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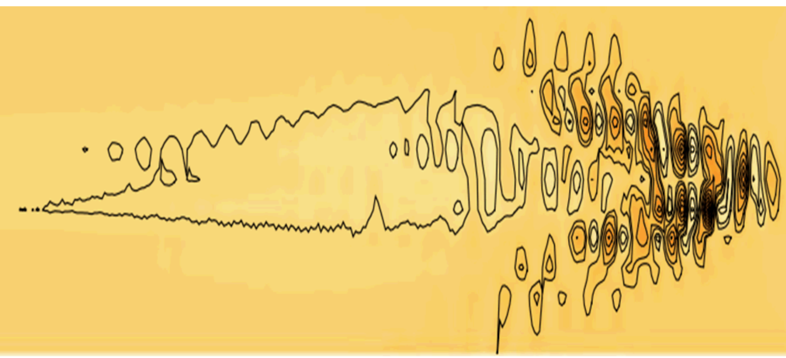

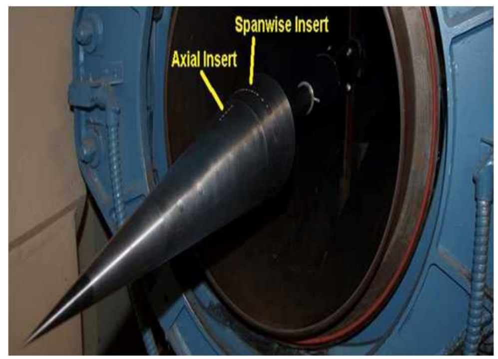

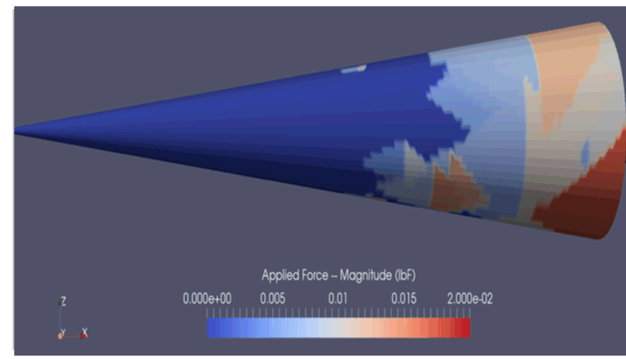

Modeling the stochastic dynamics of moving turbulent spots over a slender cone at Mach 5 during laminar-turbulent transition

Presenter: B. A. Robbins

Collaborators: R. V. Field, M. Grigoriu, K. M. Casper, M. Mesh, R. D. Jamison, L. J. DeChant, and J. A. Smith

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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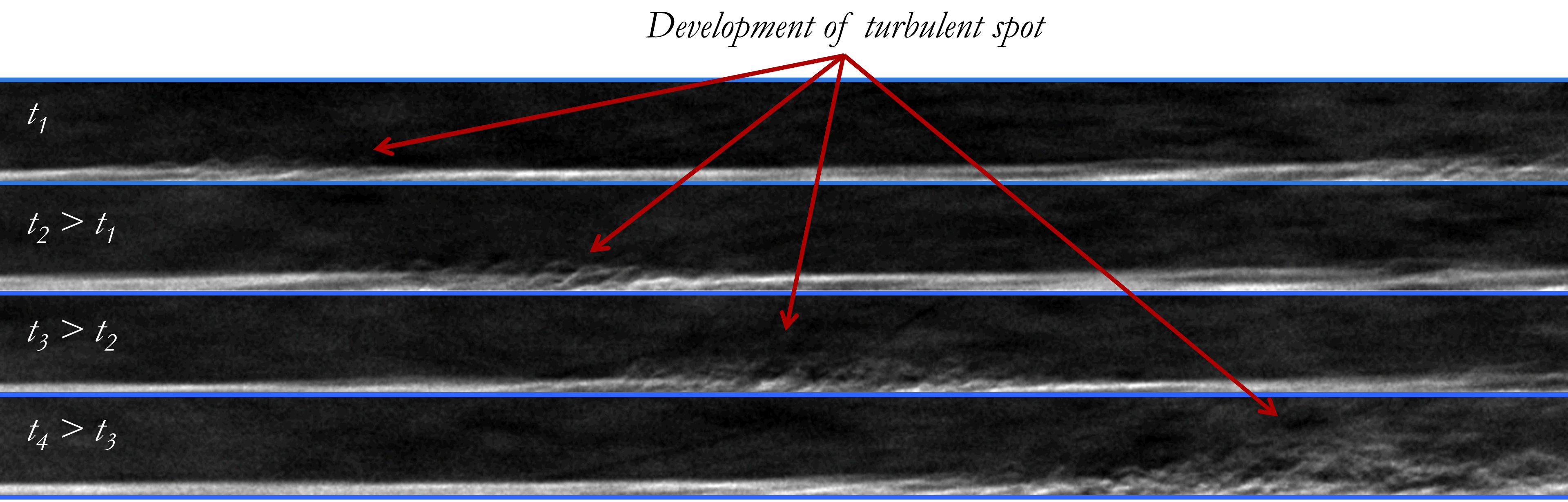
Motivation

- In order to appropriately quantify the response of an aerospace vehicle undergoing transitional flow, it is important to account for phenomenon that may influence the dynamics of the structure
- Turbulent spots are formed within the boundary layer during transitional flow
- These spots subject the structure to severe pressure fluctuations
  - Pressure fluctuations during transitional flow can be larger than during fully turbulent flow
  - Results in random vibration of the structure and its internal components

Motivation Cont.

- The resulting vibration can yield structural problems
- Model can be used to better design aerospace vehicles for flight conditions



[1] *Schlieren images from: Casper, et al., AIAA, 2014*

Objectives

1. Develop a probabilistic model that describes the birth, evolution, and pressure loading of multiple turbulent spots in a transitional boundary-layer

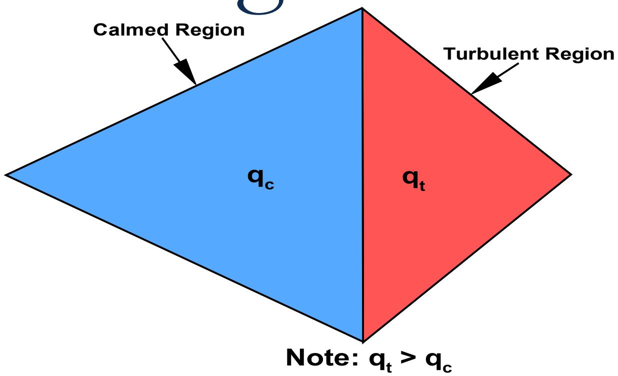
2. Collaborate with experimentalists to appropriately define important physical phenomenon that occurs during transition

3. Use experimental data to calibrate input parameters in the probabilistic model

4. Apply calibrated probabilistic model to cone FE model

5. Study model results to gain qualitative insights into laminar-turbulent transition induced random vibration

Moving Load Model



Step 1: Generate birth times of the moving turbulent spots via jump times of Poisson point process

- Simply generated by sums of independent exponential variables with unit mean, so;
- Let's say that :

$$T \sim e^{-\lambda}$$

- Then,

$$P(T \leq t) = F(t) = 1 - e^{-\lambda t}$$

- Now, solving for $F^{-1}(P)$, we get

$$t = \frac{-\ln\big(1 - P(T \leq t)\big)}{\lambda} = F^{-1}(P(T \leq t))$$

- Using the inverse transform method, we can then generate samples by,

$$T = F^{-1}(U)$$

- Therefore,

$$t_i = \frac{-\ln(1 - U)}{\lambda}$$

  - Where *U* is the CDF of the uniform distribution.

- t^i is calculated for *n* spots
- t^i_{birth} is determined chronologically by,

$$t^1_{birth} = t_1$$

$$t^i_{birth} = t^{i-1}_{birth} + t_i$$

Moving Load Model Cont.

Step 2: Generate birthing location

- We assume that spots can be born with uniform probability along the onset of transition
- Birth location generated by

$$A_{x_2}^{i} = \{A_{x_2} : 0 \le A_{x_2} \cap A_{x_2} \le l_2\}$$

$$A_{x_2}^{i} = l_2 U(0,1)$$

Step 3: Generate initial spot geometry

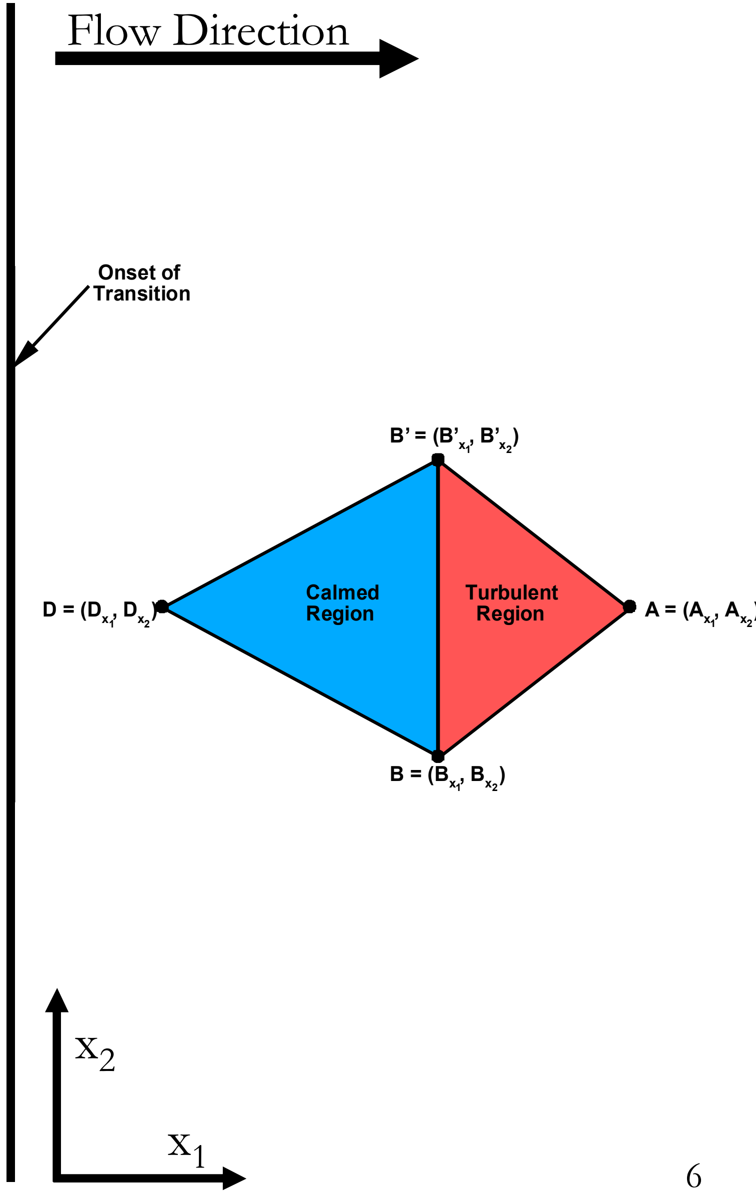
- We assume that the initial spot geometry is constant for all spots
- Can easily implement a means to select a sample of the spot geometry from a distribution of interest
  - The code has this ability for a uniform distribution
    - For example,

      $$A_{x_1}^{i} = \{A_{x_1} : a \le A_{x_1} \cap A_{x_1} \le b\}$$

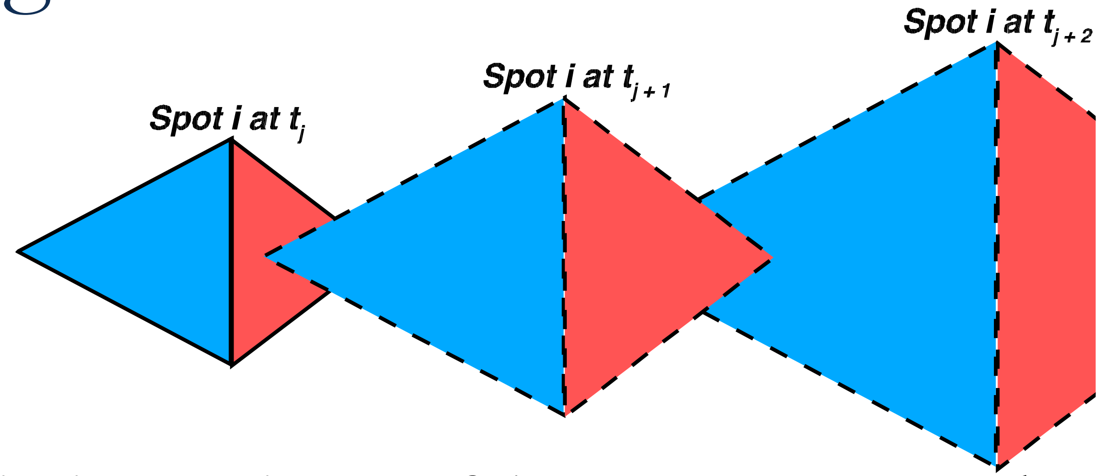
    - Then, we generate the initial geometry for spot i,

      $$A_{x_1}^{i} = a + (b - a)U(0, 1)$$

    - This is done for each vertex of each spot



Moving Load Model Cont.



Step 4: Calculate evolution of the spot geometry in both the streamwise and spanwise directions $\forall t \in [0, T]$

- Spot evolution is assumed to be linear
- The location of $A_{x_1}^i$ at some time, t_j, is

$$A_{x_1}^i(t_j) = A_{x_1}^i(t_{j-1}) + V_B \Delta t$$

- This expression does not hold for each vertex
  - Similar expression is used for vertices B, B', and D
  - Only need to calculate x_1-coordinate for A and D
  - Must calculate x_1- and x_2-coordinate for B and B'
    - Spot evolution in the spanwise direction

Moving Load Model Cont.

Step 5: Generate the pressures of the turbulent and calmed regions of the moving spot

- Turbulent and calmed region pressures are calculated for each spot
- Pressures are constant over time
- Calculated by,

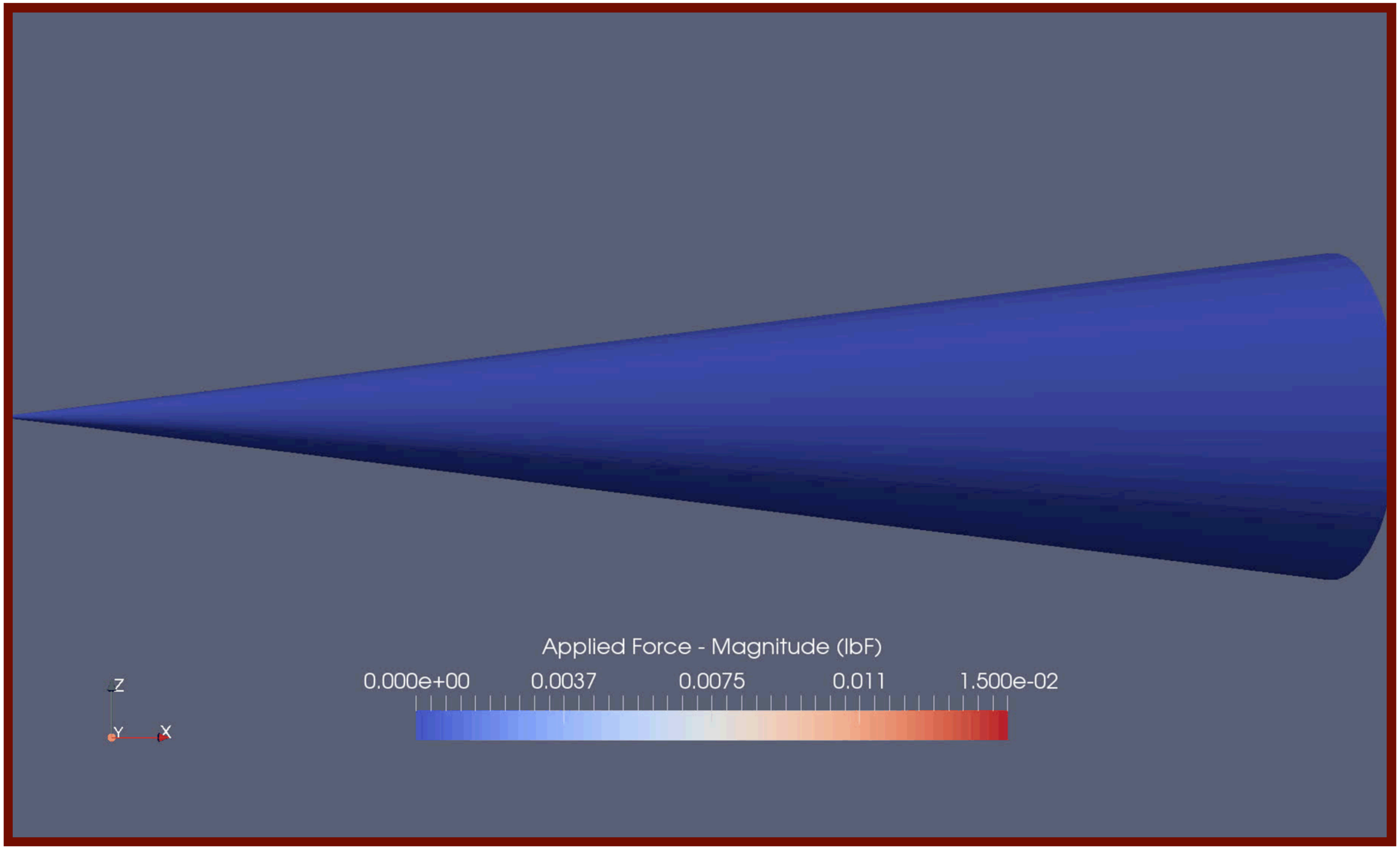
$$q_t = c_t q_0$$
$$q_c = c_c q_0$$

Note: $c_t > c_c$

- Total force imparted on structure due to moving distributed loads can be adjusted by a modulation function
  - Useful to capture physics not present in current model definition

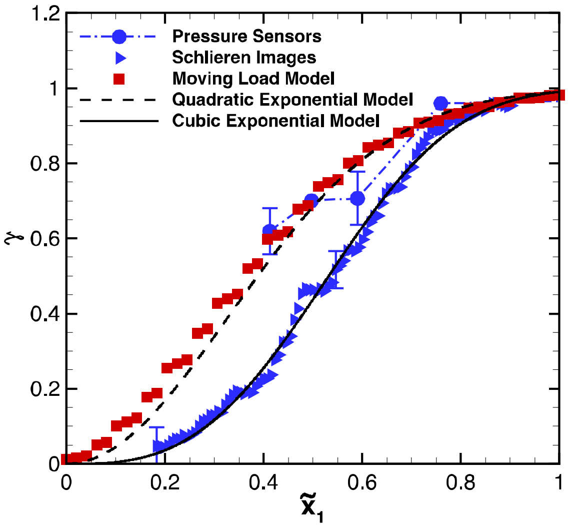
Step 6: Finite element mesh is loaded with the calculated moving turbulent spots and their corresponding pressures

Birth and Evolution of Turbulent Spots

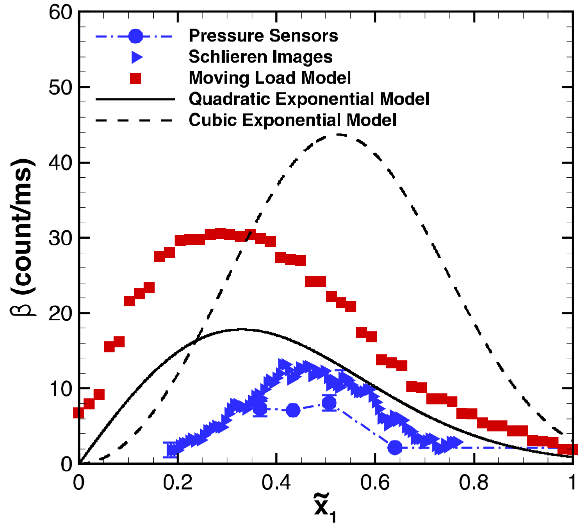


Moving Load Model Calibration

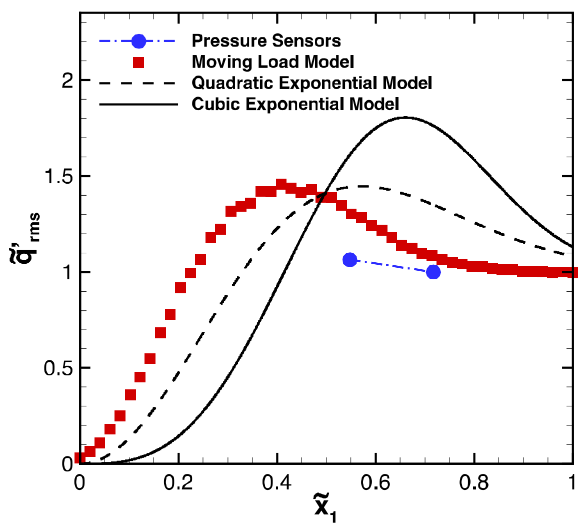
- Intermittency
  - Various values of the intensity, λ, computed for the moving load model
  - The value of λ was selected such that the moving load model intermittency agreed well with pressure sensor data
- Root-mean-square pressure fluctuations
  - Pressure/Force loading scaled by modulation function
  - Modulation function effectively accounts for internal broadband pressure fluctuations within the turbulent portion of the spot
    - Not originally accounted for in the moving load model



Intermittency

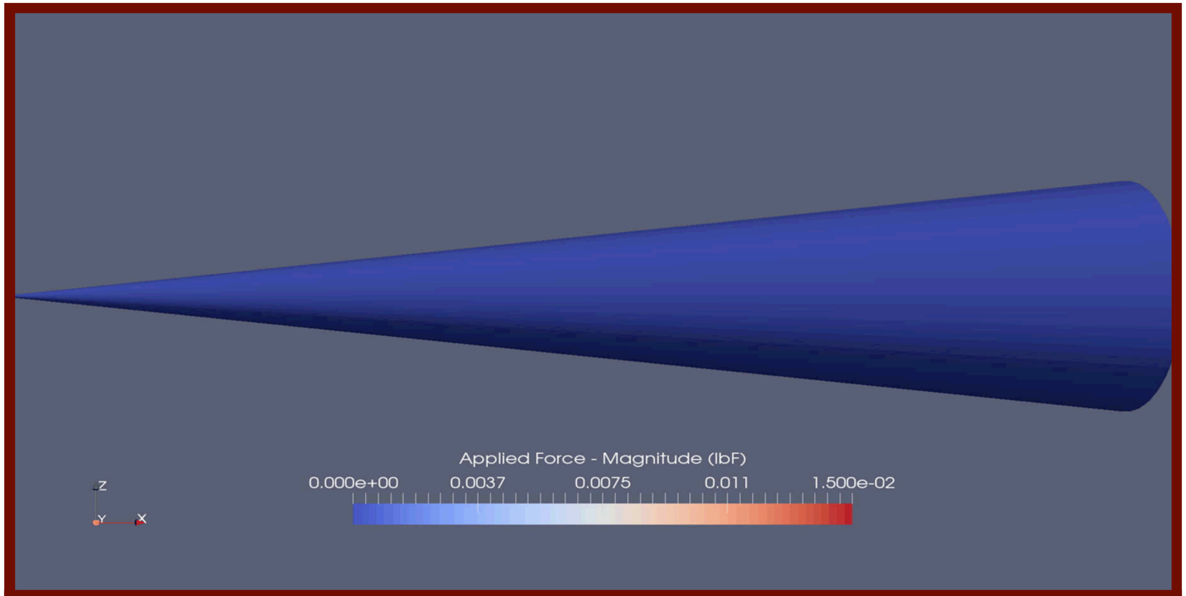


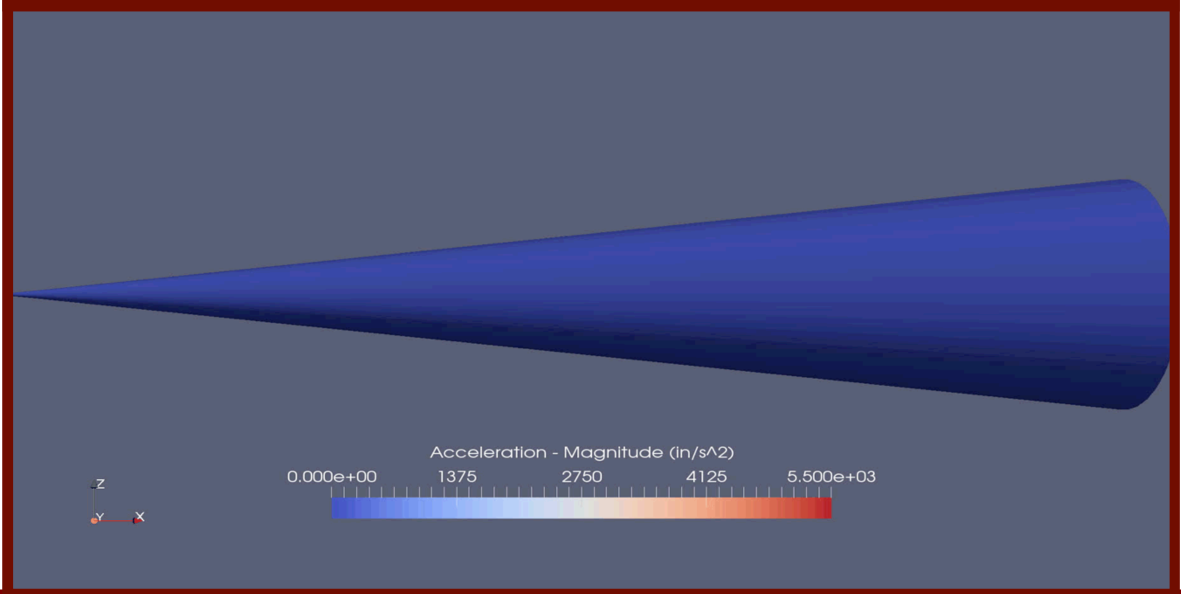
Burst Rate



RMS Pressure Fluctuations

Dynamical Response of a Housing Panel





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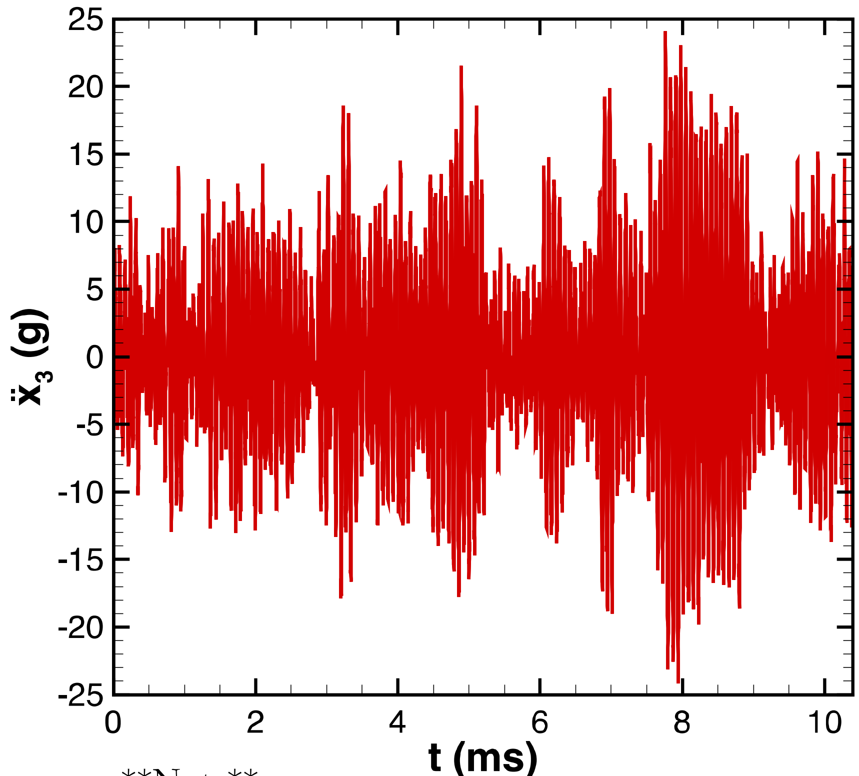
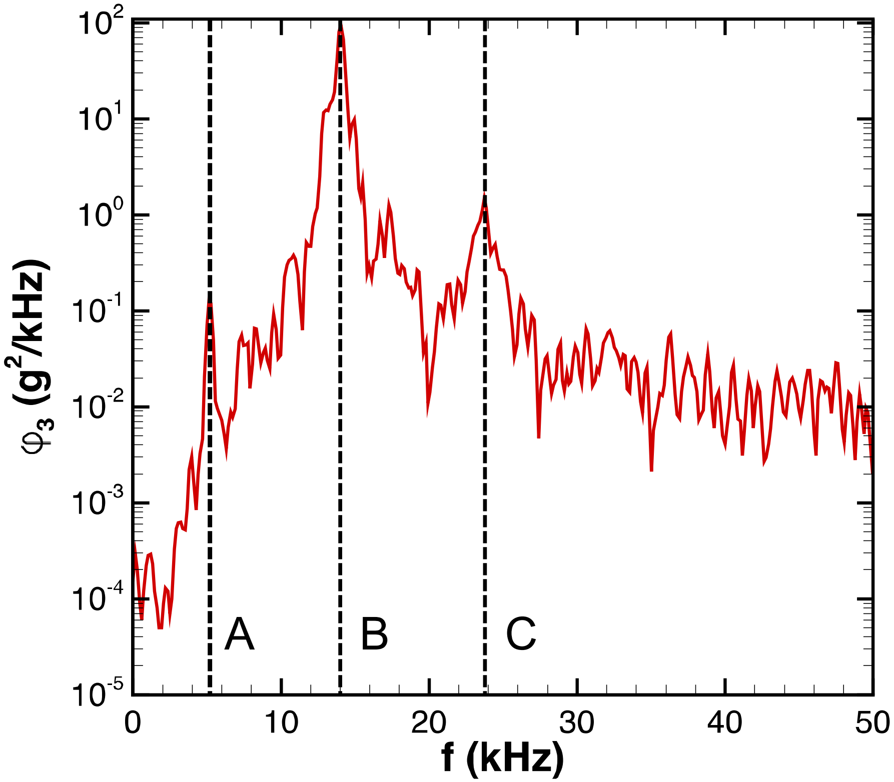




Note
Quasi-stationary portion of response data

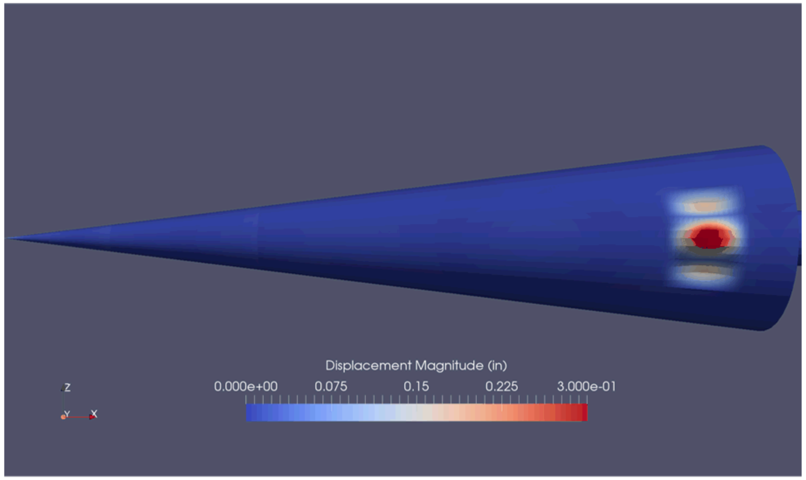
Line	Frequency (kHz)	Brief Description
A	5.17	Cone ovalization and 2 lobe panel bending mode
B	14.07	3 lobe bending Mode
C	23.79	Cone ovalization and 4 lobe panel bending mode

Dynamical Response Implications

- The PSD illustrates that a resonance peak occurs at 14.06 kHz

- Modal analysis of finite element model shows that a fundamental mode of the housing panel occurs at 14.074 kHz

- Moving turbulent spots have induced resonance of the housing panel in the x_3-direction



Concluding Remarks

- Developed a probabilistic model that predicts the dynamical behavior and pressure loading of the turbulent region and the calmed region of a spot traversing the transition region
- Model successfully produces intermittency curve that matches with pressure sensor data and the quadratic exponential model
- The model also yields a qualitatively correct burst rate curve
- Model produced an RMS pressure fluctuation curve that yields reasonable agreement with experimental measurement and quadratic exponential model
- Moving turbulent spots induced resonance of the center of the housing panel in the x_3-direction

Current and Future Work

- **Current Work:**
  - Apply moving load model to calibrated FEM of cone structure
    - Compare response with experimental measurement
  - Implement more efficient solving techniques to reduce computational expense
  - Parallelize the model script to reduce computation time
- **Future Work:**
  - Study single turbulent spot induced random vibration
    - Compare with experimental data
- **Special Thanks:**
  - **Collaborators -** R. V. Field, M. Grigoriu, K. M. Casper, M. Mesh, R. D. Jamison, L. J. DeChant, and J. A. Smith

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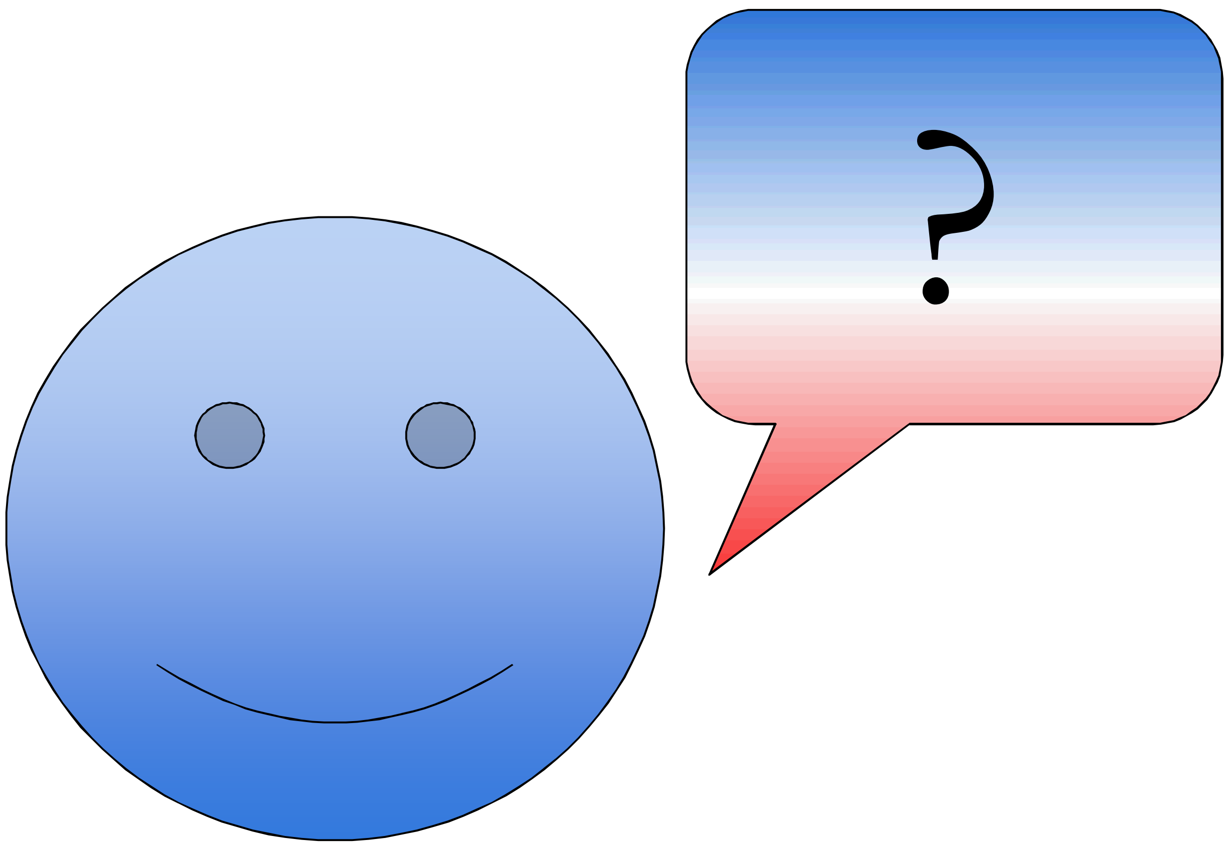
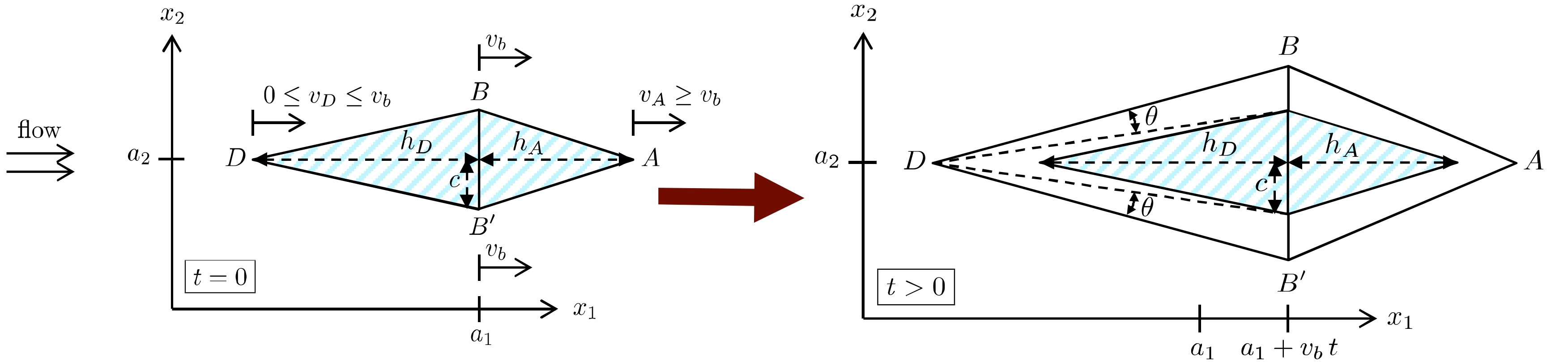
Questions?



EXTRA SLIDES

Moving Load Model



Step 1: Generate birth times of the moving turbulent spots via jump times of Poisson point process

Step 2: Generate birthing location via uniform distribution

Step 3: Generate initial spot geometry (we assume deterministic and constant)

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