

NASA Glenn Research Center

Fan Noise Research: Basic Theory and an Application

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AIAA Student Chapter
Cleveland State University

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INTRODUCTION



About me:

- I am an experimental researcher with emphasis on testing and evaluating noise reduction technologies.
- I conduct research to develop aircraft engine noise reduction technologies from concept to full-scale prototype to achieve NASA aircraft noise reduction goals.
- I assemble and lead multi-disciplinary NASA/Academic/Industry teams to develop fan noise diagnostic techniques, fan noise reduction concepts, and advance the state of the art in aero-acoustic measurement technologies.



EDUCATION:

- UNIVERSITY of CINCINNATI, B.S., 1985
  Major: Aerospace Engineering
- UNIVERSITY of TENNESSEE SPACE INSTITUTE, M.S., 1989
  Major: Aerospace Engineering, Minor: Mathematics
- NORTH CAROLINA STATE UNIVERSITY, Ph.D., 1993
  Major: Aerospace Engineering, Minor: Mathematics

EXPERIENCE:

- DAVID TAYLOR NAVAL SHIP RESEARCH & DEVELOPMENT CENTER, MD
  Cooperative Education Employee, 1982 to 1984.
- MCDONNELL DOUGLAS AIRCRAFT COMPANY, CA
  Assistant Engineer, Stability & Control Group, 1985 to 1986.
- ARNOLD ENGINEERING DEVELPOMENT CENTER, TN
  Project Engineer III, Engine/Inlet Section, 1986 to 1989
- NAVAL SURFACE WARFARE CENTER, MD
  ONR Research Fellow, Acoustics Branch, 1993 to 1994
- NASA Glenn Research Center, OH
  Research Engineer, Acoustics Branch, 1995 to present

Acoustics Branch

Fundamental and Applied Research for Integrated Engine Noise Reduction

- Noise Diagnostics
- Noise Prediction
- Noise Reduction



Noise and Performance Evaluation of New Concepts in Relevant Environment



Testing of Exhaust Systems, Fan Systems, Open Rotors: SOA Facilities and Testing Techniques for Database Generation

Enabling Low Noise Advanced Aircraft Systems

Supersonics Concept



Subsonic Concept





Subsonic HWB Concept

Advanced Noise Diagnostics/Measurement



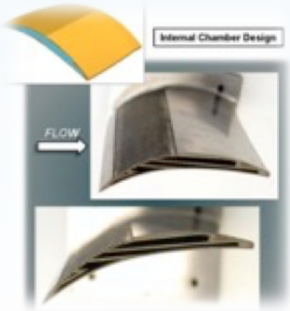
Phased Array

Advanced Noise Reduction Concepts

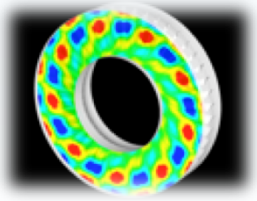


3D Nozzles with exit flow mixing concepts

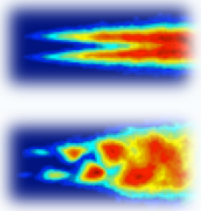
"Treated" Fan Exit Guide Vane



Computation and Code Development

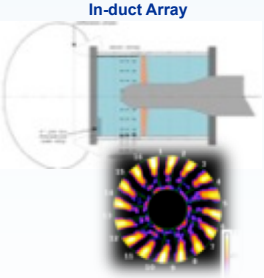


Predicted Stator Acoustic Mode

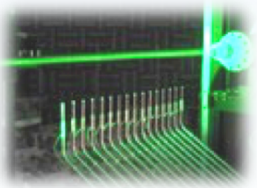


Plasma Actuator Jet Effects

In-duct Array



Near-field Array





Fan Noise Research: Basic Theory and Application

Part I: An OVERVIEW of FAN NOISE

Basic Acoustic Theory

General Aircraft Noise

Turbofan Engine Noise

Fan Noise

Reducing Fan Noise

Part II: APPLICATION

DART

General Measurements

Liner Application to Reduce Fan Noise



BASICS of ACOUSTICS

Basic Acoustics

- Fluctuating pressure that propagates at the speed of sound.
- In the time domain (measurements):

total pressure $\Longrightarrow P(t) = \bar{P} + P'(t)$

$\bar{P}$: mean pressure; $P'(t)$: fluctuating pressure

- The fluctuating pressure , *P'(t)*, can be separated into tonal and broadband (random components

$$P'(t) = P'_{tone}(t) + P'_{random}(t)$$

$$P'_{tone}(t) = P_{rms}(2\pi f * t + \emptyset)$$

$$P_{rms} = \sqrt{\bar{P}^2}$$

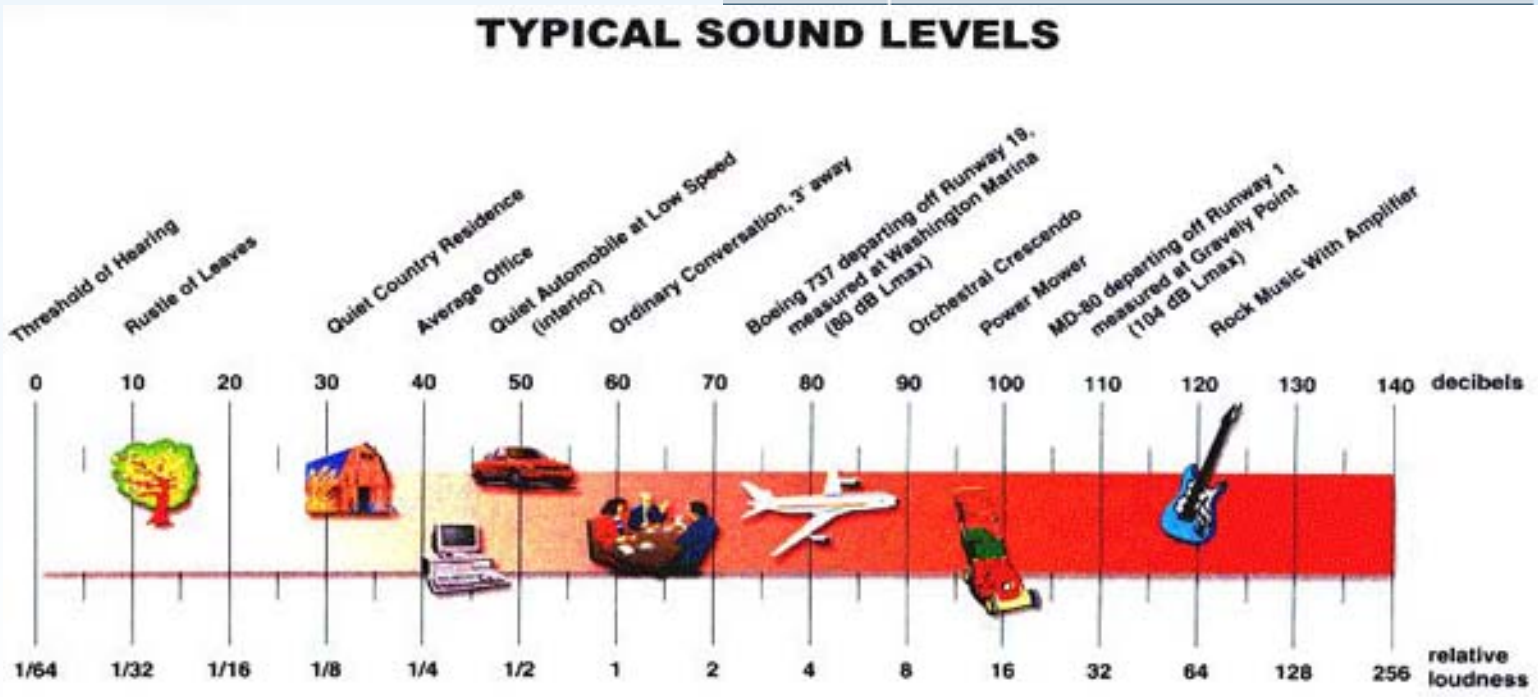
deciBels

$$P_{dB} = 10 * log_{10}\left(\frac{P}{P_{ref}}\right)^2$$

$$P_{dB} = 20 * log_{10}(\frac{P}{P_{ref}})$$

$$P_{ref} = 2.0x10^{-5}$$

Change in Perceived Loudness	
1 dB	Requires Close Attention to Notice
3 dB	Barely Perceptible
5 dB	Quite Noticeable
10 dB	Dramatic...Twice or Half as Loud
20 dB	Striking...Fourfold Change



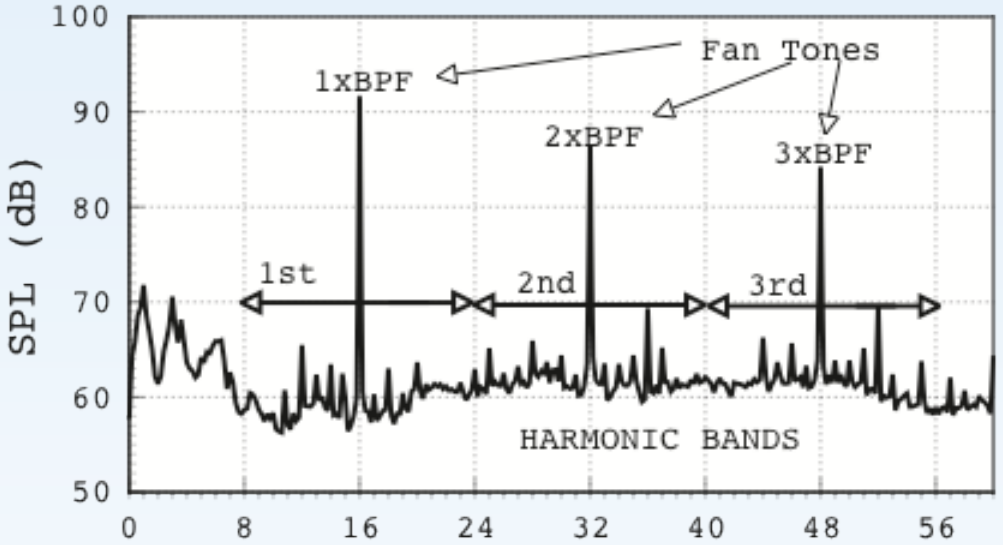
Dynamic Data Reduction

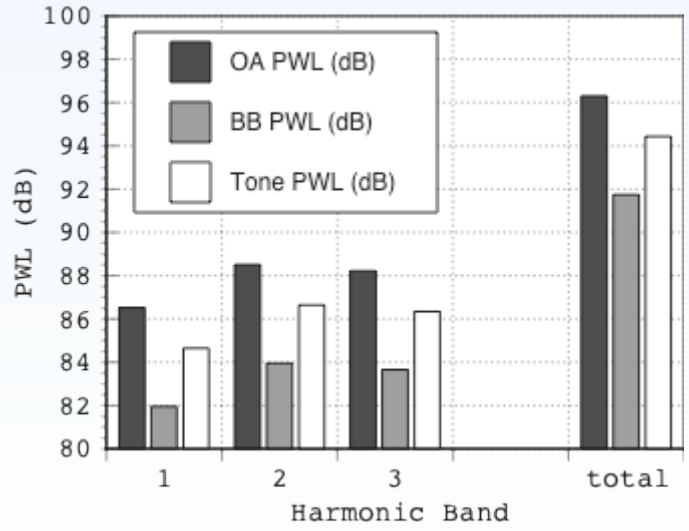
- Data acquired synchronously sampled to fan shaft @ 128/rev
- Frequency/time domain averaged
- Spectra for each microphone integrated over 'harmonic bands'

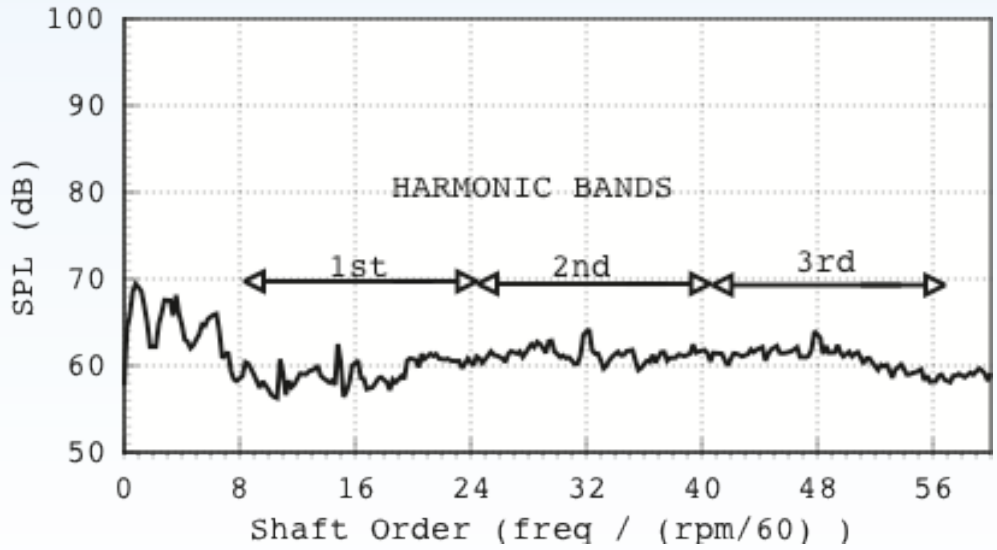
  i.e. $^1/_2$ to $1^1/_2$ harmonics

  or 8 to 24 shaft orders (etc)

  multiplied by area, etc, to obtain PWL
- Overall/Broadband/Tones



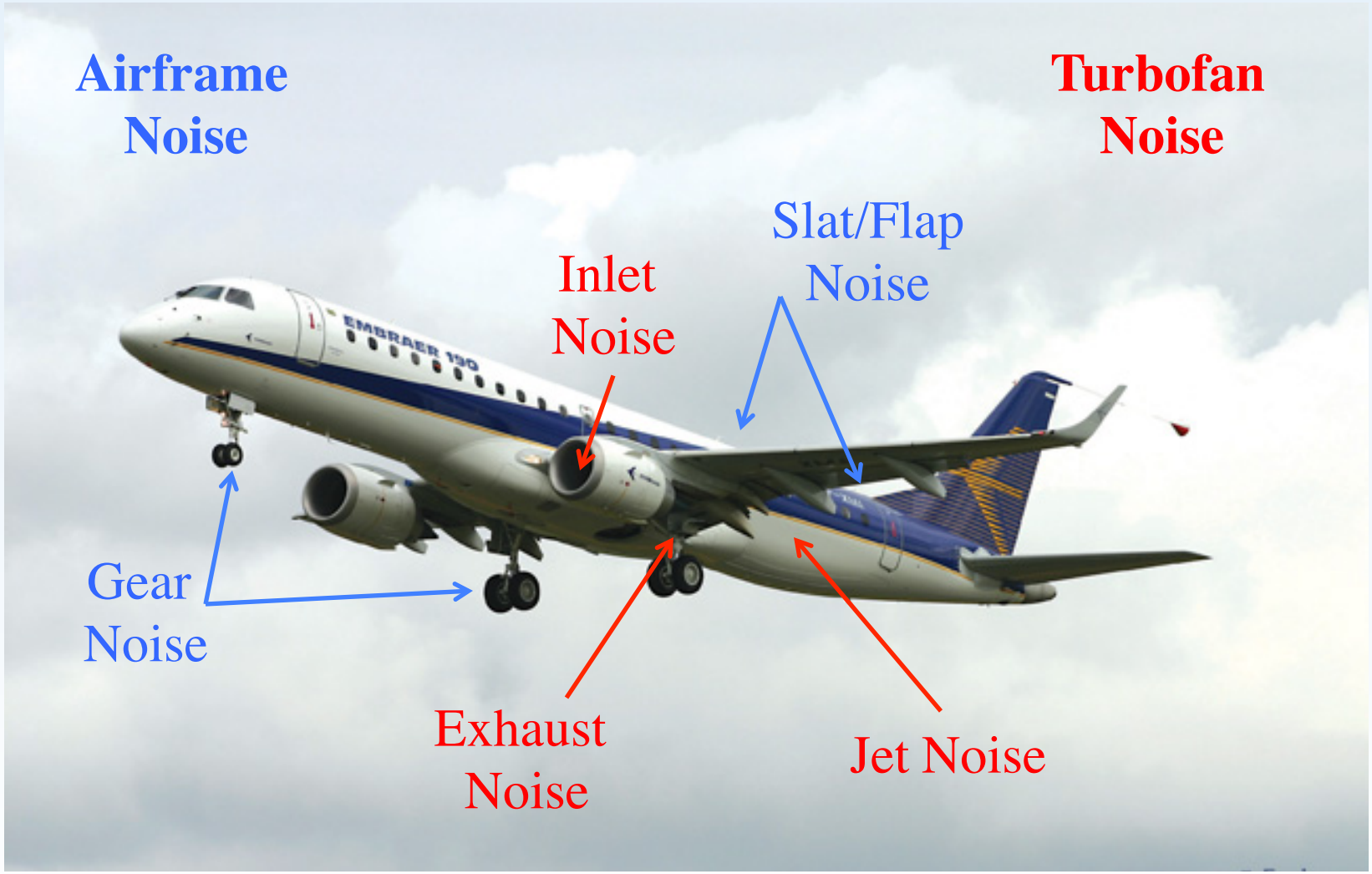






BASICS of AIRCRAFT NOISE

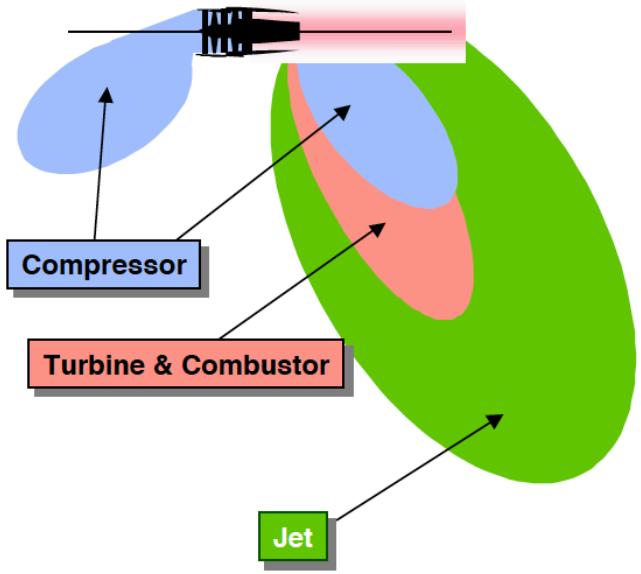
Sources of Aircraft Noise



Engine Noise Component Radiation to Far-field Observer

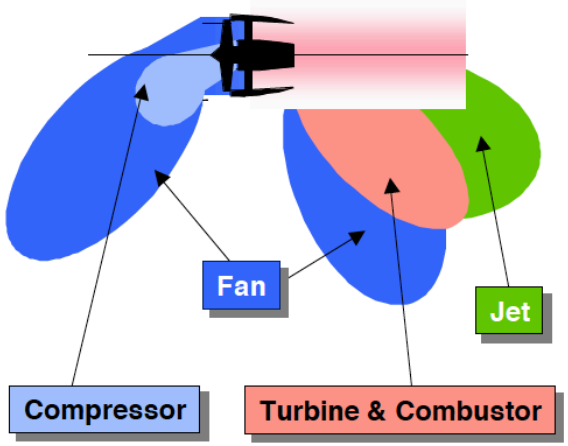
Engine Noise Sources - Old versus New

Noise of a typical 1960s engine



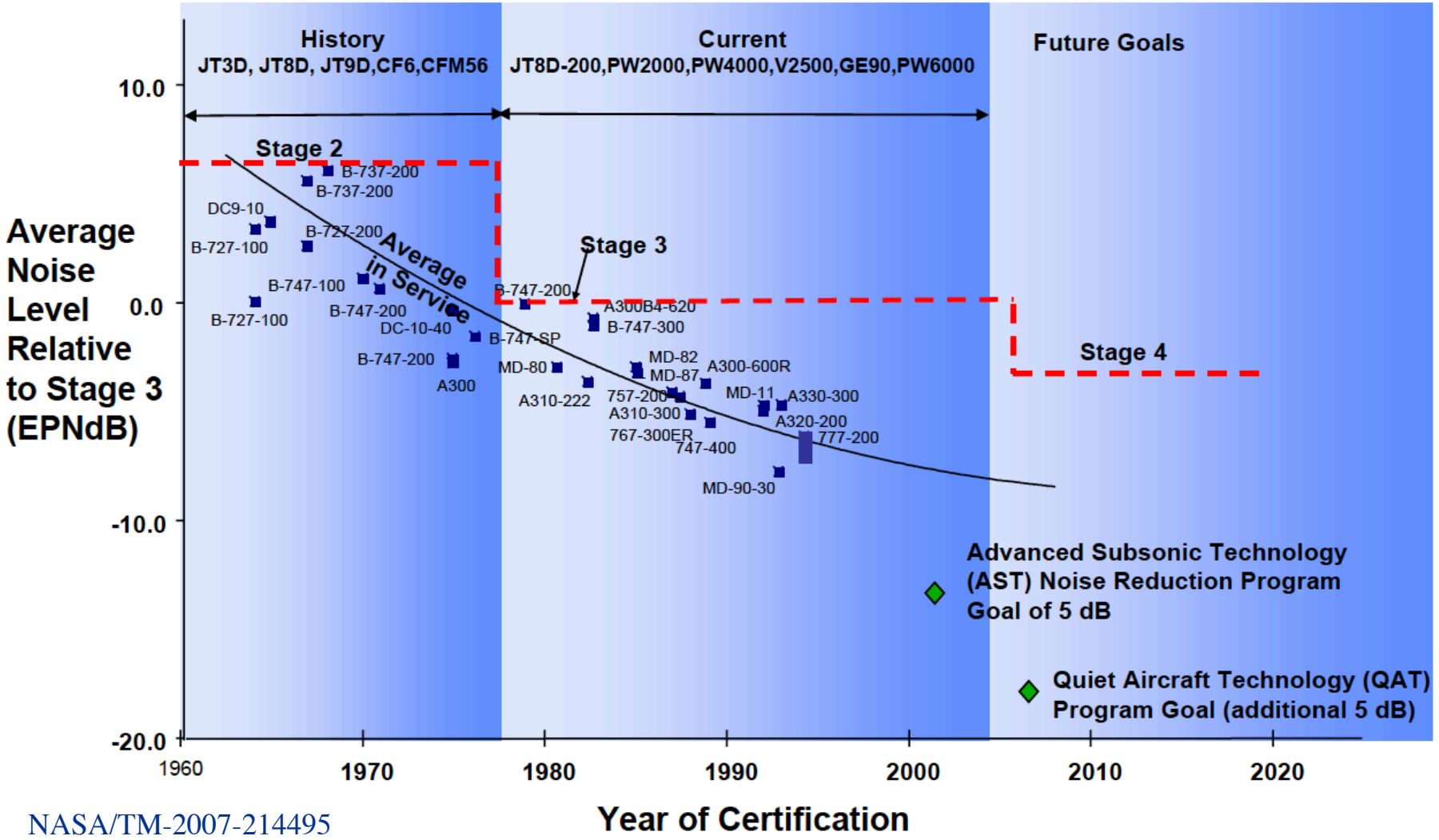
Turbojets dominated by high jet exhaust noise at departure - loud roar, rumble

Noise of a typical 1990s engine



High-bypass-ratio turbofans dominated by fan noise - whine, whistle - and lower jet exhaust noise - roar, rumble

Trends in Aircraft Noise



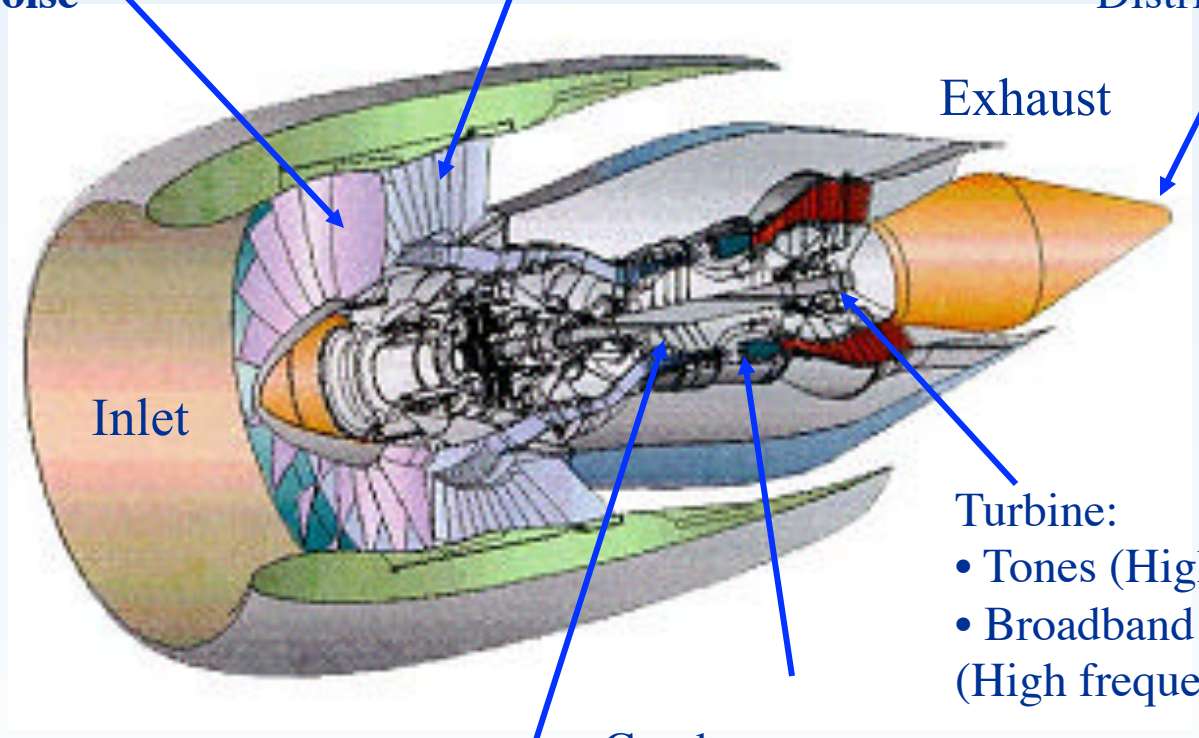
NASA/TM-2007-214495

Sources of Turbofan Engine Noise

Fan:
- **Tones (harmonics)**
- **Broadband Noise**
- **"Buzz-Saw" Noise**

Stator:
- **Tones (harmonics)**
- **Broadband Noise**
- **Duct-modes**

Jet:
- Broadband Noise (Low frequency)
- Distributed

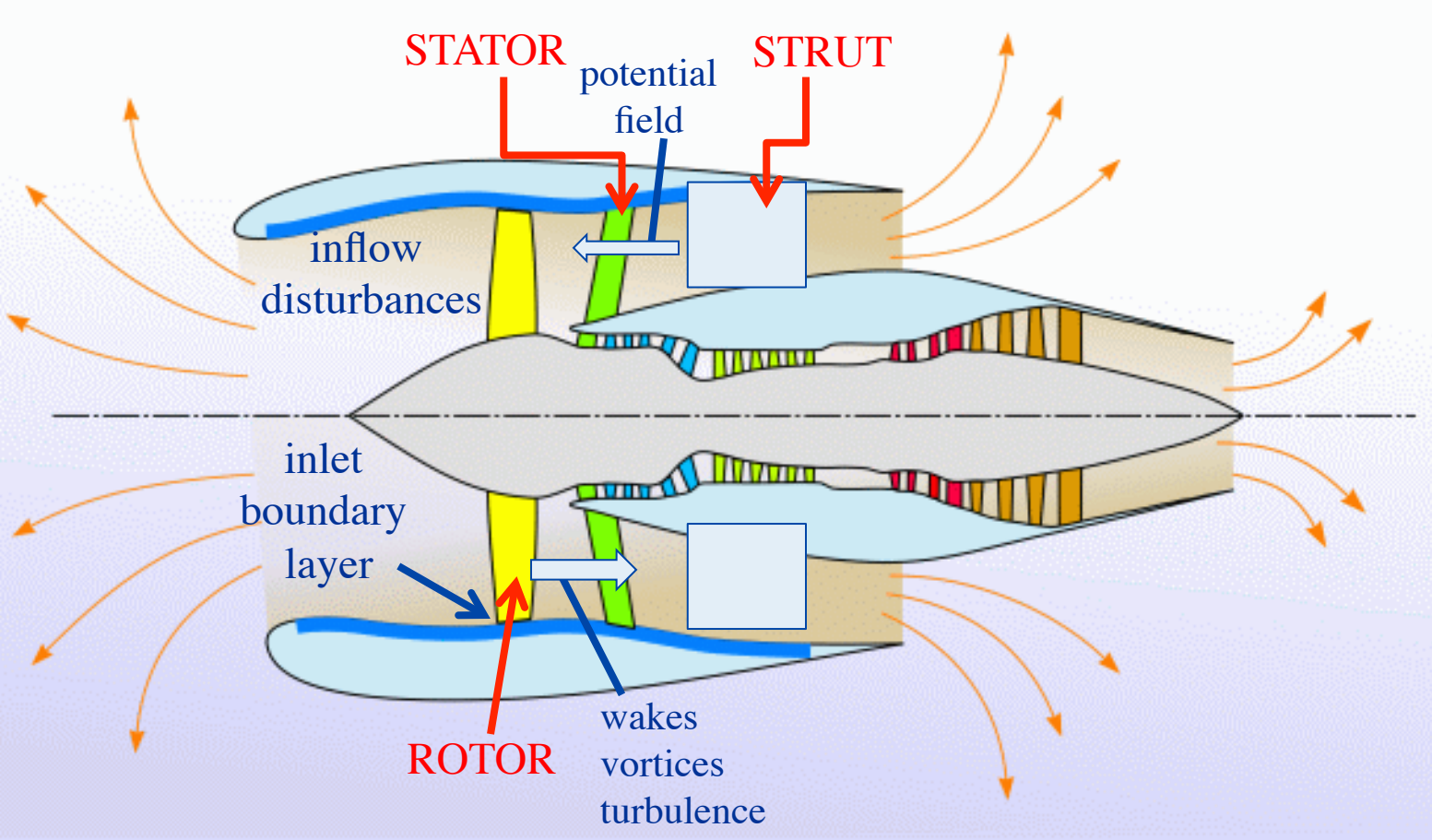


Turbine:
- Tones (High frequency)
- Broadband Noise (High frequency)

Compressor:
- Tones (High frequency)
- Broadband Noise

Combustor:
- Broadband Noise (Low frequency)

Sources of Fan Noise



Rotor Noise

- Inlet turbulence interacting with rotor leading edge noise (~V^6).
- Boundary layer interaction with rotor tips(~V^6).
- Self-noise: rotor blade boundary layer scattering at trailing edge (~V^5).

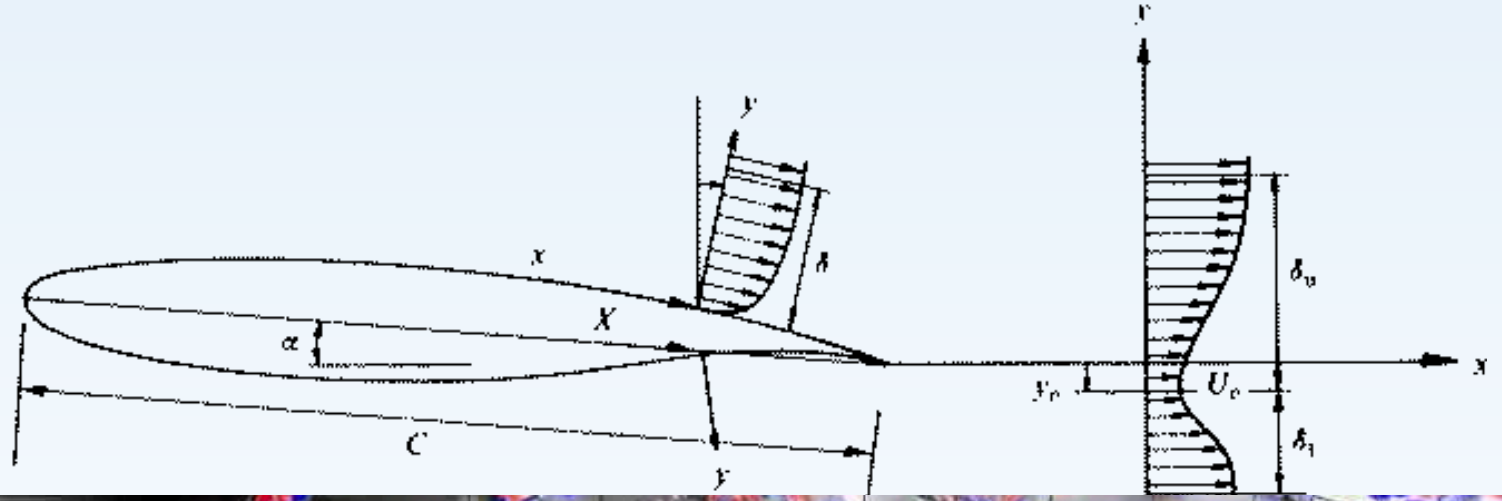
Rotor/stator interaction (~V^6)

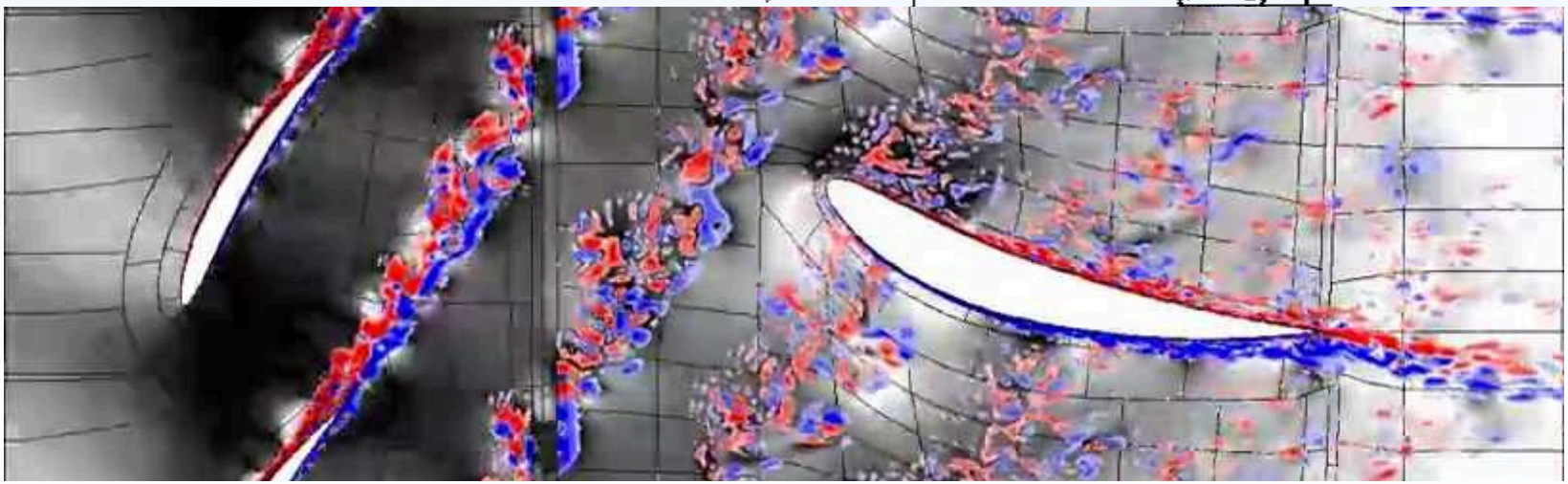
- Wake deficit impinging on stator generating tonal noise.
- Turbulence in rotor wake impinging on stator generates broadband noise.

Rotor Wakes

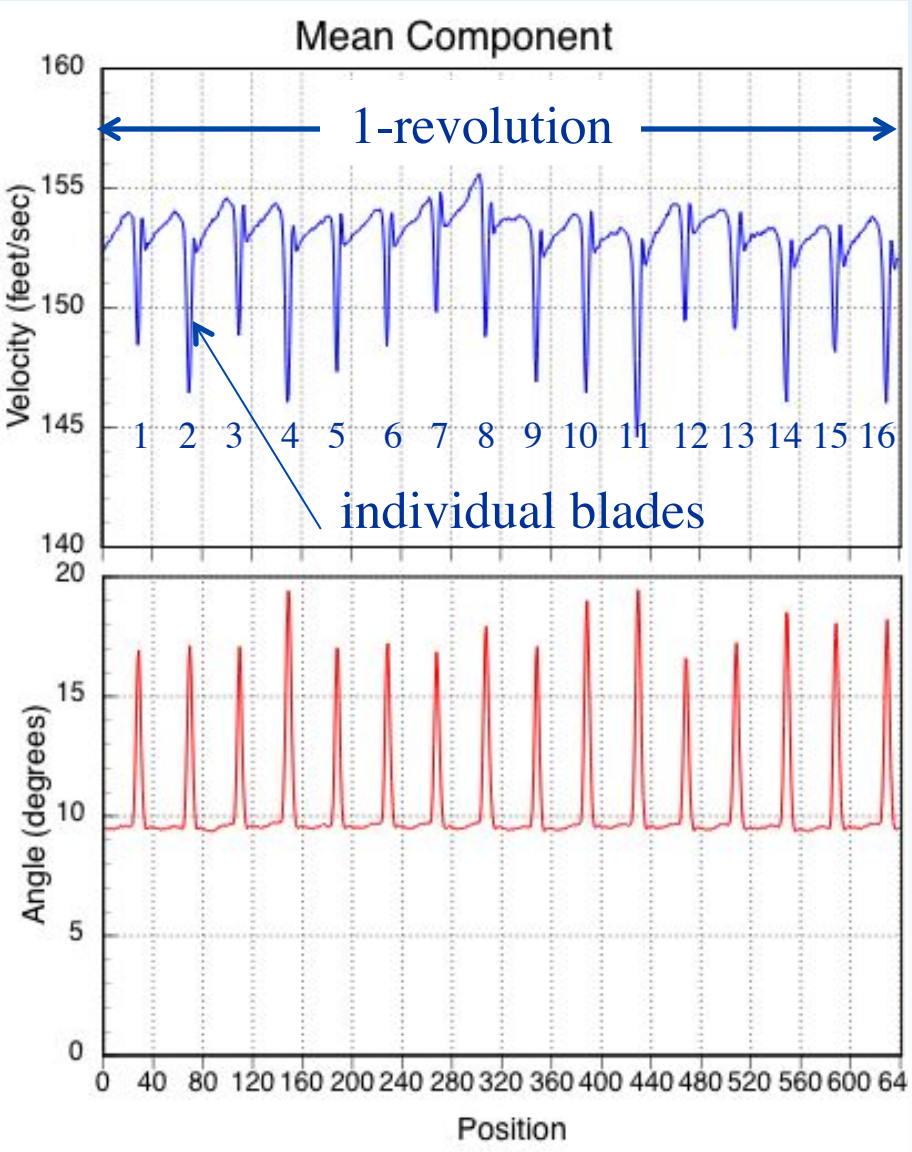
Significant source of noise is the interaction of the rotor viscous wake.

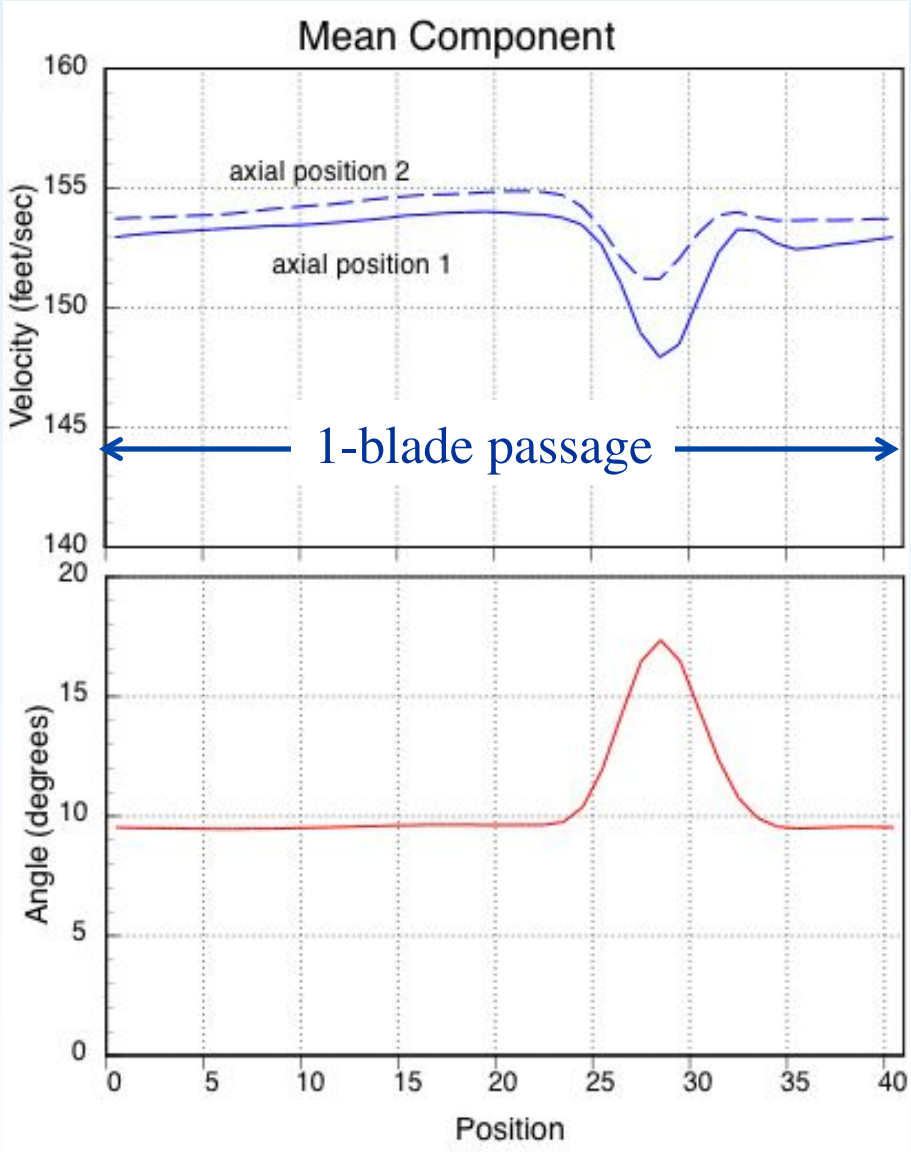
- Boundary layer growth along blade creates a velocity deficit at the trailing edge.
- This velocity profile impinging on the stator surface generates noise.





Rotor Wakes

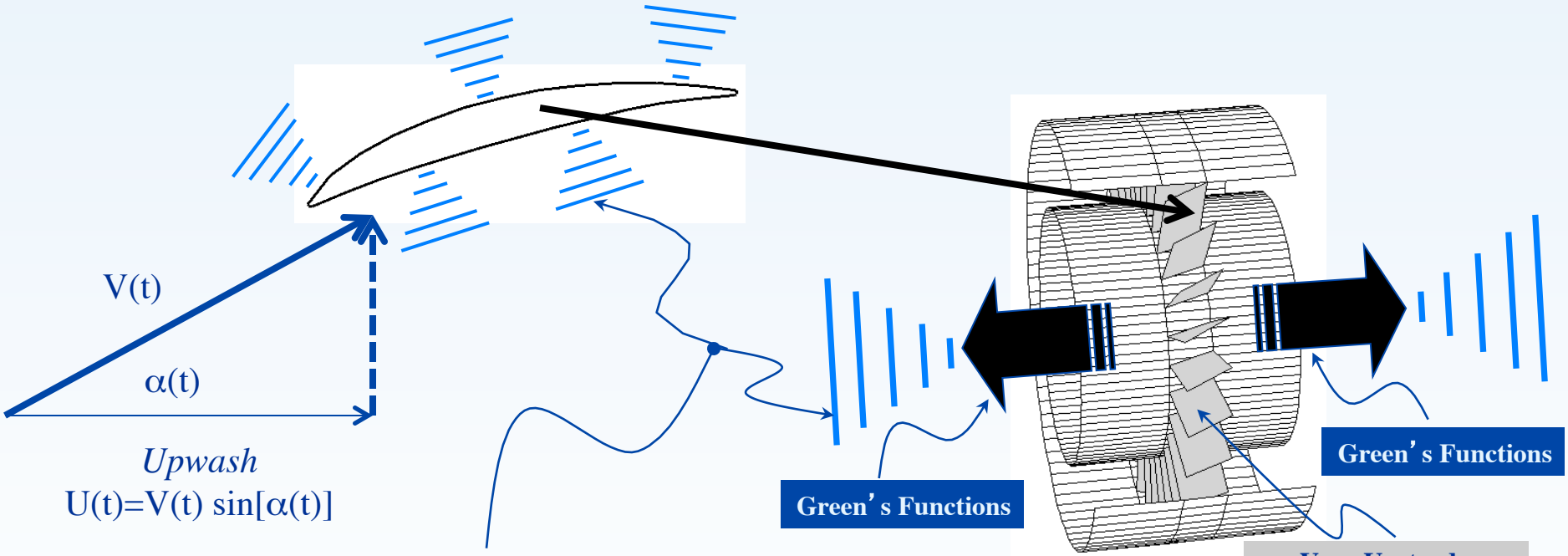

Mean Component
1-revolution
individual blades
Velocity (feet/sec)
160
155
150
145
140
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Angle (degrees)
20
15
10
5
0
0 40 80 120 160 200 240 280 320 360 400 440 480 520 560 600 64
Position


Mean Component
axial position 2
axial position 1
1-blade passage
Velocity (feet/sec)
160
155
150
145
140
Angle (degrees)
20
15
10
5
0
0 5 10 15 20 25 30 35 40
Position

Stator Response

The wake its self is not the primary noise generation mechanism, but the interaction of the wake perturbations with the stator vane.

- The fluctuation of the velocity vector normal to the surface of the stator induces a pressure since the solid surface cannot support a normal velocity.
- The fluctuating normal velocity is called the *Upwash* – combination of the variation in the velocity magnitude and angle.



Acoustic Duct Modes

Tyler, J.M., and Sofrin, T.G., "Axial Flow Compressor Studies", *SAE Transactions*, Vol. 70, 1962.

solution to separated wave equation:

$$P(\theta,r,x,t) = p_{mnf} * E_{mn}(k_{mn}r)e^{i(2\pi ft + m\theta \pm \gamma x)}$$

2-Dimensions:

circumferential direction:

$$P(\theta) = P(\theta + 2\pi); \quad \sin(m\theta)$$

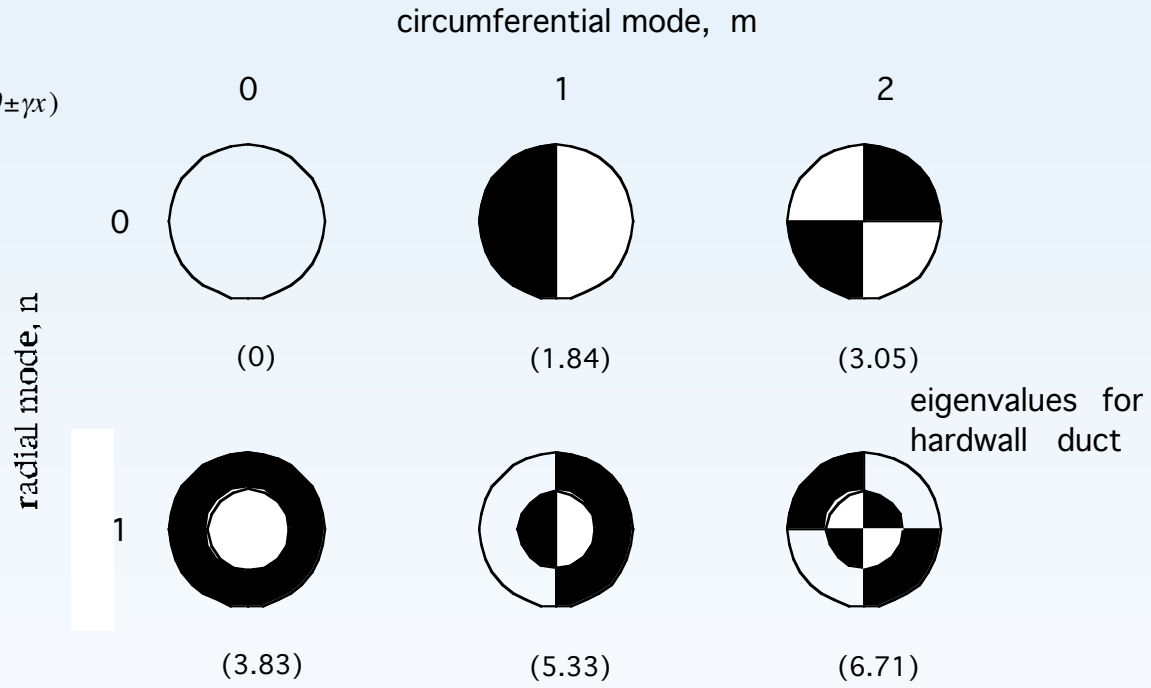
m is defined as the number of cycles
-circumferential mode, m order

radial direction:

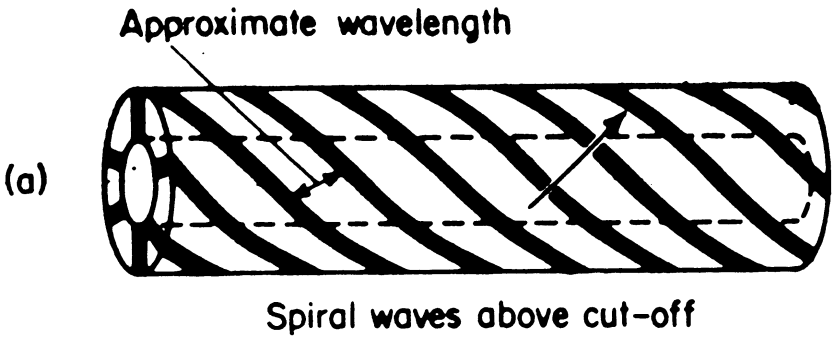
$$E_{mn}(k_{mn}r) = C_{mn}[J_m(k_{mn}r) + Q_{mn}Y_m(k_{mn}r)]$$

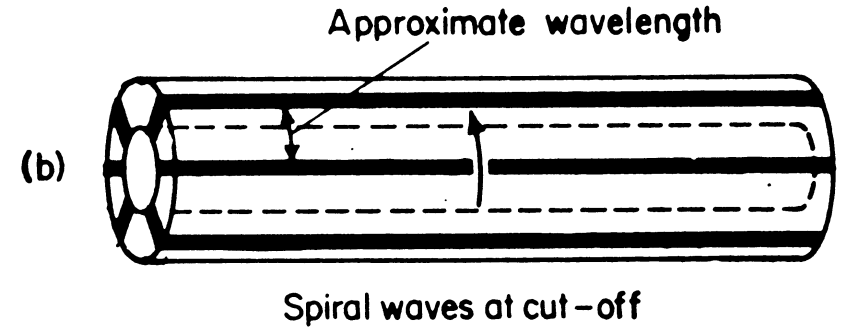
n is defined as the number of zero crossings
-radial mode, n order

J & Y are Bessel functions / k & Q are "eigenvalues"



Duct Propagation





solution to separated wave equation:

$$P(\theta, r, x, t) = p_{mnf} * E_{mn}(k_{mn} r) e^{i(2\pi f t + m\theta \pm \gamma x)}$$

3-dimensional propagation

axial wavelength:

$$\gamma_{mn}(x) = \sqrt{(2\pi f r_t / c)^2 - k_{mn}^2}$$

$i)$ $2\pi f r_t / c > k_{mn}$; γ *real, cyclical propagation*

$ii)$ $2\pi f r_t / c = k_{mn}$; *cut – off frequency*

$iii)$ $2\pi f r_t / c <; k_{mn}$; γ *imag,* exponential *decay*

physically, 3D waves are helix--propagation angle
highly cut-on modes approximate plane wave (α=0°)
cut-on modes axial wavelength is longer than free space
(shorter wavenumber)
cut-off modes have 'infinite' axial wavelength
(zero wavenumber -- decay)

define the cut-off ratio from (ii)

$$\zeta = f / f_{co}; \quad > 1 \text{ propagates}$$
$$< 1 \text{ decays}$$

Rotor-Stator Interaction

The kinematic relationship between the rotor and stator of varying counts causes a strong interaction pressure 'lobe' related to the relative positions. This 'lobe' rotates locked to the fan.

The number of lobes is related to the blade/vane count:

$m = nB - kV$
(n harmonic, k= any integer)

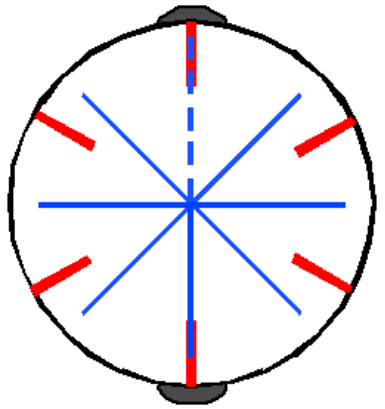
To preserve frequency a low count mode must rotate faster:

$m*\Omega_{mode} = B*\Omega_{rotor}$
$\Omega_{mode} = (B/m)* \Omega_{rotor}$

If $*\Omega_{mode} > 1.0M$ modes propagates

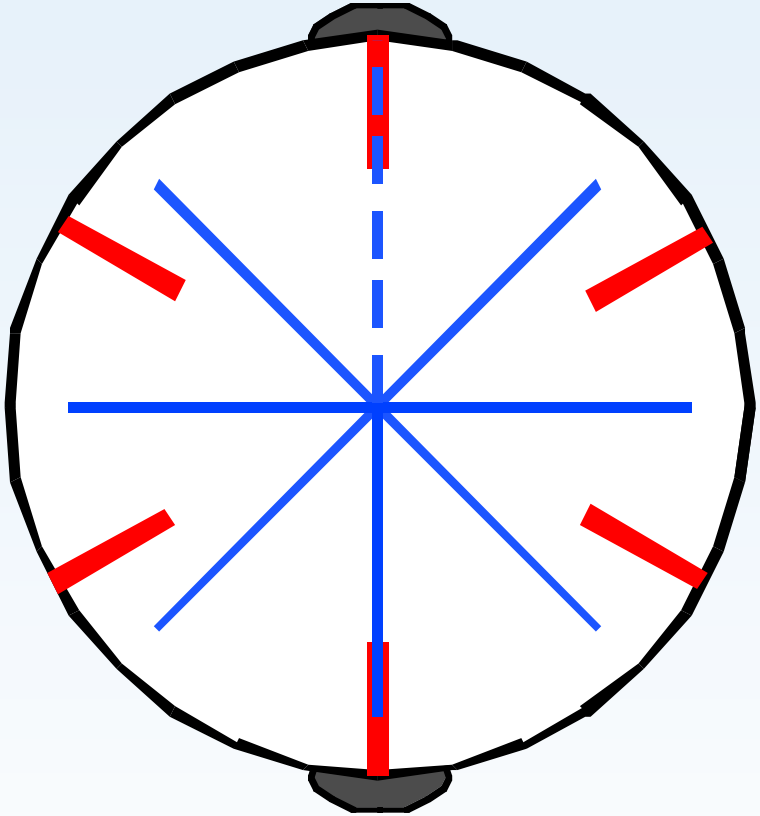
rotor blades, B = 8
stator vanes, V = 6

Blade 0°
Mode 0°

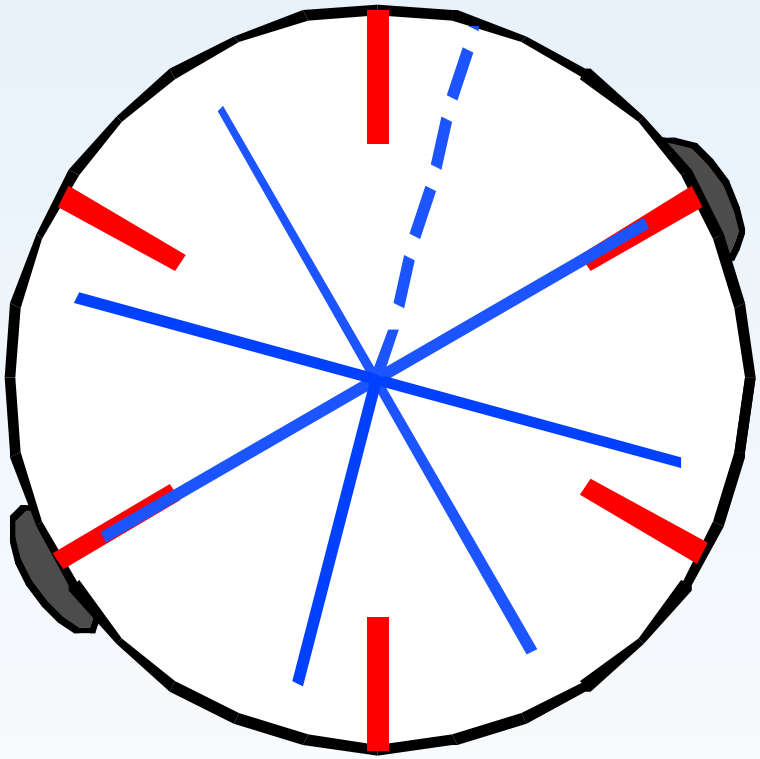


This interaction leads to a 2-lobe pattern which completes a cycle in 1/4 rotor

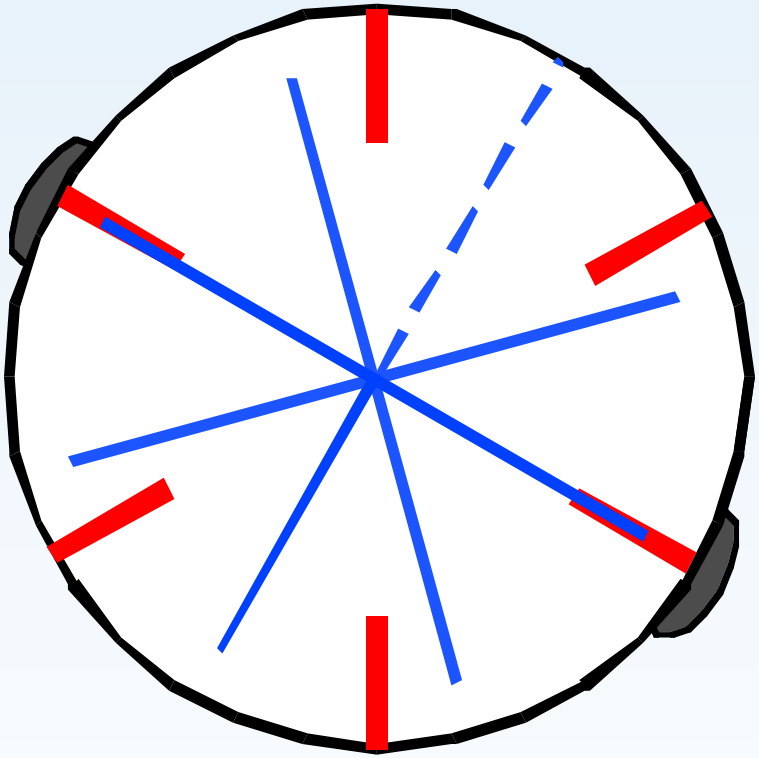
Blade 0°
Mode 0°



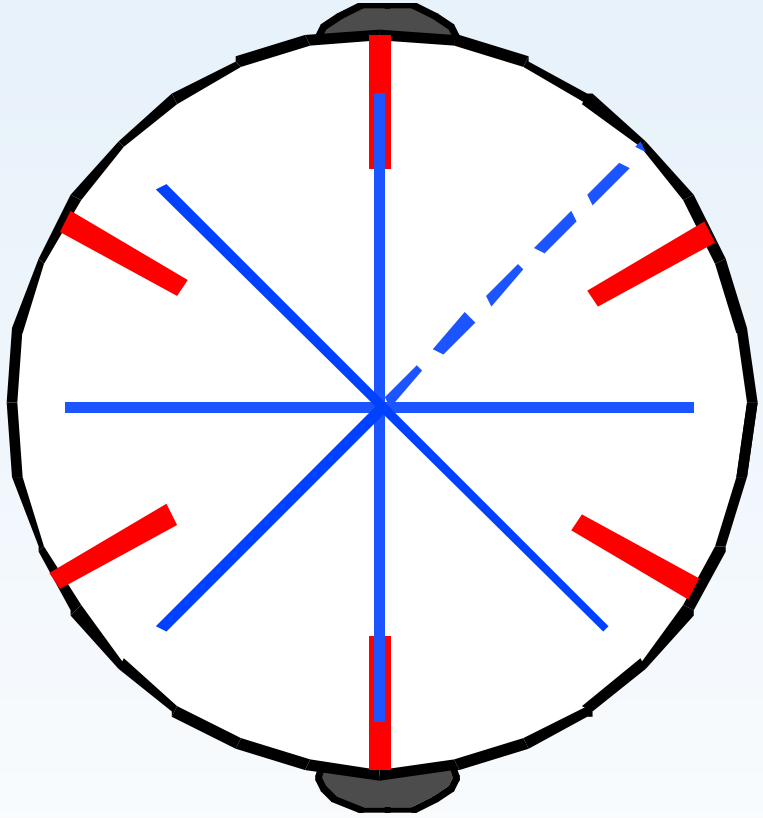
Blade 15°
Mode 60°



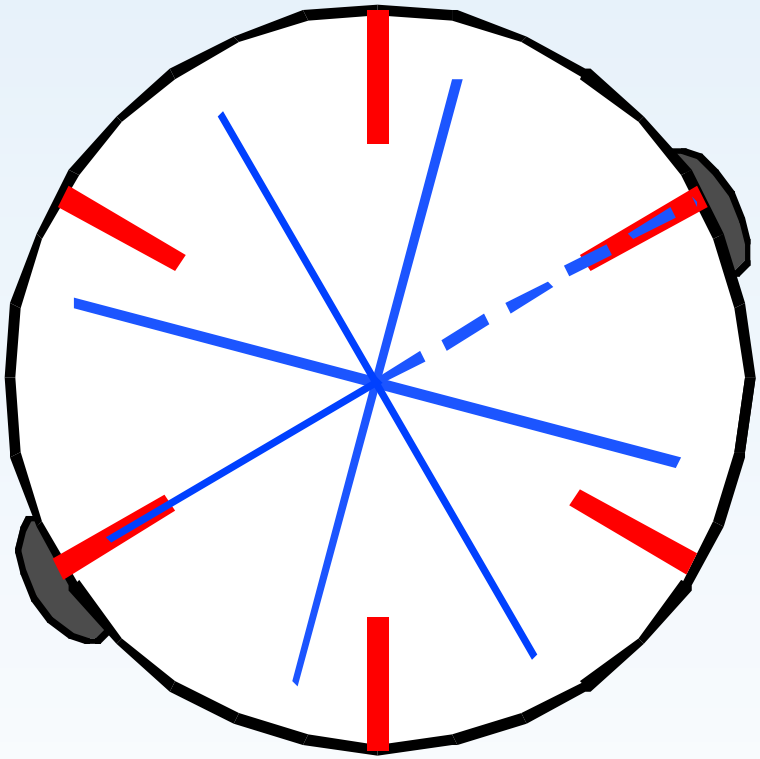
Blade 30°
Mode 120°



Blade 45°
Mode 180°

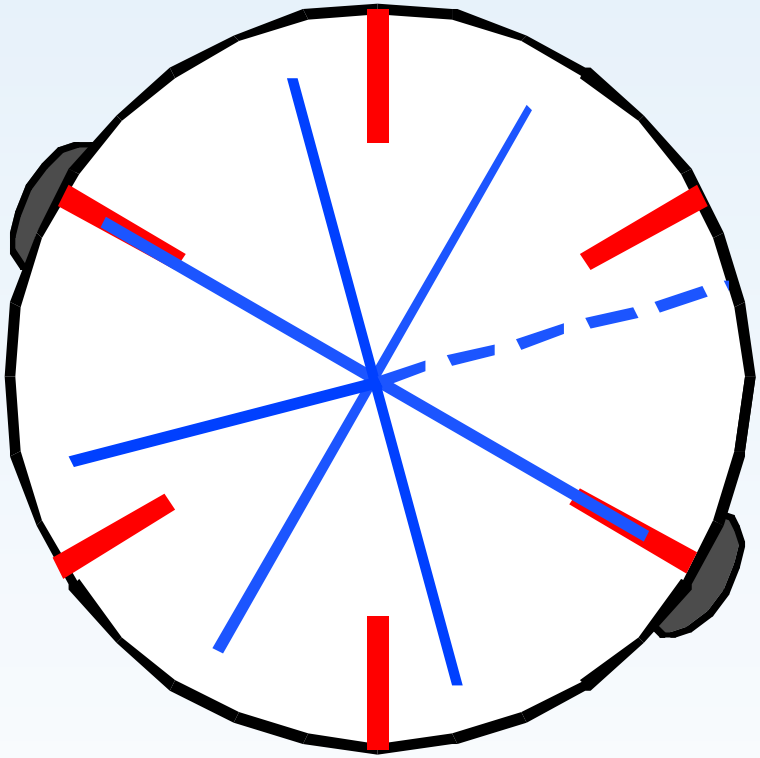


Blade 60°
Mode 240°



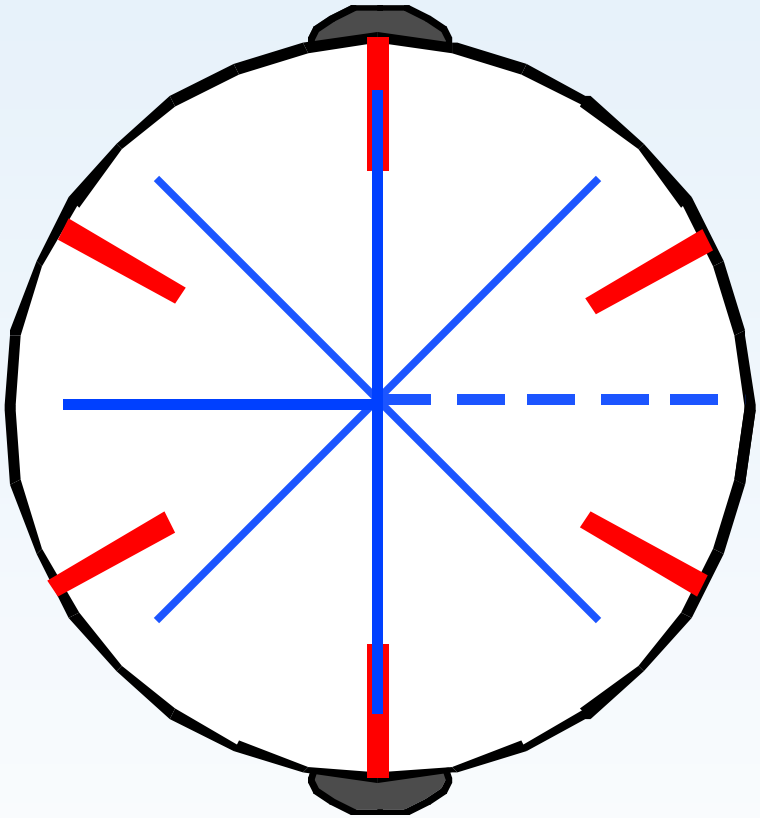


Blade 75°
Mode 300°





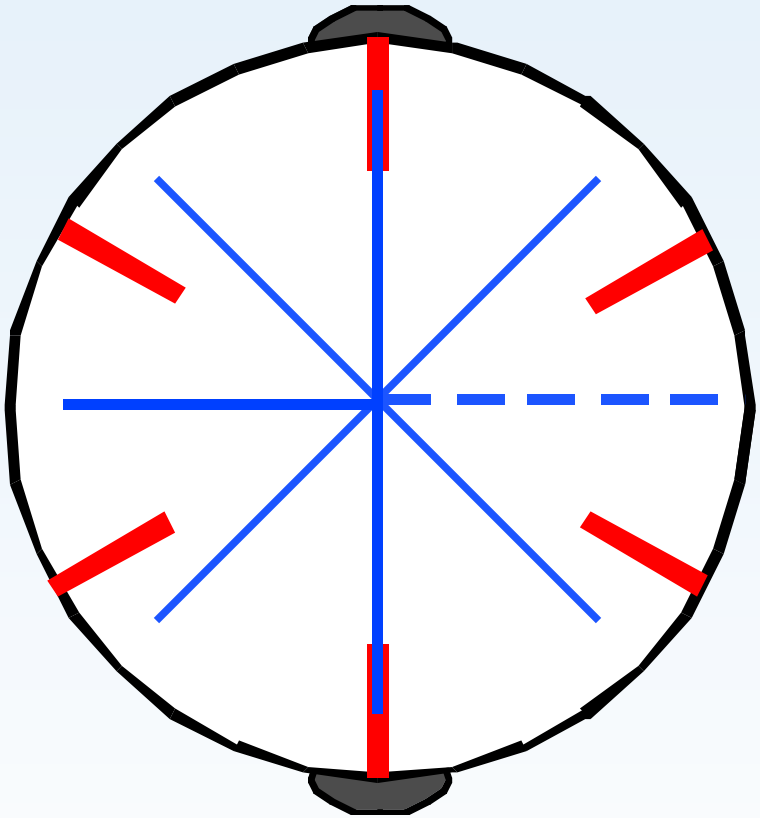
Blade 90°
Mode 360°



Blade 90°
Mode 360°

$m = nB - kV$
$m = 8 - 6$
$m = 2$

rotor blades, B = 8
stator vanes, V = 6

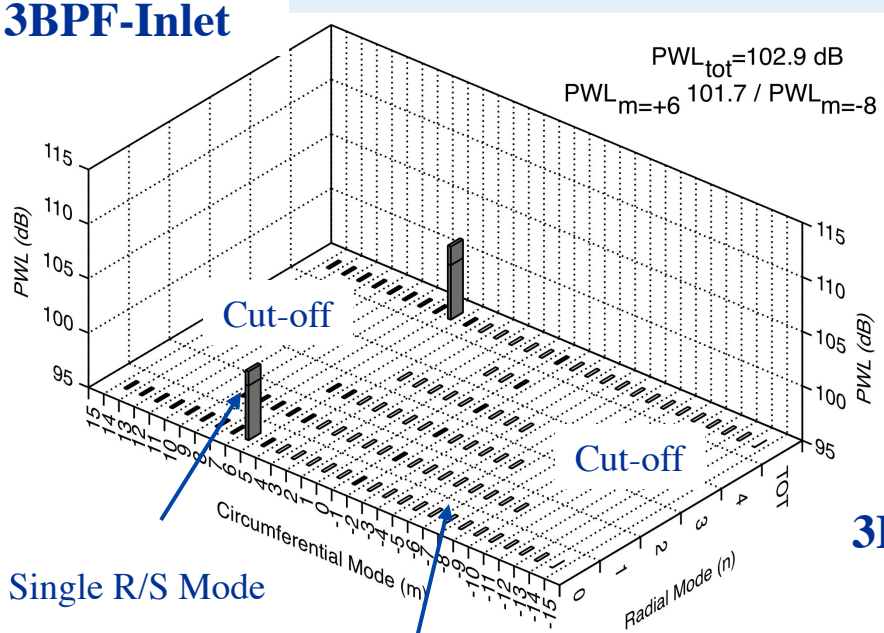


$\Omega_{mode} = (B/m)*\Omega_{rotor}$
$\Omega_{mode} = (8/2)*\Omega_{rotor}$
$\Omega_{mode} = 4*\Omega_{rotor}$

2-lobe pattern interaction completed a completed a cycle in 1/4 rotor revolution

Duct Modes

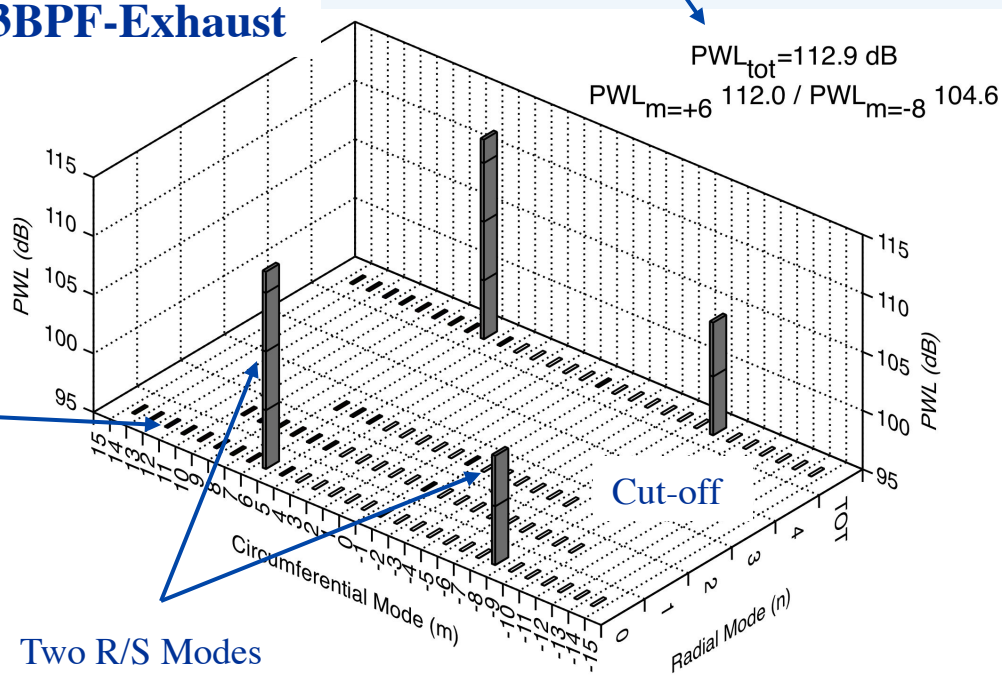
3BPF-Inlet



Single R/S Mode

Numerical R/S values

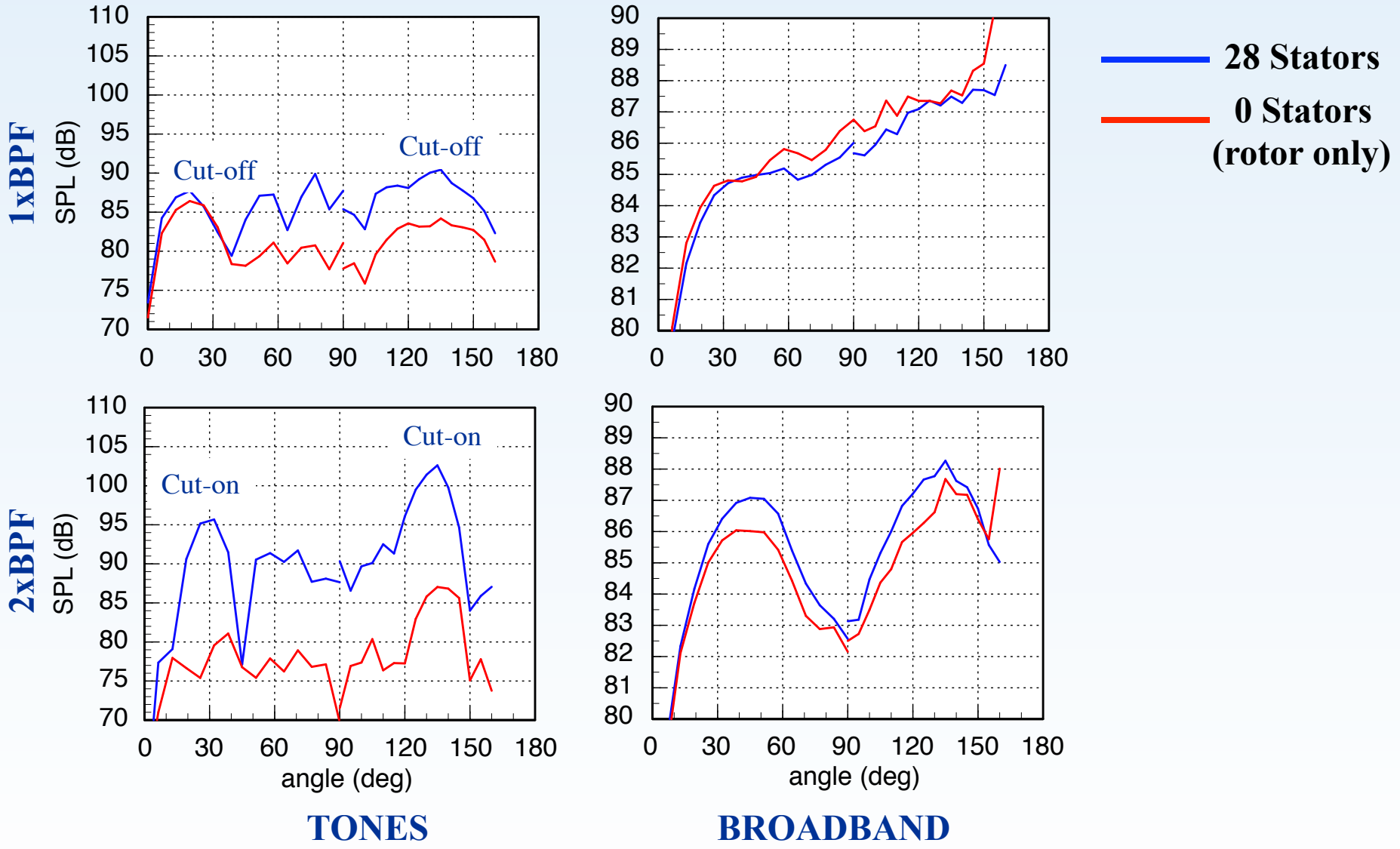
3BPF-Exhaust



Cut-on Modes
(even if below measurement noise floor)

Two R/S Modes

Far-field Radiation Directivity



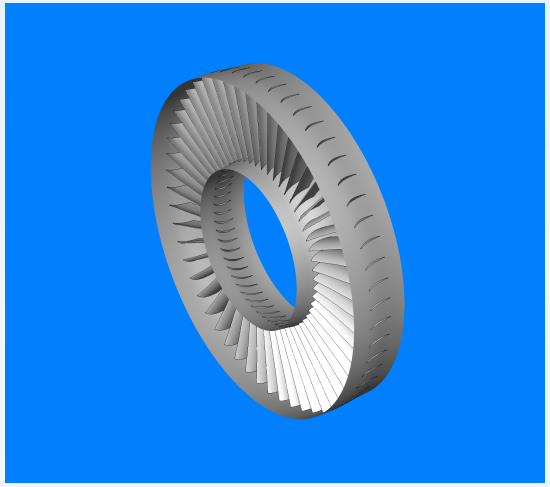


BASICS of AIRCRAFT NOISE REDUCTION

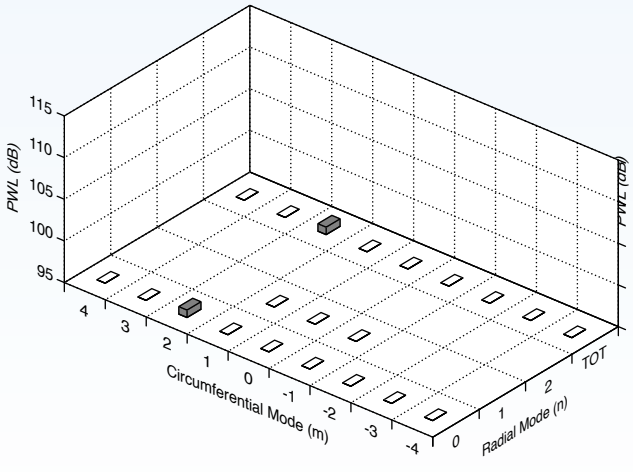
Noise Reduction: Stator Vane Design

$m = nB - kV$ Choose V such that m is outside the max cut-on m-order (V> 2B)

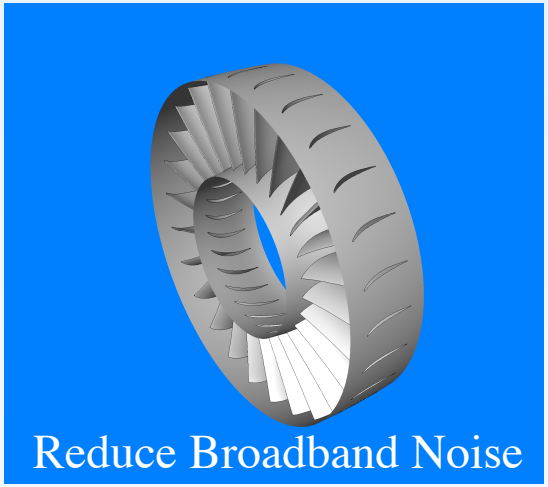
Cut-Off SV



PWL $_{m+2}$=95.6 dB

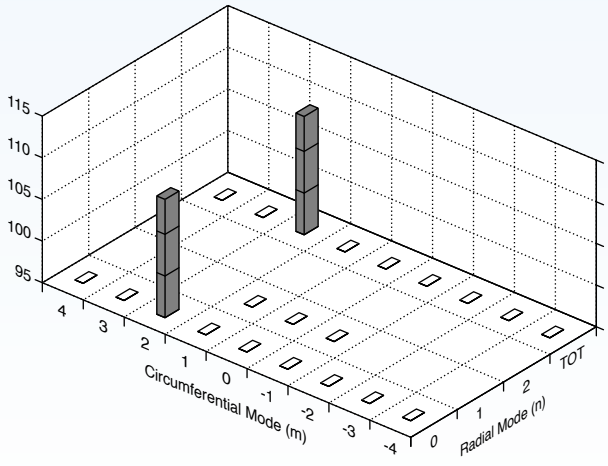


Cut-On SV

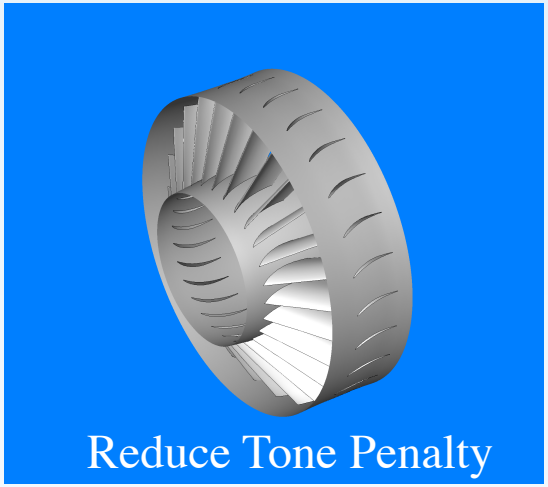


Reduce Broadband Noise

PWL $_{m+2}$=109.2 dB

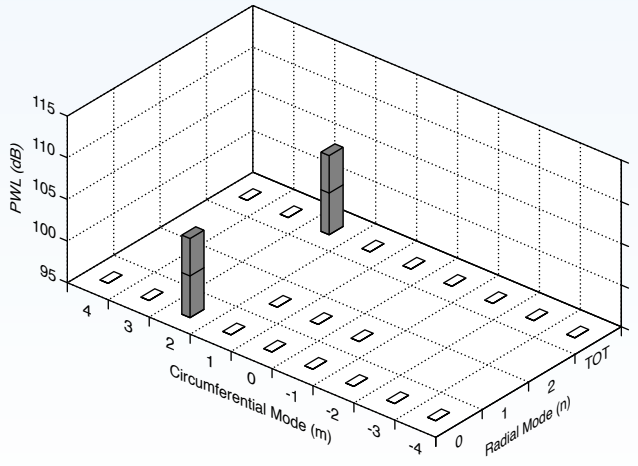


Cut-On SV(Swept)

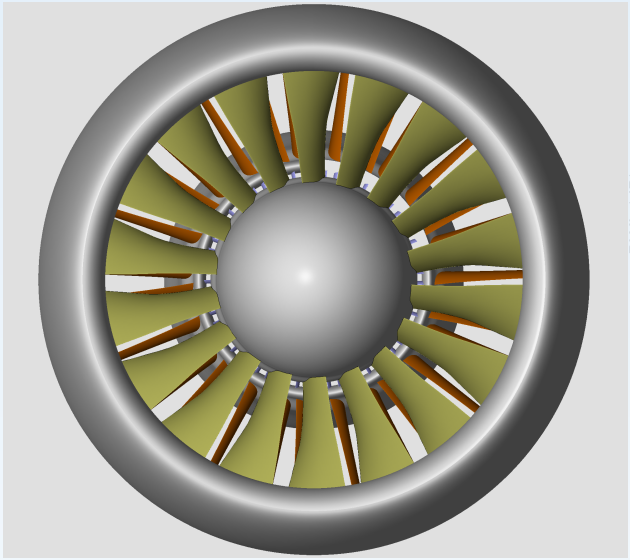


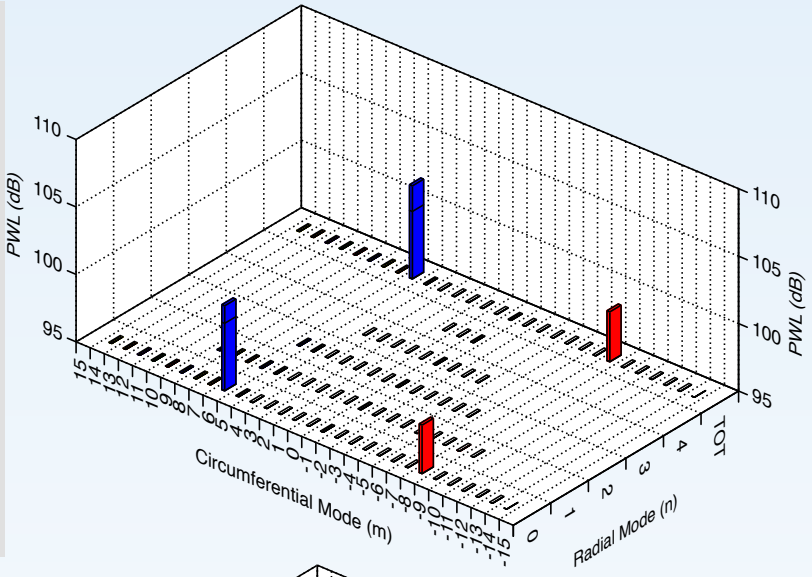
Reduce Tone Penalty

PWL $_{m+2}$=104.5dB



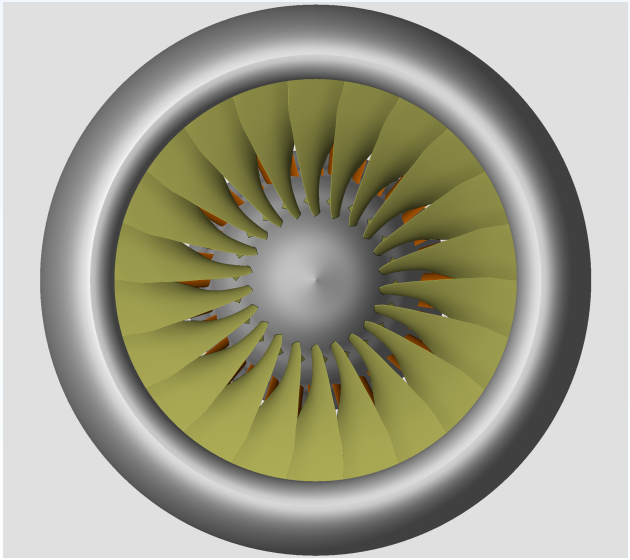
Noise Reduction: Fan Design / Rotor Blockage

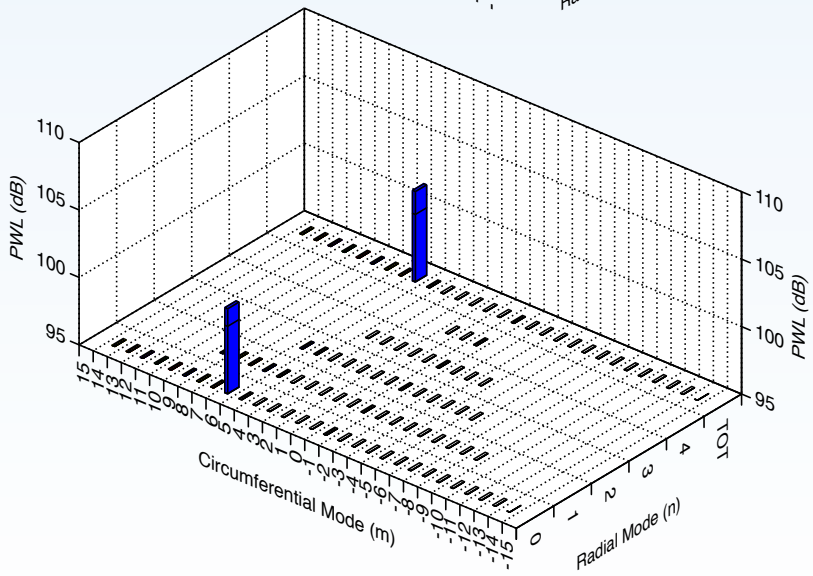




PWL $_{m+6}$=101.9 dB
PWL $_{m-8}$= 99.8 dB

PWL$_{tot}$ =104.0 dB



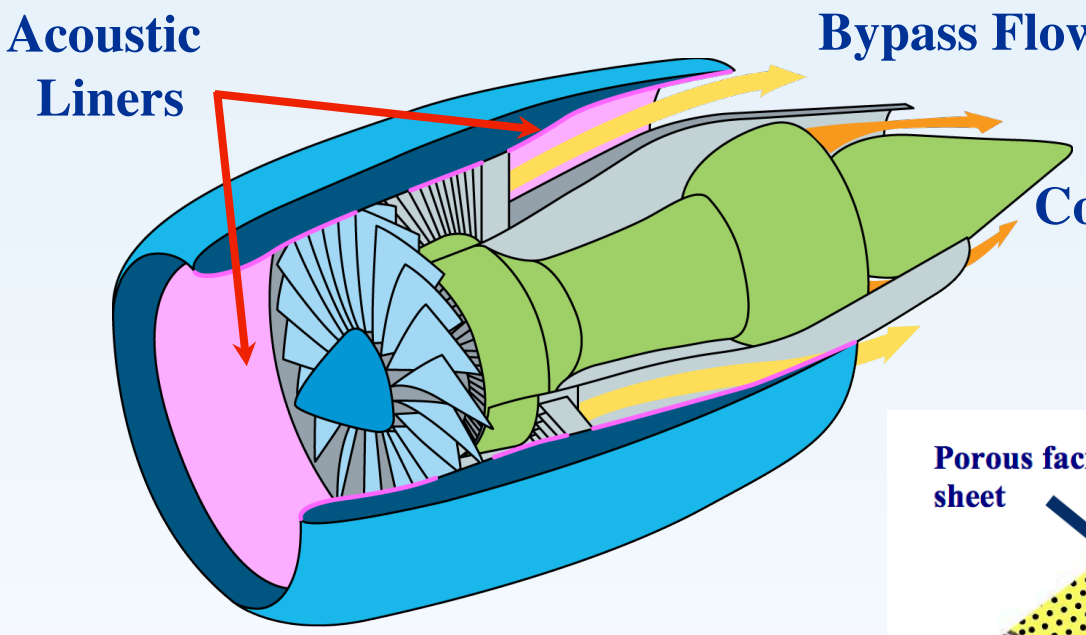


PWL $_{m+6}$=101.7 dB
PWL $_{m-8}$= 77.0 dB

PWL$_{tot}$ =102.9 dB

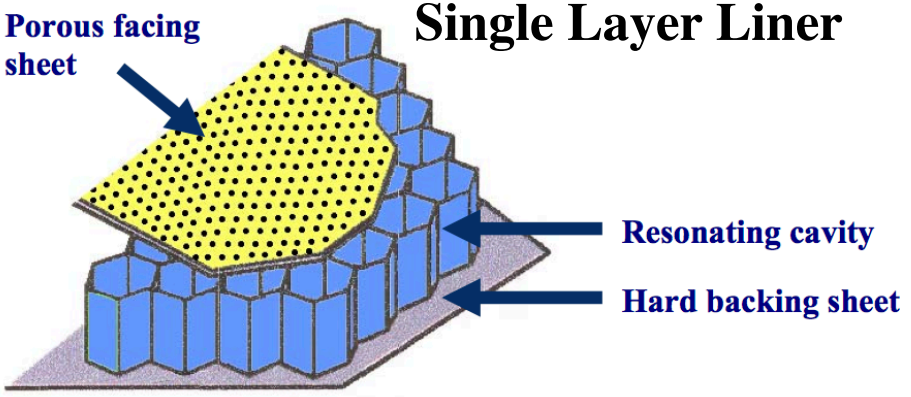
Acoustic Liners

Aircraft Engine Nacelle



Key parameter
Acoustic Impedance, ζ

$$\zeta = \frac{\tilde{p}}{\tilde{v} \bullet \hat{n}} = \theta + i\chi$$



Resistance, θ: A measure of the forces (e.g., viscous scrubbing losses) that dissipate energy

Reactance, χ: "Gate" that determines the frequencies where energy conversion process is optimized

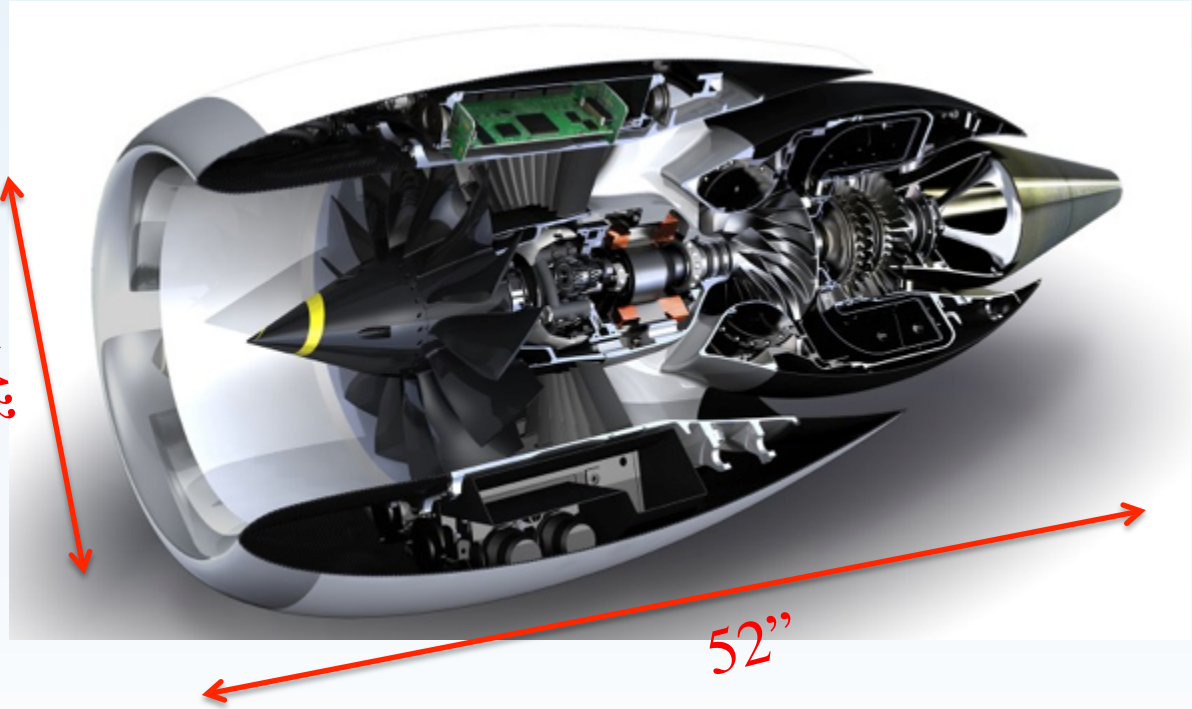
Percent Open Area : $5\% \le POA \le 15\%$
Hole Diameter: $1.0 \text{ mm} \le d \le 2.4 \text{ mm}$
Sheet Thickness: $0.5 \text{ mm} \le t \le 1.0 \text{ mm}$



APPLICATION:
DGEN Aero-propulsion Research Turbofan (DART)

DGEN380 Turbofan Engine

The DGEN engine is the world's smallest turbofan: it is intended for 4-5 seat twin-engine Personal Light Jets flying under 25,000ft and 250kts. The DGEN engine is manufactured by Price Induction.



The characteristics of the DGEN380 enable it to be an excellent representation of modern turbofan engines.

DGEN380 Turbofan Engine

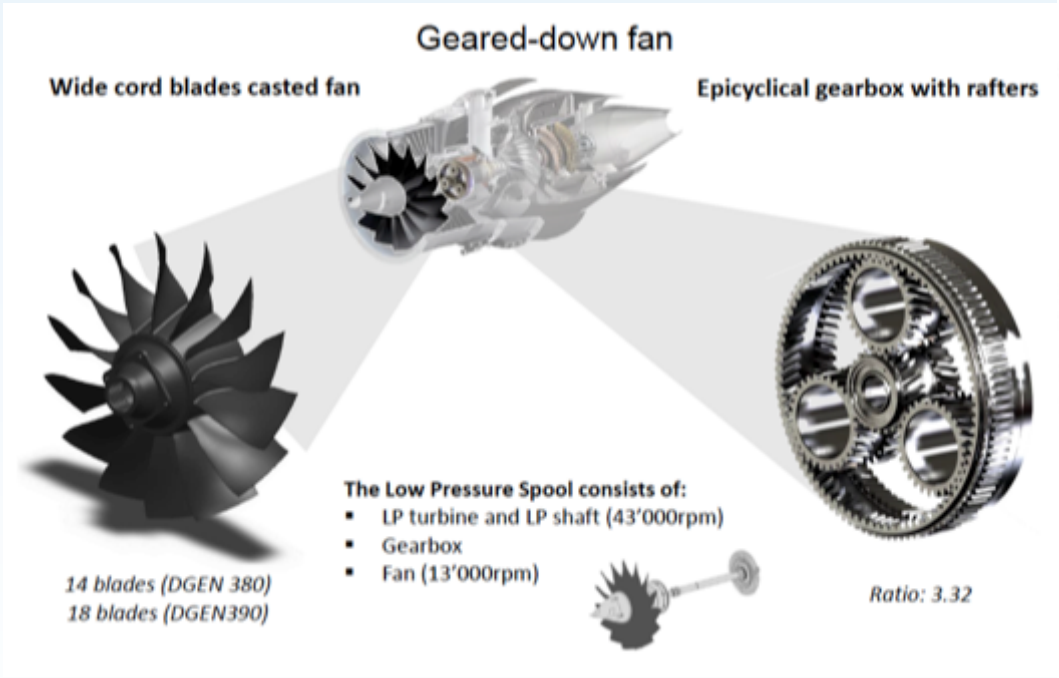
2 spool, geared fan (3.32 ratio), unmixed, separate flow exhaust

Thrust 560 lbf, **7.6 BPR**,1.2 FPR, 5 OPR, 30 lb/s mass flow

Centripetal compressor, LP/HP turbine (43,000 rpm)

14 inch diameter fan, 14 fan blades,(13,000 rpm)

V_{tip} = 800 fps subsonic tip speed



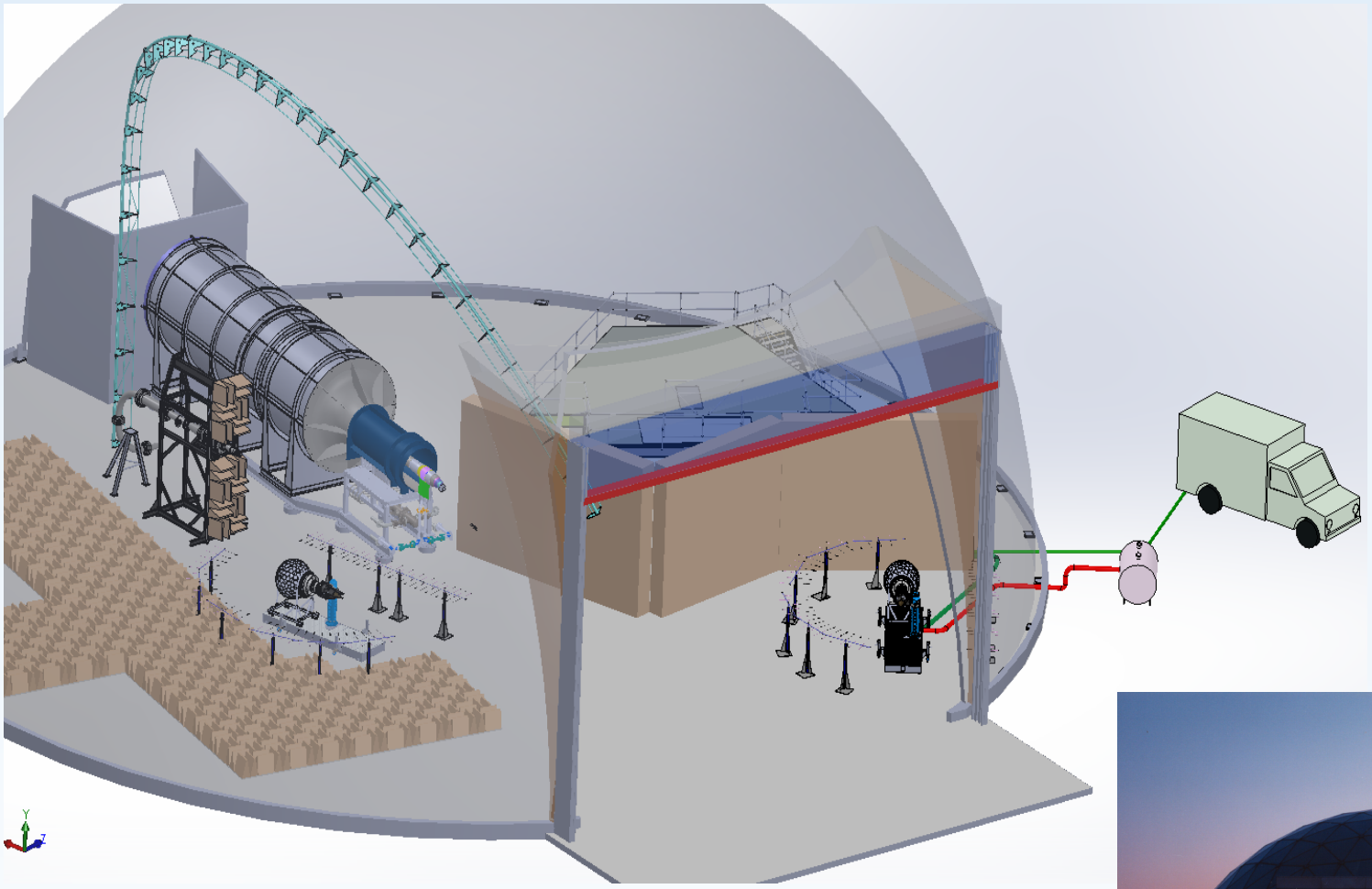


Comparisons

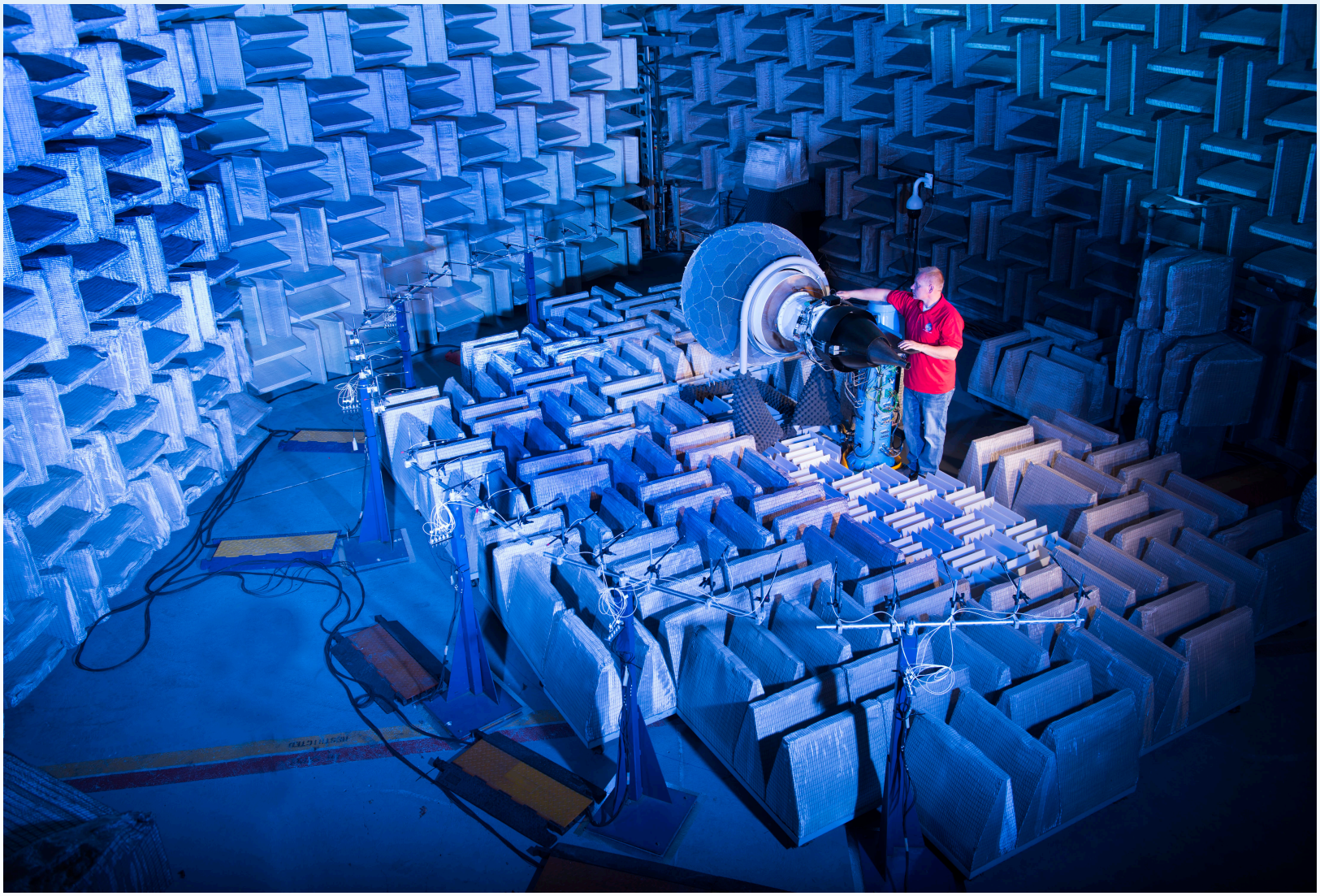


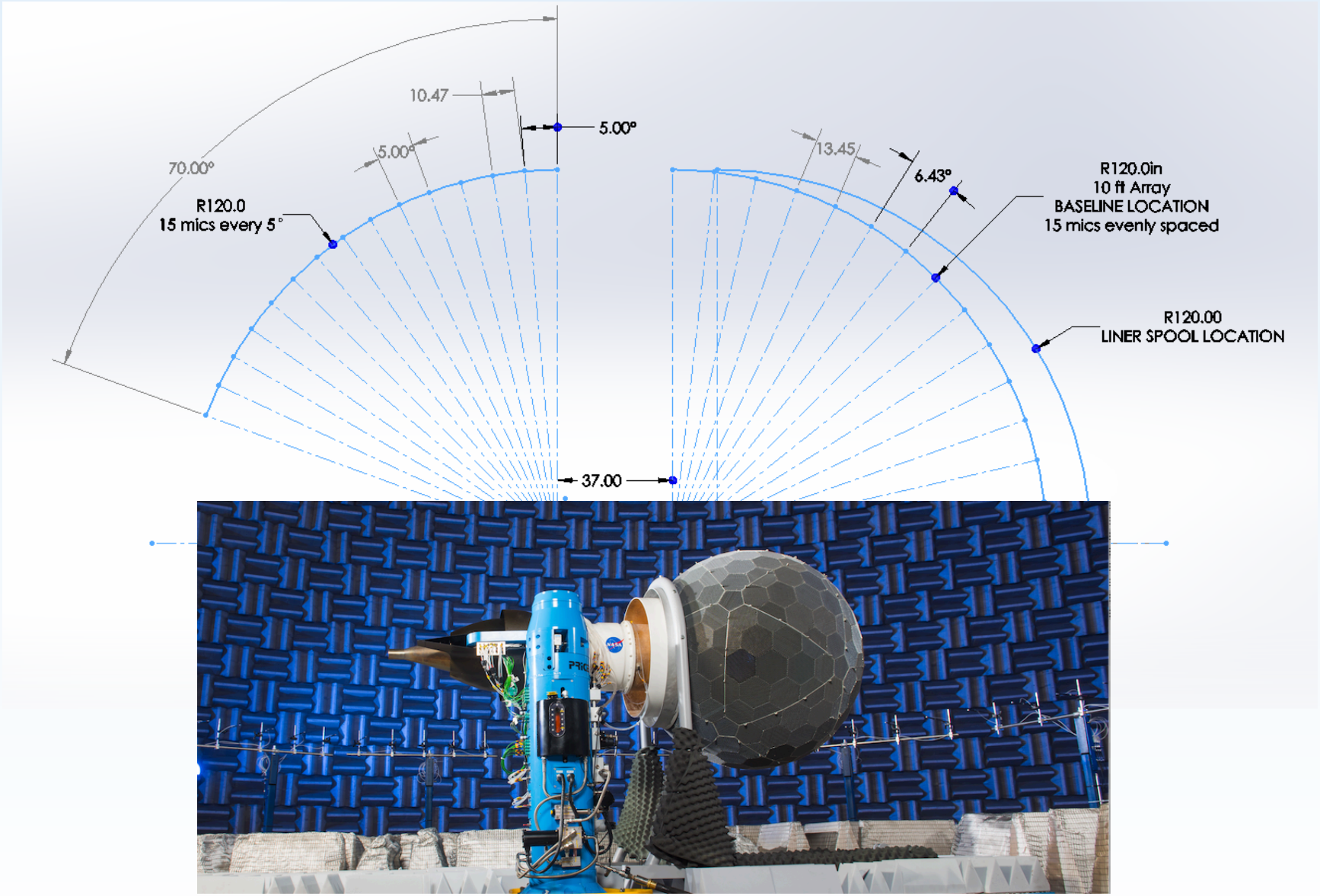


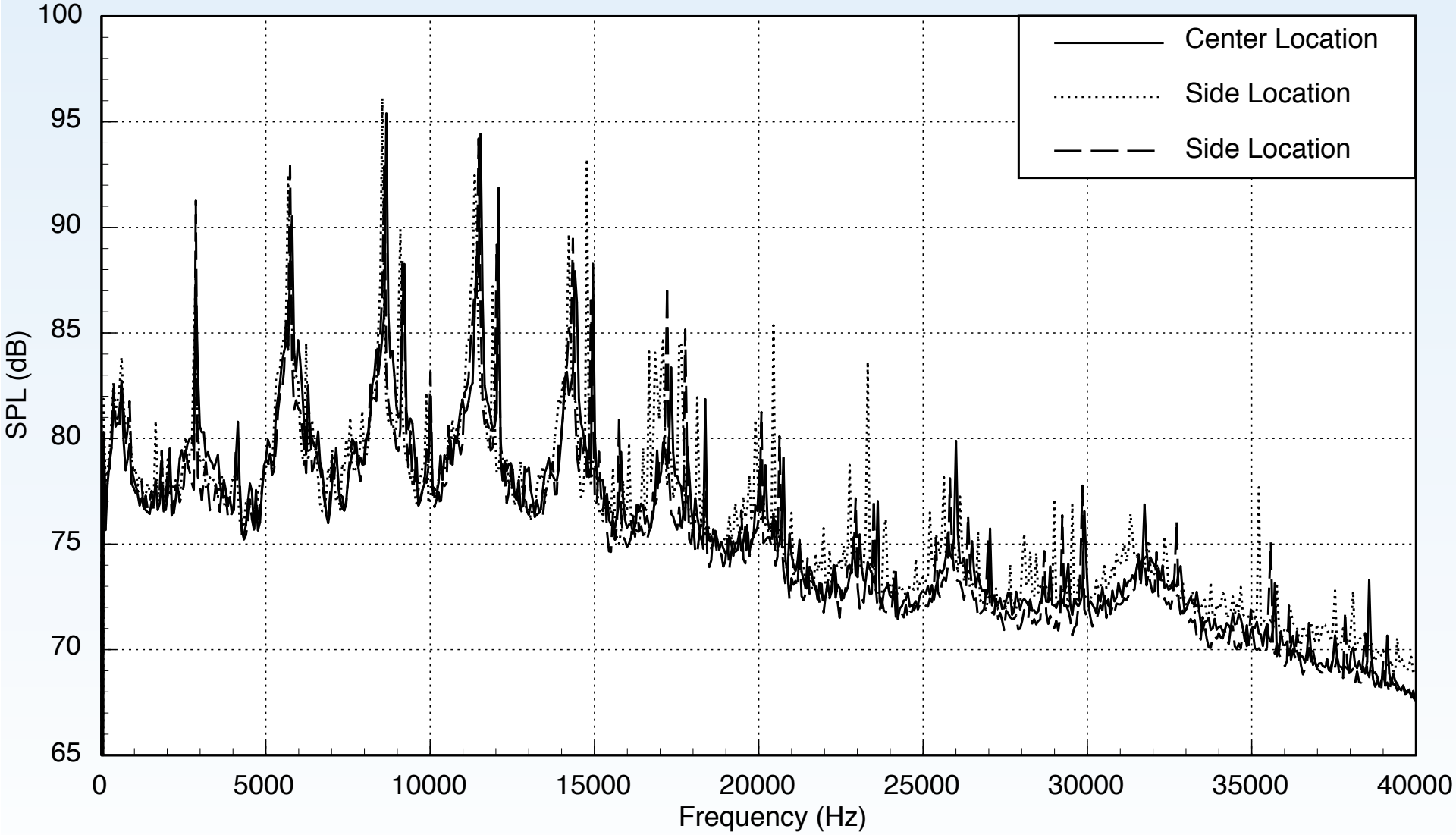
Weight:	180 lb	12,800 lbs
Thrust :	570 lbf	63,800 lbs
Diameter:	14 inches	~10 feet



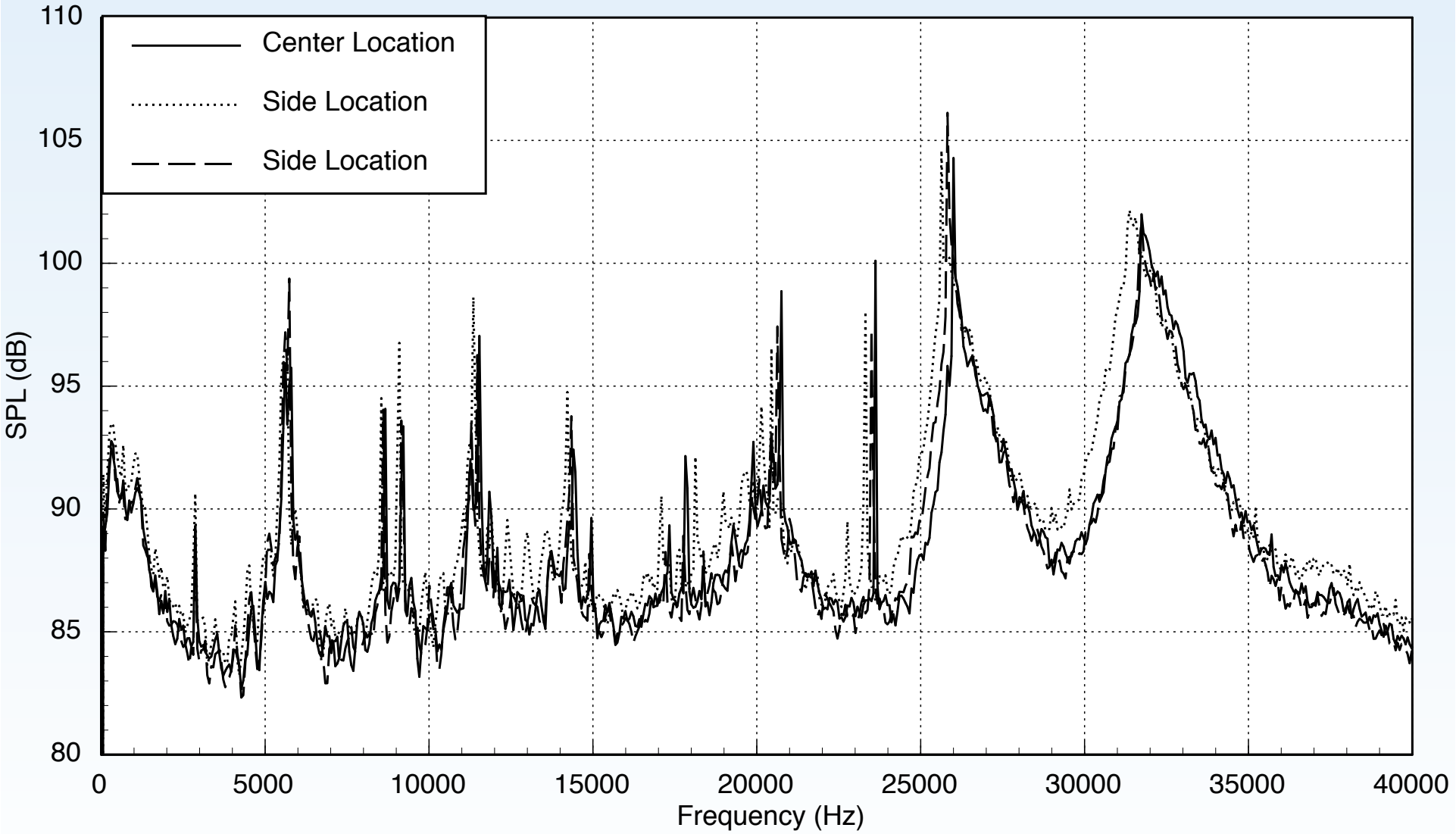




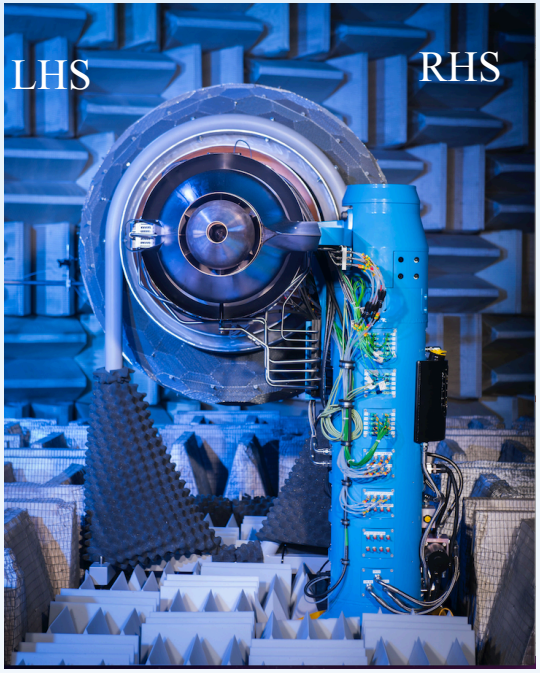

10.47
5.00°
5.00°
70.00°
R120.0
15 mics every 5°
13.45
6.43°
R120.0in
10 ft Array
BASELINE LOCATION
15 mics evenly spaced
R120.00
LINER SPOOL LOCATION
37.00

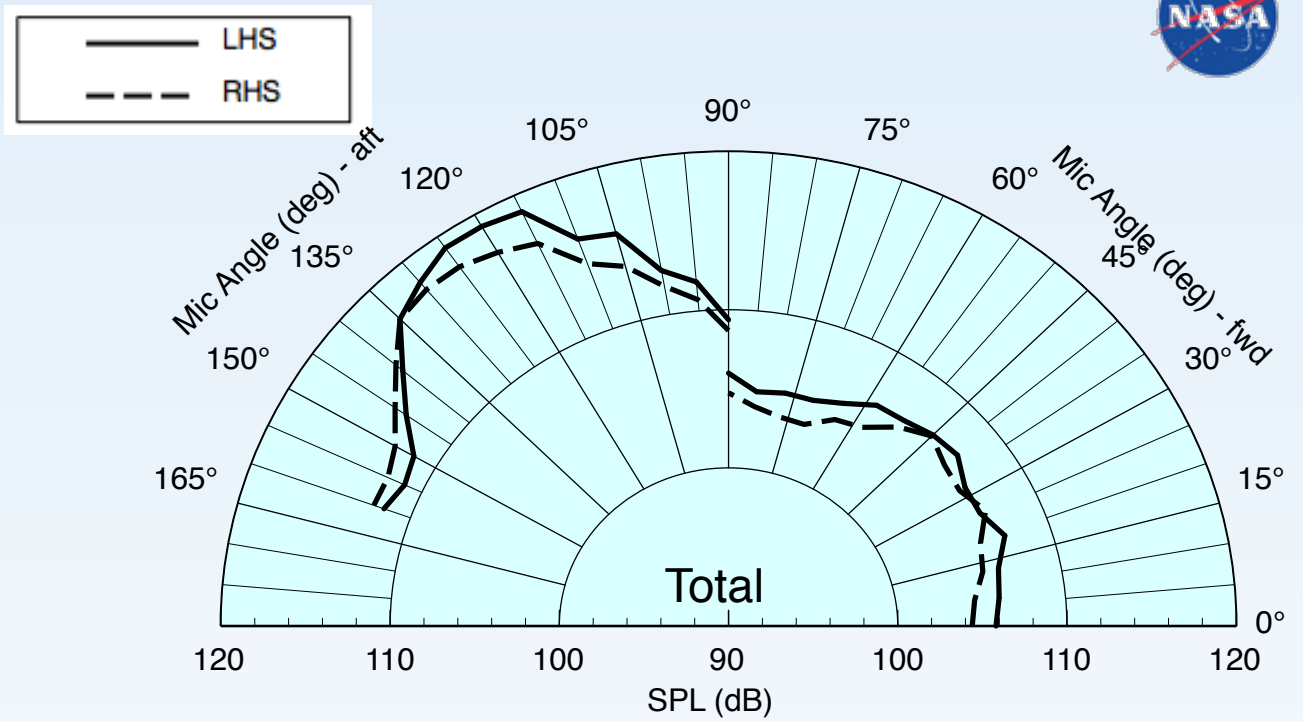


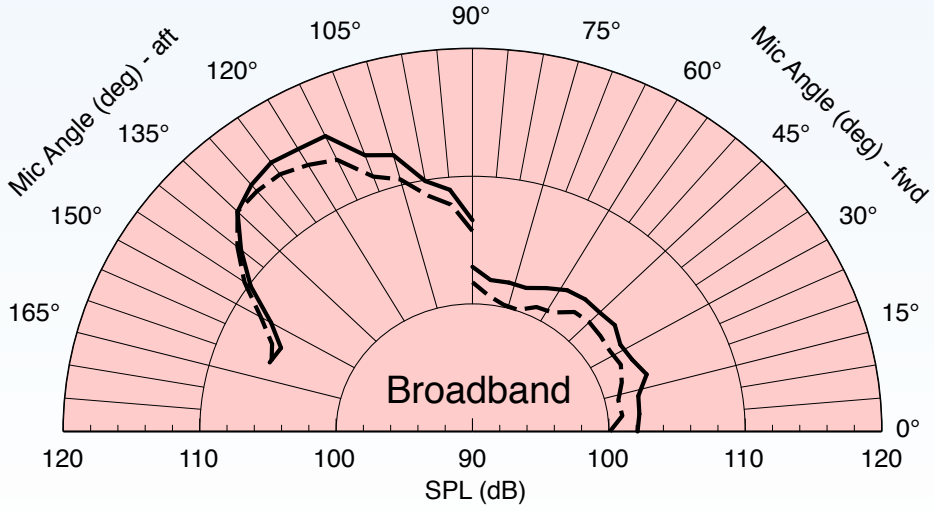
Fwd Mic @ 38.6° / 92.5% RPMc-Fan

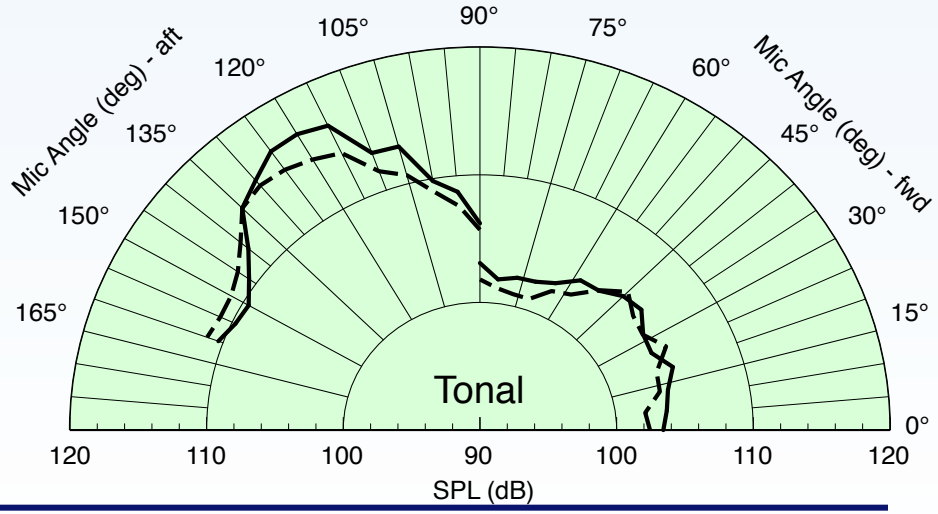


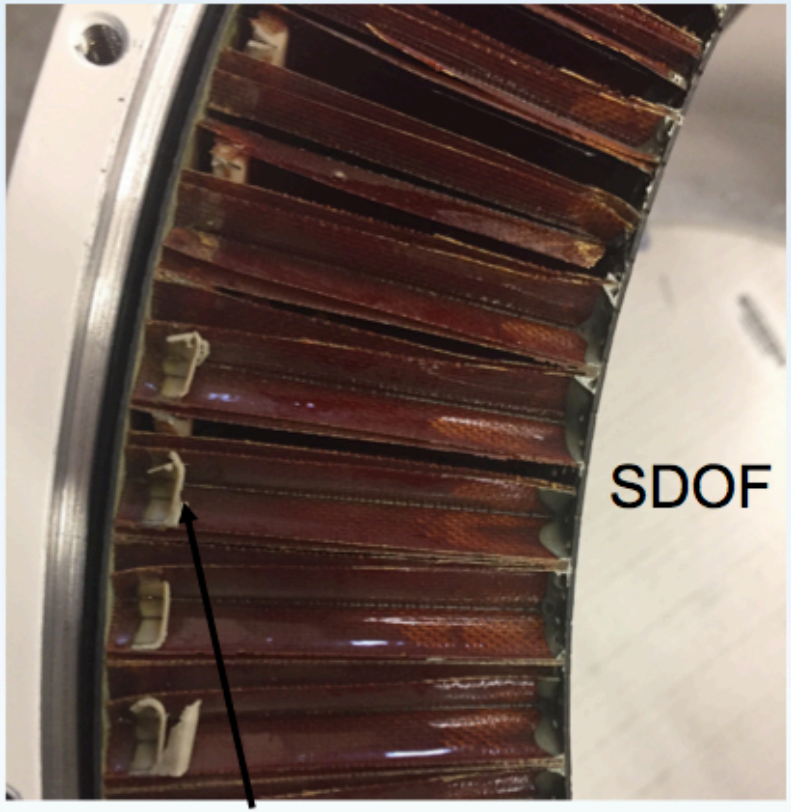
Aft Mic @ 125.0° / 92.5% RPMc-Fan


LHS
RHS

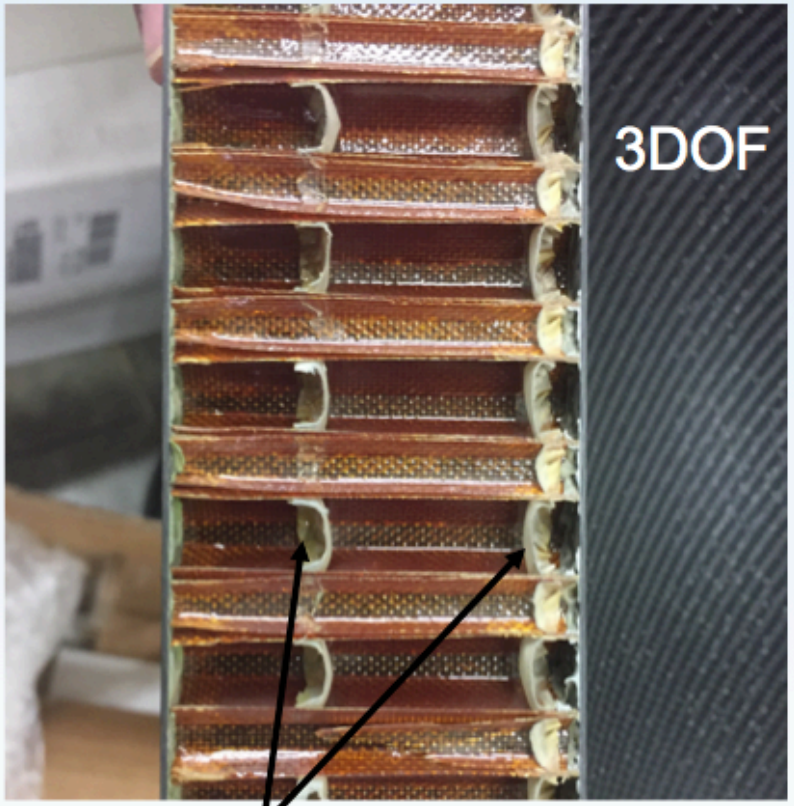

LHS
RHS
Total
Mic Angle (deg) - aft
Mic Angle (deg) - fwd
90°
105°
75°
120°
60°
135°
45°
150°
30°
165°
15°
0°
120
110
100
90
100
110
120
SPL (dB)


Broadband
Mic Angle (deg) - aft
Mic Angle (deg) - fwd
90°
105°
75°
120°
60°
135°
45°
150°
30°
165°
15°
0°
120
110
100
90
100
110
120
SPL (dB)

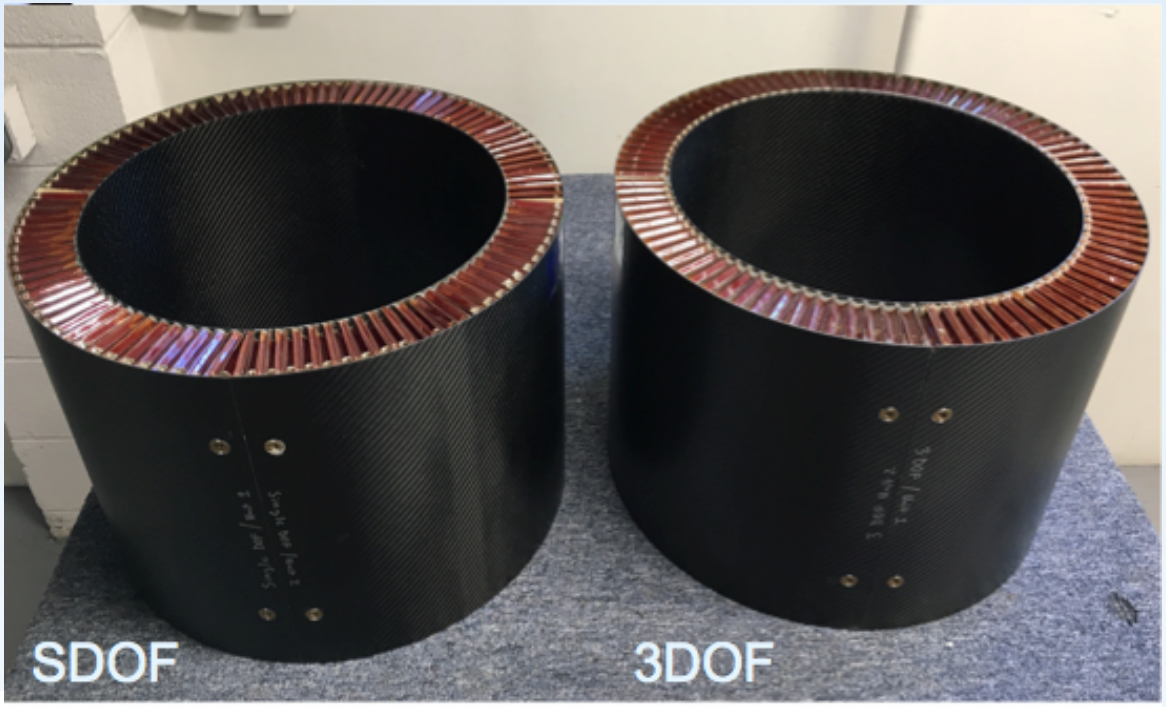

Tonal
Mic Angle (deg) - aft
Mic Angle (deg) - fwd
90°
105°
75°
120°
60°
135°
45°
150°
30°
165°
15°
0°
120
110
100
90
100
110
120
SPL (dB)

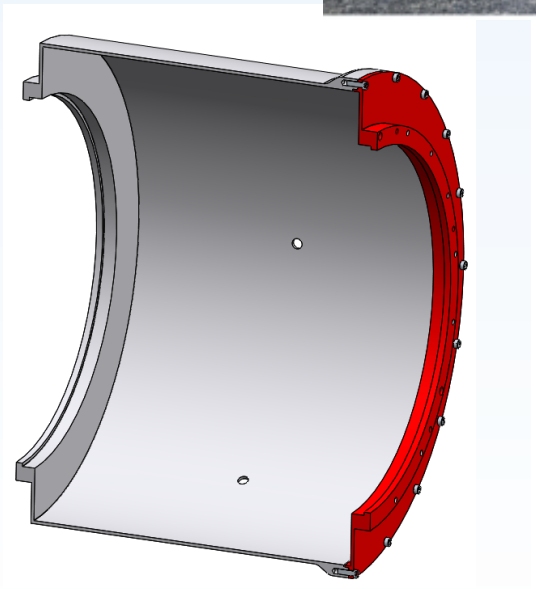


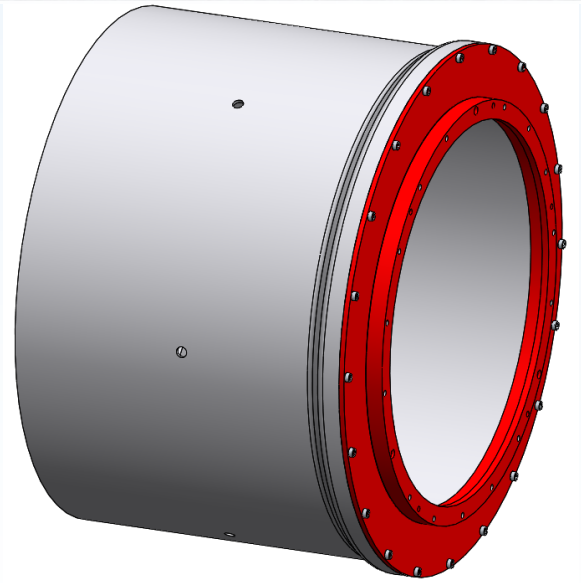
Septa: very high resistance
Essentially HW to set cavity depth

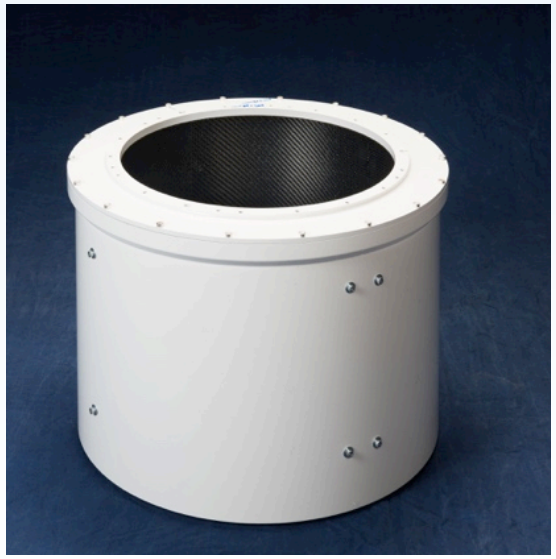


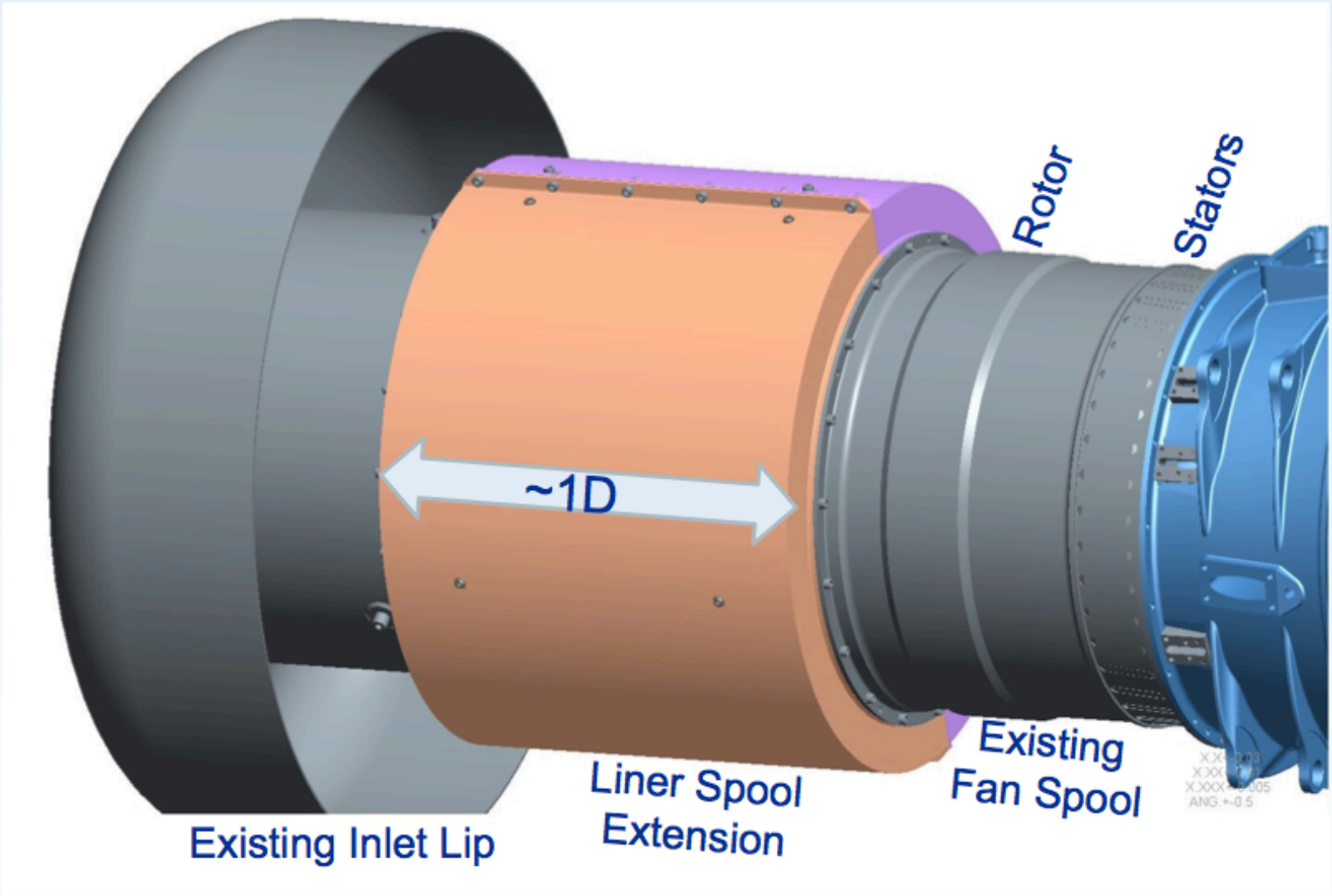
Septa: specified resistance
To create 3 cavities

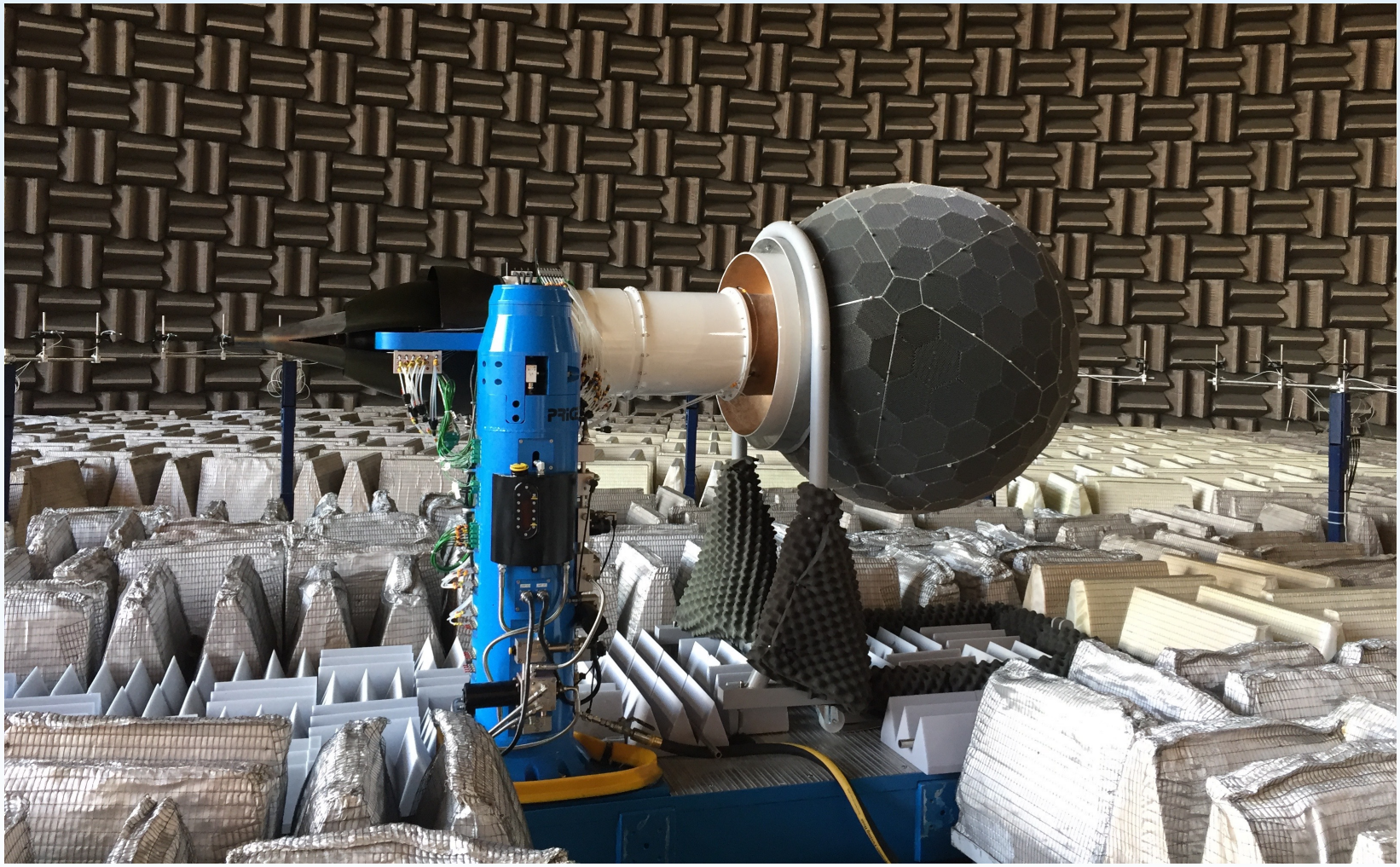

SDOF
3DOF

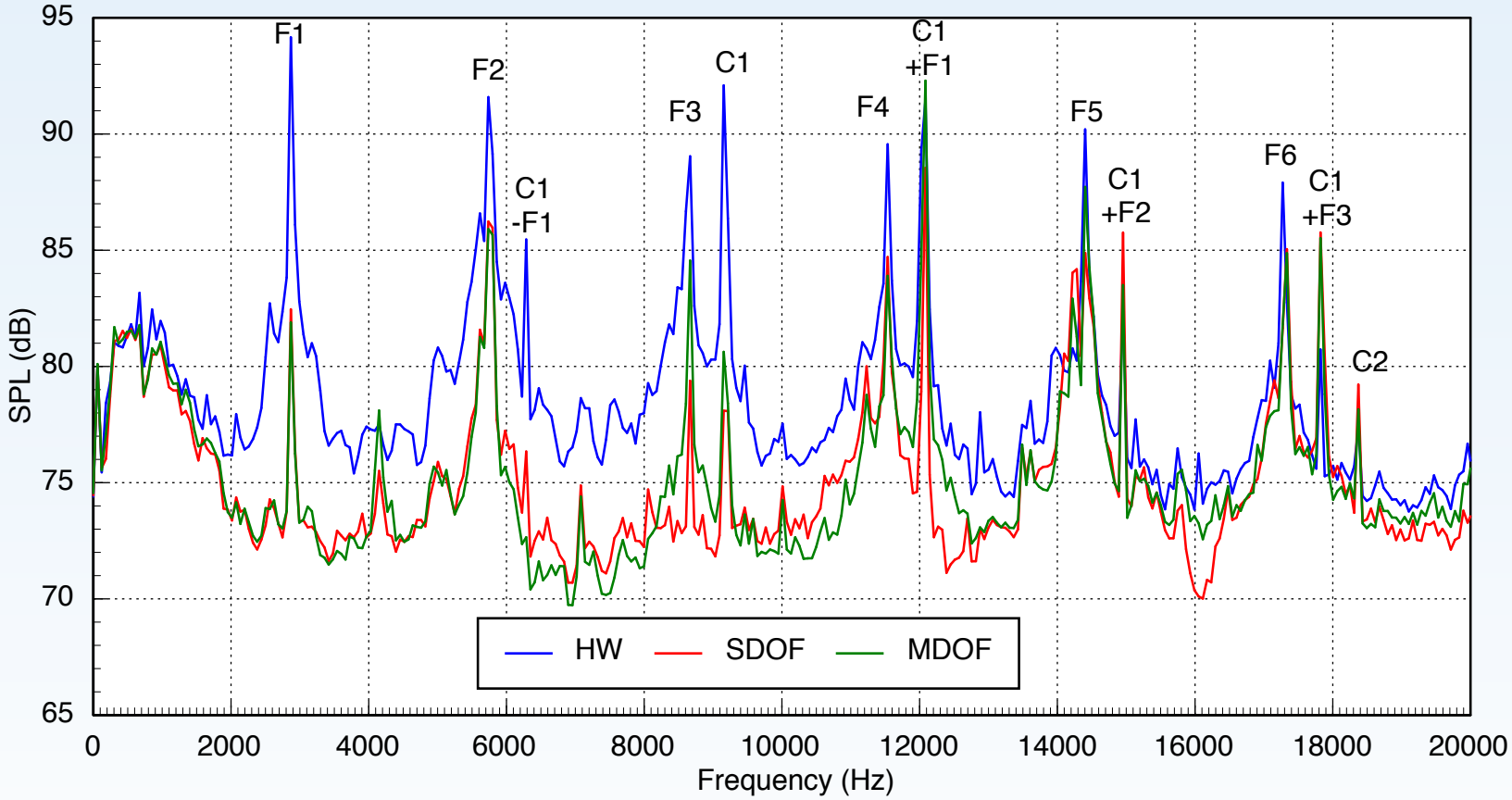


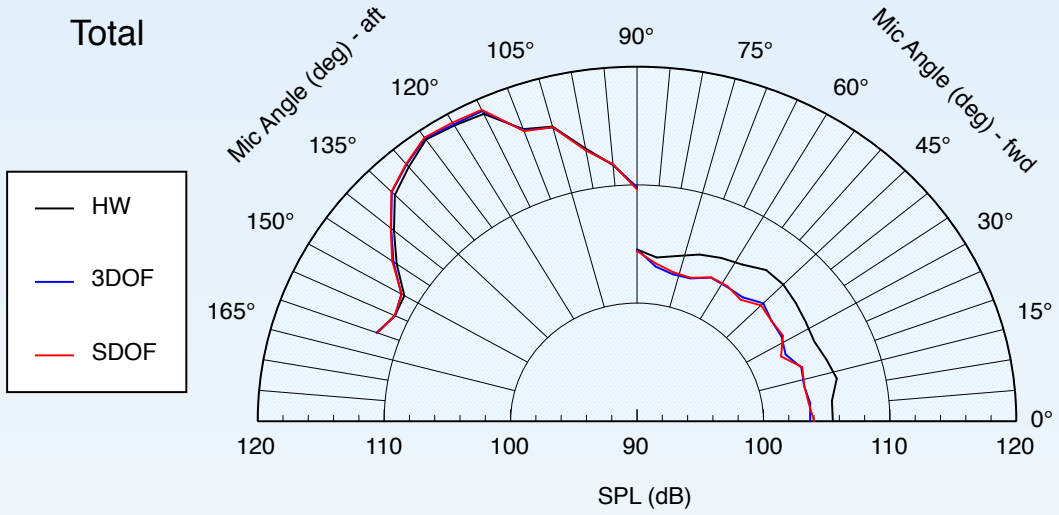


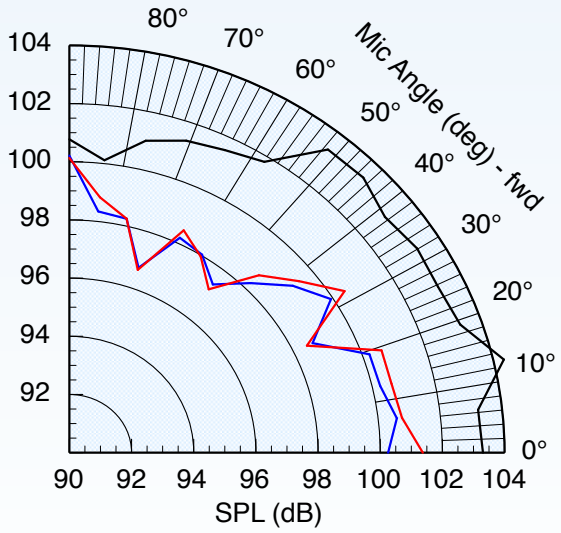


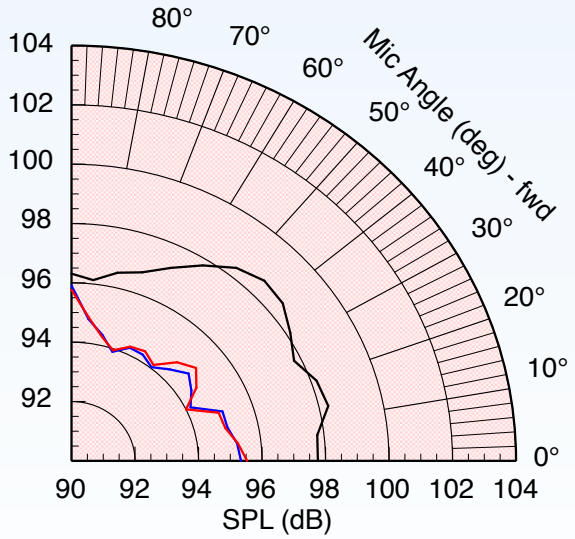

Rotor
Stators
~1D
Existing Inlet Lip
Liner Spool Extension
Existing Fan Spool

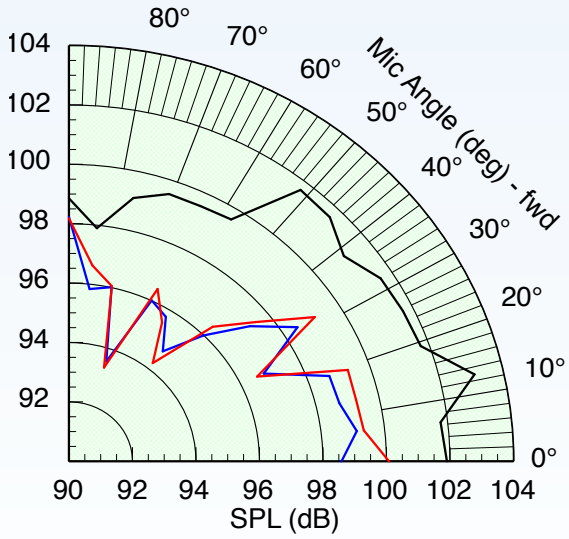



F1
F2
C1
-F1
F3
C1
F4
C1
+F1
F5
C1
+F2
F6
C1
+F3
C2
HW
SDOF
MDOF
SPL (dB)
Frequency (Hz)
95
90
85
80
75
70
65
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000


Total
HW
3DOF
SDOF
Mic Angle (deg) - aft
Mic Angle (deg) - fwd
105°
90°
75°
120°
60°
135°
45°
150°
30°
165°
15°
0°
120
110
100
90
100
110
120
SPL (dB)


80°
70°
60°
50°
40°
30°
20°
10°
0°
Mic Angle (deg) - fwd
104
102
100
98
96
94
92
90
92
94
96
98
100
102
104
SPL (dB)


80°
70°
60°
50°
40°
30°
20°
10°
0°
Mic Angle (deg) - fwd
104
102
100
98
96
94
92
90
92
94
96
98
100
102
104
SPL (dB)


80°
70°
60°
50°
40°
30°
20°
10°
0°
Mic Angle (deg) - fwd
104
102
100
98
96
94
92
90
92
94
96
98
100
102
104
SPL (dB)


NASA



QUESTIONS ?

