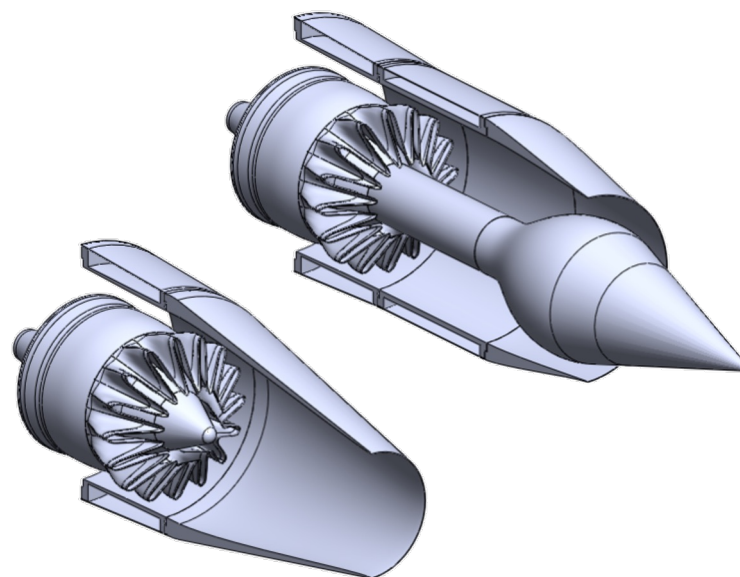


# Empirical Noise Modeling of Internally Mixed Exhaust Systems

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# Motivation

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Civil supersonic market depends upon accurate prediction of LTO noise at the level of system studies.



Commercial Supersonic Vehicles have propulsion needs that are different from conventional aircraft.

- Performance requirements dictate lower bypass ratios, internally mixed exhaust systems with variable nozzle geometry.

No empirical noise code is publicly available to predict noise of internally mixed nozzles.

# Empirical noise models for internally mixed exhaust noise



Few publicly available prediction methods exist for internally mixed exhaust systems.

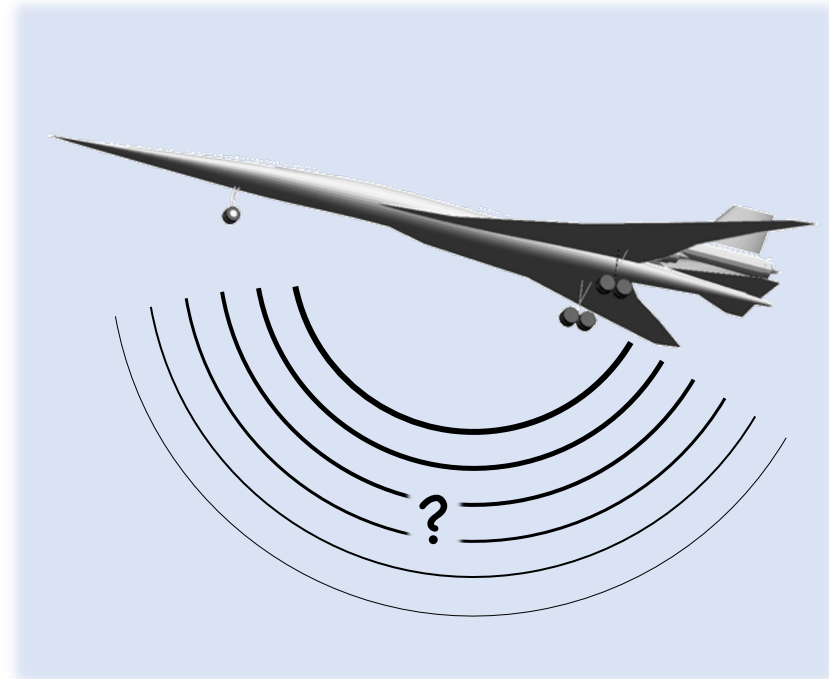
Garrison, Mengle, and Dalton, and by Tester and Fisher in 2002-2006.

- Described testing and anomalies in data acquired at NASA
- Described empirical models developed for proprietary use.

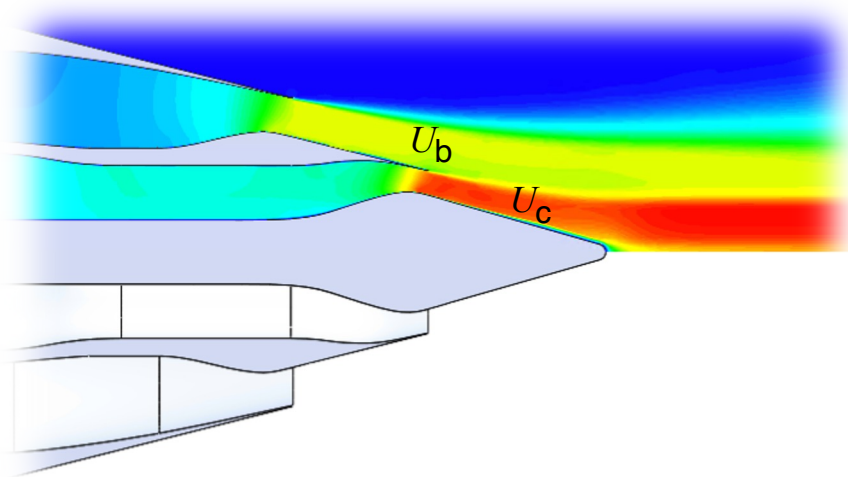
This paper documents a new empirical noise prediction method for internally mixed nozzles and quantifies of its error.

Desired attributes of method:

- Applicable to high-speed civil aircraft
- Fast, Robust
- Minimal input parameters
- Documented uncertainty

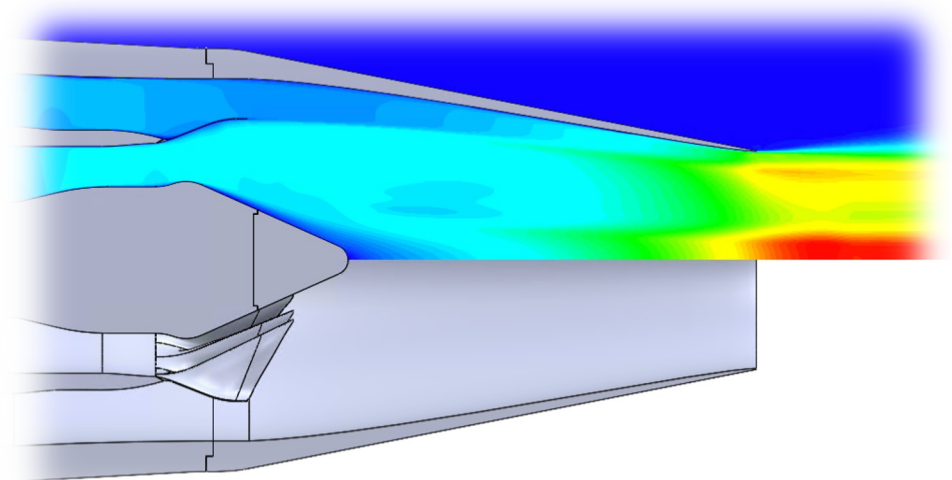


# Exhaust systems for turbofan engines and their noise sources



## Separate Flow

- Minimally coupled shear layers
- Continuously contracting
- External mixing noise sources, minimal interaction with surfaces



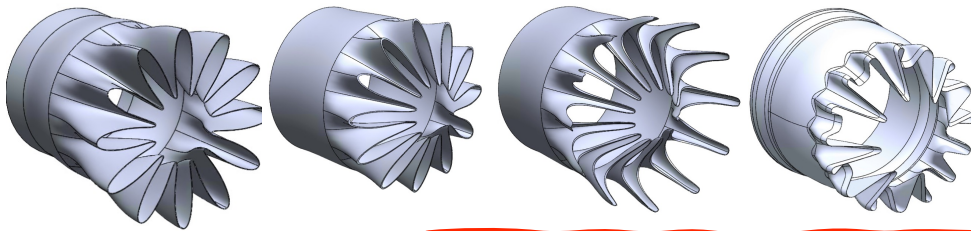
## Internally Mixed

- Coupled internal and external shear layers
- Divergent surfaces can produce separation
- Internal sources w/acoustic resonator
- External mixing noise sources, plus potential trailing edge sources, plus unsteady separation, plus...



# Geometric parameters of internally mixed exhaust systems

Mixer designs can be very complicated.

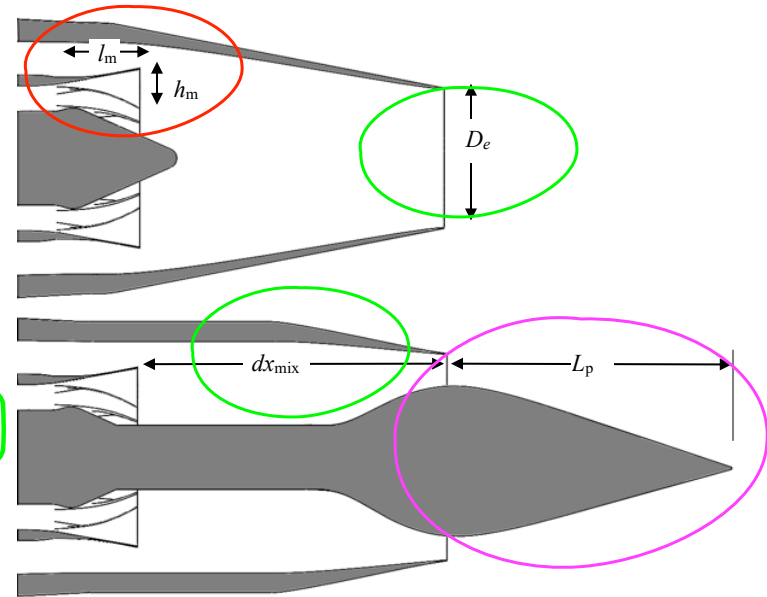


Basic mixer parameters: **lobe height  $h_m$**  and **lobe length  $l_m$** .

–  $h_m/l_m$  corresponds to divergence angle of lobes.

Basic nozzle parameters: **exit area** and **mixing length  $dx_{mix}$** .

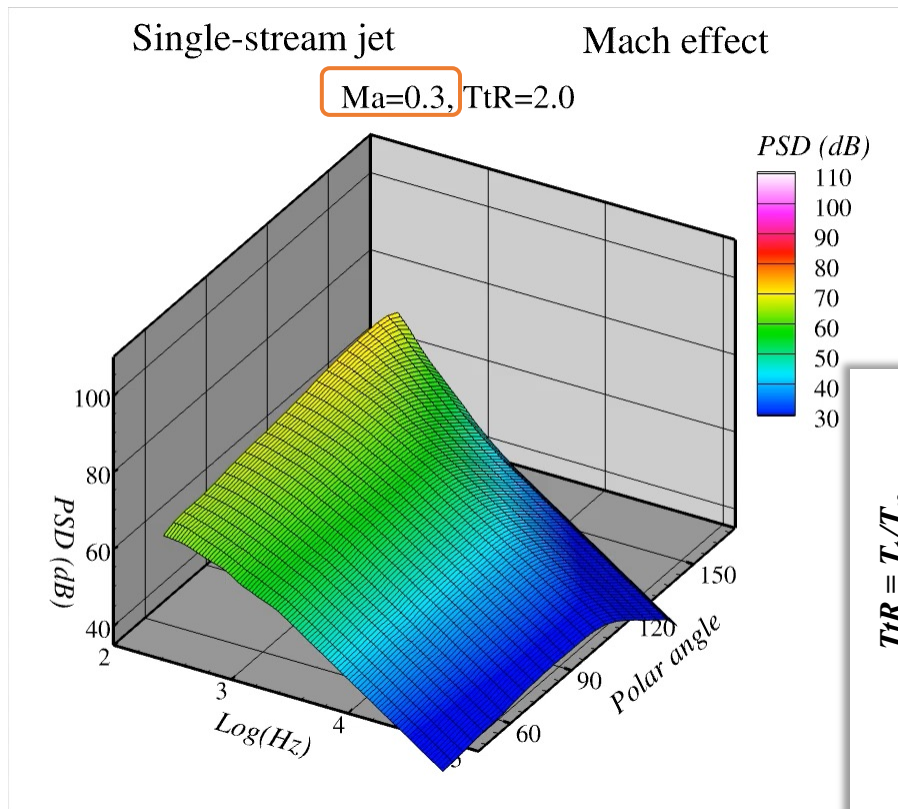
Basic plug parameters: **int/ext** and **external length  $L_p$**



- Legacy database varied #lobes, lobe divergence, nozzle length
- Plug20 database varied int/ext plug, nozzle length, plug length



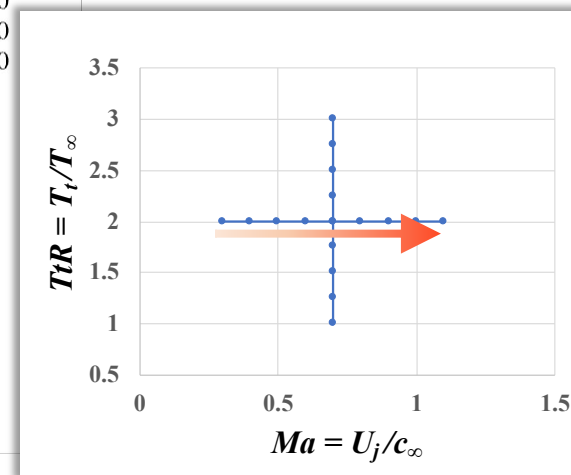
# Jet Noise Modeling—Mixing noise, Single-stream jet



Mixing noise of a single-stream jet governed by two flow parameters:

- acoustic Mach number  $Ma$  and
- temperature ratio  $TtR$

Sound power varies as  $Ma^8$ .  
Note how spectral directivity changes with increasing  $Ma$ .

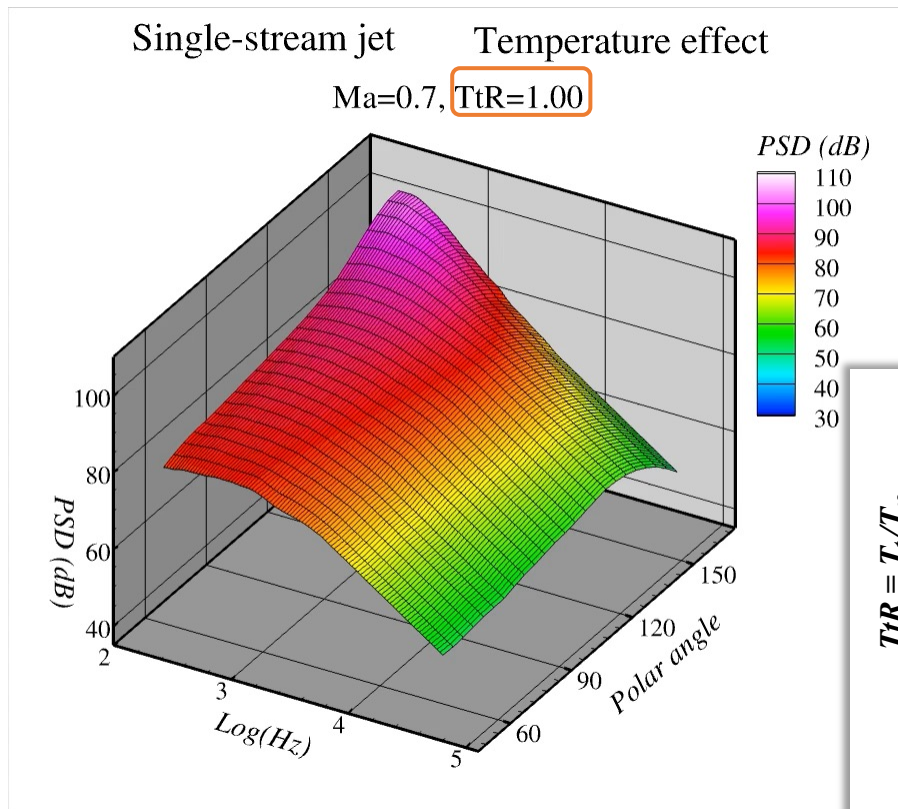


Empirical model *sjet*.

See Khavaran, A., and Bridges, J., “Development of Jet Noise Power Spectral Laws Using SHJAR Data” AIAA 2009-3378.



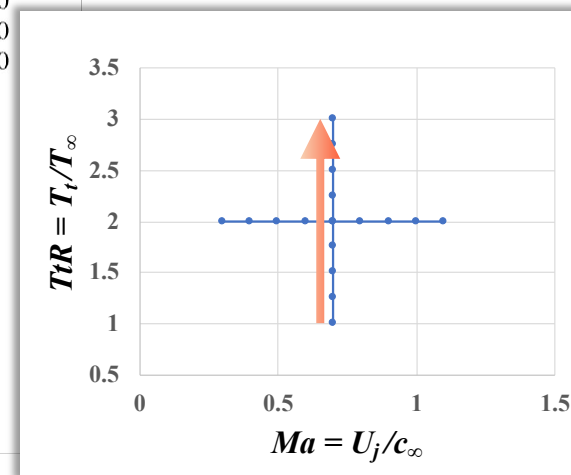
# Jet Noise Modeling—Mixing noise, Single-stream jet



Mixing noise of a single-stream jet governed by two flow parameters:

- acoustic Mach number  $Ma$  and
- temperature ratio  $TtR$

Sound power relatively constant with  $TtR$ .  
Note how spectral directivity changes with increasing  $TtR$ .



Empirical model *sjet*.

See Khavaran, A., and Bridges, J., “Development of Jet Noise Power Spectral Laws Using SHJAR Data” AIAA 2009-3378.



## Turbulent kinetic energy of internally mixed nozzles

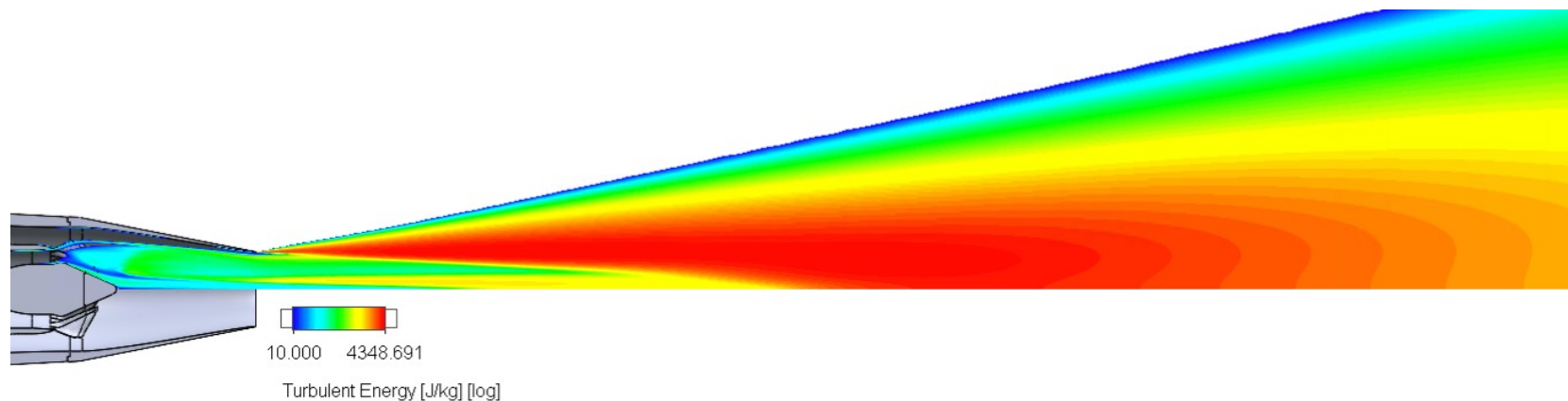
Flow external to nozzle is similar to turbulent plume of single-stream nozzle.

- A few extra flow features, but not very energetic, especially if mixer is effective.

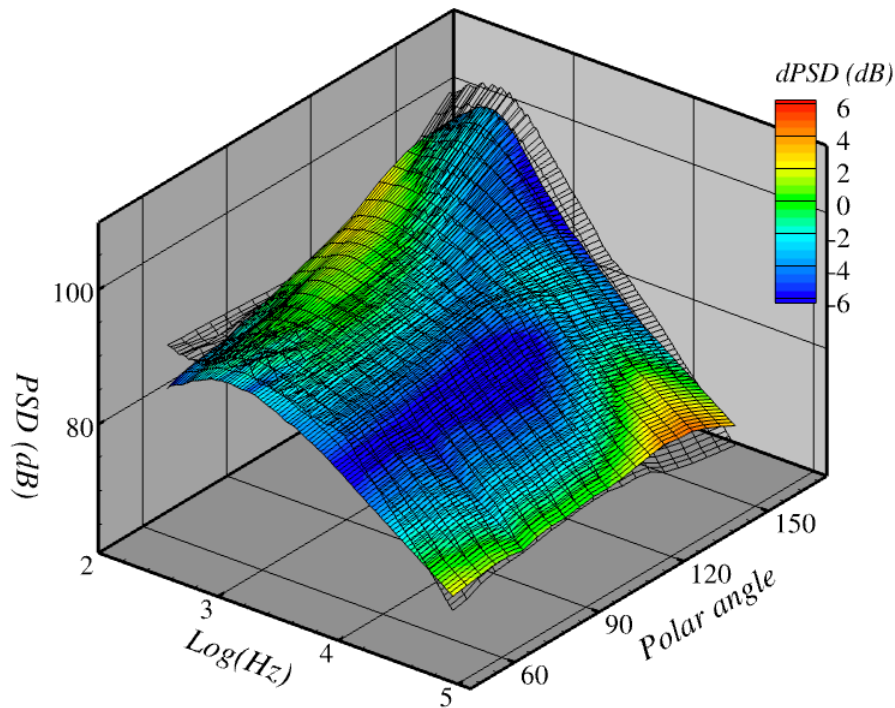
Turbulent energy inside nozzle is very small relative to outside nozzle.

- Using same scaling as external mixing noise, mixing noise from TKE inside is insignificant.

Therefore, assume noise is similar to that of single-stream jet with flow of both streams fully mixed.



# Noise prediction: single-stream jet using $Ma_{\text{mix}}, T_j/T_\infty: PSD_{1S}$



88.03 EPNdB  
84.71 EPNdB

$Ma_{\text{mix}}$  is mass-averaged, fully expanded core and bypass velocities normalized by ambient speed of sound.

$T_j/T_\infty$  is mass-averaged core and bypass total temperature normalized by ambient temperature.

*Example:*

*Lobed mixer, internal plug*

$$NPR_c = NPR_b = 1.8$$

$$TtR_c = 2.9$$

$$TtR_b = 1.2$$

$$BPR = 3.7$$

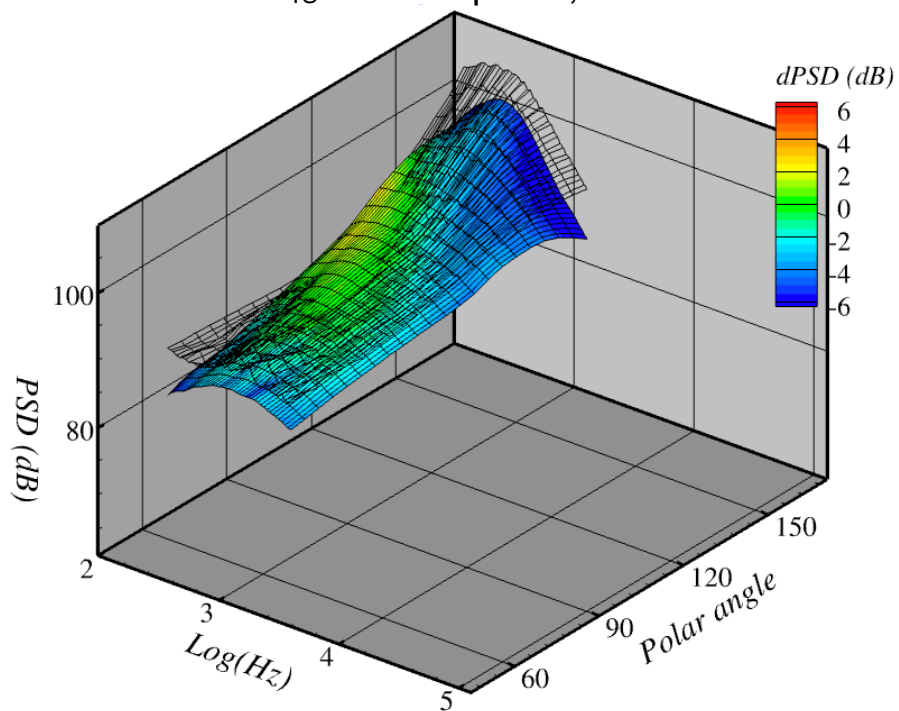
$$Ma_{\text{mix}} = 1.07$$

$$TtR_{\text{mix}} = 1.55$$

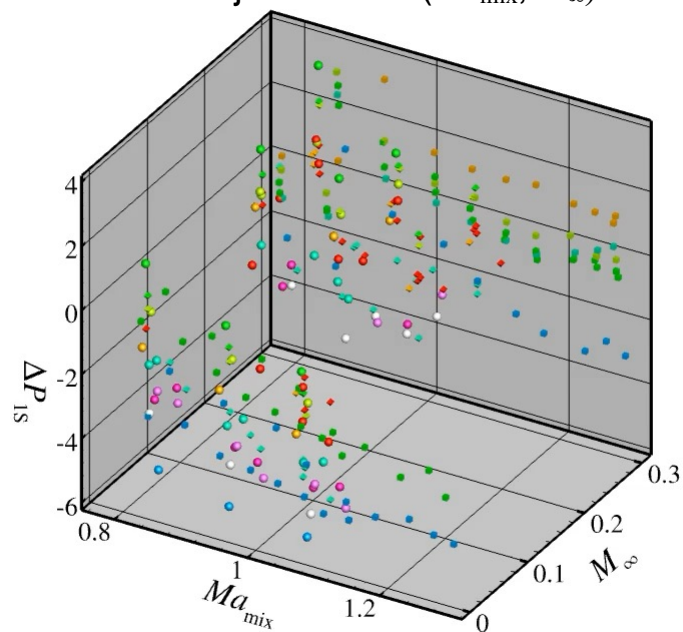


# Improved single-stream jet for noise—match low frequency power

$P_{1S}$  = Sound power,  $St < 1$



$\Delta P_{1S} = P_{1S, \text{sjet}} - P_{1S, \text{Data}}$   
Projected onto  $(Ma_{\text{mix}}, M_{\infty})$

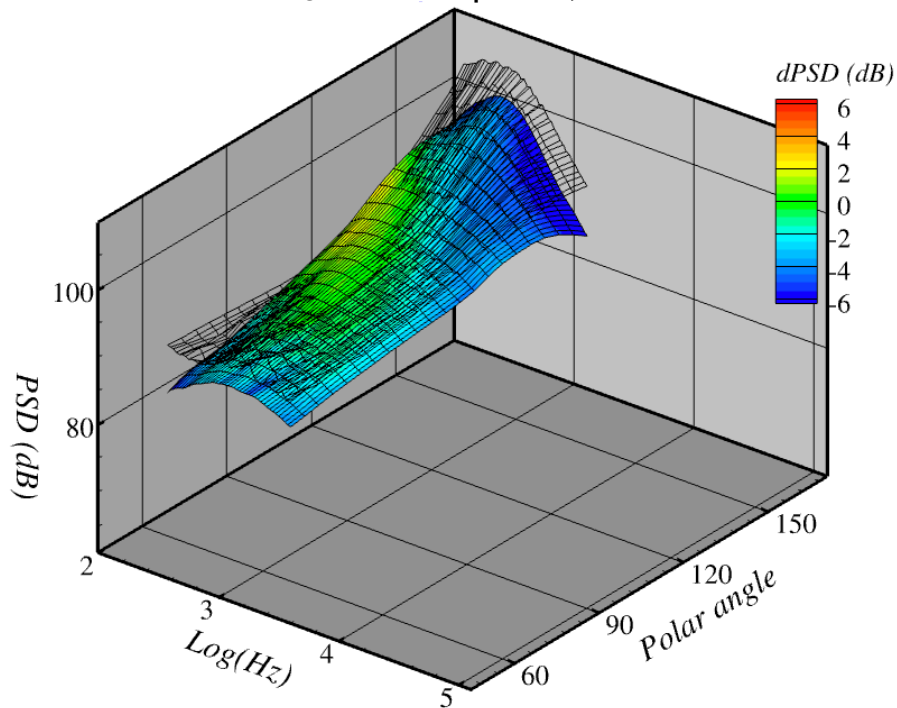


Colors indicate different nozzle geometries

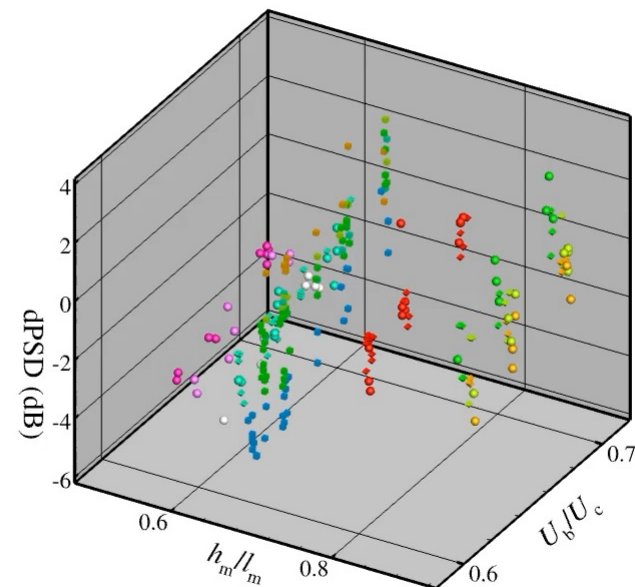
# Improved single-stream jet for noise—match low frequency power



$P_{1S}$  = Sound power,  $St < 1$



$\Delta P_{1S} = P_{1S, \text{sjet}} - P_{1S, \text{Data}}$   
Projected onto  $(h_m/l_m, U_b/U_c)$

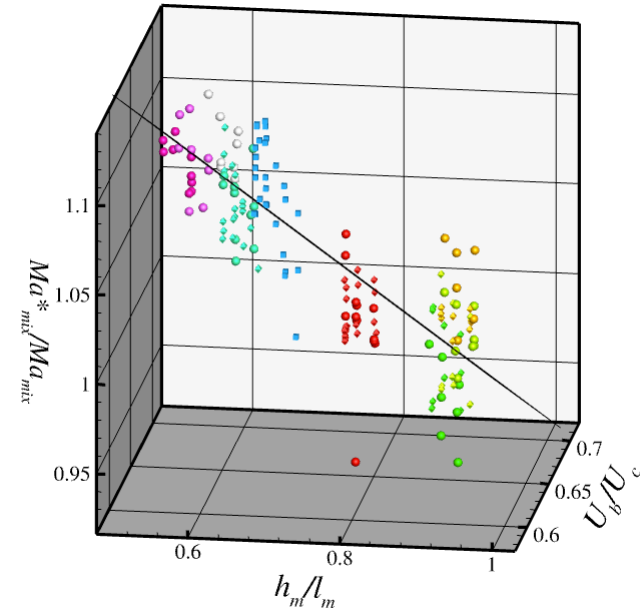
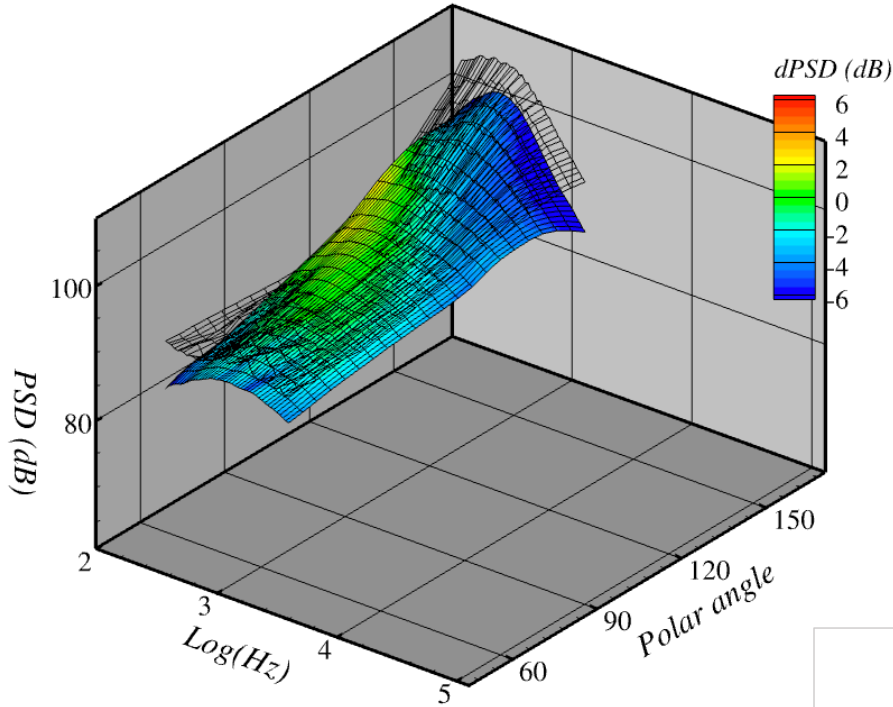


Colors indicate different nozzle geometries



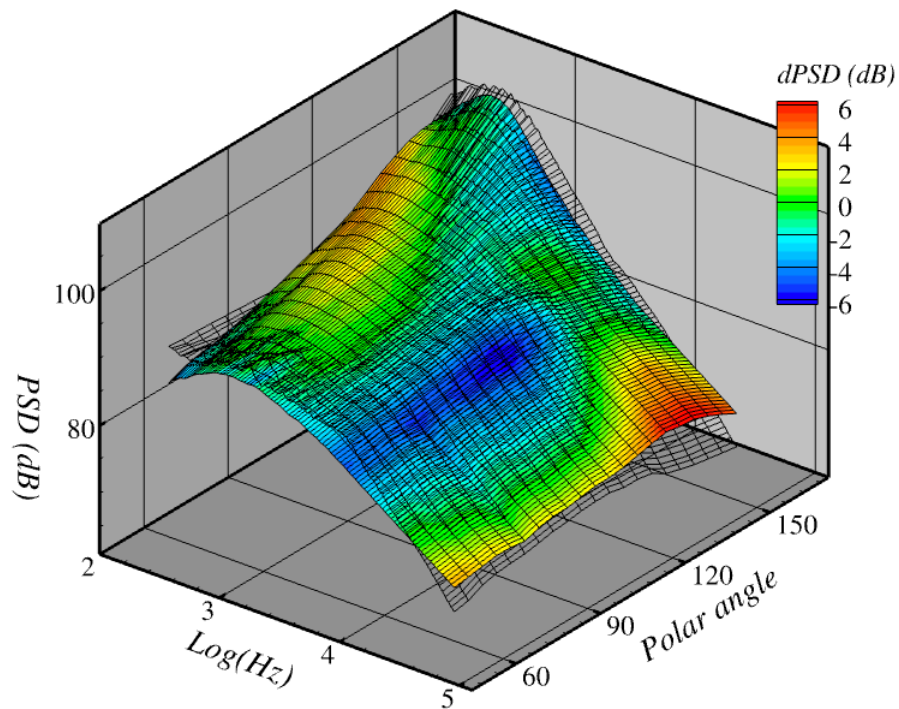
# Improved single-stream jet for noise—modify $Ma_{mix}$

$P_{1s}$  = Sound power,  $St < 1$



$$Ma_{mix}^* = \frac{Ma_{mix}}{\left(1 - \left(0.66(1 - U_b/U_c) - 0.3(h_m/l_m)\right)\right)}$$

# Noise prediction: single-stream jet using $Ma_{\text{mix}}^*$ , $T_j/T_\infty$ : $PSD_{1S}^*$



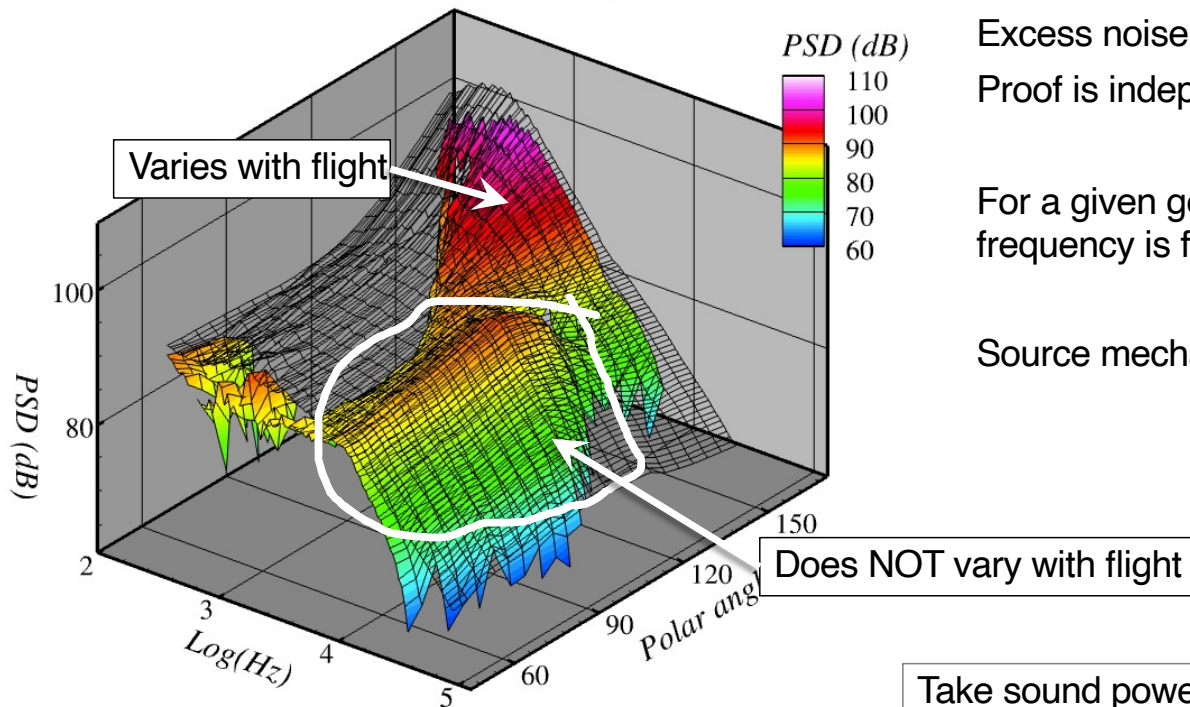
- Good fit for low frequency, aft peak of PSD.
- Now looking at underprediction at forward angles, higher frequencies.

88.03 EPNdB

86.52 EPNdB



# Subtracting $PSD_{1S}^*$ from Data: 'excess noise'



Excess noise is generated internal to nozzle.  
Proof is independence to flight. (see ref below)

For a given geometry, peak directivity and peak frequency is fixed.

Source mechanism? How to model?

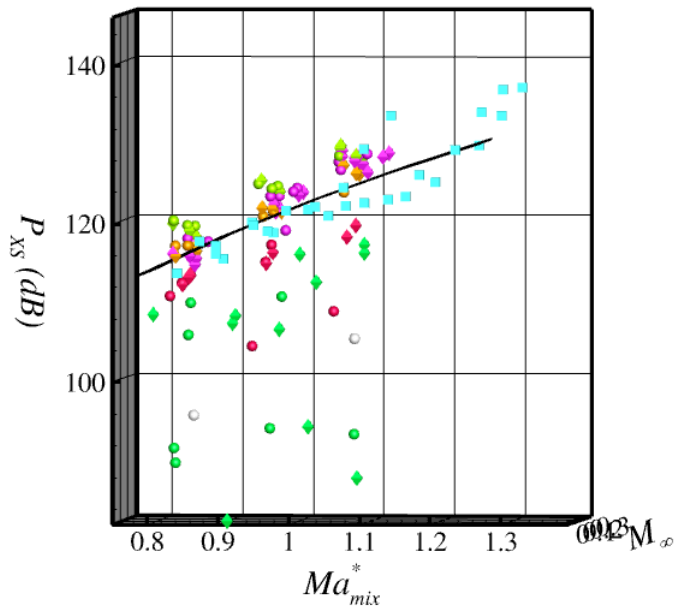
Take sound power in high frequency portion...

Bridges, J., "Diagnosing Noise Features of Internally Mixed, External Plug Exhaust Systems," *AIAA 2023-3210*

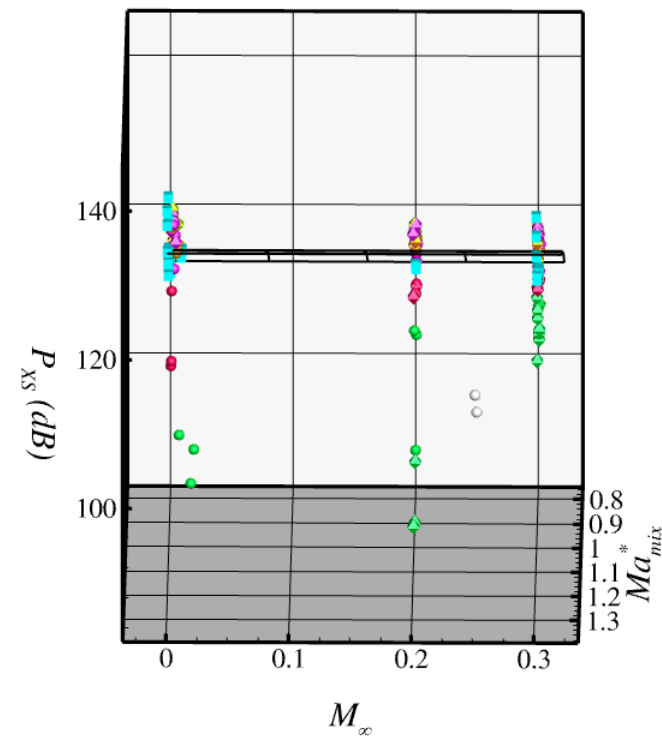
# Scaling of excess noise power $P_{XS}$



$(Ma_{mix}^*)^8$  scaling



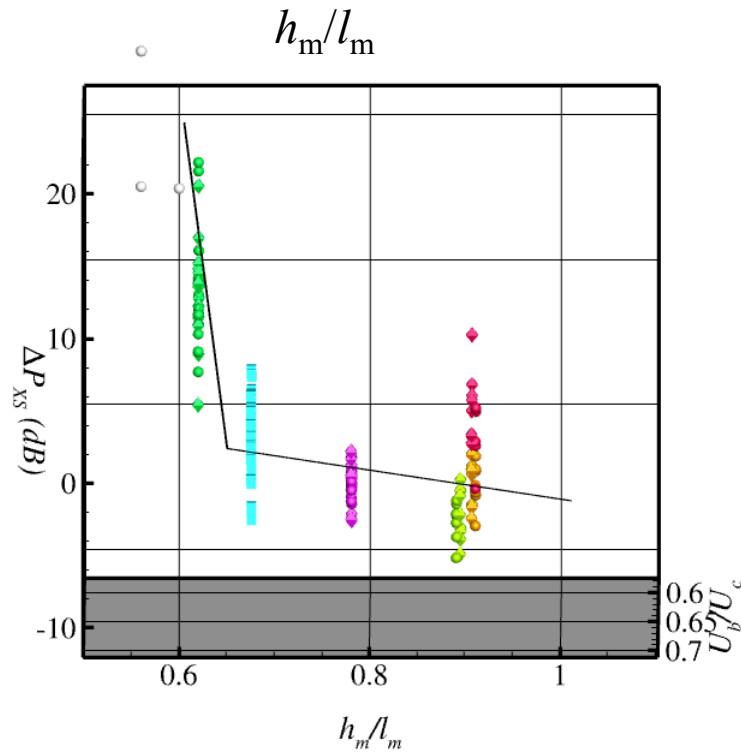
No  $M_\infty$  dependence



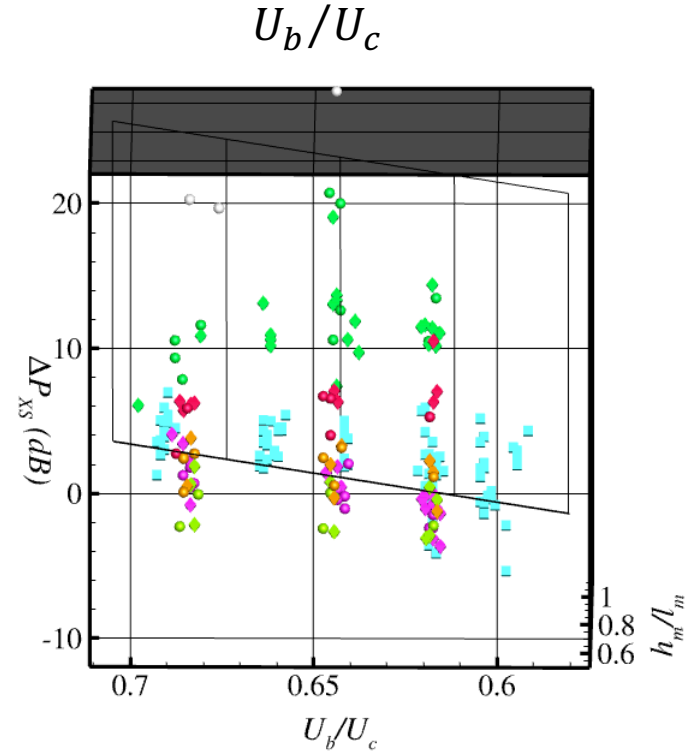
# Scaling of $P_{XS}$ after $(Ma_{mix}^*)^8$ trend removed: $\Delta P_{XS}$



Dependence on lobe divergence



Dependence on velocity ratio





## Model for $PSD_{XS}$

Model for  $PSD_{XS}$  features:

Amplitude dependent on flow parameters  $Ma_{mix}^*$ ,  $U_b/U_c$  and geometric parameters  $h_m/l_m$  and presence of external plug.

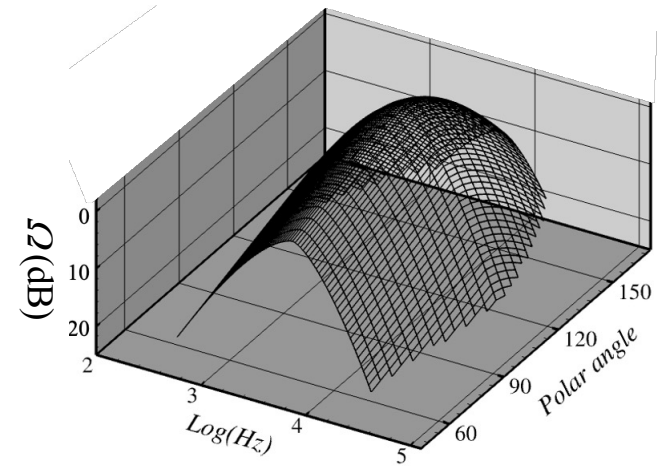
Peak frequency that is independent of polar angle.

Peak frequency and polar angle depend on  $dx_{mix}$  and presence of external plug.

Shape is modified Gaussian in frequency and angle.

$$PSD_{XS}(f, \phi) = \left[ 80 \log_{10}(Ma_{mix}^*) + \alpha \left( \frac{h_m}{l_m} - 0.65 \right) + 40 \left( \frac{U_b}{U_c} - 0.65 \right) + 6\mathcal{H}(l_p) + 89 \right] \Omega(f, \phi).$$

$$\alpha = \begin{cases} 500, & h_m/l_m < 0.65 \\ 10, & h_m/l_m \geq 0.65 \end{cases}$$

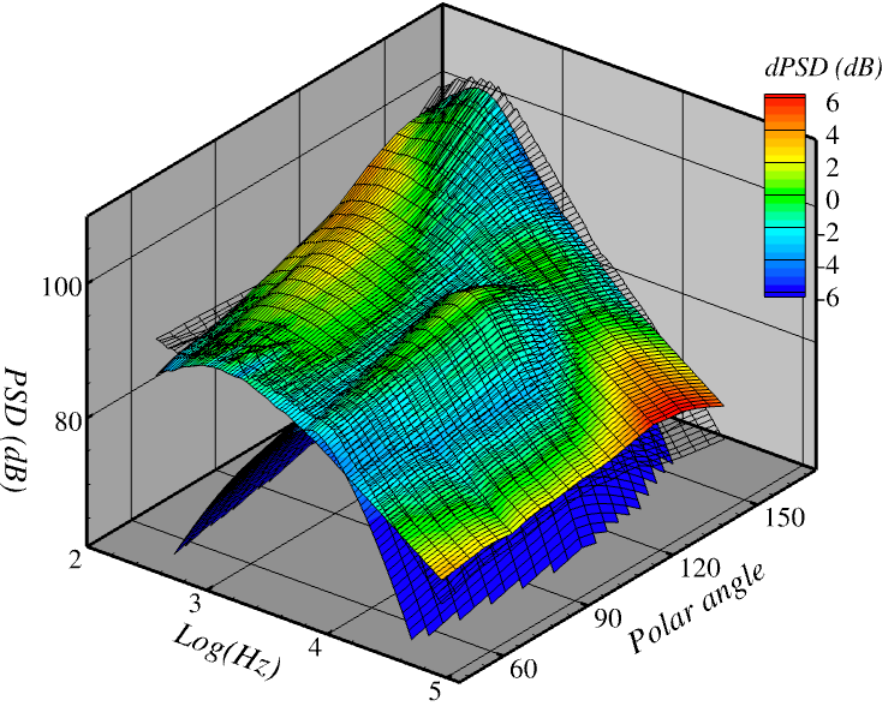


Peak of  $\Omega$  in frequency and polar angle:

$$f_{XS} = 1610/dx_{mix}$$

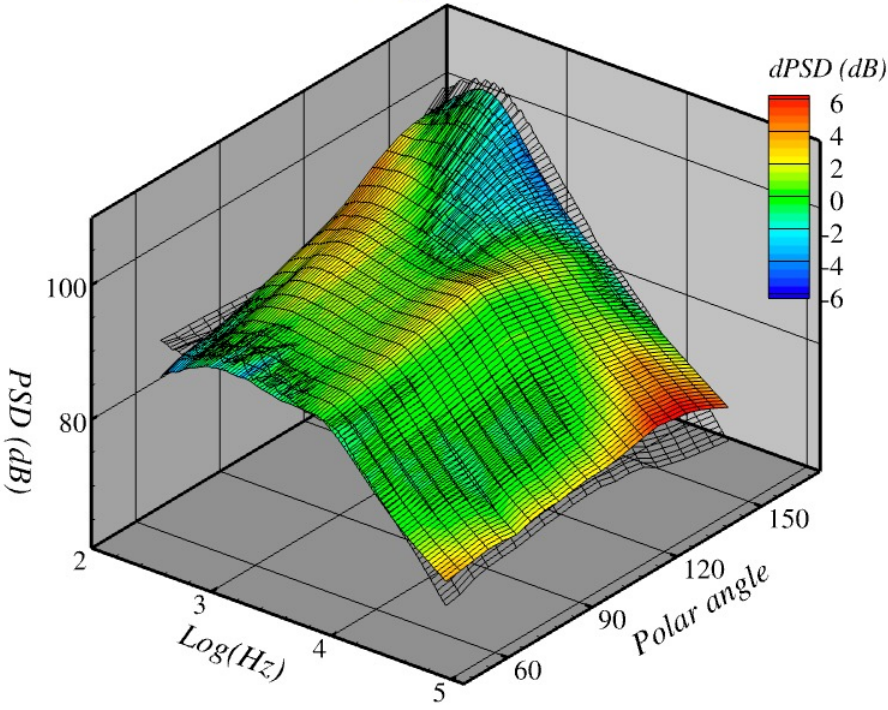
$$\phi_{XS} = \begin{cases} 110^\circ, & \text{if internal plug} \\ 120^\circ, & \text{if external plug} \end{cases}$$

# Add $PSD_{1S}^* + PSD_{XS}$





# Total noise prediction: $PSD_{2S}$



Not perfect, but good enough over most  $(f, \phi)$  to give good EPNL prediction!

88.03 EPNdB  
88.17 EPNdB



## Possible noise mechanism for excess (internal) noise

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Turbulent energy internal to nozzle too little to create observed excess noise levels mixing noise.

- More efficient mechanism required.

Abrupt onset of excess noise with mixer lobe divergence suggests separation of flow on lobes may be key.

Frequency dependence (dependent on geometry, not flow) hints that phenomenon is controlled by internal acoustic modes.

- Effect is accentuated with abrupt contraction of external plug.

Phase distortion in feedback due to turbulence and high azimuthal order lobes prohibit phase-locked resonance.

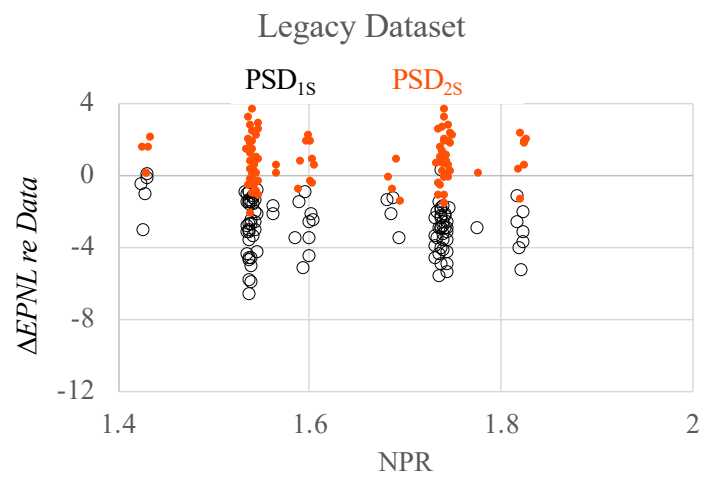
- Axisymmetric splitters do reach locked resonance—tonal excess noise

### Possible mitigation methods

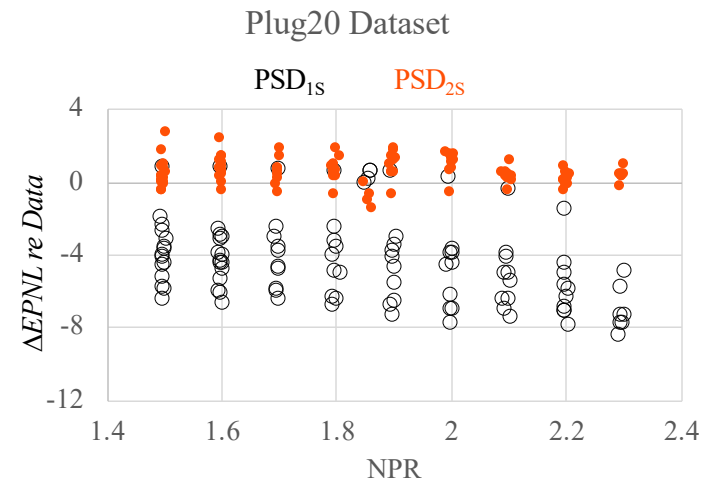
- Lower mixer lobe divergence to eliminate unsteady separation.
  - (But too low as this increases the noise of the equivalent single-stream jet!)
- Use acoustic duct mode tool to tailor acoustic response of nozzle.
- Use acoustic liner in nozzle to reduce acoustic resonance.



# Statistical results for error of $PSD_{2s}$ in predicting EPNL



	PSD <sub>1s</sub>	PSD <sub>2s</sub>
Mean	-3.08	0.72
Std dev	1.45	1.52



	PSD <sub>1s</sub>	PSD <sub>2s</sub>
Mean	-4.75	0.85
Std dev	2.52	1.12



## Summary

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Jet noise will be a major challenge for future commercial supersonic air transportation.

Accurate empirical noise models with documented uncertainty is critical to initial studies, conceptual designs, and regulatory groups.

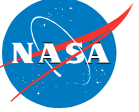
New empirical model created for noise from internally mixed exhaust systems.

- Based primarily on historical experimental data from NASA APL jet noise facility with 8 variations in mixer design and 4 nozzle lengths.
- Validated and extended for external plug configurations on recent tests of supersonic-specific designs and flows.

Total model consists of an external noise model plus a model for an internal noise component.

- The external noise model is a generic single-stream model with new modified input, based on fully mixed flow parameters and mixer geometry.
- The internal noise model is primarily dependent on internal nozzle and mixer geometry, and is expressed analytically.

The new noise model is fully described in the paper.





## Abstract

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There appear to be no non-proprietary methods to predict the noise of internally mixed exhaust systems, and no guidance for how to adapt known jet noise models for these configurations. This paper surveys literature and historical databases acquired at NASA Glenn's Aero-Acoustic Propulsion Lab to give such guidance. The core premise is that an exhaust system with well-designed mixer produces noise that is to first approximation the same as a fully-mixed jet flow. Refinement of what is meant by a “fully mixed jet” can lead to more accurate prediction of the main jet noise. Additional noise is often generated within the nozzle, typically at high frequencies, whose source mechanism(s) are not obvious. However, a noise prediction method can be established that captures some aspects of the excess noise and provide an estimate of the total jet noise. Explorations of source mechanisms associated with the internal mixer have led to a new noise model which includes the effects of having an external plug nozzle, a feature desirable for near-term supersonic aircraft. Statistical analysis of historical data is provided to estimate the uncertainty in using this method given the variations found that cannot be directly computed without detailed mixer geometry.