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Preliminary Evaluation of Noise Reduction Approaches for a Functionally Silent Aircraft

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I. Introduction

Aircraft noise is a major inhibitor of the growth of civil air transportation. Airports in key locations are operating at full capacity and the noise in the vicinity of airports is so intrusive that local communities object to any further expansion. Thus, quiet aircraft would constitute a crucial step forward on an economic, societal and urban planning level. A functionally-silent aircraft is aimed at achieving a step change in airframe and propulsion system noise reduction to noise levels below the current NASA goals. "Silent" in this context means sufficiently quiet that the aircraft noise is less than that of the background noise in a typical well populated environment. Such aircraft would enable an expansion in air transportation by creating opportunity for new airports and allowing increases in operating hours at existing sites. This Engineering Note reports on a preliminary evaluation of noise reduction technologies for a quiet aircraft. The work was conducted under a NASA Langley research contract in 2001–2003 (Manneville et al.[1]).

II. Vision and Goals

THE heretofore unasked technical question is: what would an aircraft look like that had noise as a prime design variable and a design criterion that is a revolutionary step in noise reduction compared with present configurations and beyond the current NASA quiet aircraft technology (QAT) program goals? Such aircraft are targeted to reduce airframe and propulsion system noise below the background noise level in a well-populated area, to improve quality of life near airports, to reduce the operating and societal cost of noise, and to enable the growth of commercial air transportation. In the long term, the ultimate goal of this undertaking would be a paradigm shift in aircraft and engine system design governed by noise and environmental considerations.

The research described in this Engineering Note investigates low-noise propulsion system and airframe concepts that carry promise to transform commercial air transportation, but are beyond the immediate time frame of the industry. Although the form of civil-transport aircraft has remained largely unaltered for the past 40 years, advances in engineering design capability such as computational fluid dynamics and aeroacoustics,[2] noise cancellation techniques and control,[3] and multidisciplinary optimization[4] now enable the envisioning of step changes in the template for aircraft design.

The general techniques for reducing noise generated by the airframe and propulsion systems are well known in principle (see Refs. 5, 6, and more recently 7). What is not known, even conceptually, is the configuration of an airframe and propulsion system designed from the first with noise as a primary consideration and the technological barriers to achieving this configuration. The configuration study and acoustic analysis reported here are based on an aerodynamically clean all-wing-type airframe configuration.[8] Simple analytical modeling and existing semi-empirical noise prediction methods and scaling laws are used to estimate the acoustic signature of low-noise concepts envisioned for a functionally silent aircraft. A noise-reduction assessment framework is developed to investigate the various concepts and to explore the technology necessary for a functionally silent aircraft.

III. Silent Aircraft Concepts

Traditionally, noise produced by the propulsive jet on takeoff and during climb-out and by the fan of turbofan engines during approach to landing have been the principal sources of annoyance at major airports. Although the level of noise produced by individual aircraft has been greatly reduced under the FAR 36 Stage 3 certification rules, the collective noise impact of operations at major airports is considered unacceptable by many.

The technical means to further reduce the noise generated by the propulsion systems are known in principle. They entail further reduction of the jet velocities and redesign of the fan and other turbomachinery components to produce less noise. But considerable research must be conducted to bring the techniques to the level of understanding where the increases in weight and cost of the propulsion systems can be estimated with sufficient accuracy to justify inclusion of noise-reducing technologies in new propulsion systems. From current knowledge it does seem probable, however, that the propulsion system noise can be lowered significantly enough that it will not be the principal source of annoyance.

If this is done, airframe noise will emerge as the limiting source. Here the situation is somewhat different. This problem occurs now mainly on approach to landing, when aircraft come in low over the neighborhoods lying under the approach paths. Much of this noise is generated by unsteady airflows over the deployed high-drag devices. Reducing airframe noise will require some conceptual departures from current design concepts. Within present design approaches, the aircraft must be in a high-drag configuration in order to dispose of the potential energy that it releases as it descends. The highly turbulent flows over the flaps, spoilers, and landing gear serve this function in current designs.

From these observations conceptual ideas emerge that could potentially enable the required noise reductions for a functionally silent aircraft. Some conceptual ideas are not original, and the presented work focuses on the preliminary acoustic assessment of these concepts. Although the concepts yield acoustic benefits, there are other

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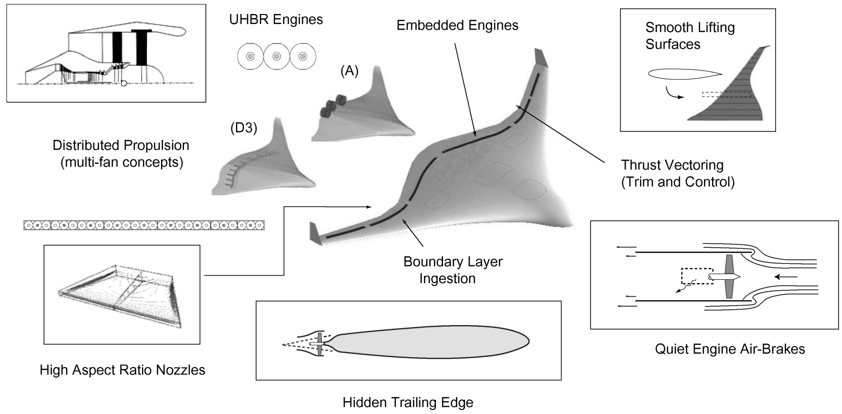

Fig. 1 Low noise airframe and propulsion system concepts for a functionally silent aircraft.

challenges and possible downsides that need further assessment and are beyond the scope of this Engineering Note. An overview of these concepts is given in Fig. 1 and is discussed next. A more detailed description can be found in Pilczer[9] and Manneville.[10]

A. Aerodynamically Smooth Lifting Surfaces

Fink[11] reports flyover noise measurements of full aircraft in clean configuration with all gear and high-lift devices retracted and cites noise reductions of 12 dB compared to standard approach configuration. Fink's results for sailplanes and gliders with seamless lifting surfaces also indicate an additional 8- to 10-dB noise reduction compared to jet aircraft. This suggests that potentially a 20-dB reduction in overall sound pressure level can be achieved using a clean airframe with no lift discontinuities and a simple trailing edge.

To avoid discontinuities in the lift distribution and noise stemming from high-drag devices an all-wing-type aircraft with no flaps or slats is suggested as the baseline airframe. At the outset of this study, it was also assumed that the landing gear can be deployed very late and within the airport boundary in order not to contribute to the airframe noise perceived on approach. Furthermore, thrust vectoring could be used to trim and to control the aircraft, and flow control techniques are envisioned to achieve high lift and to keep the flow attached at high angles of attack. Then, wing self-noise stemming from turbulent flow structures scattered at the trailing edge and wing-tip edge becomes the dominant airframe noise source.

To assess the trailing-edge noise signature of an all-wing-type airframe, the trailing-edge self-noise prediction method by Brooks et al.[12] was adopted and combined with a boundary-layer analysis in a quasi-three-dimensional manner. The baseline airframe was a scalable version of an all-wing-type aircraft reported in Liebeck et al.[8] The airframe was divided into 28 spanwise sections with locally constant profiles as sketched in Fig. 1. The wing sections had a faired trailing edge and are subject to a spanwise twist. The boundary-layer characteristics of each of the sections were computed using interacting boundary-layer theory (XFOIL by Drela[13]). Local Reynolds numbers, angles of attack, and flight Mach-number effects were accounted for. A more detailed description can be found in Pilczer.[9]

The estimates suggest that at low approach velocities (in concert with the trailing-edge noise scaling law and the data reported by Fink[11]) and steep approach angles the airframe self-noise on approach can be reduced to levels below the background noise in a well-populated area. For spherical wave propagation the far-field noise intensity is inversely proportional to the square of distance such that large glide slope angles yield lower noise levels on the ground as a result of the increased distance between source and observer.

B. Boundary-Layer Ingestion—Hidden Trailing Edge

The noise generated by scattering unsteady flow structures in the boundary layers at the trailing edge can be further attenuated by "hiding" the trailing edge. The hidden trailing-edge concept consists of an integrated engine-wing trailing-edge design where a distributed propulsion system is embedded in the airframe. The idea is to mitigate the scattering of turbulent eddies in the boundary layer at the trailing-edge discontinuity by ingesting these flow structures through a spanwise inlet slot into a distributed propulsion system. This is schematically shown in Fig. 1. The remaining airframe noise then stems from the boundary layers that develop downstream of the inlet slot and the interaction of flow structures with the wing-tip edge.

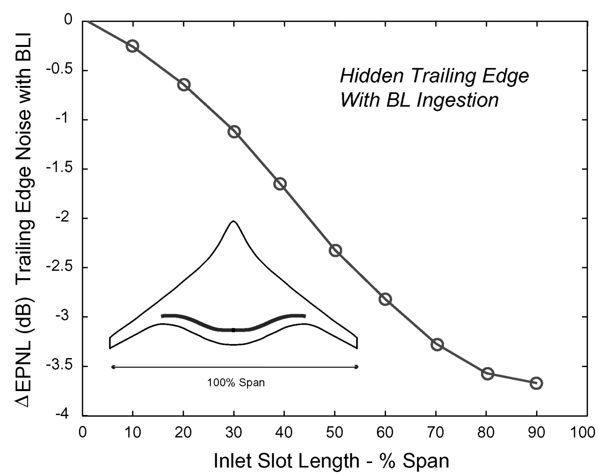

Fig. 2 Trailing-edge noise reductions using a hidden trailing edge with boundary-layer ingestion.[9]

To assess potential trailing-edge noise reductions with the hidden trailing-edge concept, the self-noise trailing-edge prediction method by Brooks et al.[12] was used. A flat-plate turbulent boundary-layer analysis on the pressure and suction side downstream of the inlet slot was conducted to calculate the boundary-layer properties necessary for the trailing-edge self-noise prediction. The analysis was carried out for different inlet slot lengths. The noise propagation, including atmospheric absorption effects and effective perceived noise level (EPNL) calculations for an observer at the standard approach certification measurement location were carried out during a standard approach profile.

The hidden trailing-edge noise prediction results were compared to the noise signature of the baseline all-wing-type airframe with smooth lifting surfaces and a seamless trailing edge. Figure 2 depicts the noise-reduction benefits relative to the baseline case as a function of inlet slot length. The relatively low level of noise reduction of order 4 EPNdB can be explained by the shift in peak frequency of the trailing-edge noise spectrum caused by the reduction in boundary-layer thickness. For an approximately constant peak Strouhal number the peak frequency in the spectrum shifts into a frequency range where the perceived noise level weighting remains relatively high.

The ingestion of boundary layers also influences the overall performance of the airframe and the propulsion system. The propulsive

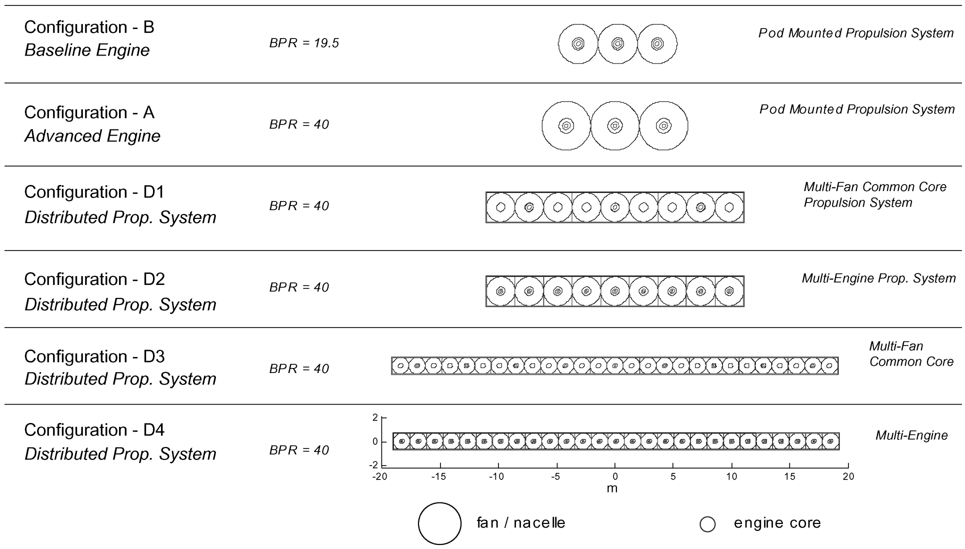

Fig. 3 Ultrahigh-bypass-ratio propulsion system configurations for a functionally silent aircraft.[10]

power required to propel the vehicle is reduced by ingesting boundary layers into the propulsion system (caused by a reduction in airframe wake size), but the thrust specific fuel consumption is increased as a result of deterioration in thermal efficiency of the engines. Thus, boundary-layer ingestion seems to yield two competing effects, and the question arises what is the impact on flight range. Although embedding the propulsion system in the airframe can yield benefits in terms of noise reduction, there are many challenges designing inlet-flow distortion tolerant engines and integrating the propulsion system in the airframe.

C. Ultrahigh-Bypass-Ratio Turbofan Engines

One dominant source of aircraft propulsion system takeoff noise is the high-speed exhaust jet. According to Lighthill's acoustic analogy,[14] jet noise scales with the eighth power of the jet velocity such that the jet noise reductions sought can be achieved by decreasing the jet velocity to well below current levels. To maintain a given thrust, this inherently results in an increase in the engine air mass flow and leads to very high bypass ratios. If this is done, then fan and core noise become the dominant noise sources and need to be addressed using low-noise fan designs and shielding methods. As the bypass ratio is increased to ultrahigh values, the fan pressure ratio can be decreased low enough such that losses accrued in the inlet duct become dominant, deteriorating engine performance and thrust output. The question thus arises what are the engine cycle and fan requirements for a defined level of jet noise reduction.

An advanced engine cycle analysis together with an engine sizing tool and an off-design engine performance tool were developed and linked to an aircraft flight dynamics simulation. The engine cycle deck was coupled to Stone's jet noise prediction method[15,16] and propagation and postprocessing modules of NASA's Aircraft Noise Prediction Program[17] to assess the jet noise levels during takeoff. The developed analysis tool allowed the investigation of both separate-flow and mixed-flow exhaust nozzles (for more details, see Manneville).[10]

Using the developed tools, an advanced core engine with a parametrically variable description of the fan and low-pressure compression system was analyzed, and the design space was explored. In the analysis the overall compressor pressure ratio, the turbine inlet temperature and the core gas-path and component efficiencies were fixed and kept constant while the fan and low-pressure compression system were varied. An advanced baseline engine was taken as the reference cycle with a bypass ratio of 19.5, a turbine inlet temperature of 2000 K, and an overall pressure ratio of 67.5 (for more cycle details, see Liebeck et al.[8]). This reference engine is referred to as configuration B in Fig. 3.

For advanced engine cycles with mixed-flow exhaust nozzles, the analysis suggests that a 30-EPNdB jet noise reduction goal requires a bypass ratio of about 40, which yields an 18% reduction in thrust specific fuel consumption (TSFC) compared to the baseline engine. Although the fuel burn is reduced, the cost for a quiet takeoff is a 60% decrease in specific thrust. This translates to fan diameters 1.3 times larger than the baseline case and entails detrimental weight and drag penalties together with airframe integration problems. A possible solution to this is a variable engine cycle with ultrahigh bypass ratio at takeoff and lower bypass ratios at cruise. A comparison between the baseline engine (configuration B) and the advanced engine cycle, which is referred to as configuration A, is also given in Fig. 3.

D. High-Aspect-Ratio Nozzles

The basic issue using ultrahigh-bypass-ratio engines is the low specific thrust and hence the very large fan diameters required, which creates challenges in the integration and embodiment of these very high-bypass-ratio engines. A solution to the propulsion system airframe integration problem is to distribute the propulsion system using either multiple small engines with very high bypass ratio or a multifan engine concept where a common core is driving multiple fan systems. A more detailed discussion of the benefits and technical challenges of these engine concepts is given later, but the point to be made here is that both of these distributed propulsion systems call for high-aspect-ratio nozzles exhausting a low velocity jet along the span at the trailing edge (see Fig. 1).

Although the physical mechanisms behind the noise generation process are not yet fully understood, rectangular and distributed nozzles have become the focus of experimental and theoretical investigations. For example, various noise measurements of rectangular nozzles with aspect ratios up to 100 are reported by Coles,[18] Maestrello and McDaid,[19] Gruschka and Schrecker,[20] and Tam and Zaman.[21] The area and jet velocity corrected OASPL of these measurements at a polar angle of 90 deg are summarized in Fig. 4. More recent publications by Munro and Ahuja[22] document aerodynamic and acoustic experiments of nozzles with very high aspect ratios (as high as 3000). These data are also shown in Fig. 4. In their analysis the authors report lower convection Mach numbers of the turbulent eddies compared to round jets and suggest an equivalent characteristic length that collapses the sound spectra obtained from different aspect-ratio nozzle tests.

To explore the acoustic benefit of a distributed propulsion system with high-aspect-ratio nozzles, a jet noise prediction tool for rectangular nozzles with aspect ratios of up to 1000 was developed. The preceding data together with the scaling laws by Munro and Ahuja[23] were used to modify Stone's jet noise prediction model implemented in ANOPP. Changes in convection Mach number of the turbulent eddies and variations to the equivalent characteristic length were implemented to modify peak frequency and overall sound pressure level depending on the nozzle aspect ratio (for more details see Manneville).[10] The noise predictions are plotted as the solid line in Fig. 4 and agree reasonably well with the experimental data over a wide range of nozzle aspect ratios.

Although high-aspect-ratio nozzles suggest reductions in jet noise, they can entail thrust losses and low discharge coefficients as a result of the increased wetted area and aerodynamic loss. For conventional aircraft configurations exhaust nozzle performance is considered a critical parameter for overall system performance. As a rule of thumb, a 1% decrease in the nozzle gross thrust coefficient is approximately equivalent to a 3% increase in specific fuel consumption.[24] Nozzle performance is also critical when considering jet noise reduction methods: a jet noise suppressor can only be considered effective if it achieves noise levels lower than the ones that occur when throttling the reference nozzle to the same thrust level.

To address these issues, a parametric study using three-dimensional computational fluid dynamics was conducted, and the thrust penalties for a family of high-aspect-ratio nozzles was assessed. The family of high-aspect-ratio nozzles was defined by the inlet area, nozzle length, exit-to-inlet-area ratio and inlet and exit aspect ratios, respectively. The nozzle flowfield was calculated for various nozzle pressure ratios and geometries. The results show that the thrust loss and dissipation increase for larger ratios of exit-to-inlet aspect ratio and are decreased if the inlet aspect ratio is reduced. This is mostly because of flow separation that can occur in the corners of the nozzle duct. In summary, high-aspect-ratio nozzles yield relatively small jet noise reductions (e.g., a 3-dB noise reduction requires an aspect ratio of 50), and the thrust penalties can be kept reasonably low (thrust coefficients >95%) if flow separation is avoided.

E. Distributed Propulsion System

A distributed propulsion system can facilitate boundary-layer ingestion and take advantage of shielding effects by embedding engines in the airframe. The ultrahigh-bypass-ratio engines necessary to reduce jet noise introduce new challenges in embedding and integrating the propulsion system with the airframe. Instead of passing the entire mass flow through one duct, the propulsion system can be divided into multiple small engines or multiple fans driven by a common core. Exhausting a low-velocity, high-aspect-ratio jet along the span at the trailing edge could yield potential benefits in acoustic signature at the cost of thrust penalties stemming from high-aspect-ratio nozzles.

Figure 3 compares the traditional pod mounted propulsion system for an all-wing-type aircraft (reference engines in Liebeck et al.[8]) to various distributed propulsion system configurations with ultrahigh-bypass-ratio engines and high-aspect-ratio nozzles. The key metrics to assess the viability of an embedded propulsion system are noise signature, thrust penalty, weight penalty, engine size effects (Reynolds-number effects), transmission loss, inlet distortion, and aeromechanical issues. Using the tools developed, some of these metrics are quantitatively assessed in a preliminary analysis and are tabulated in Table 1. For example, a distributed propulsion system with nine fan stages mechanically driven by three core gas generators (configuration D1) allows a significant reduction of the fan diameter, but the gearbox power to drive the transmission train between an individual core and three fans is 38.8 MW. To avoid significant weight penalties caused by the rather heavy gearboxes necessary to meet the transmission power requirements, the number of engines could be raised to 27 (configuration D4). Although this entails higher aerodynamic losses because of the relatively small core engines (Reynolds-number effects), the gearbox power can be reduced by a factor of 10. The integration of the pod-mounted advanced engine configuration A and the embodiment of the distributed propulsion system configuration D3 with an all-wing-type airframe are sketched in Fig. 1.

It is clear that all metrics just mentioned have to be taken into account when deciding on the propulsion system configuration for a silent aircraft. A more detailed installation study needs to be conducted assessing both the external and the internal aerodynamics. In particular, the expected inlet flow distortion levels pose a major challenge to the fan system design. In summary, a distributed propulsion system offers many opportunities in terms of embodiment and noise reduction compared to a traditional pod-mounted propulsion system but yields issues such as increased inspection and maintenance cost, reliability concerns, and overall complexity, which have to be dealt with before making such a system practical.

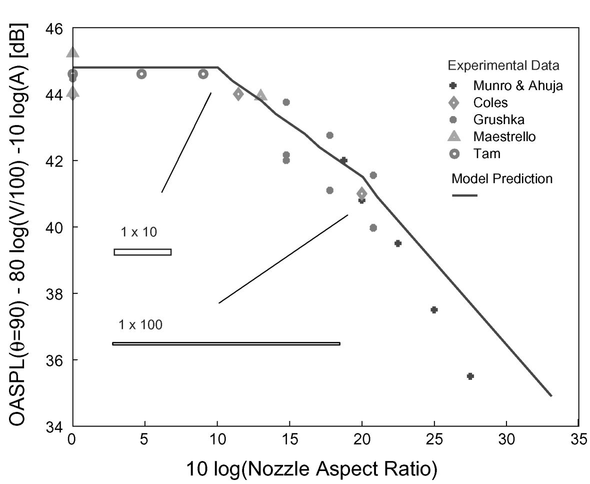

Fig. 4 Overall sound pressure level of high-aspect-ratio jet nozzles—comparison between experimental data and model prediction (Manneville[10]).

F. Quiet Drag—Engine Airbrakes

The potential to substantially reduce individual component noise on the airframe invariably leads to a reduction in drag. This means that techniques need to be developed to increase airframe drag in quiet ways. A full-sized aircraft needs to dissipate 10 to 25 MW of power during approach depending on glide slope angle and approach speed. Instead of disposing the potential energy, the aircraft releases on its approach through high-drag devices that create unsteady flow structures and radiate noise, the idea is to use quiet engine airbrakes as depicted in Fig. 1.

The basic concept behind a quiet engine airbrake is to create a loss in impulse through the propulsion system by introducing a stagnation pressure drop across the fan blade row. This can be facilitated using a variable pitch fan. In the limiting case of closed fan blades (stagger angle at 90 deg reducing the through-flow area to zero), all engine mass flow must spill around the inlet. In this case the engine behaves like a bluff body with a drag coefficient of order one. Thus for a 250-ton aircraft on a standard approach,

Table 1 Preliminary assessment of ultrahigh-bypass-ratio propulsion system configurations depicted in Fig. 3 (Ref. 10)

Propulsion system configuration	No. of engines	No. of fans per engine	Fan diam, m	Core mass flow, kg/s	Δ jet noise, EPNdB	Nozzle thrust coefficient	Fan gearbox power, MW
B - Baseline pod	3	1	3.3	68.0	−5	1.0	48.7
A - Advanced pod	3	1	4.3	56.4	−30	1.0	38.8
D1 - Distributed	3	3	2.5	56.4	−30	0.98	38.8
D2 - Distributed	9	1	2.5	18.8	−30	0.98	12.9
D3 - Distributed	9	3	1.4	18.8	−32	0.95	12.9
D4 - Distributed	27	1	1.4	6.3	−32	0.95	4.3

10 MW of power could be dissipated using four engine airbrakes with 3.25-m-diam inlets.

A compressible meanline flow model of the engine airbrake was developed to assess the flow throttling and drag-generation capability. Generic blade row loss and turning characteristics for both compressor and throttling mode were assumed to describe the blade-row performance. The model computes the force (thrust or drag) produced by a ducted rotating blade row with variable stagger angle. The analysis showed that for a given wheel speed a certain stagger angle exists that maximizes the generated drag in air-brake mode. The preliminary assessment was refined by a two-dimensional blade-to-blade analysis using MISES.[25] The results suggest that the engine airbrake can yield drag coefficients of order 0.45, which is 45% of the drag generated by a bluff body of the same cross-sectional area.

Simple preliminary noise predictions were conducted using Heidmann's fan noise prediction tool[26] and ANOPP.[17] The fan noise estimates suggest that, between the engine idle operating point (compressor mode) and the airbrake operating point (throttling mode), a 5-dB reduction in SPL can be achieved. This is mainly because of the relatively low fan tip speeds and low blade loading levels (for details see Manneville[10]).

In summary, the following technical challenges need to be addressed to facilitate a quiet descent and approach using quiet engine airbrakes: 1) the design of variable geometry turbomachinery with low noise flow throttling capability to yield the required amounts of drag on approach, 2) the transformation of transverse unsteady flow structures (vortex shedding) into streamwise steady flow structures to control wake noise at large impulse deficits, and 3) the aerodynamic integration of the internal and external flowfields to enable engine operation in both power and airbrake mode.

IV. Summary and Outlook

A highly integrated airframe propulsion system configuration is proposed to enable a functionally silent aircraft with the goal to reduce aircraft noise below the noise level in a well-populated area. The preliminary evaluation of the proposed advanced low noise airframe and propulsion system concepts suggest benefits in terms of substantial noise reductions, although many technological hurdles must be overcome before making such an aircraft concept a reality. The fidelity of the various noise estimates must be improved, and some of the aerothermodynamic issues need to be further investigated. A joint project between the University of Cambridge and Massachusetts Institute of Technology (MIT), namely, the "Silent Aircraft Initiative" funded by the Cambridge-MIT Institute (CMI), was launched in November 2003, which leverages some of these ideas. The effort is targeted to deliver a credible (as defined by industry level) conceptual design of a silent aircraft. The project involves about 35 researchers and a broad knowledge integration community with representatives from government, the civil aerospace/aviation industry, other universities, and community action groups.

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