic and attainable levels of engine compressor bleed air and blowing coefficients (14 lbm/sec, $C_u = .0026$), while still maintaining closed-loop system performance during aggressive roll doublet maneuvers. This feature can significantly improve signature characteristics by completely eliminating control surface deflections.

4. The simulated penetration strike mission test case demonstrated that successful completion of the mission is possible using only pneumatic lateral/directional effectors at low blowing coefficient levels ($= 0.00074$), provided the required turn rates are not large. Large turn rates are defined here as those which are approximately 80%-100% of the maximum full-performance turn rates which can be achieved by conventionally equipped aircraft.

**Recommendations**

Based upon the results and conclusions detailed above, the following recommendations are proposed for continued future research of this technology:

1. Employing rigorous and sophisticated control allocation methods to incorporate the PVC devices into the existing F-16XL digital flight control system.

2. Extend the test cases begun in the present research to true multi-axis PVC including forebody blowing and closed-loop pitch control. Suitable forebody PVC data was not available for the tests conducted in the present research, and the pitching moment capability of PVC was not taken advantage of because of restrictions prohibiting re-design of the digital flight control system. Incorporating these two aspects will provide the “full picture”.

3. Synthesize a new and completely PVC dedicated de-coupled digital flight control system using either a model predictive variable structure control scheme, or a model reference adaptive control scheme. The controller would use on-line system identification to handle the robustness problem associated with the control power generated by the PVC devices, and would also autonomously handle the stability augmentation function for the pitch axis. This could potentially reduce the level of massflow required.

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**References**


Figure 3 Case 0, Roll Doublet Response, Nominal Configuration F-16XL, 0.9/25k
Figure 4  Case 7, Roll Doublet Response, PVC + Augmentation F-16XL, 0.9/25k
Figure 5  Case 4, Roll Doublet Response, PVC Alone F-16XL, 0.9/25k

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Figure 6 Penetration Mission Trajectory, PVC Alone F-16XL, 0.9/25k