Advanced Low-Noise Aircraft Configurations and their Assessment: Past, Present, and Future

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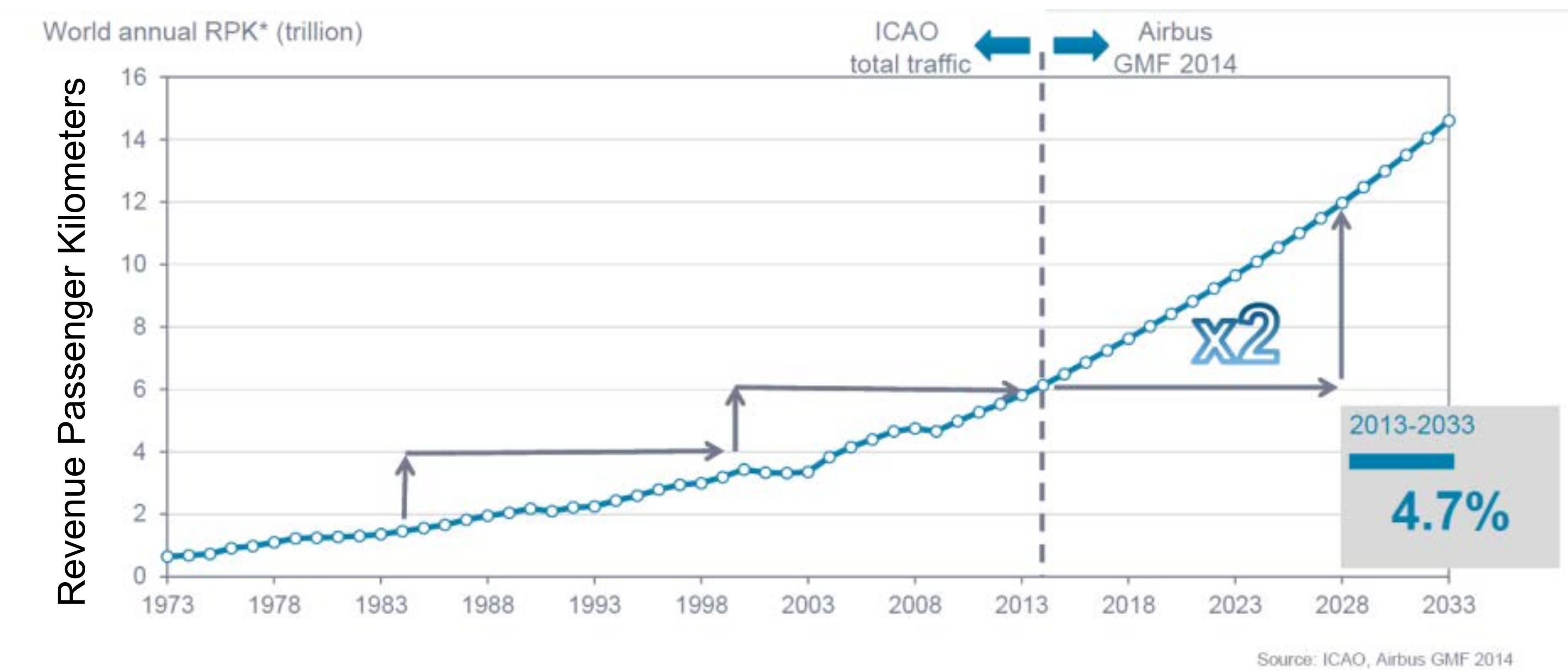
Fall Meeting of the Aeronautics and Space Engineering Board
164th Meeting
September 25th, 2019

THEMES OF THE TALK

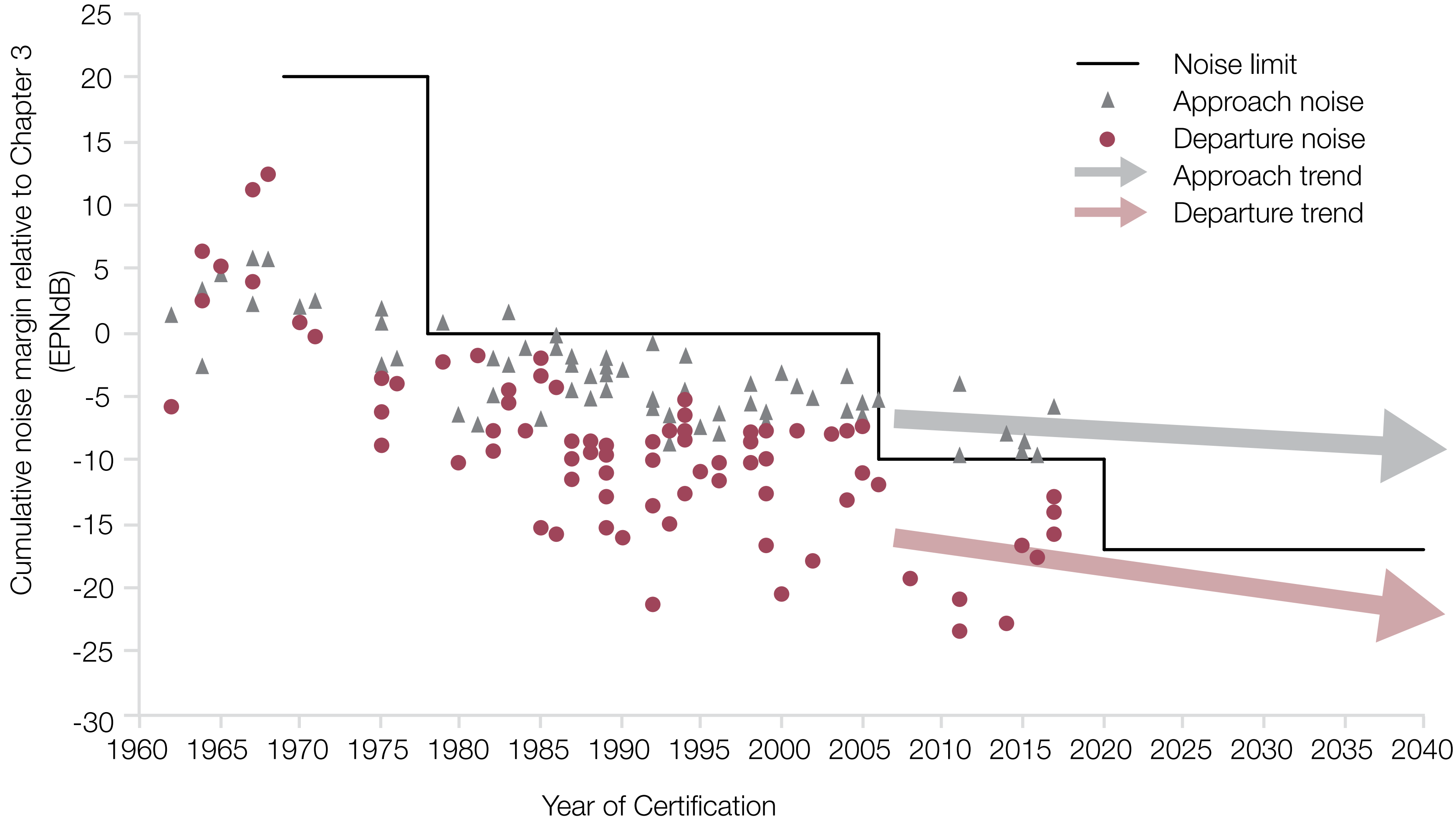
- Growth of air transportation – cleaner, safer, quieter aircraft
- Sound & sources of sound – anatomy of noise
- Aircraft noise, past & present – what has (not) changed
- The “*Silent Aircraft Initiative*” – a potential solution
- Noise reduction innovations – what it will take

POSITIVE OUTLOOK FOR COMMERCIAL AVIATION: AIR TRAFFIC WILL DOUBLE IN THE NEXT 15 YEARS



[Airbus Global Market Forecast, 2014]

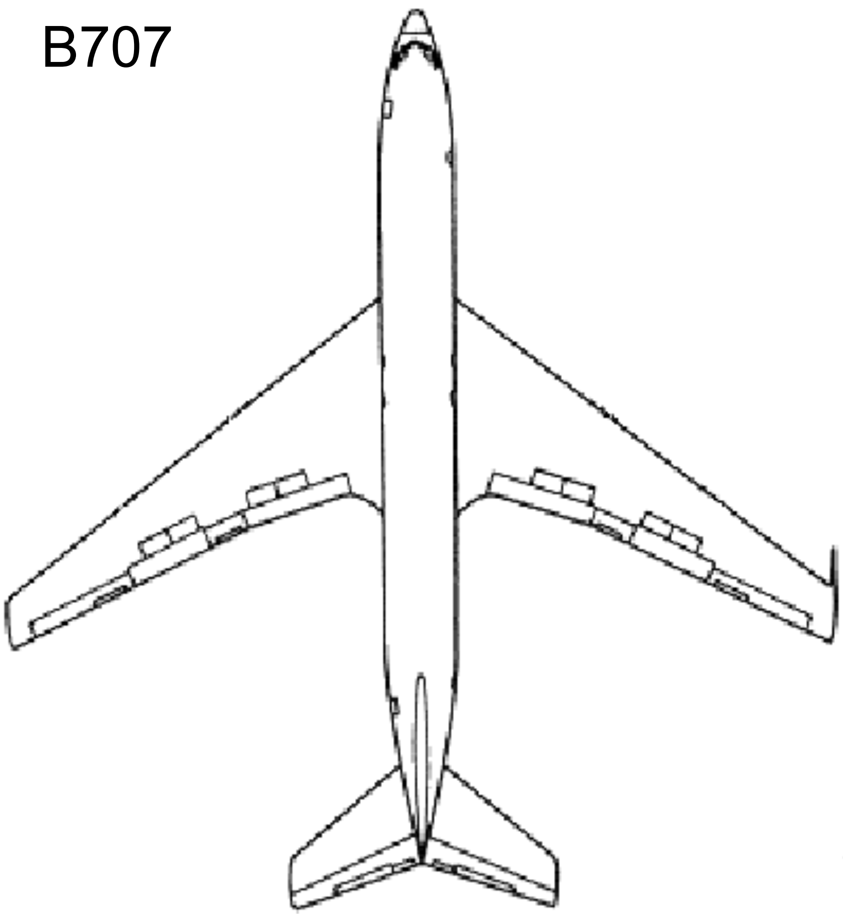
PROGRESS IN AIRCRAFT NOISE REDUCTION



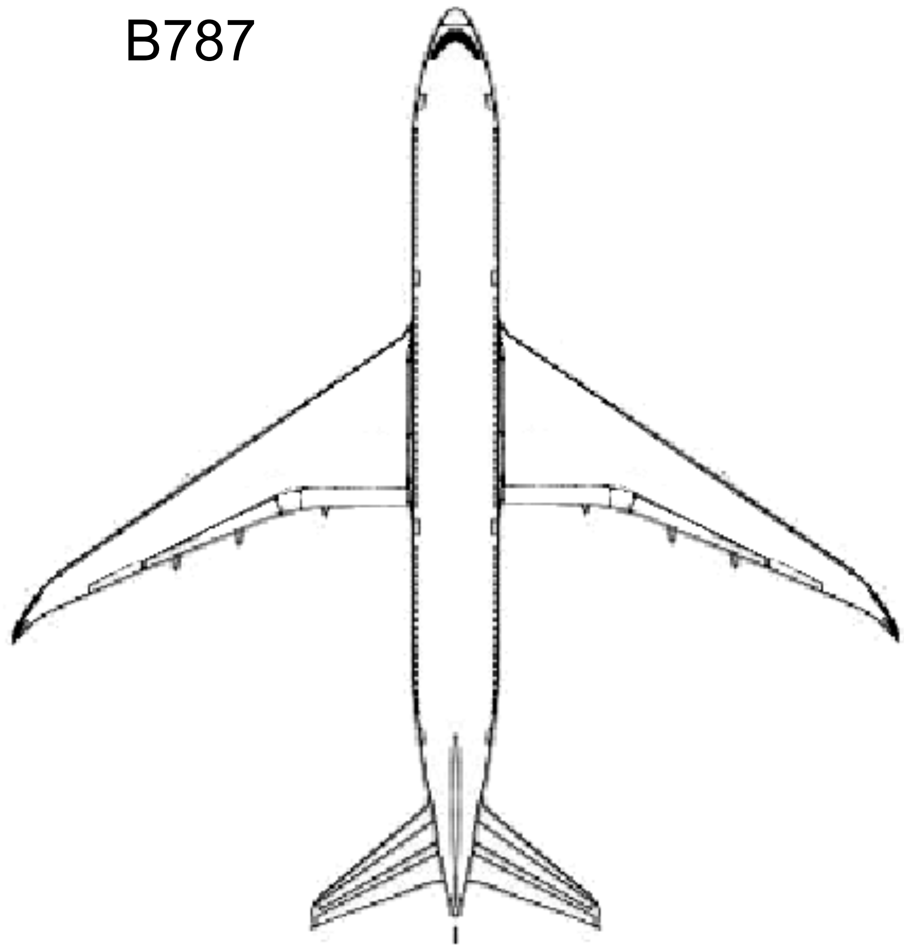
Davies, H., (2015)

FIFTY PLUS YEARS IN AIRCRAFT SILHOUETTES (1960 – 2010+)

B707



B787



Boeing 707: adapted from http://www.aerospaceweb.org/aircraft/jetliner/b707/
Boeing 787: adapted from http://news.bbc.co.uk/2/hi/business/6281582.stm

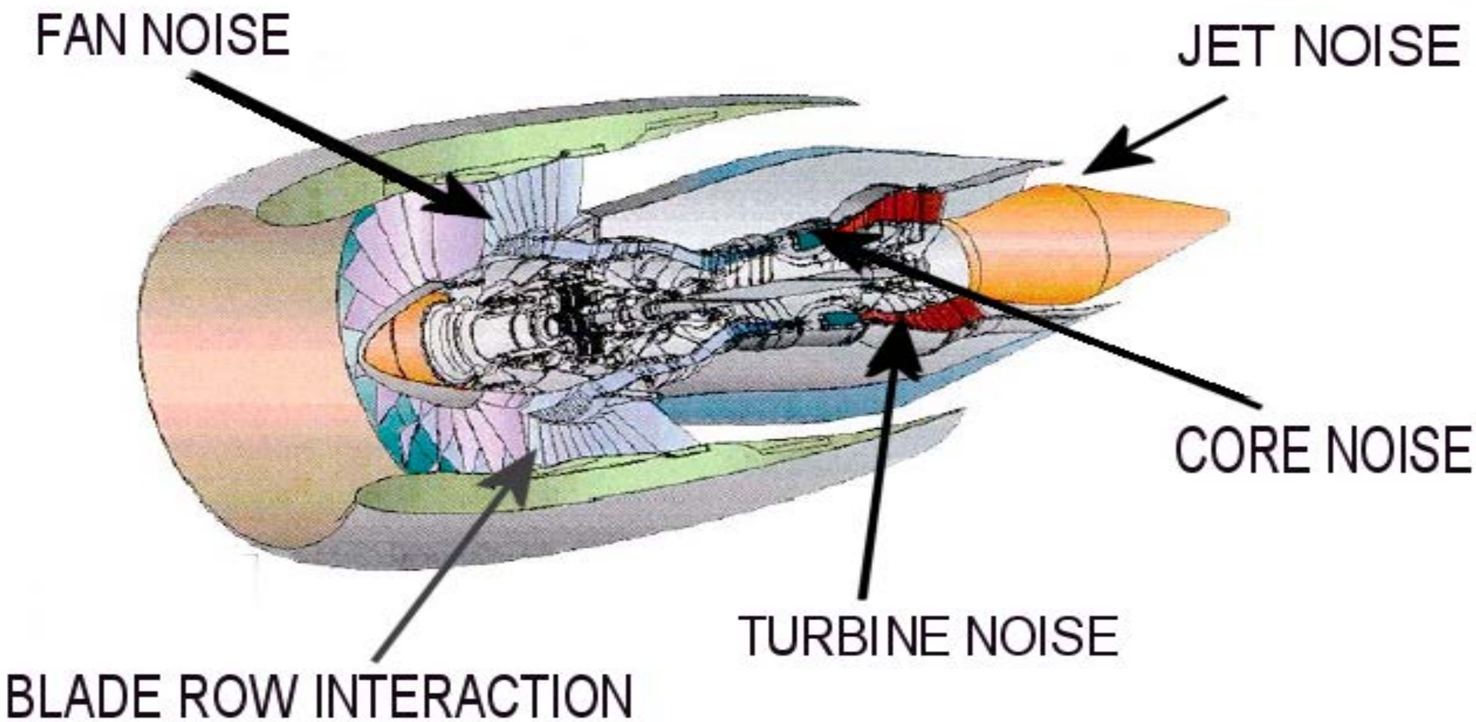
WHAT ELSE HAS CHANGED?

A320 First Flight
February 1987

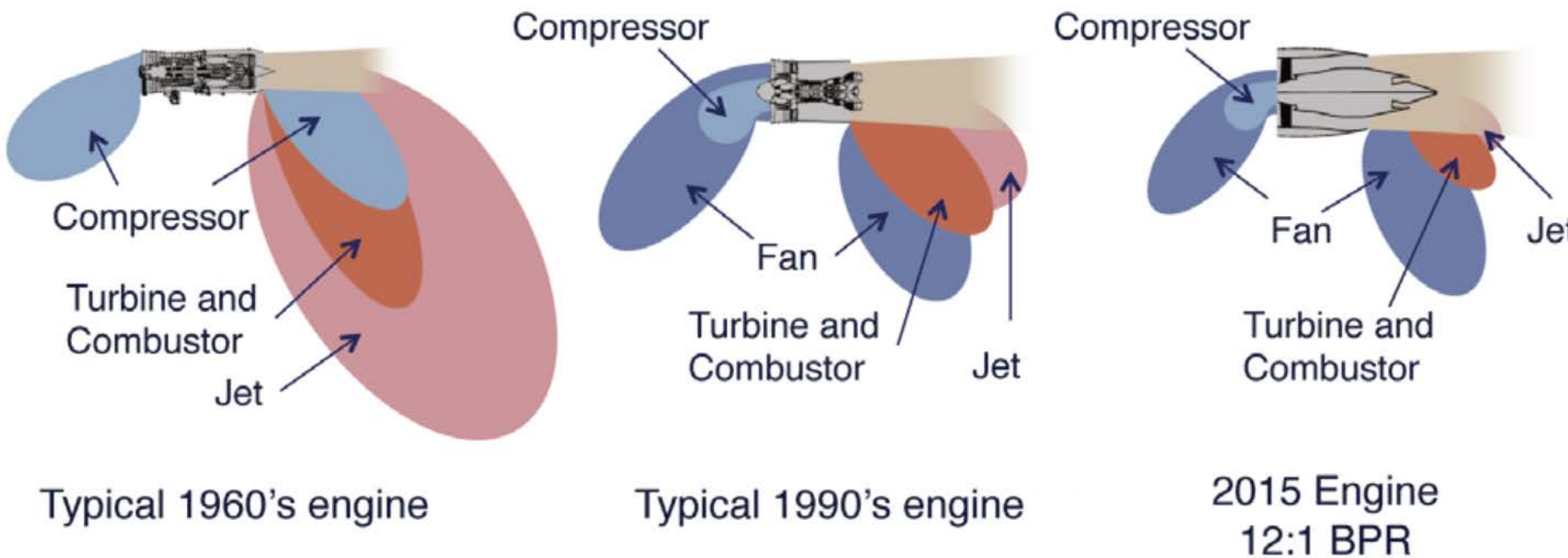
A320 NEO First Flight
September 2014

[Aviation Week]

MAJOR ENGINE NOISE SOURCES



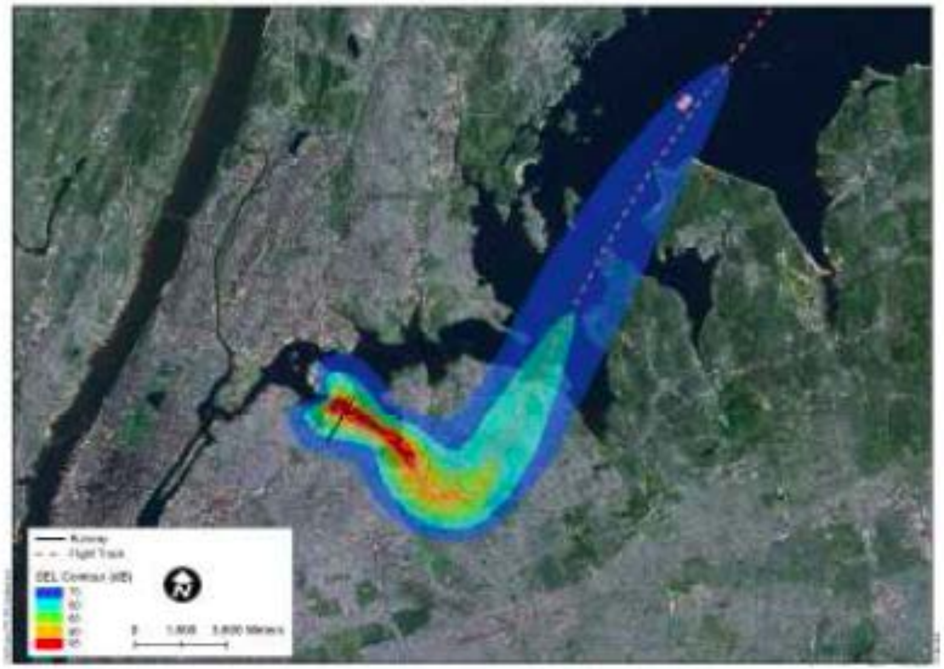
EVOLUTION OF ENGINE COMPONENT NOISE FOOTPRINTS



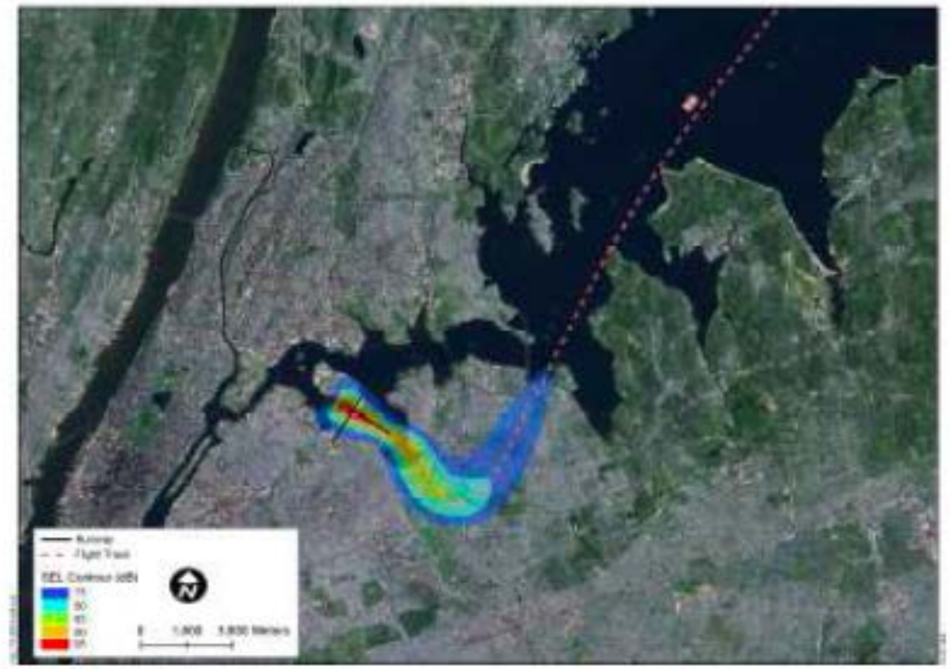
(Epstein, 2013)

12:1 BPR PROPULSORS – 73% REDUCTION IN SINGLE EVENT NOISE CONTOUR

LaGuardia Airport (LGA)



Today's Aircraft

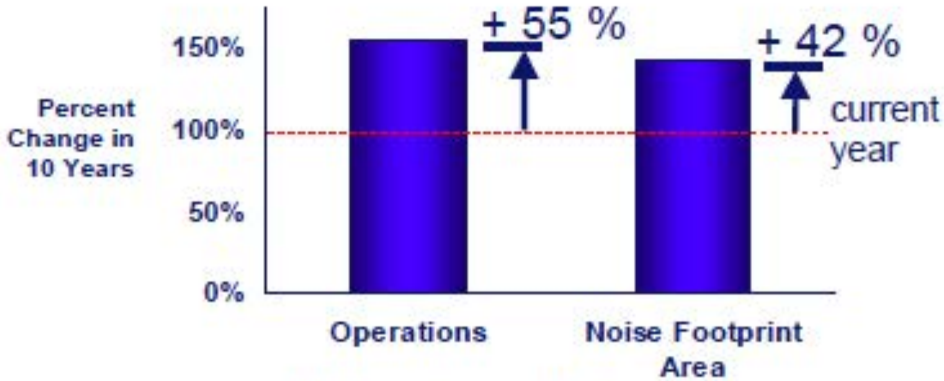


GTF-powered
Next Generation Aircraft

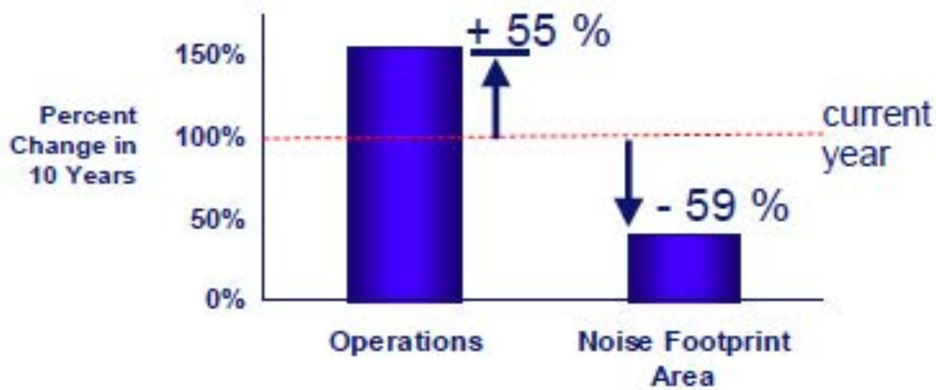
SEL Contour Source: Wyle Laboratories
FAA INM Version 6.2a
Noise Simulation: Pratt & Whitney

(Pratt & Whitney, 2008)

12:1 BPR PROPULSORS – 59% REDUCTION IN DAY-NIGHT NOISE FOOT PRINT AREA

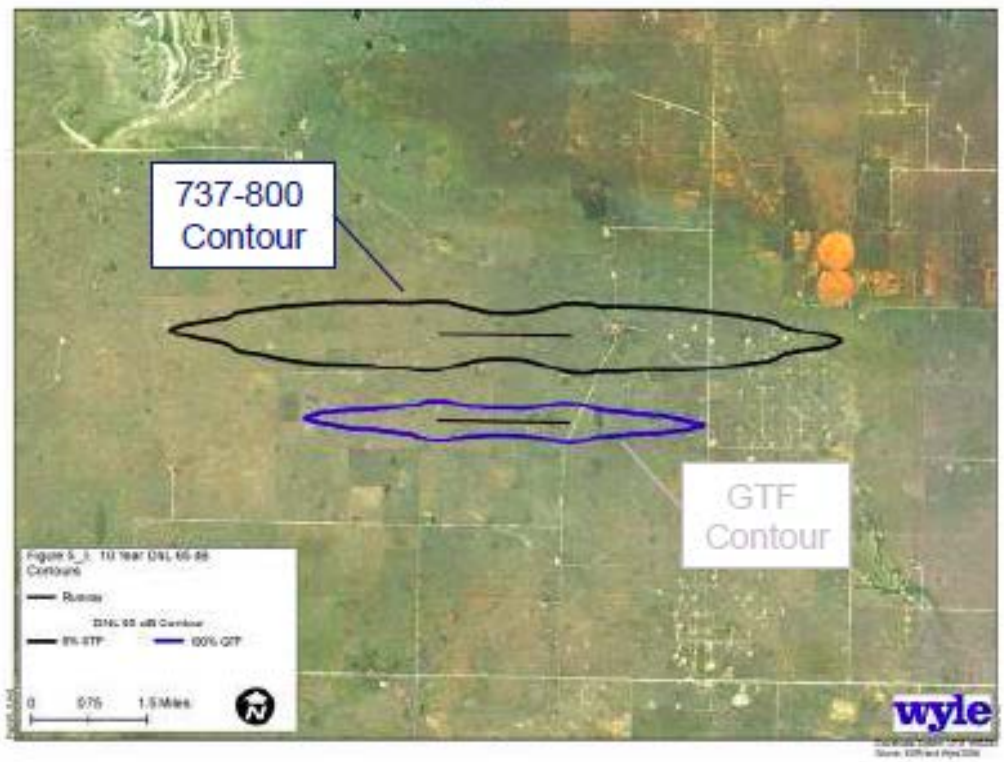


All Operations with Current Production Aircraft (737-800)



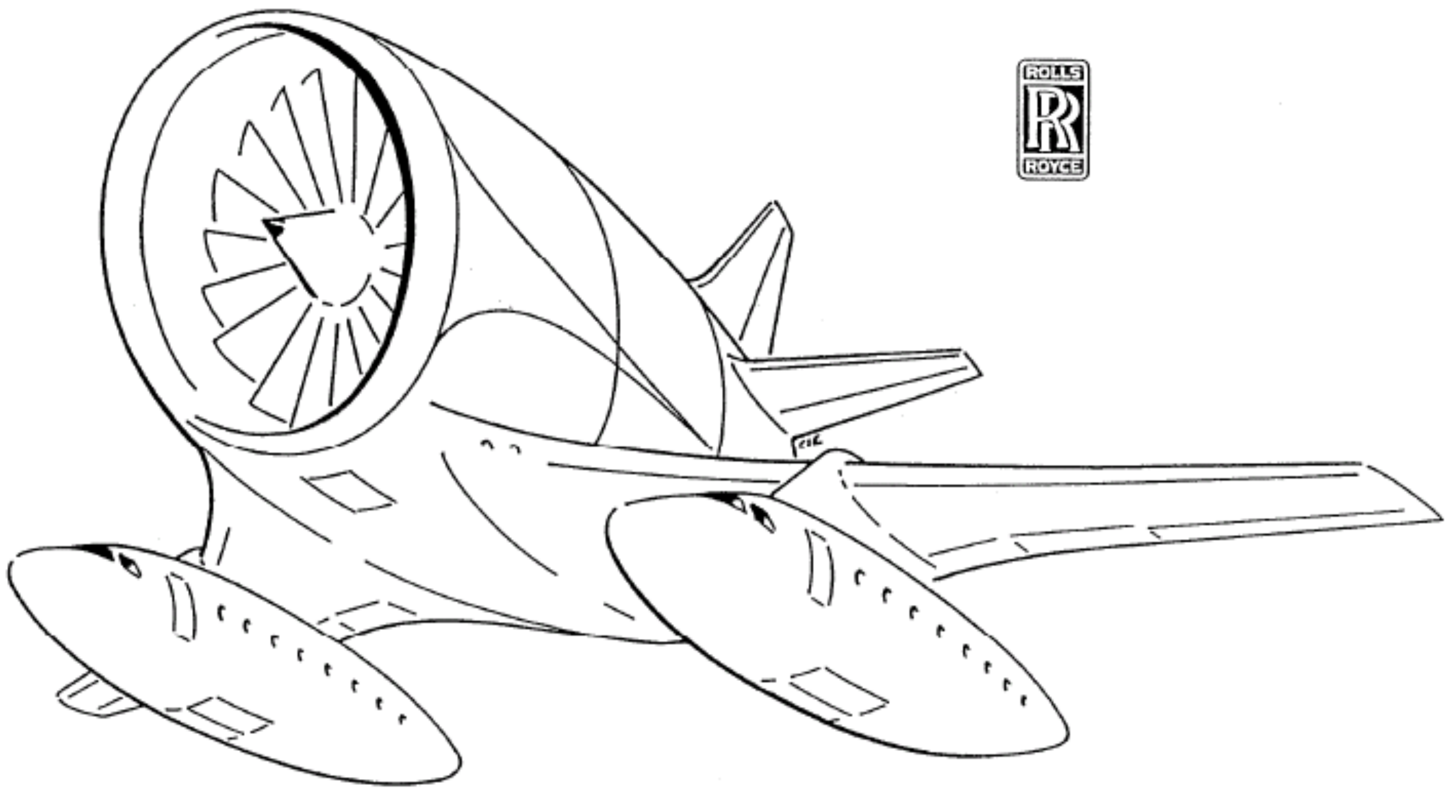
All Operations with GTF-powered Aircraft

65 DNL Noise Footprint Area in 10 years

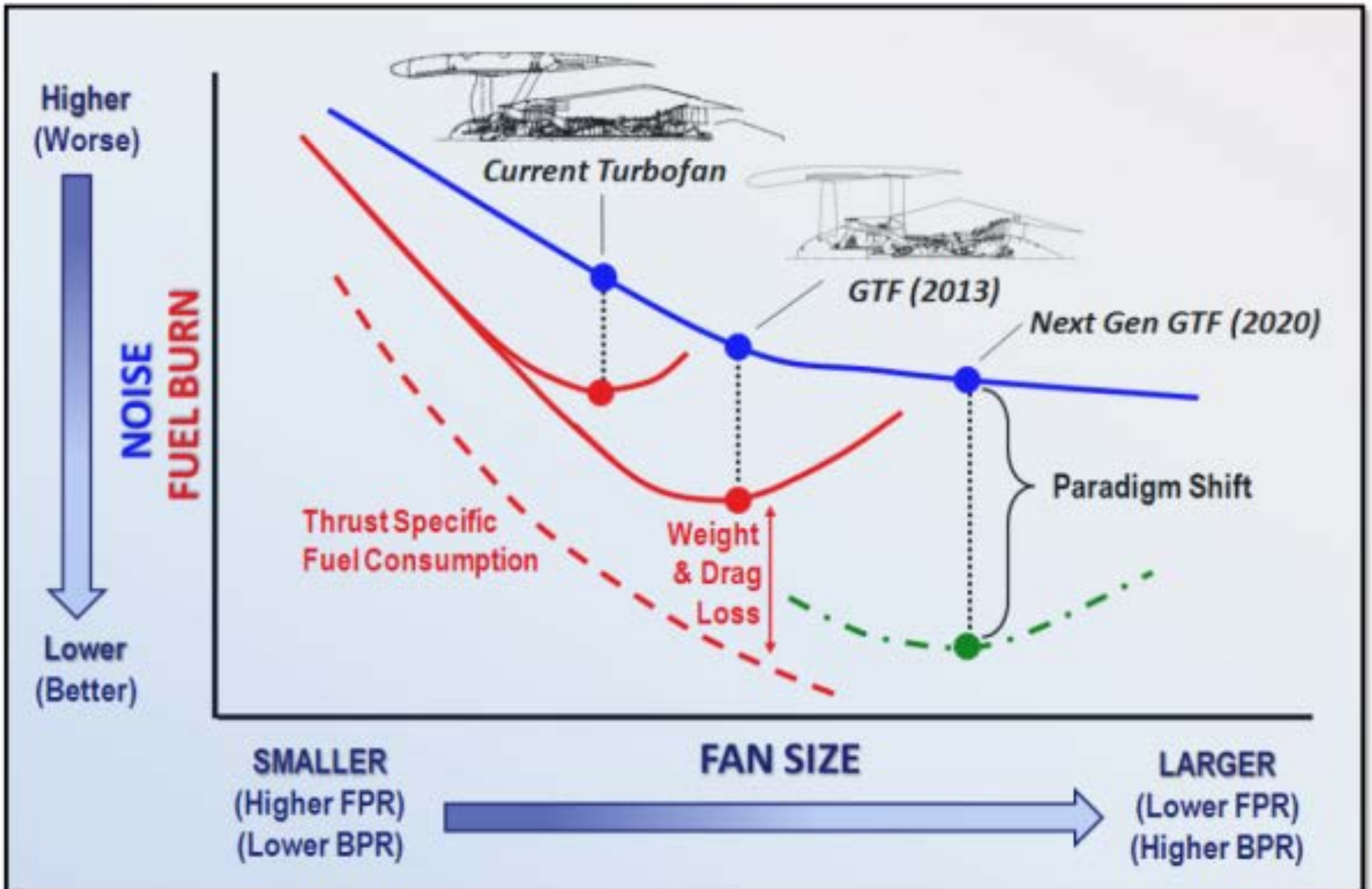


(Pratt & Whitney, 2008)

INSTALLATION STUDY FOR AN ULTRA-HIGH BYPASS TURBOFAN

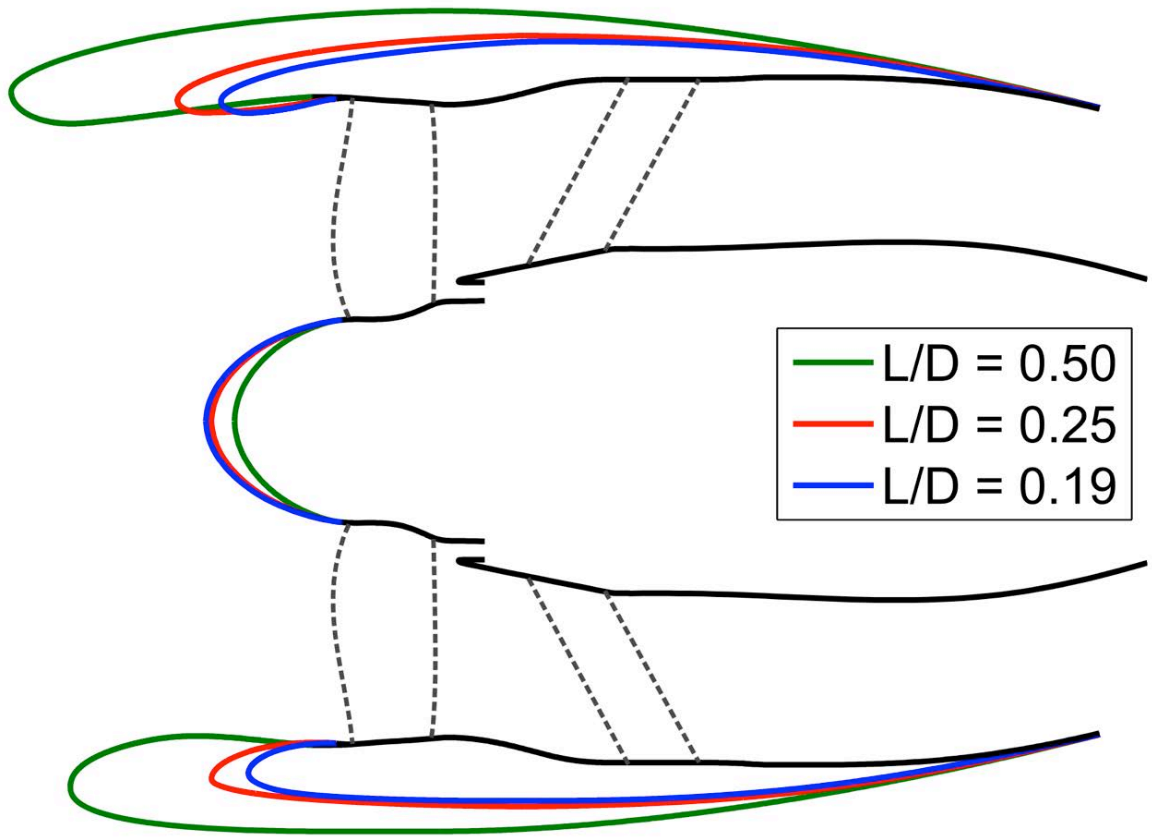


REQUIRED PARADIGM SHIFTS IN NACELLE DESIGN AND FAN NOISE REDUCTION



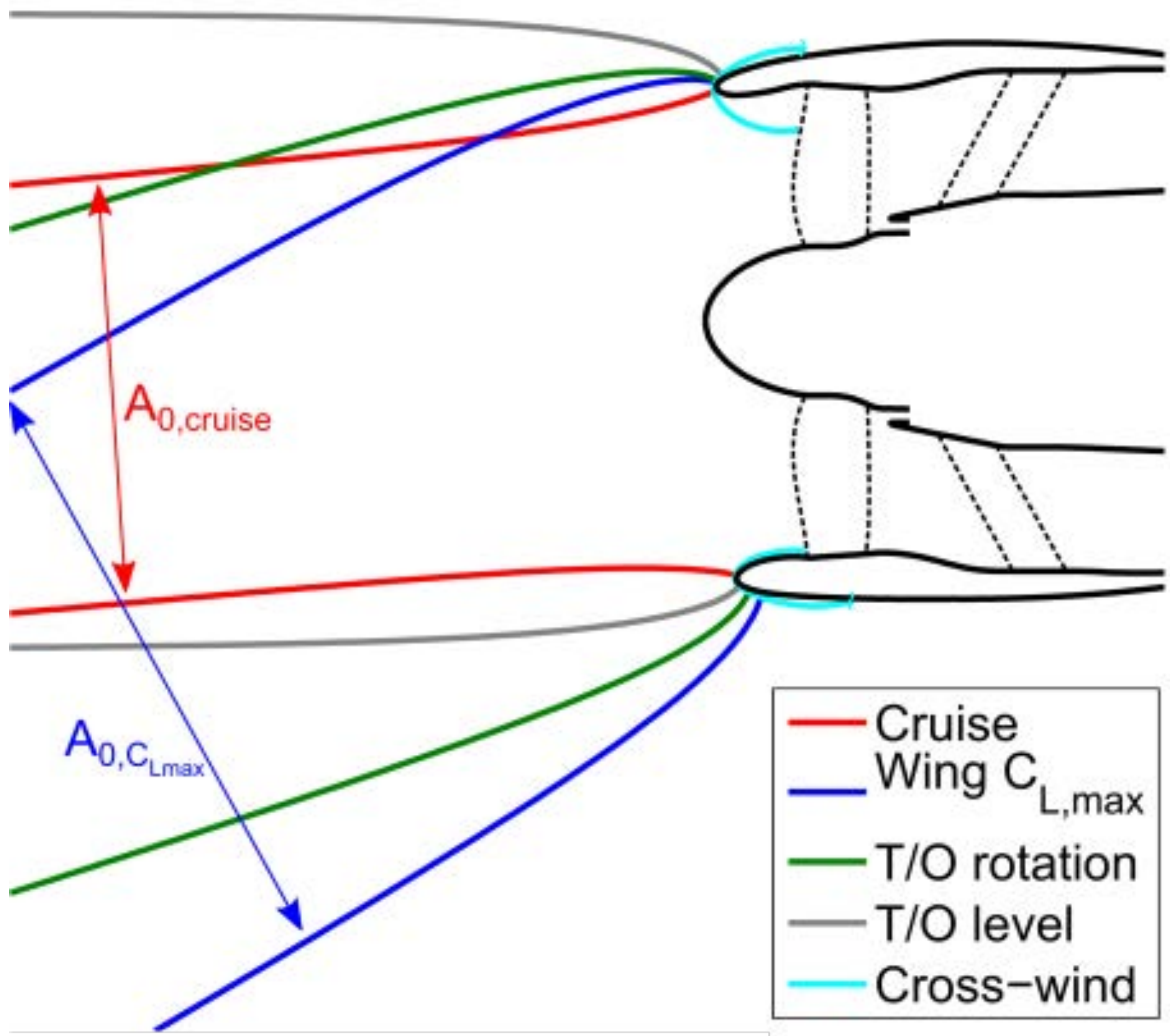
[Hughes, 2011]

HOW SHORT IS TOO SHORT?



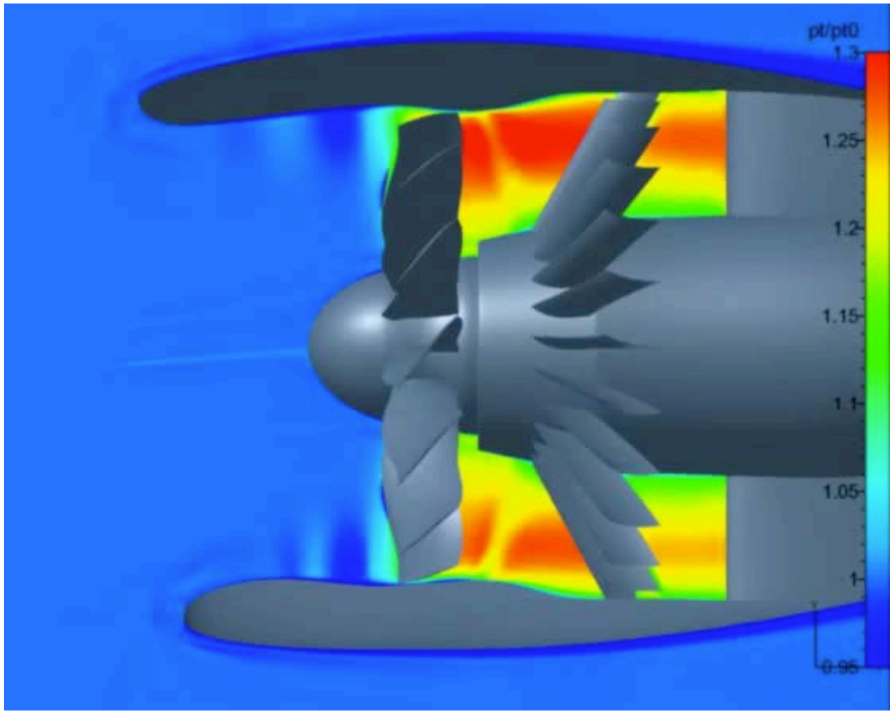
[Peters, 2013]

CHALLENGING INLET DESIGN REQUIREMENTS

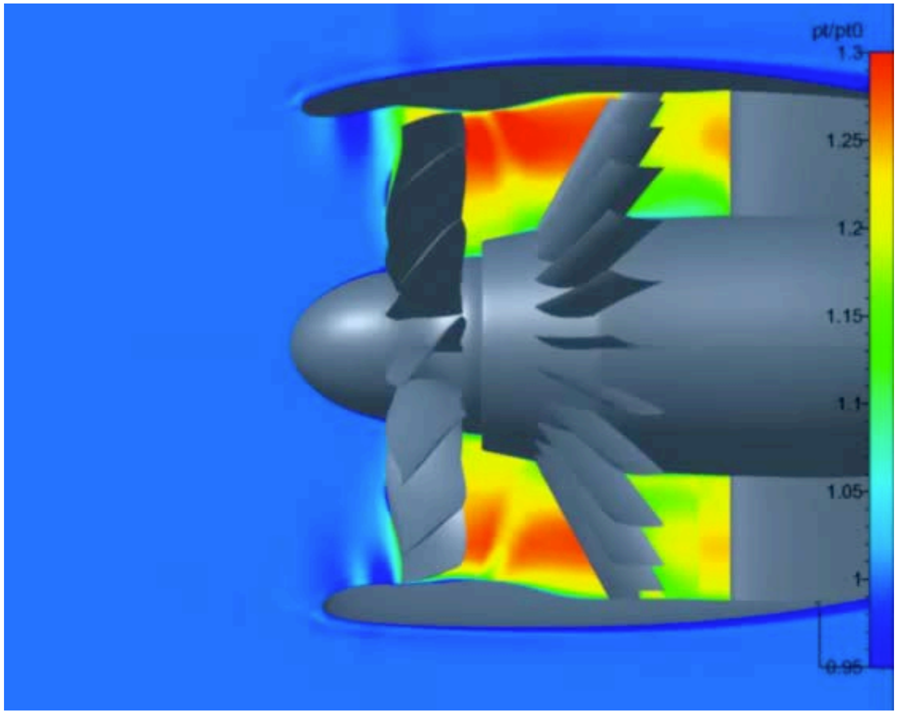


[Peters, 2013]

FAN NOISE CHALLENGE IN ULTRA-SHORT INLETS



Long Inlet



Short Inlet

[Peters, 2013]

AIRFRAME NOISE SOURCES

- Today major source on approach
- Tomorrow major source on takeoff
- Components: flap, slat, and gear

(www.airliners.net)

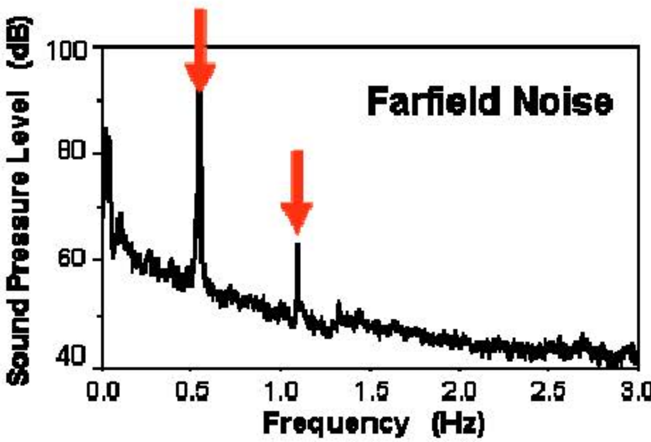
PARASITIC NOISE SOURCES – EXCESS NOISE

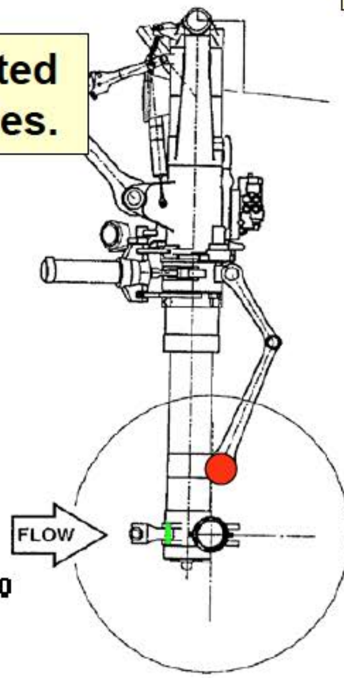
(Dobrzynski, 2008)

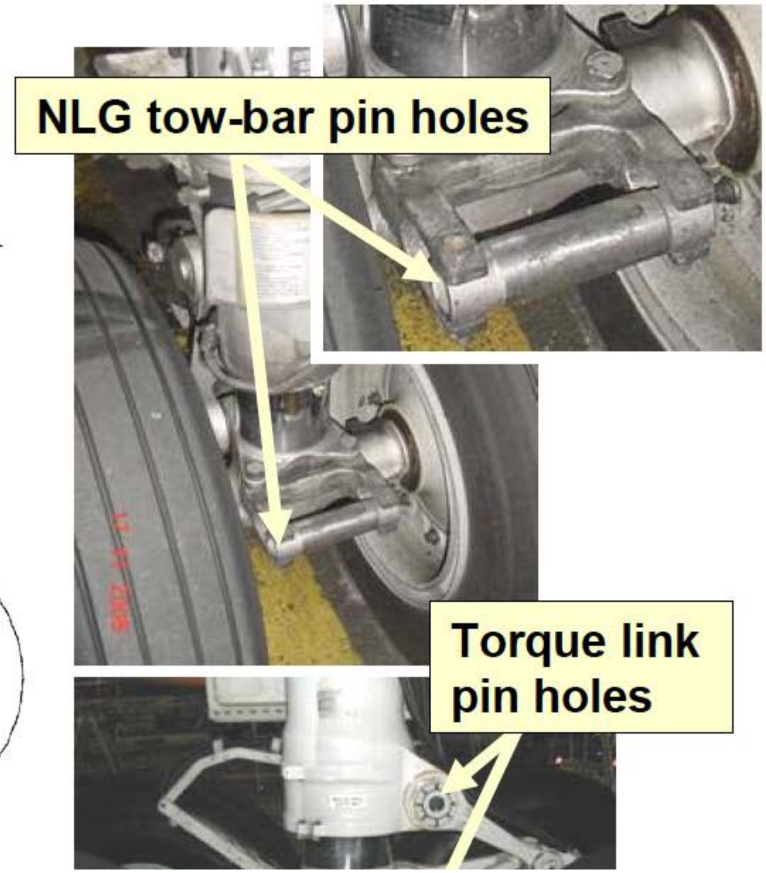
EXCESS NOISE – THE REVENGE OF QUIETER ENGINES

Tone noise from pin-holes :

Tones originate from flow excited resonances in different pin holes.

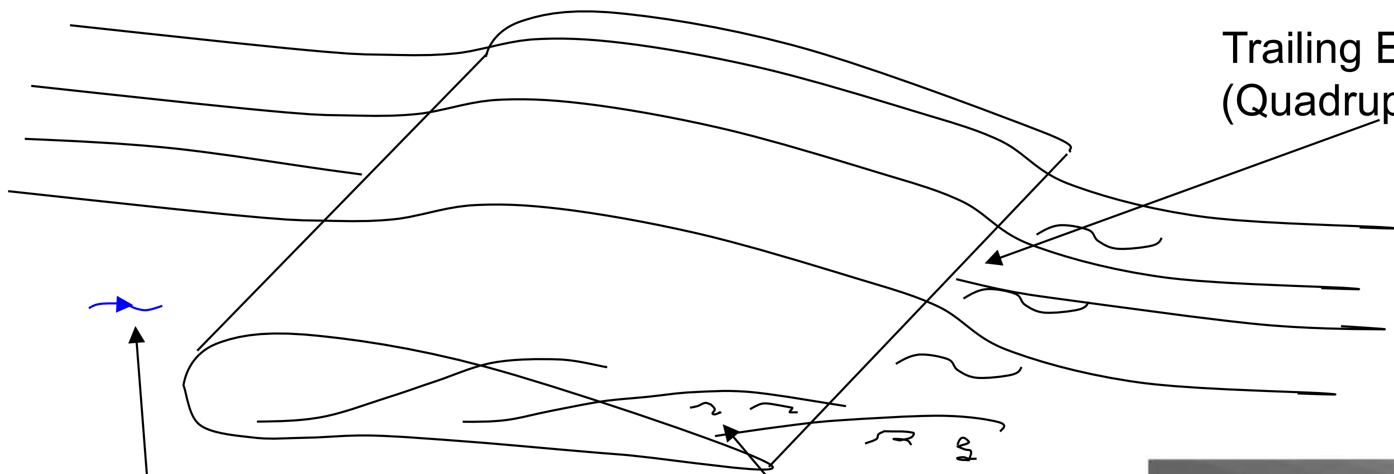


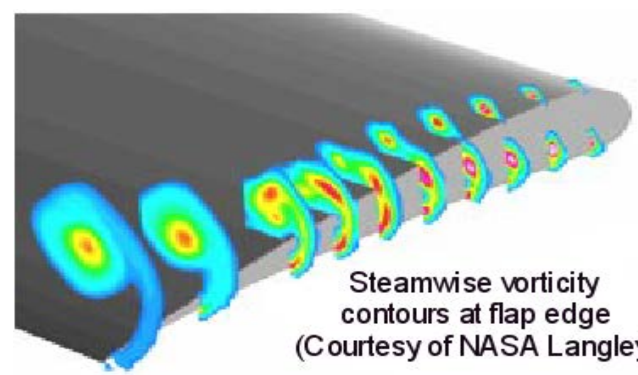




(Dobrzynski, 2008)

AIRFRAME NOISE FLOOR LIMIT: AIRFOIL SELF NOISE





Steamwise vorticity contours at flap edge (Courtesy of NASA Langley)

Scattering of turbulent eddies at edges creates sound

SOUND – LINEAR FLUID MOTION OVER LARGE RANGE OF AMPLITUDES

- **Logarithmic** response of human ear to intensity of sound

  80dB + 80dB = 83dB

- Loudness is **subjective**

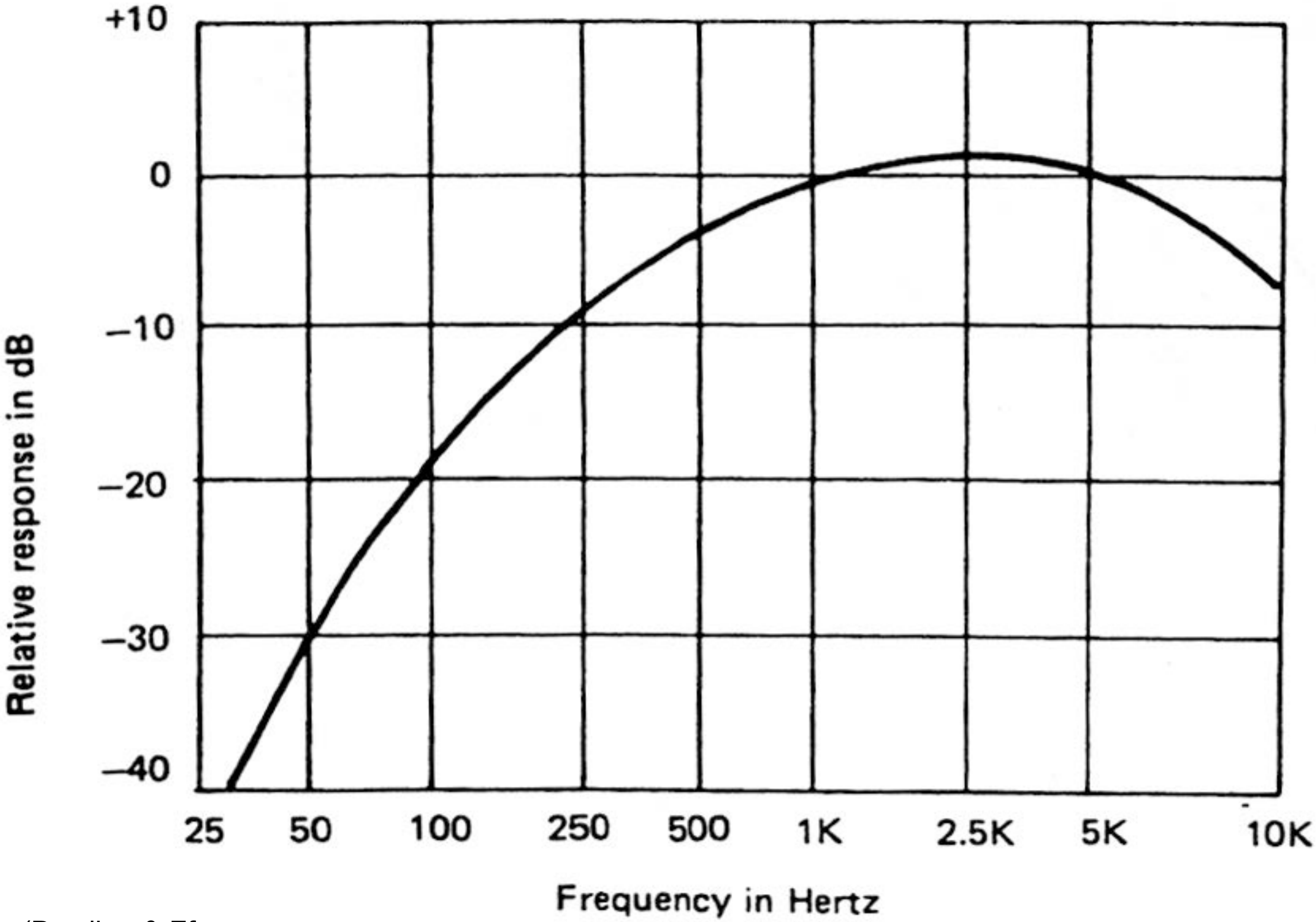
  10 dB doubles loudness

  20 dB quadruples loudness

- Sound waves transport energy - **large range** of acoustic power:

human whisper	≈ 10^{-10} W	
human shout	≈ 10^{-5} W	PWL ≈ 70dB
jet aircraft at takeoff	≈ 10^{5} W	
rocket launch	≈ 10^{7} W	PWL ≈ 190dB

THE HUMAN EAR – A BAND-PASS FILTER



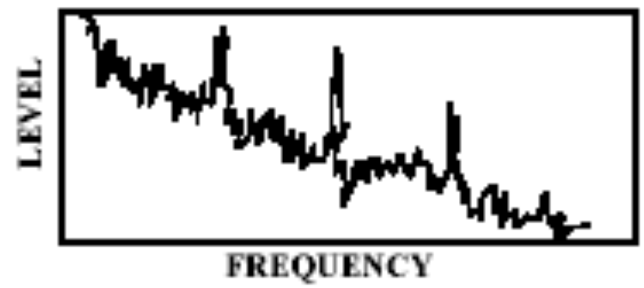
(Dowling & Ffowcs Williams1983)

AIRCRAFT CERTIFICATION: EFFECTIVE PERCEIVED NOISE LEVELS

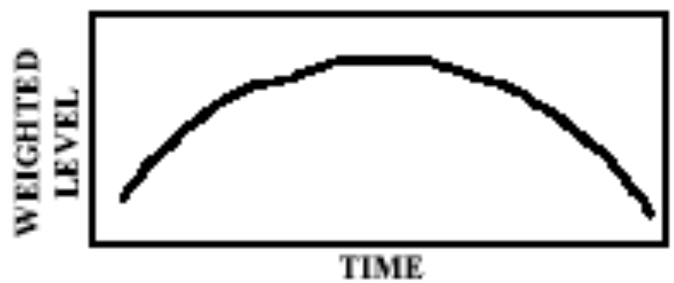
- Expressed as "EPNdB" by Integrating:

Level

Frequency & Tone Content



Duration (Time of Flyover)



(Source: NASA GRC)

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THE SILENT* AIRCRAFT INITIATIVE

- A collaborative, multi-disciplinary project between MIT and Cambridge University funded by CMI
- Goal: conceptual design of an aircraft inaudible outside airport perimeter
- Half person-century of work (3 year project, a team of ~35 researchers) on conceptual aircraft design
- Identified some hard problems and new research areas
- Received industry design reviews (by Boeing Commercial A/C Division, Boeing Phantom Works, Rolls-Royce)

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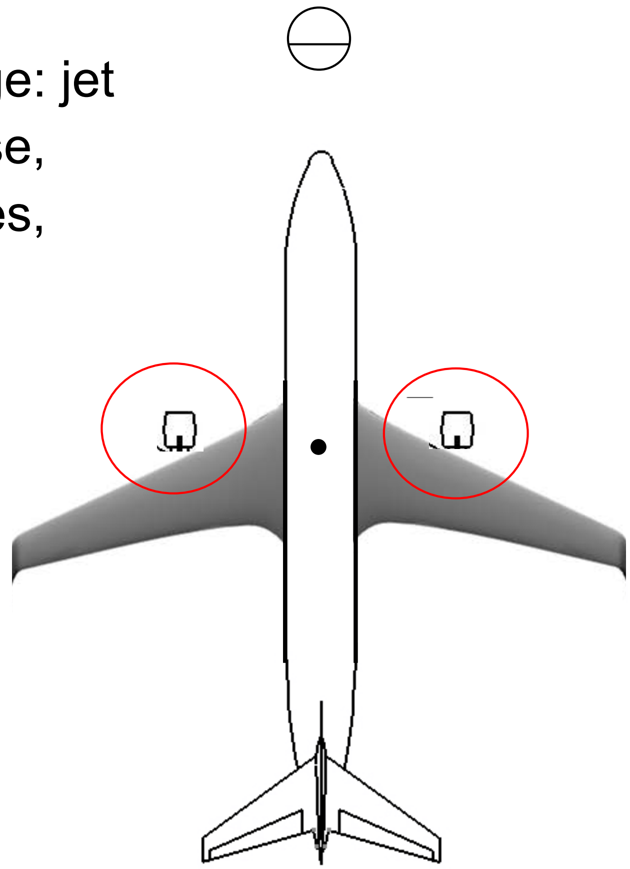
* silent = aircraft noise less than background noise in well-populated area

TECHNOLOGIES REQUIRED TO ADDRESS *ALL* NOISE SOURCES

- Advanced, highly efficient airframe centerbody design
- Advanced airfoil trailing edge treatment
- Faired undercarriage
- Deployable drooped leading edge
- Quiet drag via increased induced drag
- Embedded, boundary layer ingesting, distributed propulsion system
- Variable area exhaust nozzle and ultra-high bypass ratio engines
- Airframe shielding and optimized extensive liners
- Optimized take-off thrust management

NOISE REDUCTION CHALLENGE – CONVENTIONAL A/C

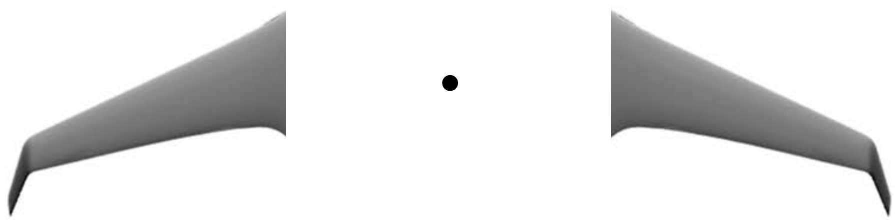
- Noise reduction challenge: jet and turbomachinery noise, airframe lift discontinuities, cavities and edges
- Limited low speed performance



Approach configuration

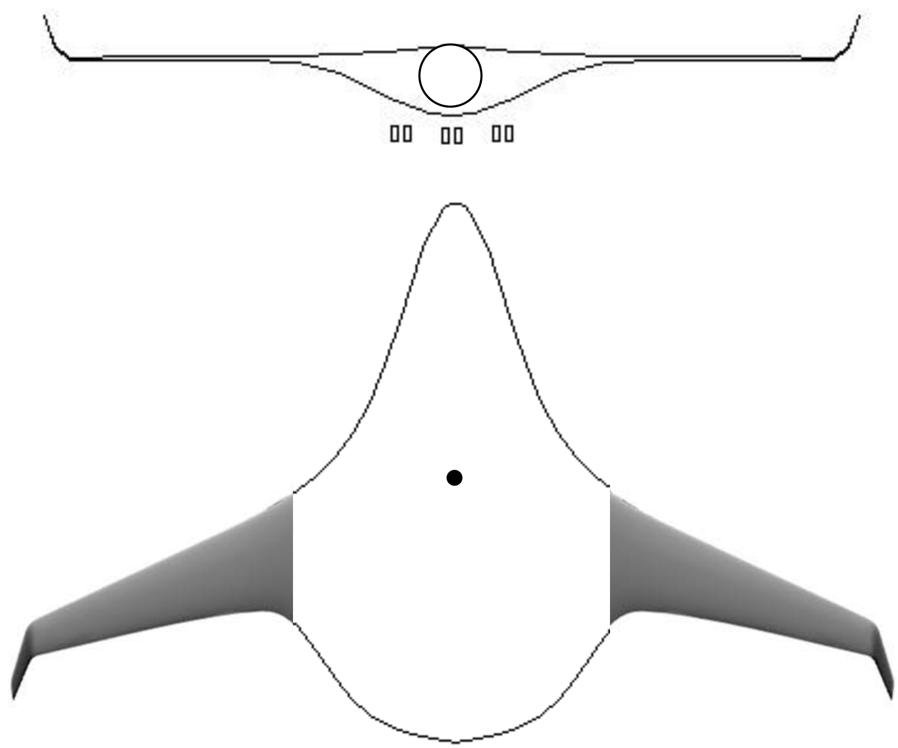
ROADMAP TO A SILENT AIRCRAFT

- Start with conventional wings (e.g. supercritical airfoils)



ROADMAP TO A SILENT AIRCRAFT

- Start with conventional wings (e.g. supercritical airfoils)
- Transform fuselage into lifting surface



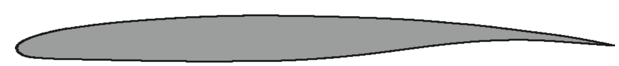
ROADMAP TO A SILENT AIRCRAFT

- Embed propulsion system to shield turbomachinery noise and to ingest airframe boundary layers

ROADMAP TO A SILENT AIRCRAFT

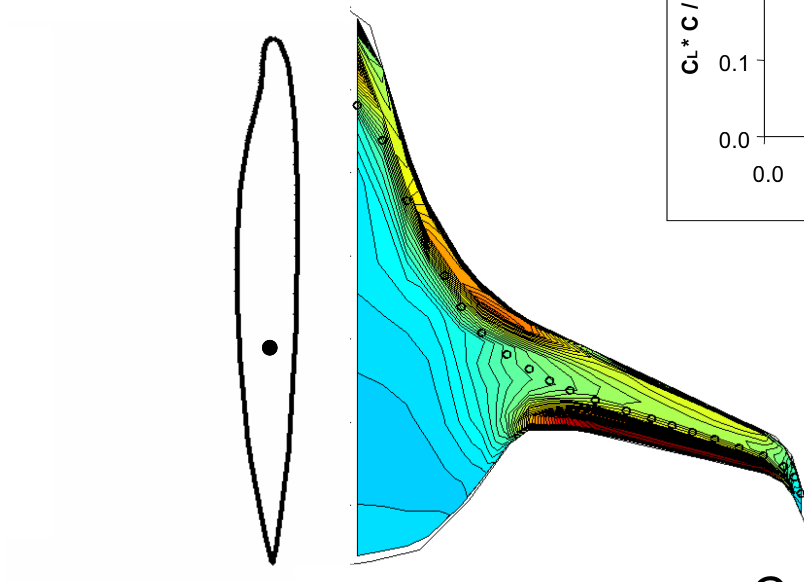
- Issue: highly loaded outer wing yields nose down moment → re-cambered profiles and relatively large control surfaces yield performance penalty

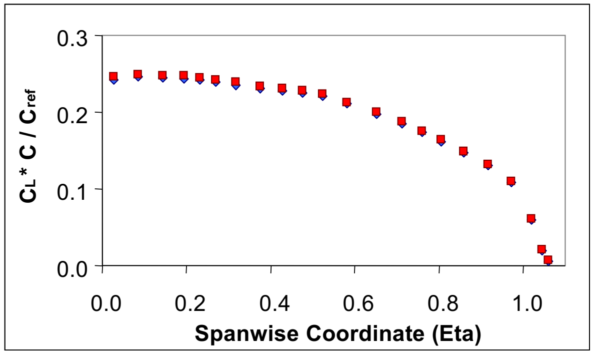
Cruise configuration



ROADMAP TO A SILENT AIRCRAFT

- Camber leading edge and twist outer wing to balance moments in cruise and achieve elliptical lift distribution

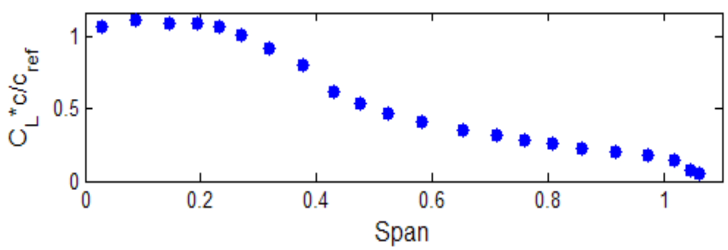


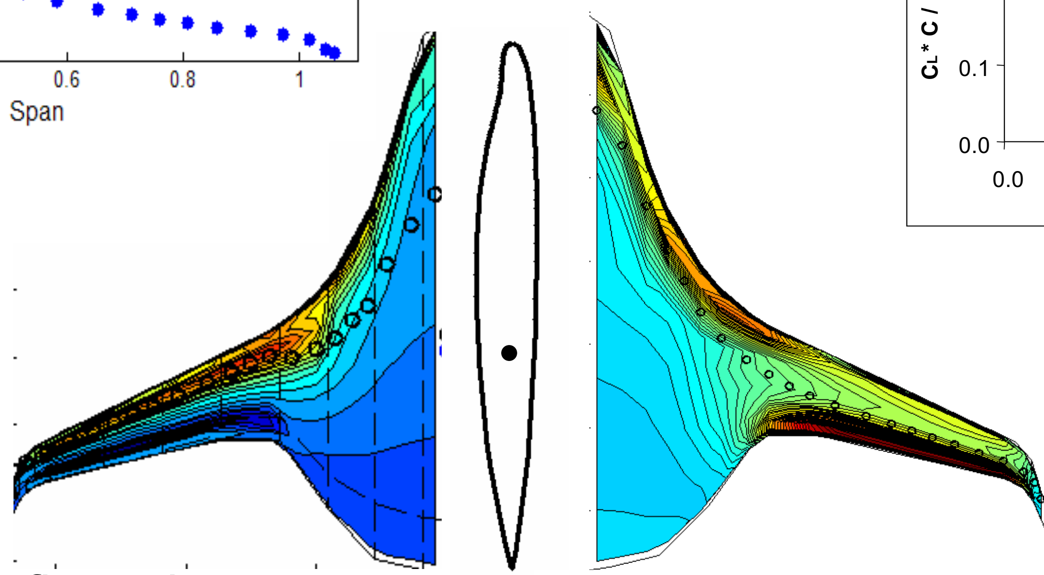


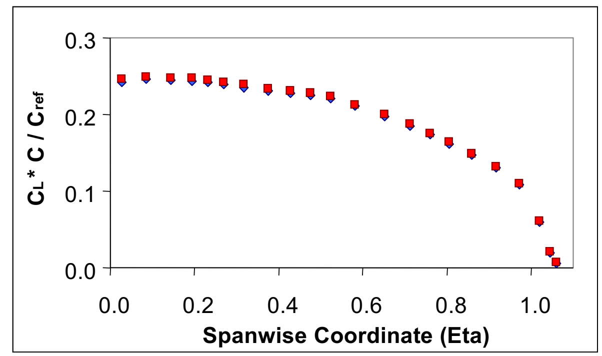
Cruise configuration

ROADMAP TO A SILENT AIRCRAFT

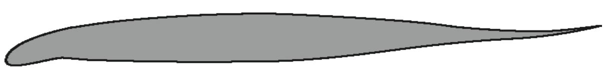
- Balance pitching moment with centerbody camber and unload trailing edge on approach → increased induced drag for quiet, low speed approach



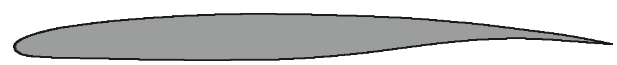




Approach configuration



Cruise configuration



SAX GENEALOGY

***SAX-10**: First Generation Design*

- Based on Boeing PW planform design tool
- Optimized on maximum take-off weight
- 4 Granta-252 engines
- First industry non-advocate reviews

***SAX-20**: Second Generation Design*

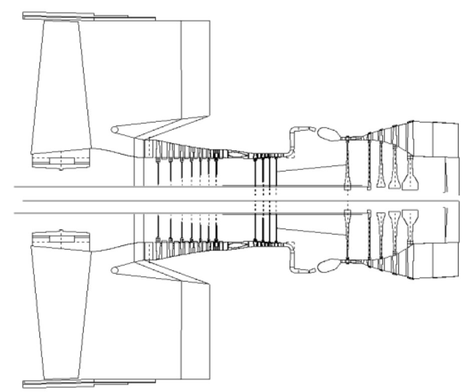
- 3D airframe design methodology
- Design for low stall speed to reduce noise
- 3 Granta-3201 clusters
- Boeing Phantom Works design review and 3D viscous analysis

***SAX-40**: Third Generation Design*

- Optimized outer wing using 3D design methodology
- Elliptical lift distribution
- Distributed propulsion: 3 Granta-3401 clusters
- Second industry non-advocate reviews

SAX-10

Granta-252 (4 Engines)



Geared Low Pressure Turbine
No Boundary Layer Ingestion

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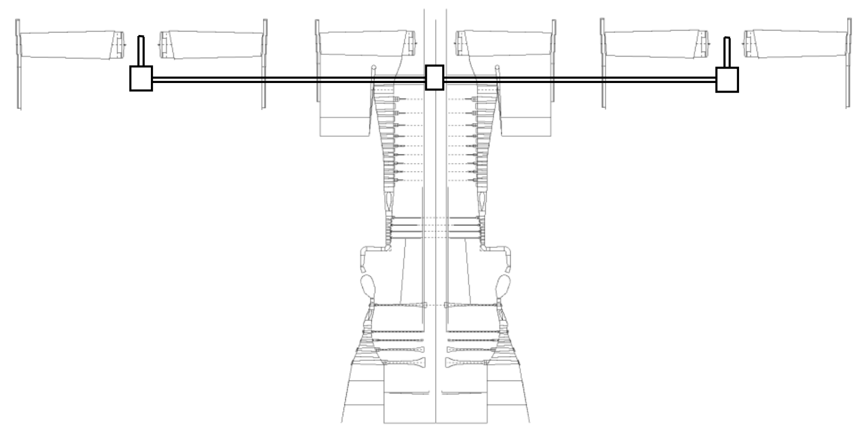
SAX-20

Granta-3201 (3 Engines)



Boundary Layer Ingestion
Gear and Transmission Concepts

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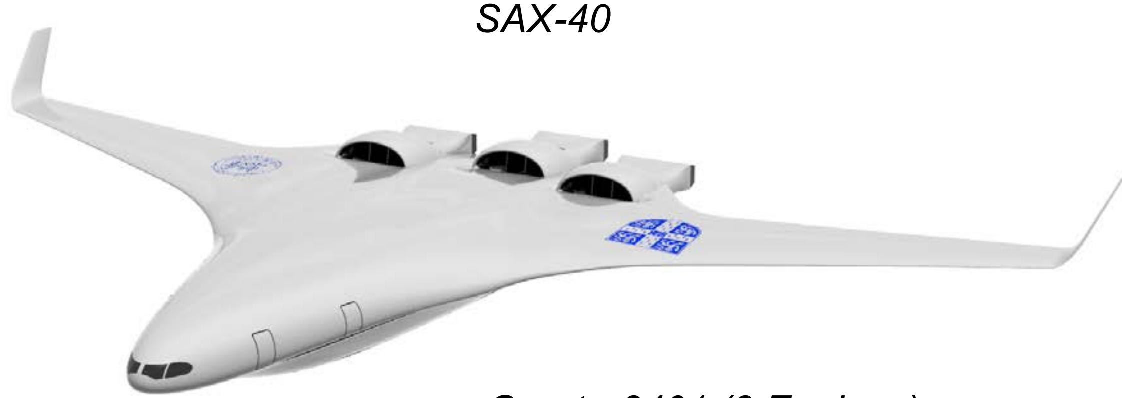
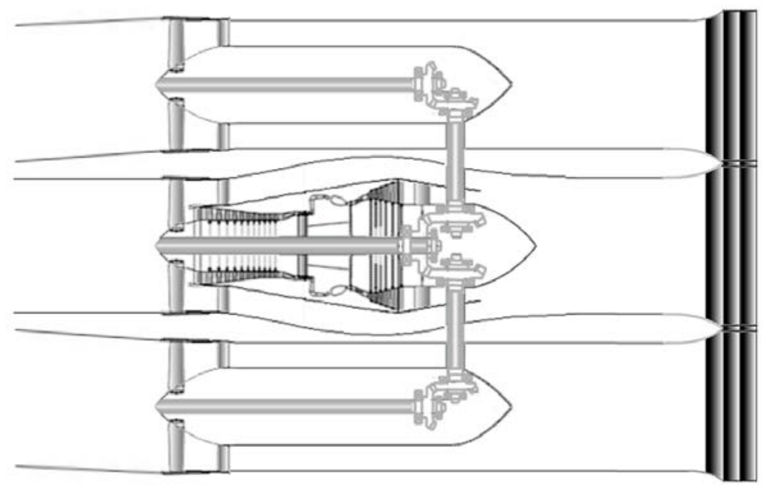
SAX-40



Granta-3401 (3 Engines)



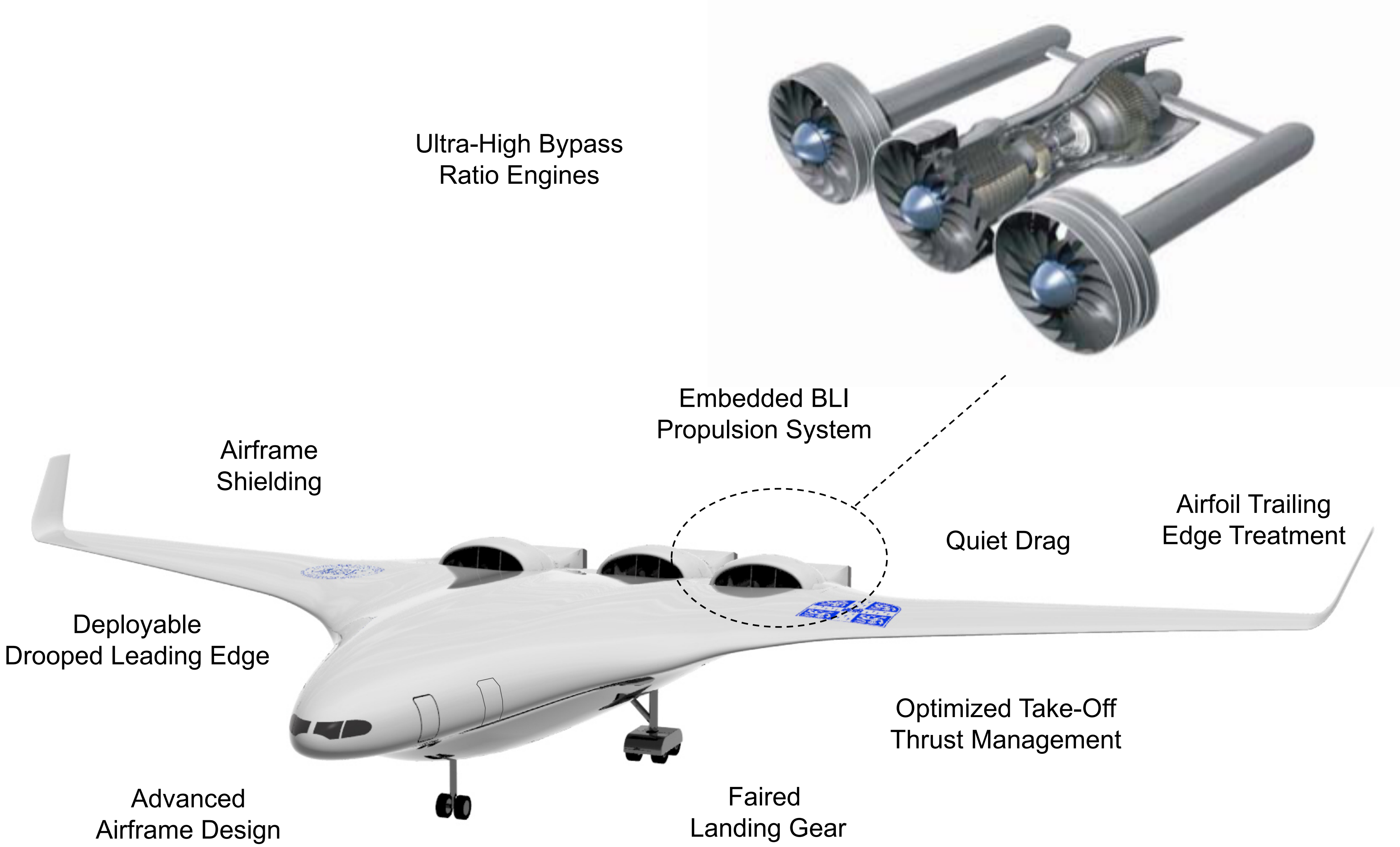
Boundary Layer Ingestion
Detailed Transmission Design

SILENT AIRCRAFT CONCEPTUAL DESIGN – SAX-40

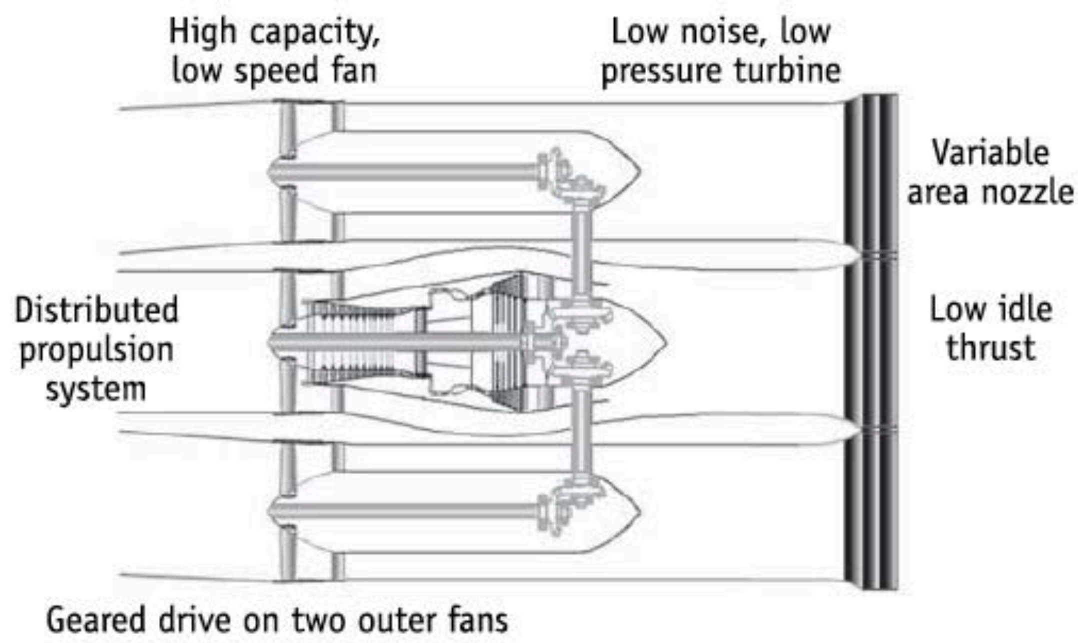
Fuel Burn potential of 124 pax-miles per gallon (85 for B777)

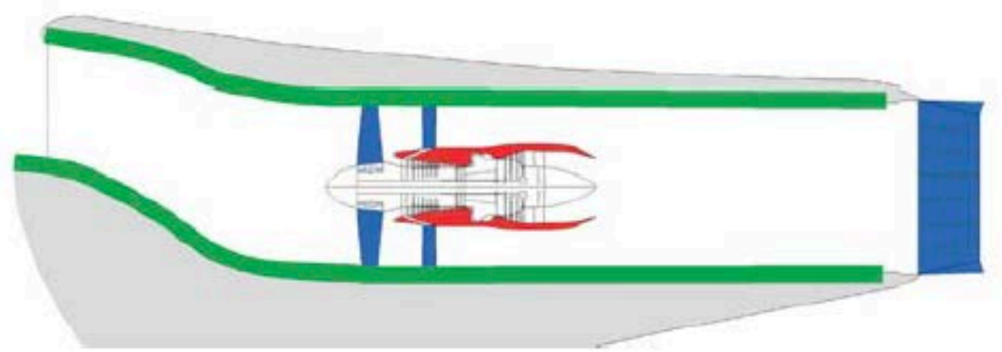
Noise estimated as 63 dBA outside airport perimeter (background noise)

ENABLING TECHNOLOGIES – SAX-40



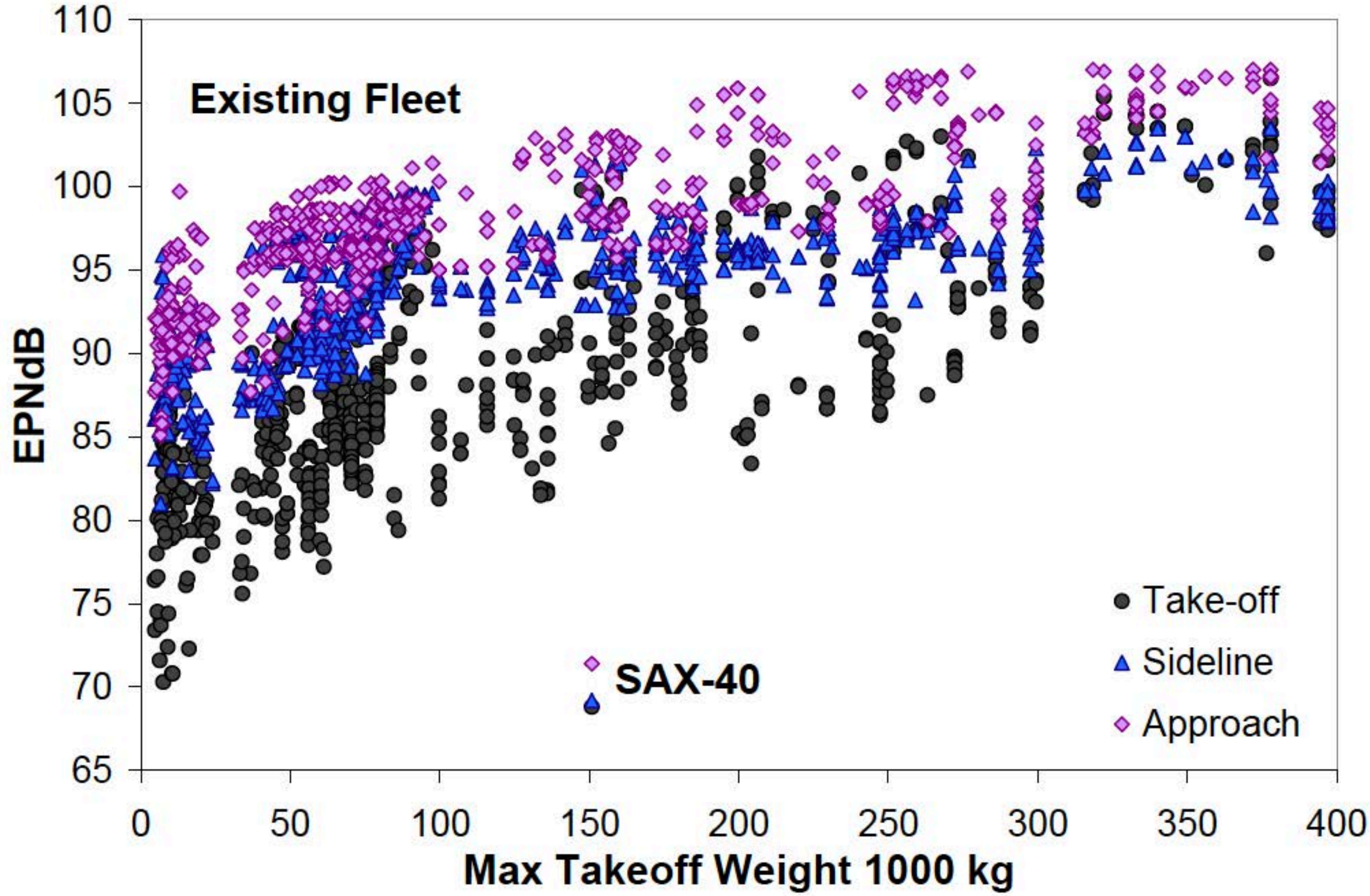
ENABLING TECHNOLOGIES – PROPULSION SYSTEM



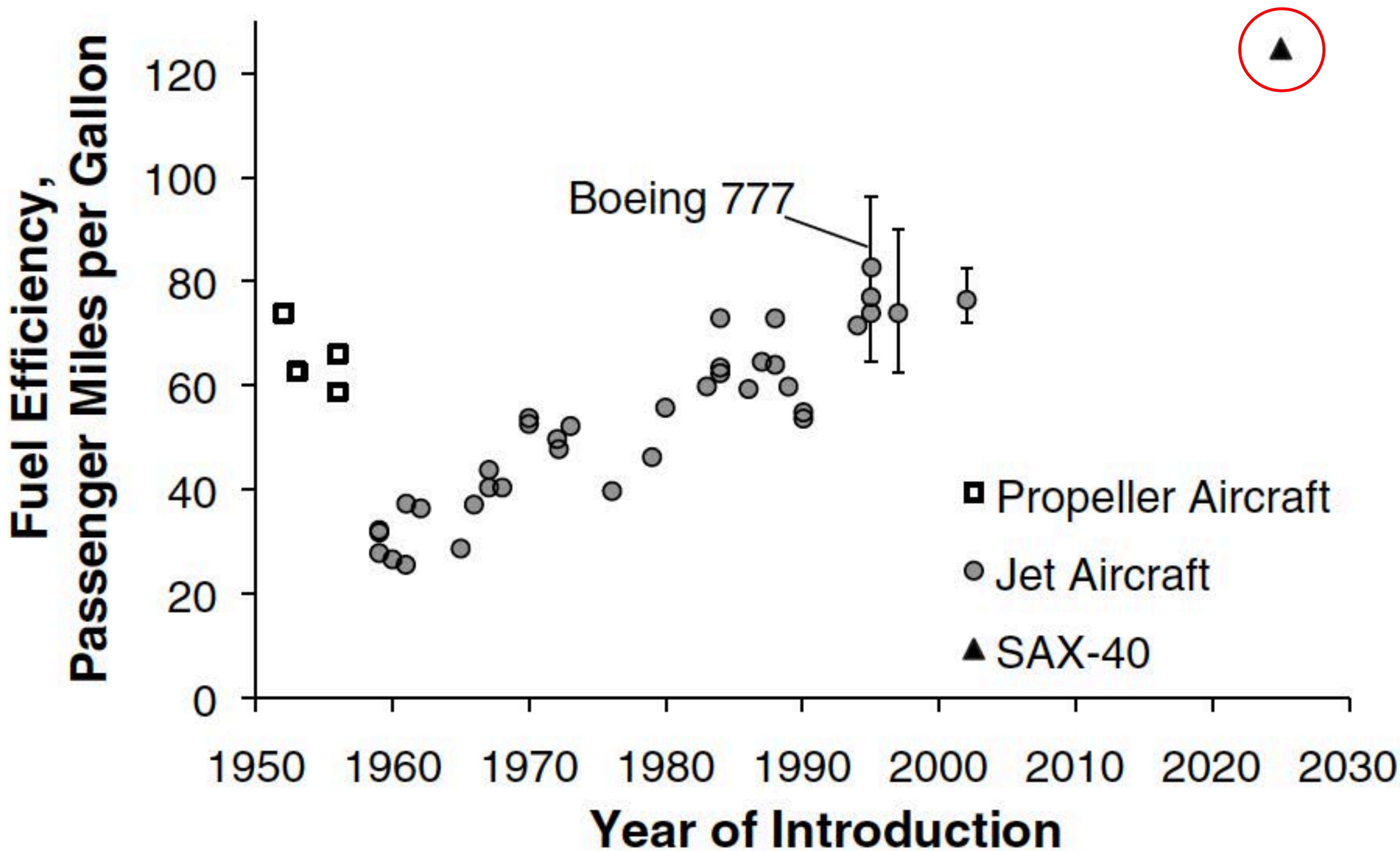


Variable Area Exhaust Nozzle
Extensive Liners

PREDICTED SAX-40 NOISE LEVELS RELATIVE TO EXISTING FLEET



ESTIMATED FUEL EFFICIENCY:
PASSENGER MILES PER GALLON



NASA FUNDED N+2 AND N+3 ADVANCED CONFIGURATIONS

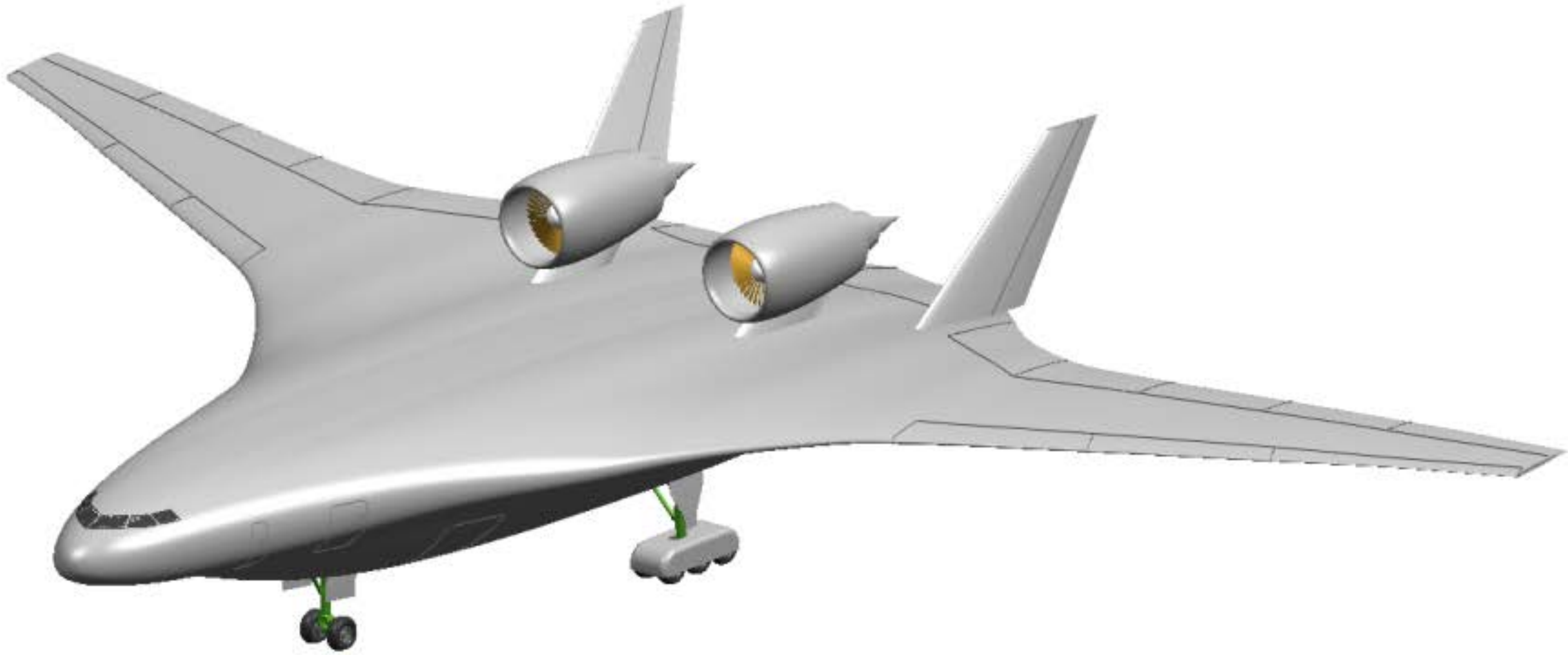
N2A (Boeing-MIT-UCI)

D8 (MIT-Aurora-PW)

NOISE REDUCTION TECHNOLOGIES: OPPORTUNITIES, CHALLENGES & REQUIRED INNOVATIONS

- Shielding benefits of advanced airframe architectures – lack of methods for unconventional configurations
- Integrated and embedded propulsors – acoustic challenges of boundary layer ingestion and distributed propulsion
- Aerodynamically clean airframes – innovative engine air brakes for quiet drag generation

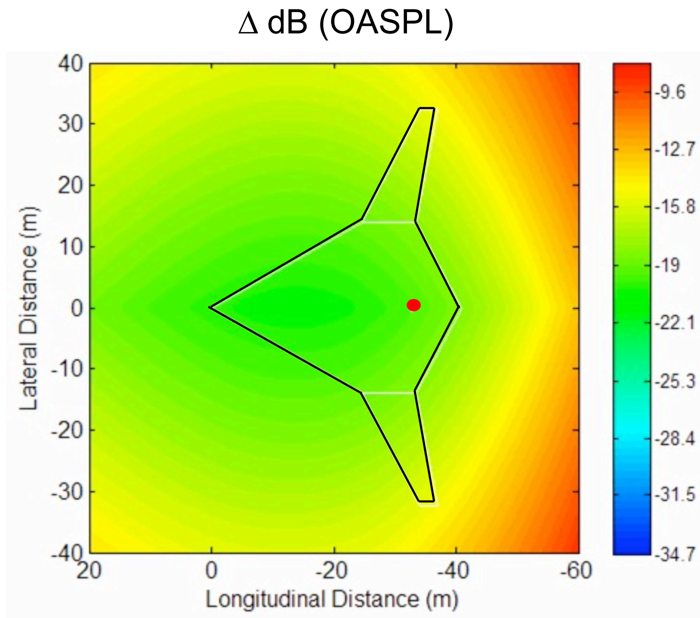
FAN NOISE SHIELDING POTENTIAL OF ADVANED AIRFRAME CONFIGURATIONS



SHIELDING ASSESSMENT CHALLENGES

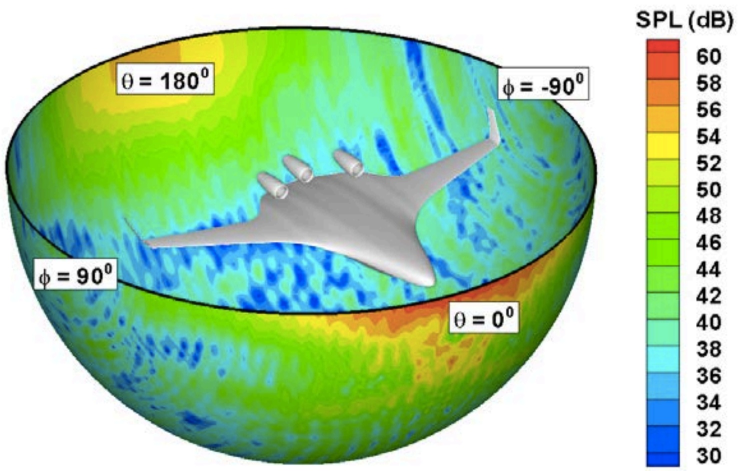
NASA Aircraft Noise Prediction Program

- Barrier shielding correlation using rectangular screens
- Fast, but limited geometry and fidelity



NASA Fast Scattering Code

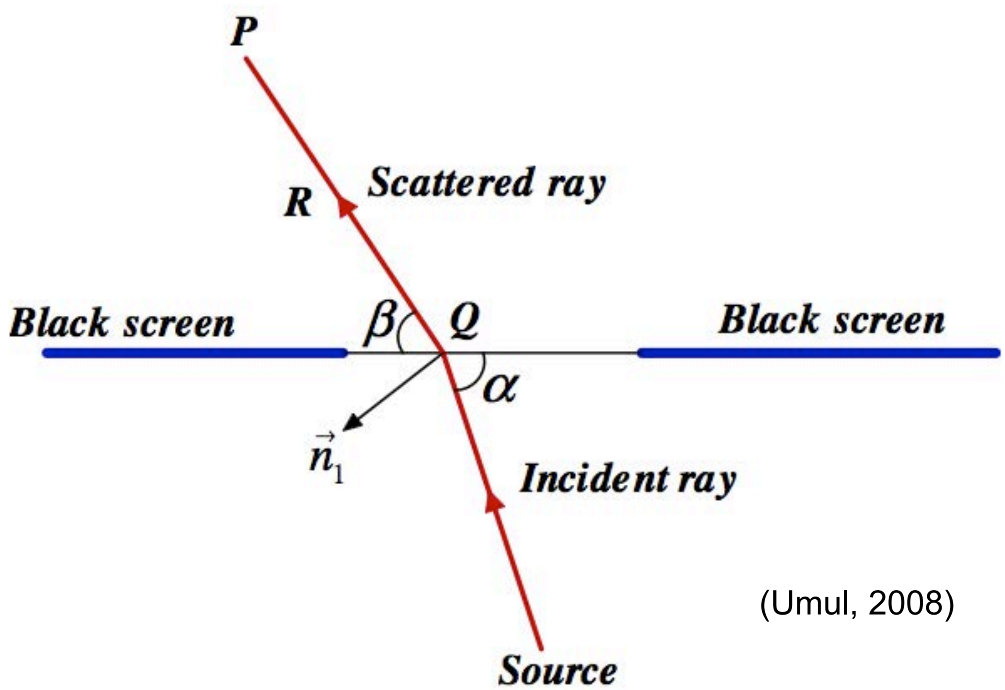
- Solves 3D exterior boundary value problem to Helmholtz equation
- Limited to low frequencies, computationally costly



(Nark et al. 2008)

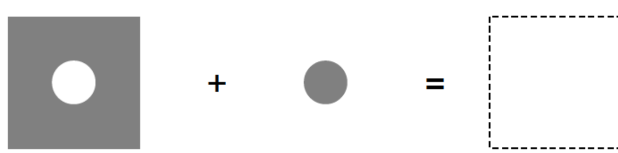
DIFFRACTION INTEGRAL METHOD FOR FAST AND ROBUST SHIELDING ASSESSMENT

- Scattered field for aperture in infinite black screen

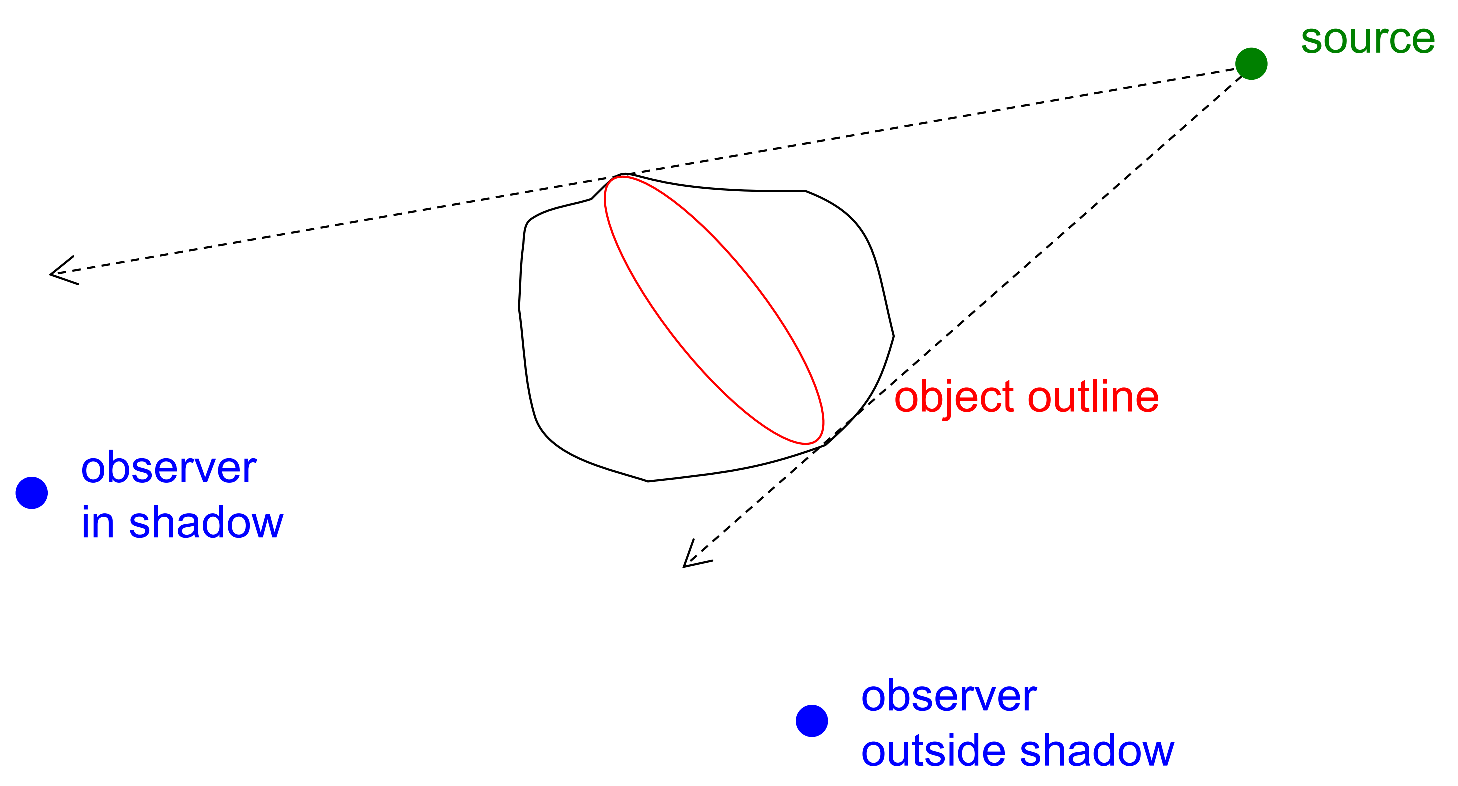


(Umul, 2008)

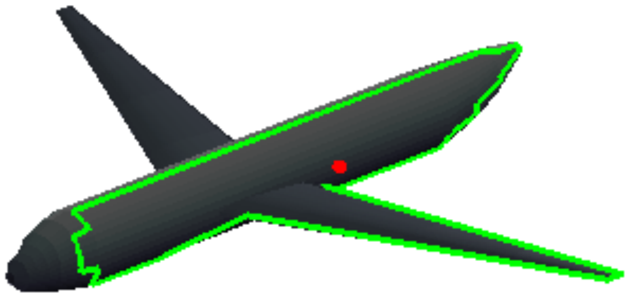
- Sum of diffracted fields of complementary geometries = free field



DIFFRACTION INTEGRAL EVALUATED AROUND ILLUMINATED OBJECT OUTLINE

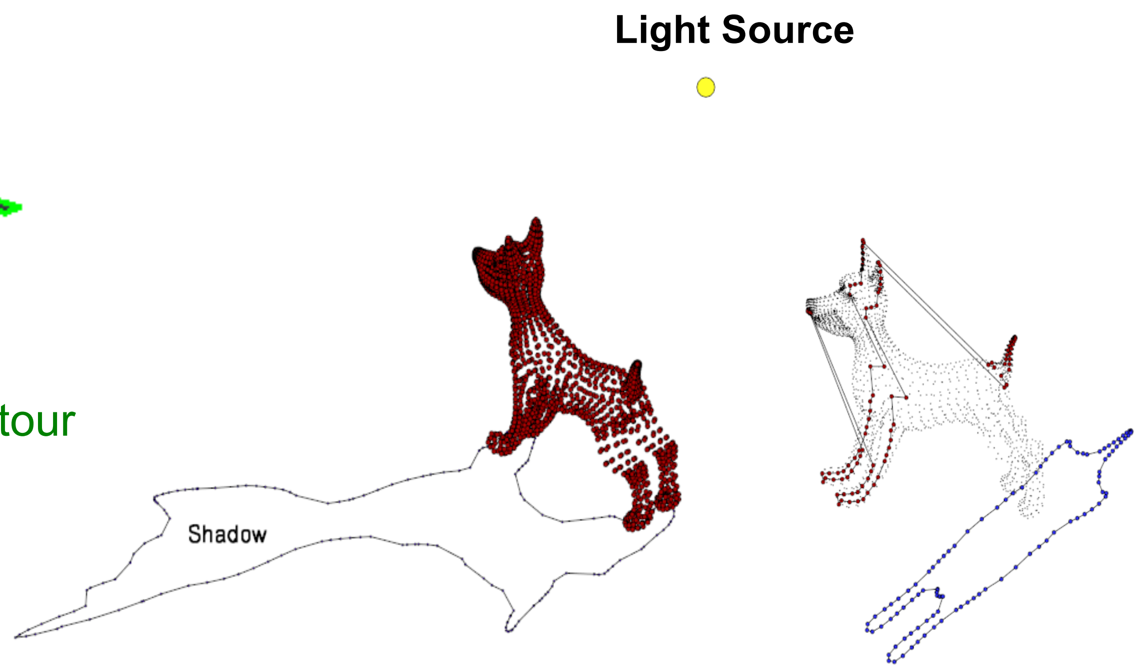


ROBUST INTEGRATION CONTOUR SEARCH ALGORITHM



Source

Integration contour



(Picture courtesy Stuart Pope)

PARAMETRIC SHIELDING STUDY OF HWB AIRFRAME CONFIGURATIONS

Baseline

Winglets

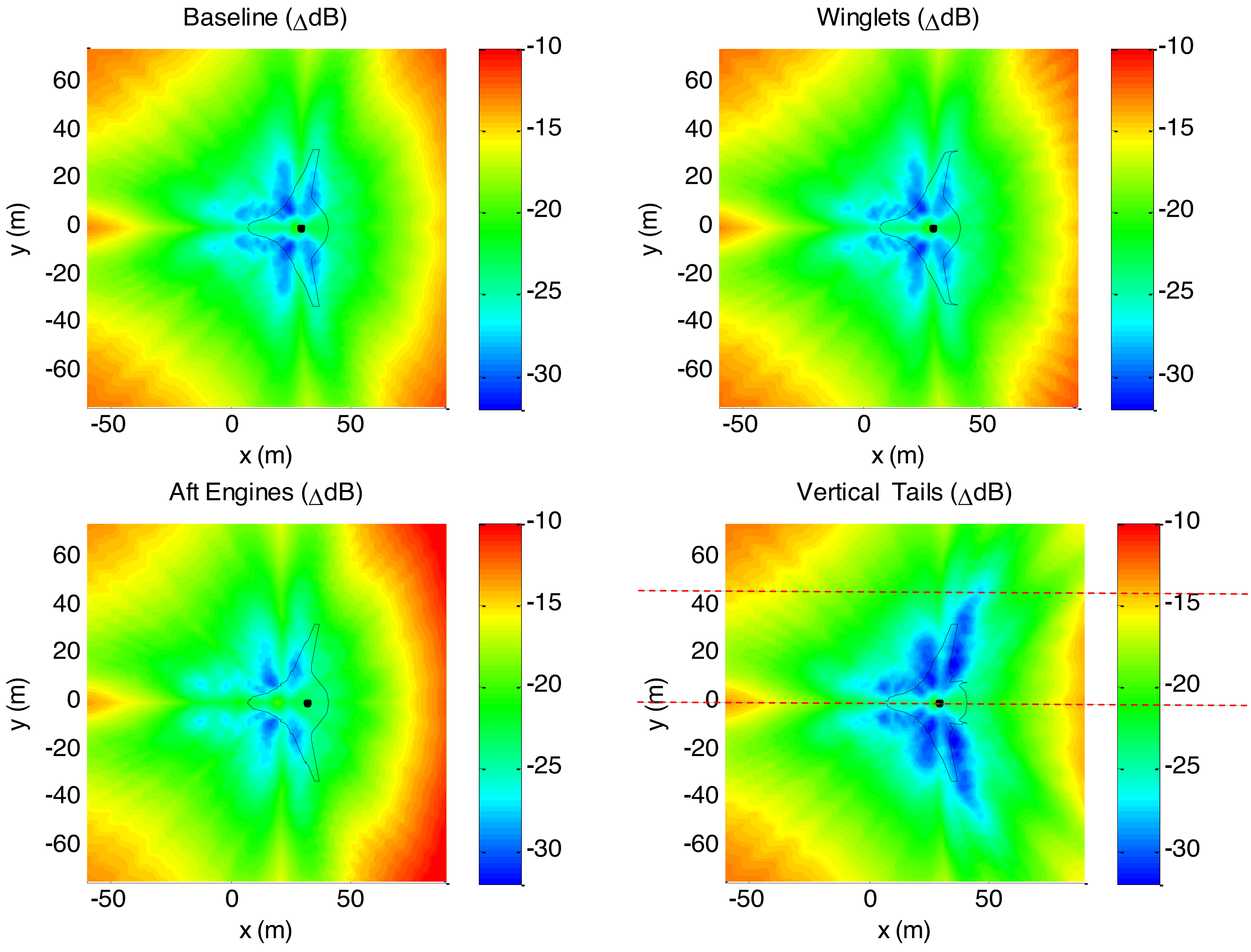
Contour of Integration

Noise Source above Airframe

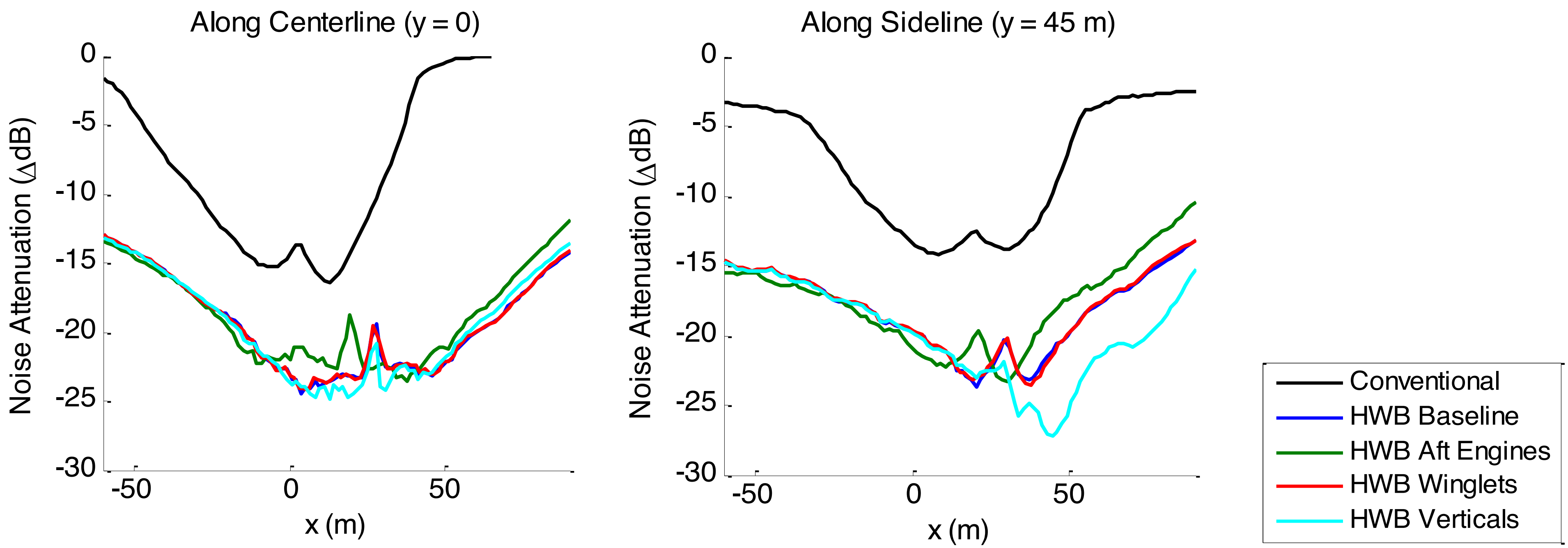
Aft Engines

Vertical Tails

HWB NOISE ATTENUATION IN OASPL



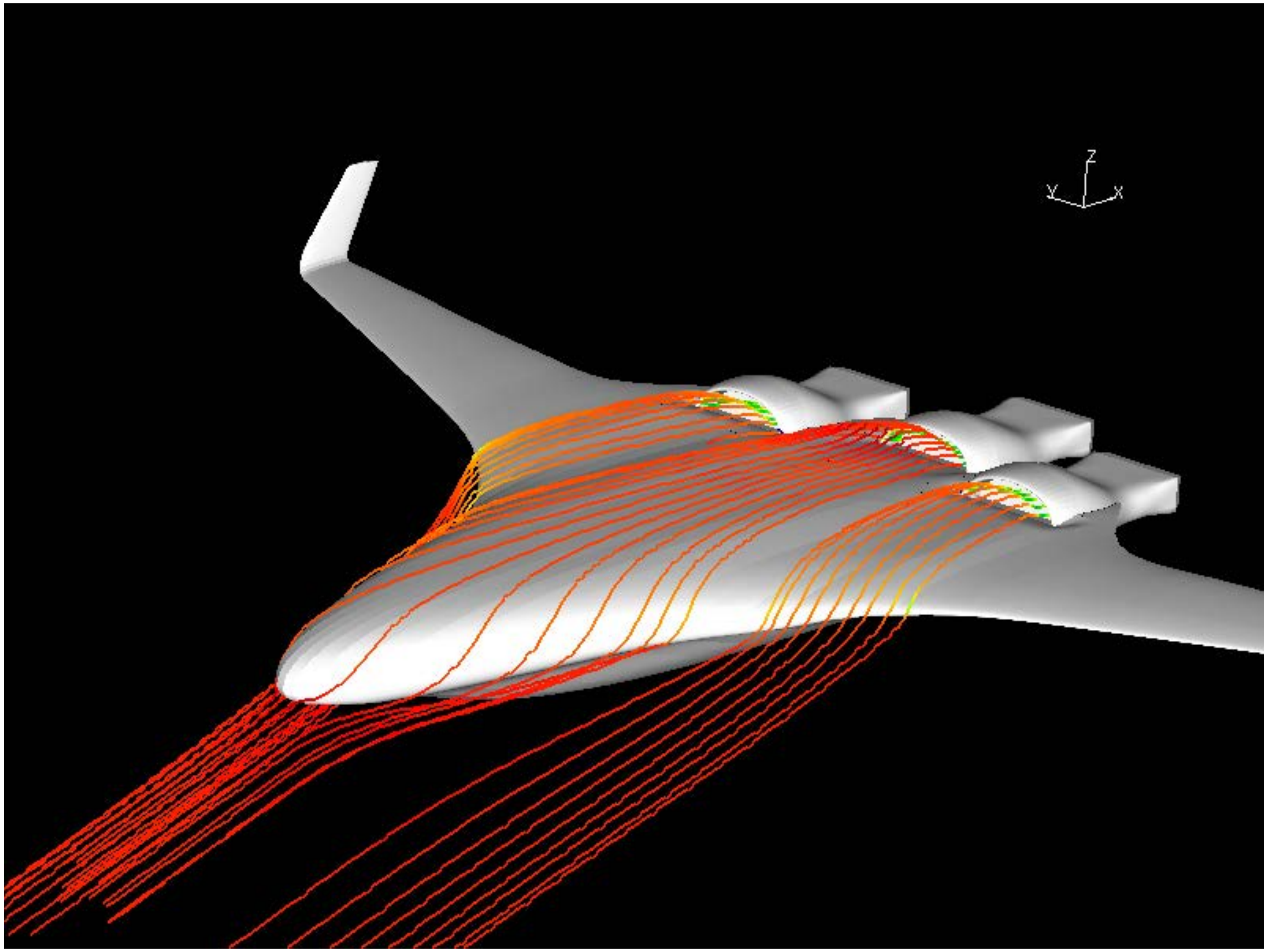
DESIGN IMPLICATIONS – FAN NOISE SHIELDING



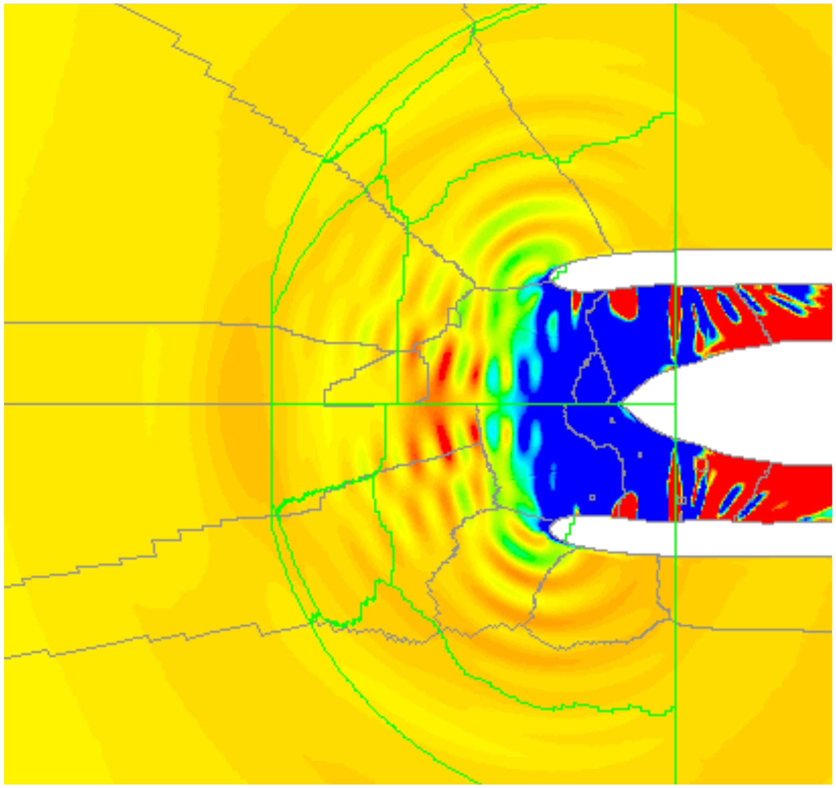
- HWB airframe provides 20 to 25 dB shielding, 7 dB more than conventional airframe (with engines above wing)

- Vertical tails increase shielding up to 5 dB along sideline

FAN NOISE IN SERPENTINE INLET WITH BOUNDARY LAYER INGESTION



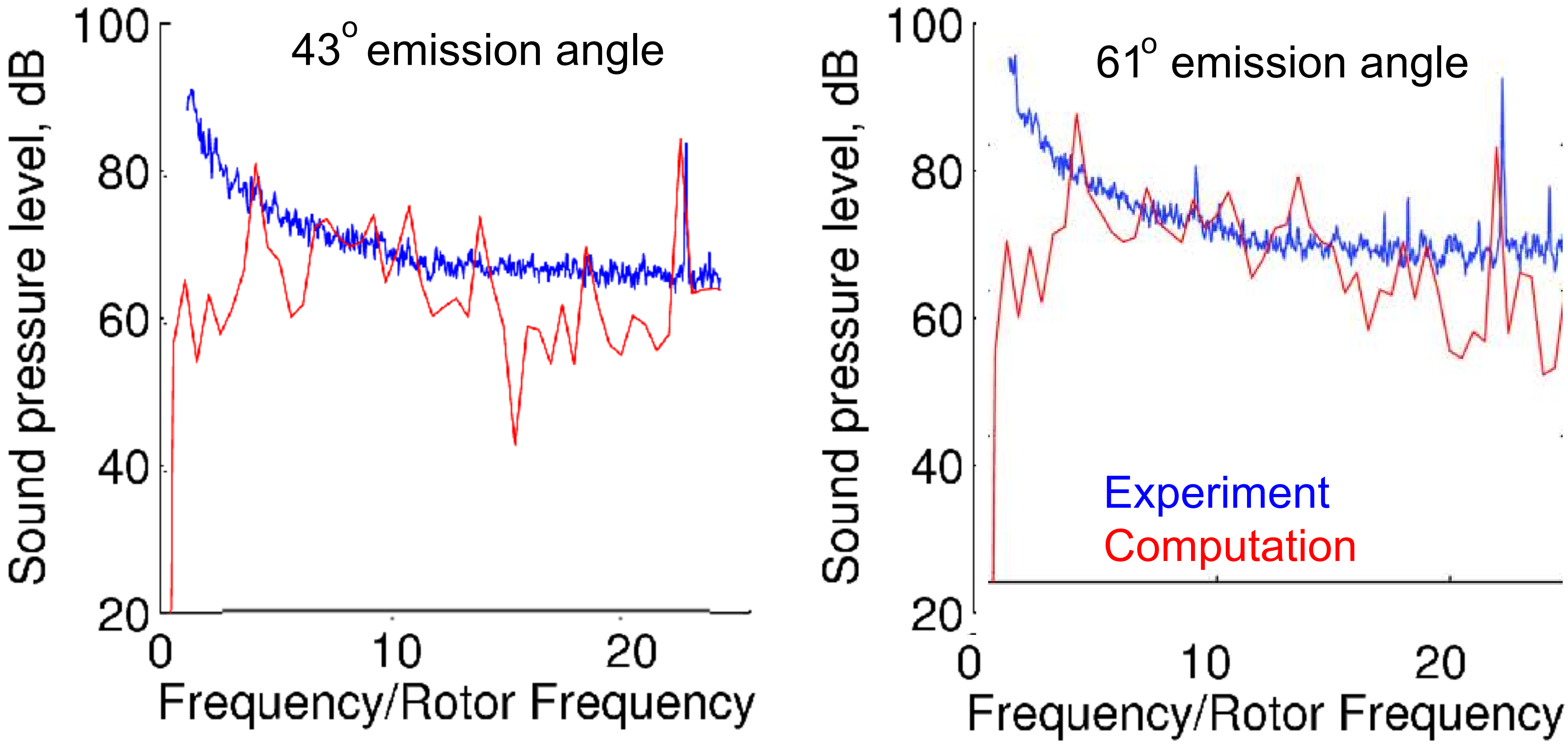
CONVENTIONAL INLET-FAN SYSTEM: A HARD ACOUSTIC MODELING PROBLEM



NASA / GE R4 Fan
Acoustic Tests

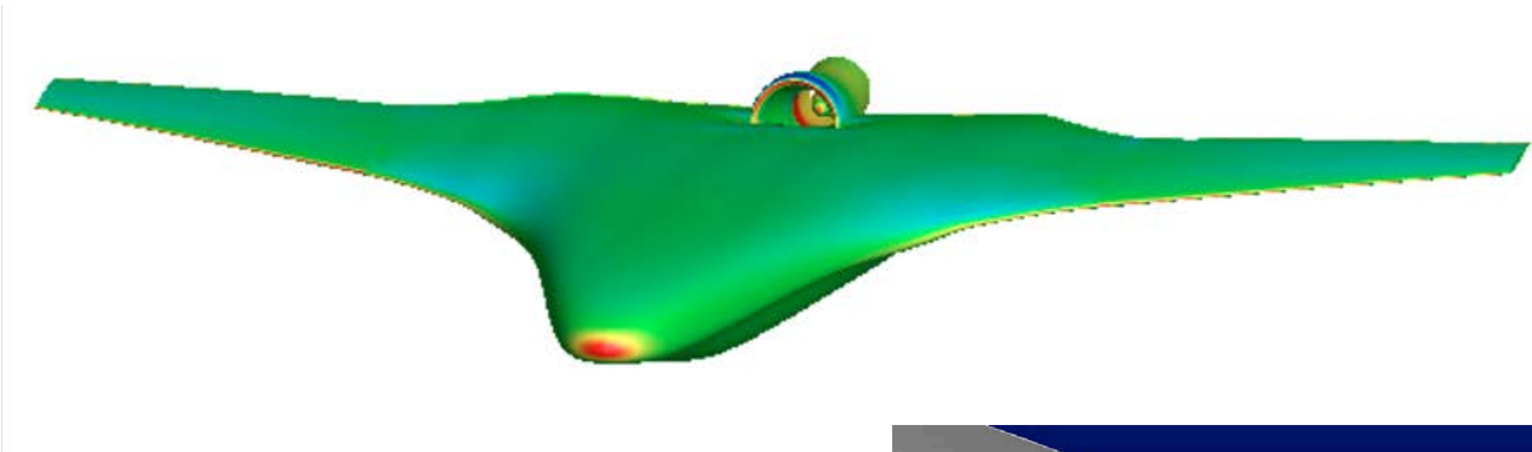
Body Force "Buzz-Saw"
Noise Computation

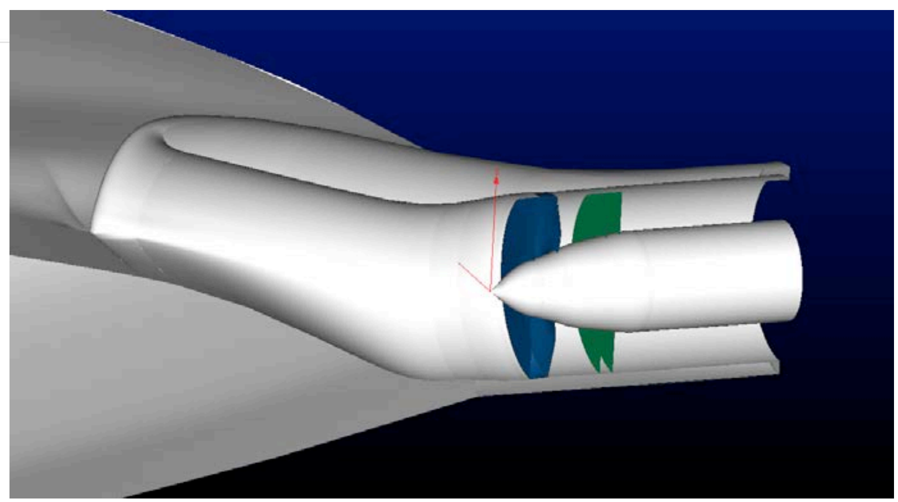
CONVENTIONAL INLET:
FAR-FIELD NOISE COMPARISON



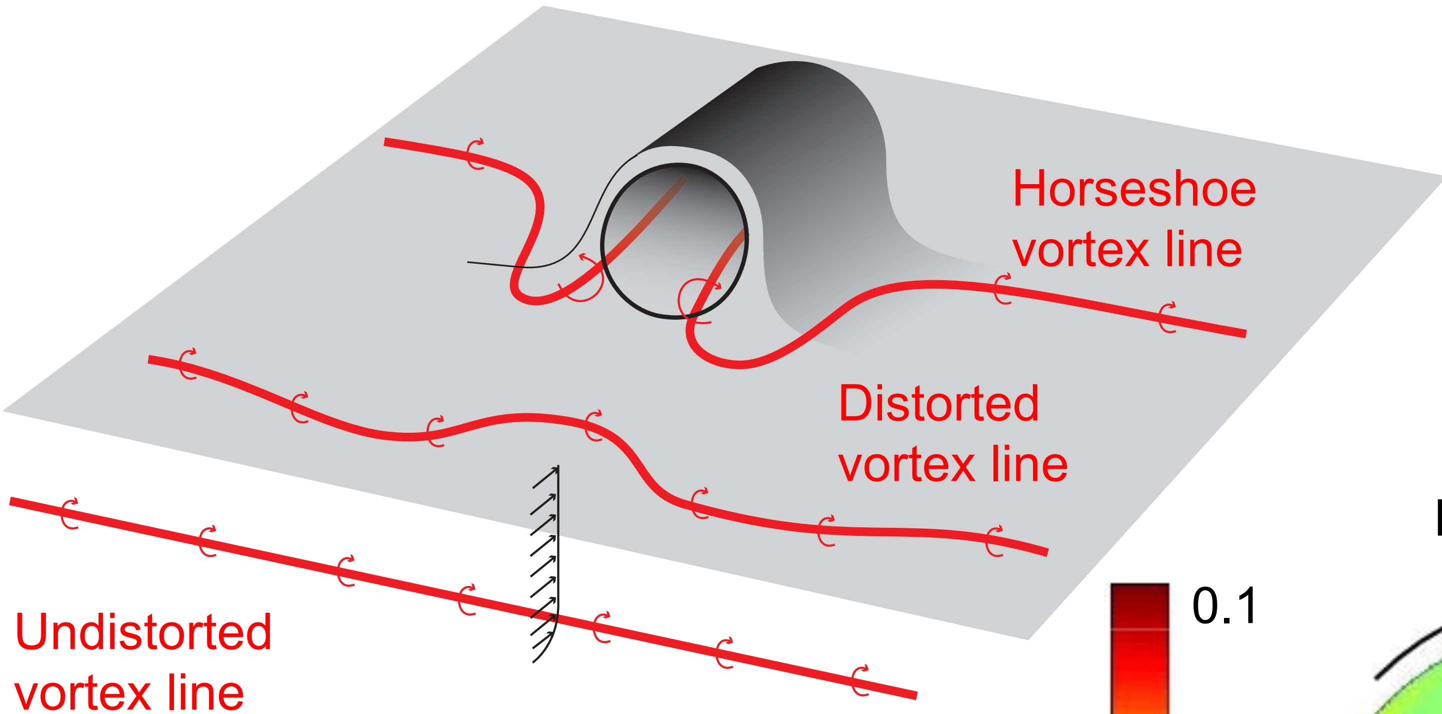
- Computed ratio of multiple-pure-tones to blade-passing tone amplitude in good agreement with experiment

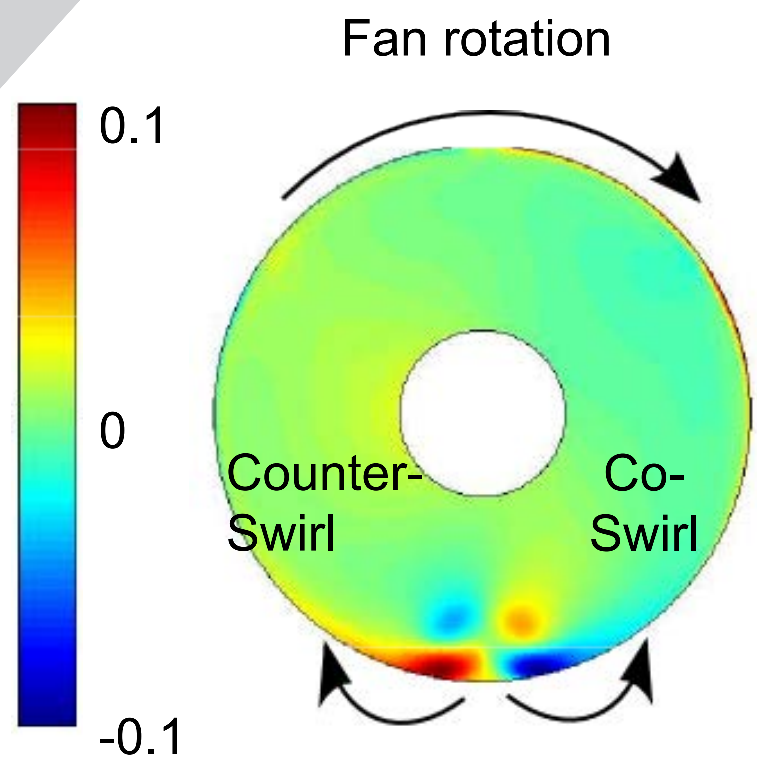
WHAT IS IMPACT OF BOUNDARY LAYER INGESTION ON FAN SHOCK NOISE IN S-INLET?





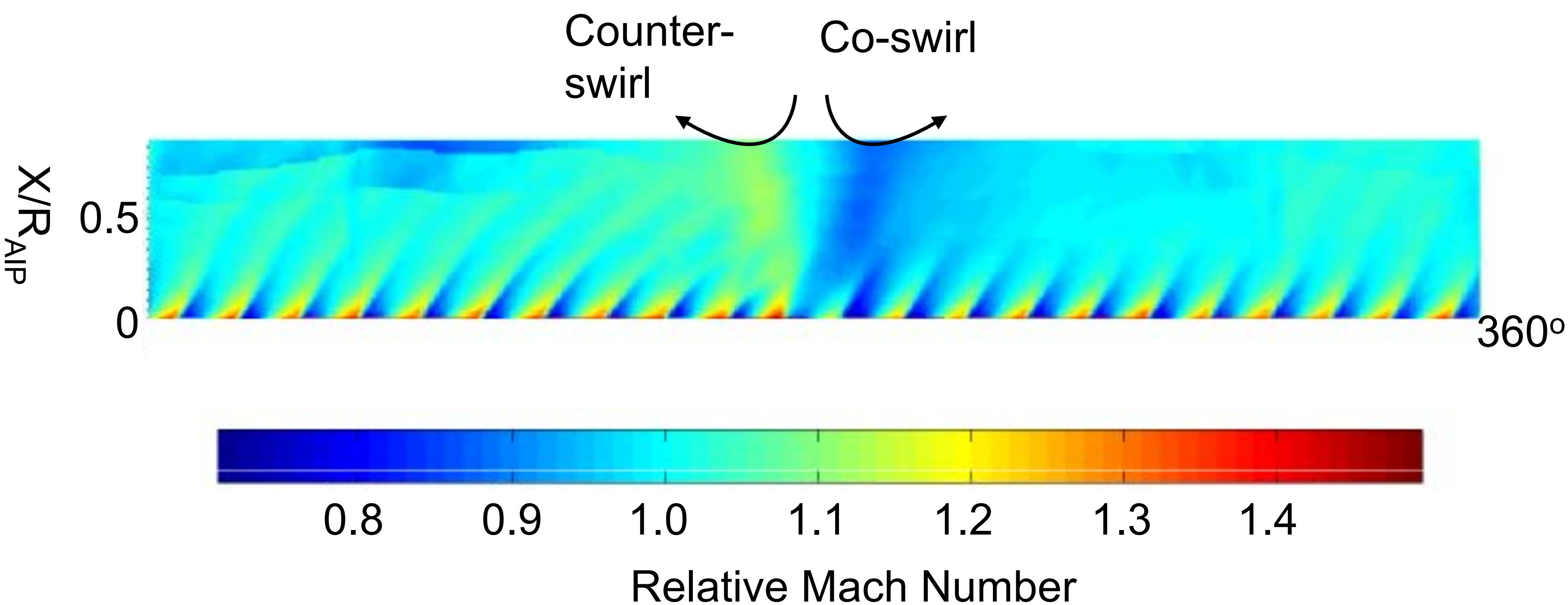
BOUNDARY LAYER INGESTION: CO- AND COUNTER SWIRLING VORTICES





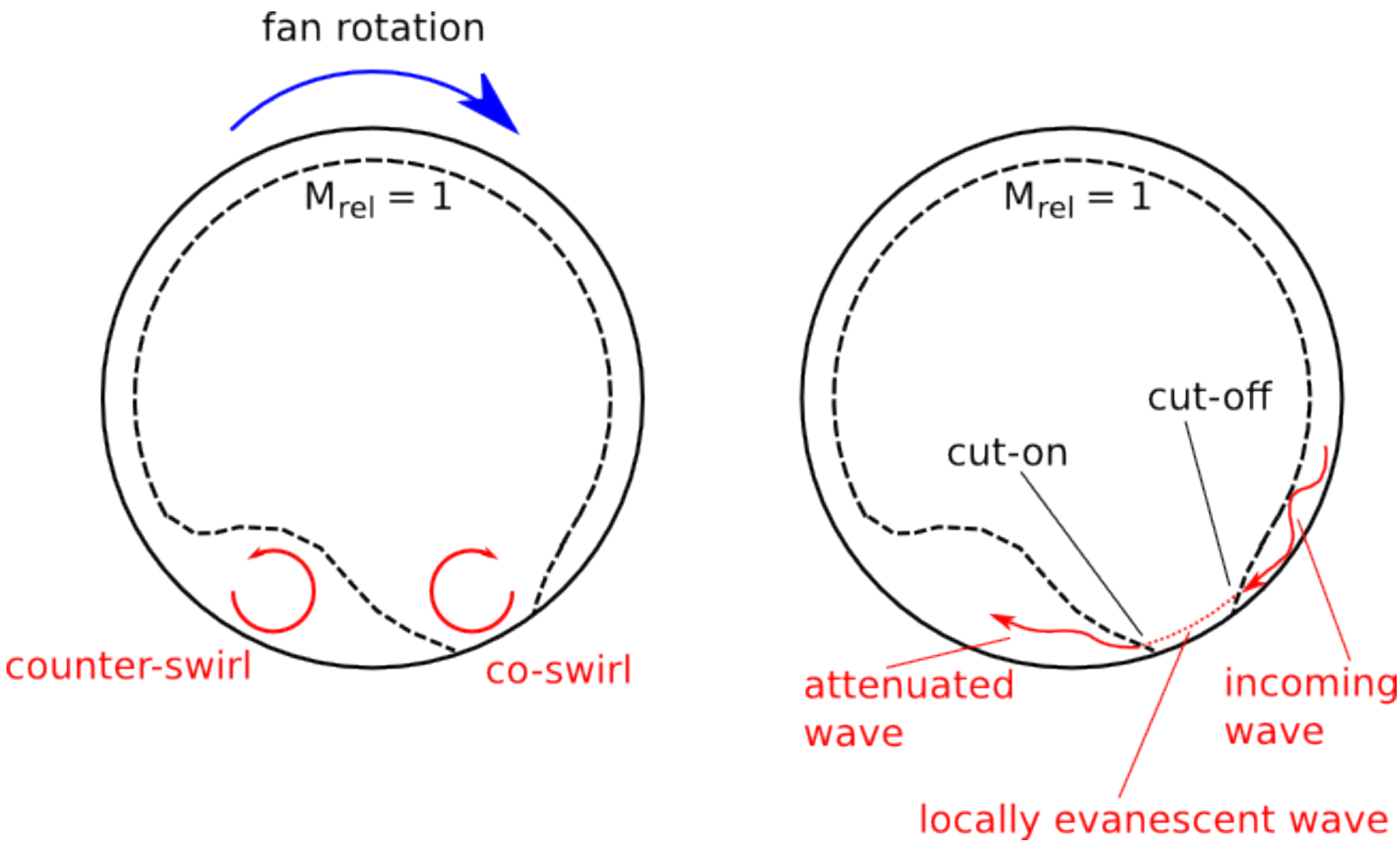
Tangential Mach no. at Fan Leading Edge

COUNTER-SWIRLING VORTEX ENHANCES FAN SOURCE NOISE GENERATION

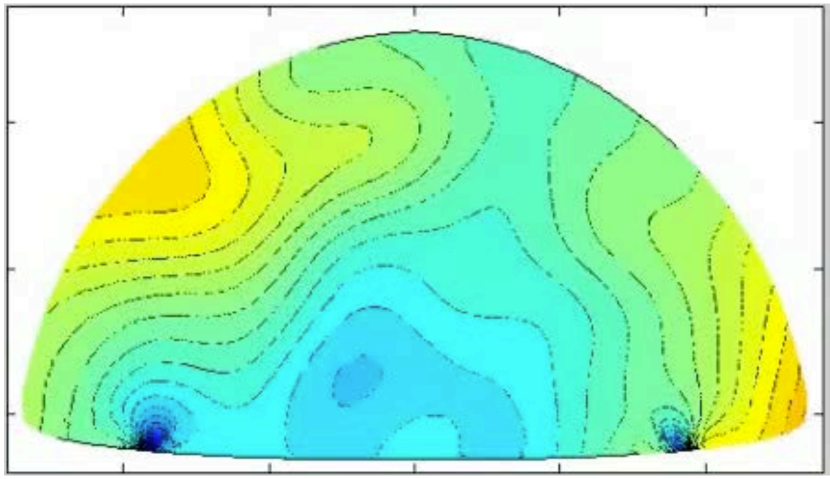


- Sound power at fan increased by 45 dB due to streamwise vorticity increasing incidence angles and shock strengths

CO-SWIRLING VORTEX ATTENUATES WAVE PROPAGATION

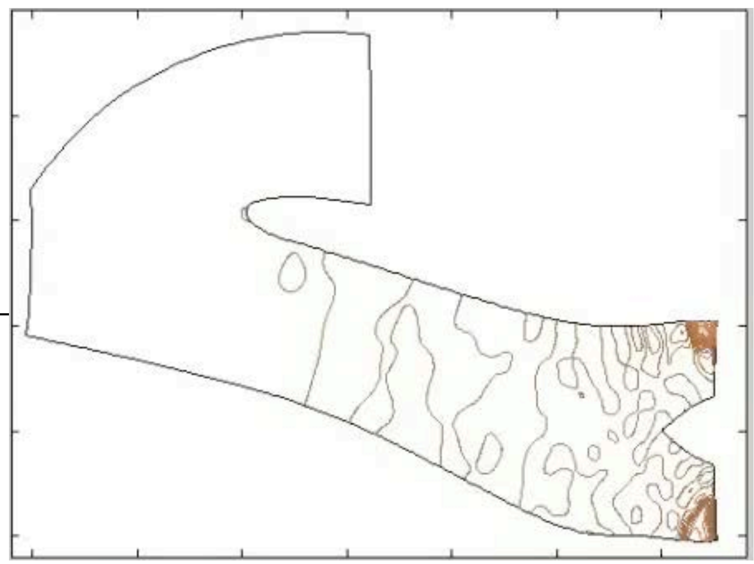


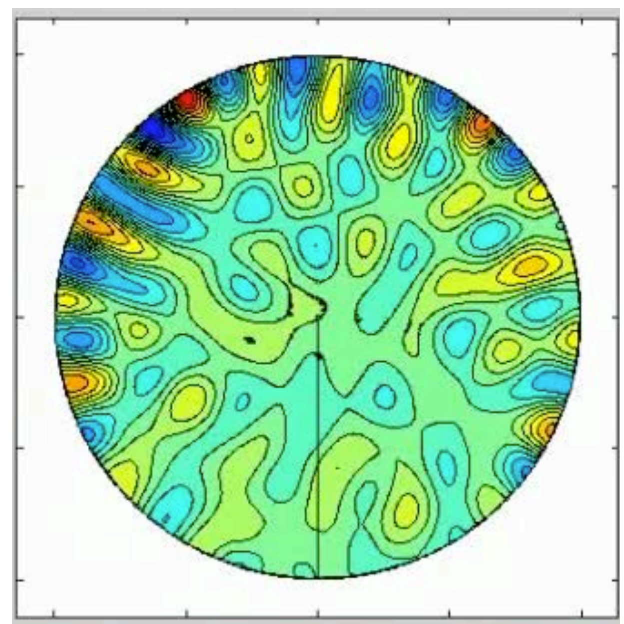
BLADE PASSING TONES AND MPTS CUT-OFF AT INLET PLANE



Inlet Plane

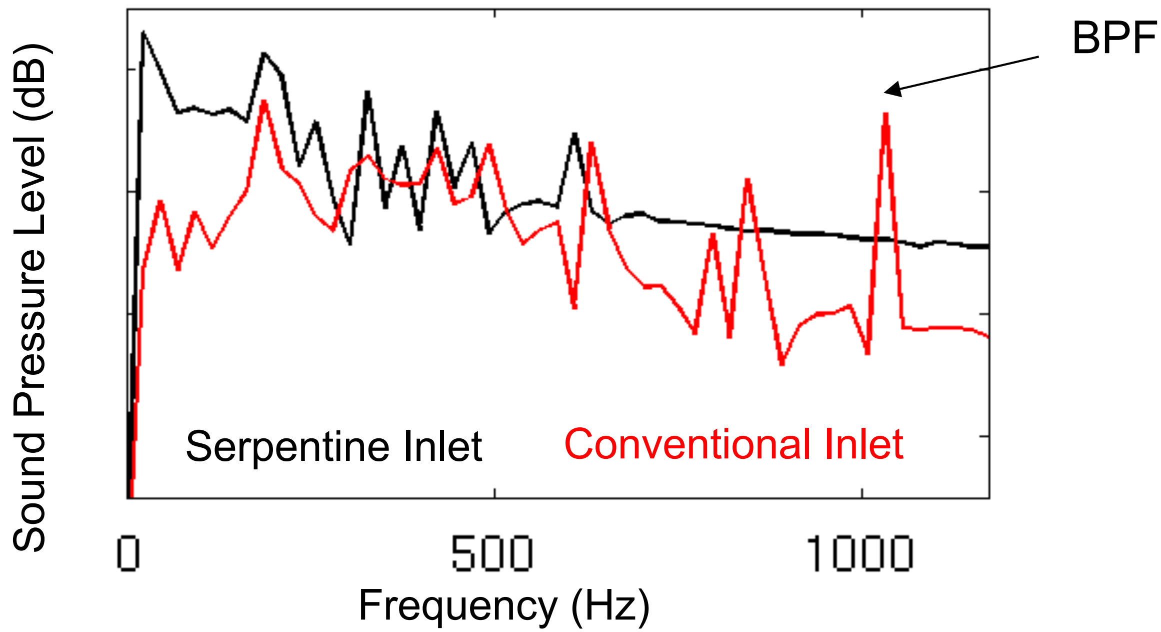
Fan Face





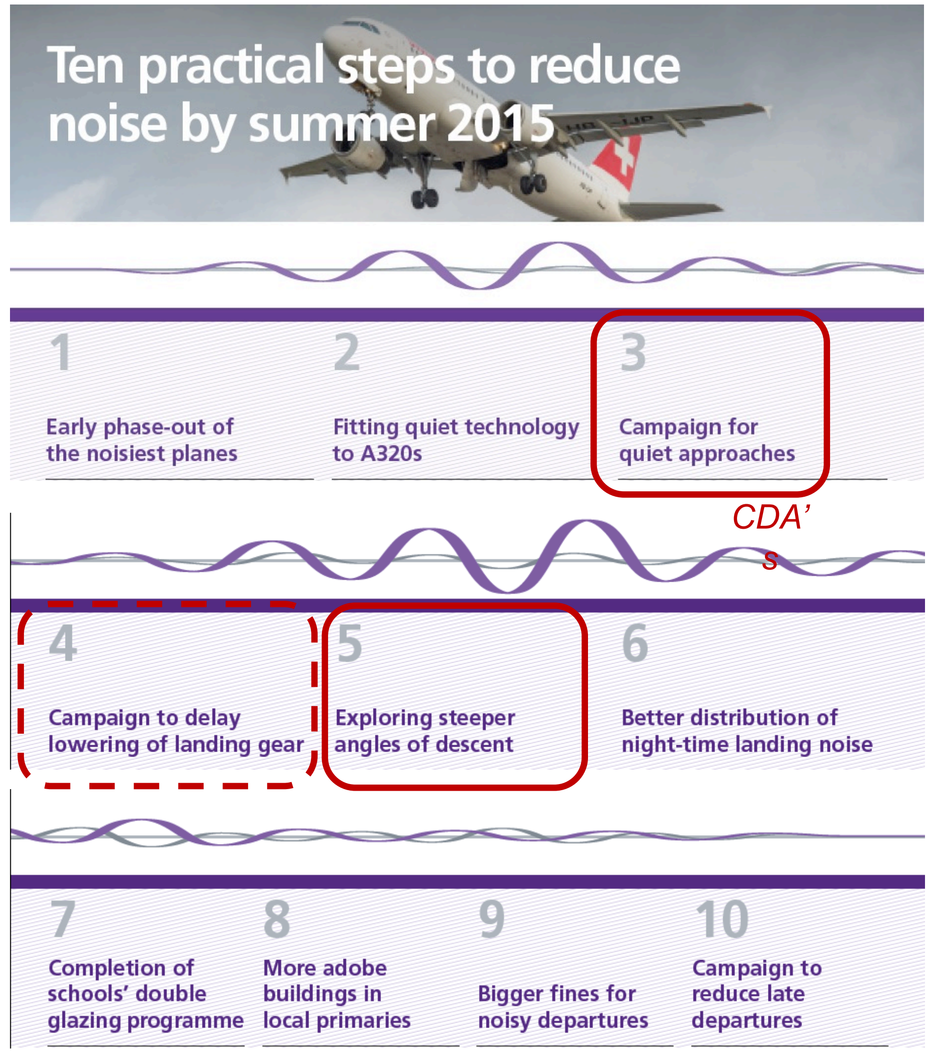
Contours of unsteady pressure

NEW LEARNINGS – BLI EFFECT ON FAN NOISE



- Streamwise vortictiy governs sound power increase at fan (counter-swirl) and enhances sound attenuation in duct (co-swirl)
- Boundary layer ingestion in serpentine inlet increases average OASPL increased by 7 dB (3 dBA)

NOISE REDUCTION BLUEPRINT
HEATHROW AIRPORT (LHR)



LONDON CITY (LCY)
STEEP APPROACH (5.5 DEG) EXAMPLES

BAE146

- ***Two-petal air-brake*** below tail rudder replaces thrust reverser
- Weight / complexity traded for competitive advantage of airport access

Modified A318

- High power to reduce go-around spool up time
- Full flaps & slats plus ***speedbrakes*** → Dirty Approach
- Increased approach speed (Vref) +8 kts from reduced lift

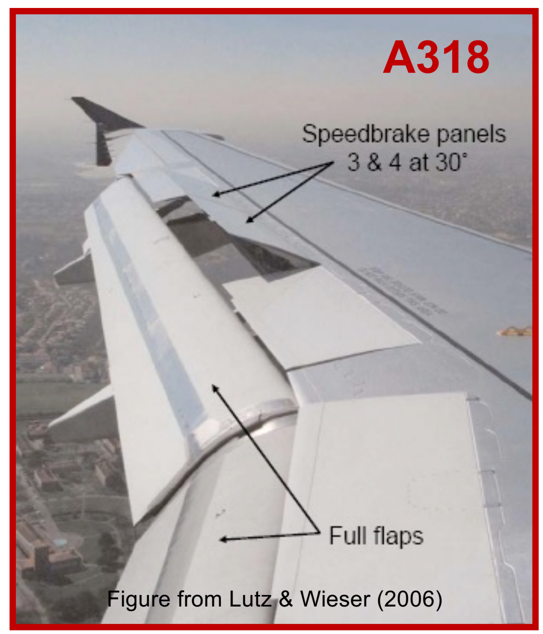
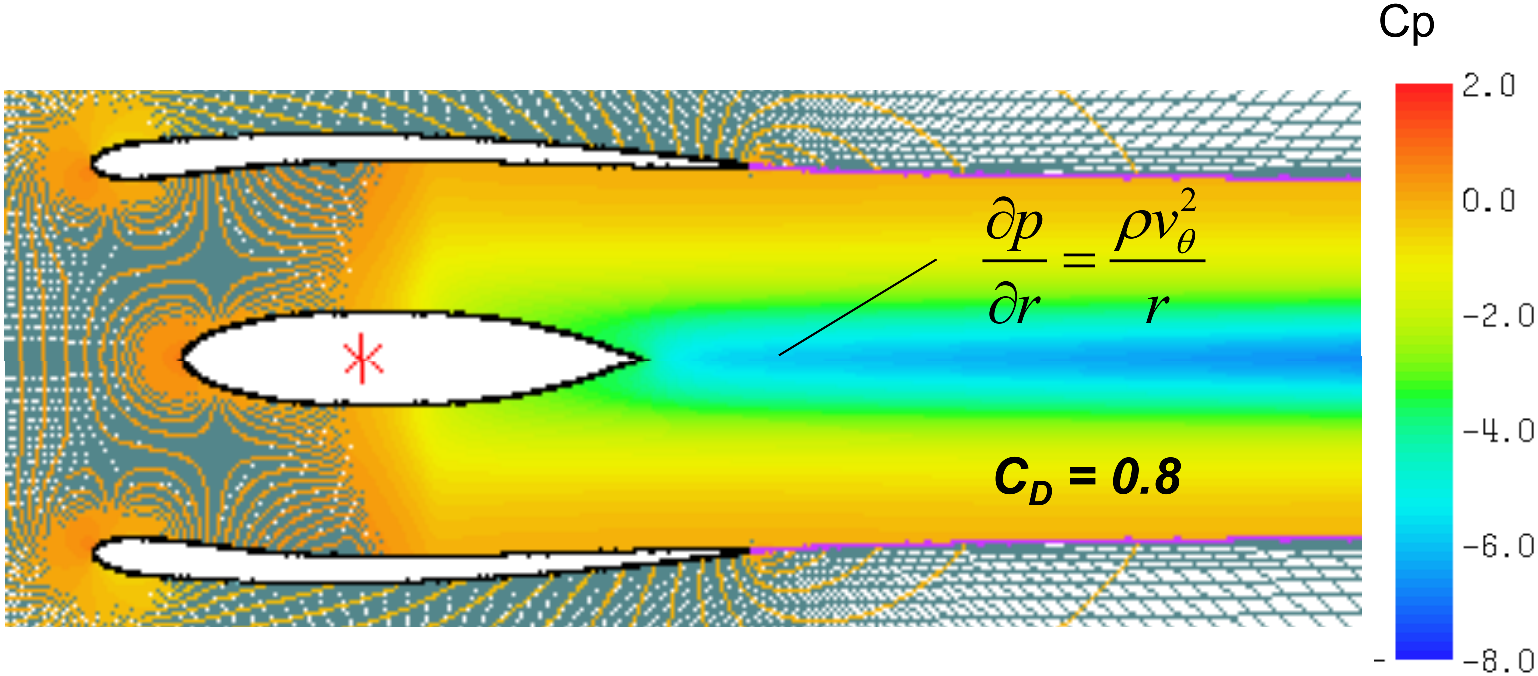


Figure from Lutz & Wieser (2006)

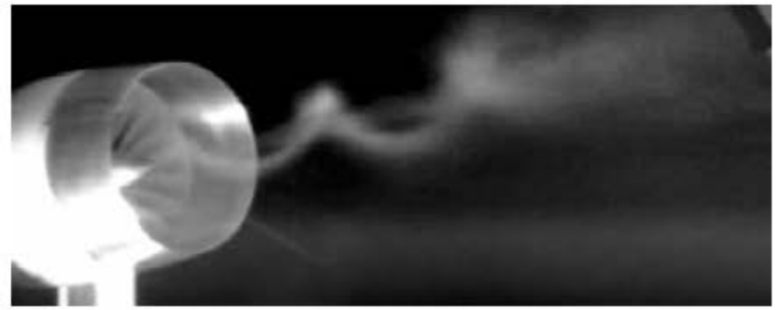
AN INNOVATIVE IDEA:
QUIET ENGINE AIR BRAKES



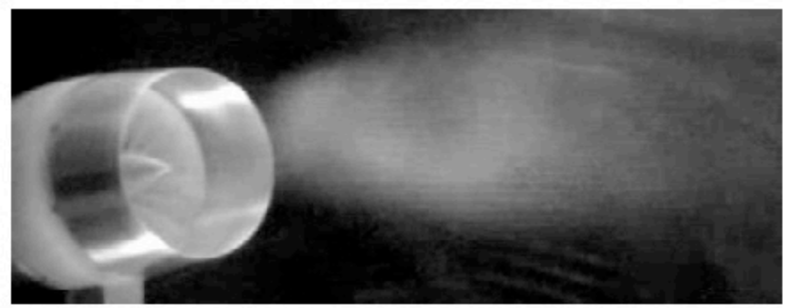
- Swirling exhaust flow yields steady (quiet) streamwise vortex supported by radial pressure gradient responsible for pressure drag

AERODYNAMIC TESTING OF "SWIRL TUBE" AT MIT

Stable Swirling Flow (47°)

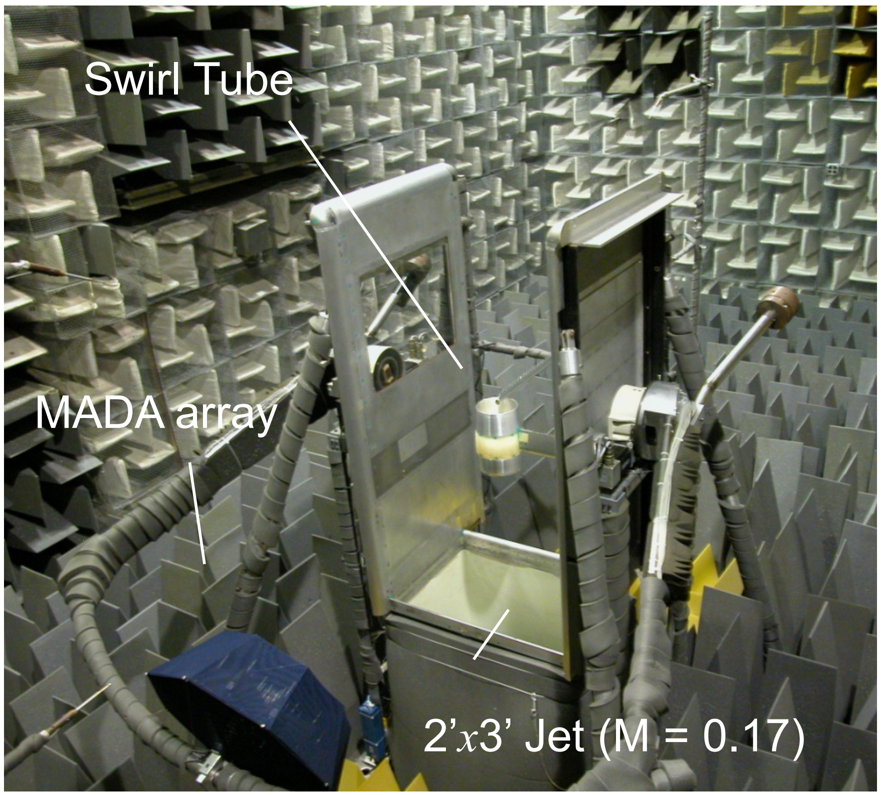


Vortex Breakdown (57°)

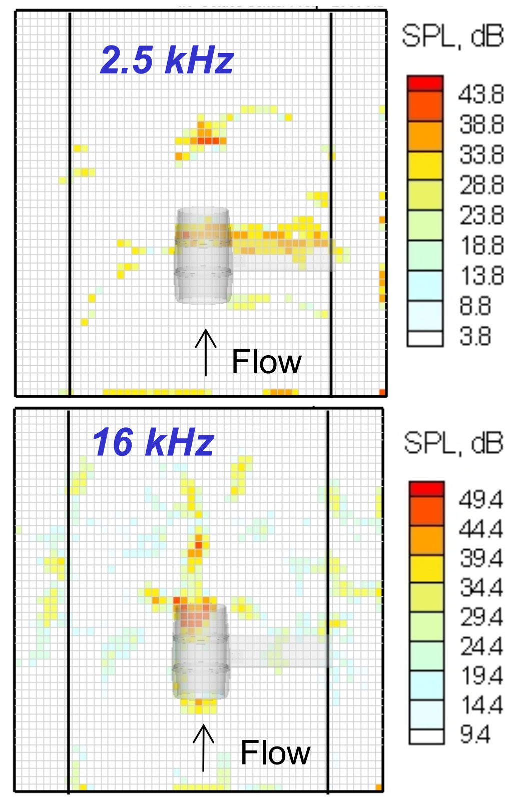


- Vortex breakdown at high swirl angles as expected
- Drag measurements in good agreement with computations

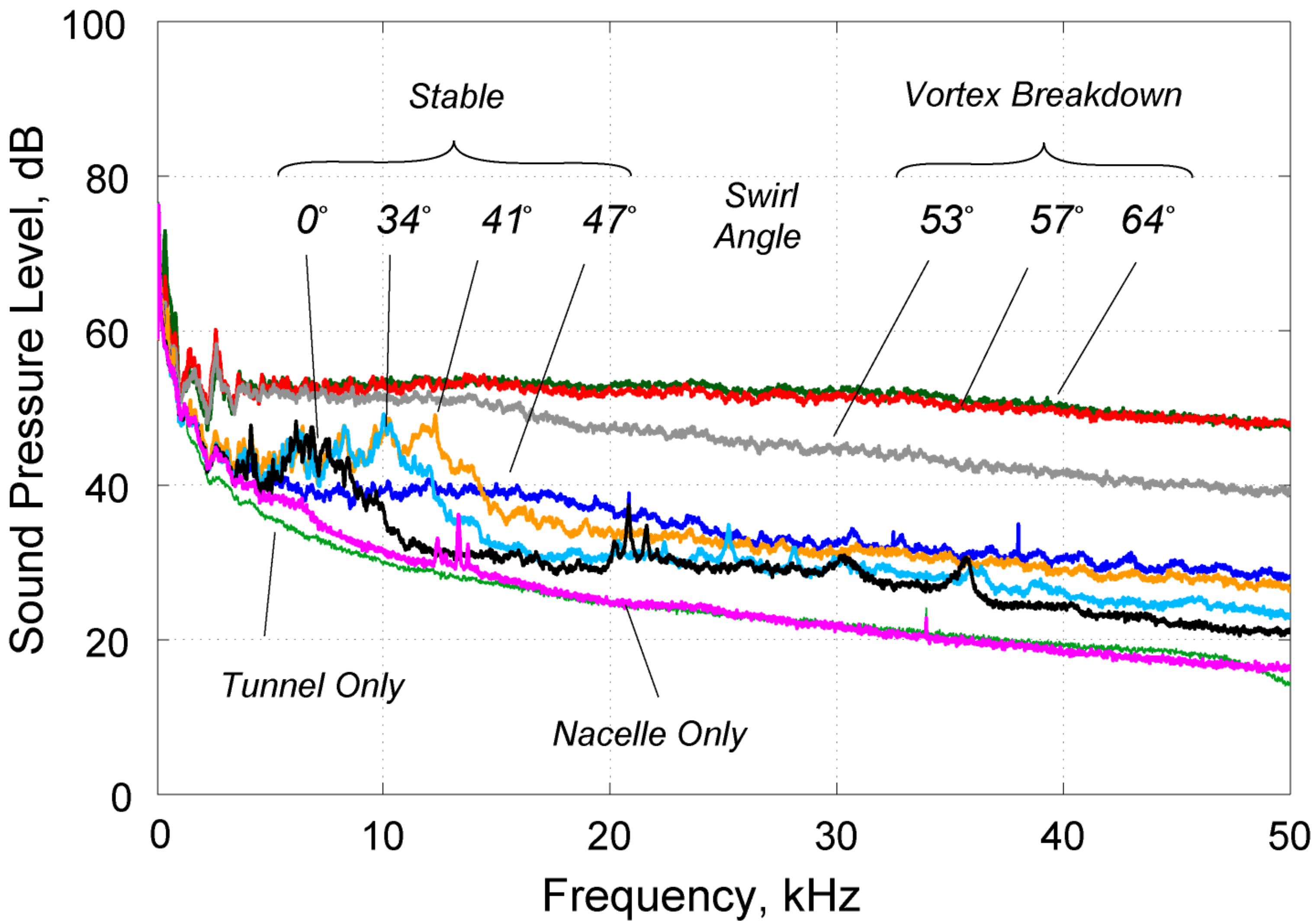
ACOUSTIC TESTING IN NASA LANGLEY QUIET FLOW FACILTY (QFF)



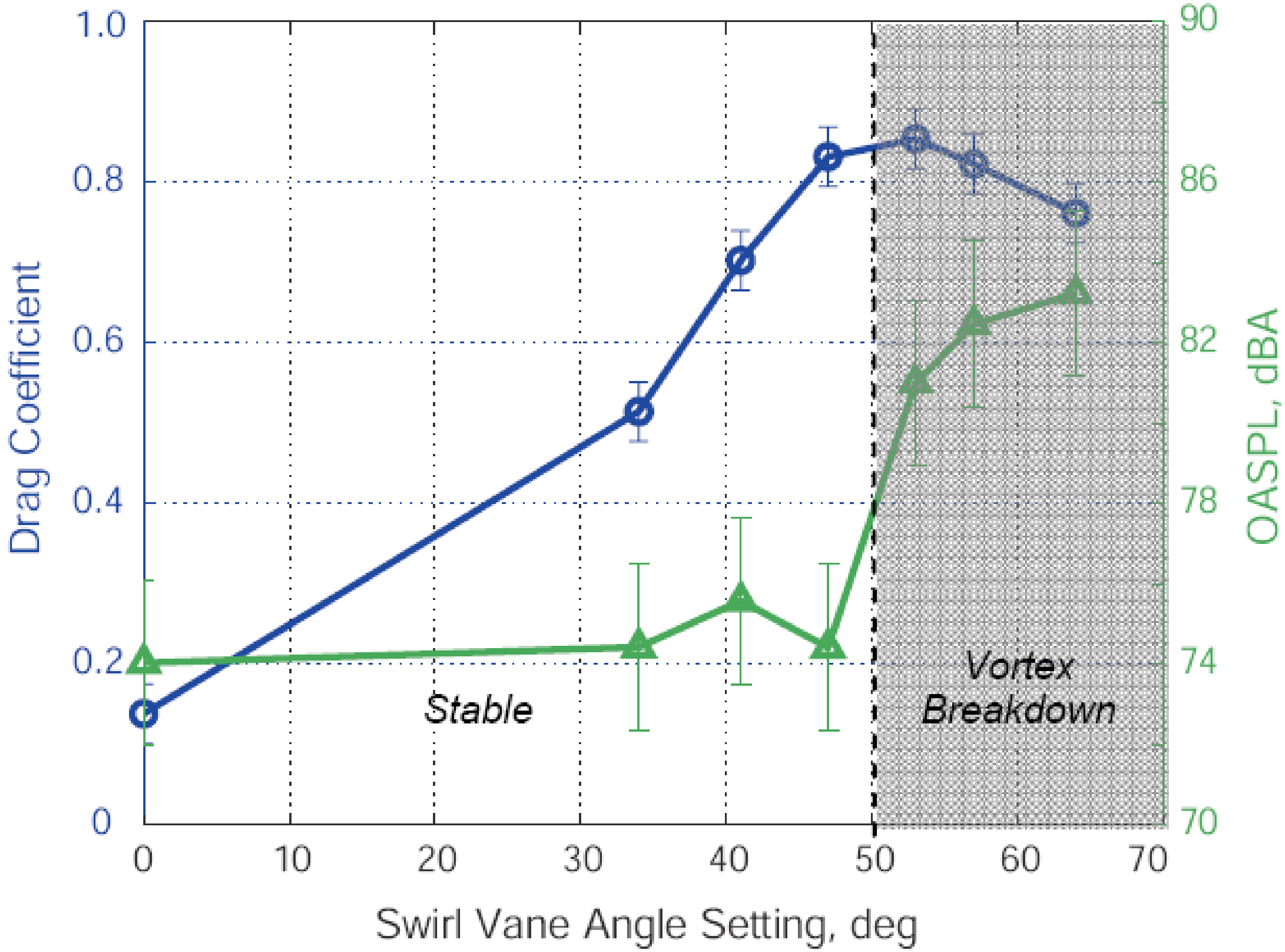
Swirl Angle = 47°



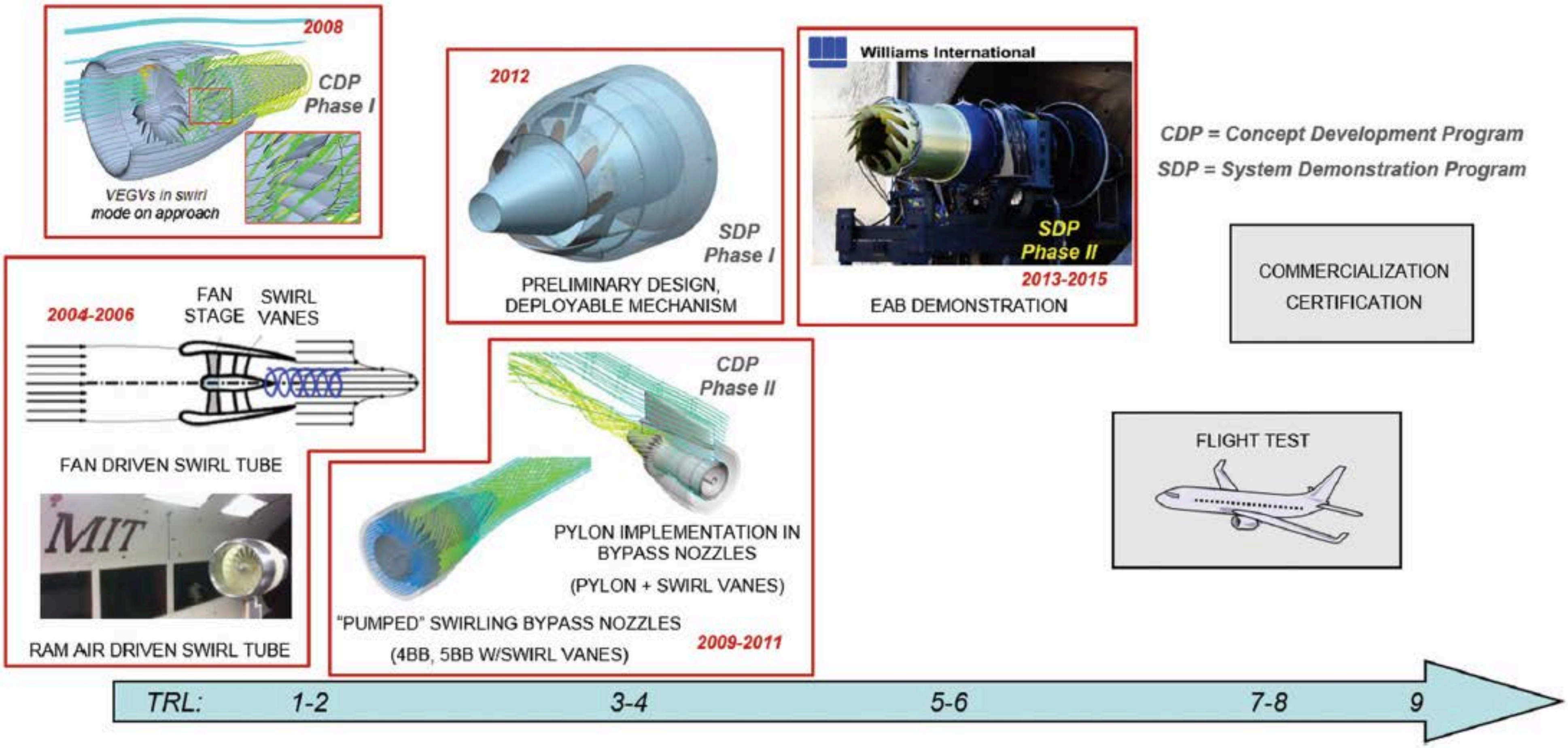
DISTINCT ACOUSTIC SIGNATURE BETWEEN STABLE SWIRLING FLOW & VORTEX BREAKDOWN



NEW DRAG-NOISE RELATIONSHIP: HIGH DRAG AT LOW NOISE



TECHNOLOGY ROADMAP OF ENGINE AIR BRAKE IN CONTEXT OF NASA TRL DEFINITIONS



FULL-SCALE EAB DEMONSTRATION ON WILLIAMS INTERNATIONAL FJ44-4 ENGINE

(Image courtesy Williams International)

FJ44-4 engine specs:

- 3600-pound class
- medium-bypass
- 2-spool
- mixed exhaust

Aircraft powered:

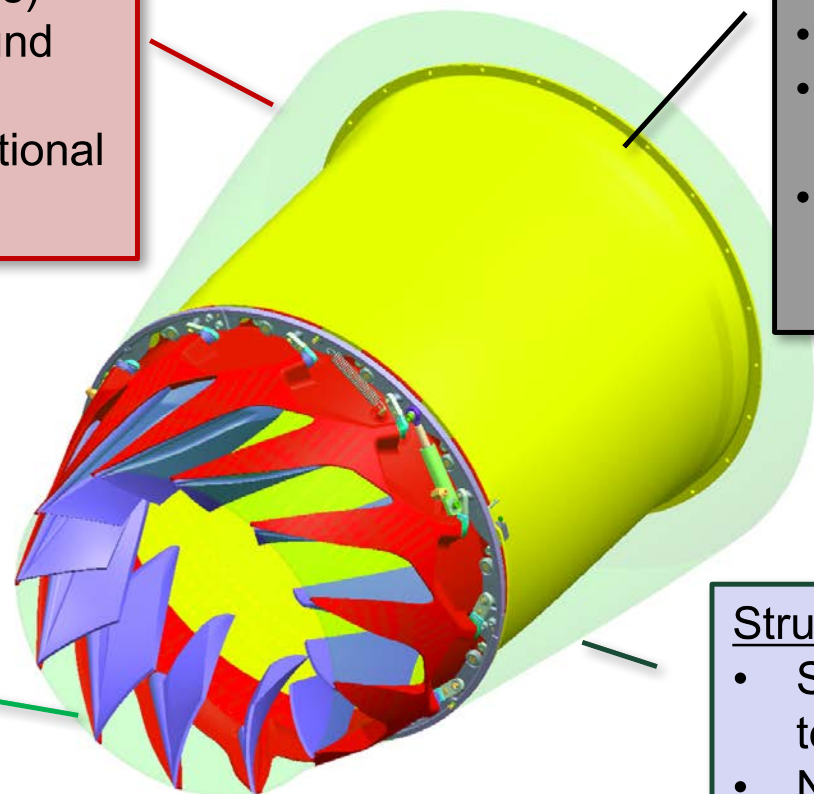
- Cessna CJ4
- Hawker 400XPR
- Pilatus PC-24

(Image courtesy Cessna)

DESIGN REQUIREMENTS SPAN MULTIPLE DISCIPLINES

Mechanical Systems
- Deployment time (< 5s)
- Stow time for go-around (<0.5 s)
- Packagable within notional flight engine cowl

Aero-performance
- Thrust reduction > 15%
- Operability/flow margin
- Stowed, no change
- Fully deployed, excess A8
- Partially deployed, adequate surge margin



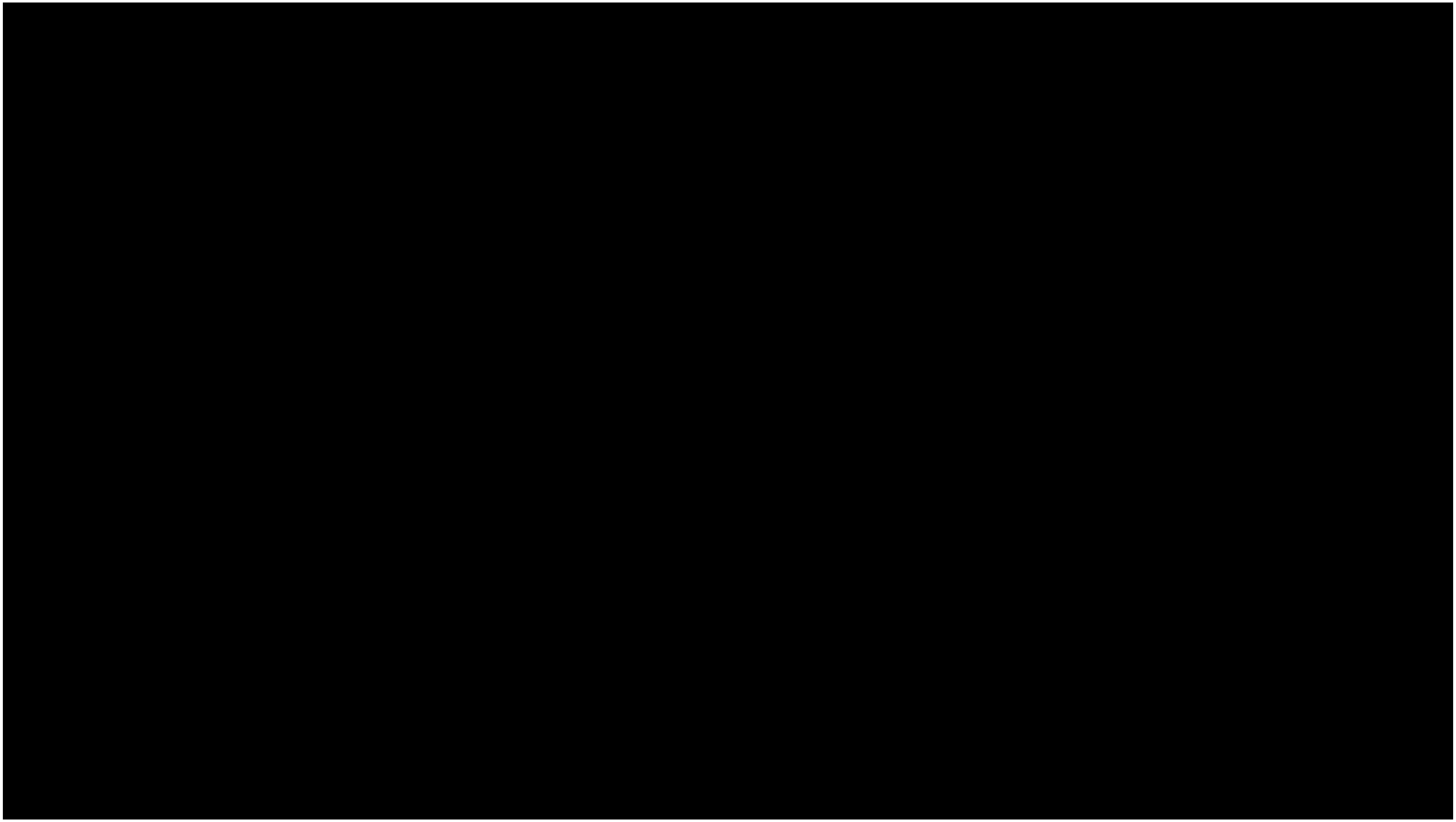
Acoustics
- Minimize noise to enable steep approach potential
- <1-1.5 EPNdB

Structures
- Strength &HCF at temperature
- Natural frequency & stiffness
- Material selection for thermal environment

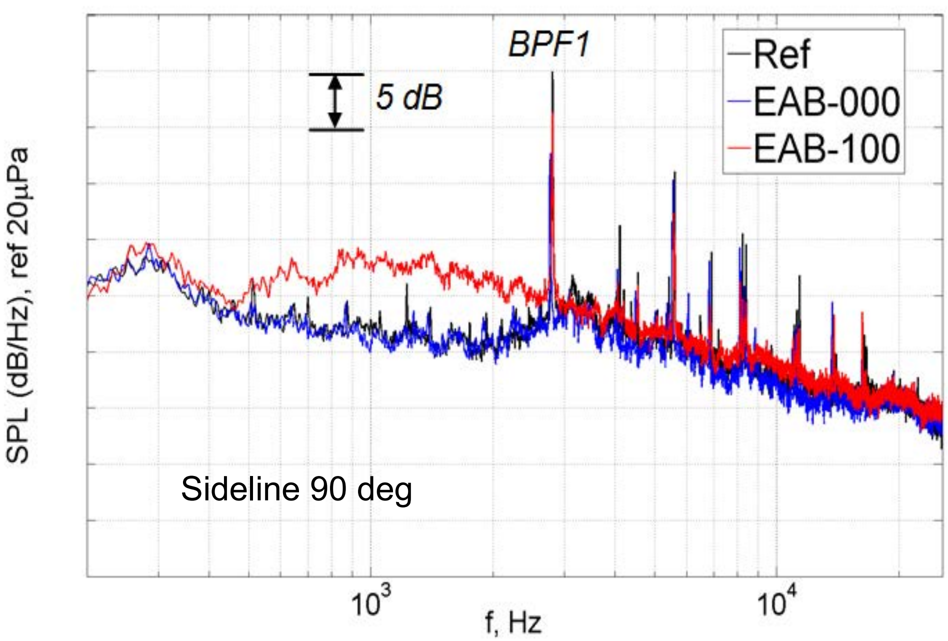
DEPLOYABLE SWIRL VANE DEMONSTRATION – LAB TEST

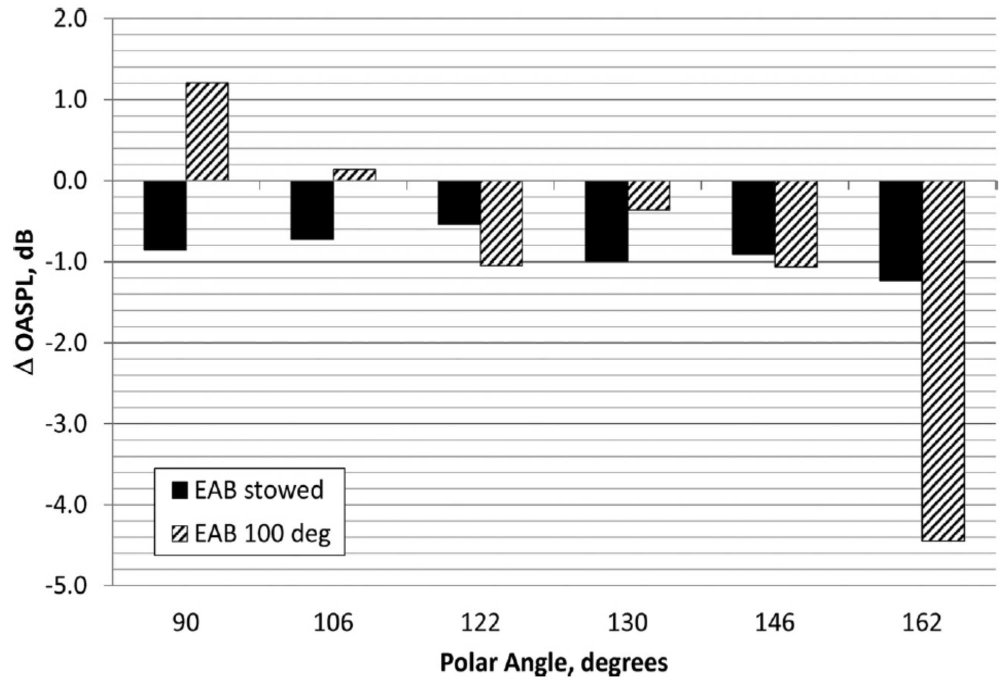
DEPLOYABLE SWIRL VANE ENGINE DEMONSTRATION – POWER OFF

DEPLOYABLE SWIRL VANE ENGINE DEMONSTRATION – STATIC POWER ON



STATIC ENGINE FAR-FIELD ACOUSTICS: OVERALL NOISE REDUCTION





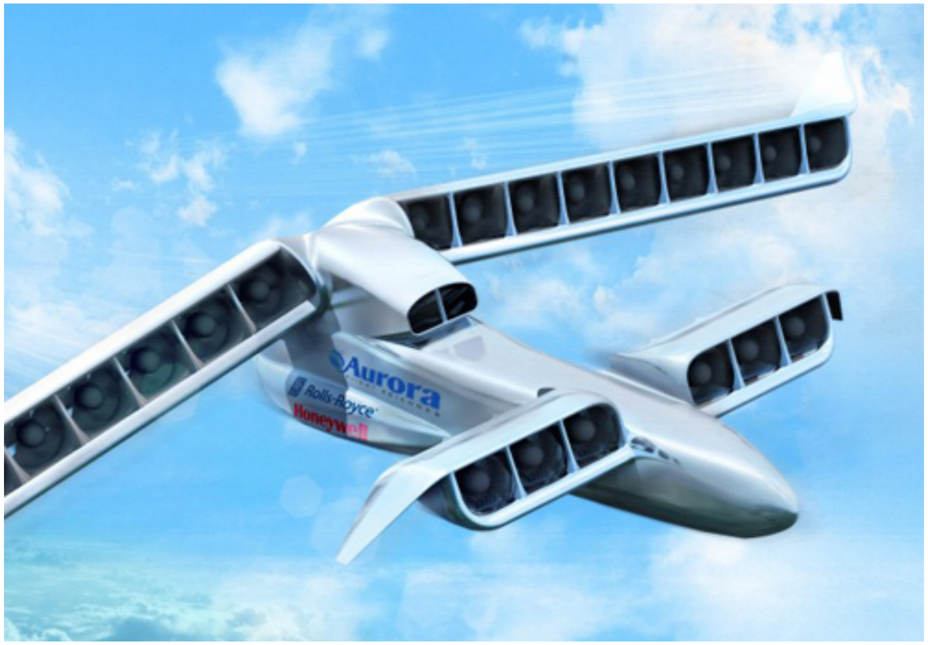
ANOPP BASED AIRCRAFT LEVEL IMPLICATIONS: ~3 EPNdB NOISE REDUCTION

Jet Noise Impact	Gross Thrust Reduction	Glide Slope Change	ΔEPNL	ΔPNLT Max
	%	degrees	dB	dB
Measured Static ΔSPL, all angles, NO Flight Effect	15	+1.3	-3.1	-4.5
Measured Static ΔSPL, all angles, + 2.5 dB Flight Effect Penalty	15	+1.3	-2.8	-4.3

OUTLOOK: AN ELECTRIFIED FUTURE OF AVIATION

STARC-ABL (NASA)

Lightning Strike (Aurora FS)



- Boundary layer ingestion and distributed propulsion enabled by electrification and vice versa
- Noise will remain a major challenge – NOT as quiet as a Toyota Prius!

WHAT WILL IT TAKE?

- New airframe architectures – improved noise shielding
- Integrated propulsion systems – BLI and DP to enable high BPR
- Low noise aircraft operations – optimized T/O thrust management
- Innovations in quiet drag for "clean" airframes
- Acoustic treatment of lifting surfaces edges
- Fairings and elimination of parasitic noise sources
- Solutions to fan broadband & combustion noise grand challenges
- Dramatically shorter inlets – new and innovative acoustic liners
- Technology demonstrations and X-planes

CLOSING REMARKS

- No silver bullet – ALL noise sources must be addressed for dramatic noise reductions
- Advanced airframe and propulsion system concepts more strongly integrated and coupled → hard acoustic problems
- Well-defined modeling goals and careful treatment of unsteady flows help tackle complex acoustic problems
- Technological problems cut across disciplines – call for teaming / collaboration and new directions in aero-acoustics
- Technology roadmaps exist – the time to act is now