

Application of Synthetic Jets to Enhance the Performance of a Vertical Tail

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ABSTRACT

The performance enhancement of a vertical tail provided by aerodynamic flow control could allow for the size of the tail to be reduced while maintaining similar control authority. Decreasing tail size would create a reduction in weight, drag, and fuel costs of the airplane. The application of synthetic jet actuators on improving the performance of the vertical tail was investigated by conducting experiments on 1/9th and 1/19th scale wind tunnel models (relative to a Boeing 767 tail) at Reynolds numbers of 700,000 and 350,000, respectively. Finite-span synthetic jets were placed slightly upstream of the rudder hinge-line in an attempt to reduce or even eliminate the flow separation that commences over the rudder when it was deflected to high angles. Global force measurements on the 1/9th scale model showed that the flow control is capable of increasing side force by a maximum of 0.11 (19%). The momentum coefficient that created this change was relatively small ($C_{\mu} = 0.124\%$). Furthermore, for some conditions, when the individual jet strength was held constant, reducing the spanwise density of active actuators (e.g., turning on every other or every fourth jet) results in more control authority relative to when all jets are on. Scaling considerations were also studied by comparing the performance of actuation systems on the 1/9th and 1/19th scale models. Experiments showed better agreement in side force augmentation when the jet orifice cross-section and spanwise spacing are scaled dimensionally as opposed to non-dimensionally.

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INTRODUCTION

The vertical tail on most commercial transport aircraft is much larger than required for static directional stability. The stabilizer and rudder must be significantly oversized in order to maintain controllability in the event of asymmetric engine failure and meet flying qualities requirements related to dynamic motion [1]. Using aerodynamic flow control techniques, it may be possible to reduce the size of the tail while maintaining similar control authority during inclement flight conditions. Reducing the size of the tail decreases the weight and the drag of the airplane, which results in considerable savings in fuel costs. Synthetic jets are a means of enhancing the performance of a vertical tail such that its total size can be reduced and those savings realized.

The infrequent need for flow control in this application makes active control preferable to passive control, which

provides no proportional control and frequently introduces a drag penalty when the control is not desired [2]. Active flow control has been demonstrated in many applications to increase airfoil efficiency by reducing or even eliminating flow separation [3, 4, 5, 6]. It has been shown that periodic blowing can be used to delay separation or promote reattachment on a flap at a dimensionless frequency of $O(1)$ and is much more effective for boundary layer control than steady blowing [7]. The perturbations couple with the separated shear layer and evolve into large vortical structures, which lead to a Coanda-like tilting of the separated shear layer toward the surface [8]. This approach, however, relies on the narrowband receptivity of the separated shear layer to the actuator input and may induce unsteady flow reattachment.

In a different approach, the unsteady character of the flow reattachment and corresponding unsteady aerodynamic loads

are avoided by using synthetic jet (zero-net-mass-flux) actuators [9, 10, 11, 12, 13] that operate at a dimensionless frequency of $O(10)$. In this range, the carrier frequency of the actuator is decoupled from the characteristic frequency of the flow, and a quasi-steady flow interaction domain is created near the surface, which alters the local streamlines and pressure field [14, 15]. The modification of the apparent shape of aerodynamic surfaces has been shown to be beneficial in controlling separation on wind turbines [16], UAVs [17], and in inlet ducts [18]. In addition, synthetic jet actuators have been widely used to control the flow over airfoils. It has been extensively shown that these actuators are effective for improving the performance of 2-D airfoils [19, 20, 21]. More recently, work has been conducted on finite span wings; [22] investigated active flow control efficacy in unswept and sweptback semi-span wing configurations with 2-D synthetic jets. Improved aerodynamic performance was measured with actuators at the leading edge and flap shoulder. Similarly, synthetic jets were shown to be capable of providing trimmed lift benefits on a thin wing fighter aircraft with simple hinged flaps [23]. The physics of the interaction of finite span synthetic jets with the cross-flow over unswept and swept finite span wings was investigated by [24] and [25]. They showed that interaction results in the formation of secondary finger-like streamwise structures, which can improve the efficacy of the flow control.

The results reported here are a continuation of our previous work conducted on two vertical tail models [26, 27]. In the current study, synthetic jet flow control is applied to a third vertical tail model capable of sideslip rotation. Results highlighting the performance of the jets at various sideslip angles are presented. This is followed by an analysis of the effect of spanwise jet density. Then scaling will be discussed by comparing the experiments on the third wind tunnel model to those obtained on one of the other models.

EXPERIMENTAL SETUP

The experiments were conducted at two wind tunnel facilities and on two separate vertical tail models. At the first facility, Caltech's Lucas Adaptive Wind Tunnel, a 1/9th scaled-down model (named here *the Gamma Model*) was tested. The second model, named here *the Beta Model*, was 1/19th scale and was tested at the RPI Subsonic Open Return Wind Tunnel. The focus of this discussion will be on the Gamma Model, and the experiments on the Beta Model will be shown as part of the discussion regarding scaling.

The jet strength was characterized by the area-based momentum coefficient (C_μ , Eq. (1)) and blowing ratio (C_b , Eq. (2)). The respective parameters relate the synthetic jet momentum and velocity to the freestream flow. In the equations, n is the number of synthetic jets, A_j is the area of the jet orifice cross-section, T is the oscillation period, and U_j is the synthetic jet average velocity (Eq. (3)). The velocity was measured with a single hot-wire placed in the orifice at the location in which the peak velocities of the blowing and

suction cycles were equal. F^+ , the dimensionless frequency of the actuation, is given by Eq. (4).

$$C_\mu = \frac{nU_j^2 A_j}{1/2 U_\infty^2 S} \quad (1)$$

$$C_b = \frac{U_j}{U_\infty} \quad (2)$$

$$U_j = \frac{1}{T} \int_0^{T/2} u_j(t) dt \quad (3)$$

$$F^+ = \frac{f\bar{c}}{U_\infty} \quad (4)$$

Gamma Model Experiments

The experiments on the Gamma Model were conducted in the Caltech Lucas adaptive wall wind tunnel, a closed-return tunnel with a width and height of 1.8 m and 1.5 m, respectively. The model was attached to a ground plate that decreased the effective height to 1.295 m. The working section of the tunnel was 7.6 m and the maximum speed was 70 m/s. A Task 3161 force balance, capable of measuring two normal forces and the drag, was used. The maximum side force and drag loads were 4400 N and 900 N, respectively. In addition, a Pressure Scanners, Inc. 8400 system was used to acquire the surface pressure data.

The cross-section was a NACA 0012, and the platform was designed based on publicly available dimensions of a Boeing 767 (Figure 1a). It was approximately 1/9th scale with a mean aerodynamic chord $\bar{c} = 0.538$ m, span $b = 1.07$ m, leading edge sweep $\Lambda_{LE} = 43.5^\circ$, and reference area $S = 0.535$ m². The freestream speed was held constant at 20 m/s, correspond to a mean aerodynamic chord-based Reynolds number $Re_{\bar{c}} = 700,000$. A boundary layer trip was placed at $x'/c' = 0.05$ on the suction side and $x'/c' = 0.10$ (local chordwise distance perpendicular to the leading edge) on the pressure side of the stabilizer to ensure a turbulent boundary layer. Sideslip angle β varied from 0° to $0.67 \cdot \beta_{max}$ (β_{max} is the maximum sideslip of all experiments), and a 33% chord rudder was deflected from $\delta_r = 0.4 \cdot \delta_{r,max}$ to $0.8 \cdot \delta_{r,max}$ ($\delta_{r,max}$ is the maximum rudder deflection). Note that the sideslip angle and rudder deflection will be presented in terms of β^* (β/β_{max}) and δ^* ($\delta_r/\delta_{r,max}$).

Twenty-four synthetic jets with cross-sections of 1 mm $\times$ 19.1 mm were placed parallel to the rudder hinge-line. The jet orifices were located at a chordwise distance (Δx) of 15.0 mm upstream of the hinge-line. Non-dimensionally, with respect to the mean aerodynamic chord, $\Delta x/\bar{c} = 0.026$. They were oriented at a 20° angle with respect to the chord line and were driven at a frequency $f = 1900$ Hz ($F^+ = 51.1$). The characteristic frequencies of the flow based on the mean chord of the entire vertical tail and the rudder alone are

approximately 37 Hz and 112 Hz, respectively, which are inversely proportional to the time of flight.

The model was instrumented with roughly 230 static pressure ports arranged in various chordwise and spanwise rows. Three major chordwise rows, which consisted of between thirty-six and thirty-nine ports, were located at 40.3%, 69.9%, and 89.6% of leading edge reference line (imaginary line which runs from the root to the tip of the model and is parallel to the stabilizer leading edge). For brevity, only the 69.9% and 40.3% rows will be presented, which will be referred to as the outboard and inboard distributions. They are presented in terms of x' (distance from and in the direction perpendicular to the leading edge) normalized by c' (local chord in the direction perpendicular to the leading edge). Spanwise rows were arranged such that each port was at the same x'/c' location and are shown as normalized values of y' (distance from the root of the model) with respect to b' (local distance from the root to the tip of the model in a direction of constant x'/c').

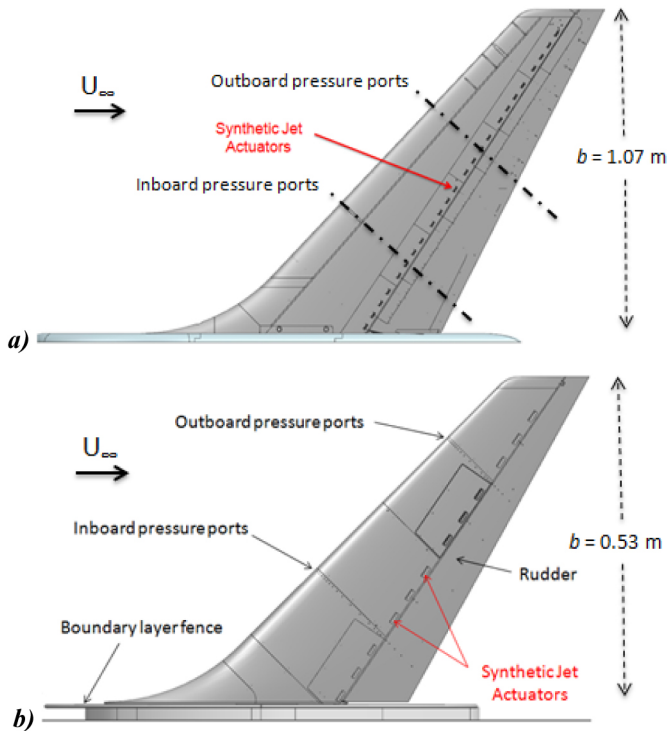


Figure 1. a) Gamma Model - 1/9th scale vertical tail model with synthetic jets and b) Beta Model - 1/19th scale model.

Beta Model Experiments

This model was very similar to and roughly half the size of the Gamma Model. The experiments on the Beta Model were conducted at Rensselaer Polytechnic Institute in an open-return wind tunnel with a cross-section of 80 cm $\times$ 80 cm and maximum speed of 50 m/s. In this work, the freestream speed was held constant at 20 m/s, corresponding

to $Re_c = 350,000$. The model was also designed based on publicly available planform dimensions of a Boeing 767 vertical tail, used a NACA 0012 airfoil section, and had a span $b = 0.53$ m (Figure 1b). It was approximately 1/19th scale with a mean aerodynamic chord $\bar{c} = 0.271$ m, leading edge sweep $\Lambda_{LE} = 45^\circ$, and a reference area $S = 0.134$ m². A boundary layer trip, made of a 24-grit roughness, was used to ensure a turbulent boundary layer. The trip was placed at 5% chord on the suction side and 10% chord on the pressure side of the vertical tail. Size and location of the trip were selected based on a detailed study (not discussed here). A boundary layer fence was used to offset the model from the tunnel floor to inhibit interaction with the boundary layer. Sideslip angle β^* varied from 0 to 1 and a 29.5% chord rudder was deflected from $\delta^* = 0$ to 1.

The model incorporated twelve piezoelectric disks, each with its own cavity. Orifices were placed with their long axis parallel to and approximately 7.7 mm ($\Delta x/\bar{c} = 0.028$) upstream of the rudder hinge-line. In the initial set of experiments, there was one orifice per cavity, but in one set of tests there were two orifices per cavity (twenty-four jets). The configuration with twelve orifices had 1 mm $\times$ 19.1 mm cross-sections, and in the design with twenty-four jets, the orifice cross-section was 0.5 mm $\times$ 9.5 mm. Furthermore, jets were oriented at 20° elevation with respect to the mean chord line for all of the arrangements mentioned above.

The jets were driven at a range of frequencies $f = 1000$, 1500, and 1600 Hz ($F^+ = 13.6$, 20.3, and 21.7) for the various orifice configurations. This is due to the fact that the resonant frequency of the jets (frequency at which the largest velocity can be obtained) changed with each design. The characteristic frequencies of the flow based on the mean aerodynamic chord of the entire vertical tail and the rudder alone are ~ 74 Hz and 250 Hz, respectively. Note that these frequencies are roughly an order of magnitude lower than the jet carrier frequency; therefore, the change in the driving frequency between orifice configurations should not have any influence on control effectiveness [28].

A six-component ATI Delta force/torque sensor was used to measure the aerodynamic loads on the tail. The resolution of the drag and side force was 0.0625 N. The aerodynamic load data were acquired twice for this model since two runs were necessary to measure the pressure at all port locations. Both sets are nearly identical (although only one set will be shown), demonstrating the repeatability of the experiments.

RESULTS

This section begins with results highlighting the performance enhancement of the Gamma Model using synthetic jet actuators. The effect of synthetic jets is examined using global force measurements and multiple pressure distributions. Following is the analysis of the influence of reducing actuator density (e.g., turning on every other jet) while maintaining constant individual jet strength.

Finally, a discussion of scaling, based on a comparison of the performance of synthetic jets in the Gamma and Beta Models, is presented.

General Performance of Synthetic Jets

Global force measurements

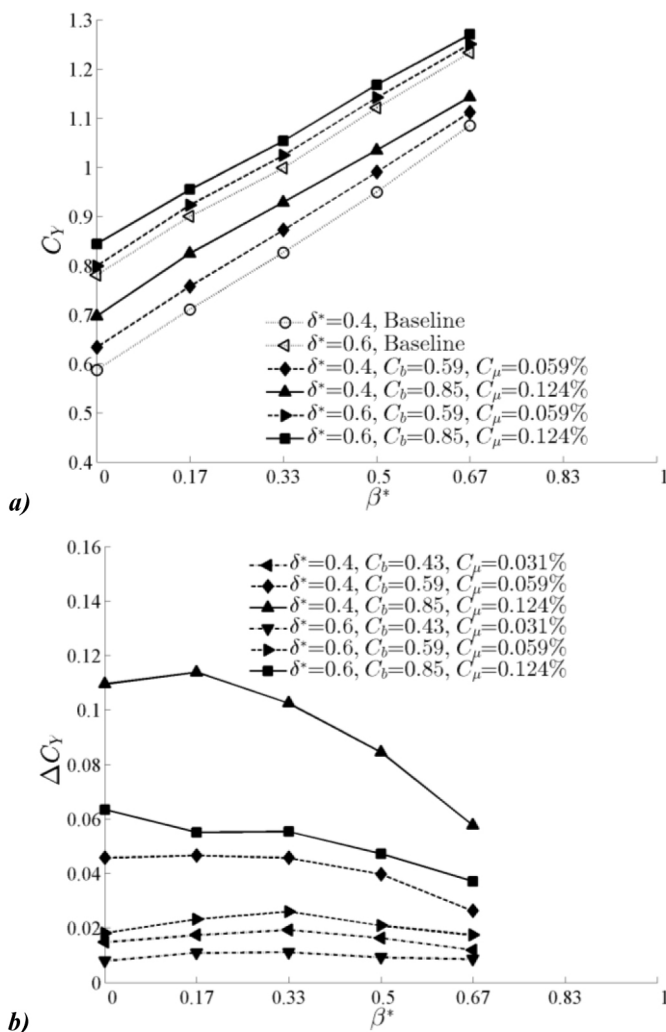


Figure 2. The effect of flow control at $\delta^* = 0.4$ and 0.6 for various sideslip angles on a) C_Y and b) ΔC_Y .

The performance of synthetic jets is analyzed in this section using data collected with the Gamma Model. The side force coefficient, C_Y , at $\delta^* = 0.4$ and 0.6 is shown in Figure 2a. The baseline represents cases in which the jets are not active, but the orifices are open. Data acquired with orifices taped closed (not presented here) revealed a negligible change in C_Y . As expected, baseline C_Y increases with rudder deflection and sideslip angle. Furthermore, it is clear that the jets are capable of enhancing C_Y for all sideslip angles and rudder deflections tested. Note that level of momentum input required to create this change is relatively small ($C_\mu \leq 0.124\%$). The jets appear more effective at the smaller rudder

deflection ($\delta^* = 0.4$) and their performance is dependent on C_μ (and C_b). Higher momentum results in a larger side force augmentation.

These results are more clearly illustrated in Figure 2b, which presents the change in side force, ΔC_Y , for the same two rudder deflections when $C_\mu = 0.031\%$, 0.059% , and 0.124% . At the lowest C_μ , a very small change in side force is created for both deflections. Actuation at $C_\mu \geq 0.059\%$ notably increases side force. The largest increment of $\Delta C_Y = 0.11$ (19% increase over the baseline) is obtained when $C_\mu = 0.124\%$, $\delta^* = 0.4$, and $\beta^* = 0.17$. Moreover, the jets' performance generally decreases as sideslip angle increases. This is related to the fact that the flow separation over the rudder becomes more severe as the sideslip angle increases, due to the stronger adverse pressure gradient. The relatively low amount of jet momentum likely is not capable of completely reattaching the flow at higher angles. The amount by which the side force is augmented also decreases when rudder deflection increases to $\delta^* = 0.6$ (e.g., when $\beta^* = 0$, $\Delta C_Y = 0.11$ and 0.06 at $\delta^* = 0.4$ and 0.6 , respectively).

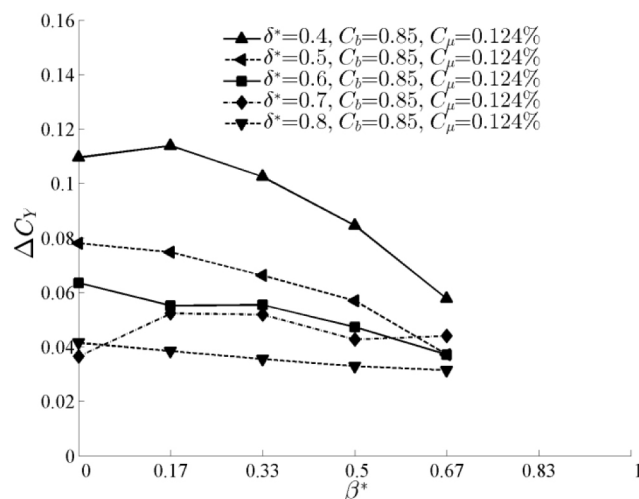


Figure 3. Effect of flow control for various sideslip angles on ΔC_Y at $\delta^* = 0.4, 0.5, 0.6, 0.7$, and 0.8 .

The effect of rudder deflection as it applies to the performance of synthetic jets is given in Figure 3, where only data with $C_\mu = 0.124\%$ is shown (the influence of rudder deflection is relatively invariant to the momentum coefficient). Actuation is most effective at $\delta^* = 0.4$ in comparison to the other rudder deflections, and for nearly every condition tested, jet performance decreases as the deflection increases. This can also be attributed to the growth in the magnitude of flow separation with increasing rudder deflection. Stereoscopic Particle Image Velocimetry (SPIV) conducted in previous work on a similar model [26] showed that synthetic jets are capable of completely reattaching the flow at $\beta^* = 0$ and $\delta^* = 0.4$. However, pressure measurements given below suggest that this is not the case when $\delta^* = 0.6$ (i.e., the incremental increase in side force decreases at this