Inserting Noise Metrics Into An Aircraft's Early Design Process

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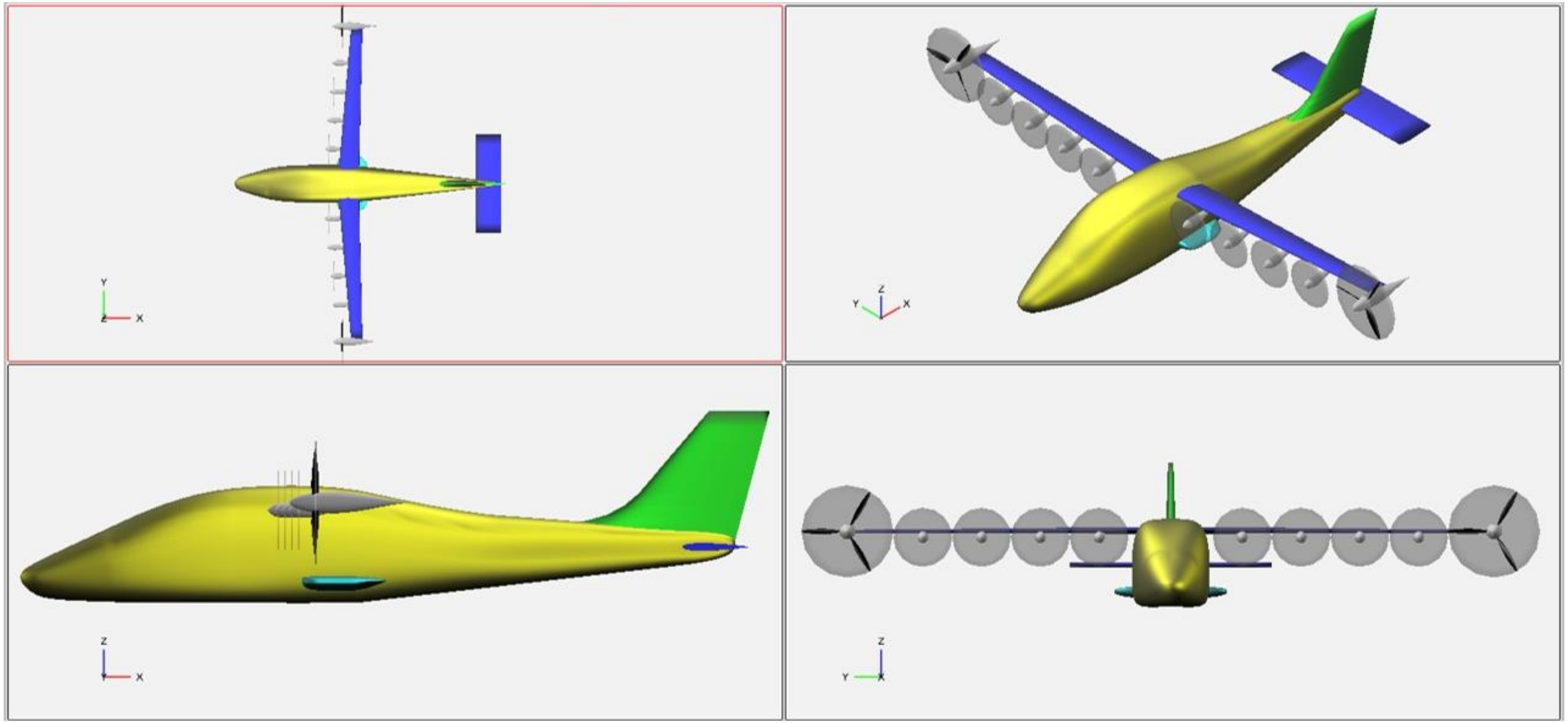
What we’ll see (and hear)

- The proposed LEAP Distributed Electric Propulsion aircraft (DEP).
  - Leading Edge Asynchronous Propeller (more lift than propulsion)
- Current focus and limitations of study thus far
- The noise prediction dataflow
  - The downside of this approach
- An alternate approach
- QuickLook
  - some results
- DEP psychoacoustics test

The LEAP aircraft

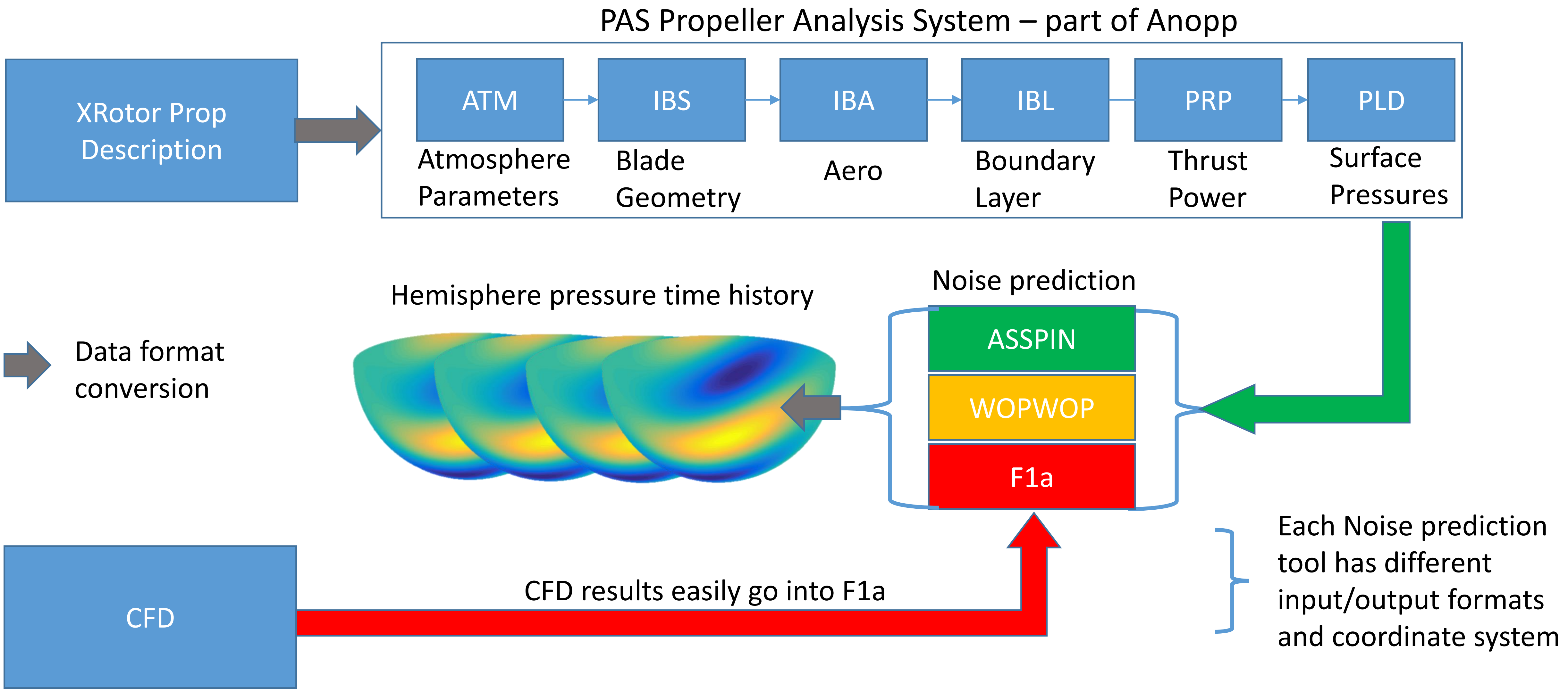


Leading edge props are designed for lift augmentation only, i.e., minimum power per unit ΔV. Props will fold away in cruise.
Tip props are designed for cruise, i.e. minimum power per unit thrust.

Current focus

- Modeling leading edge props only
- No angle of attack
  - Straight, level, and constant speed flight
- No atmospheric attenuation or turbulence
- No prop-prop or prop-structure interaction
- Explore design envelope of electric propulsion
  - Different control approaches include uniform vs. different RPMs/phases achieved through constant and random RPM/phase steps.
- Design configurations include different number of LEAP props (changes in prop diameter, RPM and, therefore, loading)
  - Every time the design changes a new prediction is necessary

The noise prediction dataflow



An alternate approach – Analytical models

- Directivity function from well established theory (Gutin*)
- Pure tone synthesis of significant harmonics

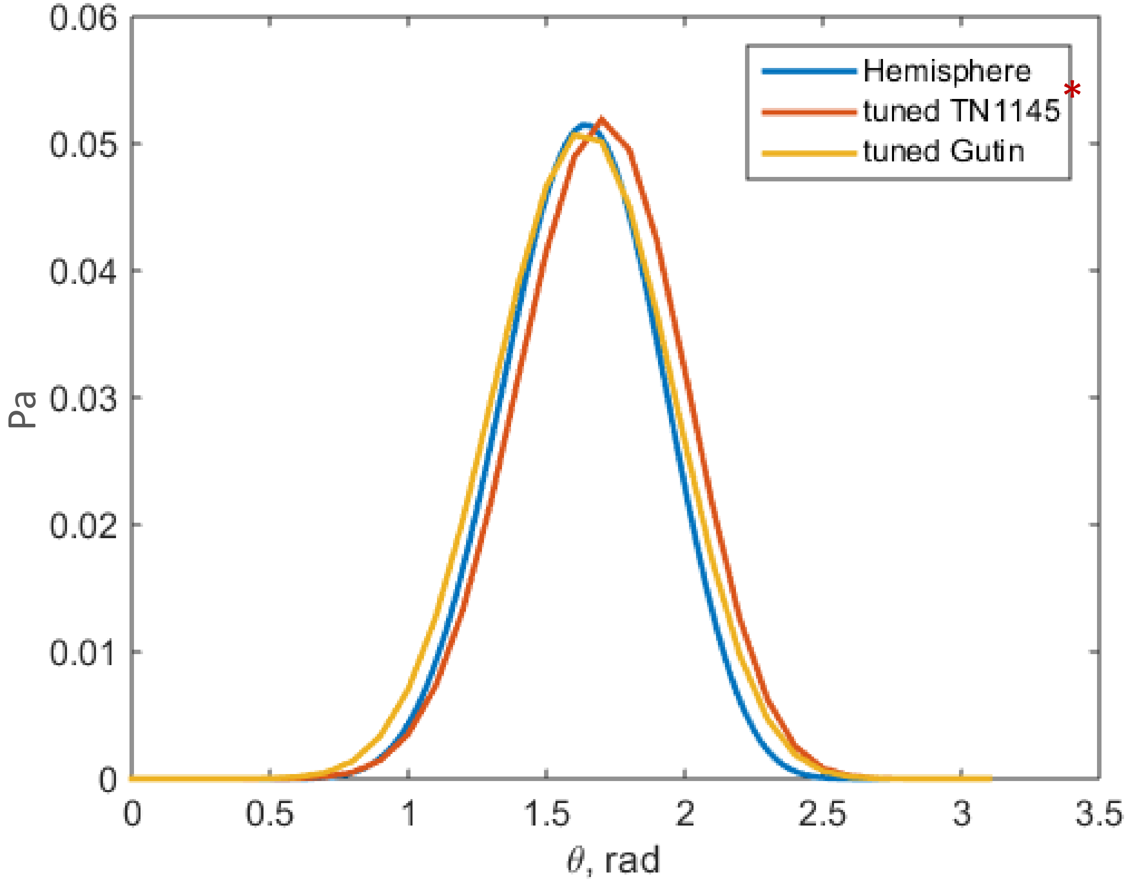
* Gutin, L., "On the Sound of a Rotating Propeller", NASA TM 1195, Oct. 1948;

An alternate approach – Directivity function

$$P = \frac{q\omega_1}{2\pi cL}\left[-TJ_{qn}(k\overline{R_1}sin\theta)cos\theta + \frac{ncM}{\omega_1\overline{R_2^2}}J_{qn}(k\overline{R_2}sin\theta)\right]$$

P: rms pressure
q: harmonic order
ω_1: fundamental of BPF
c: speed of sound
L: distance to observer
T: thrust
J: Bessel function
k: wavenumber in air
θ: elevation (polar) angle
n: number of blades
M: prop tip Mach number
R1,R2: 'certain mean value' typically $0.75R_p$

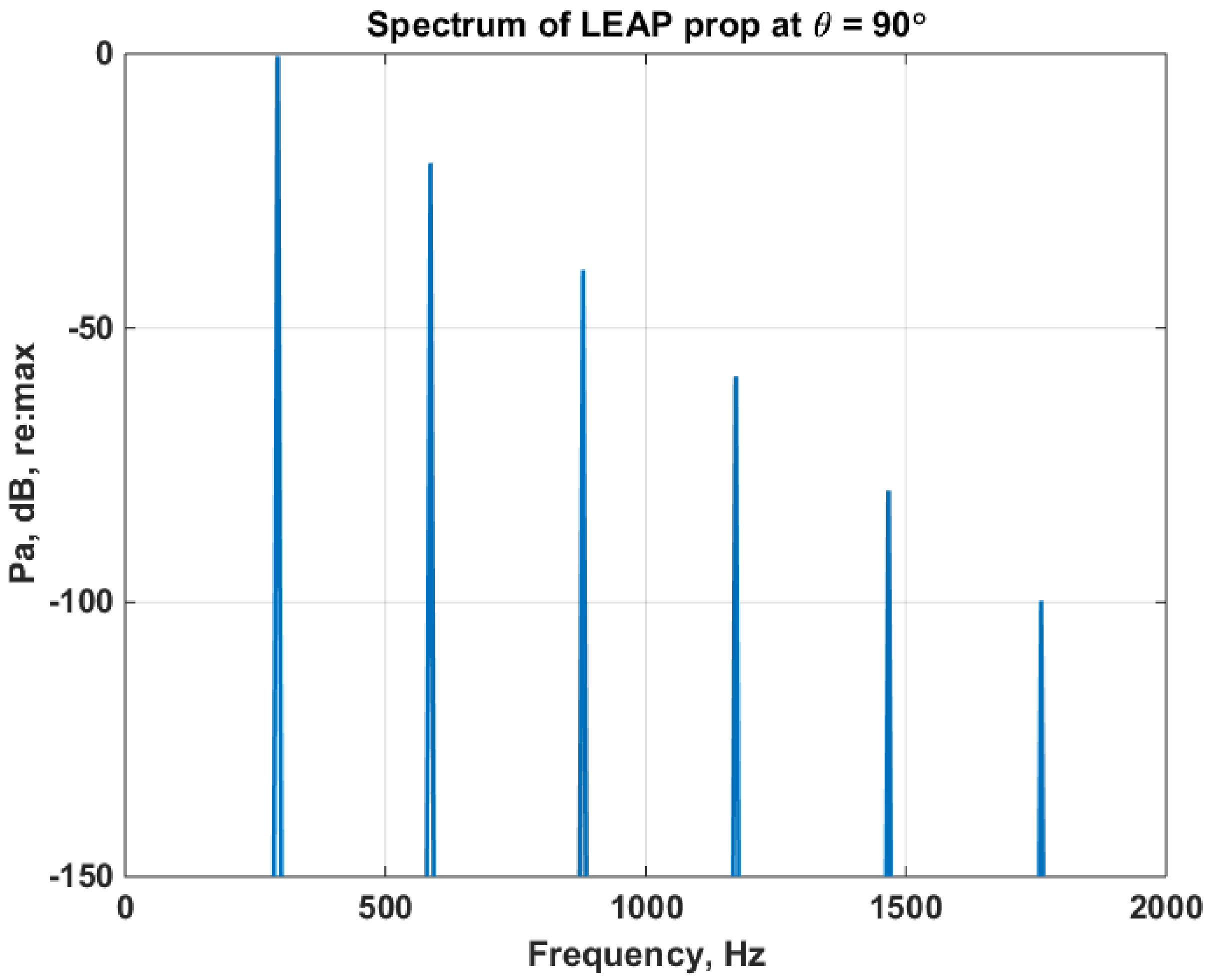
Using $R_1 = 0.8R_t$ and $R_2 = 1.12R_t$

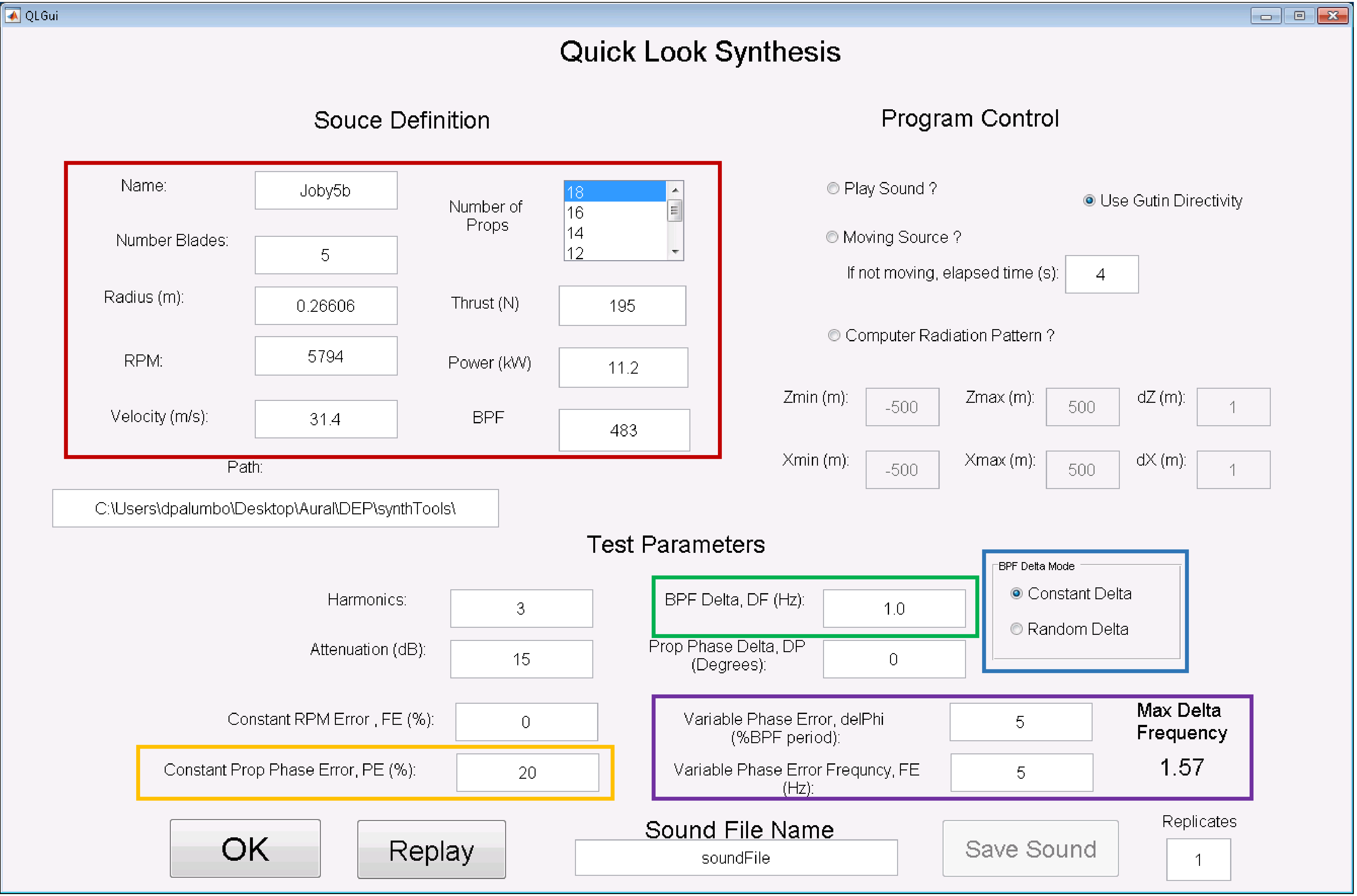


* Theodorsen, T and Regier, A., "The Problem of Noise Prediction with Reference to Light Airplanes, NASA TN No. 1145, Aug., 1946.

Alternative approach – Pure tone synthesis

- LEAP prop has ~15 dB drop between harmonics
- 3rd harmonic of LEAP prop is down over 30 dB.
- High performance props may take 10 or more harmonics.





- Source properties

- Set BPF step

- Constant or random step?

- Model controller

- Random prop error phase

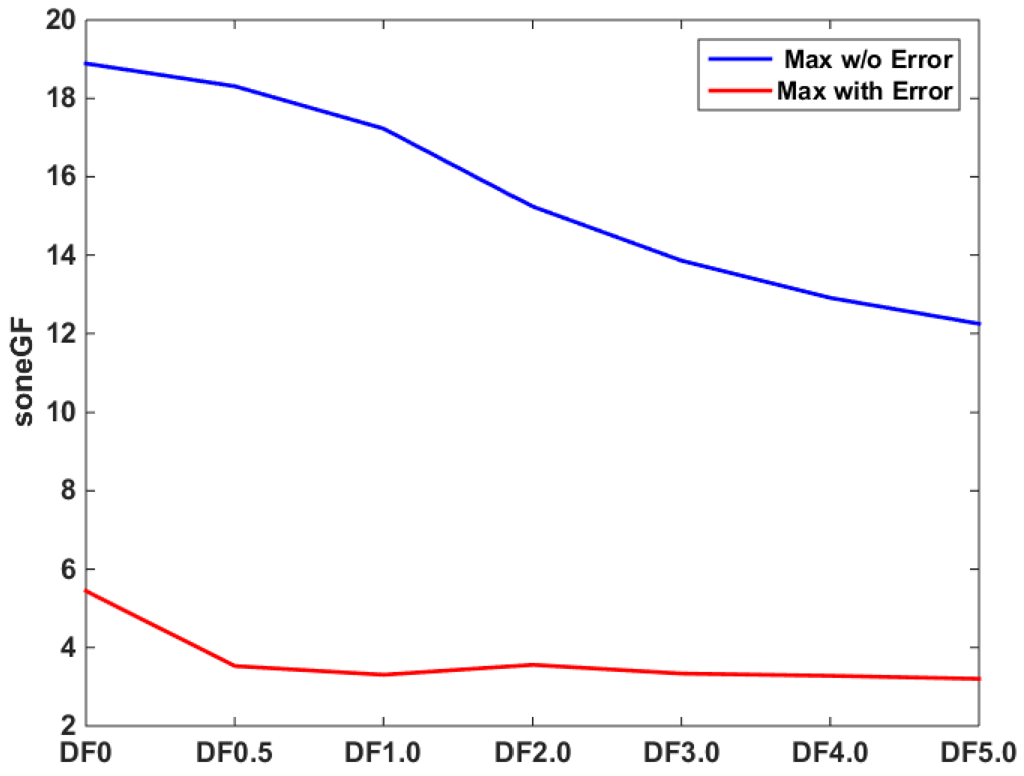
What we learned using QuickLook

- Randomness in phase and frequency **may** improve sound quality.
  - Discovered while evaluating effect of controller error
- Improved sound quality is harder to achieve using randomness as the number of sources decreases.
  - Initial ‘discovery’ was made with 18 prop configuration. Most randomized setups sounded good.
  - When configuration was changed to 8 props, good sound quality was harder to achieve with one random setup. Some sounded bad.
  - Need to generate statistics to describe effect of randomness
- QuickLook provided means of generating dozens of sound samples necessary to evaluate statistics of noise metrics.

With and without controller error
18 Synchronized* Props

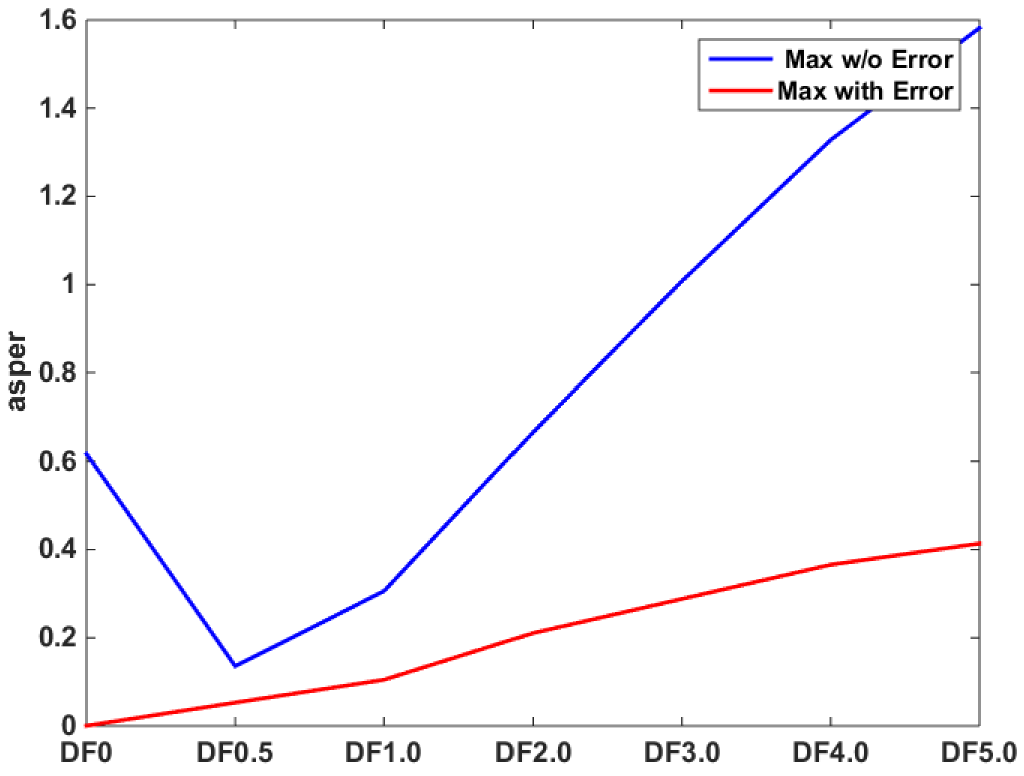
*start at phase = 0

Loudness



Roughness

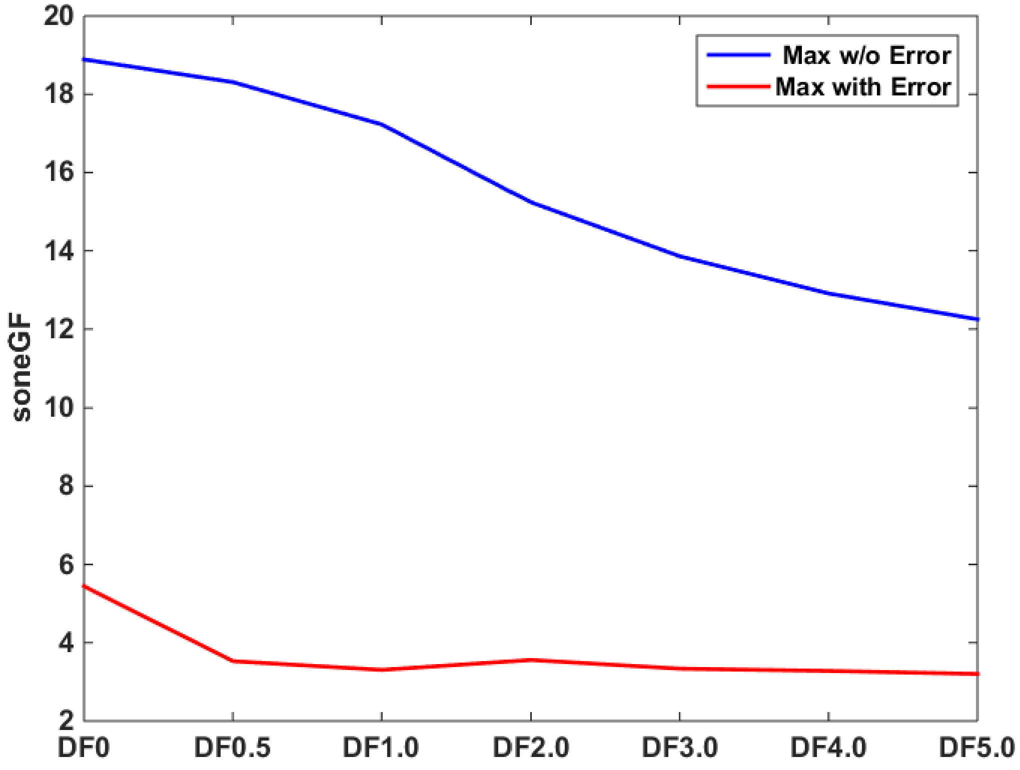
(low frequency time varying envelope)



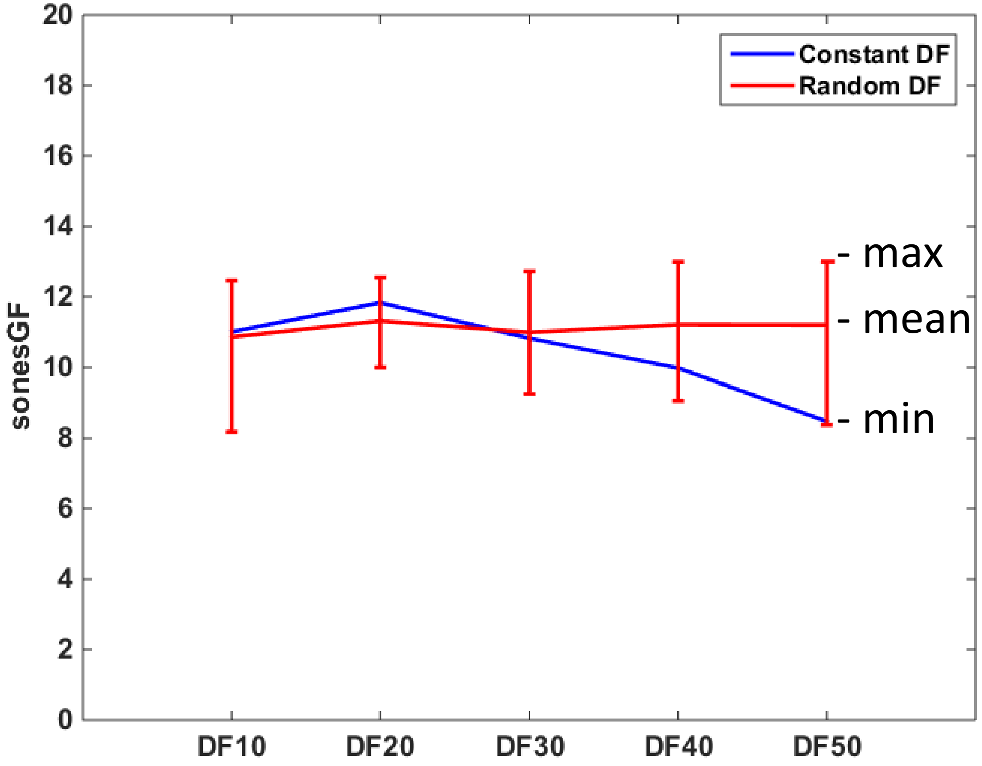
Loudness: Constant BPF vs Random BPF Synchronized vs. Unsynchronized*: 18 Props

* start at random phase

Synchronized Phase
with/without Controller Error



Random Phase
Constant/Random Step



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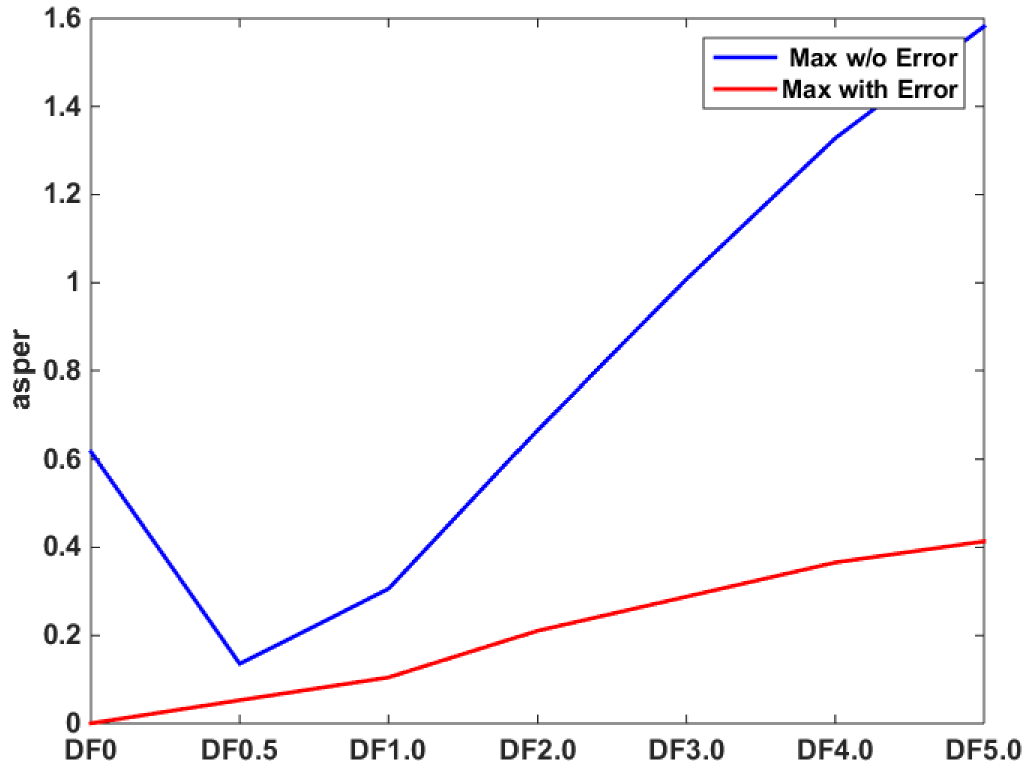
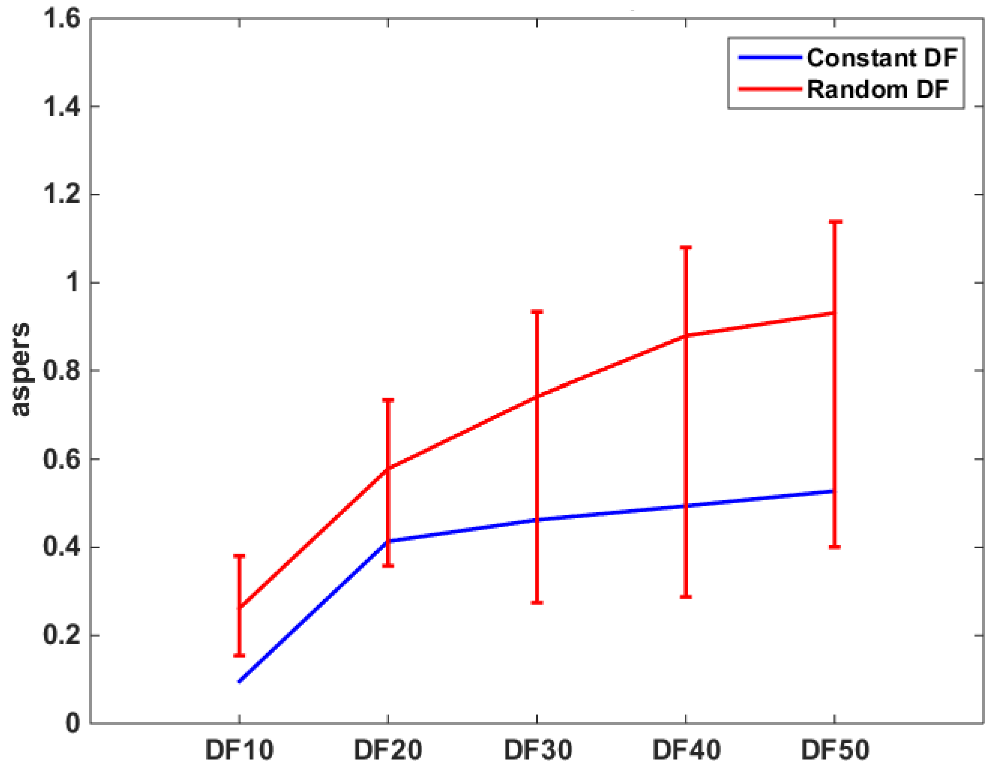
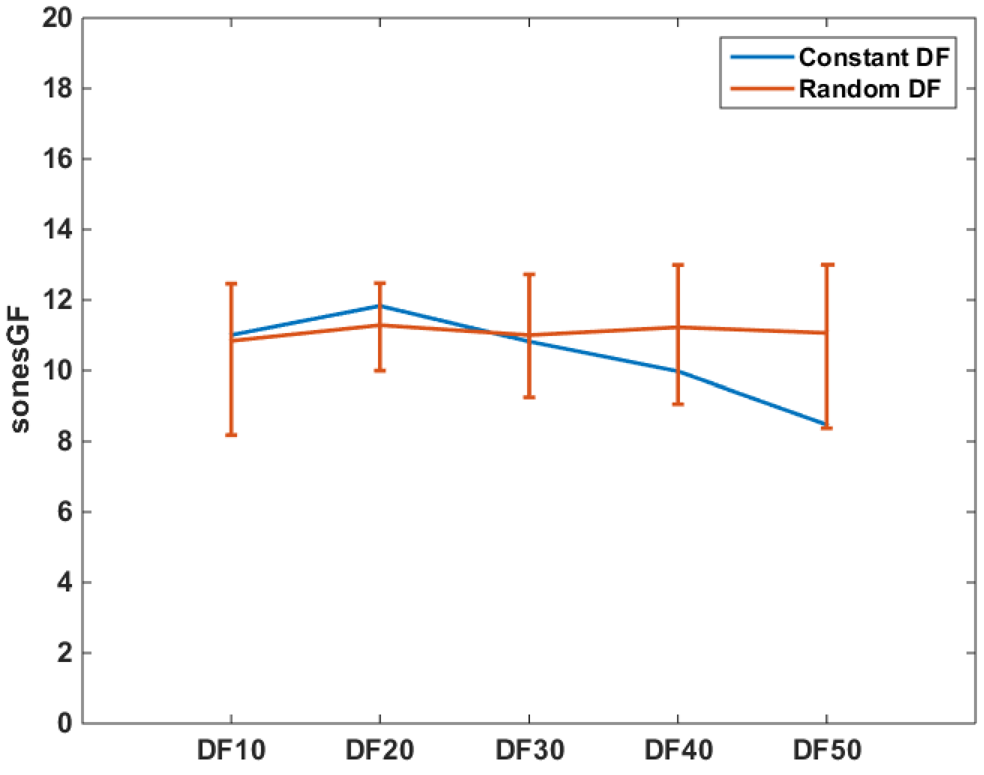


Random Phase
Constant/Random Step

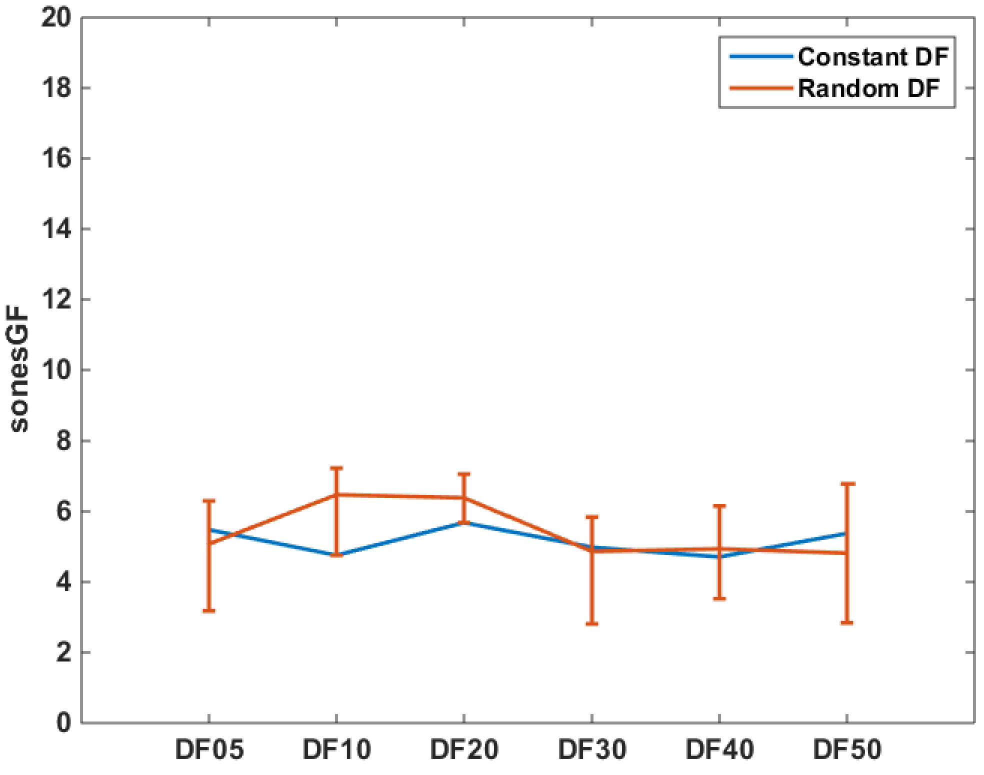


Loudness: 18 vs. 8 props, Unsynchronized

Random Phase – 18 Prop

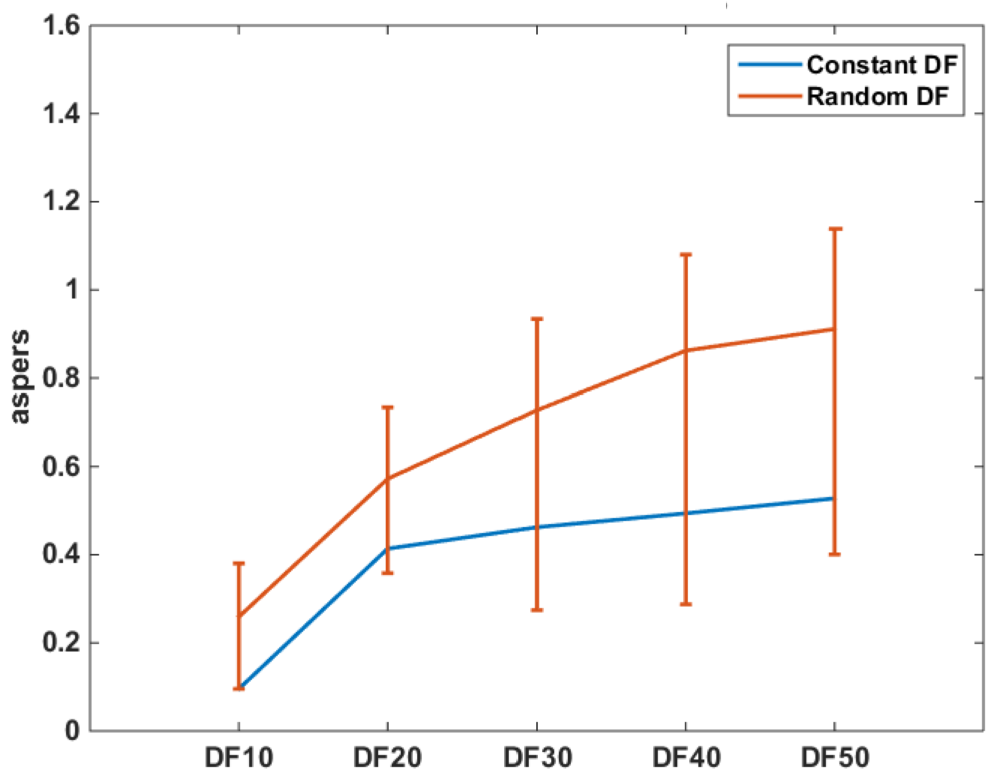


Random Phase – 8 prop

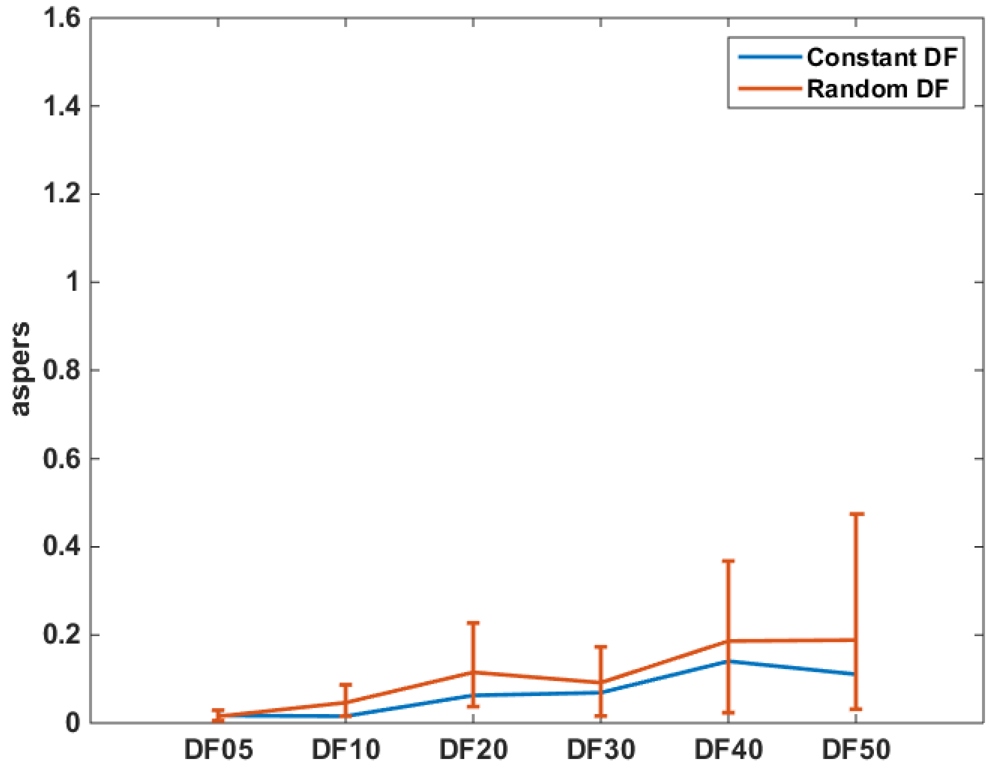


Roughness: 18 vs. 8 props, Unsynchronized

Random Phase – 18 Prop



Random Phase – 8 prop



Some samples

18 prop DF50

No Randomness – DF50

Random Phase Only

MAX DF50NP18R17

MIN DF50NP18R10

8 prop DF30

No Randomness – DF30

Random Phase Only

MAX DF30NP8R19

MIN DF30NP8R5

Shortcomings – many …

- Need random sampling of unsynchronized, constant DF configuration
  - Obtained only 1 sample of configuration with constant DF
- Need to model slowly varying phase and frequency
  - If controllers are indeed unsynchronized, phase and frequency will change over time
- In short, need a better model of motor/controller behavior
  - What is baseline controller error
  - How programmable is controller, can I set a rate of phase variation?
- Need sideline data
  - All results are centerline
  - Phase relationships will change off axis.

The DEP Psychoacoustics test

Objective of test is twofold

1. Provide guidance to design team on noise effects of design decisions
   - number of props, BPF, frequency spreading, synchronization
2. Formulation of annoyance model
   - If we have confidence in annoyance prediction then design decisions can be quickly evaluated.

Guiding Principle

Avoid artificially limiting the design space. Instead define the design space within which changes in parameters are not statistically significant.

Major Hurdle

Considering the huge design space, designing a test that can be confidently executed and still return relevant results is a major challenge

Concluding remarks

- o Derivation of an annoyance model would enable confident design decisions when new designs are modeled in increasing detail
    - Maybe the annoyance model should be primary goal of test
- o Include angle of attack, interaction effects and tip props in model
    - Whether or not the more complicated sounds can be synthesized in the QuickLook tool in a timely manner is a good question.
- o This work has been exciting, challenging, rewarding and fun (mostly)