AIAA's Aircraft Technology, Integration, and Operations (ATIO) 2002 Technical
1-3 October 2002, Los Angeles, California

AIAA 2002-5868

OPTIMIZING AIRCRAFT AND OPERATIONS FOR MINIMUM NOISE

Nicolas E. Antoine *, Ilan M. Kroo †
Stanford University, Stanford, CA 94305

Abstract

Environmental concerns, including emissions and noise, are gaining increasing importance in the design and operations of commercial aircraft. The purpose of this research is to evaluate the feasibility of an aircraft that combines design and operational features to reduce certification noise. By optimizing the aircraft design and mission for minimum cost under specific noise constraints, the best combination of aircraft and operations is obtained.

Introduction

Advances in engine technology such as high bypass ratio and acoustic liners have helped to greatly reduce the noise emitted by commercial aircraft. Nevertheless, the combination of continuing air travel growth, intolerance of communities towards disturbances, and growing airport neighborhoods point to aircraft noise as an increasing problem.

In fact, noise has become a major growth inhibitor of air traffic: over 60% of all airports consider noise as a major problem and the nation's 50 largest airports view it as the biggest issue.[1] New runways and airports cannot be built due to public fears of increased traffic and consequently increased (or more frequent) noise.

In response to public concerns, airports have adopted restrictions that are considerably more severe than required by the ICAO (which is to introduce updated noise certification requirements for new aircraft in 2006). The Quota Count system at London Heathrow, for example, restricts the operations of aircraft during nighttime through a points system. Airplanes are classified based on their certification noise, with only the quietest allowed to operate at nighttime. The result is that airlines, especially those likely to operate at night, face equipment and scheduling constraints. Airbus and Boeing are now using the London QC system as a benchmark for the noise levels of their aircraft. Although modifications can be implemented on existing aircraft to meet current noise requirements, additional reductions will require a more systematic consideration of noise constraints during design.

The objective is to estimate the trade-off between operating cost and certification noise; this will allow a range of aircraft to be designed based on the noise performance required. This approach makes noise certification levels an explicit design constraint rather than a post-design concern. It provides the opportunity to study improvements to the design and operations of current aircraft configurations as well as unconventional designs that could provide dramatic reductions in noise.

Methodology

The design tool is composed of a library of routines used to compute many aspects of aircraft design and performance (Figure 1). NASA Langley's Aircraft Noise Prediction Program (ANOPP) is used for noise modeling. Engine performance, as a function of bypass ratio, altitude, and Mach number, is estimated using NASA Glenn's Engine Performance code (NEPP). A multidisciplinary design framework, CaffeApp,[2] is used in conjunction with a non-linear optimizer. The engine performance and noise estimation modules are coupled to programs that compute performance and operating cost.[3] These approximate methods are particularly well-suited for optimization due to their rapid execution and robustness.

Engine Performance

Developed at NASA Glenn, NEPP is a 1-D steady thermodynamics analysis program. At the design point, NEPP automatically ensures continuity of mass, speed, and energy by changing the scale factors on the performance maps for the compressor and turbine components. Off-design is handled through the use of component performance tables

*Doctoral Candidate, AIAA Student Member
†Professor, AIAA Fellow

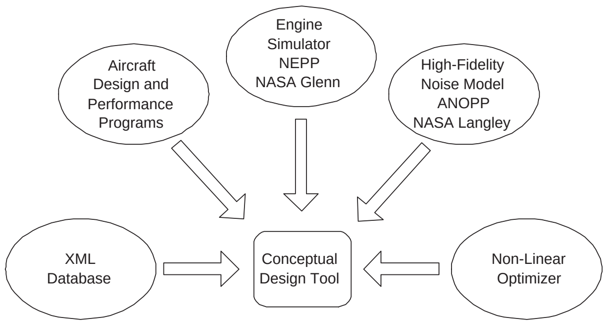

Figure 1: Approach

and minimization of work, flow, and energy errors. The engine is then balanced by altering free variables of available components. Variable controls can also be used to obtain a certain performance. For example, airflow or combustion temperature can be varied to reach a desired thrust level. Controls are also used to limit and optimize engine parameters. Variables sent to NEPP from the optimizer include bypass ratio (BPR), sea-level static (SLS) thrust, and fan pressure ratio.

For the purpose of the design tool, the baseline engine was designed to represent technology that would be available by the end of the decade, including increased combustion temperatures and higher turbomachinery efficiencies. The engine is limited to bypass ratios between 1 and 13.5, and SLS thrust is limited to values between 20,000 and 120,000 lbs.

Noise Estimation

The importance of aircraft noise has grown with increasing air traffic as well as with the introduction of the turbojet. While high-bypass turbofans and lining materials have helped reduce noise by approximately 20 dB since the early 1960s,[4] most airport communities are demanding further improvements.

Three measurement points are used by the ICAO and FAA for noise certification. Noise is continuously recorded at these locations during the takeoff and landing procedures. Time-integrated sideline, climb, and approach noise (Figure 2) for a complete takeoff-landing cycle must be below a limit based on the maximum takeoff weight of the airplane (and, for take-off, the number of engines). Jet noise typically dominates in sideline and climb. On approach, high bypass ratios diminish the contribution of the engine to noise at low power, making aerodynamic noise an increasingly relevant component.

NASA Langley's Aircraft Noise Prediction Program (ANOPP) is used to compute noise on take-off and approach. ANOPP is a semi-empirical code that incorporates publicly available noise prediction schemes and is continuously updated by NASA Langley. The relevant engine data is passed from NEPP, and the aircraft geometry and take-off profile from the other aircraft analysis routines. The modelled noise sources include fan noise, combustor noise, jet noise, and airframe noise.

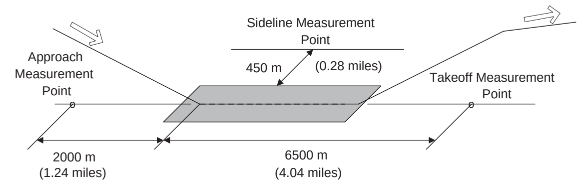

Figure 2: ICAO Noise Measurement Points.

The ANOPP fan noise module is based on the model developed by M. F. Heidman.[5] The components include inlet broadband noise, inlet rotor-stator interaction noise, discharge broadband noise and discharge rotor-stator interaction noise. The method employs empirical correlations to predict the sound spectra as a function of frequency and polar directivity angle. Combustion noise is computed based on the methods described in SAE ARP 876.[6] Empirical data from turbofan engines is used to predict the sound spectra.

Stone's method[7] is used to predict the coaxial circular jet noise. Because only high-bypass ratio subsonic engines are under consideration, shock turbulence interference is neglected, leaving jet mixing noise as the only component. The airframe noise sources include the wing, tail, landing gear, flaps, and leading edge slats. Broadband noise is computed using Fink's methodology,[8] which employs empirical functions to produce sound spectra as a function of frequency, polar directivity angle and azimuth directivity angle.

Once the near-field sound spectra is computed for each noise source, the propagation module is run to determine the tone-corrected perceived noise level as measured at the ICAO certification points. Finally, the time-averaged Effective Perceived Noise Levels (EPNL) values are computed.

Optimization

Once the maximum certification noise levels are selected, the optimizer is run and the design with the minimum cost is obtained.

MINIMIZE :	Direct Operating Cost
CONSTRAINTS:	Noise Emissions Range Initial Climb Performance Takeoff Field Length Landing Field Length Second Segment Climb Enroute Climb Stability and Trim
VARIABLES:	Bypass Ratio SLS Thrust Maximum Take-Off Weight Wing Area Wing Sweep Wing t/c Wing Location Wing Taper Ratio Cruise Mach Number Initial Cruise Altitude Final Cruise Altitude Approach Angle Location Thrust Cutback Extent of Thrust Cutback

The optimization framework integrates codes such as NEPP and ANOPP with other disciplinary analyses ranging from component weights to stability and control and mission performance. This was accomplished using a version of the Caffe framework which facilitates the coupling of multidisciplinary analyses and optimization. In the present application, approximately twenty different analysis modules were combined with nonlinear optimization and a database management system to allow rapid reconfiguration of the design variables, objectives, and constraints.

In addition to traditional performance constraints such as range and field performance, maximum cumulative certification noise (the sum of the noise at each certification location) is included. This approach allows us to explicitly specify the extent of the increase in environmental acceptability: from slight improvements in noise to "silent" aircraft. Design variables include parameters from the aircraft configuration, propulsion, and entire flight profile.

The engine simulator (NEPP) is run first, as several engine characteristics are required by the performance analyses (e.g. range and takeoff calculations). The aircraft design programs, which are run next, include subroutines that compute various aspects of performance. Noise calculations (ANOPP) are run last. Several nonlinear programming methods are available to solve this type of optimization problem; a constrained scheme based on a Nelder-Mead algorithm was employed as the optimizer.

Results

The design, performance, approach and takeoff profiles of the aircraft are optimized to meet the specified noise constraints with minimum cost. The individual contributions to noise reduction of aircraft configuration, approach noise abatement procedures, and takeoff thrust cutback are examined below, followed by a trade study including all three noise reduction methods.

Aircraft Design for Low Noise

As previously explored by the authors,[9] the engine bypass ratio (BPR) is the most important variable in noise reduction. With an increasing bypass ratio, the amount of airflow going around the combustion chamber relative to the amount of air going through it increases, resulting in enhanced mixing between the flows on exit and a reduction of the exhaust velocities. The result is a considerable decrease in jet noise (Figure 3).

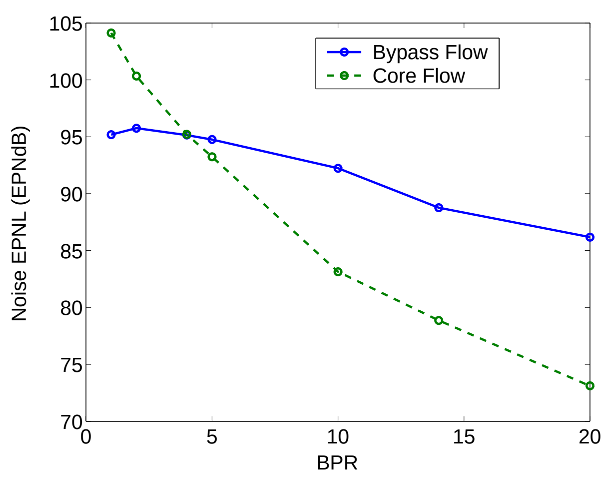

Figure 3: Noise as a function of bypass ratio.

As the bypass ratio is varied, the optimizer changes the other design variables to restore compliance with the specified constraints. The effect on operating cost is not as obvious: a higher bypass ratio usually demands a larger fan, increasing parasite drag. In addition, for a given thrust requirement at cruise conditions, a higher bypass ratio engine will require higher installed thrust at sea-level to offset the greater thrust lag. An engine with a BPR of 6, for example, would produce approximately 20% more thrust at 31,000 ft than an engine of equivalent sea-level thrust with a BPR of 10.

Steeper Approaches

Noise-based operating restrictions at airports around the world have triggered the development of noise abatement procedures to lower the impact of increasing traffic on the growing airport-neighboring population. On approach, the aircraft flies at low speed and descends at a shallow angle, in the process exposing a large ground area for an extended amount of time. Because fan noise tends to dominate on approach, increases in bypass ratio do not always contribute to reducing noise. In addition, the low throttle settings used during this regime have the consequence of increasing the relative noise contribution of airframe aerodynamic noise. Landing profiles that reduce these effects have been studied and in some cases implemented. Because most of these methods are meant to be applied to current aircraft with little or no modifications, they do not offer significant reductions.

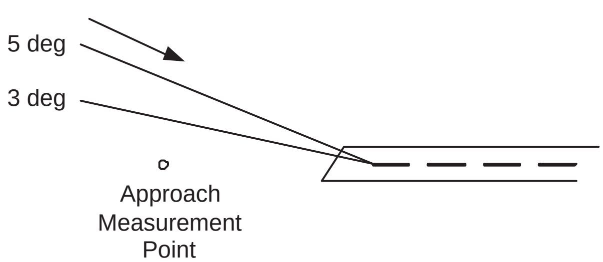

Figure 4: Steeper approaches.

Steeper approaches (Figure 4) hold great promise[10–12] for reducing noise. However, they are not typically implementable with existing aircraft that have difficulties adopting glide slope angles beyond 4 degrees without exceeding a comfortable descent velocity (a maximum of approximately 1100 ft/min). By including the approach angle as a variable during the preliminary design of the aircraft, on the other hand, the optimum combination of approach profile, engine, and aircraft performance can be obtained.

Steeper approaches offer two advantages in noise reduction: the greater angle increases the distance between the aircraft and the noise measurement point, and reduces the amount of thrust required to maintain approach speed. For example, increasing the approach angle from 3 degrees to 4.5 degrees raises the height at the certification point from 344 ft (105m) to 516ft (157m).

Angle (deg)	3.0	3.5	4.0	4.5
Height (ft)	343.9	401.3	458.8	516.5
Throttle (%)	25.9	22.2	18.4	14.7
Noise (EPNdB)	91.6	89.1	86.5	83.9

Table 1: Noise reduction due to steeper approach.

The combined advantages of the reduced noise at the source and greater propagation distance to the measurement point are considerable. The data in Table 1 illustrates the effects of increasing approach angle from 3 to 4.5 degrees for a 250-passenger twin-engine aircraft. Simply by increasing the approach angle by 1.5 degrees, the noise measured at the approach certification point decreased by 7.7 EPNdB.

Takeoff Thrust Cutback

Thrust cutback on takeoff (Figure 5) has been used since the early days of the turbojet as a method to minimize the noise exposure of specific communities. However, this method has lost effectiveness following the development of high-bypass ratio turbofans whose noise emissions are relatively unaffected by throttling.

Because the amount of energy required to attain cruising altitude does not change, adopting thrust cutback on takeoff simply displaces the noise to a different location. Thrust cutbacks to lower noise near airports are counter-balanced by a reduction of the aircraft climb angle and an increase in noise further down when the engines ares returned to full power. This makes cutback ideal at some airports such as John Wayne Orange County where the procedure is carried out over the airport neighboring community. The aircraft resume their full climb once the ocean is reached.

The ICAO and FAA allow pilots to execute thrust cutback between the altitudes of 800 ft (240m) and 3000 ft (900m). To determine the applicability of adopting trust cutback during climb to reduce the noise measured at the certification points, a parametric study was carried out; results are shown in Table 2.

Since the objective is to limit certification noise (that is, noise close to the airport), it must be kept in mind that an adverse effect of thrust cutback may

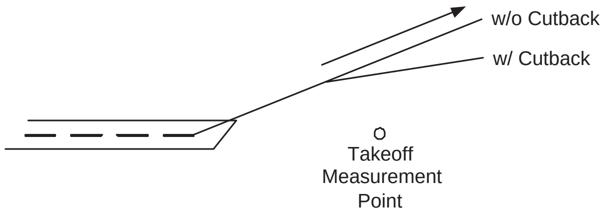

Figure 5: Thrust Cutback on Take-off.

	800 ft	1350 ft	2000 ft
80 %	-1.26	-1.69	-1.88
70 %	-2.21	-2.92	-3.06

Table 2: Takeoff noise reduction in dB due to thrust cutback (relative to a no-cutback climb) as a function of throttle setting and cutback start altitude.

be increased community noise further down the aircraft's flight path. Future studies will focus on other noise metrics such as day-night levels around airports.

The extent of the noise reduction as measured at the takeoff point is limited to a few decibels; changes in noise amplitude have to be significant to impact the time-integrated Effective Perceived Noise Level (EPNdB) unit. This phenomenon is well illustrated in Figure 6: the area under the curve corresponding to the cutback case is only slightly smaller than for the case without any noise-abating procedure. Nevertheless, the greatest gain involves cutting thrust as much as allowable to maintain the minimum climb gradient and should be carried out close to the noise measurement point. Cutback at lower altitudes are not as beneficial – while the source noise has decreased, the resulting shallower climb results in an increased time-averaged certification noise metric.

Trade Study

Starting with a baseline, a 250-seat twin-engine, 4500nm range aircraft, the goal was to determine the cost impact of reducing cumulative certification noise by various amounts.

First, the aircraft was optimized without any noise constraints to obtain the design with the lowest possible operating cost; this is the reference aircraft (labelled "ref" in Table 3). In addition, the approach angle was fixed to the standard value of 3 degrees and no thrust cutback was allowed on takeoff.

The design was then optimized to meet the desired cumulative noise reduction, allowing both steeper approaches and cutback. The relative operating cost

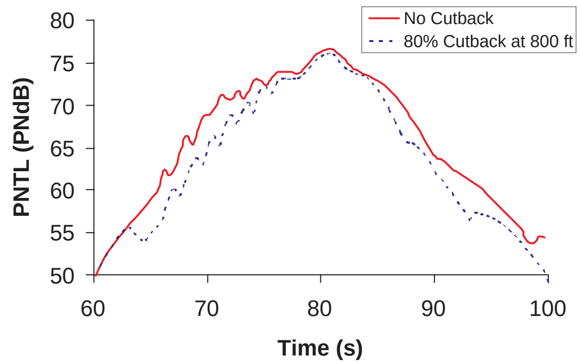

Figure 6: Perceived noise level during simulated flyover of two procedures: without cutback and with 80% throttle cutback at 800 ft.

Design Variable	**Ref**	**-18 dB**	**-21 dB**
MTOW (lbs)	322,589	357,872	363,767
Sref (ft^2)	2,571	2,932	2,898
Thrust/engine (lbs)	51,015	60,075	62,465
Initial Cruise Alt (ft)	32,060	36,456	37,084
Final Cruise Alt (ft)	42,568	46,808	47,147
Wing Location (%)	42.38	42.12	40.85
Wing Aspect Ratio	9.20	9.82	9.77
Wing Sweep (deg)	26.59	29.11	29.97
Wing Thick/Chord	0.149	0.120	0.120
Tail/Wing Area	0.28	0.33	0.333
Approach Angle	3.0	5.45	5.45
Thrust Cutback	1.0	0.62	0.64
Bypass Ratio	6.54	6.23	7.84
Relative Cost	1.00	1.055	1.063

Table 3: Optimization results.

represents a measure of total operating costs based on the ATA method[13] for direct operating cost and more recent data from Schaufele.[14]

In the first case, the design tool was run with a target noise reduction of 18 dB. The results are shown in the third column of Table 3. The second case includes a further 3 dB of cumulative noise reduction as a constraint. Initially, the optimizer exploited the variables that could reduce noise with little or no cost impact: the approach angle and thrust cutback location and throttle setting. However, further decreasing the noise demanded an increase in bypass ratio, resulting in a considerable cost increase for just three decibels of reduction.

As can be seen in the iteration history (Figure 7), the optimizer increased the approach angle from 3 to approximately 5.5 degrees, the allowable limit. This was expected as steeper approaches are the most effective method of reducing noise on approach. The remaining variables were selected by the optimizer to restore the aircraft and meet the performance and geometry constraints. The result is a decrease in noise of 18 dB for a cost increase of 5%. Decreasing the allowable noise by a further 3 dB, however, required the bypass ratio to be increased, as the benefits of both the steeper approach and takeoff cutback noise abatement procedures have already been taken into account. In the case of the -21 dB aircraft, the optimum BPR was found to be 7.84, for a cost increase of 1% beyond the -18 dB aircraft. The effective perceived noise levels predicted at the ICAO locations are summarized in Table 4.

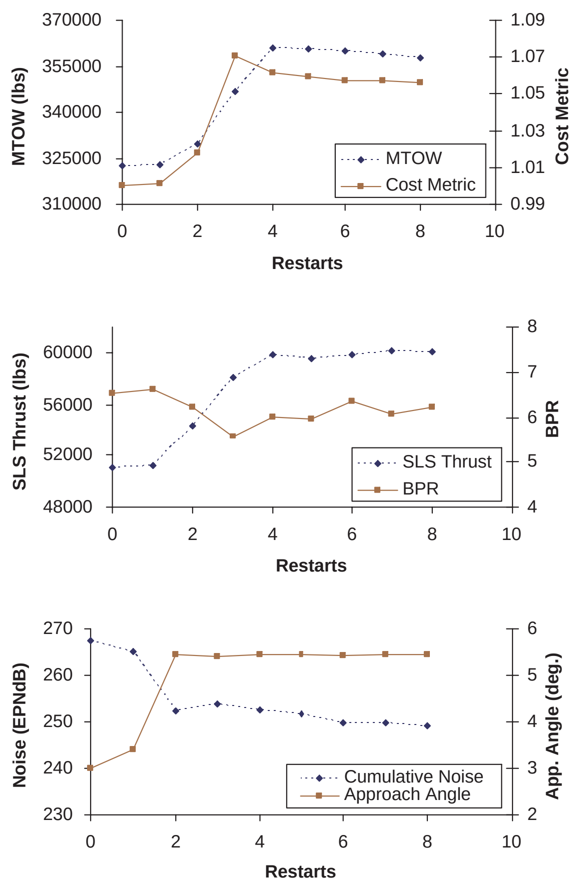

Figure 7: Optimization History (80 iterations between restarts).

Notice that the -18 dB aircraft features higher noise on take-off than the baseline due to the greater installed thrust of its engines. However, the increase in takeoff noise is more than offset by the reduction in noise on approach: for a desired level of approach thrust, a more powerful engine can operate at a comparatively lower throttle setting than an engine with less power, therefore generating less noise (Figure 8).

ICAO Point	Ref	-18 dB	-21 dB
Takeoff	90.65	92.54	90.71
Sideline	84.76	83.70	82.56
Approach	91.74	73.23	72.93

Table 4: Predicted Noise (EPNdB)

The case study demonstrates how changing the entire aircraft to meet noise constraints affects the operating cost. While small reductions in noise (2-3 dB cumulative) can be attained in practice by adding sound-proofing liners or by installing chevron nozzles, more important reductions will require a redesign of the aircraft.

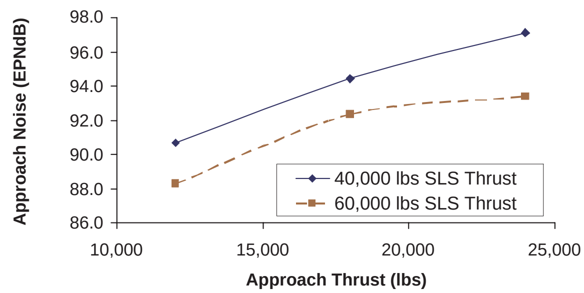

Figure 8: Comparison of the approach noise of 40,000 lbs and 60,000 lbs sea level static thrust engines as a function of approach thrust.

Beyond the direct operation costs increase associated with the redesign of the aircraft for low-noise, the financial impact of adopting noise abatement procedures cannot be underestimated. Introducing steep approaches in the order of 5 degrees requires considerable investment in staff training as well as modifications to on-board equipment; new safety guidelines would have to be developed. While these costs are not included in this study, they may ultimately decide the feasibility of noise abatement procedures.

Future Work

NASA has set a goal of reducing aircraft noise by an additional 20 db in the next 25 years. However, increasing environmental acceptability by adapting conventional configurations will eventually become prohibitively expensive. Unorthodox concepts such as the Blended-Wing-Body[15] (Figure 9), which requires less thrust than conventional aircraft and features a geometry conducive to noise reduction (the engines are mounted above the body and result in a significant shielding effect[16]) hold considerable promise. Multidisciplinary design tools have been used extensively on the Blended-Wing-Body platform, an ideal candidate for such methods because of the closely coupled airframe and engines.[17,18]

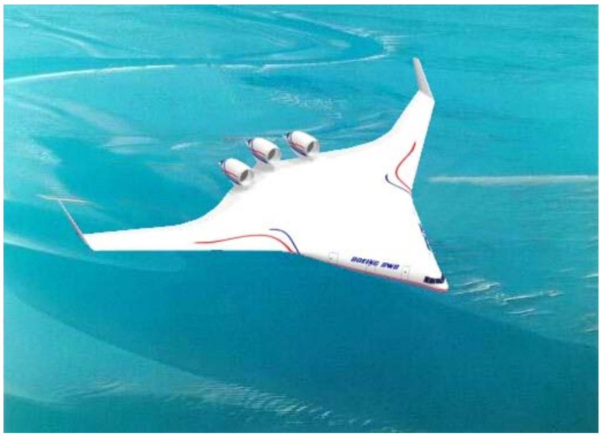

Figure 9: A Blended-Wing-Body aircraft (Boeing).

Conclusion

The objective of this research was to determine the feasibility of including explicit noise constraints during the conceptual phase of the aircraft design. Multidisciplinary optimization allowed us to examine the trade-off between noise performance and direct operating cost. High fidelity engine and noise models were integrated within an optimization framework and the initial application of this design approach was successful in producing optimal solutions.

The entire aircraft and mission were optimized to meet specified noise constraints; abatement procedures such as steeper approaches and thrust cutback on take-off were also included in the analysis. As expected, the engine bypass ratio was the driving factor in reducing engine noise. Optimizing the aircraft to allow for steeper approaches was shown to be an effective way of reducing noise while the usefulness of thrust cutback on takeoff to reduce flyover noise was not found to be as significant.

Upcoming work will define the limits of reducing the community noise of conventional designs and will explore the potential for unconventional configurations and propulsion concepts to further decrease noise.

Contact Information

Nicolas Antoine: nantoine@stanford.edu

References

[1] F. Sietzen Jr., "New Blueprint for NASA Aeronautics", Aerospace America, August 2002, p.25.

[2] I. Kroo, V. Manning, "Collaborative Optimization: Status and Directions," AIAA Paper 2000-4721, September 2000.

[3] I.M. Kroo, "An Iteractive System for Aircraft Design and Optimization," AIAA Paper 92-1190, February 1992.

[4] M.J.T. Smith, *Aircraft Noise*, Cambridge University Press, 1989, p. 248-249.

[5] M.F. Heidmann, "Interim Prediction Method for Fan and Compressor Source Noise", NASA Technical Memorandum X-71763, 1979.

[6] Anon., SAE Aerospace Recommended Practice 876 Rev D: Gas Turbine Exhaust Noise Prediction, Society of Automotive Engineers, Inc., 1994.

[7] J.R. Stone, D.E. Groesbeck, and C.L. Zola, "An Improved Prediction Method for Noise Generated by Conventional Profile Coaxial Jets", AIAA Paper 81-1991, 1981.

[8] M.R. Fink, *Airframe Noise Prediction Method*, Federal Aviation Administration FAA-RD-77-29, 1977.

[9] N. Antoine, I. Kroo, "Aircraft Optimization for Minimal Environmental Impact," AIAA Paper 2002-5667, September 2002.

[10] R.E. Caves and D.P. Rhodes, "Steeper Approaches: A Contribution to Alleviating Airport Environmental and Physical Capacity Constraints," Loughborough University, http://www.daz-technology.demon.co.uk/steep/steep.html, 1995.

[11] D.P. Rhodes, "Steeper Approaches," Loughborough University, http://www.daz-technology.demon.co.uk/steep2/steep2.html, 1996.

[12] R.E. Caves, L.R. Jenkinson, and D.P. Rhodes, "Development of an Integrated Conceptual Aircraft Design and Noise Model for Civil Transport Aircraft," ICAS Paper 98-6,4,3, 21st ICAS Congress, Melbourne, Australia, Sept. 13-18, 1998.

[13] *Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes*, Air Transportation Association of America, December 1967.

[14] R. Schaufele, *The Elements of Aircraft Preliminary Design,* Aries Publixations, Santa Ana, CA, 2000.

[15] R.H. Liebeck, M.A. Page, B.K. Rawdon, "Blended-Wing-Body Subsonic Commercial Transport," AIAA Paper 98-0438, January 1998.

[16] L.R. Clark and C.H. Gerhold, "Inlet Noise Reduction by Shielding for the Blended Wing Body Airplane," AIAA Paper 99-1937, May 1999.

[17] S. Wakayama and I. Kroo, "The Challenge and Promise of Blended-Wing-Body Optimization," AIAA Paper 98-4736, September 1998.

[18] D. Rodriguez, "A Multidisciplinary Optimization Method for Designing Inlets Using Complex Variables," AIAA Paper 2000-4875, September 2000.