

A Model of Turbulence in the Langley Transonic Dynamics Tunnel for Aeroservoelastic Analysis

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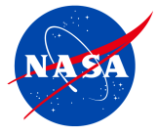
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- Turbulence
 - In flight length scales are typically much larger than the span
 - Although new configurations may not be
 - Turbulence in a tunnel has much shorter length scales than in flight
- In loads analysis
 - FAR part 25 and JSSG-2006
 - Assume uniform across the span
 - Usually conservative for loads
- In flying qualities
 - MIL-STD-1797
 - Linearly varying across the span to give rolling motion
 - Many simplifying assumptions and numerical approximations to make simpler
 - E.g., unswept wing, no convective delay, additional nonphysical filtering



Credit: NASA/Mark Knopp



- Correlation of turbulence between two points, $P(\delta)$, separated by distance d
 - From Houbolt and Sen 1972
 - As $\delta \rightarrow 0$ becomes standard von Karman turbulence spectrum
 - Standard assumptions
 - Isotropic turbulence (not actually true in a wind tunnel)
 - Taylor (frozen) hypothesis
 - Correlation distance, δ , by Fourier transform in the direction of the freestream

$$\delta(k) = \frac{d}{1.339L} \sqrt{1 + \left(1.339k \frac{2L}{\bar{c}}\right)^2}$$

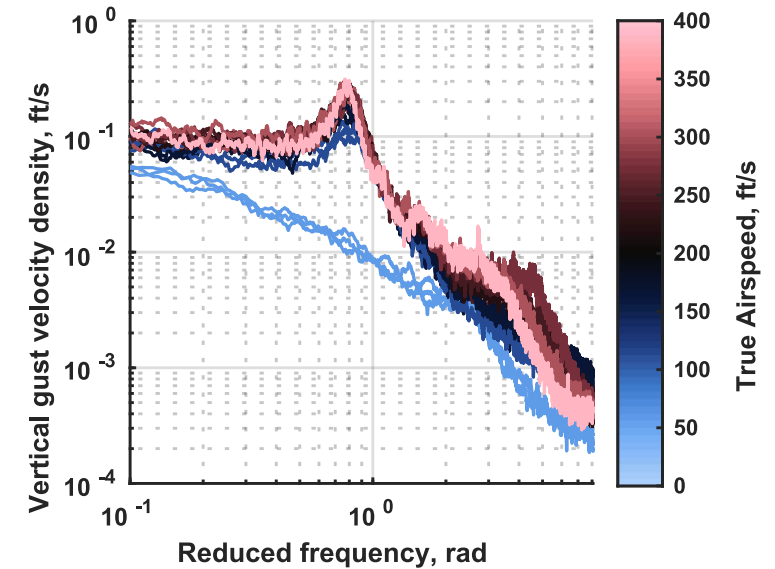
- Construct a correlation matrix, $\mathbf{P}(k)$, for doublet lattice panels
 - Separate correlation matrix for each reduced frequency
 - Describes relationship of turbulence between panel control points
- Use a singular value decomposition of these correlation matrices

$$\mathbf{A} = [\mathbf{P}(k_1) \quad \mathbf{P}(k_2) \quad \dots \quad \mathbf{P}(k_n)]$$

$$\mathbf{A} = \mathbf{U}\mathbf{S}\mathbf{V}^T$$

- Reducing the columns of $\mathbf{U}$ creates a simplified representation of the turbulence field
- Coupling of frequency response between the columns of $\mathbf{U}$ is small but not fully decoupled

- Air data vane used to measure flow disturbances from gust generator
 - Also detects turbulence
 - Sniffer mounted slightly below the model and the tunnel centerline
- Data shows a large peak at a reduced frequency ~ 0.8 rad
 - Does not appear at low airspeed
 - Consistent reduced frequency with tunnel speed.
 - Model is not being excited at this frequency
 - Not observed in previous characterization of tunnel turbulence
 - Appears to be a flow feature of the sniffer and not the tunnel
- Von Karman turbulence spectrum is fit to the data (2 unknown parameters)

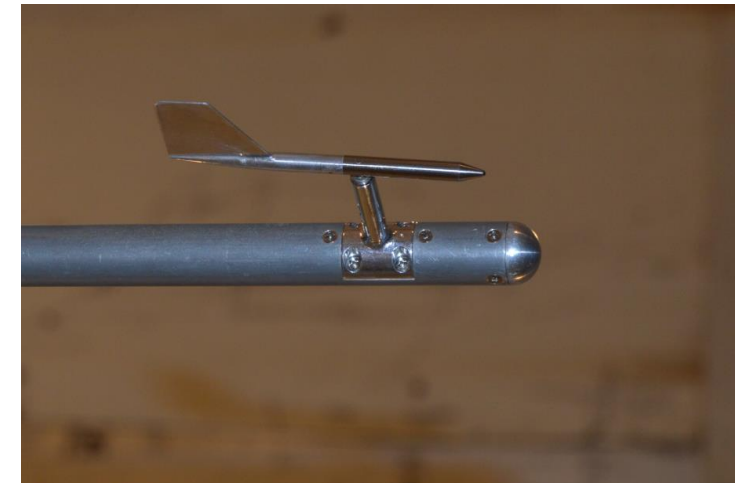


$$\varphi(\omega) = \frac{\sigma^2 L V_T}{2\pi} \frac{1 + \frac{8}{3} \left(1.339 \frac{L\omega}{V_T} \right)^2}{\left[1 + \left(1.339 \frac{L\omega}{V_T} \right)^2 \right]^{11/6}}$$

- L - Length scale
- σ^2 - Intensity
- An extra second order mode is added to the fit of the turbulence



Credit: NASA



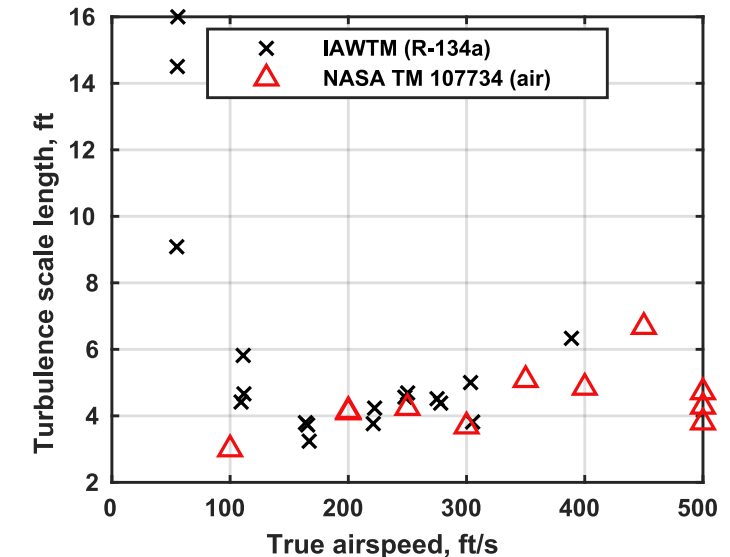
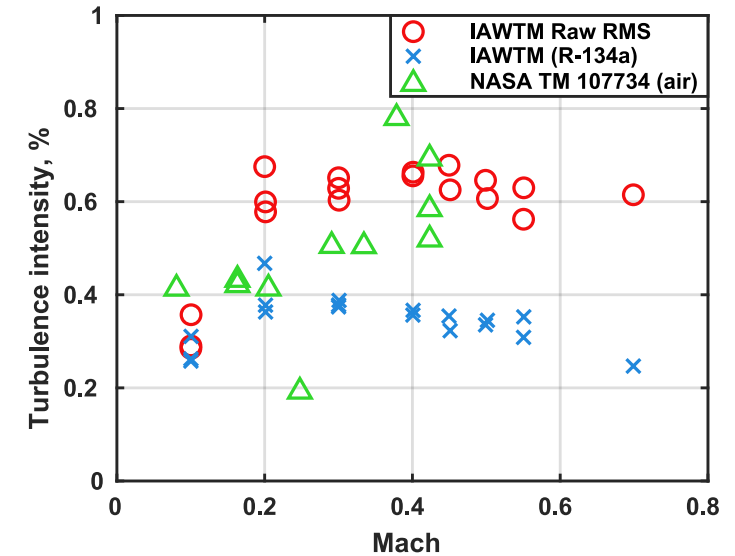
Credit: NASA



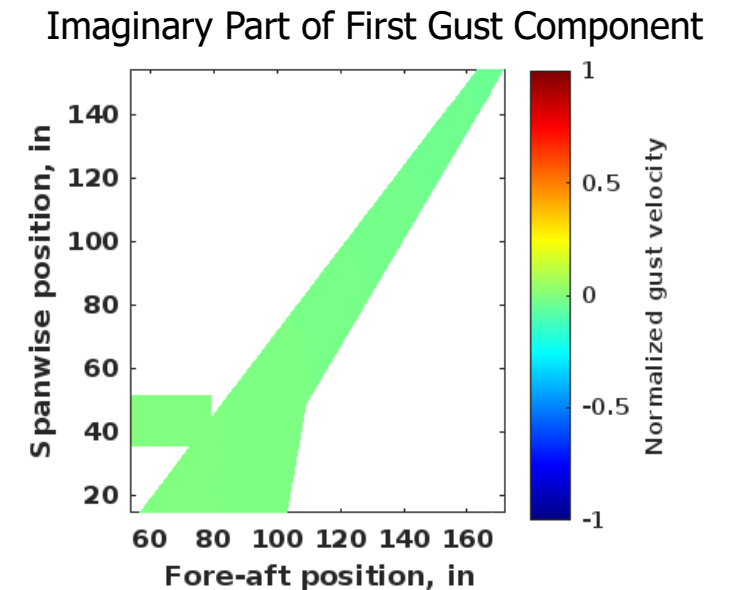
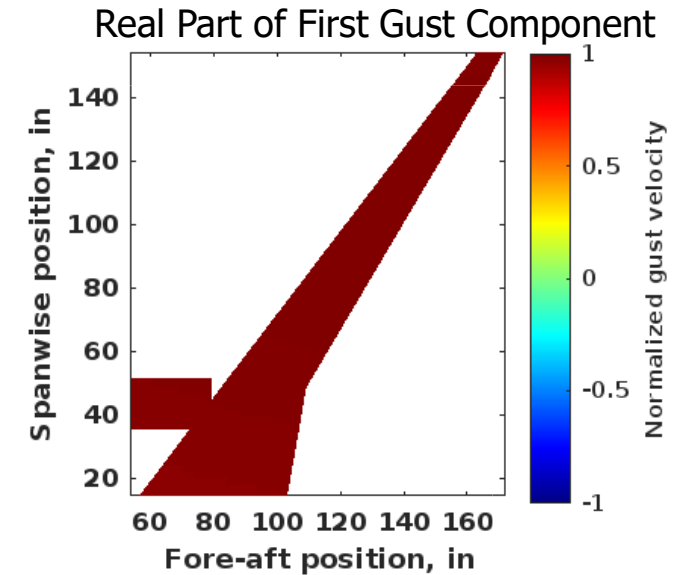
Results: TDT Estimated Turbulence Parameters



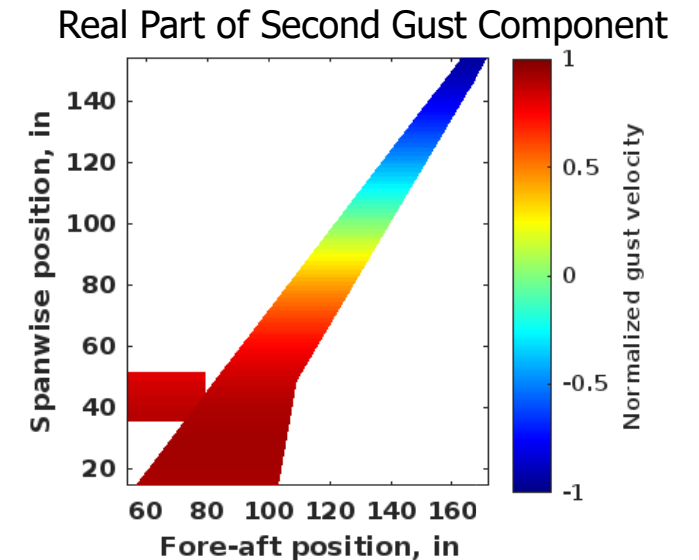
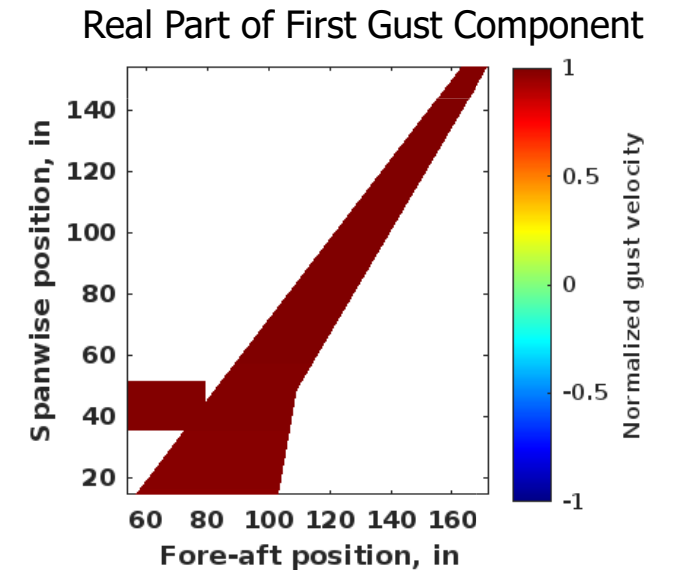
- Comparing to earlier tests in TDT using hot wire
 - Tests were in air at a high wind off pressure
- Turbulence intensity
 - Turbulence intensity is lower in R-134a then in air
 - Raw RMS omits additional second order mode
 - Raw RMS matches well to fit PSD because the peak does not appear
 - At higher Mach, omitting the peak causes a large overprediction of turbulence.
- Turbulence length scale
 - Length scales very similar between R-134a and air
 - Fit was poor at lowest airspeed, giving large variability in estimates.
 - Generally, lengths are 3-6 ft.
 - >2 orders of magnitude smaller than standard gust models (500+ ft)
 - Standards assume length scale is >10x the wingspan
 - In TDT the length scale is 0.2 x the wingspan

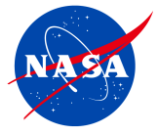


- Assumptions
 - Length scales are large, 10x the wingspan
- Gust components
 - One gust component captures 96% of the RMS due to the turbulence
 - The first component is very uniform and real
 - Imaginary part is nearly zero indicating no phase
 - This is partially due to the configuration with no tail



- Assumptions
 - Length scales are large, 10x the wingspan
 - No delay due to convection
 - True for unswept wing
- Gust components
 - The first component is still uniform
 - The second component is linearly varying spanwise as assumed in MIL-STD-1797
 - For IAWTM these spanwise velocity variations are still small
 - It is show in the paper how these assumption of no convection has a small effect on these spanwise variations

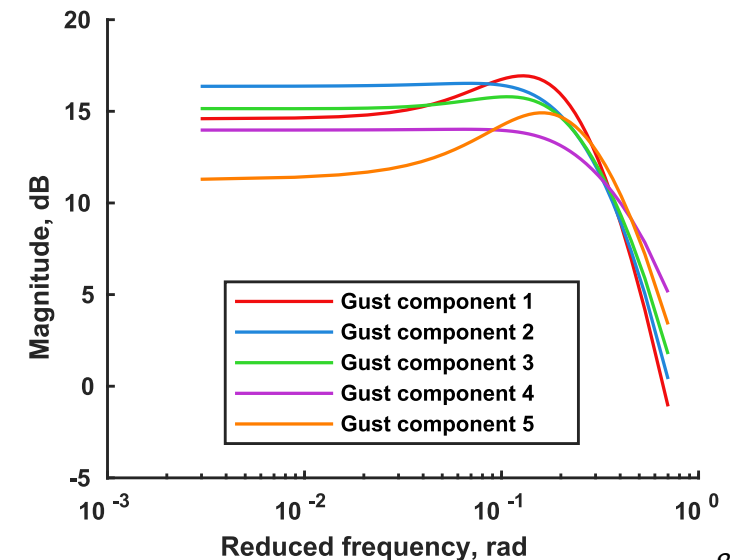
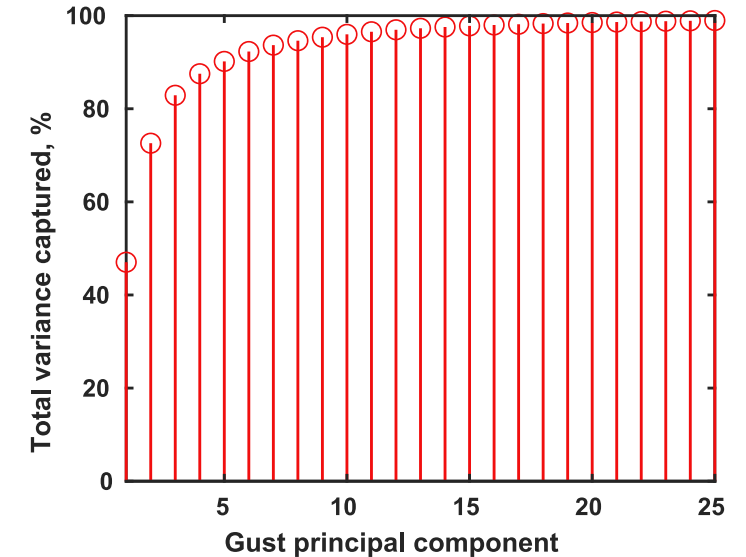




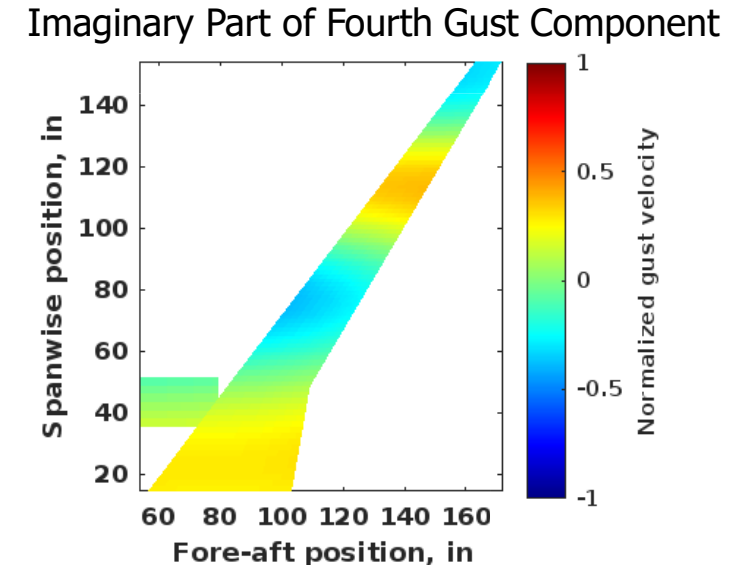
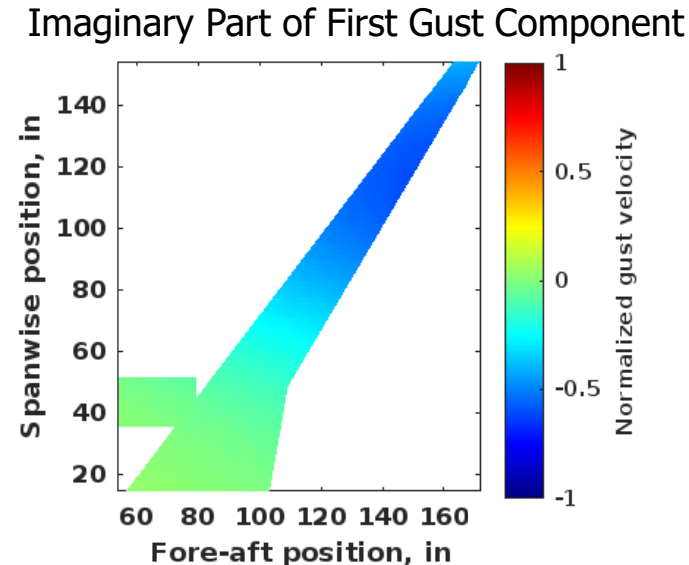
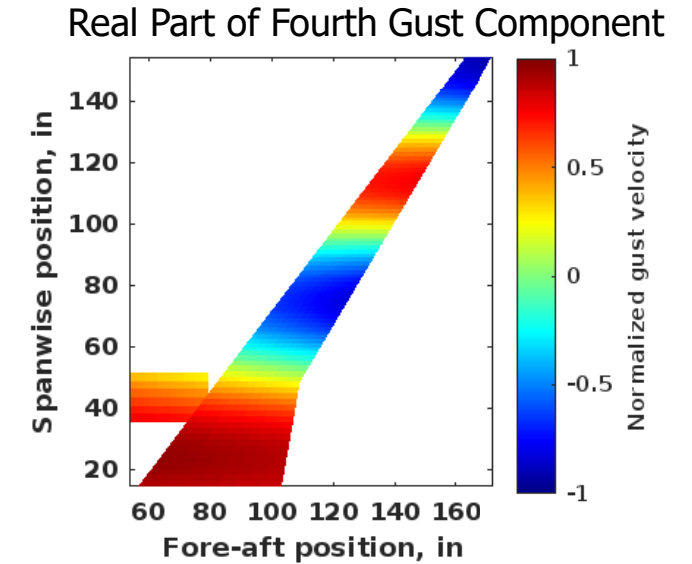
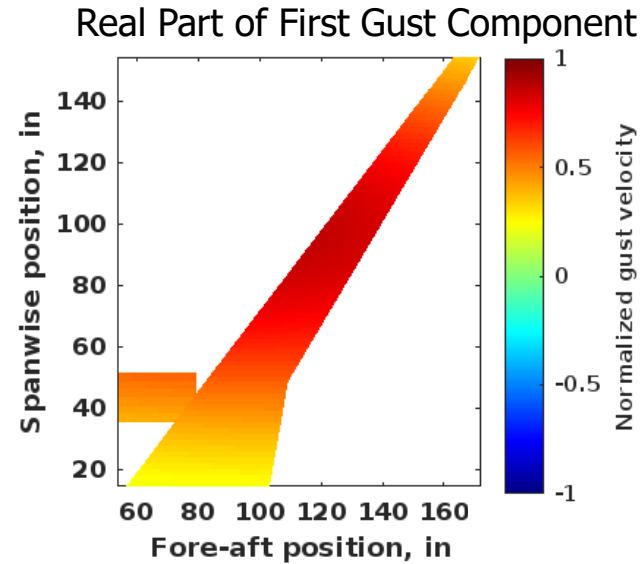
Results: Turbulence in the Transonic Dynamics Tunnel



- Much shorter length scale (4.2 ft)
- 5 gust component required to capture 90% of the RMS due to the turbulence
 - Large length scales only required 1 component to get 96%
- The principal components give PSD spectra that are similar to the classical spectra
 - Finite magnitude at steady state
 - A knee in the curve
 - Rolling off at higher frequency
 - These would still require a filter to be fit for time domain analyses
- Unlike MIL-STD-1797 these are using a single spectrum definition
 - MIL-STD-1797 uses von Karman for the uniform and Dryden for the spanwise component



- First gust component
 - Not uniform
 - Significant imaginary part
 - Indicates a time varying shape
 - E.g., spanwise traveling waves
- Fourth gust component
 - Relatively complex shape
 - Would be difficult to define simple shapes as done in the standards for such a flow field
 - Indicates significantly more variations in the turbulence across the span



- The length scales of turbulence in a wind tunnel are much smaller than in flight
 - The smaller length scales results in a more complex flow field that can excite structural modes
 - The length scales from the IAWTM test in July 2025 were examined
- A simplified gust field was generated that is suitable for integration with aeroservoelastic models
 - With suitable assumptions and simplifications, the model also replicates typical turbulence models from loads and flying qualities analyses
 - The present model of wind tunnel turbulence is more complex than the standards
 - The model was able to capture much more of the flow field than traditional approaches and is still suitable for an aeroservoelastic model



Credit: NASA/Mark Knopp