# DART Core/Combustor-Noise Initial Test Results

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**Presented at the Acoustics Technical Working Group Meeting**
**Cleveland, Ohio, October 17-18, 2017**

## Summary

Contributions from the combustor to the overall propulsion noise of civilian transport aircraft are starting to become important due to turbofan design trends and advances in mitigation of other noise sources. Future propulsion systems for ultra-efficient commercial air vehicles are projected to be of increasingly higher bypass ratio from larger fans combined with much smaller cores, with ultra-clean burning fuel-flexible combustors. Unless effective noise-reduction strategies are developed, combustor noise is likely to become a prominent contributor to overall airport community noise in the future. The new NASA DGEN Aeropropulsion Research Turbofan (DART) is a cost-efficient testbed for the study of core-noise physics and mitigation. This presentation gives a brief description of the recently completed DART core/combustor-noise baseline test in the NASA GRC Aero-Acoustic Propulsion Laboratory (AAPL). Acoustic data was simultaneously acquired using the AAPL overhead microphone array in the engine aft quadrant far field, a single mid-field microphone, and two semi-infinite-tube unsteady pressure sensors at the core-nozzle exit. An initial assessment shows that the data is of high quality and compares well with results from a quick 2014 feasibility test. Combustor-noise components of measured total-noise signatures were educed using a two-signal source-separation method and are found to occur in the expected frequency range. The research described herein is aligned with the NASA Ultra-Efficient Commercial Transport strategic thrust and is supported by the NASA Advanced Air Vehicle Program, Advanced Air Transport Technology Project, under the Aircraft Noise Reduction Subproject.

The overarching goal of the Advanced Air Transport Technology (AATT) Project is to explore and develop technologies and concepts to revolutionize the energy efficiency and environmental compatibility of fixed wing transport aircrafts. These technological solutions are critical in reducing the impact of aviation on the environment even as this industry and the corresponding global transportation system continue to grow.

# DART Core/Combustor-Noise Initial Test Results

## …. *Research in Support of Ultra-Efficient Commercial Vehicles*

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NASA Advanced Air Vehicles Program
Advanced Air Transport Technology Project
Aircraft Noise Reduction Subproject

# Core/Combustor Noise – DART Utilization

## Core Noise More Important in Future

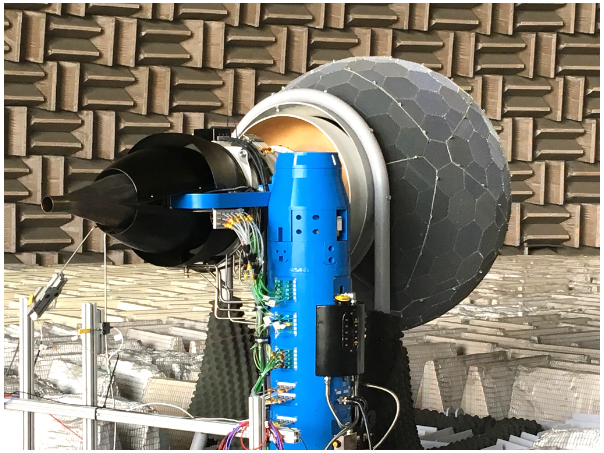
- Turbofan design trends, engine-cycle changes, and noise-mitigation advances are expected to reduce other propulsion noise sources
- Emerging lean-combustor designs could increase combustor noise level; Also less transmission loss
- Airframe, combustor and fan noise all need reduction to meet future noise goals (alphabetical order)

## NASA DART: Cost-Efficient Platform

- Development/Evaluation of measurement and noise-mitigation techniques
- It is not a turbofan-engine development program

## Objective of 2017 (Initial) Testing

- Baseline core-noise acoustic measurements
- Comparison with 2014 DGEN380 test results
- Enhance branch experience with semi-infinite-tube technique



*DART/DGEN380 inside NASA GRC AAPL*

*NASA GRC AAPL Facility*

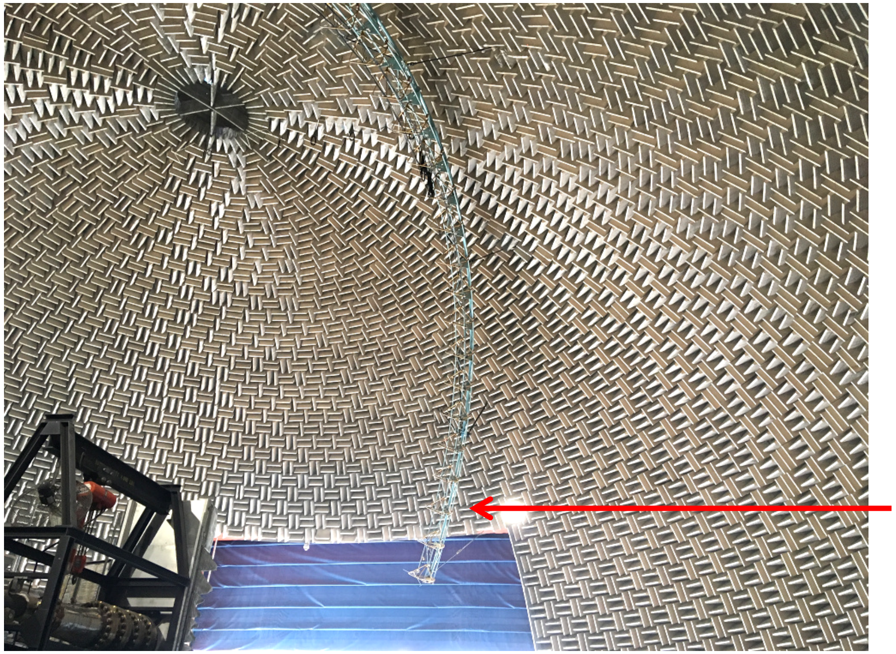
# DART Core/Combustor-Noise Test
## …. *Experimental Setup*

## Setup

- 7 far-field microphones in AAPL overhead array in engine aft quadrant
  - polar angle range: about 110º to 140º
- 1 mid-field stand-mounted microphone
  - 130º direction, engine-center height, 10 ft distance
- 2 semi-infinite-tube pressure sensors (ITPs) at core-nozzle exit
  - 270º and 300º azimuthal position

## Data Acquisition

- Acoustic data acquired simultaneously by National Instruments' LabView system
  - 100 kHz sampling rate, 60 s duration
- Engine performance data recorded by DART engine-control system

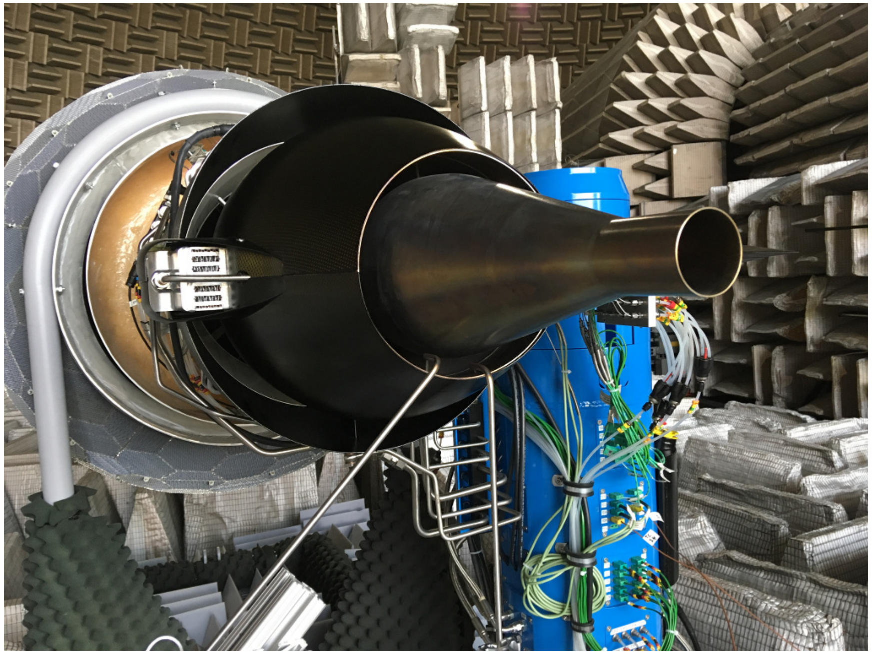


*AAPL overhead array*

*Mid-field microphone (left) - ITPs (right)*

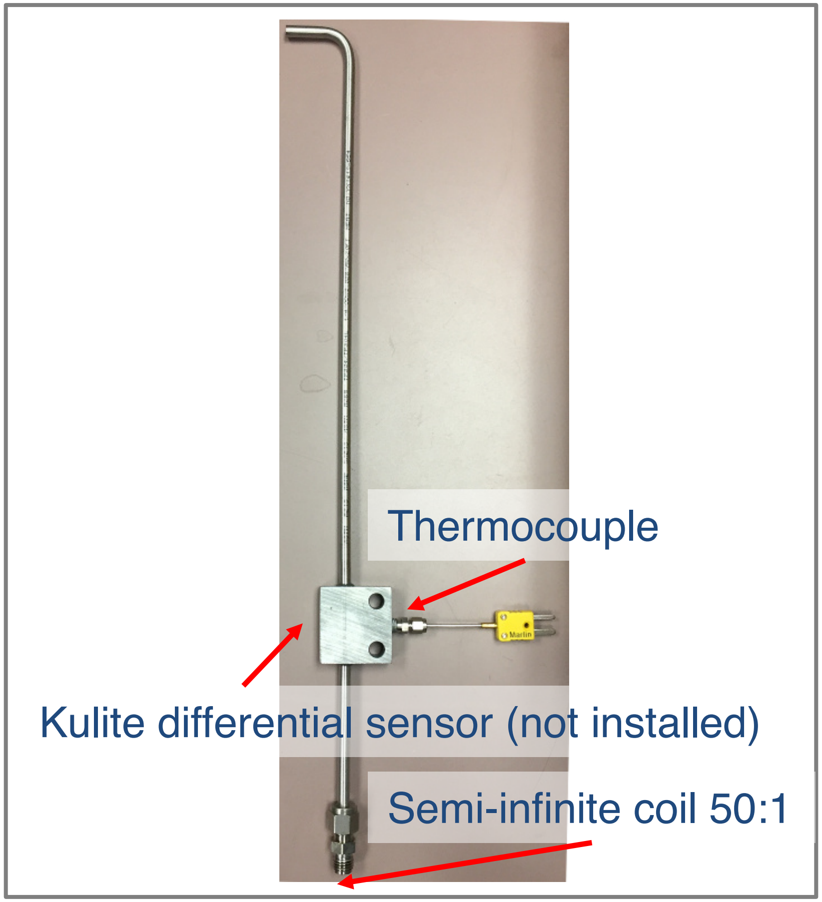
# DART Core/Combustor-Noise Test

## *…. Semi-Infinite-Tube Probes*



*Semi-infinite-tube probes at core-nozzle exit 6 and 7 o'clock positions*

- Kulite XCS-190, 10 psi differential
- Type-K thermocouple
- 50:1 ratio - tube length after/ahead of sensor
- $N_2$ purge flow ready, but not needed




*Basic design of semi-infinite-tube sensors*

# DART Core/Combustor-Noise Test

## …. *Acoustic Sensor Locations & Test Matrix*

## Sensor Locations

AAPL overhead array: FF017–FF023

Stand-mounted floor microphone: MF101

Core-nozzle exit: NE801, NE802

| Sensor | Radial Distance, ft | Polar Angle, ° | Azimuthal Angle, ° |
|---|---|---|---|
| FF017 | 39.56 | 108.04 | 83.04 |
| FF018 | 38.81 | 113.48 | 83.02 |
| FF019 | 38.25 | 119.22 | 82.98 |
| FF020 | 37.55 | 125.18 | 83.05 |
| FF021 | 37.05 | 131.21 | 83.95 |
| FF022 | 36.63 | 137.22 | 84.74 |
| FF023 | 36.57 | 143.35 | 87.20 |
| MF101 | 10.00 | 130.00 | 0 |
| NE801 | 0 | 0 | 270 |
| NE802 | 0 | 0 | 300 (nominal) |

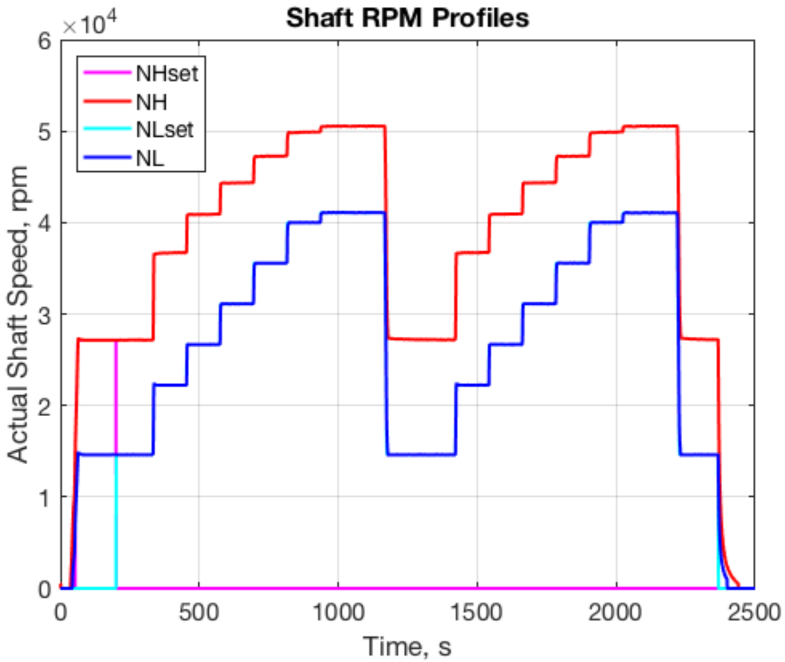
| Run # | Power, % | Run # | Power, % |
|---|---|---|---|
| 1 | 33 | 9 | 33 |
| 2 | 33 | 10 | 33 |
| 3 | 50 | 11 | 50 |
| 4 | 60 | 12 | 60 |
| 5 | 70 | 13 | 70 |
| 6 | 80 | 14 | 80 |
| 7 | 90 | 15 | 90 |
| 8 | 92.5 | 16 | 92.3 |
| | | 17 | 0 |

## Test Matrix

- Two sequential sets of points
- Each set: idle to max power
- Max power limited by $T_{ambient}$
- One background-level point (engine off)
- Aug 15, 2017

# DART Core/Combustor-Noise Test

## …. *Shaft RPM Profiles and Relevant Frequencies*




- FADEC/ECU in automatic mode
- Holds RPM extremely steady
- Two sequential sets of points
- Each set: idle to max power

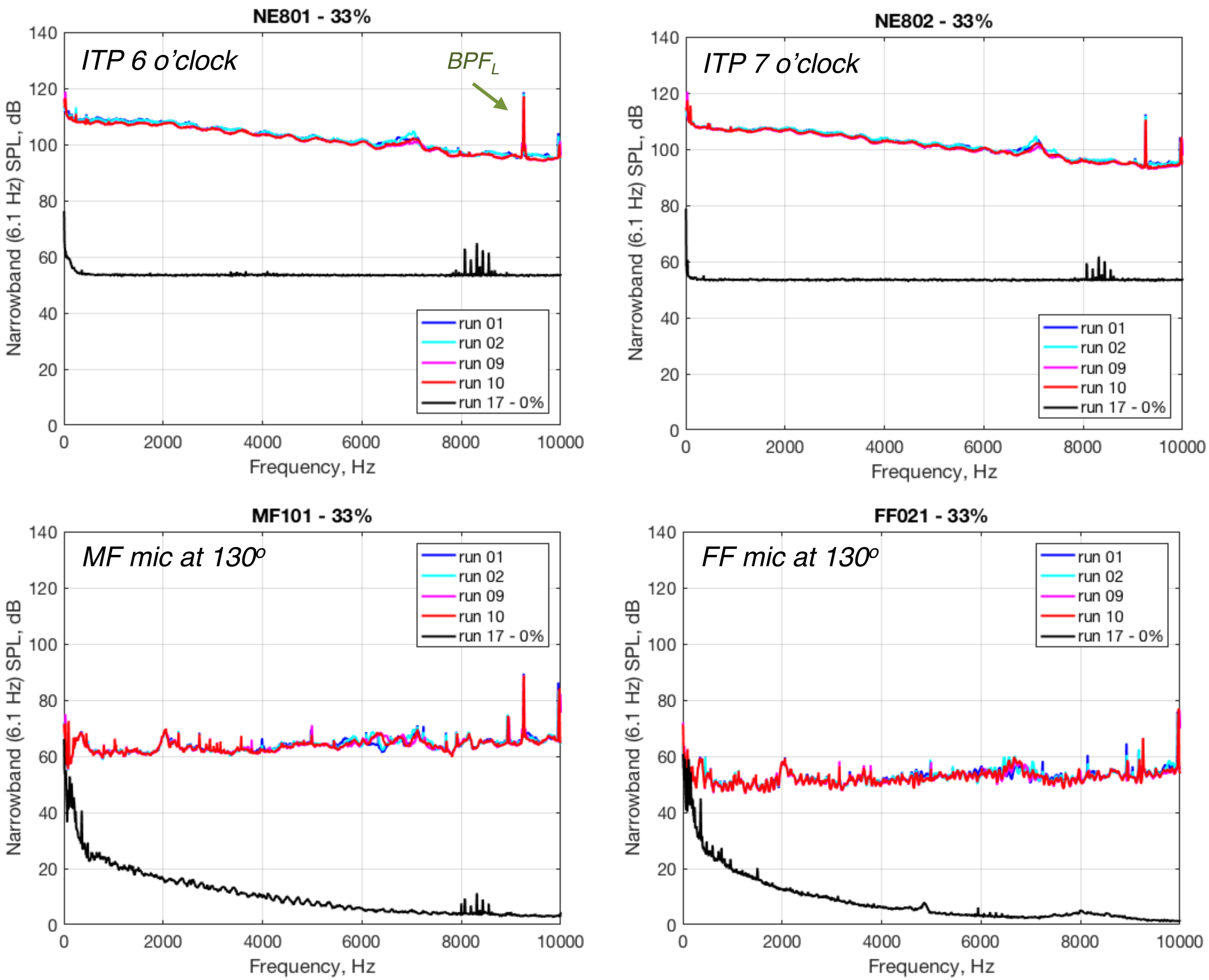
**Relevant Frequencies**

| Run # | Power % | $SPF_H$ Hz | $SPF_L$ Hz | $SPF_F$ Hz | $BPF_L$ Hz | $BPF_F$ Hz |
|---|---|---|---|---|---|---|
| 1 | 33 | 452.3 | 243.5 | 73.3 | 9252.8 | 1026.8 |
| 2 | 33 | 452.6 | 243.6 | 73.4 | 9255.8 | 1027.1 |
| 3 | 50 | 611.2 | 370.2 | 111.5 | 14069.2 | 1561.3 |
| 4 | 60 | 681.3 | 444.3 | 133.8 | 16884.1 | 1873.6 |
| 5 | 70 | 738.8 | 518.4 | 156.2 | 19700.5 | 2186.2 |
| 6 | 80 | 787.4 | 592.6 | 178.5 | 22518.1 | 2498.8 |
| 7 | 90 | 831.0 | 666.6 | 200.8 | 25332.4 | 2811.1 |
| 8 | 92.5 | 842.2 | 684.8 | 206.3 | 26022.2 | 2887.7 |
| 9 | 33 | 453.9 | 243.6 | 73.4 | 9255.4 | 1027.1 |
| 10 | 33 | 453.1 | 243.6 | 73.4 | 9255.9 | 1027.1 |
| 11 | 50 | 611.8 | 370.4 | 111.6 | 14074.3 | 1561.8 |
| 12 | 60 | 681.9 | 444.5 | 133.9 | 16890.0 | 1874.3 |
| 13 | 70 | 739.0 | 518.6 | 156.2 | 19707.1 | 2186.9 |
| 14 | 80 | 787.3 | 592.7 | 178.5 | 22520.8 | 2499.1 |
| 15 | 90 | 830.9 | 666.7 | 200.8 | 25336.5 | 2811.6 |
| 16 | 92.3 | 842.0 | 684.3 | 206.1 | 26001.6 | 2885.4 |

- 3.32 fan gear ratio
- 14 fan blades
- 38 LPT rotor blades

# DART Core/Combustor-Noise Test

## …. *Signal at 33% Power Compared to Background Level*




6.1 Hz narrowband *SPL*

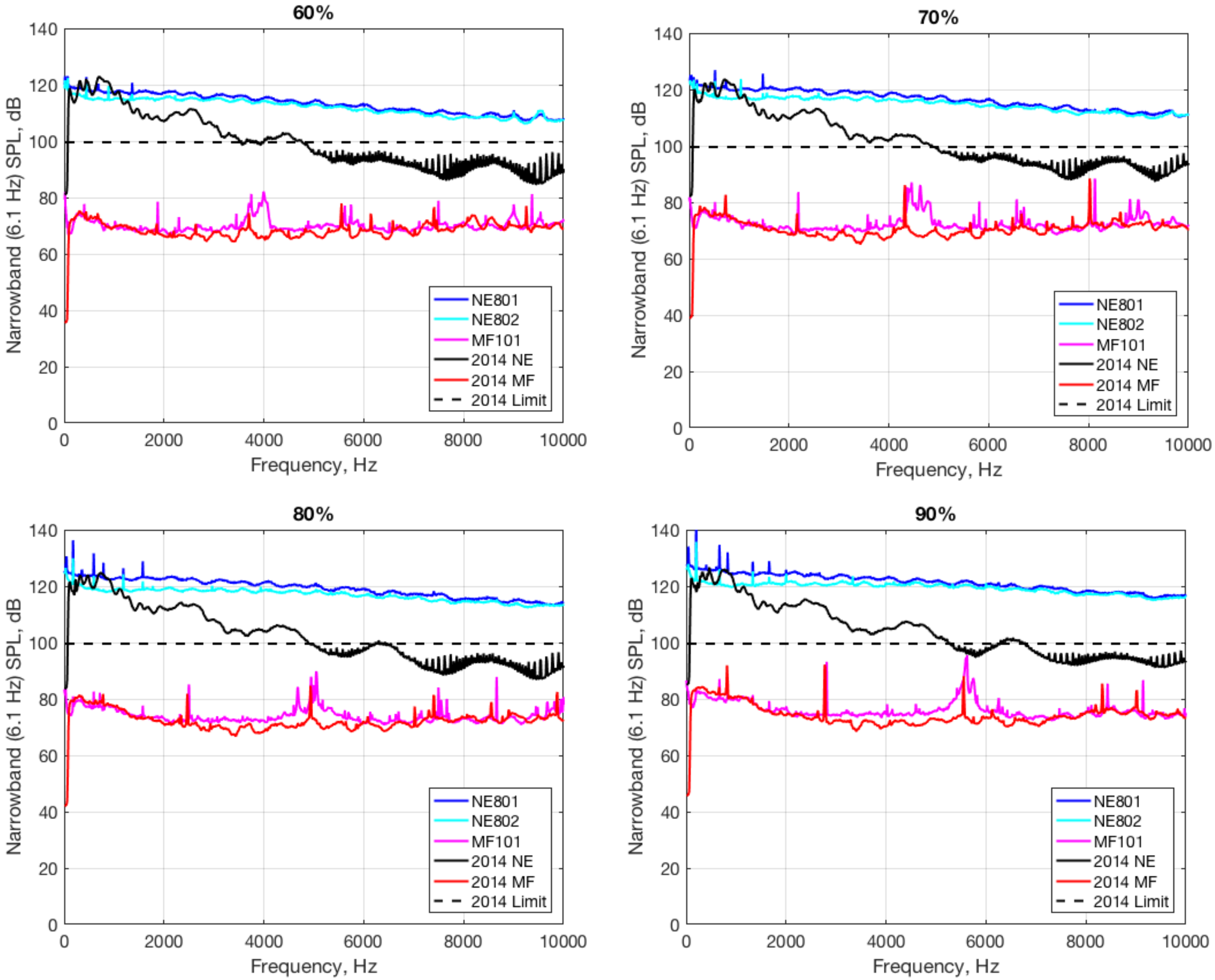
Combustor broadband noise range < 1 kHz

$BPF_L$ = 9255 Hz

Excellent measurement repeatability

# DART Core/Combustor-Noise Test

## …. *Comparison of IPT SPL and MF SPL to 2014 Results*




6.1 Hz narrowband *SPL*

2014 12.2 Hz *SPL* rescaled to 6.1 Hz binwidth

2014 MF results adjusted to 10 ft distance ($r^2$)

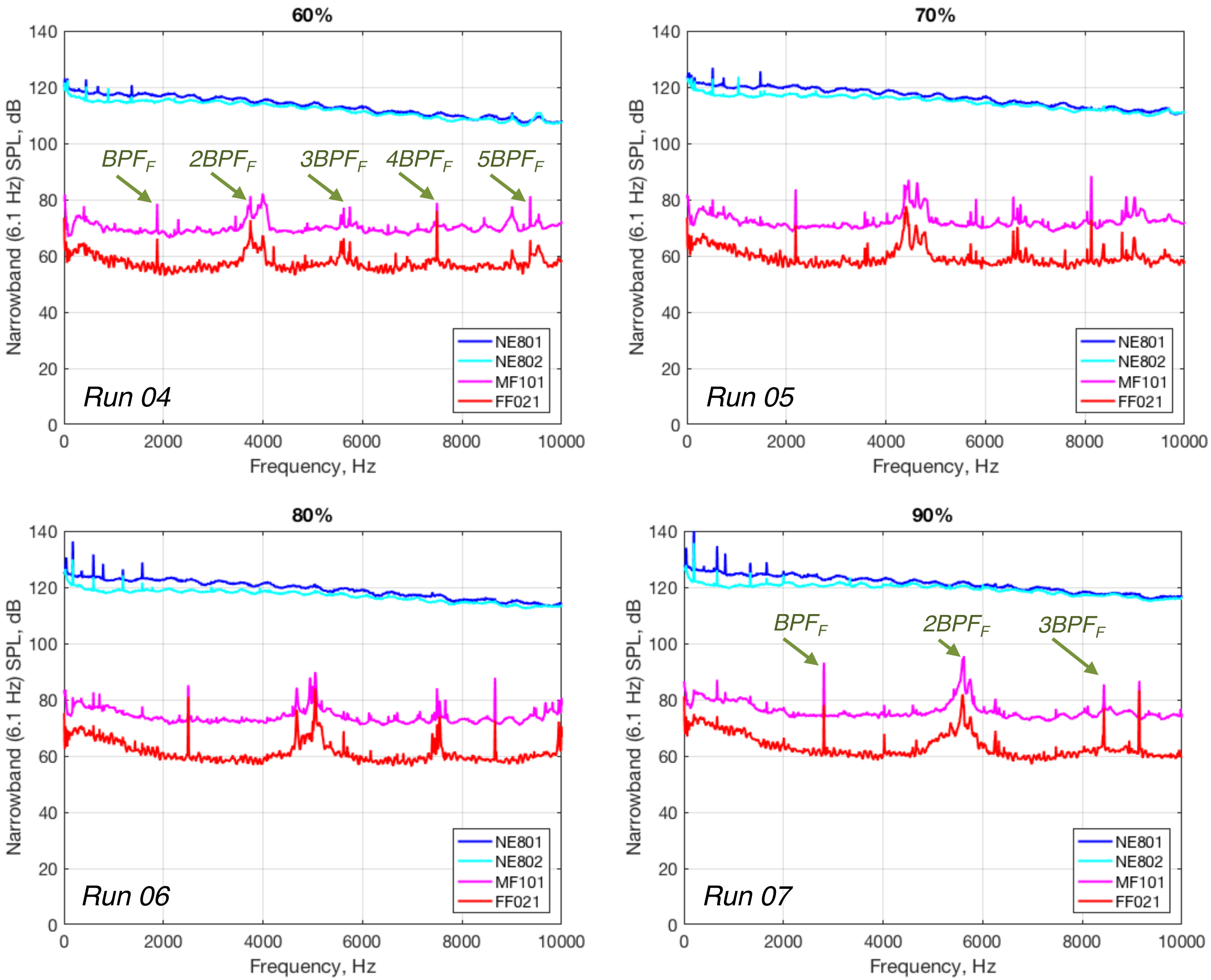
Combustor broadband noise range < 1 kHz

Comparable IPT levels: $f \leq 1$ kHz

MF broadband levels are in good agreement

# DART Core/Combustor-Noise Test

## *…. IPT, MF and FF SPL Variation with Power Level*




6.1 Hz narrowband *SPL*

NE801 & NE802 6 & 7 o'clock IPT

MF101 mid-field mic at 10 ft, 130°

FF021 far-field mic at 37 ft, 131°

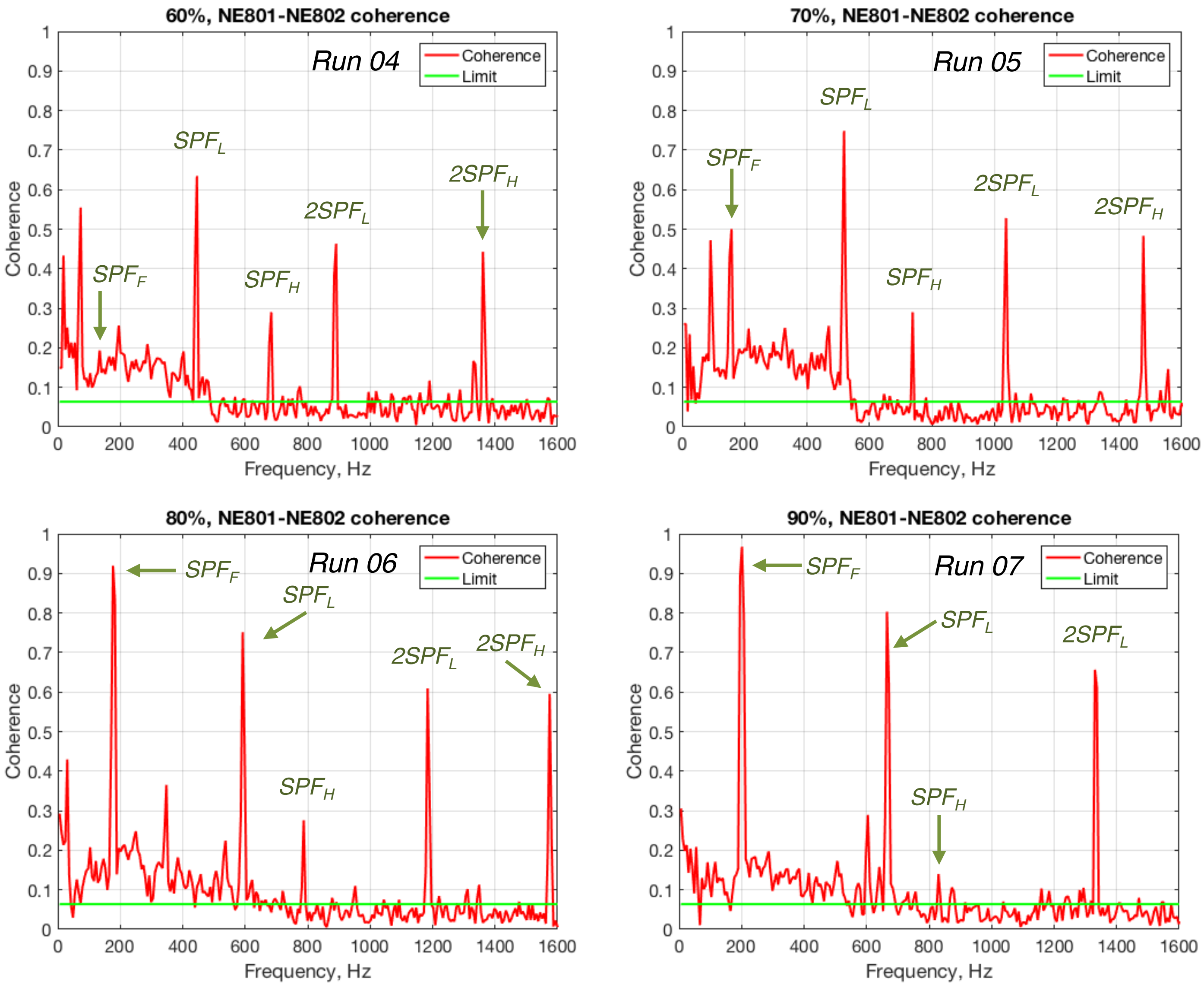
Fan BPF and harmonics

Unclear reason for haystack around $2BPF_F$

No clear evidence of ITP-tube vortex shedding

# DART Core/Combustor-Noise Test

## …. *Core-Nozzle IPT Coherence Variation with Power Level*




6.1 Hz binwidth

NE801 & NE802
6 & 7 o'clock IPT

Coherence level below statistical limit meaningless

Shaft Passing Frequencies *SPF* and harmonics

Combustor broadband noise region identified

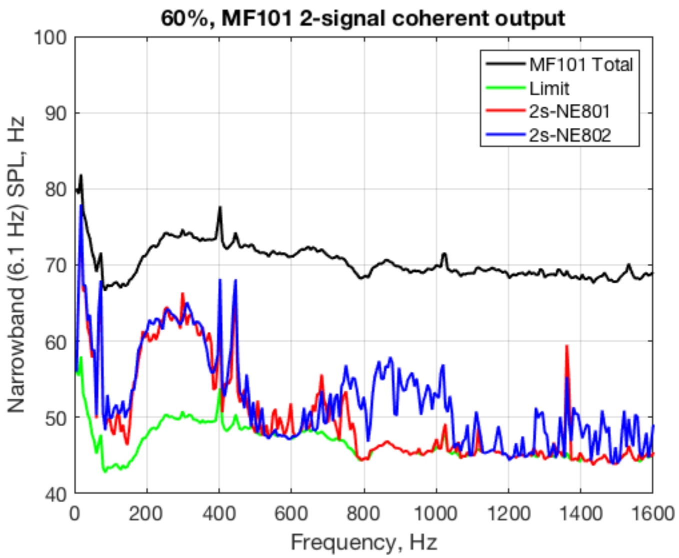
Plane wave mode: $m = 0$

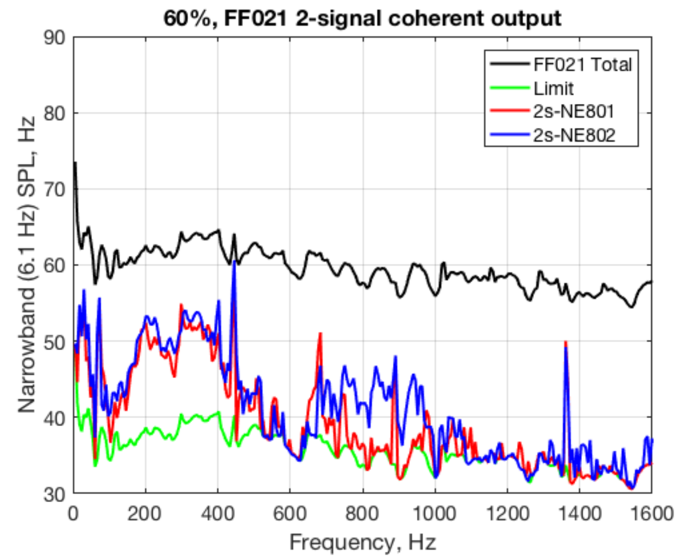
Up to about 450 Hz at 60%

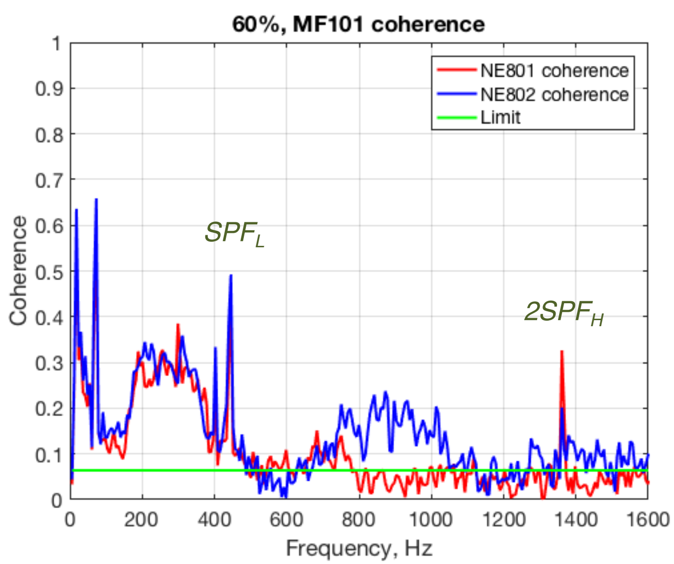
Range increases with power

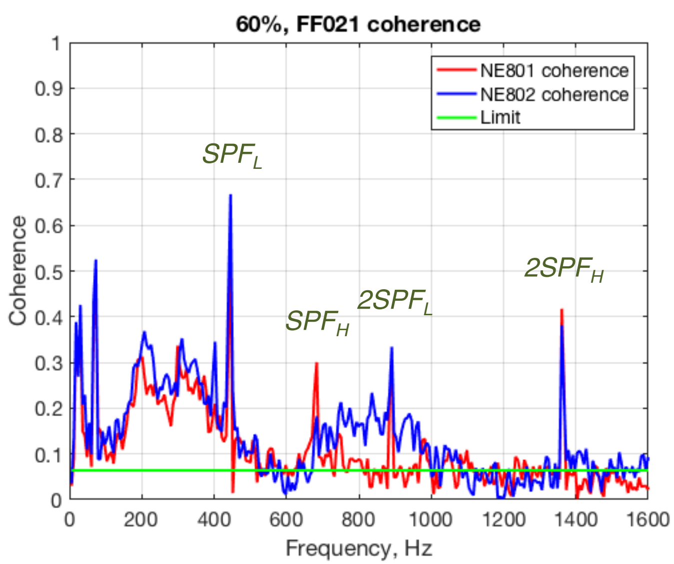
# DART Core/Combustor-Noise Test

## …. *MF and FF Coherent Power and Coherence Results at 60%*




6.1 Hz binwidth

NE801 & NE802
6 & 7 o'clock IPT

MF101 mid-field mic at 10 ft, 130°

FF021 far-field mic at 37 ft, 131°

Combustor noise ($m = 0$) detected up to about 500 Hz using either reference IPT

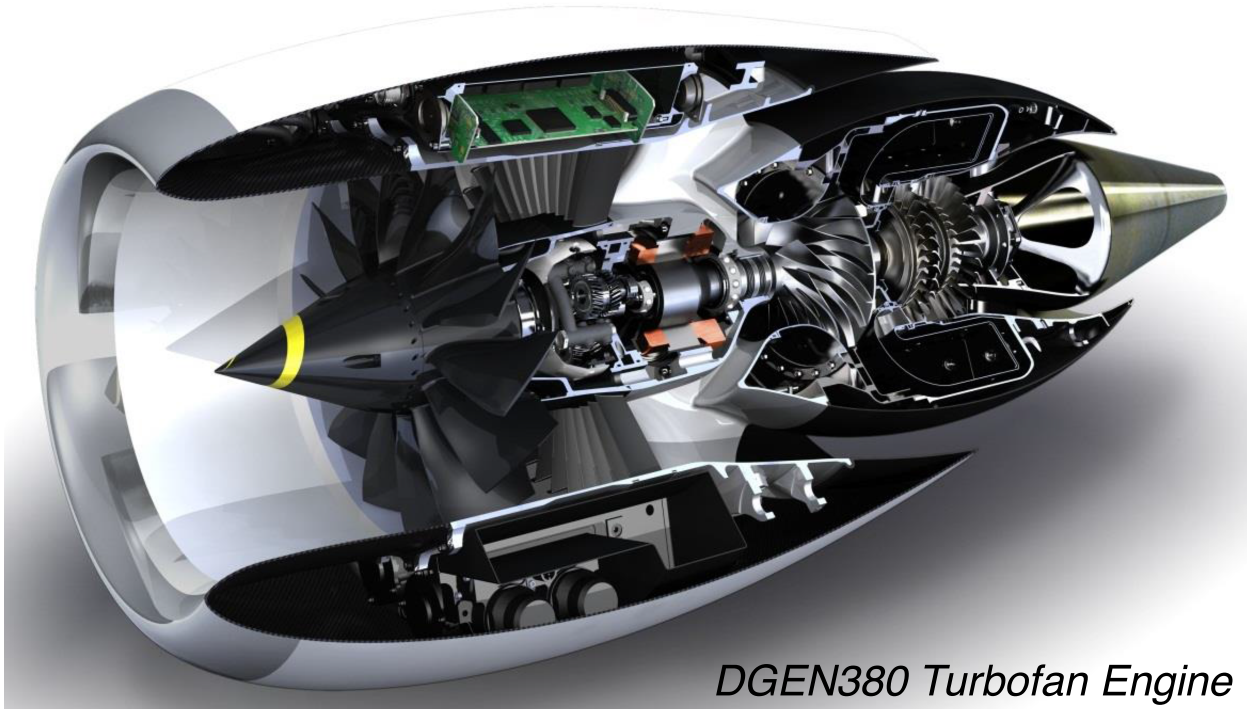
2s-method with 7 o'clock IPT also detects second broadband-noise frequency range ($m = \pm 1$ ? )

*SPFs* present

# DART/DGEN CORE-NOISE RESEARCH PATH

**…. *Development/Evaluation of Measurement and Noise-Mitigation Techniques***

**Baseline Combustor Noise Measurements** → **Instrumentation Refinements** → **Core-Nozzle Circumferential Array Measurements** → **Design Tailpipe for Liner Testing** → **Hot-Liner Testing Circumferential and Axial Array**



*DGEN380 Turbofan Engine*

**Source Separation Techniques**

**Determine Noise-Source Structure**

**Update Core-Noise Prediction Tools**

**Validate Liner-Design Tools for Hot Conditions**

# Summary

- DART/AAPL core/combustor-noise baseline test completed on Aug 15, 2017
- Initial data analysis and preliminary conclusions presented here
  - Acoustic data deemed to be of high quality, compares well with 2014 results and serves as a solid baseline for future work with DART
  - Combustor noise components of total noise signatures were educed using a two-signal source-separation method
  - Combustor coherent broadband noise was detected in expected frequency range
  - A second frequency range of coherent broadband noise was also detected – likely first azimuthal mode of the combustor noise (*preliminary, subject to further evaluation*)
- DART is a cost-efficient venue for studying core-noise physics and mitigation
- Core/Combustor noise must be addressed to ensure that far-term concept aircraft meet anticipated noise limits

*Thanks to:*

*Dan Sutliff and the Facilities Team for envisioning and bringing about the DART*

*The AAPL staff for their expertise and dedication in preparing for and executing this test.*

# BACK-UP

# DART Core/Combustor-Noise Test

## …. *Engine RPM Table*

| Run # | $NH_{mean}$ | $NL_{mean}$ | $NH_{rms}$ | $NL_{rms}$ | $NH_{maxdev}$ | $NL_{maxdev}$ | Control |
|---|---|---|---|---|---|---|---|
| 1 | 27138.1 | 14609.7 | 4.7 | 4.4 | 10.9 | 10.7 | H |
| 2 | 27154.3 | 14614.4 | 10.2 | 4.5 | 23.7 | 10.4 | L |
| 3 | 36671.1 | 22214.6 | 22.4 | 7.2 | 47.9 | 16.6 | L |
| 4 | 40879.5 | 26659.0 | 10.0 | 5.9 | 25.5 | 16.0 | L |
| 5 | 44325.3 | 31106.0 | 16.6 | 6.6 | 39.7 | 20.0 | L |
| 6 | 47241.0 | 35554.9 | 16.5 | 5.4 | 32.0 | 13.1 | L |
| 7 | 49859.3 | 39998.6 | 22.1 | 8.6 | 42.3 | 23.4 | L |
| 8 | 50529.2 | 41087.7 | 15.8 | 11.6 | 41.2 | 24.3 | L |
| 9 | 27234.1 | 14613.8 | 19.1 | 5.2 | 37.9 | 13.2 | L |
| 10 | 27188.9 | 14614.5 | 13.3 | 4.1 | 34.9 | 9.5 | L |
| 11 | 36707.5 | 22222.6 | 13.9 | 8.2 | 29.5 | 21.6 | L |
| 12 | 40915.1 | 26668.4 | 11.9 | 7.7 | 34.9 | 17.6 | L |
| 13 | 44339.0 | 31116.5 | 13.7 | 9.1 | 26.0 | 28.5 | L |
| 14 | 47236.0 | 35559.2 | 15.2 | 9.2 | 37.0 | 21.8 | L |
| 15 | 49856.6 | 40005.0 | 30.0 | 8.2 | 89.6 | 20.0 | L |
| 16 | 50522.6 | 41055.2 | 23.0 | 16.2 | 51.6 | 26.8 | L |

- Two sequential sets of points – each set: idle to max power (limited by $T_{ambient}$)
- NH control during run # 1 – NL control otherwise
- FADEC/ECU provides precise and steady control
- Aug 15, 2017

# DART Core/Combustor-Noise Test

## …. *Vortex-Shedding Frequencies*

**Vortex-Shedding Frequencies and Reynolds Numbers**

| 2014 run # | Power, % | $F_{core}$, Hz | $F_{fan}$, Hz | $ReD_{core}$ | $ReD_{fan}$ |
|---|---|---|---|---|---|
| 01A | 47 | 3931 | 2396 | 11241 | 31207 |
| 02A | 60 | 4896 | 3140 | 13797 | 40772 |
| 03A | 70 | 5826 | 3772 | 15700 | 48868 |
| 04A | 80 | 6769 | 4339 | 17227 | 56076 |
| 05A | 90 | 7927 | 4952 | 18722 | 63814 |
| 06A | 95.6 | 8500 | 5232 | 19357 | 67319 |

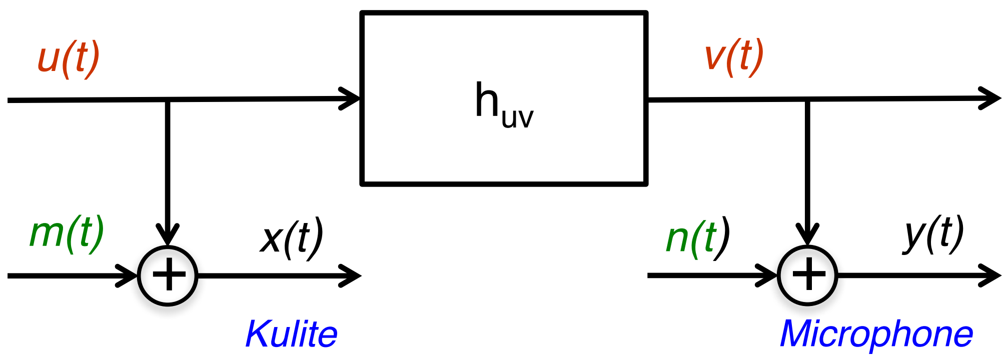
- Estimates based on DGEN380 mean-line data from the 2014 test
- $F = St\ U/D$ , where $St = 0.198\ (1 - 19.7/ReD)$
- Valid for Reynolds number $ReD$ in the range $250 < ReD < 2 \times 10^5$

# DART Core/Combustor-Noise Test

## *…. Coherence Techniques*

- Direct measurement of core noise difficult due to jet noise
  - Core noise masked by jet noise during static engine tests
  - Forward-flight effects reduce jet noise more than core noise
- Coherence techniques used to identify mid- and far-field core-noise components

*u(t)* & *v(t)*: coherent signals
*m(t)* & *n(t)*: uncorrelated signals
*x(t)* & *y(t)*: measurable signals




- Coherence function: $\gamma_{\alpha\beta} = |G_{\alpha\beta}| / (G_{\alpha\alpha}\, G_{\beta\beta})^{1/2}$
  - $G_{\alpha\beta}(f)$ = one-sided cross power spectrum & $G_{\alpha\alpha}(f)$ = one-sided auto power spectrum
  - theoretically: $0 \leq \gamma_{\alpha\beta}(f) \leq 1$
- Finite data sequences – estimated coherence always non-zero: $\varepsilon \leq \gamma_{\alpha\beta}(f) \leq 1$
  - $\varepsilon = [1 - (1-P)^{1/(M-1)}]^{1/2}$; $P$ = confidence interval & $M$ = number of independent segments
  - If estimated coherence is less than $\varepsilon$, the signals are independent with probability $P$

# DART Core/Combustor-Noise Test

## …. *Two-Signal Source Separation Technique*

## Goal

- Determine core-noise one-sided auto spectrum at microphone: $G_{vv}(f)$

## Approach

- Two-signal or Coherent Power Method (Bendat & Piersol 1980)

$$G_{vv}(f) = |G_{uv}|^2 / G_{uu} = |G_{xy}|^2 / ( G_{xx} - G_{mm} ) \approx |G_{xy}|^2 / G_{xx} = (\gamma_{xy})^2 G_{yy}$$

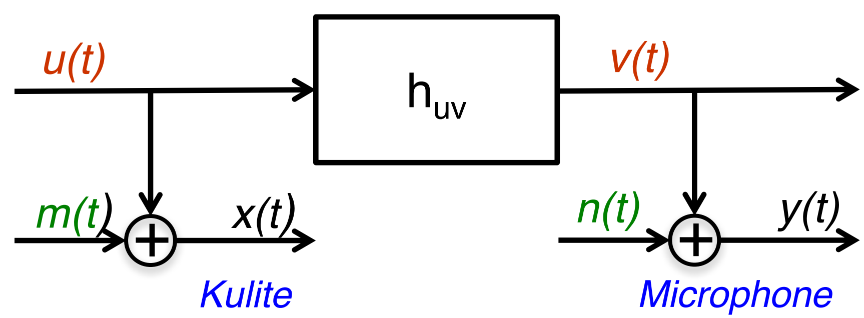
- Positive bias error introduced by $G_{uu} \approx G_{xx}$ ➔ $G_{vv}(f)$ is underestimated

## Implementation

- $G_{vv}(f) = (\gamma_{xy})^2 G_{yy}$ if $\gamma_{xy} > \varepsilon$ and $G_{vv}(f) = \varepsilon^2 G_{yy}$ if $\gamma_{xy} \le \varepsilon$

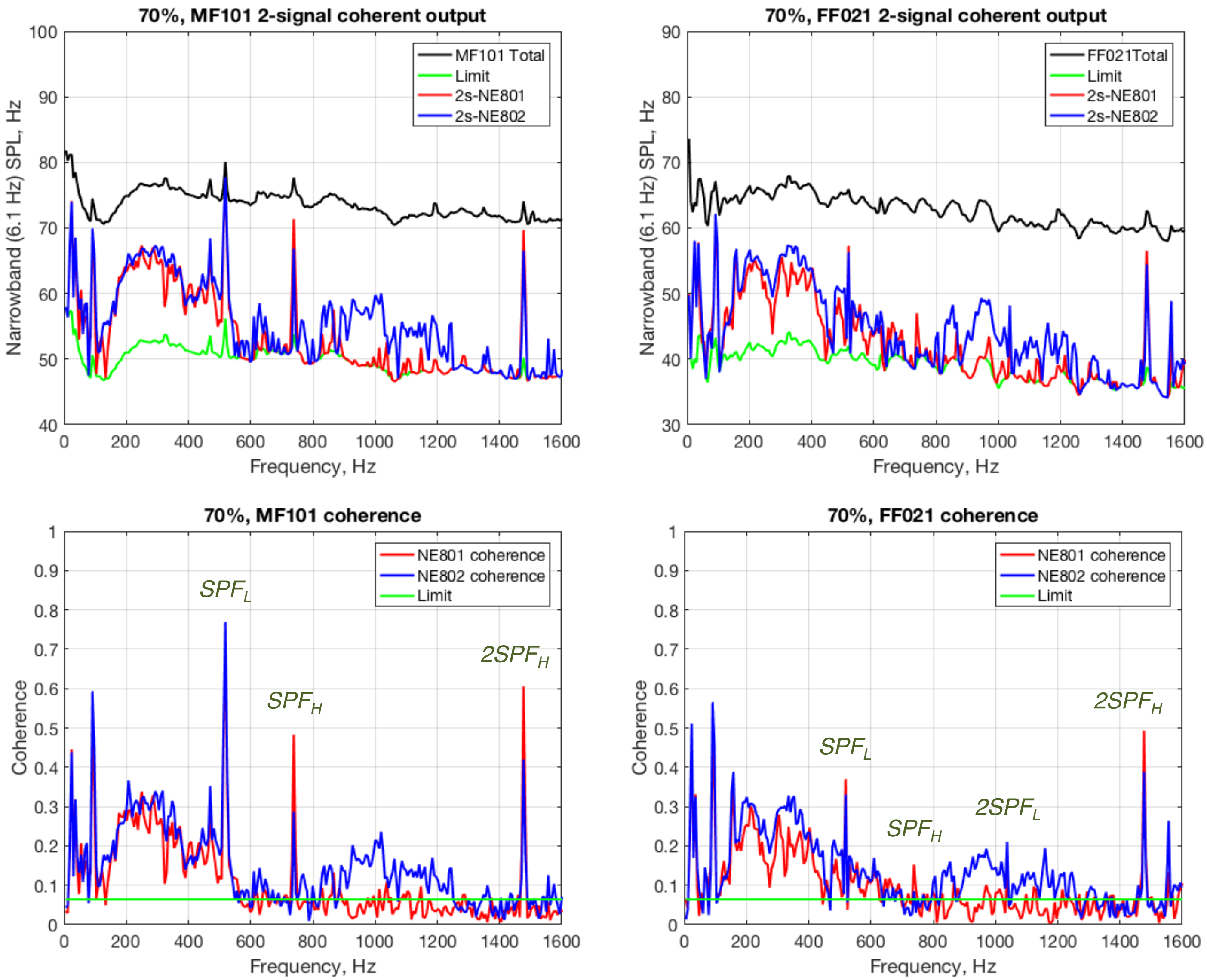
Core-noise component ($G_{vv}(f)$)

Total-noise signature ($G_{yy}$)



# DART Core/Combustor-Noise Test

## …. *MF and FF Coherent Power and Coherence Results at 70%*




6.1 Hz binwidth

NE801 & NE802
6 & 7 o'clock IPT

MF101 mid-field mic at 10 ft, 130°

FF021 far-field mic at 37 ft, 131°

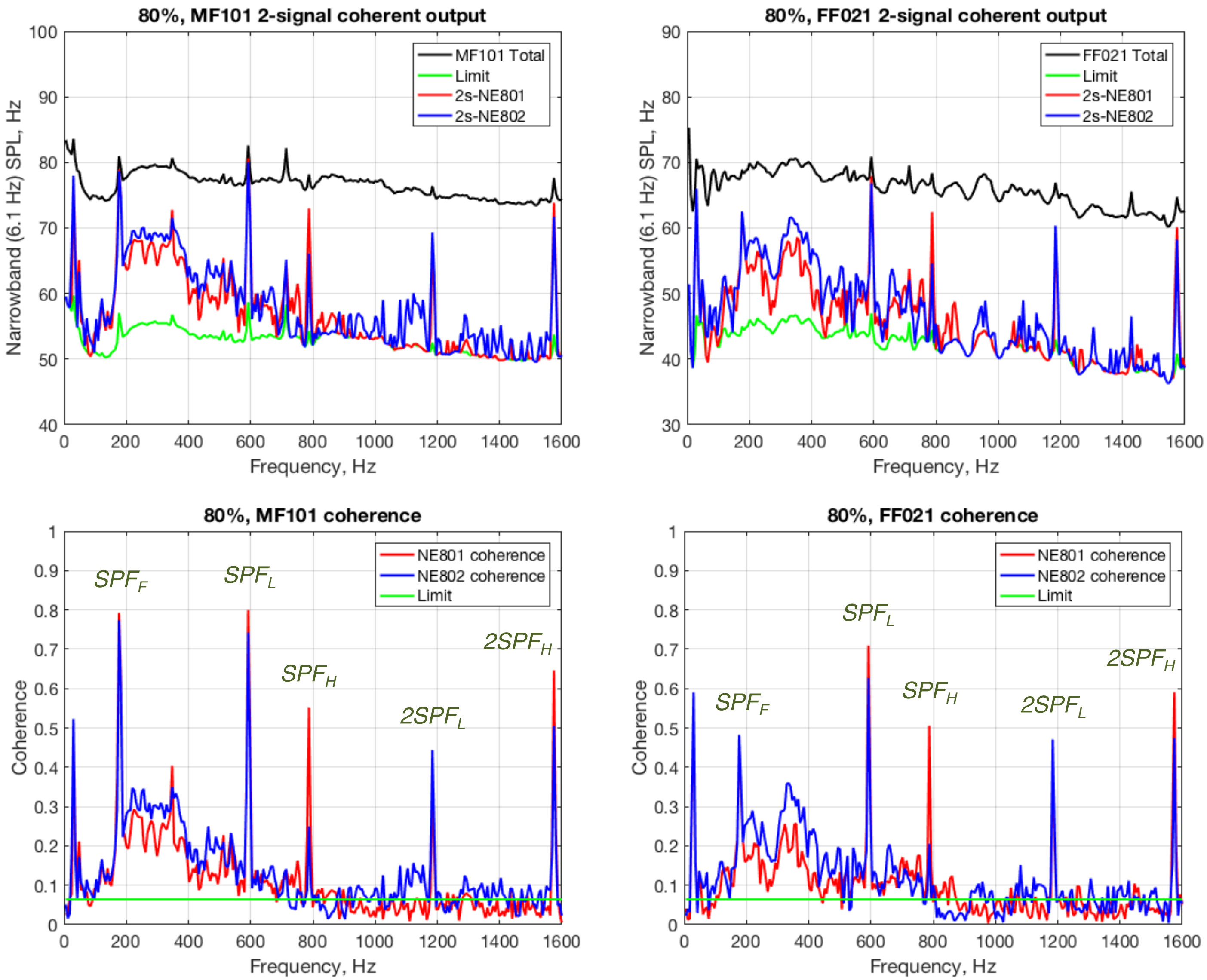
Combustor noise ($m = 0$) detected up to over 500 Hz using either reference IPT

2s-method with 7 o'clock IPT also detects second broadband-noise frequency range ($m = \pm 1$ ? )

*SPFs* present

# DART Core/Combustor-Noise Test

## …. *MF and FF Coherent Power and Coherence Results at 80%*




6.1 Hz binwidth

NE801 & NE802
6 & 7 o'clock IPT

MF101 mid-field mic at 10 ft, 130°

FF021 far-field mic at 37 ft, 131°

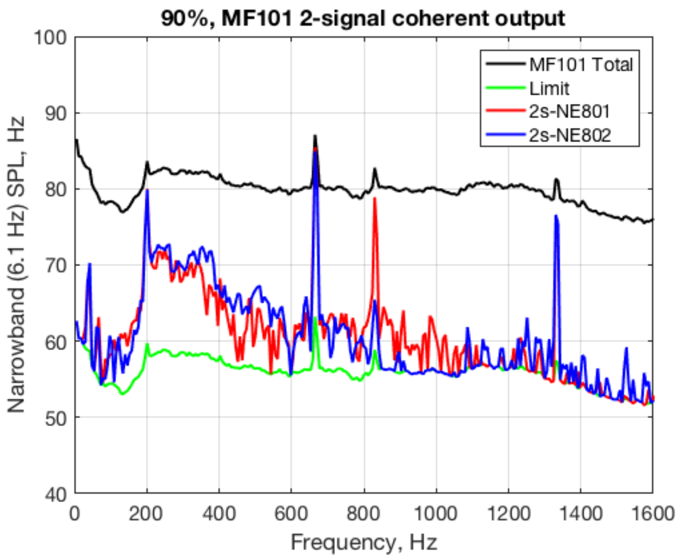
Combustor noise ($m = 0$) detected up to about 800 Hz using either reference IPT

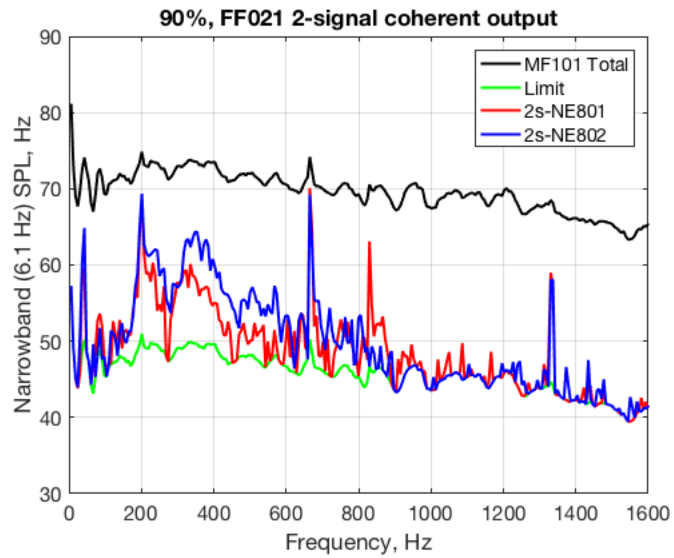
Weak evidence of second broadband-noise frequency range ($m = \pm 1$ ?)

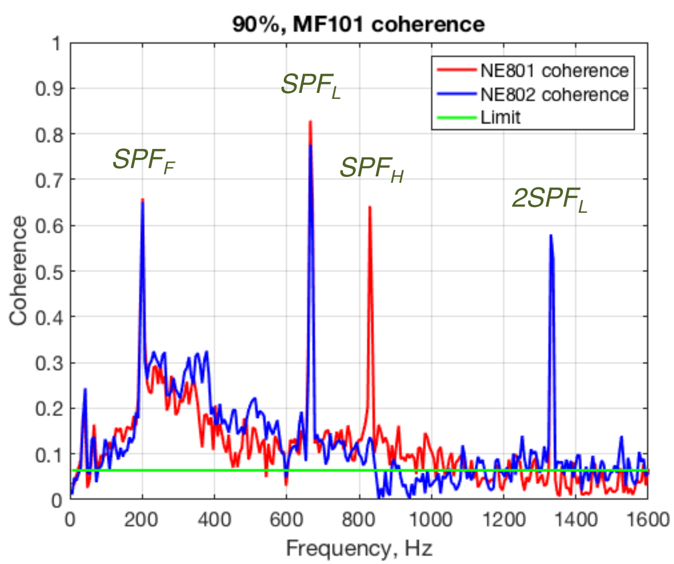
*SPFs* present

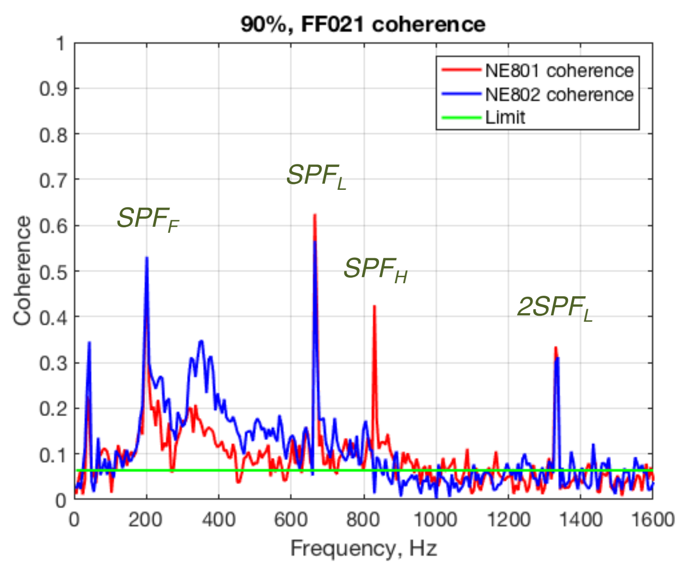
# DART Core/Combustor-Noise Test

## …. MF and FF Coherent Power and Coherence Results at 90%




6.1 Hz binwidth

NE801 & NE802
6 & 7 o'clock IPT

MF101 mid-field mic at 10 ft, 130°

FF021 far-field mic at 37 ft, 131°

Combustor noise ($m$ = 0) detected up to over 800 Hz using either reference IPT

Too low coherence to detect second broadband-noise frequency range ($m = \pm 1$ ? )

*SPFs* present