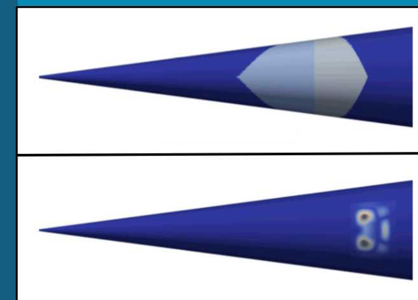
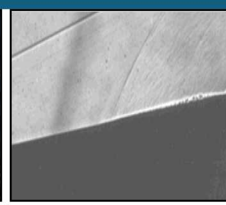
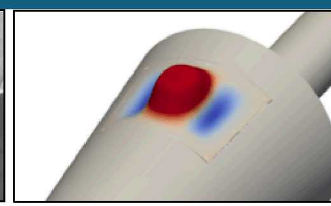
SAND2019-0204C

# Quantifying the Structural Response of a Slender Cone to Turbulent Spots at Mach 6







PRESENTED AT

2019 AIAA SciTech

January 7th-11th, 2019

San Diego, CA

AUTHORS

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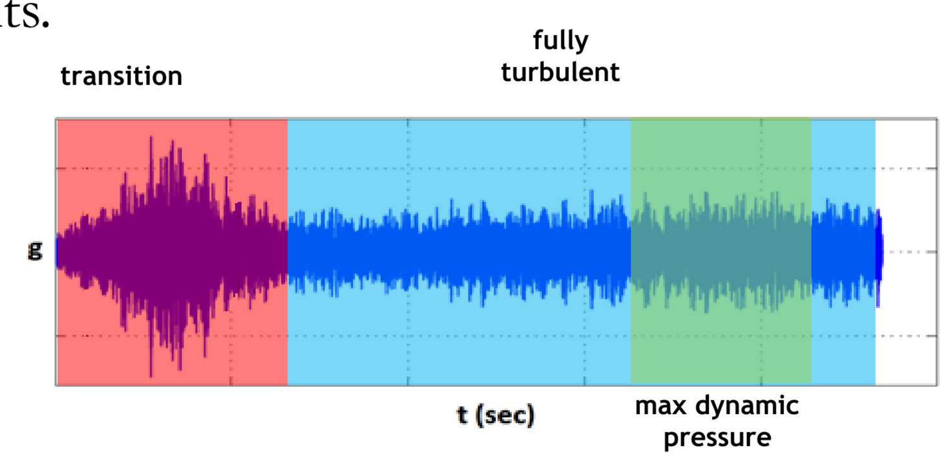
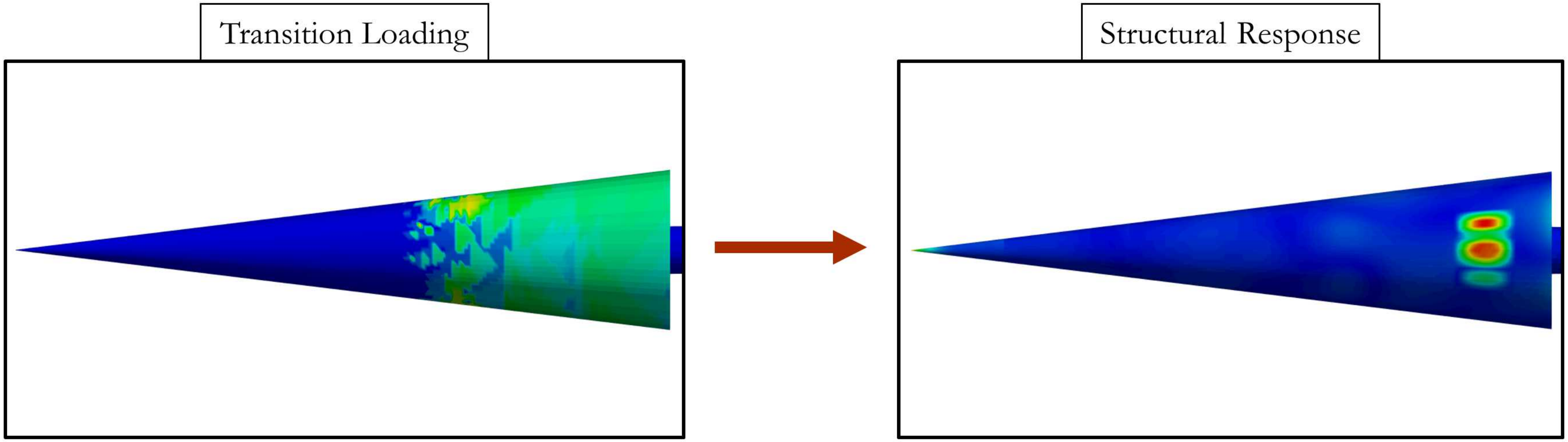
# Introduction

- In order to appropriately quantify the response of an aerospace vehicle undergoing transitional flow, it is important to account for phenomena 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.

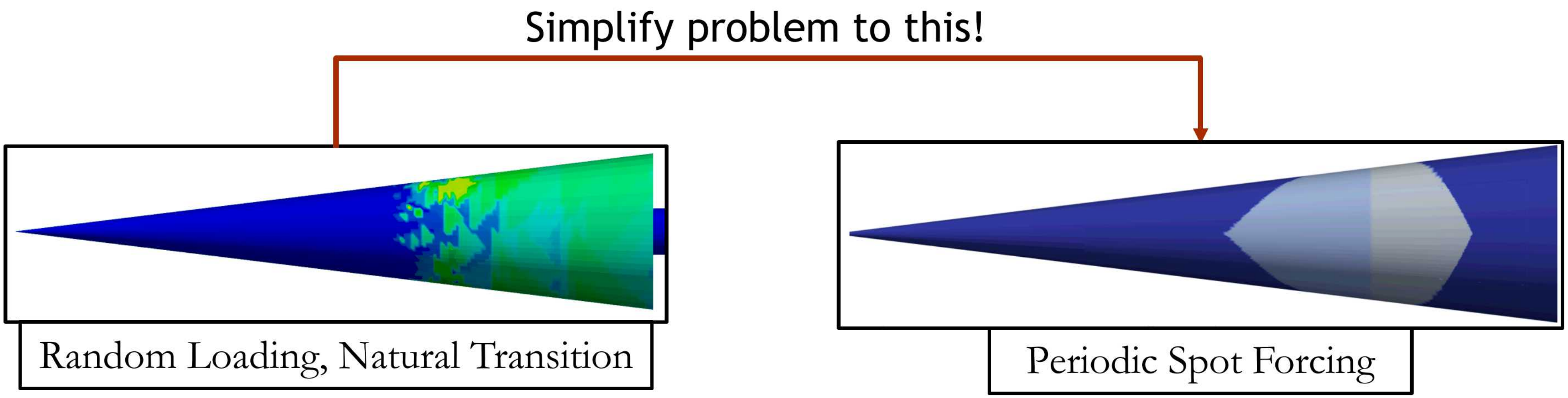


# Introduction Cont.

- The resulting vibration can yield structural problems;
- We seek to model the phenomena associated with random turbulent spots and transitional behavior that lead to structural response.
- Model can be used to better design aerospace vehicles for flight conditions;



# Introduction Cont.



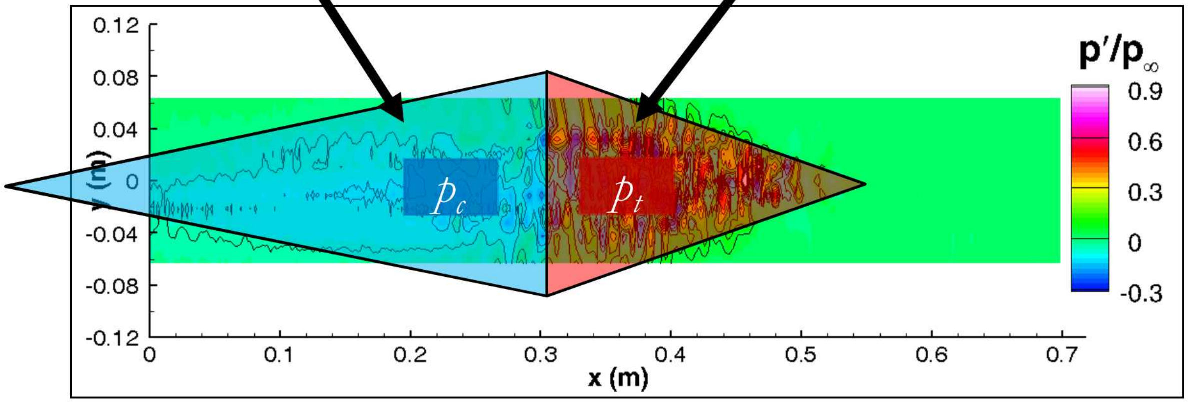

- Develop a deterministic model that describes the birth, evolution, and pressure loading of turbulent spots born at a given forcing frequency, $f_f$,
  - Calibrate and inform model using experimental data;
  - Compare results with experiments conducted by Casper *et al.*[1]
- This will allow us to tune our structural model,
  - For example, structural damping.
- Study the affect of the fluid model parameters,
  - Convection velocity;
  - Half-spread angle;
  - Time between spot events.

[1]Casper, K. M., Beresh, S. J., Henfling, J. F., Spillers, R. W., Hunter, P., and Spitzer, S., "Hypersonic fluid-structure interactions due to intermittent turbulent spots on a slender cone," Accepted for Publication in AIAA Journal, September 2018.

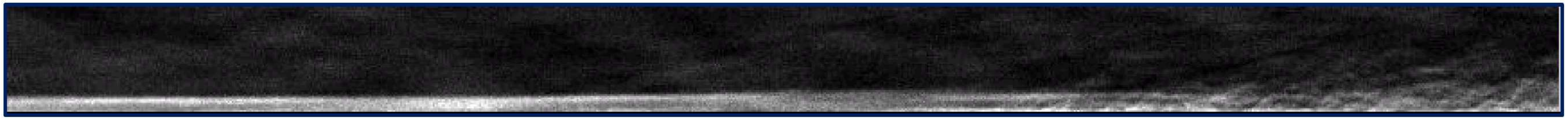
# Turbulent Spot Pressure Loading

## Transitional pressure loading is generated by intermittent turbulent spots in the boundary layer.

- We model these spots as isosceles triangles with conjoined base;
- The turbulent and calmed regions are assumed to be constant values that are the mean pressure fluctuation for that region.

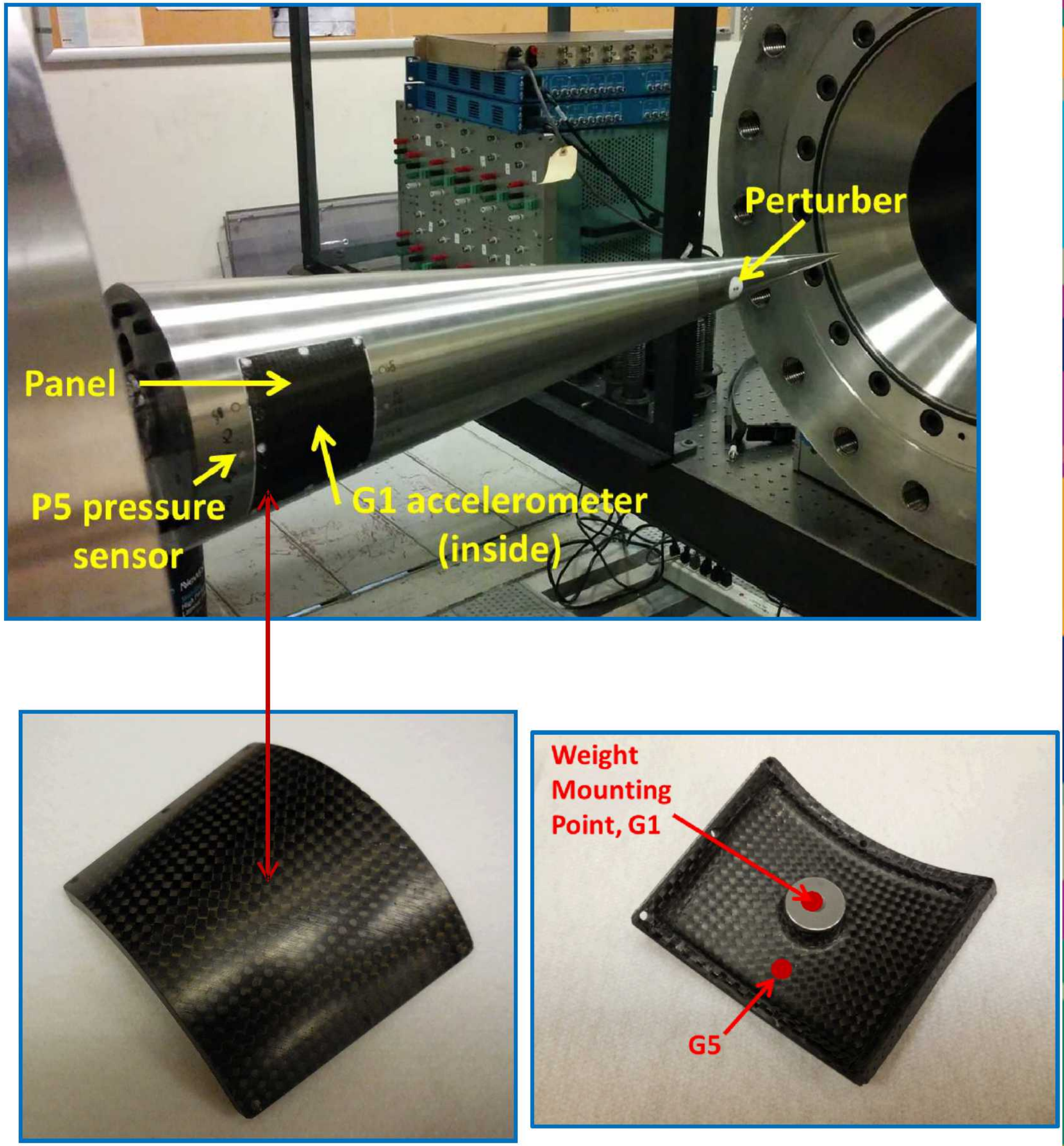



Pressure footprint of turbulent spot, Mach 6



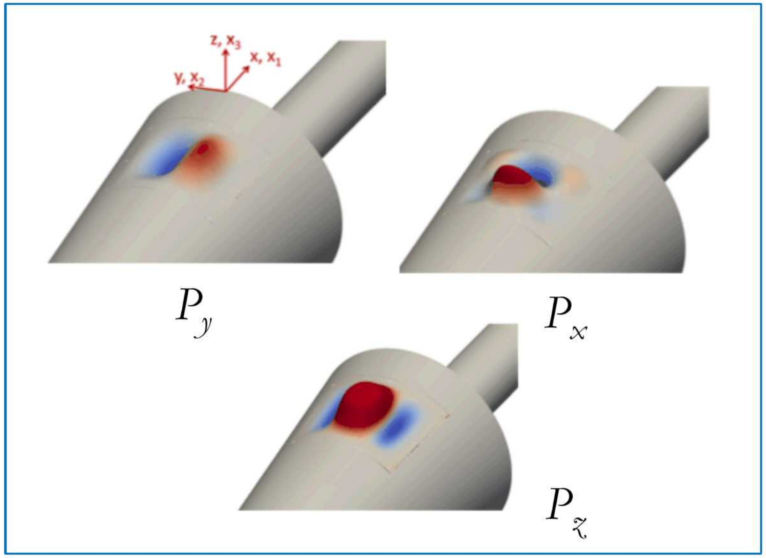
# **Work of Casper *et al.*:** Brief Experiment Overview

- Designed a cone with integrated thin panel that will vibrate from flow excitation,
  - Panel response measured with accelerometers on inside of panel;
  - Boundary later was characterized using pressure sensors upstream and downstream of panel.
- A spark perturber was used to create isolated or periodic turbulent spots in the boundary layer;
- Experiments conducted at the Purdue BAM6QT quiet tunnel.



# **Work of Casper *et al.*:** Brief Experiment Overview Cont.

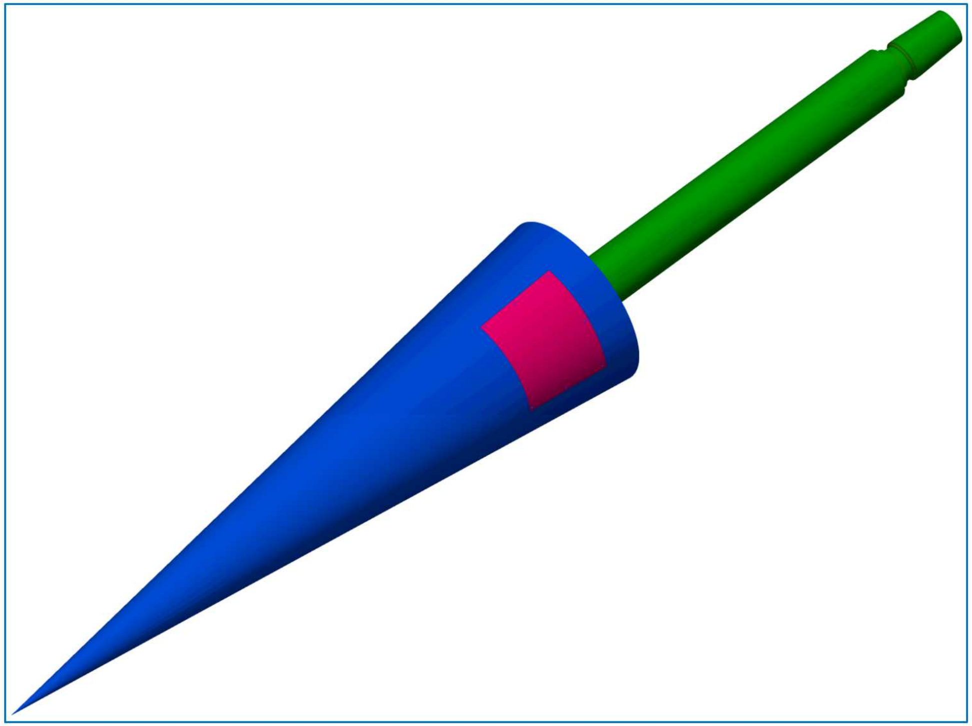
- Hammer test was performed to determine the structural natural frequencies of the panel and model,
  - Measure structural response to a known input;
  - Also characterized mode shapes.
- Modes of interest are,



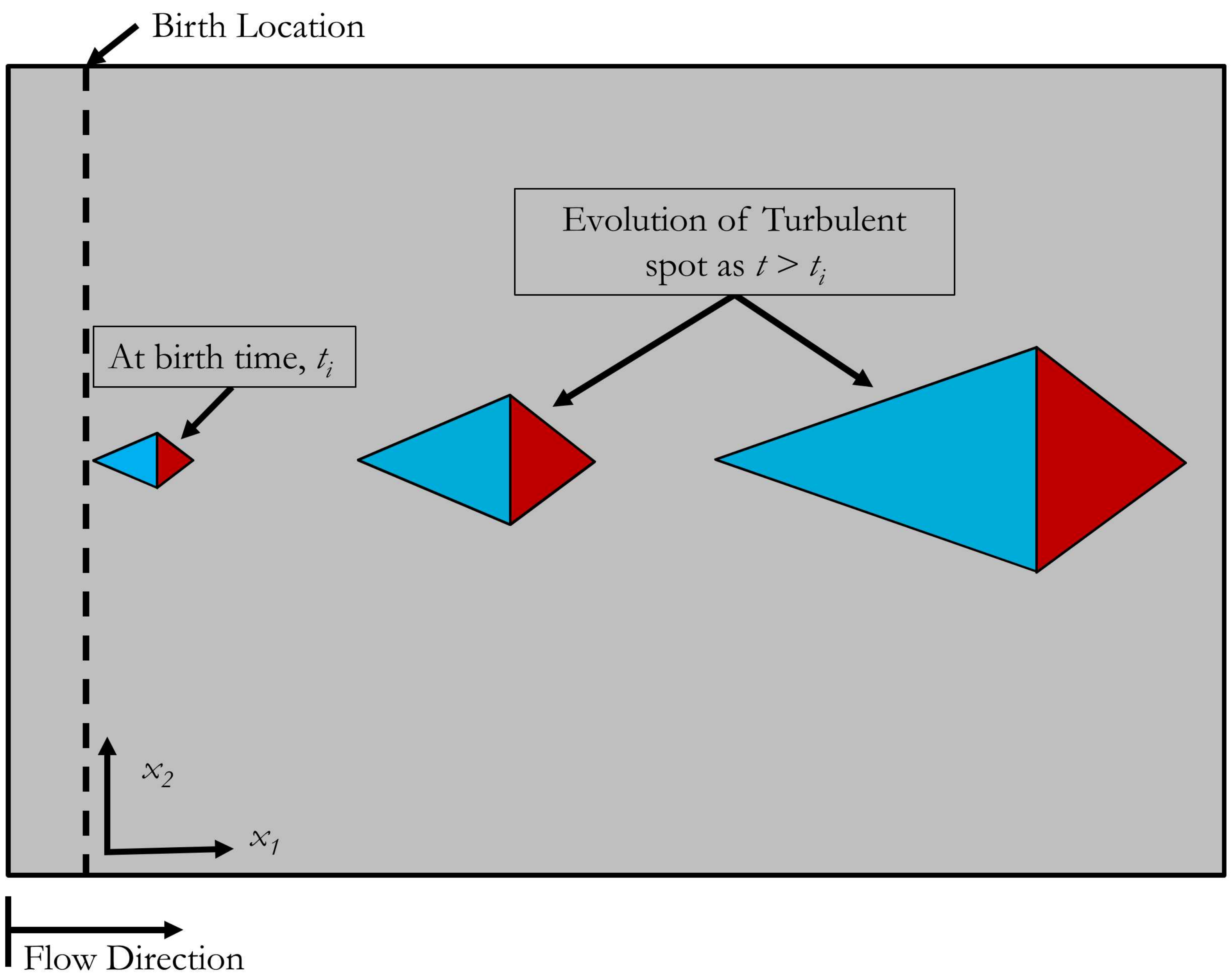

| Mode Description | Structural Natural Frequency (kHz) | Damping (%) |
|---|---|---|
| 2-lobe panel mode, lobes along Y ($P_y$) | 2.099 | 2.57 |
| 2-lobe panel mode, lobes along X ($P_x$) | 3.381 | 4.96 |
| 3-lobe panel mode, mostly motion in center lobe ($P_z$) | 2.831 | 2.44 |

# **Finite Element Model:** Sharp Cone Structure

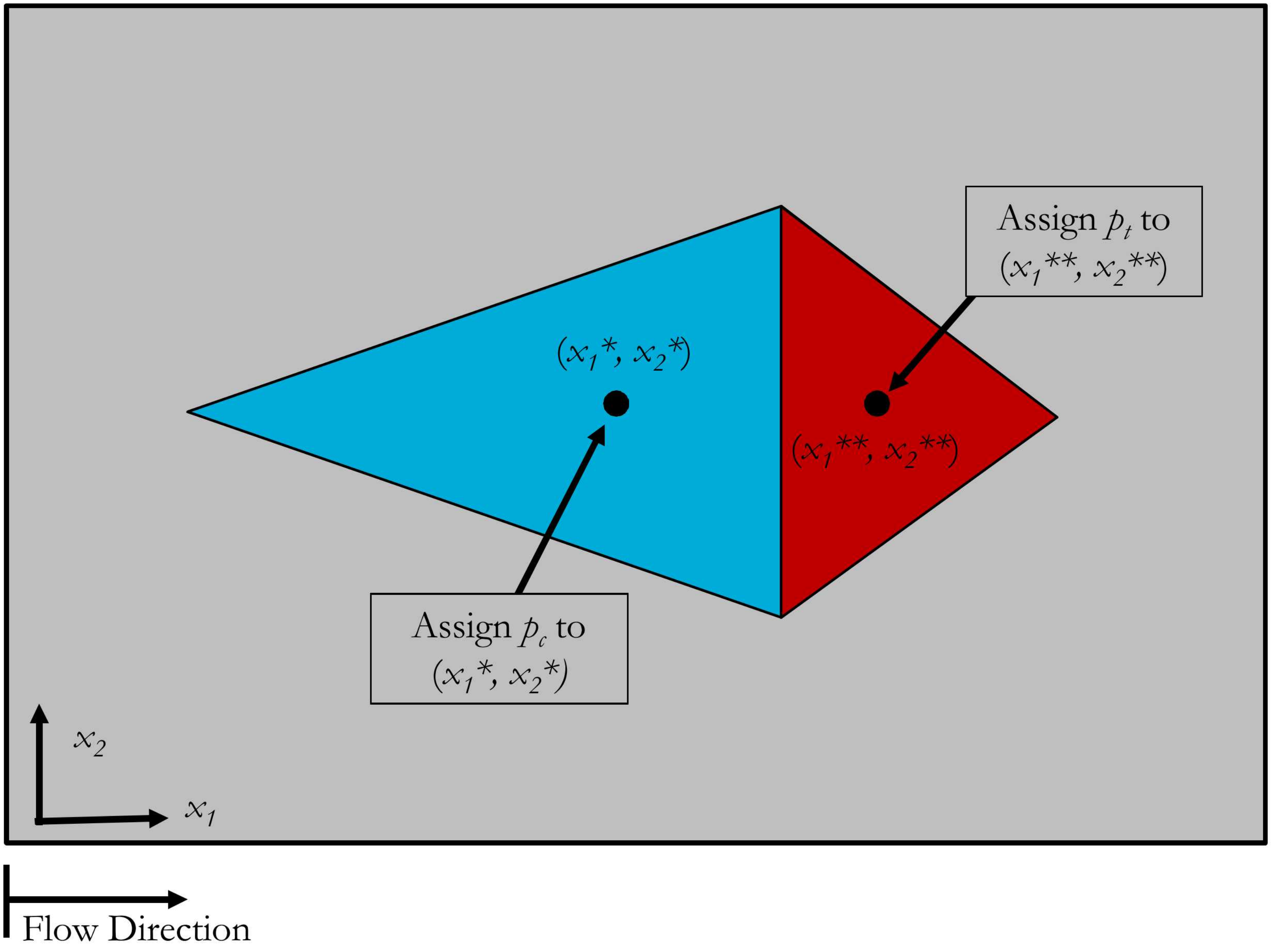
- 3-D finite element (FE) structural model was created and calibrated,
  - FE model consists of 5.24E5 first order, 3-D elements and 5.77E5 nodes;
  - A total of 50 modes were identified in the range of 0-10.5 kHz.
- Incorporates all of the experimental hardware;
- Hammer test data was used to calibrate the model from 0-4 kHz;
- Model and the resulting dynamical response simulations were performed using Sierra/Structural Dynamics software,
  - Each case used $\Delta t = 1/100000$ s and $N_{\Delta t} = 100000$.



# **Brief Description of Model:** Birth Time, location, and spot evolution

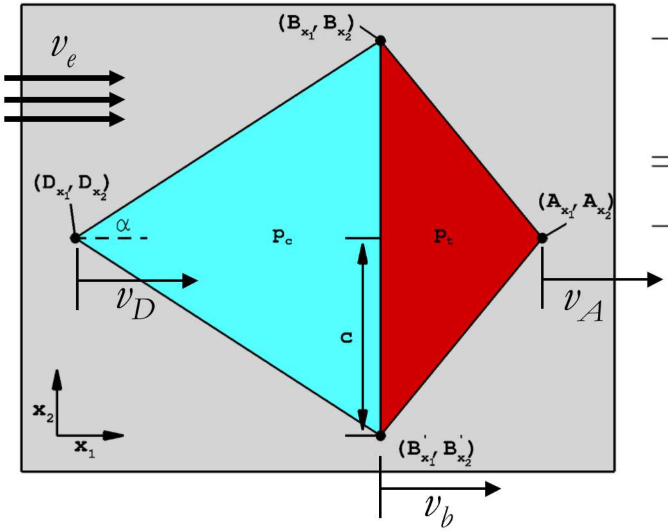


# **Brief Description of Model Cont.:** Pressure Loading



# Fluid Model Parameters

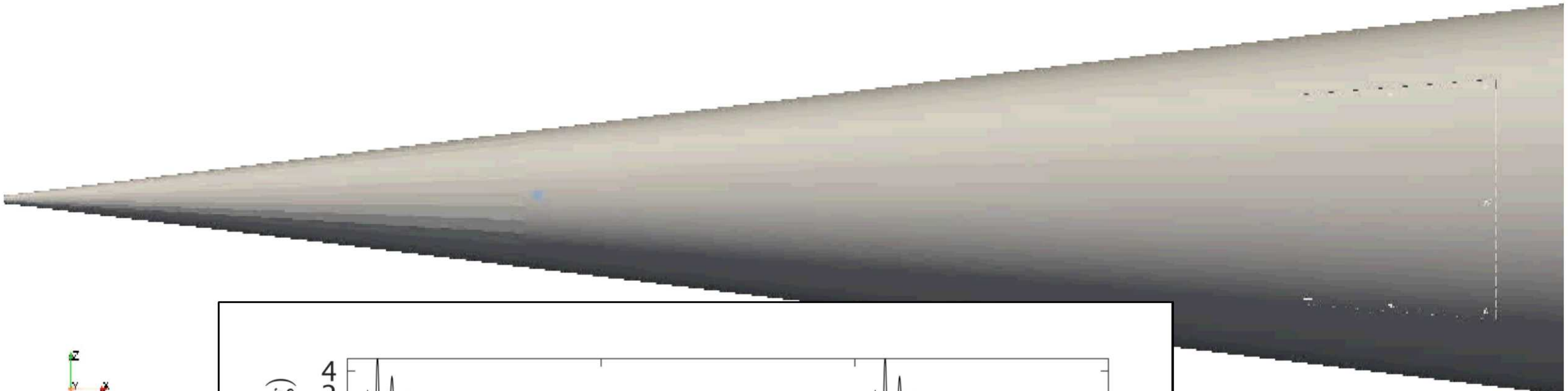
- The FE model was loaded with periodic turbulent spots at various forcing frequencies;
  - The forcing frequencies used illustrated a quasi-isolated spot case and 3 cases in which the forcing frequencies were close to a resonant frequency of the panel;
  - These forcing frequencies are: $f_f = \{\mathbf{0.1}, \mathbf{2.2}, 2.7, 3.9\}$ kHz,
    - The 2.2, 2.7, and 3.9 kHz forcing frequencies match the $P_y$, $P_z$, and $P_x$ mode shapes, respectively, from experiment.
- We also varied the convection velocity, $v_e$, to see its affects;
- Other parameter variations are not studied here,
  - $\alpha$, Half-spread angle;
  - $p_e$, boundary layer edge pressure.



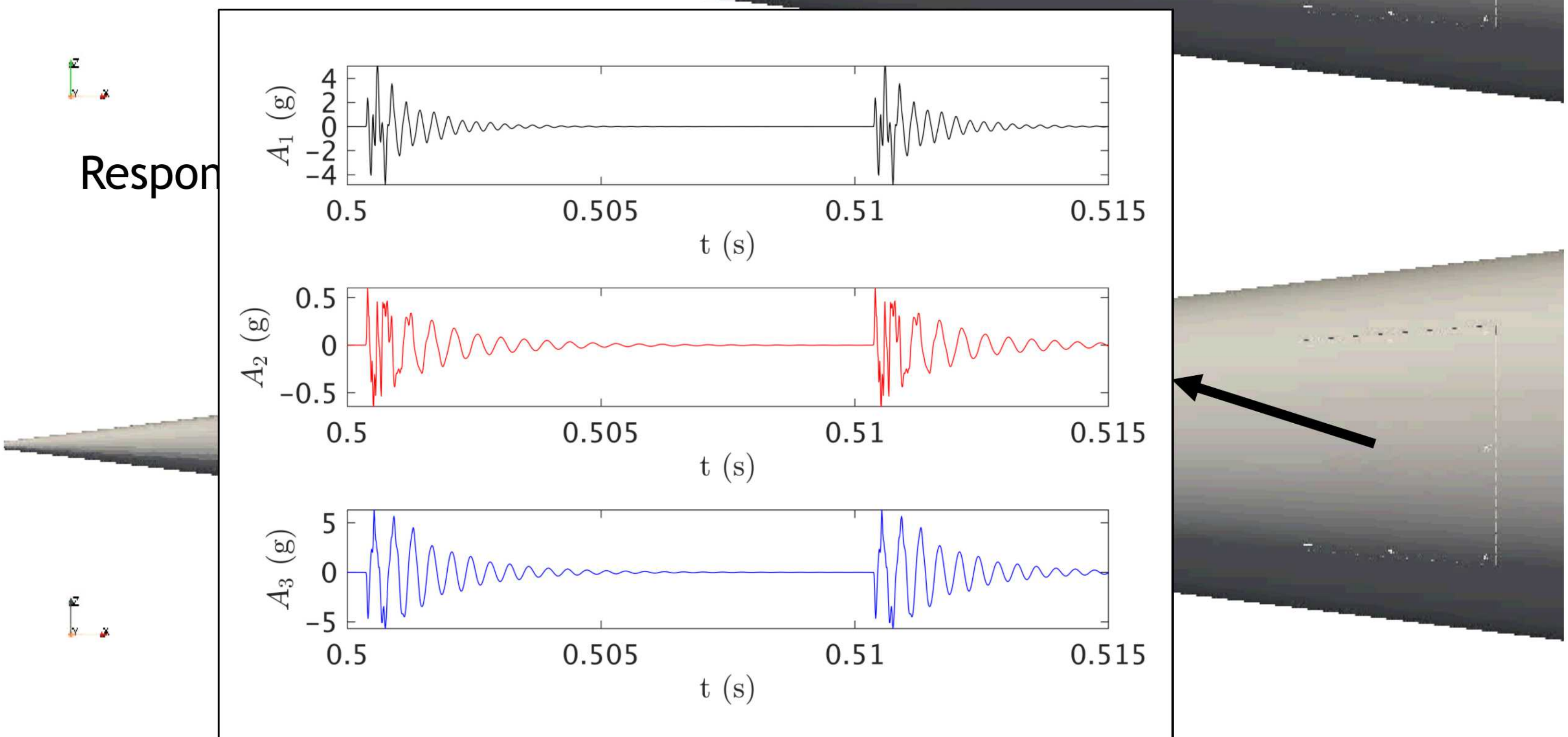

| $v_e$ (m/s) | $p_e$ (kPa) | $v_D/v_e$ (–) | $v_b/v_e$ (–) | $v_A/v_e$ (–) | $p_t/p_e$ (–) | $p_c/p_e$ (–) | $\alpha$ (degrees) |
|---|---|---|---|---|---|---|---|
| 870 | 1.31 | 0.52 | 0.71 | 0.95 | 0.4 | -0.2 | 3 |

# Case 1: $f_f$ = 0.1 kHz

## Force Loading From Periodic Spot Model



## Respon



# Case 1: $f_f$ = 0.1 kHz

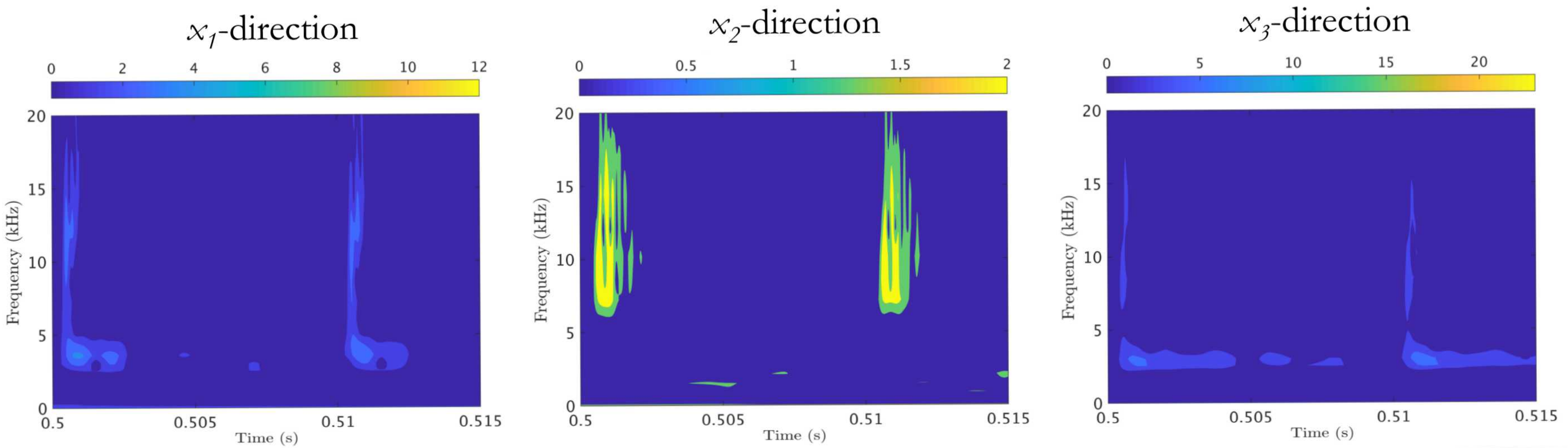
| Damping Times | | |
|---|---|---|
| **Direction** | **Experiment (ms)** | **Computation (ms)** |
| $x_1$ | 4.50 | 5.64 |
| $x_2$ | 4.20 | 6.04 |
| $x_3$ | 9.00 | 8.16 |

| Max$\|A_i\|$ | | |
|---|---|---|
| **Direction** | **Experiment (g)** | **Computation (g)** |
| $x_1$ | 3.09 | 5.03 |
| $x_2$ | 3.79 | 0.65 |
| $x_3$ | 4.86 | 6.31 |

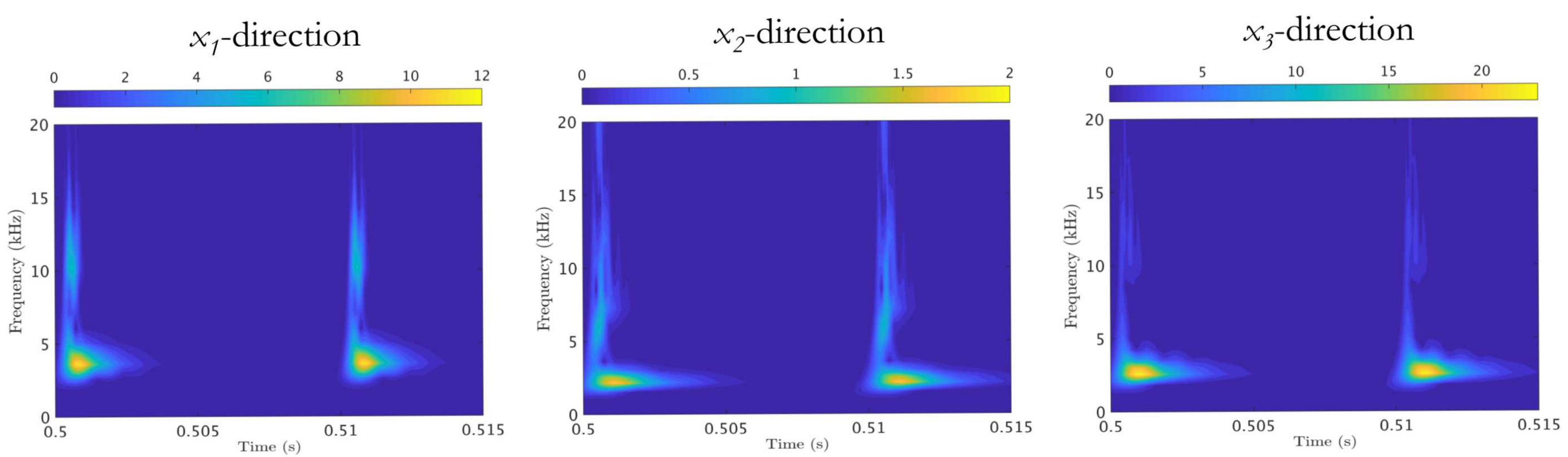
- The damping times and Max$|A_i|$ are comparable between experiment and computation;
- Some of the discrepancies in the comparison may be due to,
  - Uncertainty in the structural damping in the FE model;
  - No spanwise variation in the perfectly symmetric computation,
    - There will be some asymmetry in the experiment.
  - Sensitivity to the forcing frequency offset from the resonant natural frequency.

# Case 1: $f_f$ = 0.1 kHz

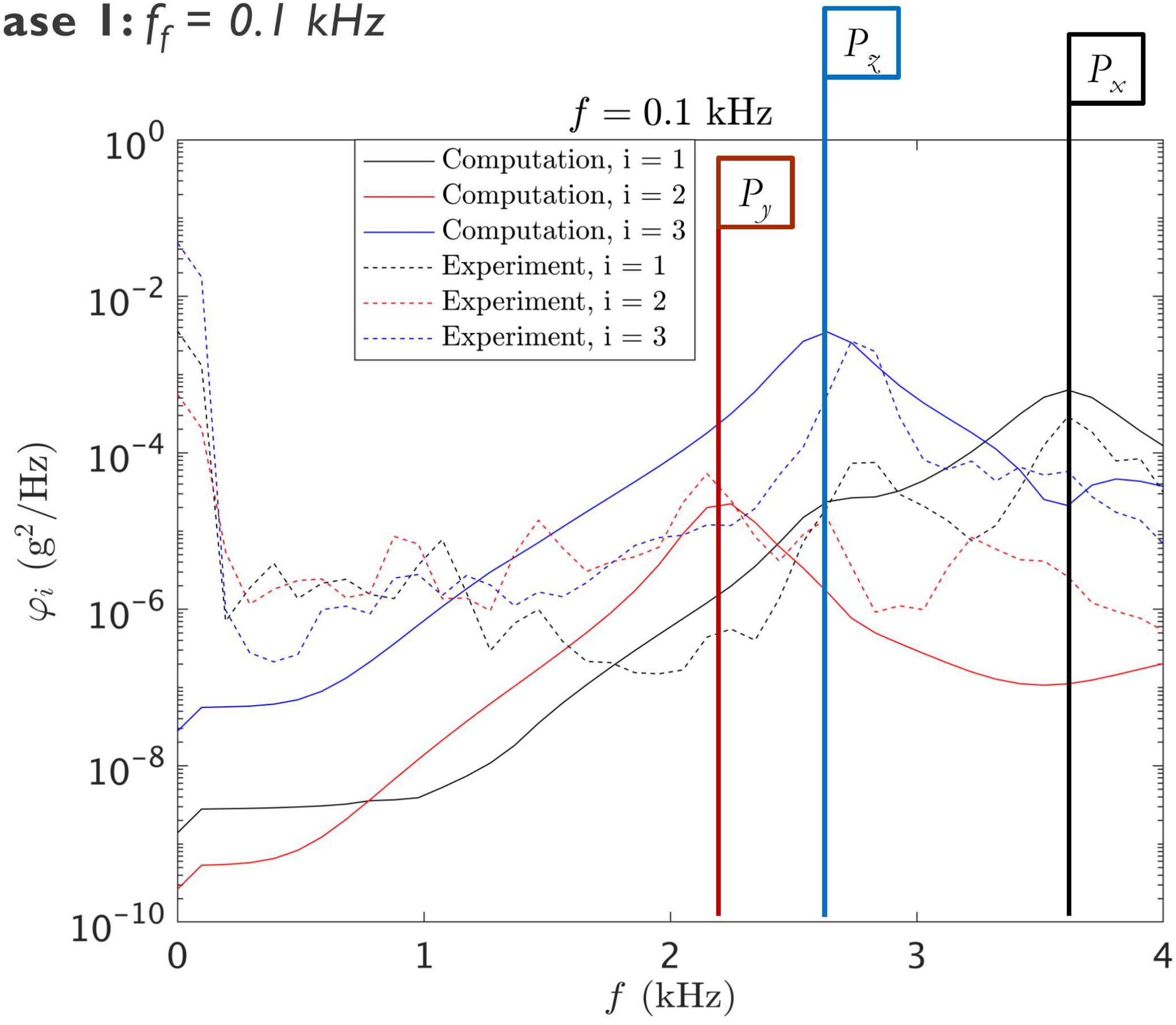
Experiment




Computation

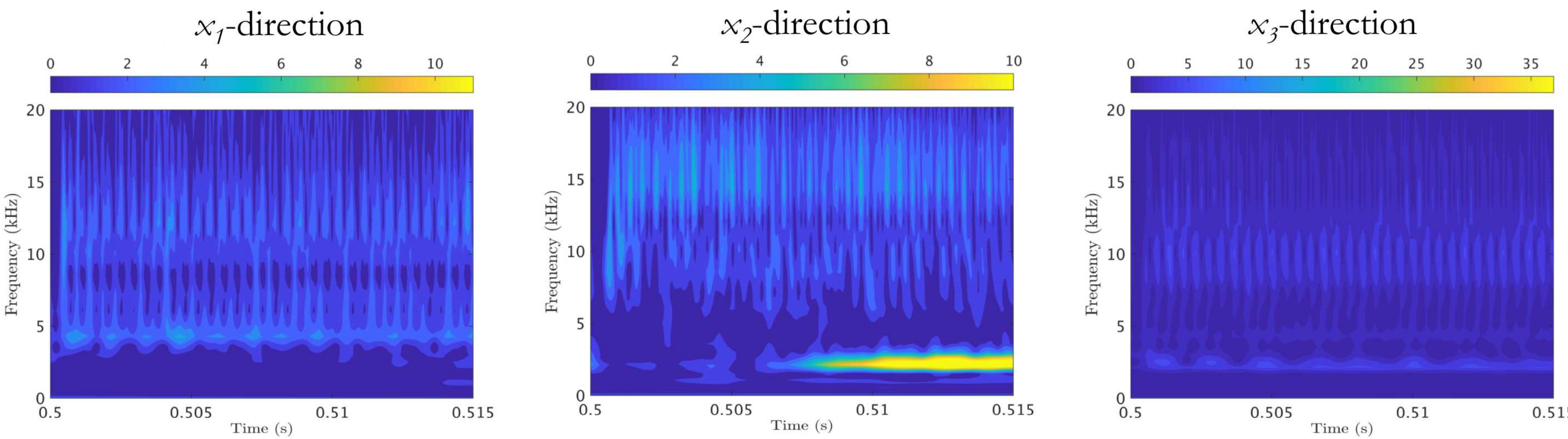


# Case 1: $f_f$ = 0.1 kHz

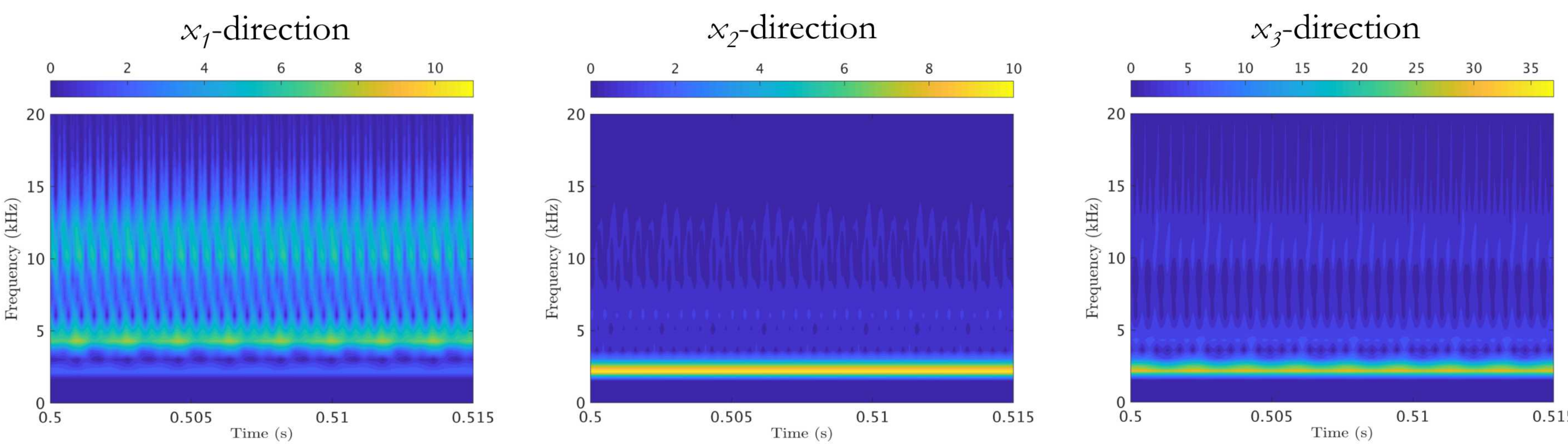


# Case I: $f_f = 2.2\ kHz$

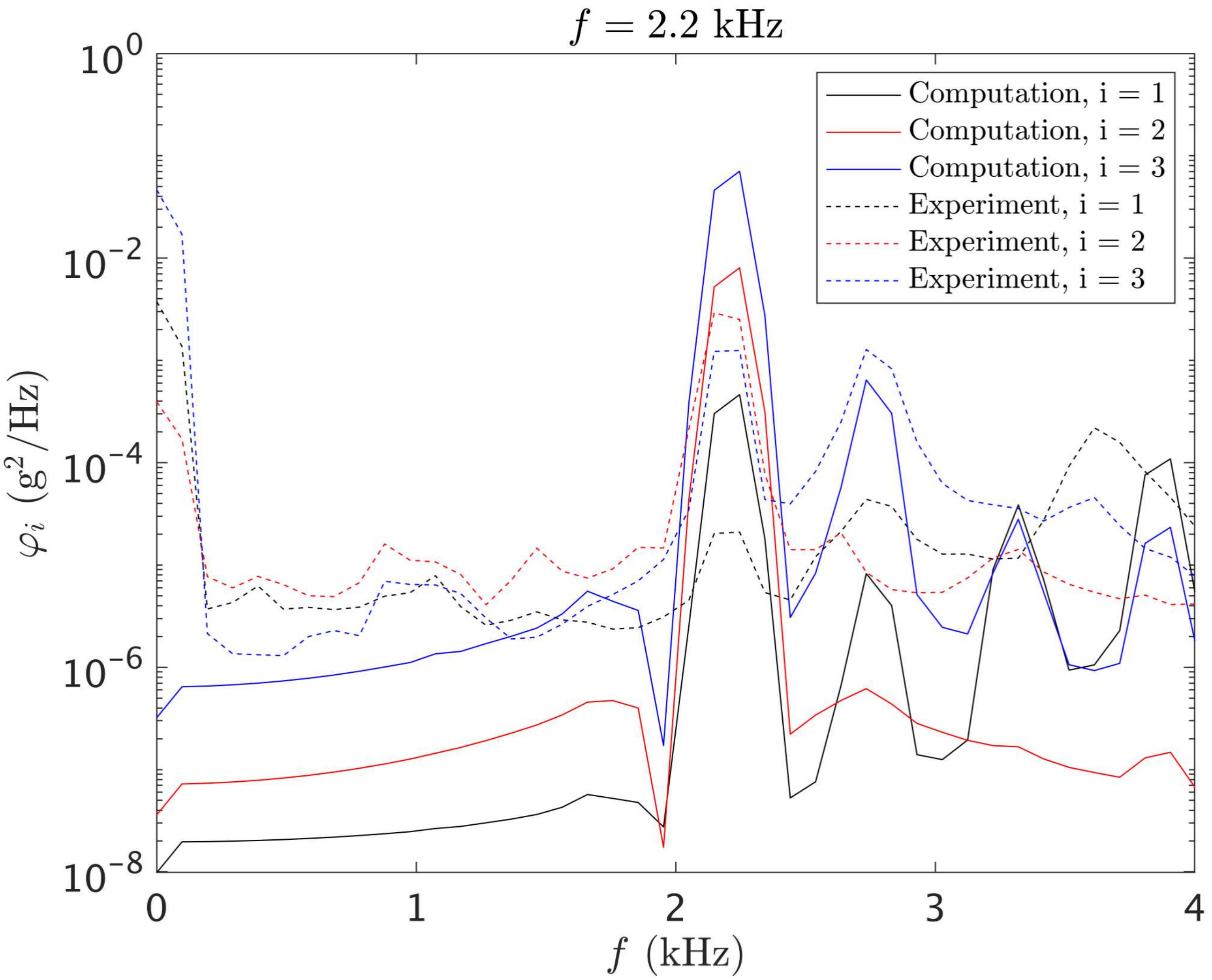
Experiment



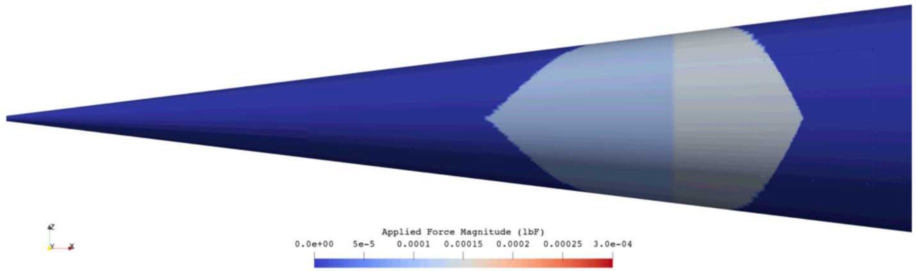

Computation

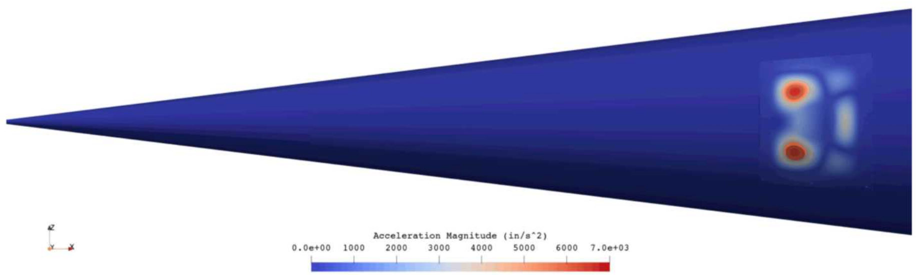


# Case I: $f_f = 2.2\ kHz$



# Qualitative Impact of Turbulent Spot Convection Velocity

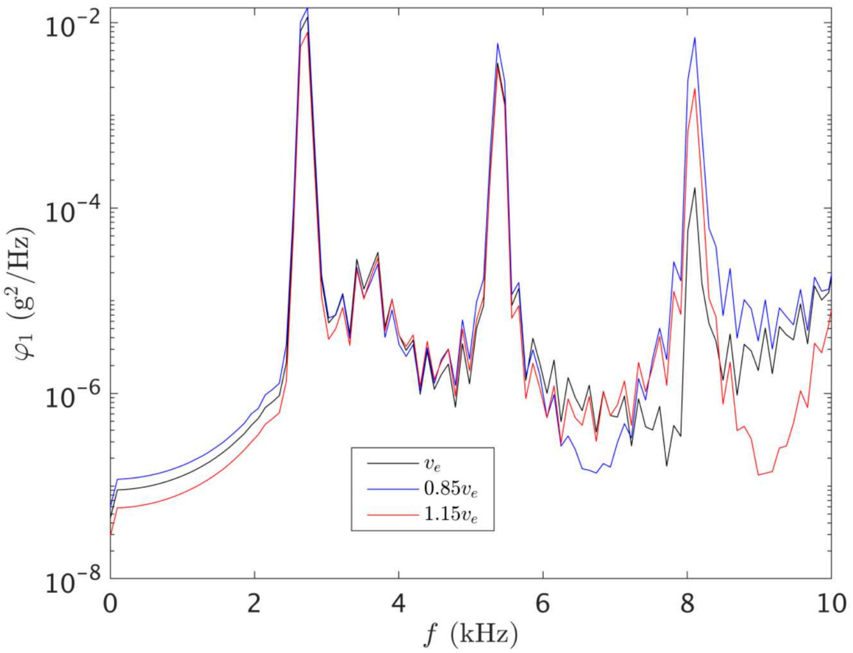


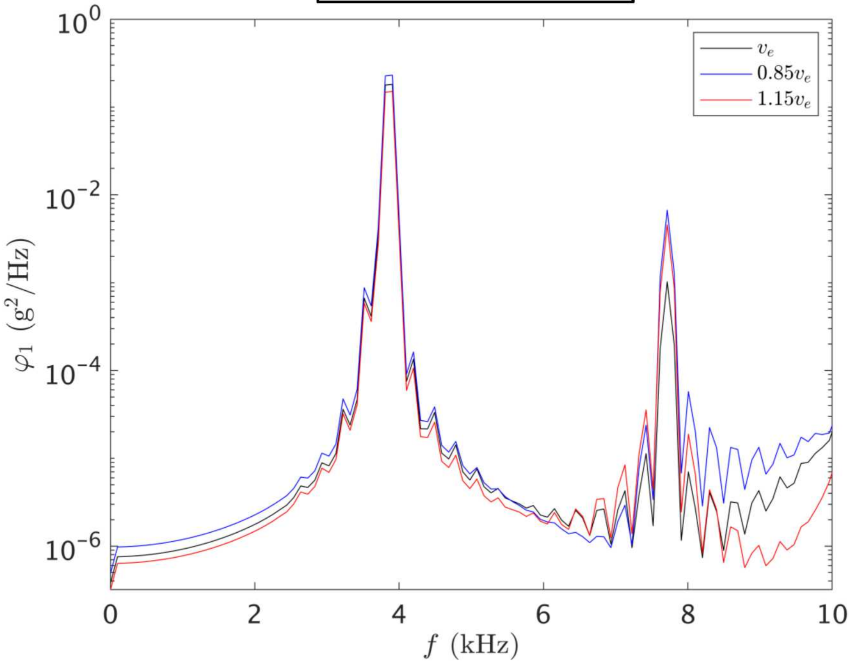

- It was shown that our simulations yield qualitatively comparable results when compared to experiment;
- We want to leverage our simulation capability to study the dominating phenomena that leads to the frequency content seen in the response;
- We have already shown that $f_f$ , which corresponds to the time between spot events, dictates the modes and mode shapes that were excited;
- We also want to determine if the convection velocity of the turbulent spots also contributes to the frequency content of the structural response;
- For $f_f = \{2.7, 3.9\}$ kHz, the convection velocity will be varied by $\pm 0.15 v_e$.

# **Turbulent Spot Convection Velocity Study:** Results

$f_f = 2.7$ kHz

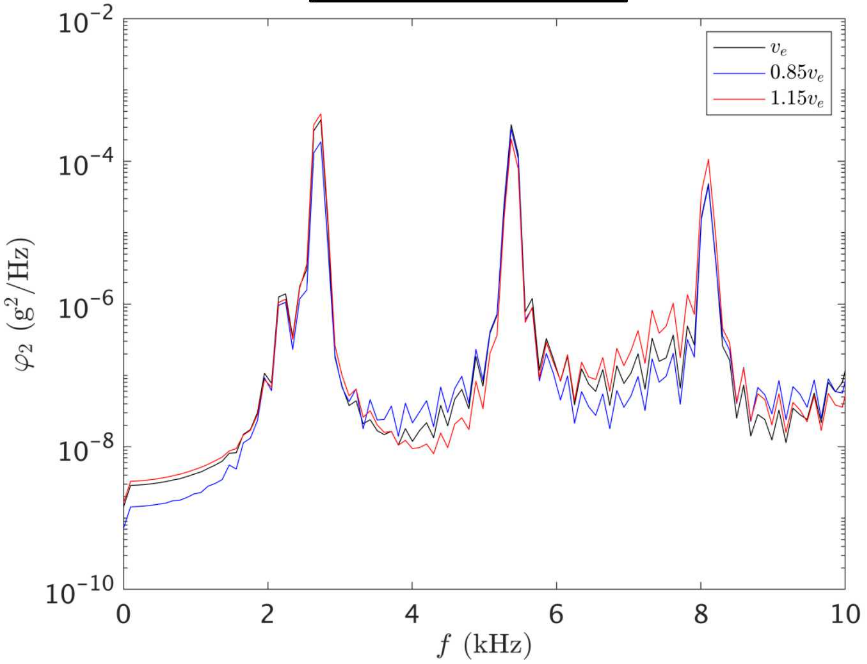



$f_f = 3.9$ kHz

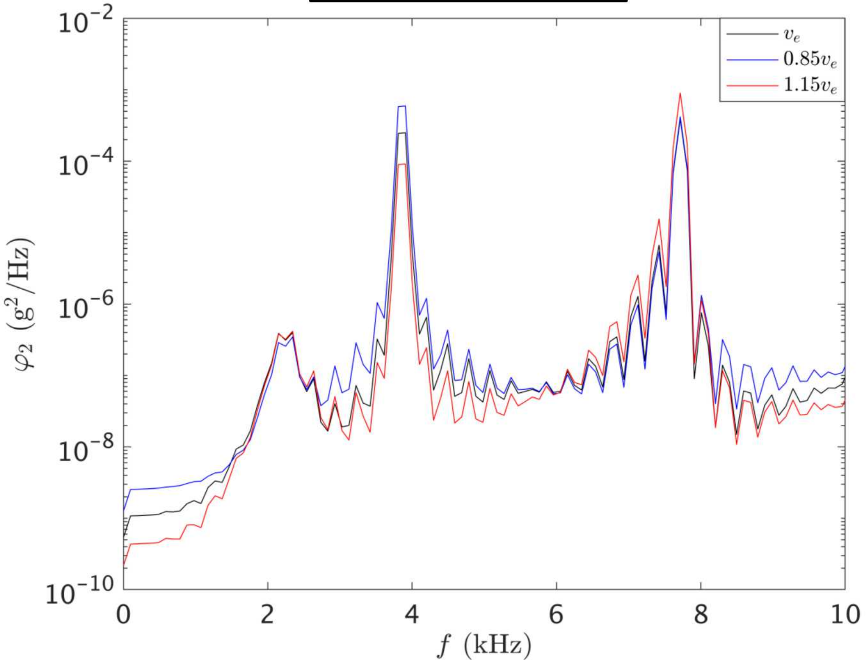


# Turbulent Spot Convection Velocity Study: Results

$f_f = 2.7$ kHz

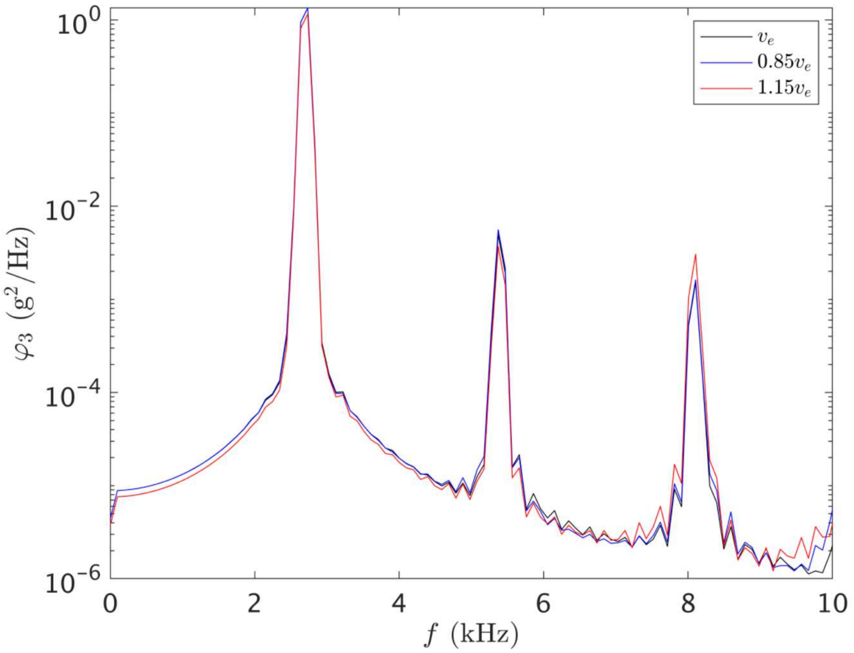



$f_f = 3.9$ kHz

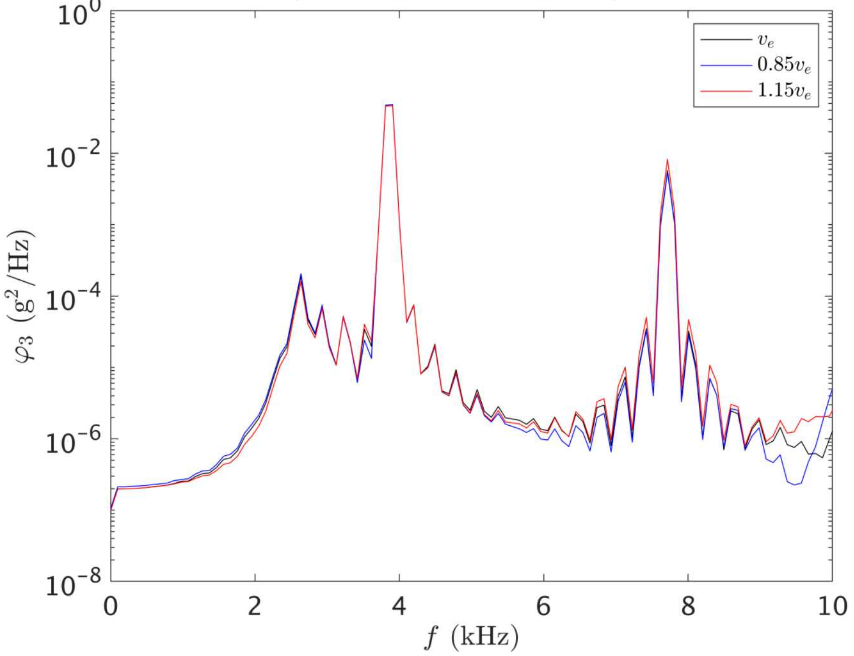


# Turbulent Spot Convection Velocity Study: Results

$f_f = 2.7$ kHz

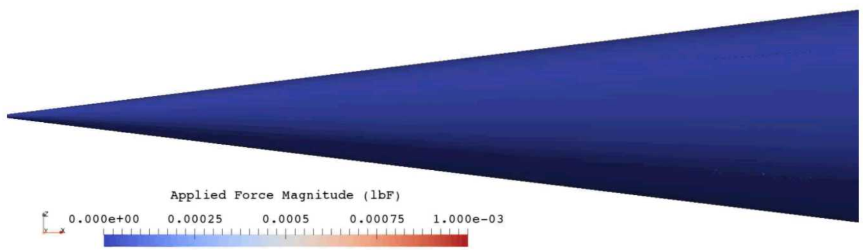


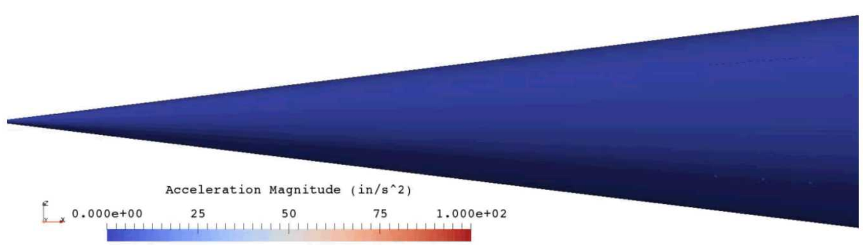

$f_f = 3.9$ kHz



# Concluding Remarks and Future Efforts

- Deterministic model that describes the birth, evolution, and pressure loading of turbulent spots being born at a given $f_f$ developed;
- The model as well as a FE model of a sharp cone structure was used to perform a numerical analysis of the work of Casper *et al.*;
- The numerical simulations provided qualitatively insightful responses when compared to experiment;
- It was illustrated that the convection velocity of the turbulent spots plays a small role in the modes and mode shapes excited in the structure;
- The dominating contributor is the $f_f$, or the time between spot events;
- **Future Efforts:**
  - Explore additional fluid and structural model variations to understand their effect;
  - These results have been leveraged to improve our random loading/natural transition loading model;

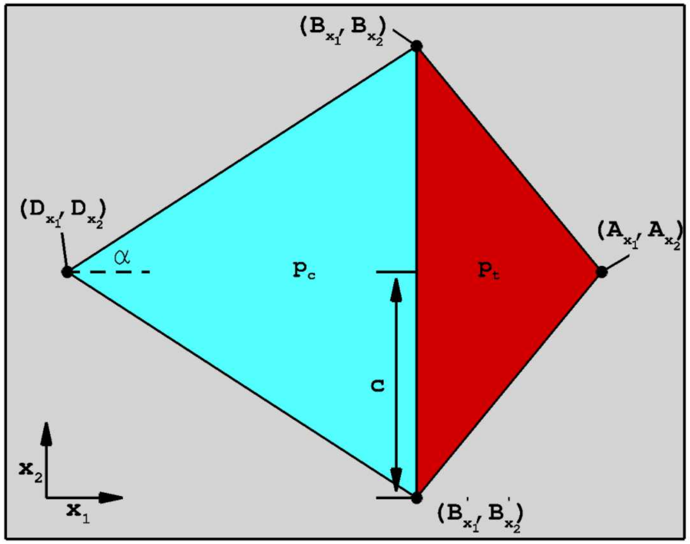


# Questions?

# Extra Slides

# **Model Definition:** Deterministic Description of Single Turbulent Spot Evolution and Pressure Loading




- *Step 1. Spots at birth:* Generate birth times, $t_i$, $i = 1, \ldots, n$, such that $t_1 = 0$ s and $t_n = (n - 1)/f_f \leq t_{tol}$ and assign each spot $i$ with birth geometry $(c, h_A, h_D)$;
- *Step 2. Spot evolution:* Calculate the positions of vertices $B$, $B'$, $A$, and $D$ for any time $(t_i + t) > 0$ by using,

$$\begin{aligned}
&(a_1 + v_b t, a_2 + c + v_b t \tan\alpha), && \text{For vertex } B,\\
&(a_1 + v_b t, a_2 - c - v_b t \tan\alpha), && \text{For vertex } B',\\
&\left(a_1 + h_A + \int_{t_i}^{t_i+t} v_A(s)ds, a_2\right), && \text{For vertex } A,\\
&\left(a_1 - h_d + \int_{t_i}^{t_i+t} v_D(s)ds, a_2\right), && \text{For vertex } D.
\end{aligned}$$

# **Model Definition Cont.:** Deterministic Description of Single Turbulent Spot Evolution and Pressure Loading

- *Step 3. Spot pressure loading:* Determine if coordinate location ($x_1^*$, $x_2^*$) is within the turbulent or calmed region of turbulent spot *i* by means of checking the conditions;

If all conditions are met, (x1*, x2*) is within the **turbulent region**.

Condition 1: $(a_1 + v_b t) < x_1^*,$

Condition 2: $\left(a_1 + h_A + \int_{t_i}^{t_i+t} v_A(s)ds\right) > x_1^*,$

Condition 3: $(a_2 - \delta x_{2,t}) \leq x_2^* \leq (a_2 + \delta x_{2,t}),$

$$\delta x_{2,t} = \left(a_1 - x_1^* + h_A + \int_{t_i}^{t_i+t} v_A(s)ds\right)\left(\frac{c + v_b t \tan\alpha}{h_A + \int_{t_i}^{t_i+t} v_A(s)ds - v_b t}\right).$$

Condition 1: $(a_1 + v_b t) > x_1^*,$

Condition 2: $\left(a_1 - h_D + \int_{t_i}^{t_i+t} v_D(s)ds\right) < x_1^*,$

Condition 3: $(a_2 - \delta x_{2,c}) \leq x_2^* \leq (a_2 + \delta x_{2,c}),$

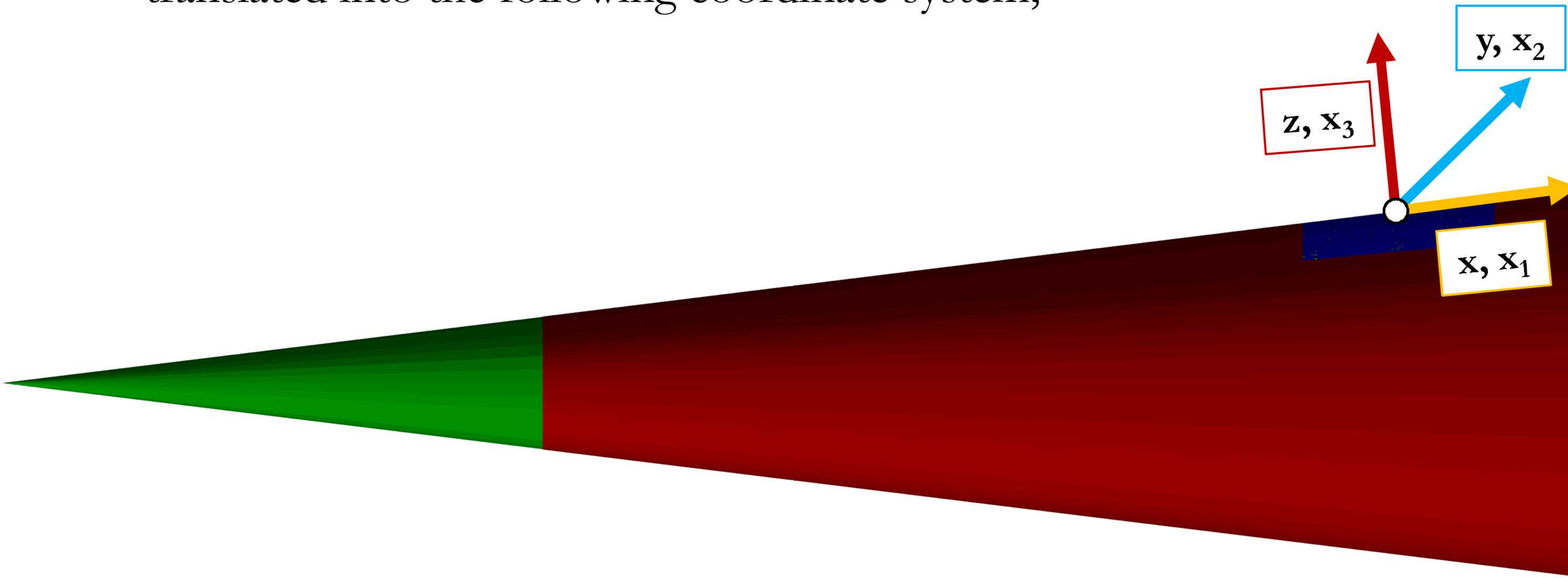
$$\delta x_{2,c} = \left(x_1^* - a_1 + h_D - \int_{t_i}^{t_i+t} v_D(s)ds\right)\tan\alpha.$$

If all conditions are met, (x1*, x2*) is within the **calmed region**.

- *Step 3 Cont. Spot pressure loading:* additionally, assign pressure loading to location if a set of conditions is met. If spot *i* and (*i* + 1) have overlapping regions, allow the turbulent pressure loading to take precedence.

# Coordinate System

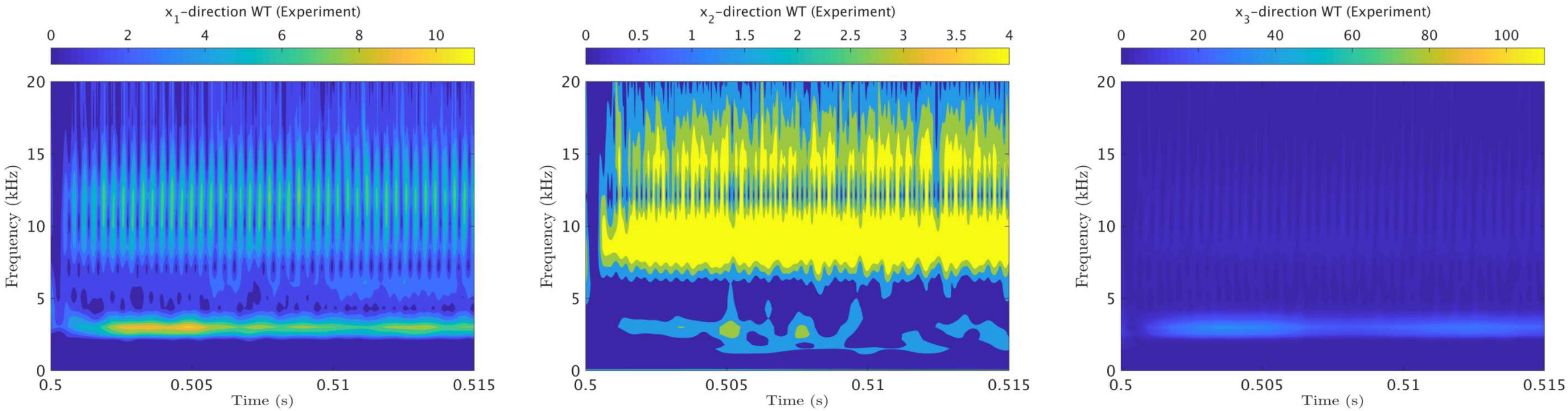
- All acceleration response simulation data, once extracted, is translated into the following coordinate system;



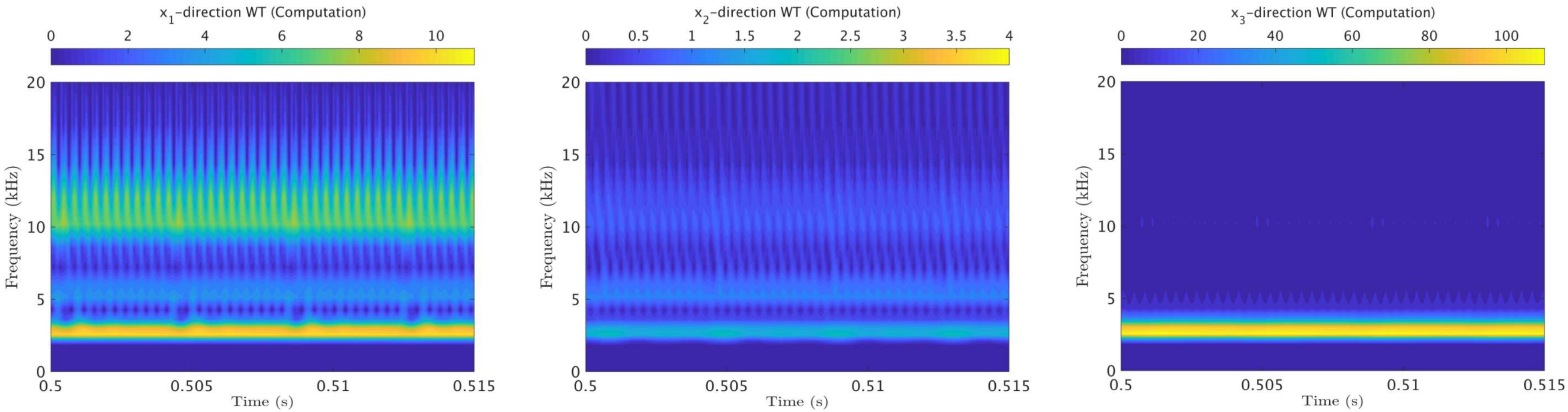

- This coordinate system was defined by Casper *et al* [1];
- The experimental data is measured assuming this coordinate system, therefore we are adopting it for comparison purposes.

# Case I: $f_f = 2.7\ kHz$

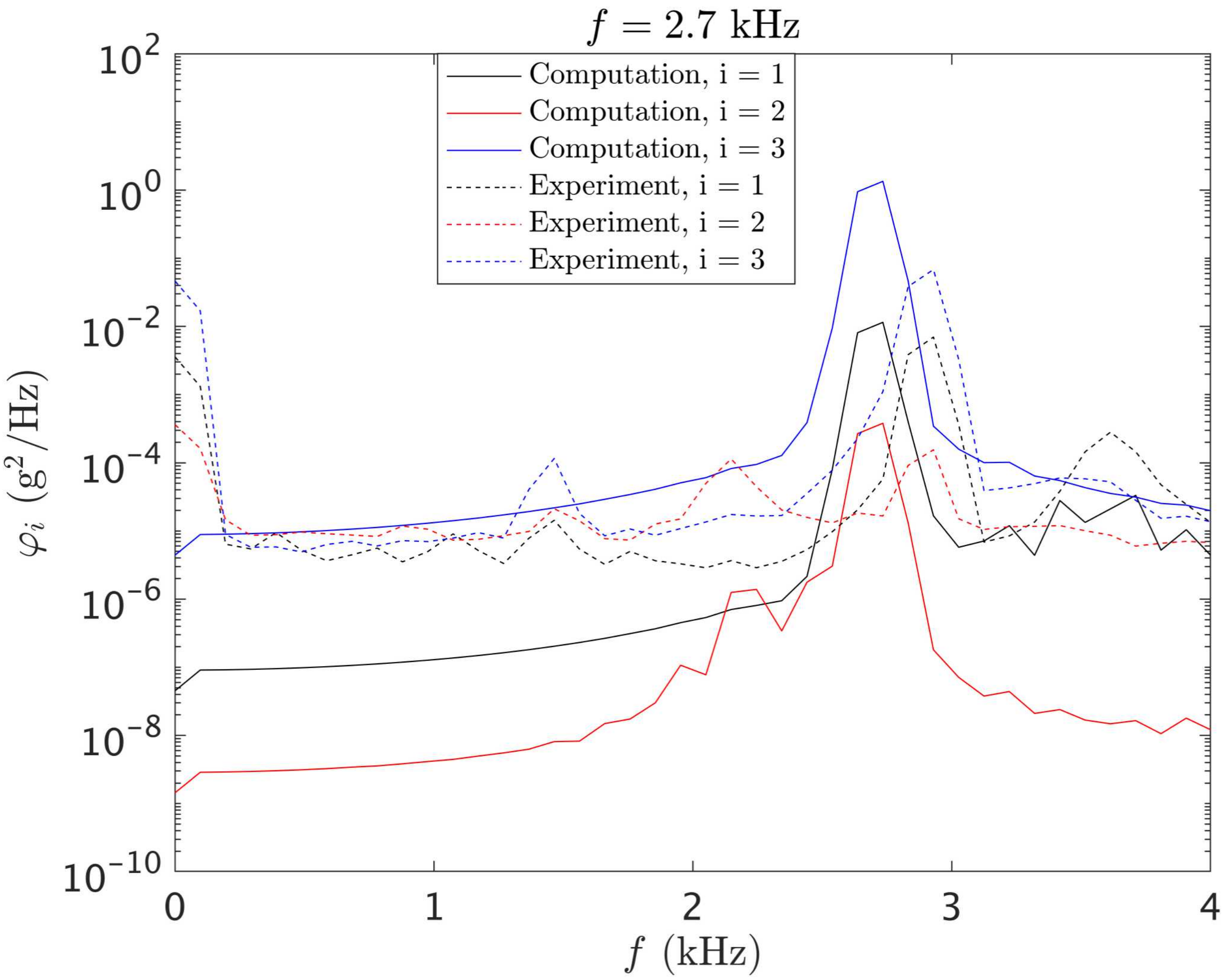
## Experiment




## Computation

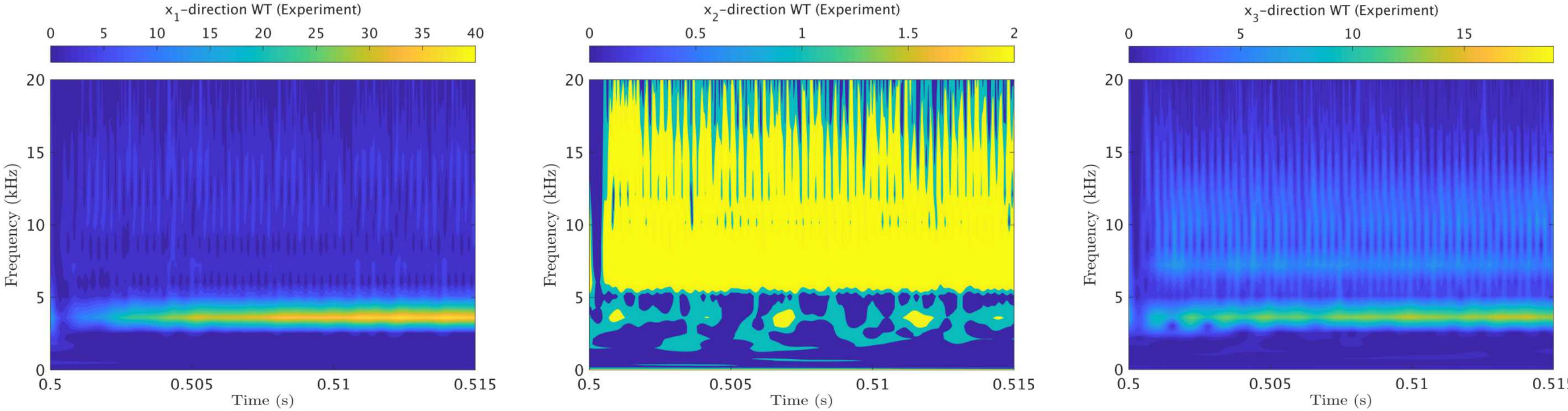


# Case I: $f_f$ = 2.7 kHz

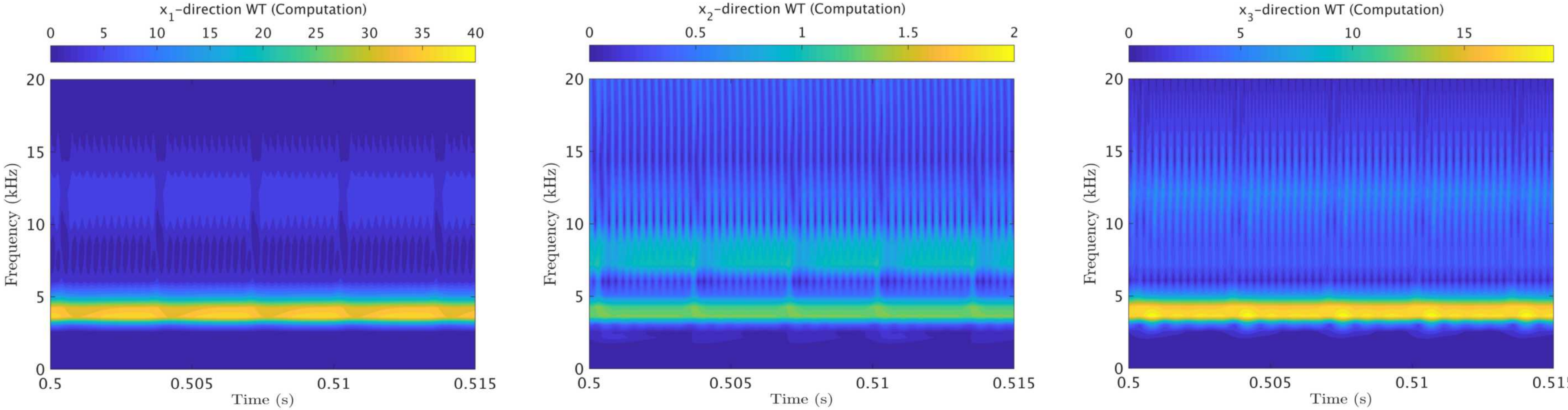


# Case I: $f_f$ = 3.9 kHz

## Experiment




## Computation



# Case I: $f_f$ = 3.9 kHz