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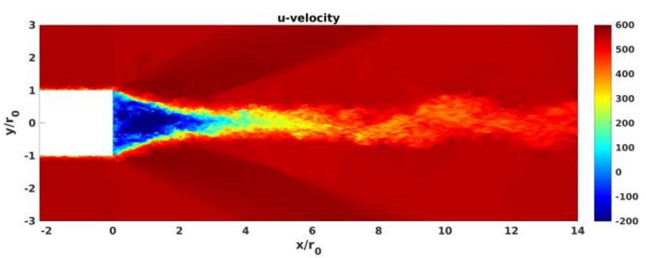

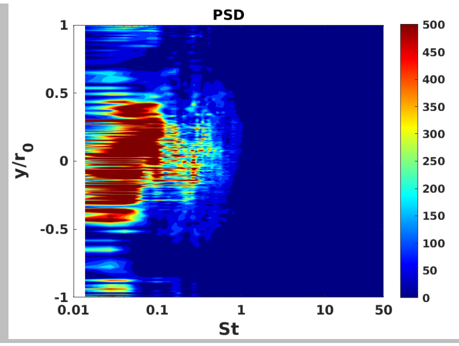

Base Pressure Fluctuation Modeling: Theory, Simulation and Measurement

Lawrence DeChant, Brian Robbins, Cory Stack, Ashley Saltzman

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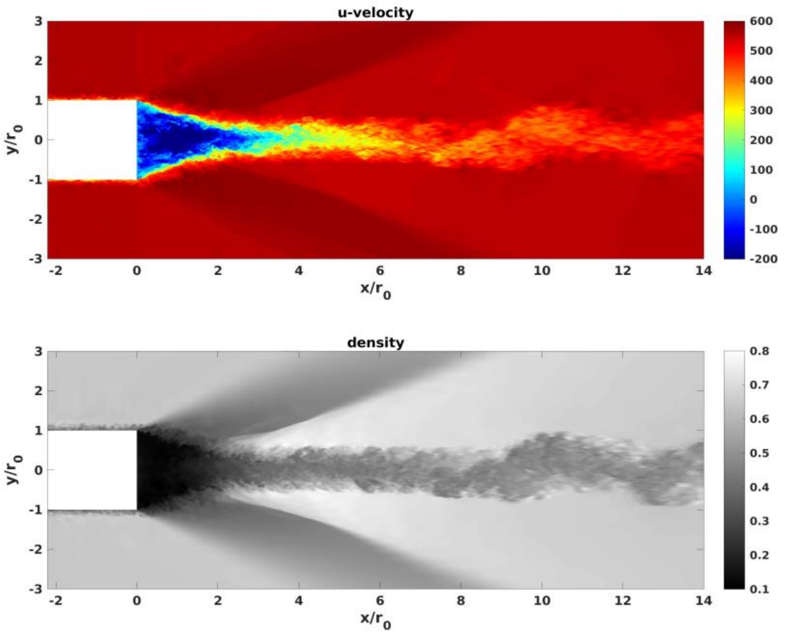
Base Pressure Fluctuations…

- Base pressure fluctuation
- Can induce significant system vibratory input
- Potentially important for some FSI problem classes



Outline

- Introduction
- PSD Model DeChant and Smith (2011)
- Critical Strouhal Number
  - Janssen and Dutton
  - Offset sting
  - Shear layer instability
- Loading Amplification Theory
- RMS behavior
- Mean Base Pressure Estimates
- Conclusions
- Future Work

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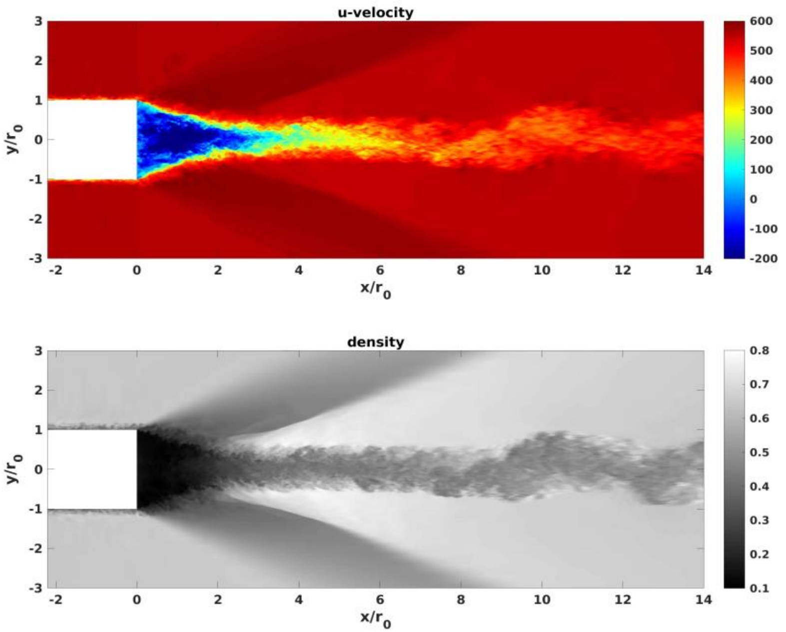


Base Pressure Fluctuations… DeChant et. al.

- **Base pressure fluctuation PSD essential for FSI problem**
- **Theory-based model Dechant and Smith (2011)**
- **Leverages Ahlborn et. al. (2002)**

$$\Phi_{pp}(\omega) = \Phi_{mag} \frac{\left(a^2 + c^2 + \omega^2\right)}{\left(a^2 + c^2 - 2a\omega + \omega^2\right)\left(a^2 + c^2 + 2a\omega + \omega^2\right)}$$

- **Where**

$$a = \left(\frac{1.53 S_t (1 + C_D)}{2\pi^2 C_D}\right)^{1/2} \qquad \Phi_{mag} = \frac{D}{U} \frac{(1.75(2)(K_C) a q_e)^2}{(1 + M_e)^4}$$

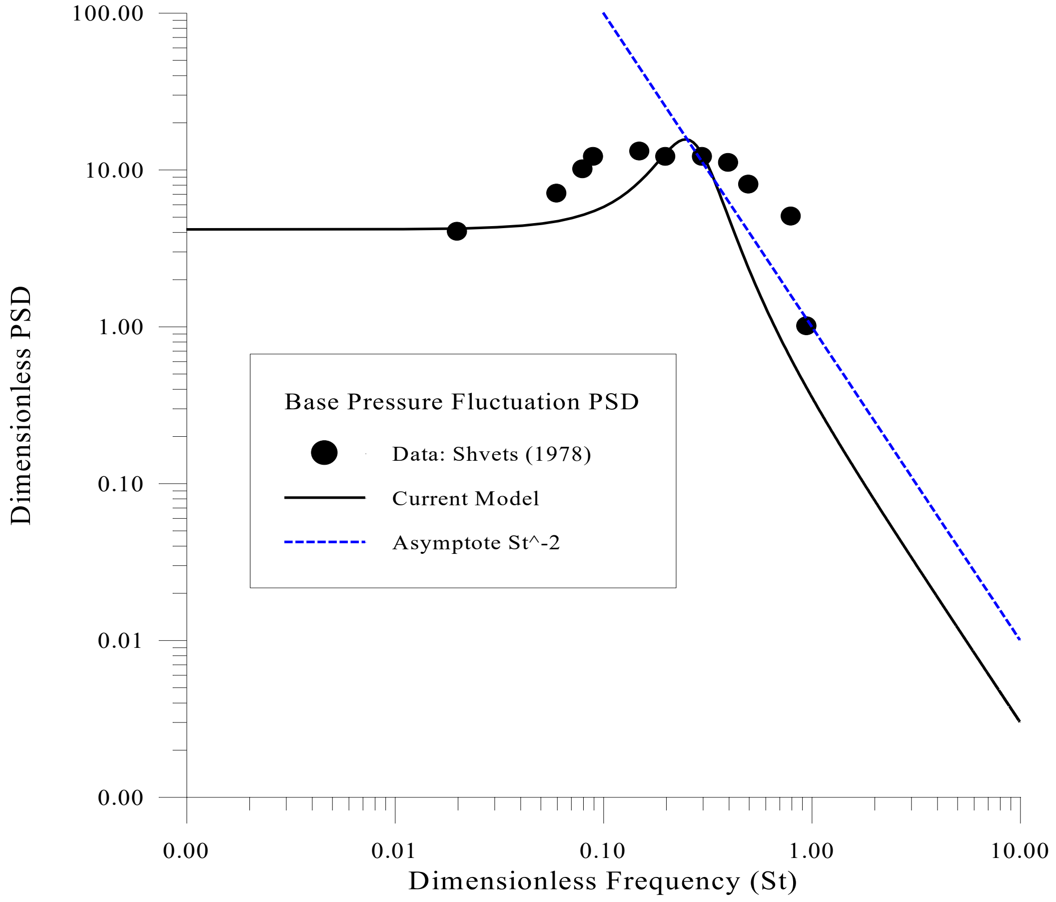
- **Notice that the critical frequency “a” depends on body drag Cd**

Base Pressure Fluctuations… DeChant et. al.

- **PSD model Dechant and Smith (2011)**

- **Note maximum amplitude near critical Strouhal number**

$$St = \frac{\frac{1}{2\pi^2}K\left(1+C_D\right)}{C_D + \frac{4NK}{\mathrm{Re}}}$$



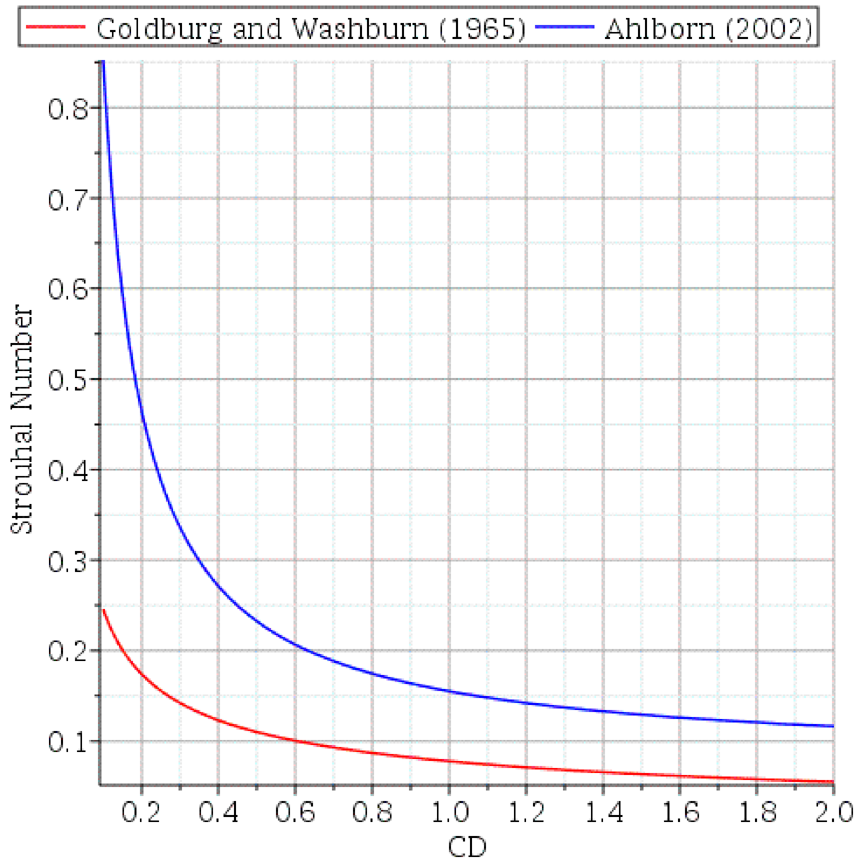
Critical Strouhal Number

- Critical Strouhal number
- Notice the dependence on Cd

$$St = \frac{\frac{1}{2\pi^2} K(1 + C_D)}{C_D + \frac{4NK}{\mathrm{Re}}}$$

- Low frequency requires large drag
- Other models known

$$St_D = \frac{fD}{U} \approx \frac{\sqrt{2}}{4}(0.22)C_D^{-1/2}$$

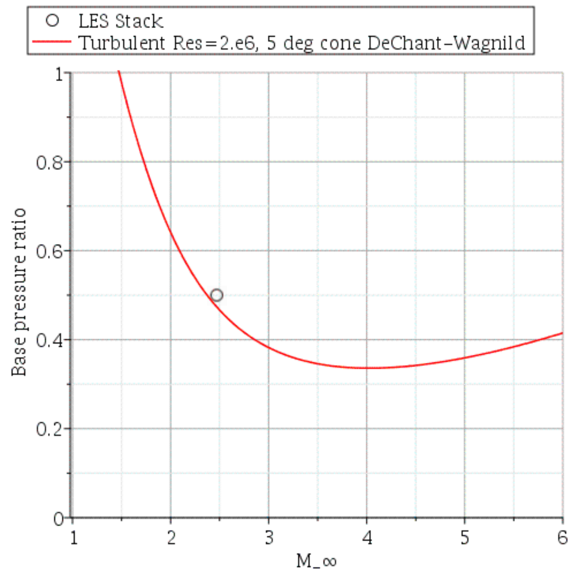


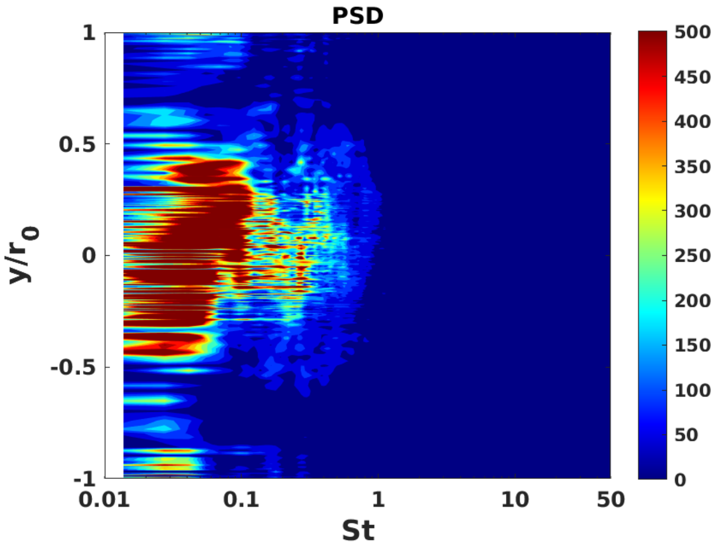
Critical Strouhal… Janssen and Dutton/Simulation

- **Bluff body base unsteadiness**
- **Janssen and Dutton (2004)**
- **Base pressure ratio correlated with drag**

$$C_{D\_base} = 2\left(1 - \frac{p_b}{p_\infty}\right)\left(\frac{q_\infty}{p_\infty}\right)^{-1} = \frac{2}{\gamma M_\infty^2}\left(1 - \frac{p_b}{p_\infty}\right)$$

- **Theory… St=0.09**
- **Reasonable agreement with computation**



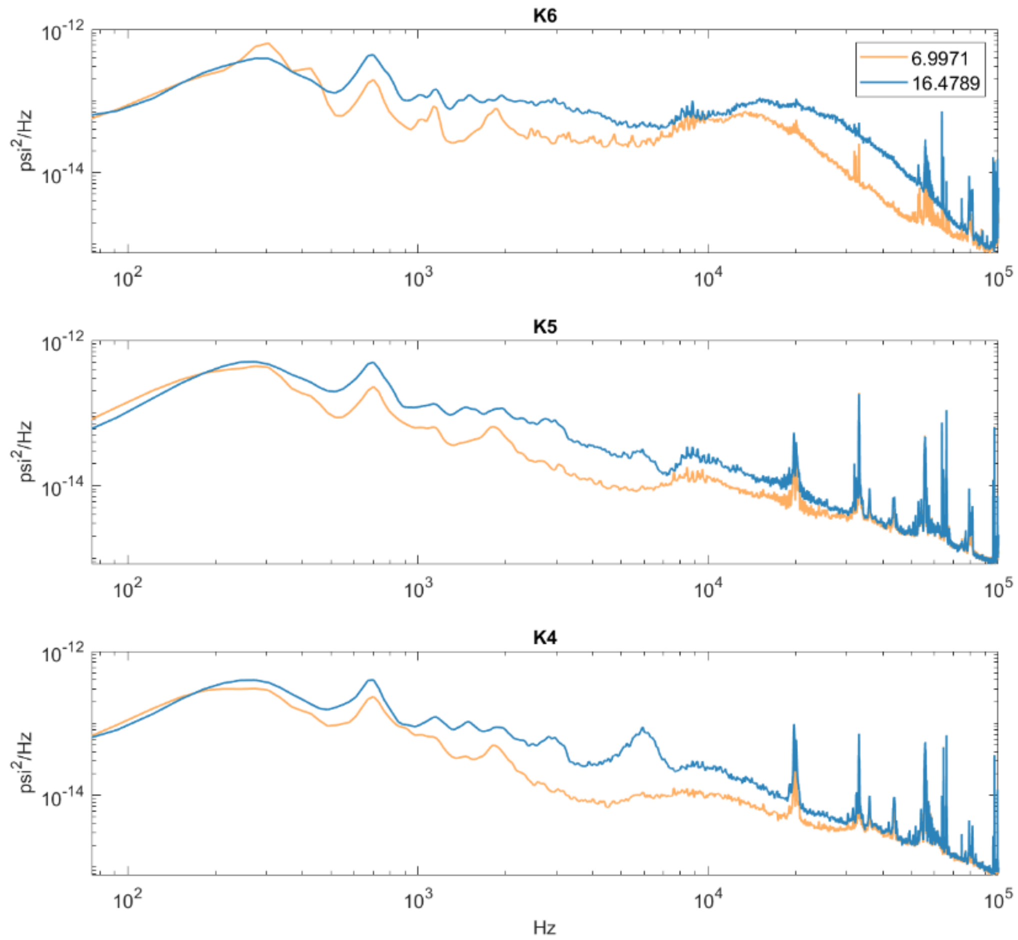


Critical Strouhal number… Offset Sting

- **5 degree Mach 8 cone experiments**
- **Zhang et. al. (2019)**

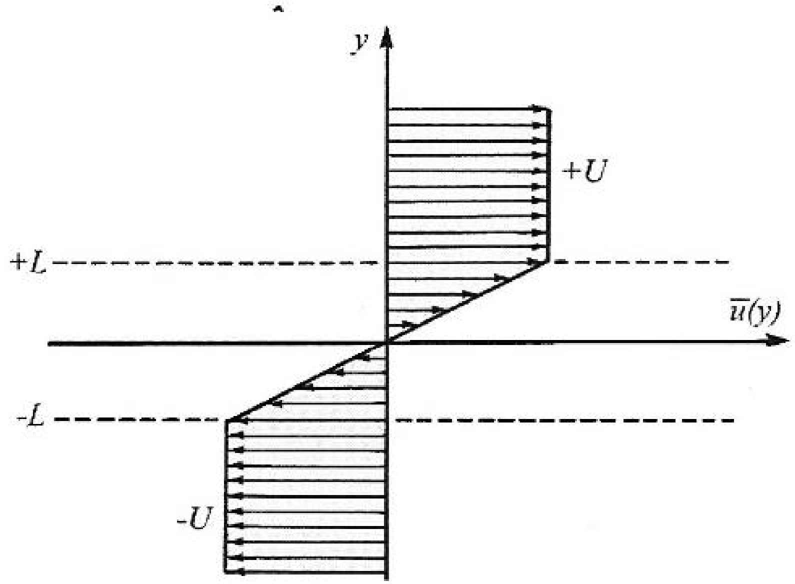
$$St = \frac{fD}{U} = \frac{(700)(0.077)}{1160} = 0.046$$

- **Presence of sting significantly modifies base pressure region and changes critical Strouhal behavior**



Critical Strouhal number… Shear Layer Instability..

- **Shear layer instability introduces a shear layer shedding frequency**
- **"Most dangerous" fastest growing frequency offers estimate for low frequency behavior.**
- **Probably best suited to blocked base problem**



$$f = \frac{\frac{\omega}{k}}{\lambda} = \frac{\omega}{2\pi} = \frac{(0.20)(0.40)}{2\pi}\left(\frac{U}{L}\right) = 0.051\left(\frac{U}{D}\right)$$

Loading Amplification Factor….

- The PSD responds with maximum magnitude at the critical frequency
- Estimation of the magnitude is essential
- Consider these simple expressions for pressure fluctuation

$$p' \sim \rho u'u' \propto \rho (U_2 - U_1)^2 \exp(-(\sigma \frac{y}{x})^2)$$

- One can estimate a pressure correlation function and a coherence function. One can demand a relationship between correlation and coherence so as to estimate parameters (focusing on the damping function) β

$$f(y,\alpha,\beta,B,C) = \exp(-2\sigma y) - C\int_0^\infty \exp(-\frac{2}{\pi}\frac{\beta}{(\alpha^2+\beta^2)}\omega)\exp(-B\omega y)d\omega = 0$$

- Damping… notice damping is a function of critical frequency α

$$\beta = \frac{2\sigma - \sqrt{4\sigma^2 - \pi^2\alpha^2 B^2}}{\pi B} \approx \frac{\sqrt{2}\pi}{4}\frac{\alpha^2}{\sigma}$$

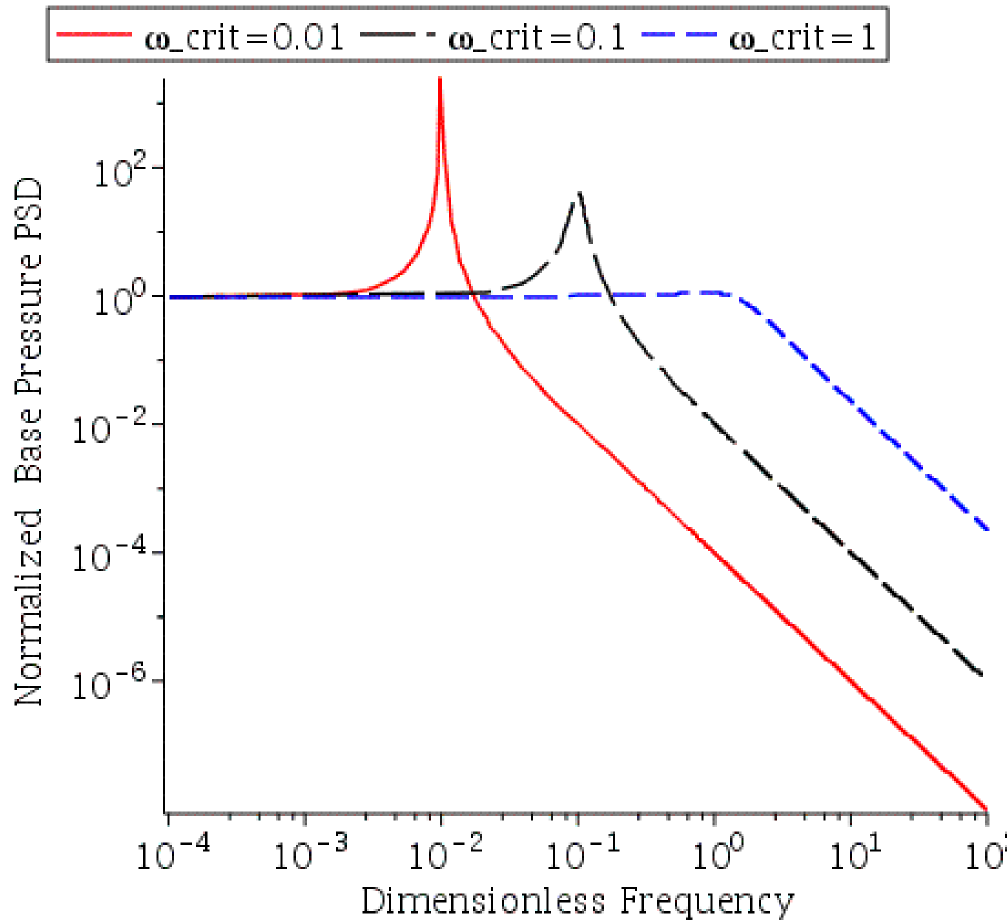
Loading Amplification Factor….

- **Use of this damping expression in the PSD yields..**
- **Notice that lower frequency behavior induces increased amplitude at the critical frequency**

$$\beta = \frac{\sqrt{2}\pi}{4}\frac{(0.257)^2}{1.4} \approx 0.052$$

- **Compares well with empirical closure…**

$$\beta = \frac{1}{20} = 0.05$$

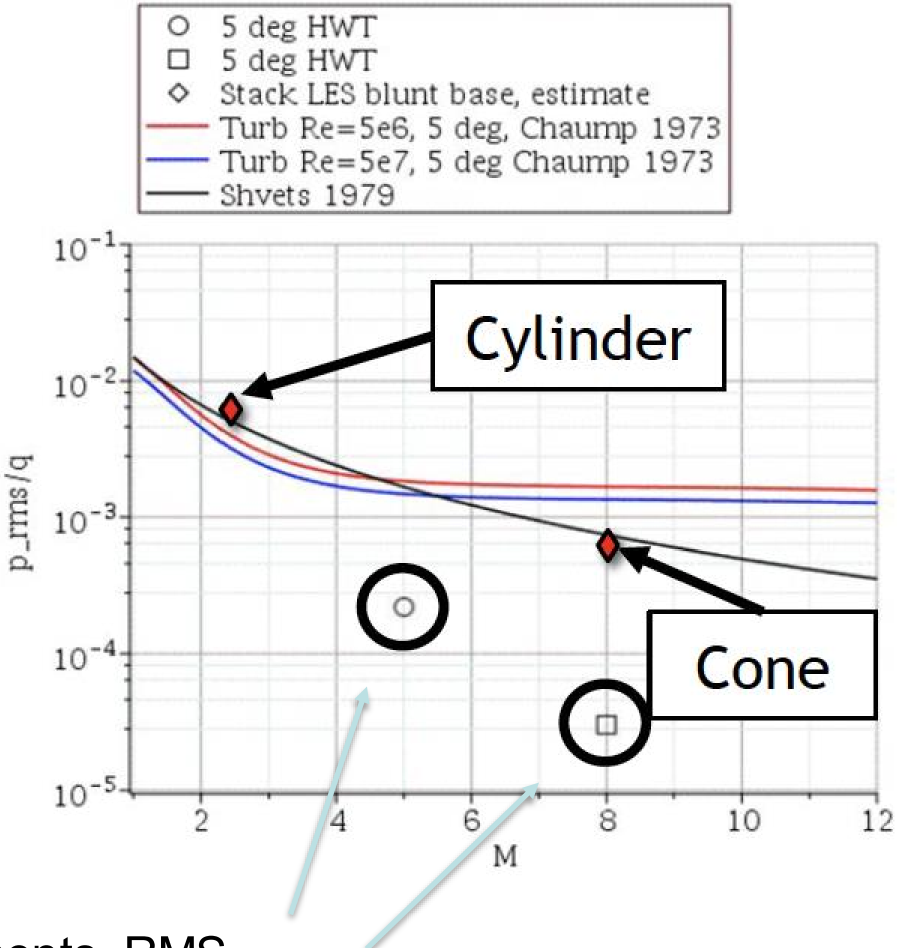


Base Pressure Fluctuation…. RMS

- **Amplification applies at critical frequency, but magnitude requires base pressure RMS**
- **Pressure fluctuation RMS is required**
- **Traditionally a simple Mach number correction is used**

$$\frac{p_{rms}}{q_\infty} = \frac{0.06}{(1+M_\infty)^2}$$

- **"Cylinder" and "Cone" simulations trend well**



HWT measurements, RMS suppressed by presence of sting

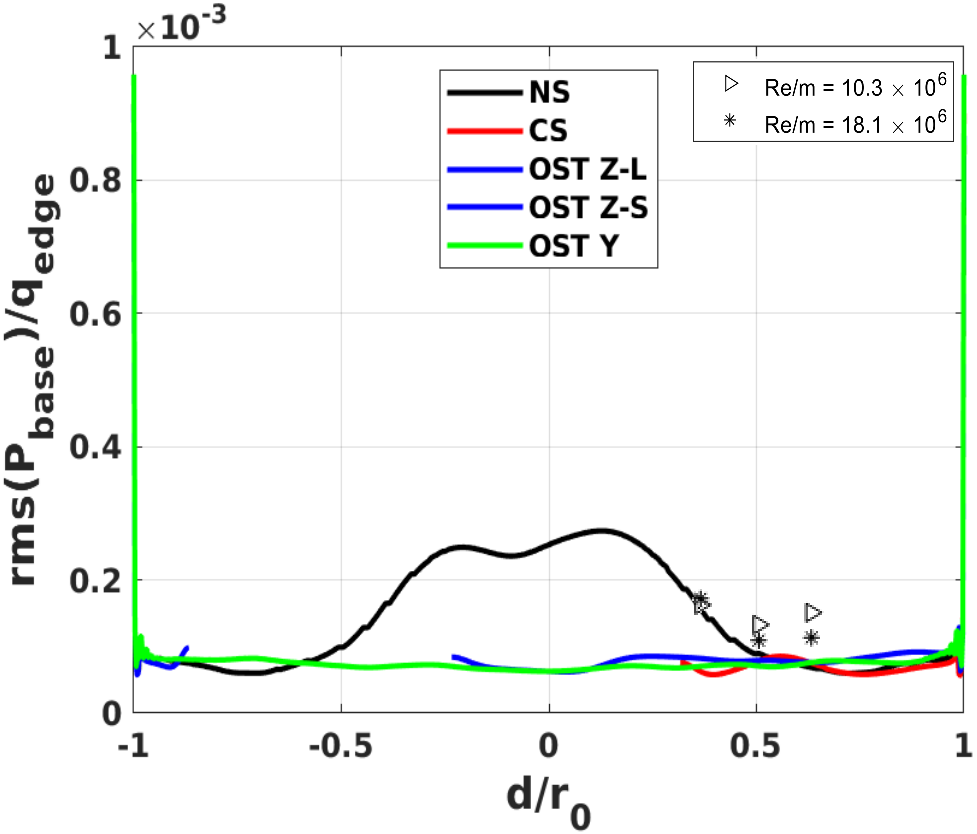
Base Pressure Fluctuation…. RMS

- The modification of base pressure field due to the presence of sting is apparent in the previous measurements

- Recent measurements (Saltzmann) mounted model on an upstream blade suggests different behavior

- NS=no sting

- Base pressure has been indeed suppressed by the presence of the sting



Mean Base Pressure Model

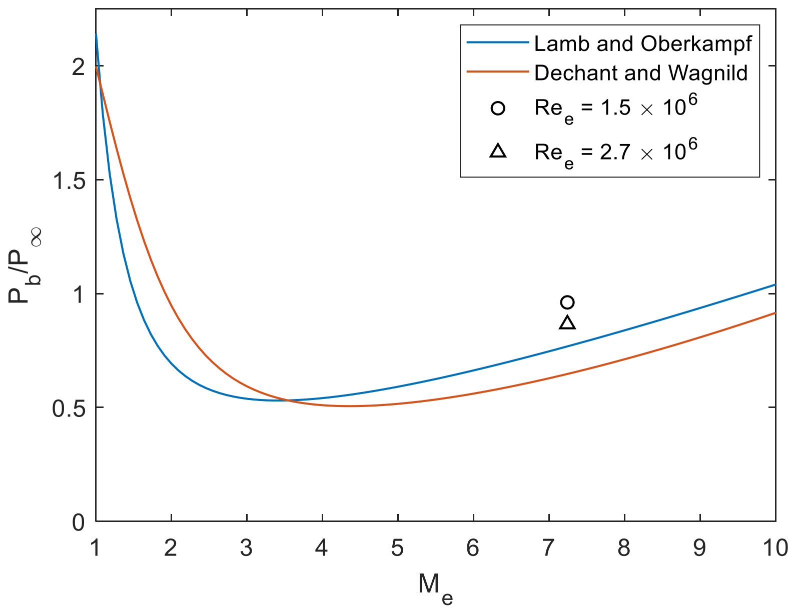
- **Part of the base pressure problem is involves estimates for the mean base behavior**
- **A theory-based model (DeChant and Wagnild) uses:**
  - **Adiabatic expansion (Prandtl-Meyer)**
  - **Energy conservation (Crocco-Buseman)**
  - **Simple viscous mixing model describing dividing streamline**
  - **A stagnation pressure**

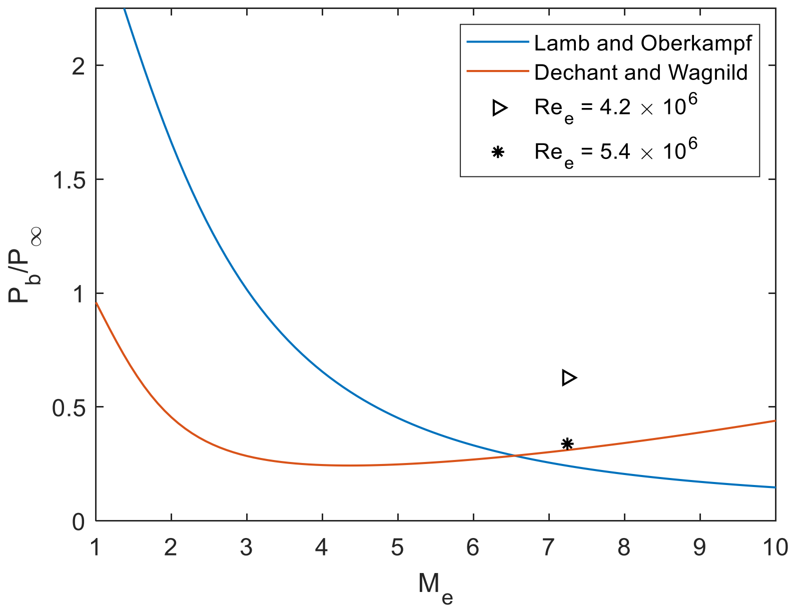
$$\frac{p_b}{p_\infty} = \left.\frac{p_b}{p_\infty}\right|_0 \left(1 + \frac{\frac{\gamma-1}{2}(1-cM_e^{1.25})^2\left(\frac{u_D}{u_2}\right)^2 M_e^{2.5}}{1+\frac{\gamma-1}{2}[1-(1-cM_e^{1.25})^2\left(\frac{u_D}{u_2}\right)^2]M_e^{2.5}} \right)^{\gamma/(1-\gamma)}$$

$$\left.\frac{p_b}{p_\infty}\right|_0 = c_0\left(\frac{u_m}{u_2}\right)^2 = c_0\left(1-\frac{1}{2}\left(erf\left(\frac{\sqrt{2}}{4}\left(\frac{\mathrm{Re}_s}{\mathrm{Re}_{s0}}\right)^{1/2}\right)\right)\right)^2$$

Mean Base Pressure Model

- Compare to 5-degree cone problem, Mach 8
- NS sting/blade mount
- Laminar and turbulent conditions
- Compare with Lamb and Oberkampf (1995) (Classical)
- Both models perform satisfactorily





Conclusions and Future Work

- **Simplified base pressure fluctuation PSD model (DeChant and Smith (2011)) provides reasonable approach**
  - **Examine critical (maximum amplitude) base region Strouhal models**
  - **RMS models**
  - **Reasonable agreement between theory, computation, and measurement**
  - **Mean base pressure estimate useful**

- **Future work:**
  - **Develop Integrated Approximate Base Pressure Fluctuation PSD Model**

Acknowledgements/Questions

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Questions???