Application of an Aligned and Unaligned Signal Processing Technique to Investigate Tones and Broadband Noise in Fan and Contra-Rotating Open Rotor Acoustic Spectra

ISABE 2015-20243

Jeffrey Hilton Miles and Lennart S. Hultgren, NASA Glenn Research Center, Cleveland, OH 44135

Presented at the 22nd International Symposium on Air Breathing Engines Conference
Phoenix, Arizona, October 25–30, 2015

Summary

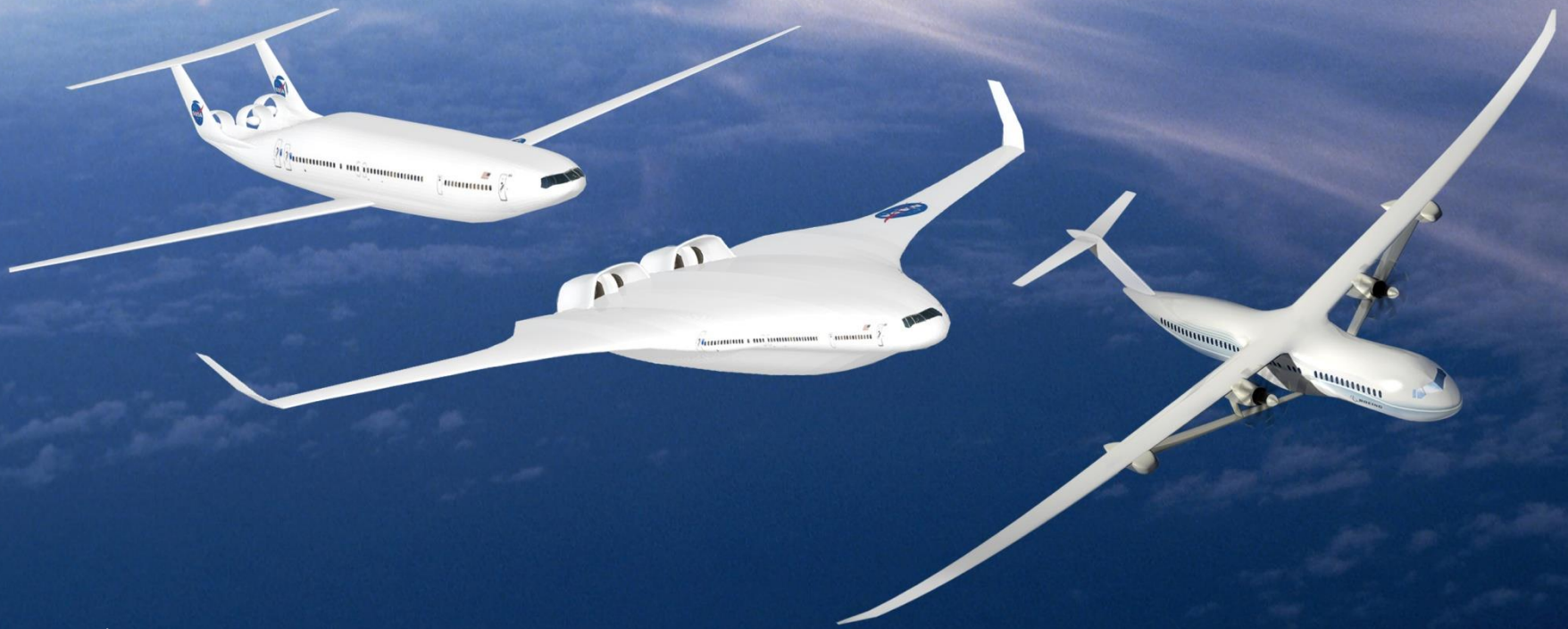
The study of noise from a two-shaft contra-rotating open rotor (CROR) is challenging since the shafts are not phase locked in most cases. Consequently, phase averaging of the acoustic data keyed to a single shaft rotation speed is not meaningful. An unaligned spectrum procedure that was developed to estimate a signal coherence threshold and reveal concealed spectral lines in turbofan engine combustion noise is applied to fan and CROR acoustic data in this paper (also available as NASA/TM–2015-218865). The NASA Advanced Air Vehicles Program, Advanced Air Transport Technology Project, Aircraft Noise Reduction Subproject supported the current work. The fan and open rotor data were obtained under previous efforts supported by the NASA Quiet Aircraft Technology (QAT) Project and the NASA Environmentally Responsible Aviation (ERA) Project of the Integrated Systems Research Program in collaboration with GE Aviation, respectively.

The overarching goal of the Advanced Air Transport (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.

National Aeronautics and Space Administration

Application of an Aligned and Unaligned Signal Processing Technique to Investigate Tones and Broadband Noise in Fan and Contra-Rotating Open Rotor Acoustic Spectra – ISABE 2015-20243

Jeffrey Hilton Miles and Lennart S. Hultgren
NASA Glenn Research Center
Cleveland, OH 44135



The 22nd International Symposium on Air Breathing Engines
Phoenix, AZ, October 25-30, 2015

www.nasa.gov

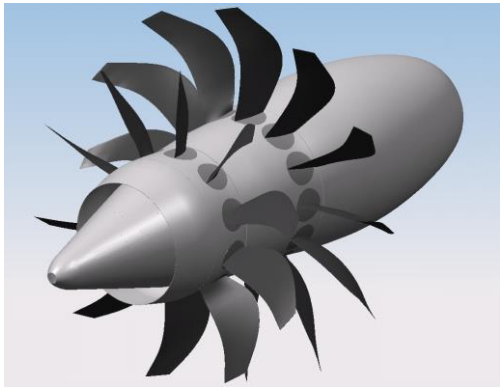
NASA Advanced Air Vehicles Program
Advanced Air Transport Technology Project
Aircraft Noise Reduction Subproject

OUTLINE

- Background and Motivation
- Brief Remarks and Perspective on Signal Processing Methods
- Existing NASA 9- by 15-Ft Wind-Tunnel Data
  - single-shaft single-stage fan acoustic data – NASA QAT Project
  - CROR acoustic data – NASA ERA Project in collaboration with GE Aviation
- Data Processing Procedure
  - aligned and unaligned spectra
  - unaligned magnitude-squared coherence
  - broadband and tonal spectra
- Results
- Summary and Conclusions

ALIGNED and UNALIGNED SIGNAL PROCESSING

…. background and motivation



- Contra-Rotating Open-Rotor Engines for Aircraft Propulsion
  - more efficient than equivalent-thrust turbofans
  - complex aeroacoustic systems – tonal and broadband noise
  - primarily noise and installation issues
    - predicted to meet upcoming Stage 14 for short/medium-range airliner
- Decomposition Into Tonal And Broadband Components
  - important aspect for noise prediction and study of control parameters
  - challenging since the shafts are in general not phased locked

Effective procedures to identify tonal and broadband noise components are needed

TONAL AND BROADBAND NOISE DECOMPOSITION

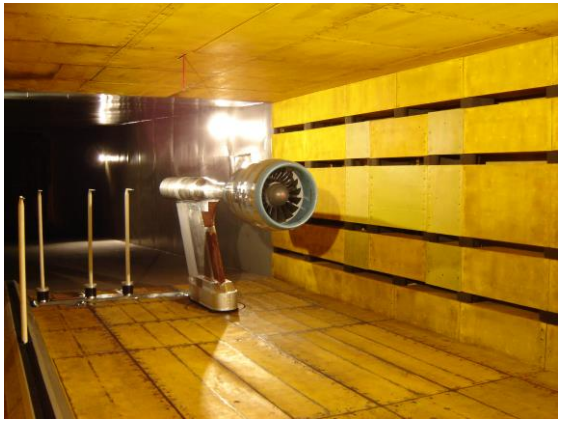
…. introduction – signal processing techniques

- Tones From Rotating Blade Rows On A Single Shaft
  - phase averaging keyed to shaft rotation is effective
- Two-Shaft Contra-Rotating Open Rotor (CROR)
  - phase averaging keyed to a single shaft rotation is not meaningful
- Existing CROR Acoustic Data Analysis Methods
  - Sree's method (IJA 2013) – Sree & Stephens (AIAA 2014-2744)
  - Vold-Kalman order-tracking filter – Stephens & Vold (JSV 2014)
- Current Method
  - tonal frequencies are identified using Miles' (AIAA 2006-0010) unaligned spectrum procedure
  - broadband component then obtained by removing tonal components from original aligned spectrum

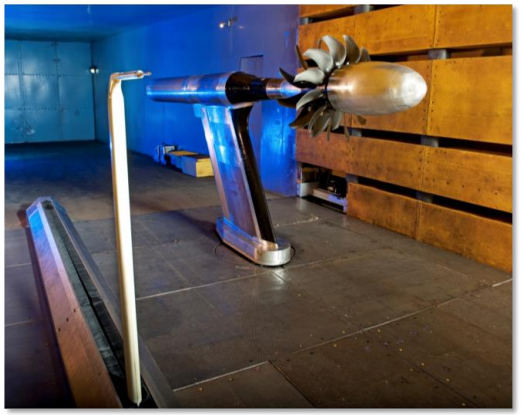
Effective procedures to identify tonal and broadband noise components are needed

NASA 9- BY 15-FT LOW SPEED WIND TUNNEL DATA

…. acoustic data for single-shaft fan stage and contra-rotating open rotor



Fan and CROR rigs in NASA GRC 9- by 15-ft low speed wind tunnel



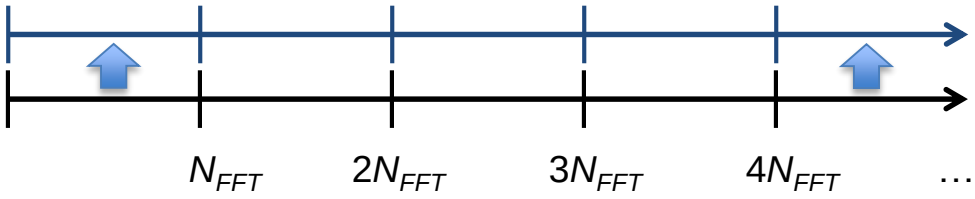
- Single-Shaft Fan Stage Data – Fite et al (AIAA 2006)
  - representative of typical modern turbofan
  - sideline data at 75.1° angle for approach conditions
  - baseline case for comparison with phase-averaged and Sree's method results – Sree & Stephens (AIAA 2014)
- Contra-Rotating Open-Rotor Rig Data – Elliott (AIAA 2011)
  - baseline blade design F31/A31- sideline data at 90°; takeoff
  - comparison with results presented by Sree & Stephens (AIAA 2014) and Stephens & Vold (JSV 2014)

DATA PROCESSING PROCEDURE

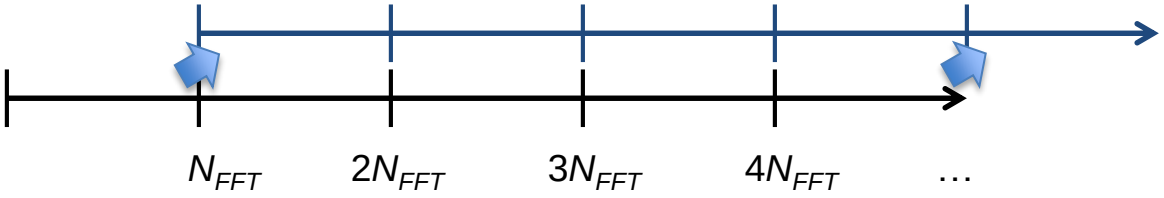
…. aligned and unaligned spectra

- Acoustic Data – time series divided into *M* data segments each of length N_{FFT}

- Aligned Spectrum: $G_a(f)$ – Contains Incoherent Broadband and Tones
  - duplicate time sequence and compute one-sided auto spectrum $G_a(f)$



- Deliberately Unaligned Spectrum: $|G_u(f)|$ – Contains Only Tones
  - offset duplicate time sequence one segment or more; compute cross spectrum $G_u(f)$



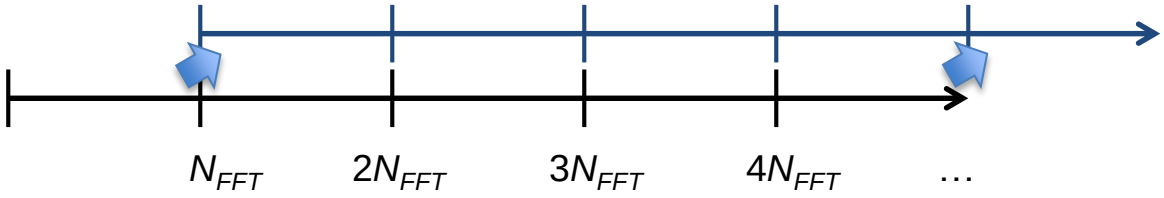
DATA PROCESSING PROCEDURE

…. unaligned magnitude-squared coherence (UMSC)

- Magnitude-Squared Coherence (*MSC*) of Two Signals *x(t)* And *y(t)*

$$MSC = |G_{xy}(f)|^2 / G_{xx}(f) G_{yy}(f)$$

- Here: The Two Signals Are Simply Related Through a Time Shift



  - Unaligned Magnitude-Squared Coherence (*UMSC*)

$$UMSC = \gamma^2 = |G_u(f)|^2 / G_a(f)^2$$

  - theoretically: $0 \le \gamma^2 \le 1$
  - finite time series: $\varepsilon^2 < \gamma^2 \le 1$, $\varepsilon^2 = 1 - (1 - P)^{1/(M-1)}$, $0 \le P \le 1$
  - If the computed *UMSC* does not exceed the threshold value ε^2, then the two signals are uncorrelated with the confidence level *P*

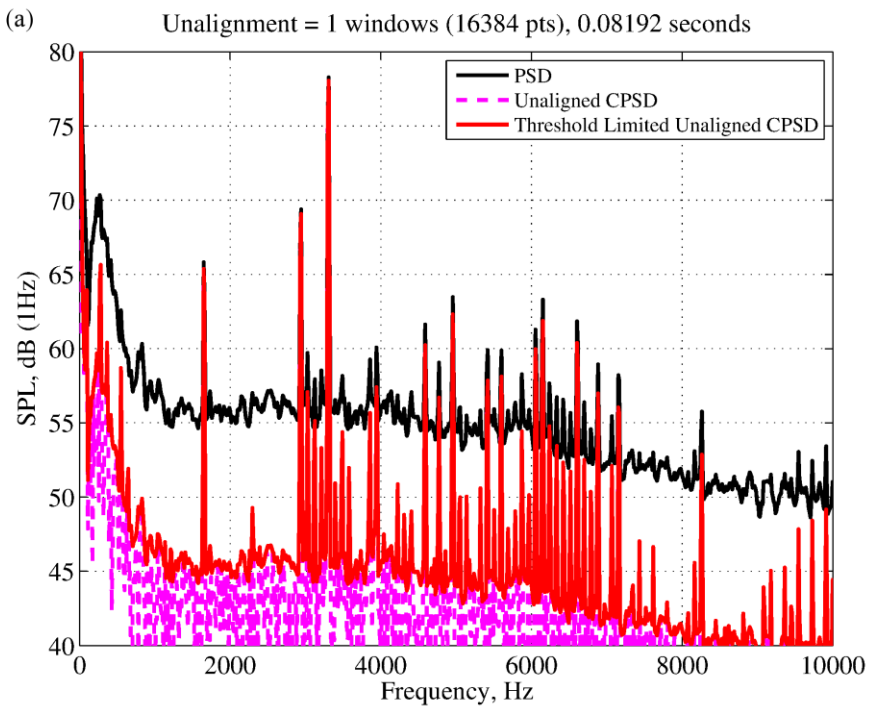
DATA PROCESSING PROCEDURE

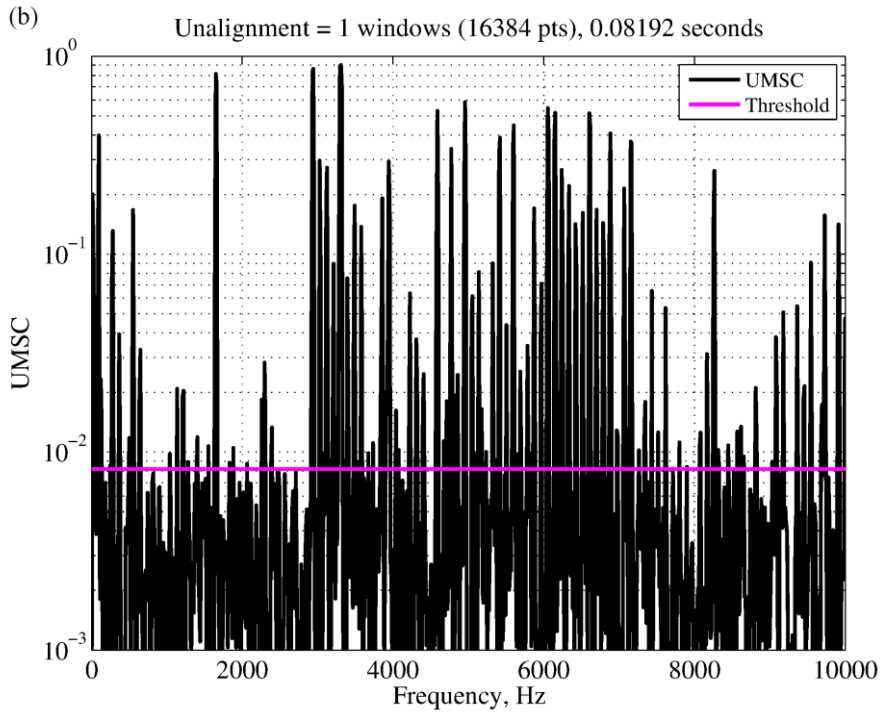
…. broadband and tonal noise spectra

- Common Practice to Determine Broadband Noise Spectrum
  - set tones to zero and use a multi-point average technique
  - decision of which spectrum points are tones is not always well defined
- Current Aligned/Unaligned Method:
  1. compute *UMSC* for spectrum points from the time series
  2. select as tones only those where *UMSC* exceeds the threshold value
     - 95 percent confidence-level threshold used here
  3. apply a multi-point average technique to obtain broadband noise spectrum
     - 4 nearest non-tonal values used here
  4. subtract this broadband spectrum from original aligned spectrum to obtain dominant tonal spectrum
  - well-defined and easily automated process

SINGLE-SHAFT FAN-STAGE RESULTS

…. aligned/unaligned spectra and UMSC





a) Aligned/Unaligned Spectra – Renormalized to 1 Hz Bin Width

- broadband absent in the deliberately unaligned spectra
- unaligned spectrum tones generally lower – more pronounced for higher harmonics
- this loss of tonal energy is believed to be caused by shaft rpm drift

b) UMSC (logarithmic scale) and 95% Confidence-Level Threshold Value

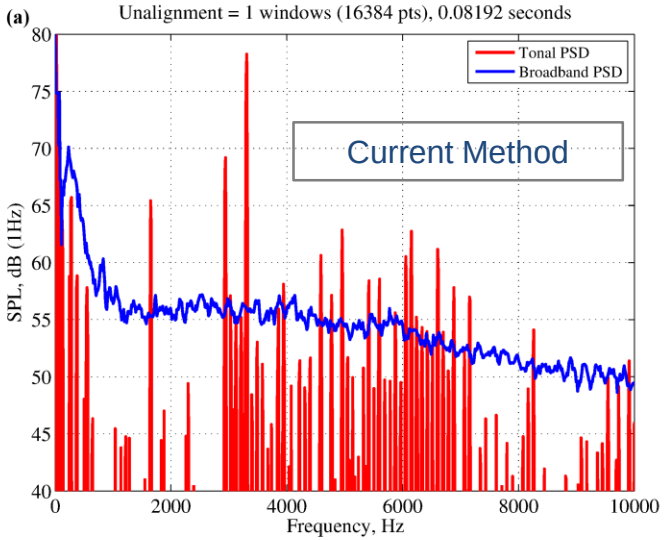
- value below threshold indicates independence of dealigned signals at that frequency

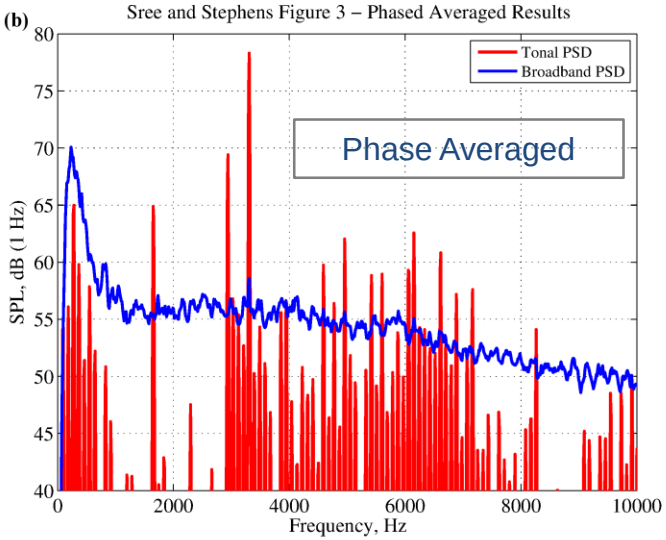
SINGLE-SHAFT FAN-STAGE RESULTS

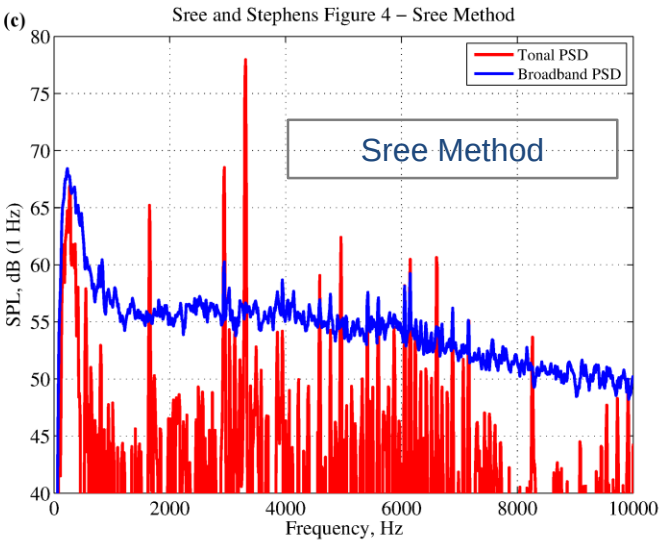
…. aligned/unaligned method compared to Sree & Stephens (2014) results

Tonal

Broadband



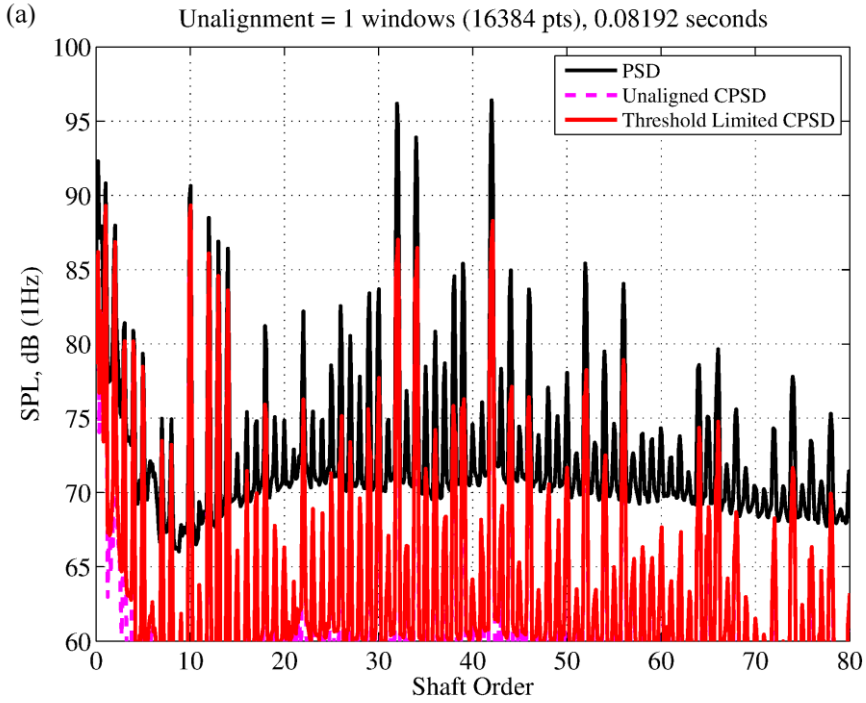


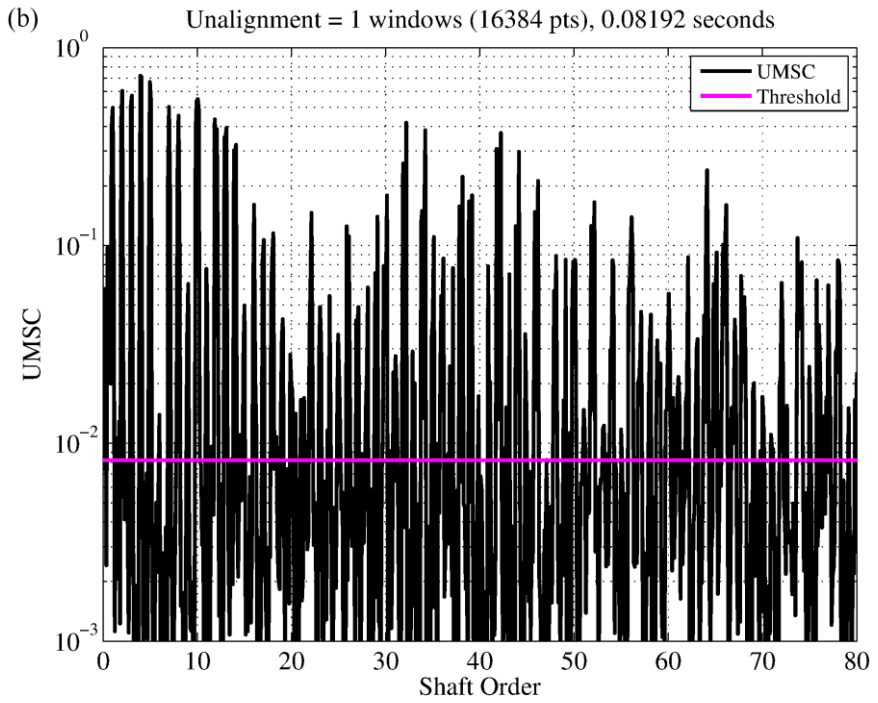


Good agreement with their results – in particular with the phase averaged (gold standard) results

CONTRA-ROTATING OPEN-ROTOR RESULTS (470)

…. aligned/unaligned spectra and UMSC





a) Aligned/Unaligned Spectra – Renormalized to 1 Hz Bin Width (Reading 470)

- much richer tonal structure compared to single-shaft fan stage
- much larger tonal-amplitude reduction between aligned and unaligned CROR spectra
- particularly so for interaction tones – shaft orders 32, 34, and 42
- fundamental aft and front BPF (shaft orders 10 & 12) are within 1 dB & 2 dB

b) UMSC (logarithmic scale) and 95% Confidence-Level Threshold Value

CONTRA-ROTATING OPEN-ROTOR RESULTS

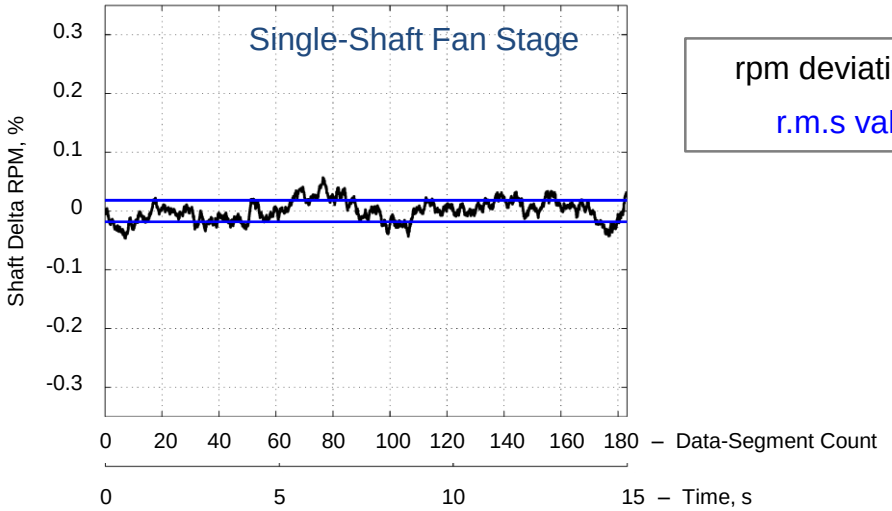
…. shaft speed variation normalized by mean rotation rate in percent

Single-shaft fan: 0.05% (3 rpm)

CROR 470: 0.30% (20 rpm)

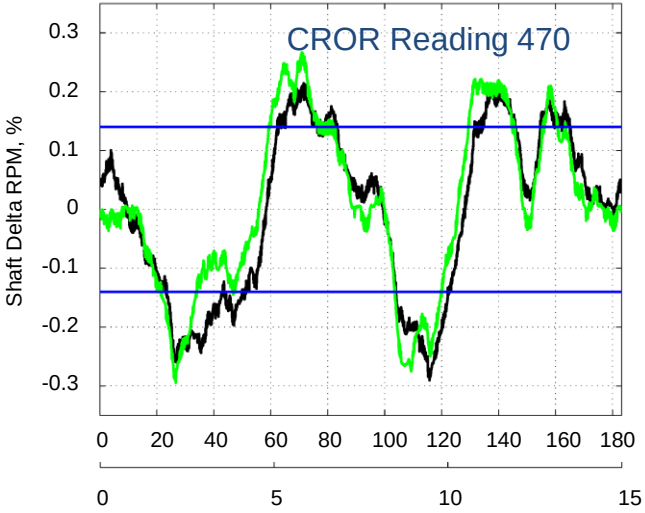
CROR 472: 0.23% (15 rpm)

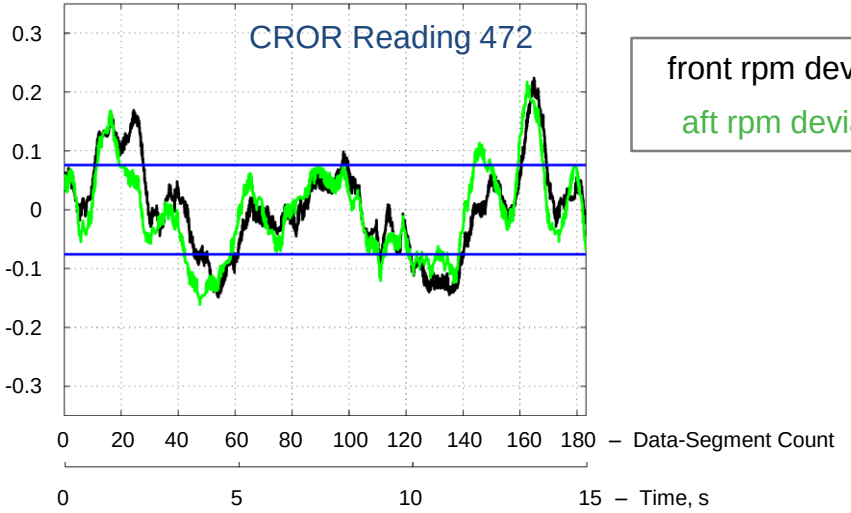
Shaft-rate excursions for front and aft shafts somewhat trace each other, but they are not synchronized



rpm deviation, %

r.m.s value





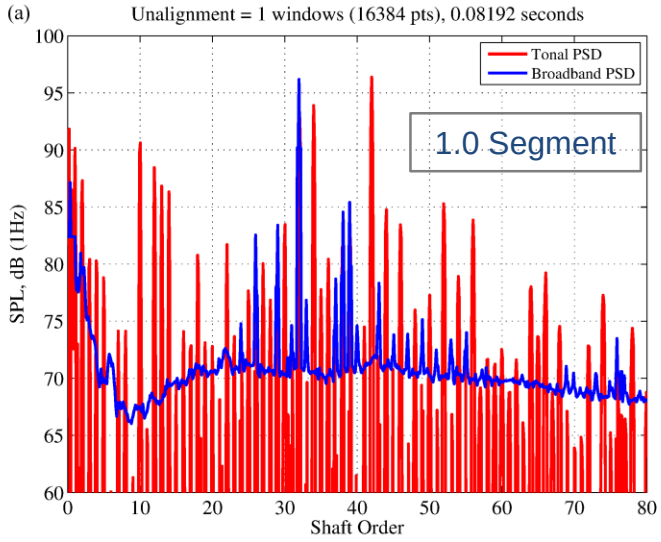
front rpm deviation

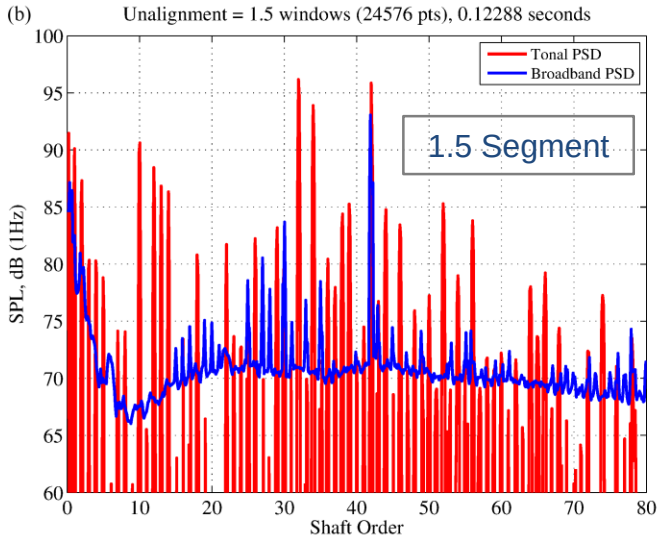
aft rpm deviation

Shaft speed deviation (%) as a function of segment count as well as time

CONTRA-ROTATING OPEN-ROTOR RESULTS (470)

…. aligned/unaligned method compared to Sree & Stephens (2014) results

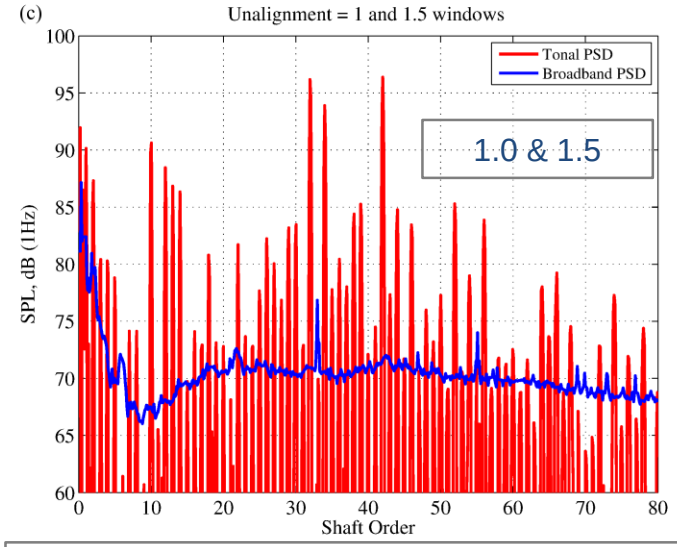


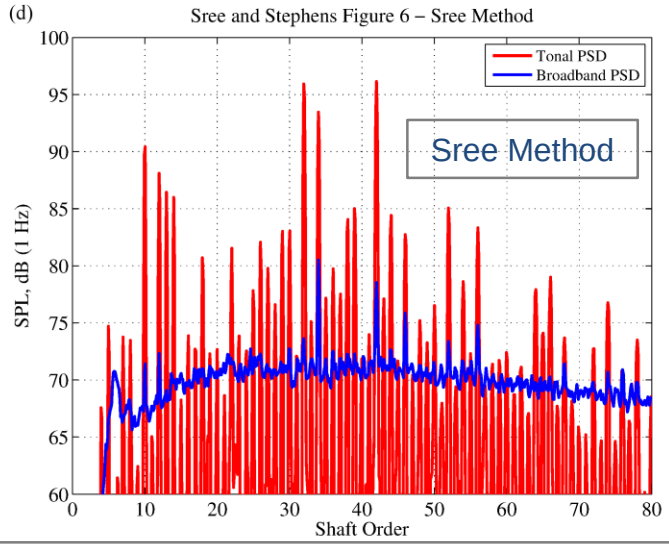


Tonal

Broadband

Tonal-energy loss in unaligned spectrum ➔ certain, but mainly different, tones are misidentified as broadband for different offsets



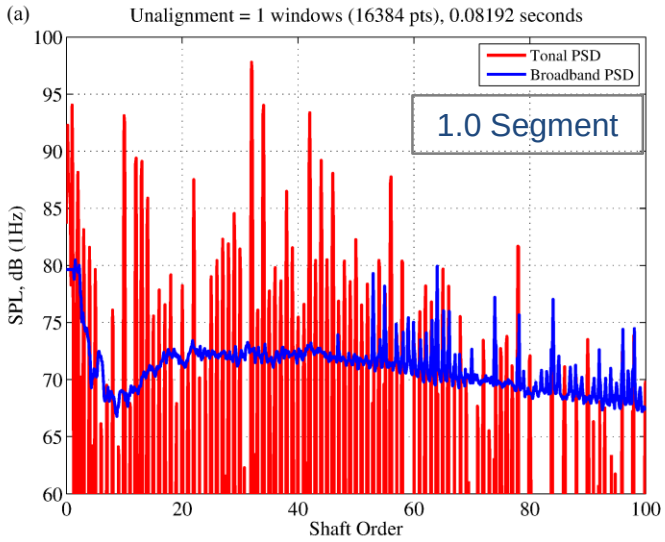


Solution: use several displacements – if UMSC > threshold value in at least one case ➔ tone is present at that frequency

Good agreement with their results when using information based on multiple displacements (1 & 1.5)

CONTRA-ROTATING OPEN-ROTOR RESULTS (472)

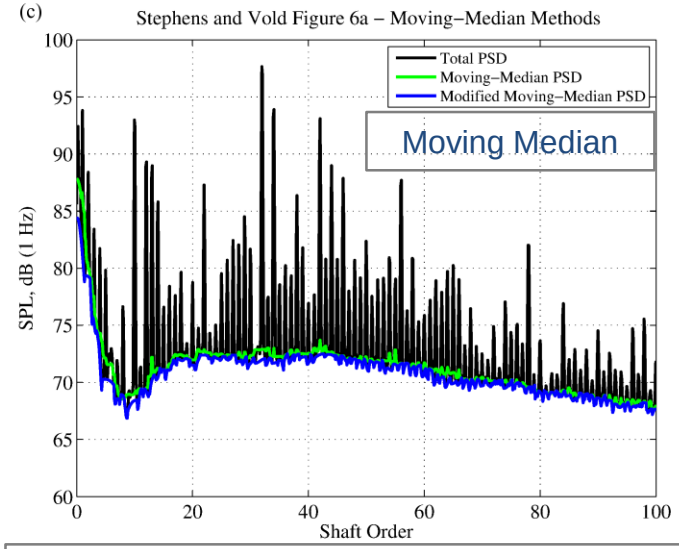
…. aligned/unaligned method compared to Stephens & Vold (2014) results

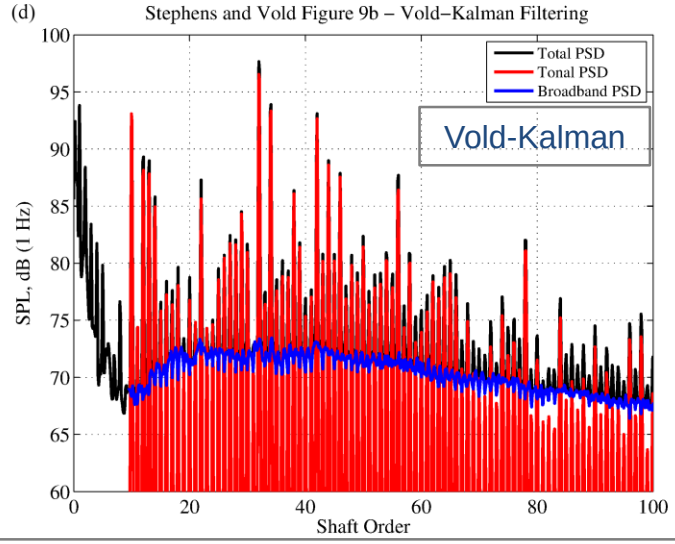


Current Method

Tonal

Broadband





Moving-Median &
Vold-Kalman Filtering

Total

Moving-Median

Modified Moving-Median

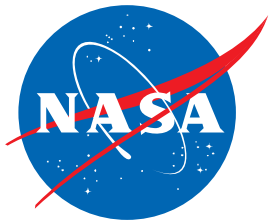
Tonal

Broadband

Good agreement with their Vold-Kalman filtering results up to shaft order 80

SUMMARY

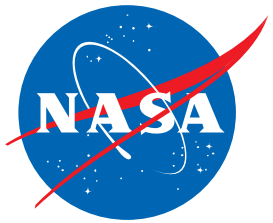
- Special Signal Processing Tools Are Needed to Study CROR acoustics
- The Aligned/Unaligned Signal Processing Technique:
  - applied to existing single-shaft fan-stage and CROR acoustic data sets
  - detects dominant tones as well as those masked by broadband noise
  - combined with magnitude-squared coherence threshold-value technique
- Well-Defined, Easily Implemented, And Effective Procedure For Extracting In Turn The Broadband And Dominant Tonal Spectra From Complex Experimental Acoustic Data Sets
- Favorably Compared To Existing Signal-Processing Results


NASA

DATA PROCESSING PROCEDURE

…. spectral estimation parameters

Sampling Rate	200,000 Hz
Total Observation Time	15 s
Segment Length, N_{FFT}	16,384
Bin Width, Δf	12.2 Hz
Segment Overlap; Window	50 %; Hamming
Number of Averages, M	363
UMSC threshold (95 %), ε^2	0.00824


NASA