# DRAG MANAGEMENT IN HIGH BYPASS TURBOFAN NOZZLES FOR QUIET APPROACH APPLICATIONS

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## ABSTRACT

The feasibility of a drag management device that reduces engine thrust on approach by generating a swirling outflow from the fan (bypass) nozzle is assessed. Deployment of such "engine air-brakes" (EABs) can assist in achieving slower and/or steeper and/or aero-acoustically cleaner approach profiles. The current study extends previous work from a ram air-driven nacelle (a so-called "swirl tube") to a "pumped" or "fan-driven" configuration, and also includes an assessment of a pylon modification to assist a row of vanes in generating a swirling outflow in a more realistic engine environment. Computational fluid dynamics (CFD) simulations and aero-acoustic measurements in an anechoic nozzle test facility are performed to assess the swirl-flow-drag-noise relationship for EAB designs integrated into two NASA high-bypass ratio (HBPR), dual-stream nozzles. Aerodynamic designs have been generated at two levels of complexity: (1) a periodically spaced row of swirl vanes in the fan flowpath (the "simple" case), and (2) an asymmetric row of swirl vanes in conjunction with a deflected trailing edge pylon in a more realistic engine geometry (the "installed" case). CFD predictions and experimental measurements reveal that swirl angle, drag, and jet noise increase monotonically, but approach noise simulations suggest that an optimal EAB deployment may be found by carefully trading any jet noise penalty with a trajectory or aerodynamic configuration change to reduce perceived noise on the ground. Constant speed, steep approach flyover noise predictions for a single-aisle, twin-engine tube-and-wing aircraft suggest a maximum reduction of 3 dB of peak tone-corrected perceived noise level (PNLT) and up to 1.8 dB effective perceived noise level (EPNL). Approximately 1 dB less maximum benefit on each metric is predicted for a next-generation hybrid wing/body aircraft in a similar scenario.

# NOMENCLATURE

$A_{ref}$	Reference area
$C_{d,eq}$	Equivalent drag coefficient
CNPR	Core nozzle pressure ratio (total-to-ambient)
CNTR	Core nozzle temperature ratio (total-to-ambient)
D	Drag
F	Thrust
FNPR	Fan nozzle pressure ratio (total-to-ambient)
FNTR	Fan nozzle temperature ratio (total-to-ambient)
$M_{\infty}$	Mach number
$V_{app}$ .	Approach velocity
$\theta^{''}$	Glideslope angle
W	Aircraft weight

## INTRODUCTION

For the current fleet of large civil aircraft, noise signature on approach is generally dominated by airframe noise sources such as flaps, slats, and landing gear. This establishes a need for deployable quiet drag devices as enabling technologies to operational changes such as steeper and/or slower and/or aeroacoustically cleaner approaches [1]. So-called "quiet" drag could (1) compensate for the loss of drag from the absence of conventional high-drag devices or faired landing gear associated with a cleaner airframe, and (2) enable a steeper and/or slower approach flight path with associated noise benefits.

It has been suggested that the operational shift to slower and steeper flight with cleaner aerodynamics is a means to reduce the community noise footprint [2]. Such operational changes offer the potential to keep noise sources farther from the communities and are a residual benefit of procedures such as continuous descent approaches (CDAs) [3],[4]. Another potential benefit of a quiet drag device is access to greater numbers of geographically confined airports. For example, in 2006, the Airbus A318 underwent a steep approach certification development for London City Airport that was cited as a potential competitive advantage that could have allowed the aircraft to be marketed as a replacement to a competing regional jet [5]. The procedure required simultaneous deployment of high-lift high-drag flaps and lift-spoiling highdrag speed brakes, due to the fact that neither could generate drag alone; this consequently required the aircraft to increase its approach speed. A quiet drag device, by contrast, could offer the opportunity to achieve comparable glideslope change by generating drag without such devices and without changing engine rotor speed or aircraft flight speed.

For airframe noise-dominated aircraft on approach, noise reduction on the ground (directly below the flight path) due to an operational change would roughly scale as the fifth power of the approach speed and as the square of the distance (or the small glideslope angle) due to spherical spreading of the acoustic wavefronts, assuming that all other system sources remain unchanged. This represents a best noise reduction scenario for a quiet drag device.

As a simple example, one may consider the steady state force balance of an aircraft on approach at a fixed approach velocity,  $V_{app}$ . For small glideslope angles,  $\theta$ , the force balance in the direction of flight equates the component of weight in the direction of flight ( $Wsin\theta$ ) with the aircraft drag minus residual engine thrust (D-F). Assuming constant approach speed and aircraft aerodynamic configuration, one may assume that the D-F quantity remains unchanged. Using the small angle approximation,  $sin\theta \approx \theta$ , doubling the aircraft's glideslope to an angle  $2\theta$  requires an additional component of drag equal to  $Wsin\theta$ . Such a small angle approximation may be used to estimate the required drag to change a conventional glideslope to a steeper angle, which places the aircraft farther from the observer on the ground. Assuming the additional drag required to fly the steep trajectory is "quiet", i.e., not appreciably louder than the other sources present, this can lead to a lower perceived noise on the ground.

This paper presents an aerodynamic and aero-acoustic assessment of a novel drag management device called an engine air-brake (EAB). The EAB is a propulsion-system integrated device that provides "equivalent drag" in the form of engine thrust reduction by swirling the bypass stream exhaust.

$$C_{d,eq} = \frac{F_{net,baseline} - F_{system,net,swirling}}{\frac{1}{2}\rho_{\infty}V_{app}^2 A_{ref}}$$
Equation 1

An equivalent drag coefficient for an EAB is defined in Equation 1 as the thrust reduction in a deployed state relative to the baseline flow condition at the same nozzle charging station conditions<sup>1</sup>, normalized by the product of the approach dynamic pressure and a reference area.

Table 1 presents a summary of the potential impact on several twin-engine aircraft classes including tube-and-wing aircraft in service and a hybrid wing/body (HWB) configuration based on the podded engine configuration described in Weed [6]. A quiet  $C_{d,eq}$  of 0.56-1.01 based on total fan circular area can enable a glideslope increase from three to four degrees at constant speed, resulting in a maximum noise reduction of 2.5 dB below the flight path. Quiet drag coefficients of 1.68–3.04 enable glideslope changes from three to six degrees at constant approach speed, with a corresponding maximum overall noise reduction of about 6 dB.

Table 1. Estimated  $C_{d,eq}$  to change conventional 3-degree glideslope to 4 or 6 degrees for several two-engine aircraft. Table expanded from [7]. Values estimated from publicly available sources.

		3 to 4 degrees	3 to 6 degrees		
	Two-En	-2.5 dB max under flight path	-6 dB max under flight path		
Aircraft Class	Assumed $V_{app}$ (m/s)	Assumed Max. Landing Mass (kg)	Assumed Total Fan (Circular) Area (m <sup>2</sup> )	"Quiet" C <sub>d,eq</sub>	"Quiet" C <sub>d,eq</sub>
CRJ-200	73.6	21,319	1.96	0.56	1.68
CRJ-900	73.6	34,019	2.11	0.81	2.43
737-700A	66.4	58,000	3.77	1.01	3.04
737-800	73.1	65,320	3.77	0.91	2.72
767-300	74.7	145,000	7.57	0.86	2.59
777- 200ER	71.1	213,000	15.33	0.80	2.40
787-8	72.0	166,000	12.49	0.72	2.17
HWB [6]	70.6	163,444	11.56	0.79	2.38

## BACKGROUND

This paper builds upon previous work on simpler configurations. Figure 1 presents a roadmap of the increasing complexity that is being addressed in the current EAB design effort. Generation of a swirling outflow from the engine's propulsion system to reduce approach thrust has been proposed in previous work [7]–[9]. While the EAB concept was demonstrated experimentally in a simple ram-pressure-driven nacelle with swirl vanes to generate drag quietly, the challenge of implementation in a real engine environment was left unanswered.

This so-called "swirl tube" was tested in the MIT Wright Brothers Wind Tunnel, as shown in the first panel of the figure.

<sup>&</sup>lt;sup>1</sup> The current definition does not include the rematching of gas turbine components when the device is deployed.

The device consisted of a duct with stationary swirl vanes that demonstrated maximum drag coefficient of about 0.8, based on through-flow area, with a relatively imperceptible far-field noise signature of about 44 dBA when extrapolated to full scale (2.16 m diameter, 120 m). Swirling motion vielded low pressure in the vortex core and therefore pressure drag. Beyond a swirl vane angle of about fifty degrees, the flow-field was found to transition from stable swirling flow to unsteady vortex breakdown near the duct exit. Far-field noise and source mechanisms were rigorously dissected [9] using a "Deconvolution Approach for the Mapping of Acoustic Sources" (DAMAS) phased array measurement technique [10] in the NASA Langley Quiet Flow Facility (QFF). The measured swirl-drag-noise relationship was found to depart from that of other drag generators, with vortex breakdown being the controlling phenomenon. At the onset of vortex breakdown, the device was found to be significantly louder (>15 dB) due to the unsteadiness of the burst vortex near the duct surfaces.

In Shah et al. [7], the concept of a fan-driven, or "pumped" swirl tube, was introduced as a means to integrate a quiet drag device into an aircraft engine, thus taking advantage of existing through-flow area instead of introducing it elsewhere on the aircraft. It was recognized that such a configuration would produce drag in the form of thrust reduction rather than drag in the conventional sense, with a potentially larger  $C_{d,eq}$  than a simple ram air-driven device. CFD simulations demonstrated that the swirling wake generated by the device in panel 1 would be replaced by the swirling jet in panel 2 with much larger Mach numbers on the centerline.

Panels 3 and 4 of Figure 1 present the current stage of development of a drag management device for approach applications. Both panels focus on HBPR turbofan nozzles. Panel 3 shows a swirling flow on the bypass stream only, generated by a row of vanes. Swirling outflow could be accomplished by vanes that deploy in the fan stream, or by fan outlet guide vanes (OGVs) that actuate to a position that allows swirl from a fan rotor to pass through them without returning the flow to the axial direction. Panel 4 depicts an example of a set of swirl vanes deployed near the exit of the fan nozzle in conjunction with a deflected trailing edge pylon that assists in generating a swirling outflow. These two configurations are assessed in this paper using CFD predictions and experimental measurements.

A limited body of previous work suggests that the noise from the devices that are shown in panels 3 and 4 will be significantly louder and different in nature than a dual-stream straight jet. For example, Tanna [11] theoretically assessed the effect of swirling motion of sources on subsonic jet noise and found that the overall mean square pressure directivity increased in the tangential direction. The magnitude of the effect was found to increase with swirl angle.



Figure 1. Engine air-brake technology development stages.

Lu et al. [12] measured the noise and flow characteristics of model swirling jets and reported that swirling jet noise is broadband in nature similar to nonswirling jet noise. The noise levels increase with swirl angle and decrease with increasing pressure ratio and total temperature. They also noted differences in noise from internal and external plug nozzles. The work of Lu et al. [12] was motivated in part by the previous work of Schwartz [13], who showed jet noise suppression in an engine application with swirling flow. Schwartz [13] obtained a ratio of 3 dB overall sound power reduction to 1% of thrust loss for a Pratt & Whitney JT15D-1 bypass flow engine by swirling a part of the primary flow. Lu et al. [12] noted that the experiments of Schwartz included more than jet noise sources alone, and concluded that considerable further testing of swirling jet flow and noise, especially under the influence of a parallel mean flow, was required to advance the understanding of the acoustic signature of such exhaust flows.

The current work builds upon these previous efforts with the goal of implementation in a modern and realistic engine setting. Application of swirling flows in HBPR applications is an unknown, as previous research has only considered turbojet flows or single stream applications, with limited consideration given to nonswirling core flows generated by swirl vanes on the outer portion of the duct only. A second unknown is the drag generation capability of swirling outflows in the presence of a pylon-a ubiquitous structure in current HBPR engine installations. Before reviewing the technical objectives of the research, a set of hypotheses are formulated based on the limited previous work and preliminary analysis:

- 1. Axisymmetric, HBPR, dual-stream nozzles can generate sufficient drag to change glideslope for noise reduction,
- 2. Internal and external plug nozzles will have uniquely different noise signatures with bypass swirl due to the difference in pumping of the core flow,
- 3. Realistic environments (pylon duct bifurcations) increase jet noise and also limit the amount of bypass swirl and drag that may be generated,
- 4. Jet noise increase can be limited to a reasonable value (e.g., 10 dB), keeping it below other noise sources (e.g., airframe noise) for large aircraft on approach, and
- 5. Modifications such as a deflected trailing edge pylon and asymmetric vane designs can assist in drag management for certain engine installations.

#### **TECHNICAL OBJECTIVES**

The research objective is to assess the viability of an EAB concept in a realistic engine environment. To do so, the primary technical objective is to quantify the performance of HBPR nozzle EAB configurations such as (1) axisymmetric swirling bypass flows, and (2), alternative pylon configurations, in terms of  $C_{d,eq}$  (i.e., thrust reduction), flow, and jet mixing noise. A secondary objective is to gain an understanding of the noise source mechanisms. Based on the estimations presented in Table 1, the success criterion of (1) is a fan circular area-based  $C_{d,eq}$  greater than 0.7 with less than 10 dB jet noise penalty, and the criterion for (2) is  $C_{d,eq}$  greater than 0.5 with less than 10 dB jet noise penalty. These success criteria are justified at the end of this paper through flyover noise simulations that estimate peak and overall noise reduction.

#### **TEST FACILITY**

To address the stated technical objectives, NASA's 4BB (Figure 2) and 5BB (Figure 3) HBPR nozzles [14] were selected for EAB aero-acoustic evaluation in the NASA Glenn Research Center Aero Acoustic Propulsion Laboratory (AAPL) [15]. The AAPL is a 65-foot-radius anechoic geodesic hemispherical dome. Acoustic wedges cover the walls of the dome and approximately half of the floor area. The Nozzle Aeroacoustic Test Rig (NATR) is contained in the AAPL and provides the airflow for the test article and a flight simulation capability. At the downstream end of the NATR is the Dual Flow Jet Exit Rig (DFJER)-the structure through which heated air can be delivered from the facility's compressed air system to the test article. However, in these experiments, no heating of air was permitted because many test articles were made of low-temperature-capability stereolithography apparatus (SLA) materials. While running cold core flow experiments reduces some of the realism associated with a turbofan engine, it enables a larger number of configurations to be tested at relatively low cost with faster configuration change.





Figure 2. 4BB internal plug dual-stream nozzle.

Figure 3. 5BB external plug dual-stream nozzle.



Figure 4. 4BB cross section.

Cross sections of the two nozzles are given in Figure 4 and Figure 5, respectively. The nozzles are designed for bypass ratios (BPRs) near 8; however, because the core flow was run cold (and hence at higher density) and off-design (approach) conditions were simulated, the tested BPRs were significantly lower. The rig is instrumented to record total temperature and total pressure at the charging station on both streams. In addition, mass flow rates are recorded using a flow venturi, and gross thrust was measured with a load cell.



Figure 6. Aft-looking-forward view of NATR with upper polar array and lower sideline array locations shown.

Noise is measured on a far-field polar arc array located at a radius of about 45 feet near the top of the AAPL dome, as well as on a sideline array of microphones located 11 feet from the centerline, as shown in Figure 6. In this paper, SPL spectra are presented as "1-foot lossless spectra," i.e., at a projected distance of 1 foot, with atmospheric attenuation added back into the level as a function of frequency.

To understand the swirling flow noise source spatial intensity and distribution, beamforming images were also generated with NASA Glenn's 48 microphone phased array (Array48) described in [16]. The beamforming array was placed 5 feet (1.52 m) from the nozzle centerline. It blocked the sideline microphones, but was found to produce negligible contamination in the polar array microphones located on the top of the dome. Therefore, all SPL spectra shown in this paper are measured on the (upper) polar array.

#### **EXPERIMENTAL HARDWARE**

ATA Engineering, Inc., (ATA) designed a family of modular hardware that could be installed into the 4BB and 5BB nozzle rigs to simulate potential EAB configurations. Both rigs share common fan flowpath hardware, including a fan nozzle with exit diameter<sup>2</sup> that was 9.629 inches (0.245 m). As previously stated, tested configurations fall into two categories: (1) periodically spaced rows of swirl vanes in the fan flowpath (the "simple" case), and (2) fan flowpath asymmetric swirl vane arrangements in conjunction with a deflected trailing edge pylon in a realistic engine geometry (the "installed" case), as shown in Figure 7.

A naming convention was created to identify different configurations that are discussed in portions of the remainder of the paper, as indicated in Figure 7. The overall convention has the format #BB-VK##-##PY. The first three digits identify the nozzle (#BB); the second four describe the type of vaned disk, or "visk" (VK##); and the final four digits identify the pylon assembly (##PY).

Simple visk assemblies are comprised of two aluminum rings, which secure a stereolithography apparatus (SLA)fabricated integral part with swirl vanes, as shown in Figure 7(a) and (b). These simple visk assemblies create an aerodynamically and aero-acoustically benign hub flowpath modification. Vanes are essentially prismatic<sup>3</sup>, and their exit angles span 30 to 60 degrees in increments of 10 degrees (VK30, VK40, VK50, and VK60). An SLA visk with no vanes (VKNN) also serves as a baseline model. As these cases contain no pylon, their pylon identification is NOPY.

Pylon configurations are more complex and include both visks and pylon hardware. A multi-piece pylon assembly was fabricated with aluminum and SLA parts, with a modular trailing edge (TE) subassembly that can be switched from a straight pylon TE (Figure 7(c), STPY) to a deflected pylon TE—without (Figure 7(d), DNPY) and with (Figure 7(e), DFPY) a fence structure to inhibit flow leakage. The straight pylon profile is based on a NACA 0012 airfoil, and is sized to mimic a fuselage-mounted engine as is seen on Canadair Regional Jet (CRJ) CF34 engine installations<sup>4</sup>. For EAB configurations, the pylon TE is deflected approximately 20 degrees to assist swirl vanes in generating a swirling outflow.

Because the pylon creates an asymmetry in the fan nozzle, two different asymmetric swirl visks were designed to assist the pylon in creating a net swirling outflow. As shown in Figure 7(d), a forward-located asymmetric visk (VKFA) was designed with varying vane exit angles and varying solidity around its circumference in order to redirect flow from the pressure side of the deflected pylon to the suction side of the deflection. Because this swirling flow is generated near the pylon leading edge, it mimics the effect of a carefully designed set of asymmetric variable OGVs behind a fan stage. CFD experiments reveal that the pylon limits the total amount of swirl (and hence drag) that can be generated by the VKFA configurations.

As shown in Figure 7(e), an asymmetric rear-located visk (VKRA) was also designed to generate about 20 degrees of swirl at the fan nozzle exit. Because of angular momentum conservation, this vane exit angle produces more drag at the fan nozzle exit location than in the upstream location of the other visks (e.g., VKFA or VK40).



(a) New vaneless hub flowpath (VKNN-NOPY).

<sup>&</sup>lt;sup>2</sup> The polar array microphones were thus >55 fan exit diameters away.

<sup>&</sup>lt;sup>3</sup> Prismatic vanes were designed to produce a desired outflow rather than represent a deployed EAB mechanism.

<sup>&</sup>lt;sup>4</sup> The CRJ installation was chosen because there are examples of both internal (CRJ-200) and external (CRJ-900) plug configurations.



(b) Periodically spaced 60 degree vanes (VK60-NOPY).



(c) Straight pylon with new hub flowpath (VKNN-STPY).



(d) Deflected trailing edge pylon with forward asymmetric visk (VKFA-DNPY).



(e) Deflected trailing edge pylon with fence structure and rear (fan nozzle exit) asymmetric visk (VKRA-DFPY).

Figure 7. Computer-aided design (CAD) models of select experimental hardware shown against 4BB cross section.

## SWIRLING BYPASS FLOW AERODYNAMICS

CFD simulations of the configurations described in the previous section were performed to quantify their drag generation capability and investigate the fundamental interaction between the bypass and core streams. All CFD results presented in this paper were generated in CD-adapco's STAR-CCM+ solver. All simulations solve the Reynolds-averaged Navier-Stokes (RANS) equations using Menter's shear stress transport (SST) two-equation, k-omega turbulence model. Both periodically symmetric and full 360-degree CFD domains were modeled, depending on the configuration. The computational domain extends radially 5 fan nozzle exit diameters from the centerline and axially 20 nozzle exit diameters from the inlet plane.



(a) Mesh topology in nozzle region. Freestream, fan and core inlet boundary conditions specified as shown.



(b) Turbomachinery mesh for swirl vane implementation Figure 8. Overview of CFD domain and mesh (4BB geometry shown).

Simulations with axisymmetry or periodic symmetry (e.g., simple visks) had block structured meshes (Figure 8 (a)) generated on a thin wedge. Turbomachinery grids for the swirl vanes (Figure 8 (b)) also used periodic passage meshes. For aperiodic geometries due to the presence of a pylon, full 360-degree simulations used unstructured hexahedral trim meshes generated in STAR-CCM+. These cases include meshes of asymmetric vanes and are computationally much more expensive than their periodically symmetric counterparts.

Three inlets to the domain include the freestream, the fan, and the core flow stream, where stagnation pressure and

stagnation temperatures were prescribed at a location similar to the NATR charging station, as shown in Figure 8 (a). Pressure outlet boundary conditions were used on the sides and downstream boundaries of the domain.

The CFD models simulate a flight Mach number of 0.212, similar to the approach speed of a large twin aircraft in the size class of a 787-8. The fan nozzle pressure ratio (*FNPR*) for most simulations is 1.191, based on the approach fan pressure ratio of NASA's Source Diagnostic Test [17] fan times the ram pressure rise associated with the flight Mach number. The core nozzle pressure ratio (CNPR) for most simulations is 1.209. CNPR and core nozzle temperature ratios (CNTR) are estimated from cycle analysis. Fan nozzle temperature ratio (FNTR) is set to 1.058 based on an assumed fan stage efficiency. Both hot core (CNTR=1.995) and cold core (CNTR=1.058) CFD simulations were run for the 4BB and 5BB geometries with prescribed inlet swirl, to investigate the impact of core temperature on flowfield.

An initial set of axisymmetric simulations prescribe a swirling flow boundary condition at the fan stream inlet. The baseline cases contain no swirl (0 degrees), and are compared to cases with fan inlet swirl values of 20, 40, and 60 degrees. The simulations reveal that increasing swirl in the fan stream reduces the fan flow, but increases the core flow rate due to lower pressure at the core nozzle exit—i.e., simple radial equilibrium creates a subatmospheric core exit pressure. For fixed charging station conditions, adding fan swirl therefore lowers the bypass ratio.

The initial axisymmetric CFD simulations also reveal several key features of the flowfield:

- 1. For a given level of inlet fan swirl, the fan mass flow is independent of the core nozzle geometry (4BB versus 5BB) and is also independent of the temperature of the core flow. Thus,  $C_{d,eq}$  (or thrust reduction) depends only on the level of fan swirl prescribed at the inlet to the domain.
- 2. The percent change in core mass flow for a given configuration (4BB or 5BB) is independent of the core temperature. This is because the fan swirl sets the exit boundary condition on the core nozzle, and since the fan flow is cold, the effective core nozzle pressure ratio in the presence of fan swirl is independent of core temperature<sup>5</sup>.
- 3. A given level of fan swirl results in a greater increase in core flow for the 4BB than for the 5BB case.

This last observation is most easily seen from a set of axisymmetric solutions with prescribed inlet swirl boundary conditions. For the cold core flow cases for both nozzles, the Mach number distributions shown in Figure 9 (4BB: 0, 20, 40 and 60 degrees) and Figure 10 (5BB: 0 and 60 degrees) demonstrate that for a given level of swirl, the pressure deficit at the core nozzle is lower for the 4BB nozzle than for the 5BB

nozzle. This is due to the fact that the core nozzle in the 5BB has a higher outer radius (and an annular exhaust), while in the 4BB case it is circular with a lower radius. The swirling outflow from the fan is therefore at a higher radius and produces less subatmospheric pressure at the 5BB core flow exit. This suggests that the two core nozzles may rematch the engine differently and implies that the design of the core nozzle exhaust may influence the EAB implementation.



Figure 9. Mach number contours for axisymmetric 4BB cold core flow simulations. Swirl prescribed at fan inlet.

<sup>&</sup>lt;sup>5</sup> Observation 2 is found to be in accord with the substitution principle of Munk and Prim [18], also discussed in Greitzer et al. [19], which states that two inviscid flowfields with identical stagnation pressure distributions but differing stagnation temperature distributions will produce identical Mach number and static pressure distributions.



Figure 10. Mach number contours for axisymmetric 5BB cold core flow simulations. Swirl prescribed at fan inlet.



Figure 11. Gray streamlines and Mach contours in horizontal iso-plane for VKRA-DFPY configuration

The higher core flow rates from fan flow swirl result in the highest core Mach numbers in the 4BB case. From a turbulence-generated noise point of view, the presence of the internal versus external plug is hypothesized to result in different noise levels. Specifically, the 4BB case is hypothesized to result in more core mixing noise due to higher Mach numbers, while the 5BB case might result in greater scattering of noise off the exposed plug.

Figure 11 presents a 4BB CFD image of streamlines and Mach contours in a horizontal iso-plane for the deflected trailing edge geometry with fence structure and rear asymmetric vanes (4BB-VKRA-DFPY). As will be shown in the noise assessment section, this case generates a similar value of  $C_{d.eq}$  as the 40-degree swirl vane (4BB-VK40-NOPY) case, and about twice as much drag as the cases having forward asymmetric vanes (4BB-VKFA-DNPY and 4BB-VKFA-DFPY). Due to aperiodicity in the geometry, the 4BB-VKRA-DFPY configuration generates some side and vertical forces that are not present in the periodic cases, but these are less than 25% of the force in the drag direction. The figure reveals that the kinematics of the swirling flow are distinct from the periodic simulations. Specifically, the wake appears to enlarge several diameters downstream of the nozzle—perhaps due to a vortex breakdown or an unraveling of vortex lines. This is hypothesized to have noise implications. It is also hypothesized that the presence of vanes at the nozzle exit plane may reveal a source of self-noise not seen in other configurations where the vanes are embedded further upstream.



Figure 12. CFD-predicted  $C_{d,eq}$  is strongly correlated to fan exit swirl angle. Fan diameter-based  $A_{ref}$ .

In terms of gross performance metrics, the equivalent drag<sup>6</sup> coefficient,  $C_{d,eq}$ , is found to be strongly correlated to the level of swirl at the fan nozzle exit plane<sup>7</sup>, as shown in Figure 12 for a variety of CFD simulations with different levels of fan nozzle exit swirl. The plot shows axisymmetric CFD cases that include a prescribed inlet swirl condition as well as periodically symmetric CFD cases with swirl vane geometries for 4BB and 5BB.  $C_{d,eq}$  is nondimensionalized to a fan (circular) area that is assumed equal to the outer diameter of the fan nozzle stream inlet. Because the 4BB and 5BB fan flowpaths are identical, the  $C_{d,eq}$  collapses to a single curve.

Equivalent drag is also found to be strongly correlated with fractional changes in fan flow and core flow, as shown in Figure 13 and Figure 14, respectively, for various 4BB configurations. The fan flow reduction and core flow increase are shown relative to a baseline configuration without swirl. For simple visks, the baseline case has no swirl vanes (VKNN-

<sup>&</sup>lt;sup>6</sup>  $C_{d,eq}$  was defined as a *net* thrust reduction per Equation 1, and was evaluated in CFD based on a control volume that accounts for both gross thrust, ram drag, and nacelle exterior drag.

<sup>&</sup>lt;sup>7</sup> The swirl angle at the fan exit plane is lower than the swirl angle prescribed at the inlet of the fan stream in the CFD domain. This is due to conservation of angular momentum because the streamtube radius and area both contract at the fan exit. The axial velocity increases faster than the tangential velocity, resulting in a lower swirl angle. In this paper, configurations are identified by vane turning angles, not fan nozzle exit swirl angles.

NOPY, Figure 7 (a)), while for pylon configurations the baseline is the case with a straight pylon only (VKNN-STPY, Figure 7(c)). The drag-flow relationship is approximately linear in the cases considered. It is seen that a given equivalent drag results in less fan flow reduction for a simple visk case versus a pylon case. It can be inferred that the relationship for the pylon cases is a small departure from the simple or "ideal" case. Because the bypass swirl enforces a pressure deficit at the core nozzle exit, this departure from ideal is also seen on the core flow fraction, where a more ideally generated swirling flow will create more suction on the core relative to one that is less ideal.

#### **EXPERIMENTAL VALIDATION**

CFD simulations from thirteen different configurations have been compared to experimentally measured flows (corrected to the same atmospheric conditions) and are found to be in good agreement. The CFD predictions with swirl in the bypass stream result in bypass ratios<sup>8</sup> ranging from 2.7 to 4.8. The magnitude of the percent difference between experiment and CFD predictions for bypass flow, core flow, and bypass ratio are found to be less than 2.6% for all thirteen configurations. These results include both periodic domains associated with simple visks and full 360-degree simulations of the pylon configurations.

The experimental facility's measured thrust and mass flow confirms the trends seen in the CFD prediction of equivalent drag as a function of fan or core flow fraction, as indicated in Figure 13 and Figure 14. The measured equivalent drag of a specific configuration is generally slightly greater in the experiment than in the CFD; therefore, to be conservative, the CFD-predicted value is employed in the flyover noise assessment at the end of this paper.



Figure 13. Correlation between fan flow reduction and  $C_{d,eq}$  based on fan (circular) area for 4BB cases.



Figure 14. Correlation between core flow reduction and  $C_{d,eg}$  based on fan (circular) area for 4BB cases.

#### SIMPLE VISKS: STATIONARY JET NOISE

The most significant finding from the set of experiments done with the simple visks tested at AAPL is that swirling bypass flows monotonically increase OASPL as a function of swirl angle. This is first revealed in stationary measurements, i.e., with freestream flow off. This differs from previous measurements on the ram air-driven "swirl" tube of Figure 1(a), and is hypothesized to be associated with the significantly higher absolute Mach numbers generated by a fan-driven swirling flow (e.g., in Figure 9 or Figure 10) that produces a swirling jet as opposed to a swirling wake.

A second observation is that the location of the dominant region of noise generation moves upstream and radially inward as swirl is increased. The low-frequency source is more compact when compared over the same dynamic range. The noise level increase is significant, as indicated by the color scales shown in the delay-and-sum (DAS) beamforming maps of Figure 15 at three different one-third-octave frequencies, though the phased array is in the acoustic near field and the differences become less dramatic in the far-field spectra.

The upstream migration and compactness associated with the swirling source is likely to also have some implications for applications where shielding is important. The beamforming maps suggest that suppression potential from the shielding of swirling flow noise may be better at low frequency but worse at high frequency.

Another important observation is that the noise source appears to be below the centerline, as seen in the swirl cases. When viewed from the aft, the direction of bypass swirl is clockwise, which implies that the component of tangential velocity is towards the observer below the jet centerline and away from the observer above it. The noise propagation direction of the source appears to be in alignment with the tangential velocity, which appears consistent with the analysis of Tanna [11].

<sup>&</sup>lt;sup>8</sup> Bypass ratios are lower than the nozzle design values because the core flow was cold and hence had higher density than hot core flows.



Figure 15. DAS beamforming images of dominant noise source for three frequency bands and three levels of swirl (rows: 0-, 40-, and 60-degree simple swirl visks).



Figure 16. RANS CFD-predicted turbulent kinetic energy contours support the general observation that the dominant region of noise generation moves forward with swirl. FNPR=1.191, CNPR=1.209, and M=0.212. Both streams are cold.

CFD-predicted turbulent kinetic energy (TKE) contours shown in Figure 16 support phased array observation of the upstream migration of the noise source, although it is not clear from the beamforming maps whether the source is associated with the inner shear layer, outer shear layer, or the merging of the two.

As noted in the aerodynamic assessment, a given bypass swirl configuration produces essentially the same  $C_{d,eq}$  between 4BB and 5BB because bypass flow is largely unaffected by the core stream. However, the 5BB nozzle with swirl is found to be slightly less noisy than 4BB due to the higher radius of the 5BB bypass flow at the core nozzle exit, which imposes a lower pressure deficit there. Consequently, the core Mach number is lower, and it appears that the external plug configuration experiences a lower noise penalty, as suggested in the 90-degree observer OASPL change summary in the next section.

#### SIMPLE VISKS: EFFECT OF FORWARD FLIGHT

The effect of forward flight on flows with bypass swirl is observed to be less beneficial than forward flight on straight jets. In the rightmost column of Table 2, two deltas are shown for a few selected configurations that were measured with and without forward flight air on ( $M_{\infty}$ =0.212). The difference is

only about 0.5 dB for the vanes with 40 degrees turning (which correspond to about 20 degrees of swirl at the bypass nozzle exit plane), but becomes greater for the 50- and 60-degree vanes (up to 4.0 and 6.7 dB, respectively). It is hypothesized that this occurs because the swirling jet shear layer is not aligned with the freestream flow and because the dominant noise source may have migrated radially inward over much of the frequency range.

The 1-foot lossless SPL spectra at a 90-degree observer angle and the OASPL directivity are shown for the various 4BB simple visk configurations in Figure 17 and Figure 18, respectively, for freestream Mach numbers of 0.00 and 0.21. Figure 19 and Figure 20 present similar SPL and OASPL spectra for 5BB simple visk configurations. The 5BB configuration demonstrates a more favorable flight effect versus the 4BB. The figures show that the effect of forward flight becomes less beneficial as swirl angle increases.

Linear interpolation suggests that the stated technical objective to generate at least 0.7 equivalent drag coefficient with less than 10 dB noise penalty is met for the higher FNPR with a visk angle between 40 and 50 degrees.

		<i>M</i> <sub>∞</sub> =0.21	<i>M</i> <sub>∞</sub> =0.21	90 deg		
		FNPR=1.19	FNPR=1.27	observer		
				∆OASPL (dB)		
Nozzla	Vane Swirl	$C_{d,eq}$	$C_{d,eq}$	FNPR=1.27		
NOZZIE	Angle	(CFD)	(CFD)	CNPR=1.33		
	-			<i>M</i> <sub>∞</sub> =0/0.21		
4BB			0.00	+0.0		
5BB	VRININ-INOP I					
4BB		0.24	0.30	+3.3		
5BB	VK30-INOP I	0.25				
4BB		0.44	0.57	+5.3		
5BB	VK40-INOF I	0.45		+4.9/5.4		
4BB		0.77	1.03	+9.6/13.6		
5BB	VK30-INOP I	0.80		+8.9/12.0		
4BB		1.34	1.80	+14.9/21.6		
5BB	VR00-NOP I	1.36		+14.7		

Table 2.  $C_{d,eq}$  and 90-degree OASPL change for simple swirl visk configurations ( $\theta$  based on HWB).



Figure 17. 1-foot lossless one-third-octave SPL spectra at 90-degree observer position for various 4BB simple visk configurations; FNPR=1.27, CNPR=1.33.



Figure 18. 1-foot lossless OASPL directivity for various 4BB simple visk configurations; FNPR=1.27, CNPR=1.33.



Figure 19. 1-foot lossless one-third-octave SPL spectra at 90-degree observer position for various 5BB simple visk configurations; FNPR=1.27, CNPR=1.33.



Figure 20. 1-foot lossless OASPL directivity for various 5BB simple visk configurations; FNPR=1.27, CNPR=1.33.

# PYLON CONFIGURATIONS NOISE ASSESSMENT

The internal plug 4BB configuration was tested with a straight pylon and deflected trailing edge pylons with and without a fence structure to inhibit flow leakage between deflected and straight regions. A vaneless hub flowpath was used both without (VKNN-NOPY) and with (VKNN-STPY) the straight pylon to represent two possible baseline scenarios. In conjunction with the deflected pylon geometry there were two asymmetric visk geometries tested: one in the forward location and one in the exit plane of the nozzle. The forward asymmetric visk was paired with a deflected pylon with (VKFA-DFPY) and without (VKFA-DNPY) a fence structure. The pylon trailing edge deflection angle was approximately 20 degrees. The aft plane (rearward) located visk was paired only with the fence-containing deflected pylon (VKRA-DFPY). Images of the different hardware are shown in Figure 7(c)–(e).

	<i>M</i> ∞=0.21 FNPR=1.19	<i>M</i> ∞=0.21 FNPR=1.27	90 deg observer				
Case	$C_{d,eq}$ (CFD)	$C_{d,eq}$ (CFD)	$\triangle OASPL (dB)$ FNPR=1.27 CNPR=1.33 $M_{\alpha}$ =0/0.21				
VKNN-NOPY		-					
VKNN-STPY							
VKFA-DFPY	0.24	0.31	+4.0/7.2 (vs. NOPY) +2.2/5.6 (vs. STPY)				
VKFA-DNPY	0.25	0.32	+4.1/8.1 (vs. NOPY) +2.2/6.5 (vs. STPY)				
VKRA-DFPY	0.46	0.60	+6.9/9.3 (vs. NOPY) +5.1/7.8 (vs. STPY)				

Table 3.  $C_{d,eq}$  and 90-degree OASPL change swirling outflow pylon configurations (HWB).

The CFD-predicted  $C_{d,eq}$  and 90-degree observer OASPL noise change is summarized in Table 3. The 1-foot lossless SPL spectra at 90-degree observer angle and the 1-foot lossless OASPL directivity are shown for the various configurations in Figure 21 and Figure 22, respectively, for freestream Mach numbers of 0.00 and 0.21. The spectra and OASPLs demonstrate an increase in noise with increasing drag. Relative to the baseline case with no pylon (4BB-VKNN-NOPY), a straight pylon (4BB-VKNN-STPY) increases mid-frequency noise and results in an increase in OASPL primarily towards the forward angles. It is hypothesized this mechanism is related to scattering of turbulence past the straight pylon trailing edge.



Figure 21. 1-foot lossless one-third-octave SPL spectra at 90-degree observer position for various 4BB pylon configurations; FNPR=1.27, CNPR=1.33.

The forward asymmetric visk configurations (VKFA) generate modest drag levels and also show modest noise penalty relative to either of the two baseline cases. It appears that there is a small additional benefit in fence configuration with forward flight that is not seen with static ambient flow conditions.

The rear asymmetric visk configuration (VKRA) with fence-containing deflected pylon has the higher drag (about twice the drag of the VKFA configurations) and the highest jet noise penalty. Additionally, there is evidence of vane self-noise in the aft visk configuration at 31.5 kHz. Finally, phased array maps comparing the VKNN-NOPY, VK40-NOPY, and VKRA- DFPY configurations at 3150 Hz suggest that VKRA-DFPY has a distinct and more distributed noise source, despite having similar  $C_{d,eq}$  to the VK40-NOPY case. Referring to the CFD-generated Mach contours of Figure 11, an explanation worth pursuing may be a connection to a sudden change in vortex structure. It will be shown in the next section that the noise penalty from this case will still result in an overall noise reduction scenario for two different aircraft on steep approach at constant speed.

The stated technical objective to generate at least 0.5 equivalent drag coefficient with less than 10 dB noise penalty is met for the higher FNPR with the VKRA-DFPY configuration.



Figure 22. 1-foot lossless OASPL directivity for various 4BB pylon configurations; FNPR=1.27, CNPR=1.33.



Figure 23. DAS beamforming images of VKNN-NOPY, VK40-NOPY, and VKRA-DFPY configurations at 3150 Hz.

#### FLYOVER NOISE SIMULATION

It is important to remember that despite jet noise penalties described in the previous section, baseline jet noise is generally much quieter than other noise sources (e.g., airframe) on approach, enabling net overall noise reduction scenarios for an EAB. In this section, the example of steep approach is used to demonstrate this.

Flyover noise simulations of a single-aisle, twin-engine conventional (tube-and-wing) aircraft in the 737-800 class and the generic podded-twin-engine hybrid wing-body aircraft described in Weed [6] have been performed with NASA's Aircraft Noise Prediction Program (ANOPP). The flyover simulations include engine components such as jet, core, and fan noise, and airframe components<sup>9</sup> such as landing gear (main and nose) and trailing edge sources. The baseline jet noise component is perturbed by adding a constant noise delta, and the trajectory is altered to a steep descent relative to the conventional glideslope<sup>10</sup> for a fixed approach velocity,  $V_{app}$ .



Figure 24. Single-aisle, twin-engine aircraft (737-800 class) PNLT time history for conventional and EAB operation for 50-degree swirl vanes that generate  $C_{d,eq}$ =1.05 and 13.6 dB jet noise penalty at FNPR=1.27.

For the tube-and-wing aircraft, ANOPP flyover predictions were made for EAB configurations including the 40-, 50-, and 60-degree periodic swirl vanes and the VKRA-DFPY configuration of Figure 7(e). The tube-and-wing aircraft characteristics are similar to those listed in Table 1 for the 737-800, except the aircraft landing mass was 59,700 kg. The equivalent drag, effective approach angle, jet noise increase, and predicted overall noise change at the standard approach observer location (2000 m before touchdown) are given in Table 4. The tone-corrected perceived noise level (PNLT) time history for the case with and without an EAB is shown for the VK50, FNPR=1.27 case in Figure 24.

The table and figures demonstrate that despite an appreciable jet noise penalty due to swirl, this airframe noise source-dominant aircraft experiences up to 3.1 dB peak PNLT reduction, and up to 1.8 dB EPNL reduction. The figure also shows that this noise reduction is possible due to the fact that the nominal jet noise peak is about 20 dB quieter than the two most dominant sources, which are airframe noise in the forward emission direction. The EAB PNLT flyover also shows that the peak value is suppressed, but the PNLT time history is generally a little louder towards the end of the flyover; this suggests that selective use of the EAB while the aircraft is

approaching the observer may provide a means to generate a further EPNL reduction for this application<sup>11</sup>.

Table 4. Summary of equivalent drag, mean glideslope change (baseline 3.2 degrees), and noise impact for tubeand-wing example. Uniform jet noise increase based on 90degree OASPL for FNPR=1.27. CNPR=1.33.

CASE	FNPR	$C_{d,eq}$	$\theta_{mean}$	∆(Jet	∆(Peak	∆(Overall
(vs.			(deg)	Noise	PNLT,	EPNL,
737-			( 0,	,dB)	dB)	dB)
800						-
base)						
VK40-	1.19	0.44	3.7	15.4	-1.8	-1.1
NOPY	1.27	0.57	3.9	+5.4	-2.1	-1.4
VK50-	1.19	0.77	4.1	126	-2.2	-1.1
NOPY	1.27	1.03	4.4	+13.0	-3.1	-1.8
VK60-	1.19	1.34	4.8	121.6	-1.7	+0.3
NOPY	1.27	1.80	5.4	+21.0	-3.0	-0.4
VKRA-	1.19	0.46	3.7	170	-1.8	-1.1
DFPY	1.27	0.60	3.9	+7.0	-2.1	-1.3

Table 5. Summary of equivalent drag, modified glideslope, and noise impact for next-generation, podded-twin-engine hybrid wing/body example. Uniform jet noise increase based on 90-degree OASPL for FNPR=1.27, CNPR=1.33.

based on 90-degree OASI Lior Fill R-1.27, Cill R-1.55.						
CASE	FNPR	C <sub>d,eq</sub>	$\theta$	∆(Jet	∆(Peak	∆(Overall
(vs.			(deg)	Noise	PNLT,	ÉPNL,
HWB			( 0)	,dB)	dB)	dB)
base)						,
VK40-	1.19	0.44	3.6	15 /	-1.7	-0.6
NOPY	1.27	0.57	3.8	+5.4	-2.1	-1.1
VKRA-	1.19	0.46	3.6	170	-1.7	-0.3
DFPY	1.27	0.60	3.9	τι.0	-2.2	-0.7

For the generic hybrid wing/body, the 40-degree swirl vanes and the VKRA-DFPY configuration were flown in ANOPP. The equivalent drag, effective approach angle, jet noise increase, and predicted overall noise change at the standard approach observer location (2000 m before touchdown) are given in Table 5. For this aircraft, the baseline noise flyover model suggests the peak jet PNLT is over 15 dB lower than the total, which is dominated by main landing gear noise. The tone-corrected perceived noise level (PNLT) time history for the case with and without and EAB is shown for the VK40 cases in Figure 25. The table and figures demonstrate that this airframe noise source-dominant aircraft experiences up to 2.2 dB peak PNLT reduction, and up to 1.1 dB EPNL reduction. Because the current model neglects inboard and outboard elevon noise, these results are conservative.

The flyover simulations also reveal that the preferred swirl vane angle for the hybrid wing/body case is different from the tube-and-wing case due to the relative difference between jet noise and other aircraft sources. This reinforces the point that

<sup>&</sup>lt;sup>9</sup> The ANOPP noise module for elevon noise was not available. This source is a significant contributor to hybrid wing-body approach noise—the results for this aircraft are therefore conservative because greater noise reduction would be predicted when elevon noise is included.

<sup>&</sup>lt;sup>10</sup> Steep approach is not necessarily applicable to certification, but the example is given here due to its simplicity. Certification scenarios might include slower or aero-acoustically cleaner approach at standard glideslope angle.

<sup>&</sup>lt;sup>11</sup> The tube-and-wing analysis assumes that the generation of swirl will have little effect on fan exhaust (discharge) noise, which is the dominant source in the aft emission direction for this aircraft. If this source were affected by the presence of swirl, a similar selective use of the EAB during approach to the observer may be one way to mitigate any adverse noise impact.

the incorporation of an EAB drag management device requires a good understanding of the relative noise source strengths in the system.



Figure 25. Generic hybrid wing/body PNLT time history for conventional and EAB operation for 40-degree vanes, which generate  $C_{d,eq}$ =0.57 and 5.4 dB jet noise penalty at FNPR=1.27.

# CONCLUSIONS

An EAB implementation study is presented for two HBPR dual-stream nozzle geometries (4BB/5BB) using CFD simulations and experimental aero-acoustics assessment in the NASA AAPL facility in order to quantify the relationship between flow, thrust, and equivalent drag. Drag and noise data are used in flyover simulations to assess the drag-management potential of EAB installations.

CFD simulations and noise measurements reveal important features of these flows, including the following observations:

- 1. Bypass swirl generates a pressure deficit that applies suction to the core flow; the bypass ratio drops significantly because the fan flow decreases and the core flow increases.
- 2. Swirling flow noise increases with bypass swirl angle for the nominally prismatic vanes applied in the current study.
- 3. The external plug nozzle geometry (5BB) generates lower noise when compared to the internal plug geometry (4BB), due to the higher core flow radius when the bypass flow imposes its pressure deficit on it.
- 4. Noise source location from phased array maps suggests the primary source location migrates upstream and radially inward with increasing bypass swirl angle; this is likely due to both core/bypass shear flow interaction and merging of the shear layers emanating from the two nozzle trailing edges.
- 5. Forward flight jet noise reduction is less dramatic for a swirling flow when compared to a straight flow. This is likely due to the inward migration of the noise source away from the outer shear layer.
- 6. A pylon limits the amount of swirl that can be generated at the fan exit plane by vanes located upstream of it; the swirl generation capability can be increased by positioning swirl vanes near the fan exit. For the configurations considered, the swirl vanes near the fan exit (VKRA) produced about

twice the drag of those with vanes in the upstream location (VKFA).

The experiments meet test objectives by demonstrating a fan circular area drag coefficient above 0.7 with less than 10 dB OASPL jet noise penalty in the primary approach noise emission direction for periodically spaced vanes having between 40 and 50 degrees exit angle. A drag coefficient above 0.5 with less than 10 dB jet noise penalty is demonstrated for a deflected trailing edge pylon design used in conjunction with a set of swirl vanes located near the fan nozzle exit (configuration VKRA-DFPY).

ANOPP steep approach flyover simulations of a current and next-generation aircraft at fixed speed reveal that system overall noise reduction can be realized with such devices. In these simulations, baseline jet noise peak PNLT is more than 15 dB quieter that the overall peak PNLT.

For a 737-800-class twin-engine aircraft on a nominal 3.2 degree approach, up to 3.1 dB peak PNLT reduction and 1.8 dB EPNL reduction is predicted using 50-degree periodically spaced swirl vane data, enabling a 4.4-degree approach. Peak PNLT and overall EPNL reductions of 2.1 and 1.3 dB, respectively, are predicted for the VKRA-DFPY configuration, which enables a 3.9-degree approach.

For a next-generation podded-twin-engine, hybrid wing/body aircraft on a nominal 3-degree approach, 40-degree periodically spaced swirl vanes enable a 3.8-degree approach with peak-PNLT and overall EPNL reduction of 2.1 and 1.1 dB, respectively. The VKRA-DFPY configuration on this aircraft enables a 3.9-degree approach with 2.2 and 0.7 peak-PNLT and EPNL reduction, respectively. The ANOPP simulations also suggest that the preferred swirling outflow arrangement will be a function of the equivalent drag, jet noise penalty, and level of jet noise relative to all other system noise components.

#### OUTLOOK

Because of the inherent challenges associated with deployment of an EAB and management of flow around a pylon, it is worth commenting on two possible approaches for EAB implementation in an engine. One approach uses a variable trailing edge fan OGV. Because OGVs normally remove swirl generated by a fan rotor, EAB deployment would entail having the variable mechanism unload the OGV to allow a swirling flow to pass through. Variable stator technology could be extended to an application in a mechanically elegant manner, though the designer may still be required to contend with generation of a swirling flow past a pylon, whose limitations on swirl and drag have been explored in this paper.

A second approach is to deploy swirl vanes near the nozzle exit in conjunction with a variable trailing edge pylon during an EAB maneuver. The vanes would either return to a straight configuration in the flowpath (with some aerodynamic penalty during cruise) or disappear from the flowpath entirely using a more complex mechanism. A concern with such approaches may be the added weight. A proposal to address this concern is to incorporate the vanes into a novel thrust reverser door mechanism, which in essence swivels the vanes into a swirling flow configuration on approach and closes them into a blocker door configuration upon landing. A combined EAB/thrust reverser may be attractive because the space and weight reserved for a thrust reverser is notably significant for a device whose deployment is only for a small fraction of a typical mission.

With a model-scale aero-acoustic demonstration of a HBPR EAB complete, a static demonstration in an engine is a recommended next step. The aforementioned implementation approaches are under current consideration by the authors in defining a practical EAB design. Further development is also proposed to optimize swirling vane geometries for maximum drag and minimum noise. Future designs should consider nonprismatic vane geometries to accomplish this goal.

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