



Validation of Shadowgraph Spectral Analysis using an SLS Block 2 Wind-Tunnel Model

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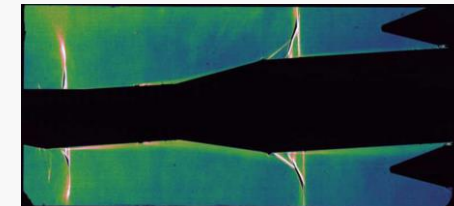
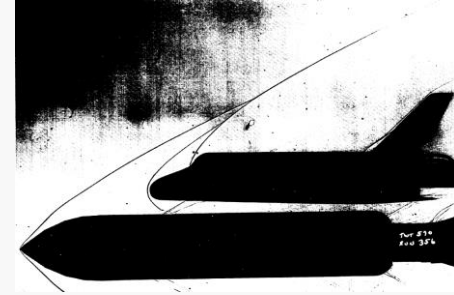
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Introduction: shadowgraph

- Shadowgraph is a method used to visualize the flow and is often used to supplement and explain direct flow property measurements
- Implementation seen in:
 - Space Shuttle (STS) program¹
 - Constellation (Ares I-X) program²
 - Space Launch System (SLS) program³



¹Springer, A., "Shadowgraph Study of Space Transportation System (STS): The Space Shuttle Launch Vehicle (SSLV)", 1994.

²Piatak D. J., Sekula, M. K., and Rausch, R. D., "Comparison of Ares I-X Wind-Tunnel-Derived Buffet Environment with Flight Data," *Journal of Spacecraft and Rockets*, Vol. 49, No. 5, 2012, pp. 822–833. <https://doi.org/10.2514/1.A32176>.

³Heaney, P. S., Soranna, F., Sekula, M. K., Piatak, D. J., and Ramey, J. M., "Analysis of Transonic Unsteady Aerodynamic Environments using Unsteady Pressure Sensitive Paint for the Space Launch System Block 1 Cargo Launch Vehicle," *AIAA SciTech 2021 Forum*, Virtual, 2021.



Introduction: objective

- Develop a technique to extract pressure measurements from shadowgraph
- Previously the quantitative shadowgraph flow visualization has been seen in:
 - Medical field to develop ultrasound techniques⁴
 - Flow properties of the supersonic free-jets⁵
 - Cavitation flows in fuel injection nozzles⁶

⁴Miyasaka, R., Harigane, S., Yoshizawa, S., and Umemura, S., "Quantitative Measurement of Highly Focused Ultrasound Pressure Field by Optical Shadowgraph," *Journal of Physics: Conference Series*, Vol. 520, No. 1, 2014, p. 012026.

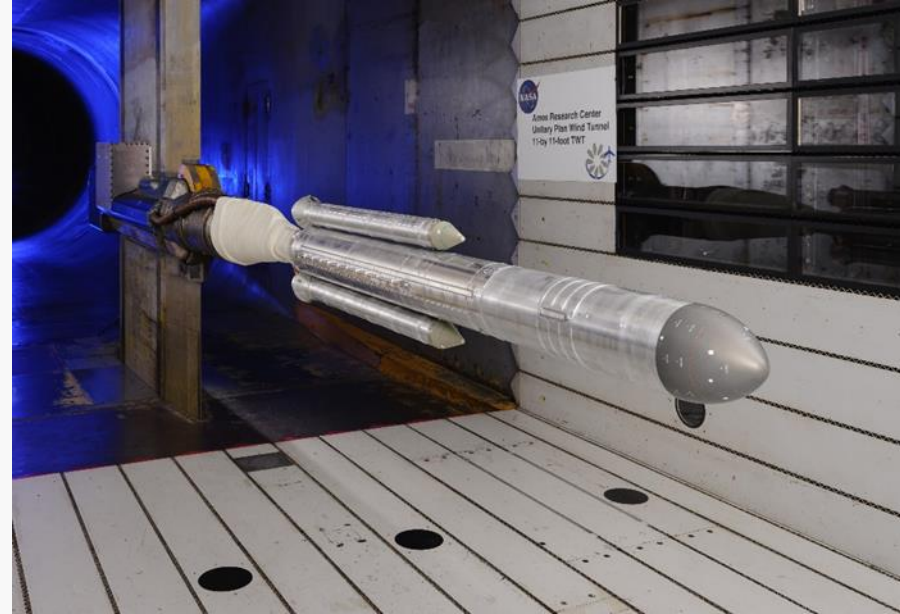
⁵Koponen, E., Leskinen, J., Tarvainen, T., and Pulkkinen, A., "Acoustic pressure field estimation methods for synthetic schlieren tomography," *The Journal of the Acoustical Society of America*, Vol. 145, No. 4, 2019, pp. 2470–2479.

⁶Kolhe, P., Ivanchenko, O., Agrawal, A., and Olcmen, S., "Experimental Measurement of Density, Pressure and Temperature Fields in a Supersonic Free Jet Using Rainbow Schlieren Deflectometry," *46th AIAA Aerospace Sciences Meeting and Exhibit*, 2008.

Experimental setup: wind-tunnel test



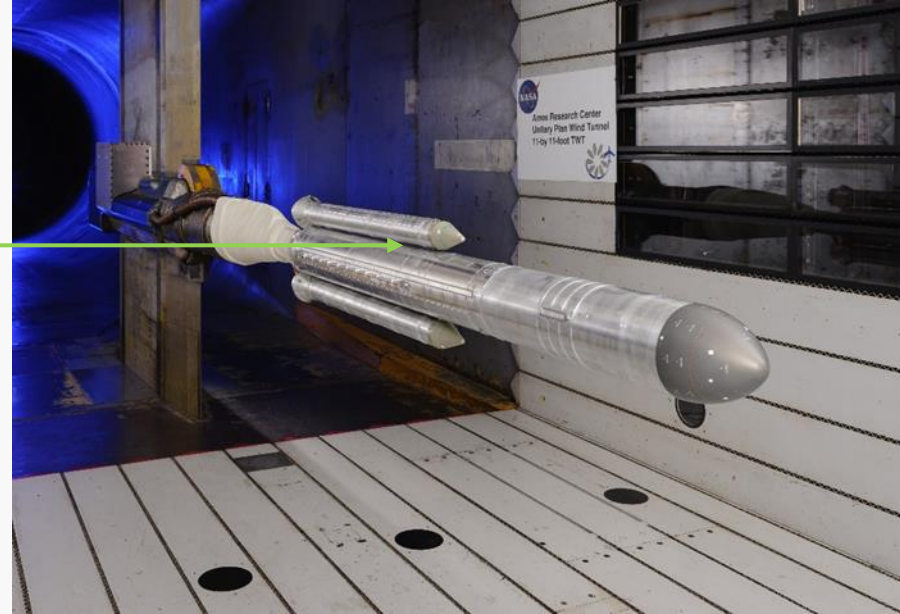
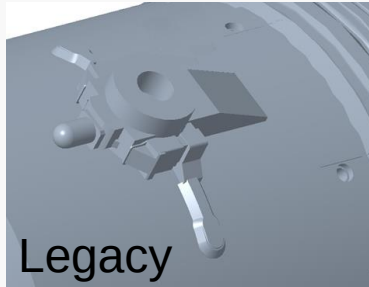
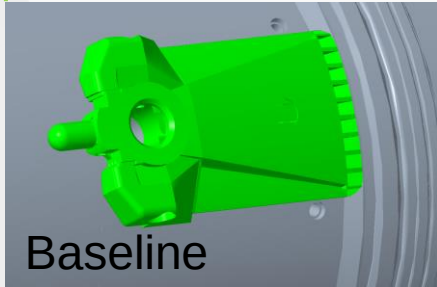
- Using data from the Booster Obsolescence Life Extension (BOLE) Forward Attachment Structure Trade Study Test (BFASTST)
- Performed at the NASA Ames Research Center Unitary Plan Wind Tunnel 11-by-11-foot test section
- 2.5 percent model of the SLS Block 2 Cargo vehicle



Experimental setup: model configurations



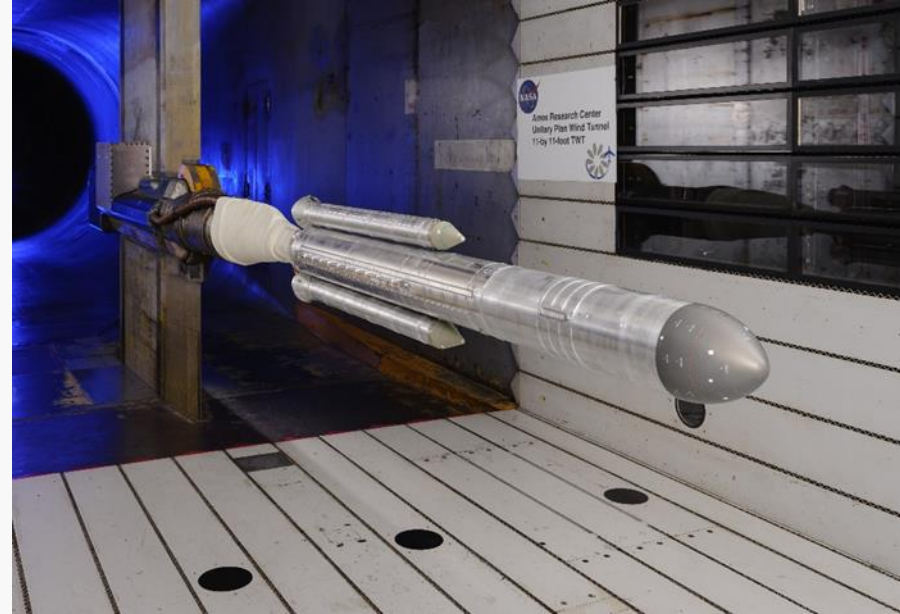
- Primary objective of the test was to investigate the aerodynamic environment downstream of various booster forward attachment hardware geometries
- In total seven geometries were studies during test
- Only two will be used in the present discussion:



Experimental setup: instrumentation



- Pressure measurements:
 - 189 Kulite pressure transducers
 - “Slow” record: 10,000 Hz for 15 s
 - “Fast” record: 200,000 Hz for 2 s
- Shadowgraph:
 - Phantom v2511 series high-speed camera
 - Production-level setup⁷
 - 51,000 Hz rate
- Flow conditions:
 - Mach number ranged from 0.60 to 1.20
 - Attitude was varied in pitch and sideslip from -6° to 6°

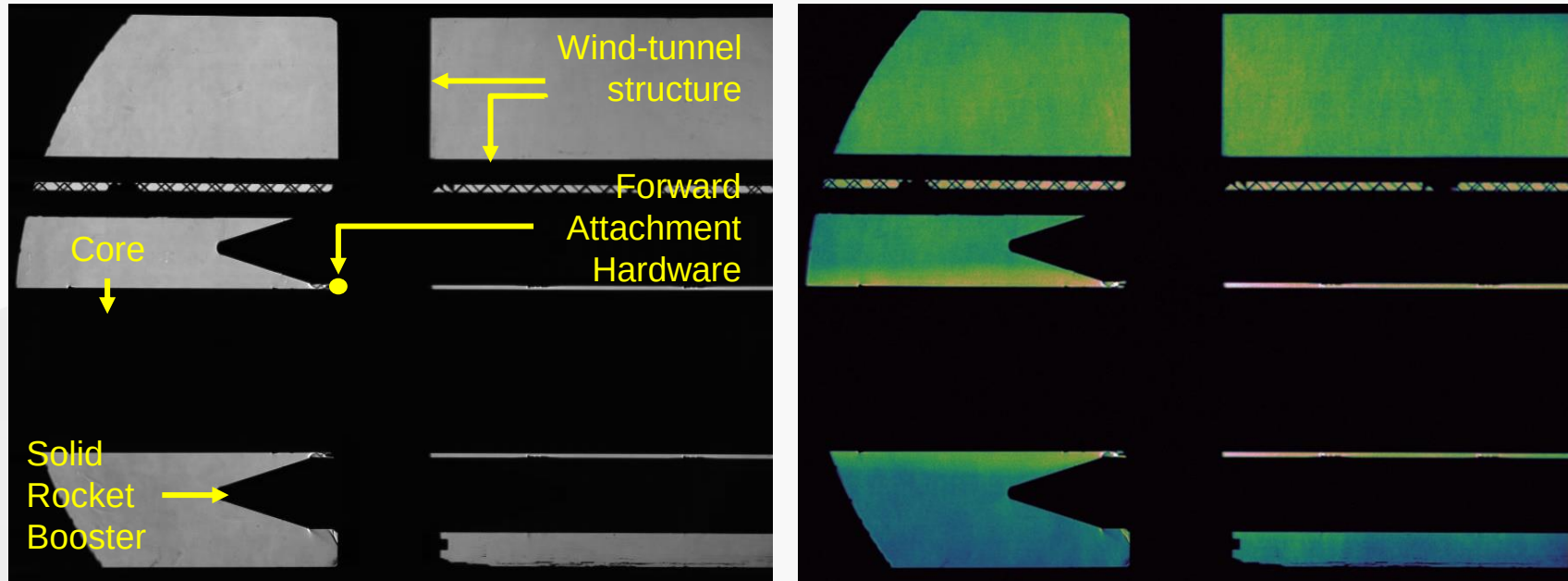


⁷Garbeff, T. J., Baerny, J., and Ross, J. C., “Wind Tunnel Flow Field Visualizations of the Space Launch System Vehicle Ascent,”

Experimental setup: shadowgraph view



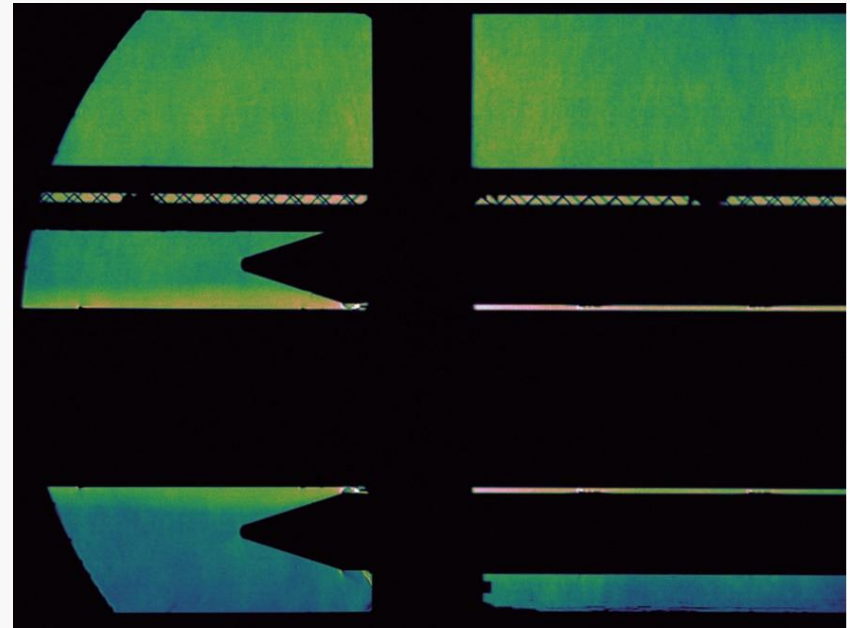
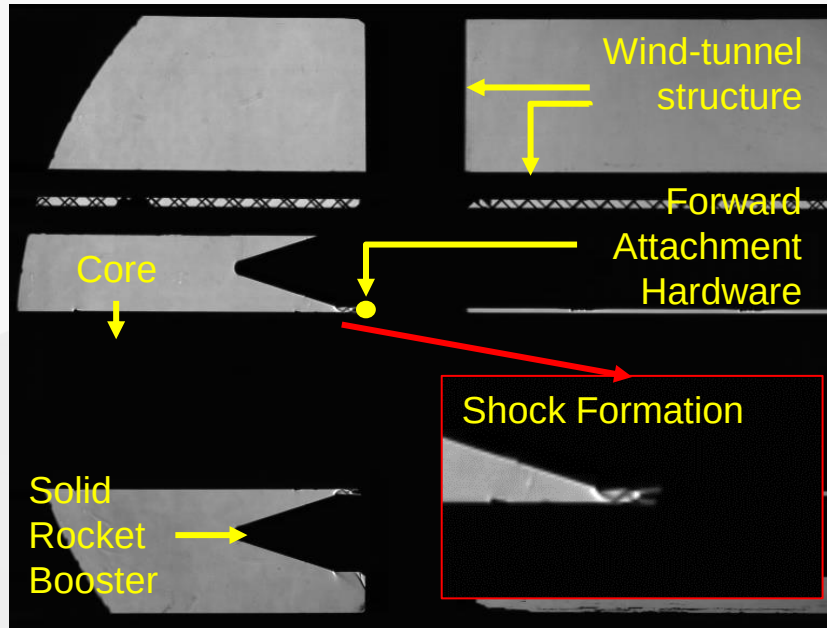
- Representative shadowgraph images obtained at $M = 0.92, \beta = 0^\circ$
- Ensemble-averaged image and standard deviation image



Experimental setup: shadowgraph view



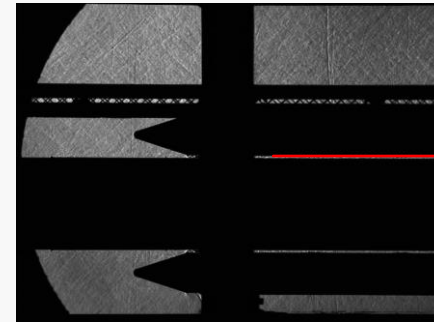
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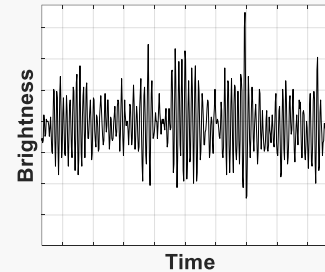
Analysis: FFT of shadowgraph



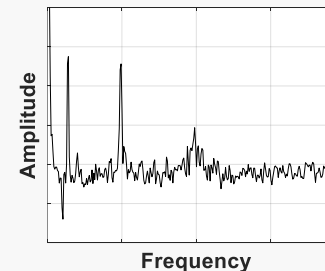
- Analysis begins by **extracting a time-series of the light intensity, I** , from a shadowgraph video for each pixel
- **Discrete Fast Fourier Transform (FFT)** analysis was performed on each time-series
- For each frequency, the **FFT amplitudes of all pixels in the frame were averaged** to produce an ensemble FFT amplitude



Extract pixel
brightness time-series



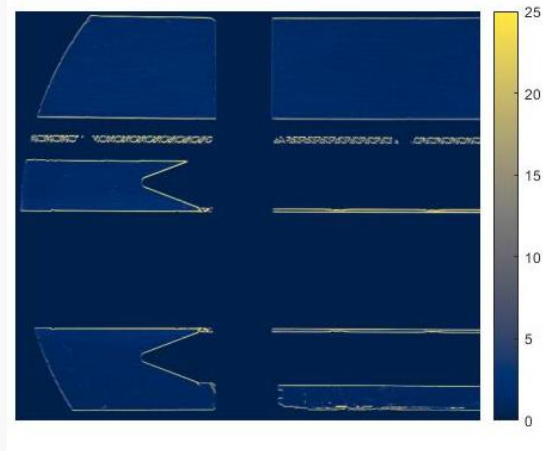
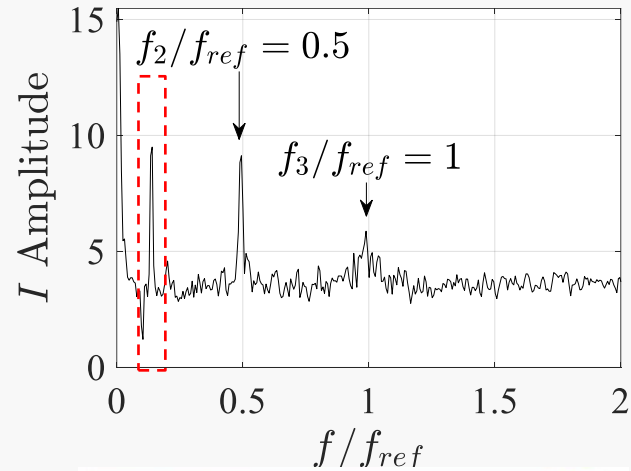
Perform FFT analysis



Ensemble
average of all
pixels in region of
interest

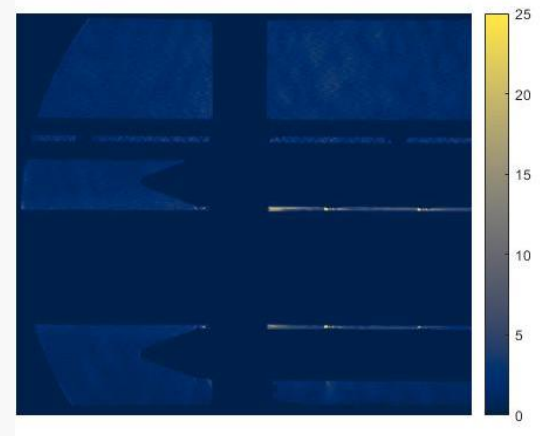
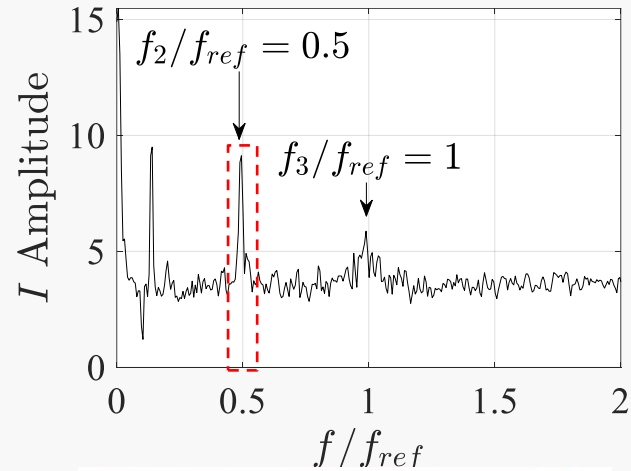
Analysis: shadowgraph peaks

- All frequencies were normalized by f_3 which was used as reference frequency f_{ref}
- Examining three dominant amplitude peaks:
 - f_1 likely corresponds to model and camera vibration



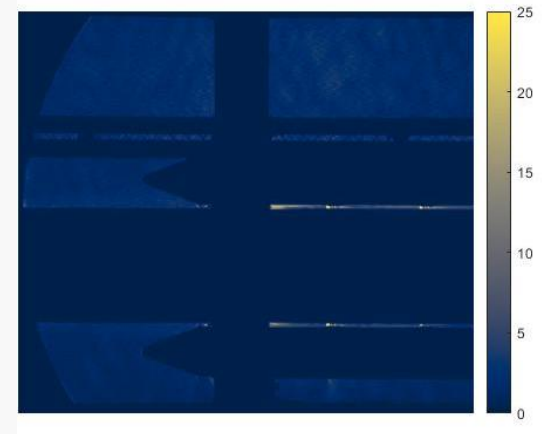
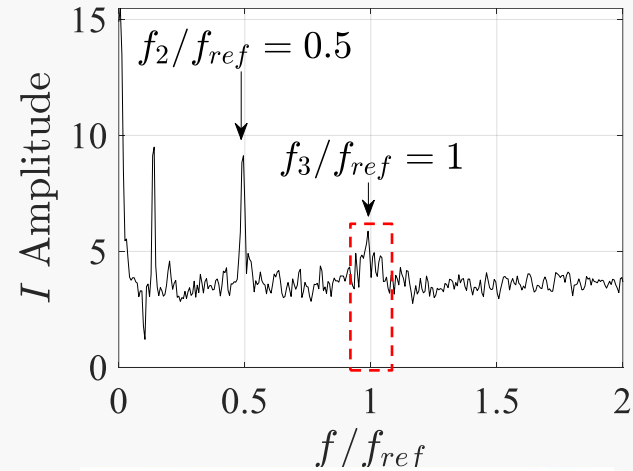
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 - f_1 likely corresponds to model and camera vibration
 - f_2 fluctuations in flow downstream of the forward attachment hardware



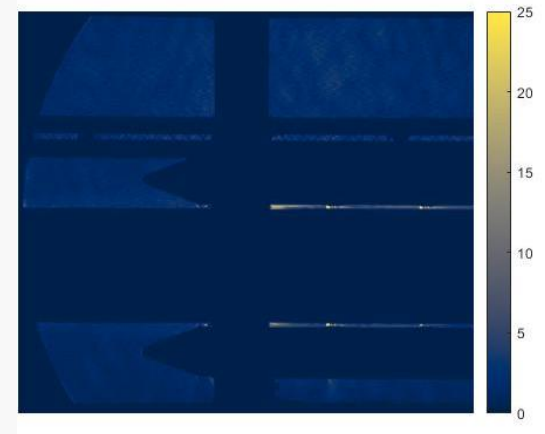
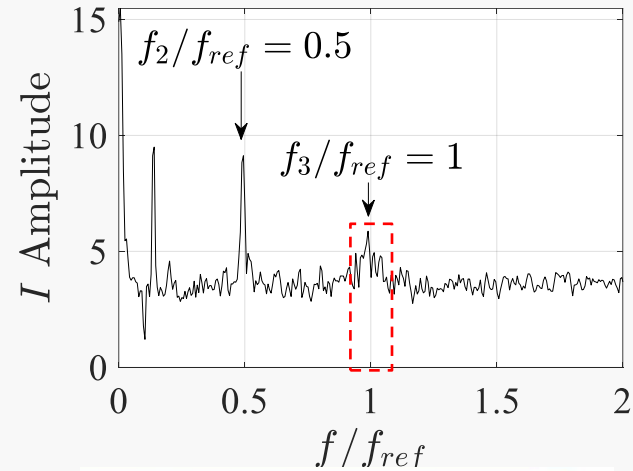
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 - f_1 likely corresponds to model and camera vibration
 - f_2 fluctuations in flow downstream of the forward attachment hardware
 - f_3 fluctuations in flow downstream of the forward attachment hardware, harmonic of f_2



Analysis: shadowgraph peaks

- All frequencies were normalized by f_3 which was used as reference frequency f_{ref}
- Examining three dominant amplitude peaks:
 - f_1 likely corresponds to model and camera vibration
 - f_2 fluctuations in flow downstream of the forward attachment hardware
 - f_3 fluctuations in flow downstream of the forward attachment hardware, harmonic of f_2
- Dominant fluctuations in the flow field occur downstream of the forward attachment region
- **How to relate amplitudes of I at f_2 and f_3 to pressure fluctuations?**



- $$\frac{\Delta I}{I} = l \int_{\zeta_1}^{\zeta_2} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) (\ln n) dz$$

-
- The diagram illustrates the light ray propagation in a tapered optical fiber. A light ray enters from the left, passes through a core, and is reflected by a booster. The diagram shows the ray's path, the core, the booster, and the resulting light intensity distribution $I(x, y)$ and $I^*(x^*, y^*)$.

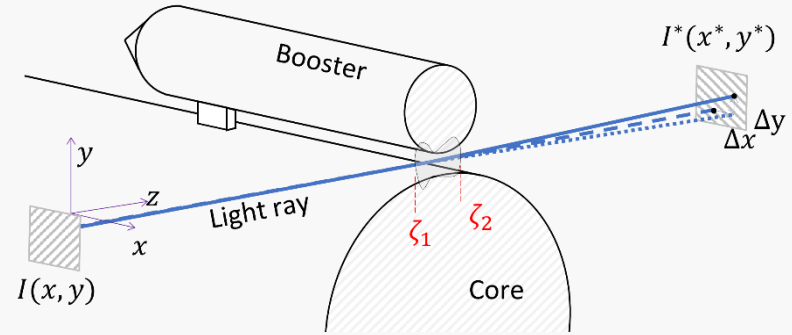
$$I^* = \sum I + \Delta I$$

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Assumptions:

- Linearizing $\ln n$ and applying Gladstone-Dale formula
- Ideal gas law, assuming:
 - Constant temperature (validated in more recent experiments)
 - Density variation is negligible everywhere along each path, s , except for the booster region between ζ_1 and ζ_2 , or width L

$$\frac{\Delta I}{I} = lLK \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) P$$



Analytical considerations: periodic signal

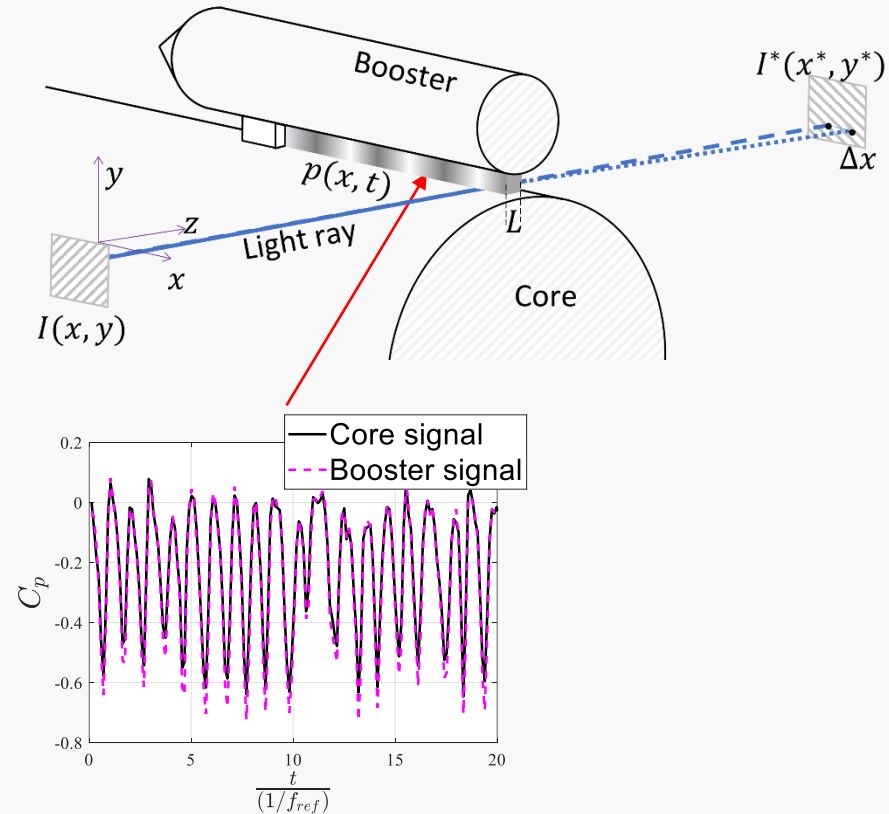
$$\frac{\Delta I}{I} = lLK \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) p$$

- Pressure signal downstream of the forward hardware attachment is periodic. So, p and $\frac{\Delta I}{I}$ can be expressed as sine functions:

$$p(x, t) = A_1 \sin(2\pi f_{x1}x + 2\pi f_1t + \phi)$$

$$\frac{\Delta I}{I}(x, t) = A_2 \sin(2\pi f_{x2}x + 2\pi f_2t + \phi)$$

- Assumed p is not a function of y , which is validated by nearly-identical signal observed in sensors on the booster and the core.



Analytical considerations: final equation form



$$\frac{A_2}{A_1} = lLK4\pi^2 f_{x1}^2$$

- Knowing the fluctuation amplitude of pixel brightness and pressure a constant $C_1 = lLK4\pi^2$ can be solved for:

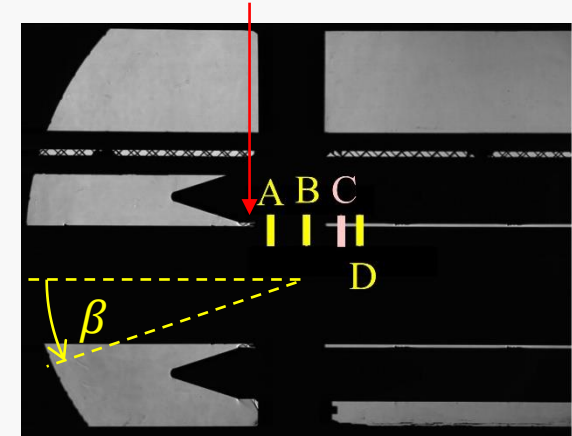
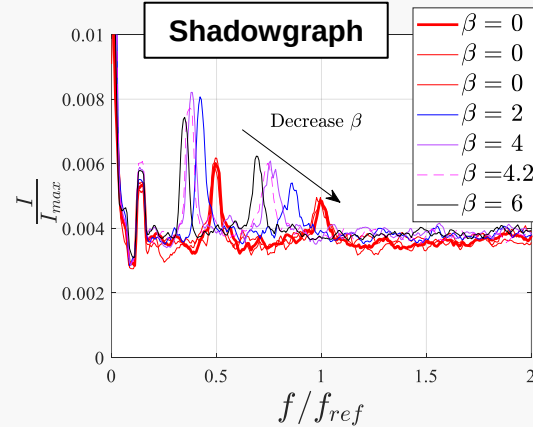
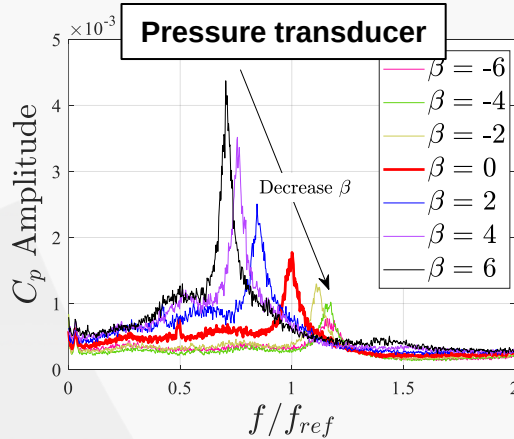
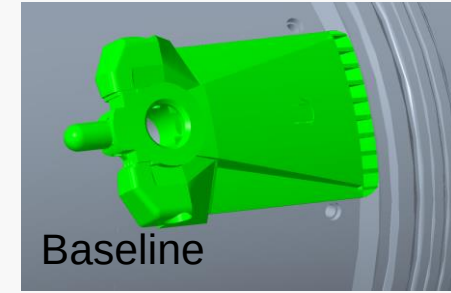
$$\frac{A_2}{A_1} = C_1 4\pi^2 f_{x1}^2$$

- Next step is to use the available shadowgraph and pressure data to find C_1

Results: β polar



- Sideslip, β , polar was used for the Baseline hardware attachment configuration to obtain C_1 calibration constant
- β polar provided a continuous variation of fluctuation amplitude, ideal for this calibration
- Pressure measurements at **station C** were used first

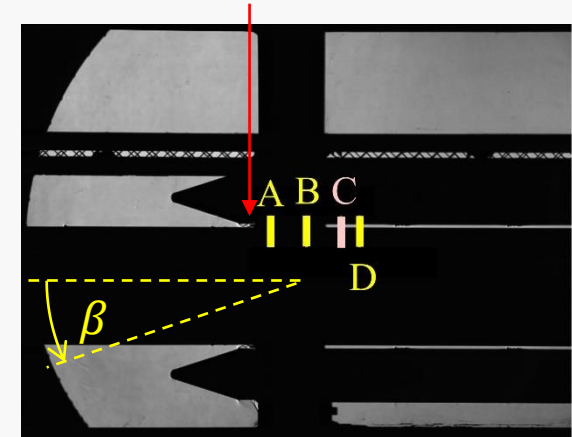
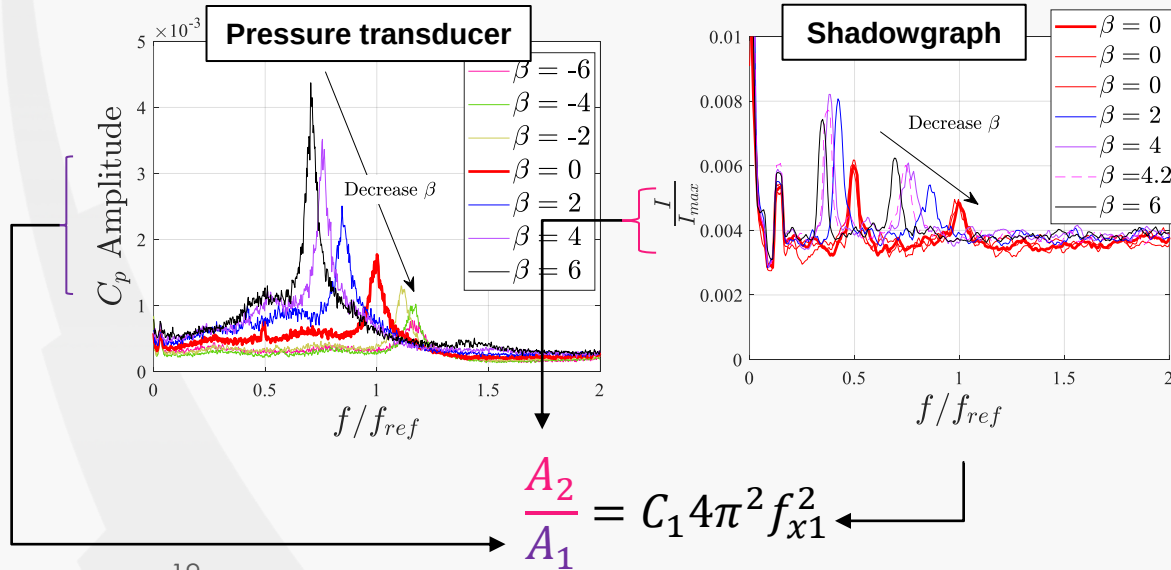
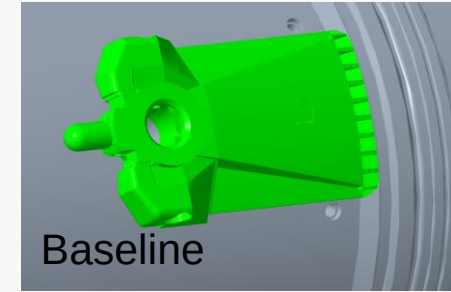


$$\frac{A_2}{A_1} = C_1 4\pi^2 f_{x1}^2$$

Results: β polar

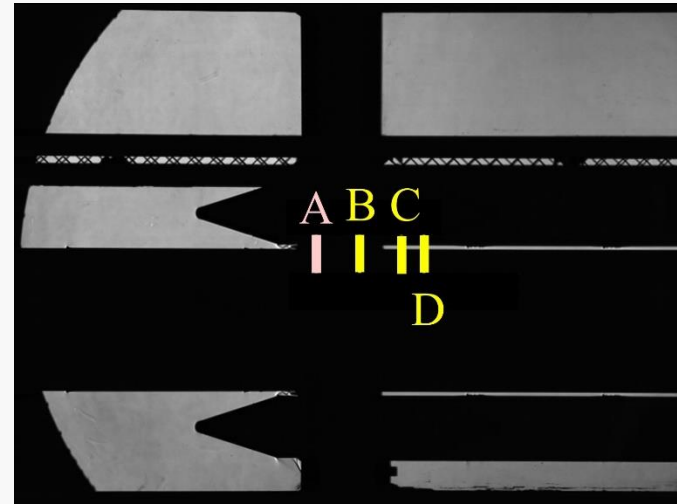
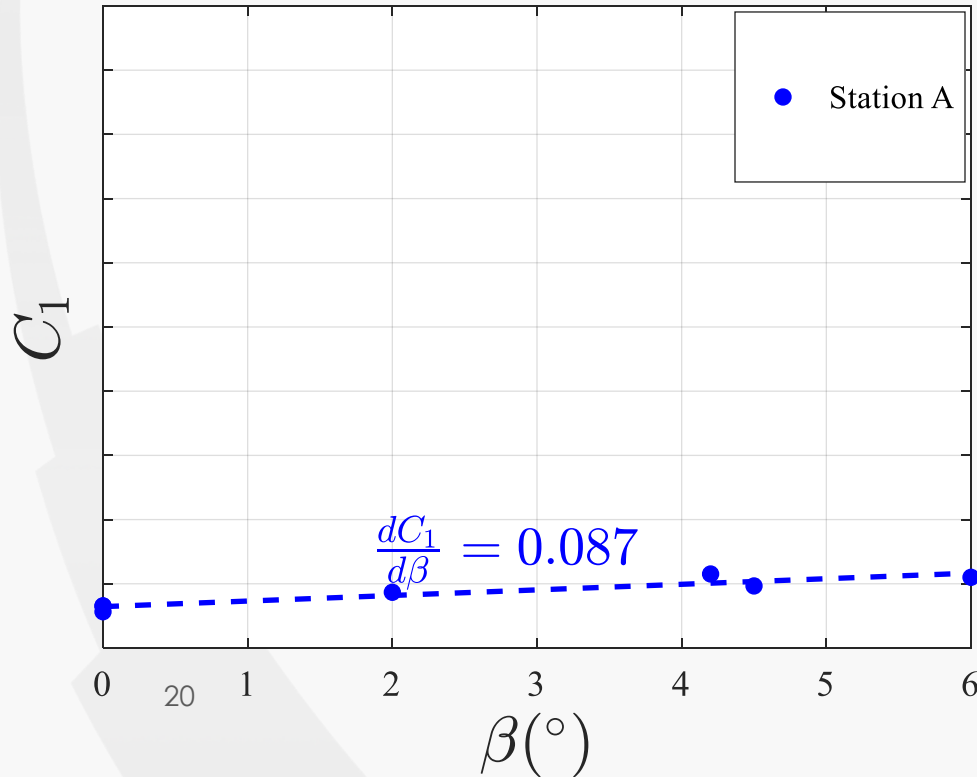


- For each β a unique C_1 was computed
- $f_{x1} = f v_c$ where v_c is convective speed obtained from station-to-station cross correlation



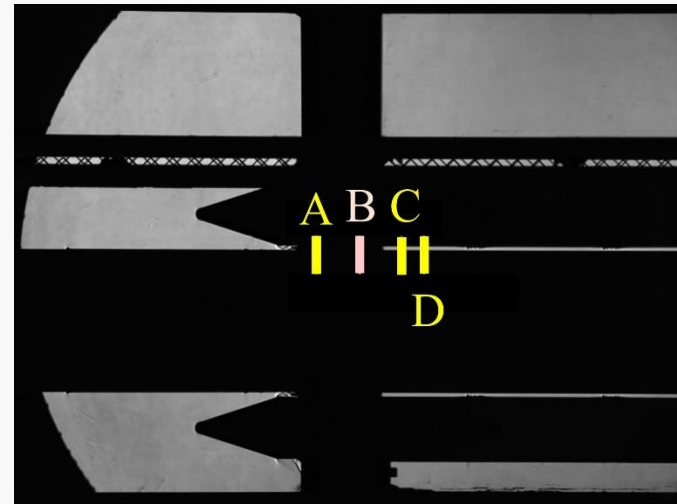
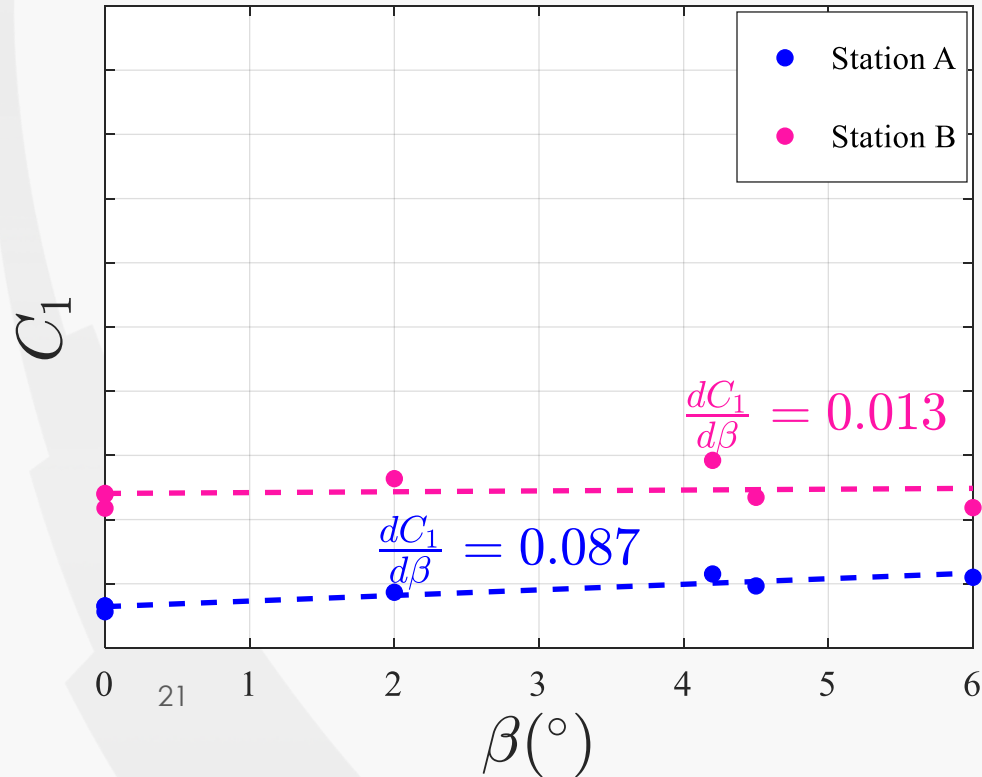
Results: calibration constant

- C_1 for each β angle computed by comparing shadowgraph brightness intensity amplitude to measured pressure fluctuation amplitude at **Station A**



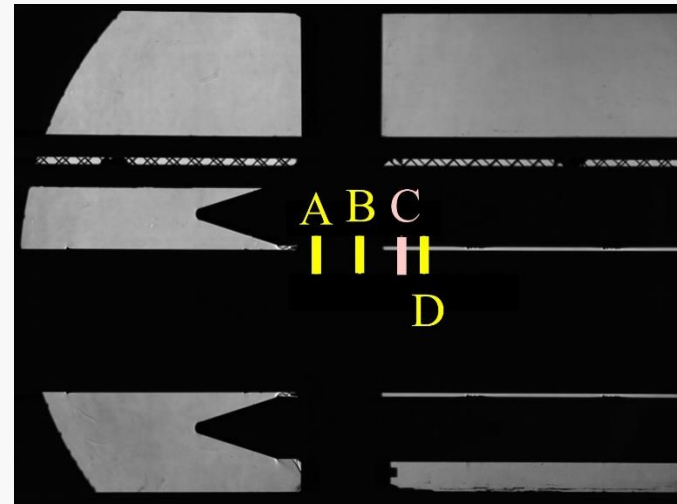
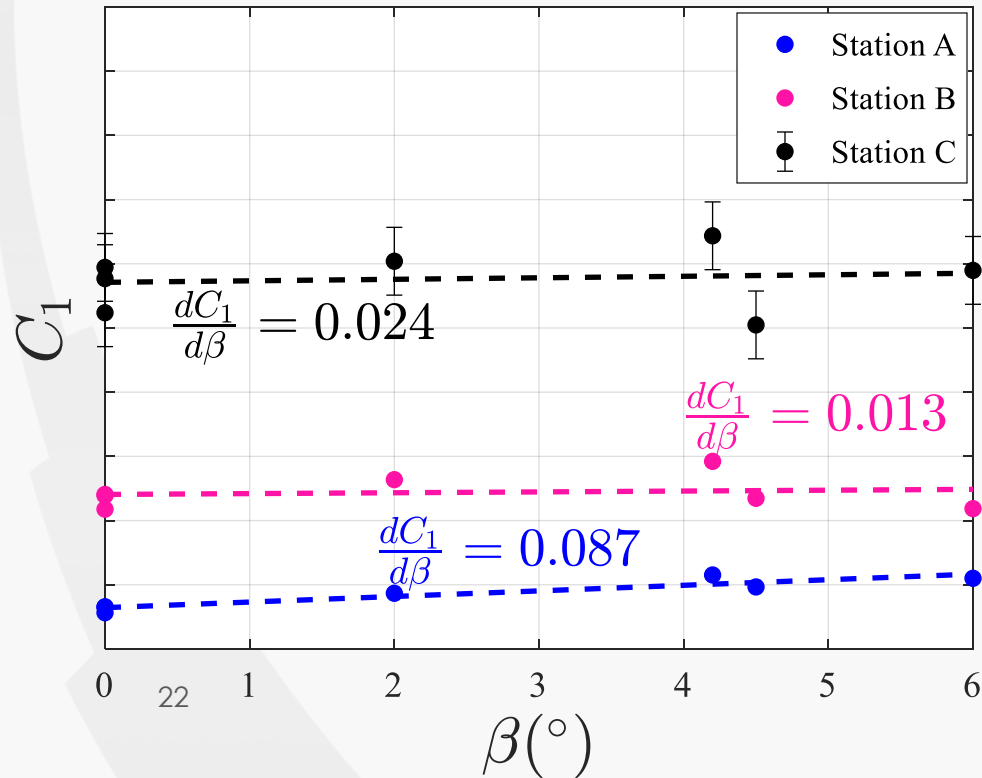
Results: calibration constant

- C_1 for each β angle computed by comparing shadowgraph brightness intensity amplitude to measured pressure fluctuation amplitude at **Station B**



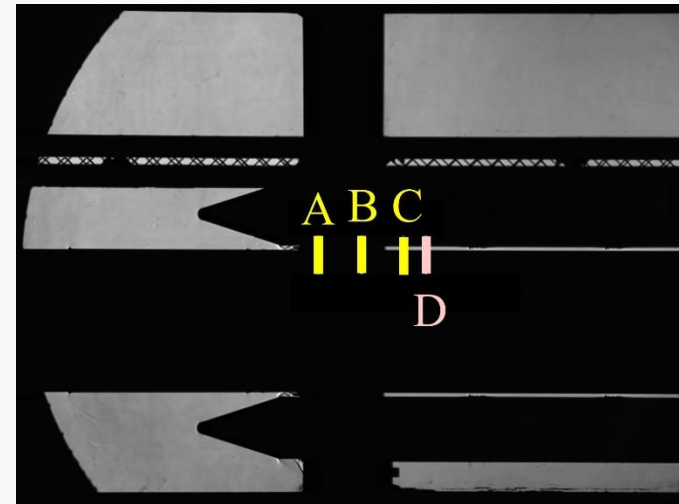
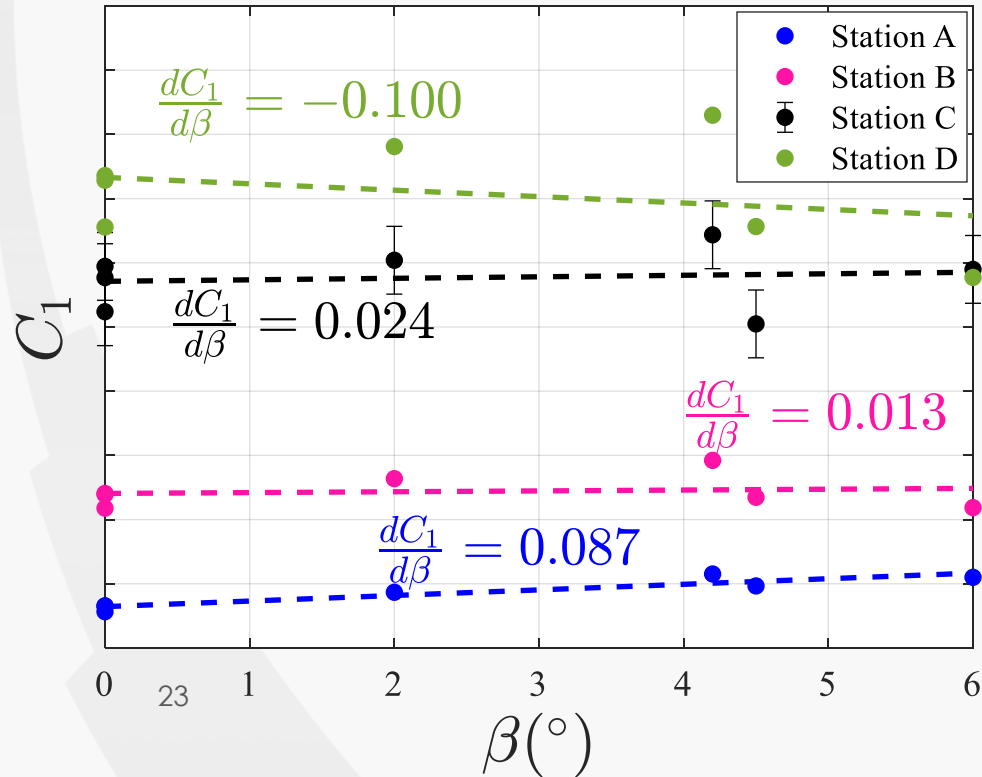
Results: calibration constant

- C_1 for each β angle computed by comparing shadowgraph brightness intensity amplitude to measured pressure fluctuation amplitude at **Station C**



Results: calibration constant

- C_1 for each β angle computed by comparing shadowgraph brightness intensity amplitude to measured pressure fluctuation amplitude at **Station D**

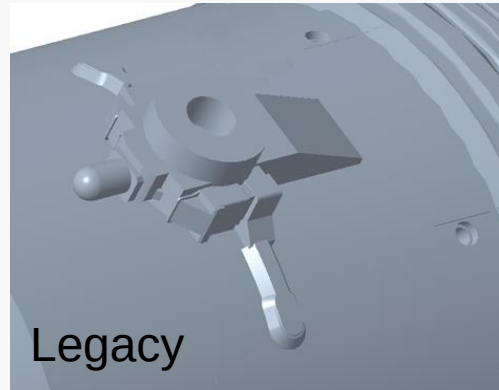


Results: calculation of pressure

- With known calibration coefficient C_1 , shadowgraph-based pressure measurements can be obtained

$$A_1 = \frac{A_2}{C_1 4\pi^2 f_{x1}^2}$$

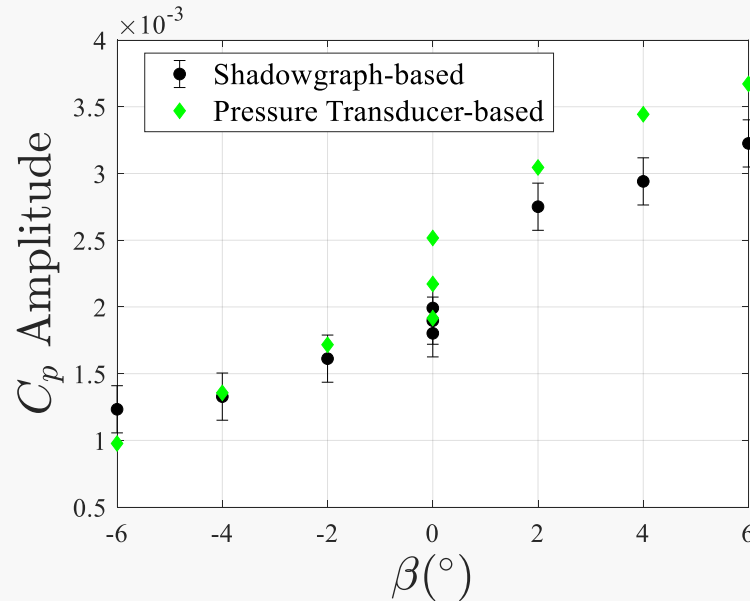
- Shadowgraph data for the Legacy hardware attachment test run was used to compute pressure fluctuations and compared them to the pressure transducer-based measurements.



Results: pressure fluctuation result



- Shadowgraph-based pressure measurements are within the experimental uncertainty for negative β values.
- Offset in measured pressure amplitude values is introduced starting at $\beta = 0$.
- This offset remains unexplained. Potential issue with excitation voltage.



Conclusions



- Quantitative flow visualization analysis was developed to **measure pressure fluctuations**
- The analysis required simplifications that were valid in the core-booster gap region
 - Constant-temperature
 - One-dimensional flow
 - Dominant fluctuations in density occur in the core-booster gap
- Calibration was performed using a **Baseline attachment** configuration of the wind-tunnel test
- The calibration constant was used to compute shadowgraph-based pressures and compare them to the pressure transducer-based measurements
- **Legacy attachment** configuration was used to verify the calibration constant
- Fluctuating pressure values were within experimental uncertainty for negative β angles

Questions?

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