



Parametric Study of the Forward Attachment Geometry for the Space Launch System Next Generation Booster

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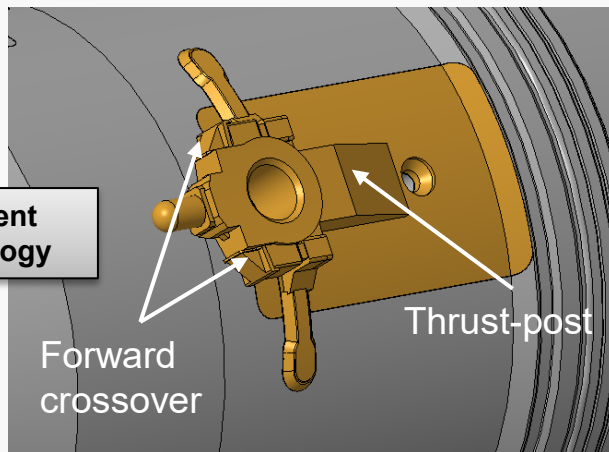
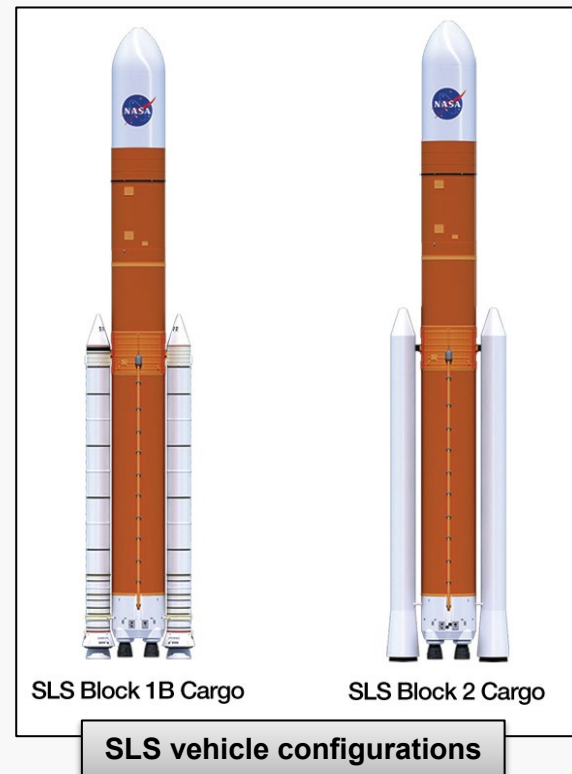
Background and motivations

- **Transonic launch vehicle buffet environments can generate large dynamic loads**
 - Sensitive to the outer mold line (OML) of the forward attachment between the booster and the core of the vehicle
- **Space Launch System (SLS) boosters are being updated to replace expended boosters and to satisfy mission goals**
 - Booster Obsolescence and Life Extension (BOLE) program
 - Forward attachment geometry will be changed
- **BOLE Forward Attachment Trade Study Test (BFASTST) conducted to evaluate potential designs**
 - Objective 1: Aid in the down-selection of the forward attachment geometry for the BOLE booster among several viable candidates
 - Objective 2: Provide qualitative observations and relative merits for specific geometry components



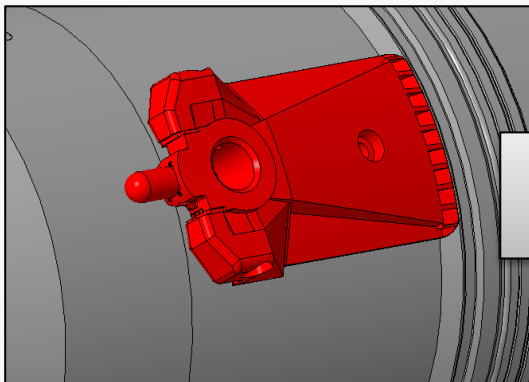
BFASTST - Model description

- **Full-stack representation of the Block 2 Cargo vehicle**
- **Utilized an existing SLS 2.5% core and forebody for all configurations**
 - Core: based on OML established in July 2012, with updates
 - Forebody: Cargo variant with 60-40 ogive payload fairing
- **New BOLE boosters manufactured**
- **Seven interchangeable forward attachment geometries produced**

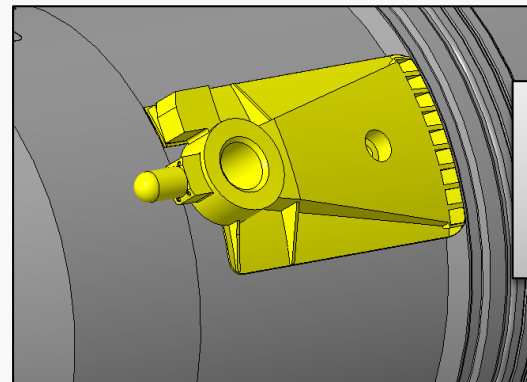


Model configurations - Candidate

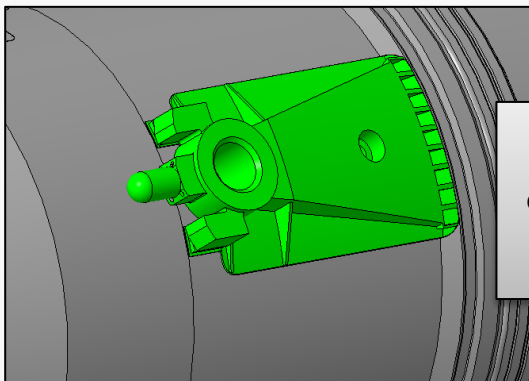
- Candidate** design options were provided by Northrop Grumman for direct assessment



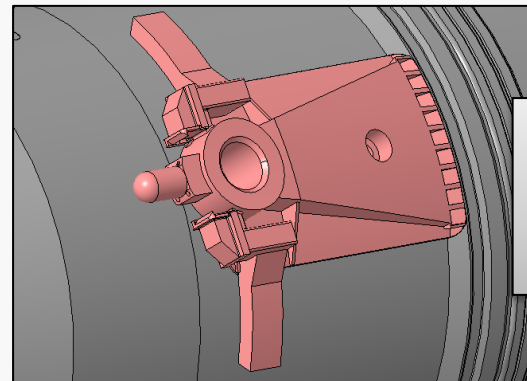
Baseline -
Original March
2020 concept



One-sided -
March 2021
concept based
on a previous
umbilical



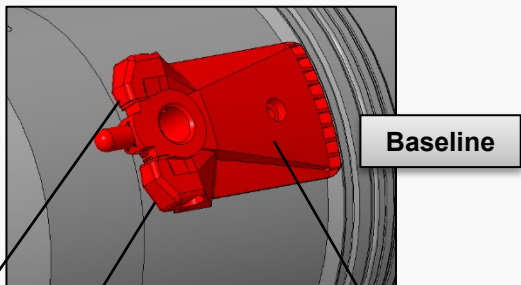
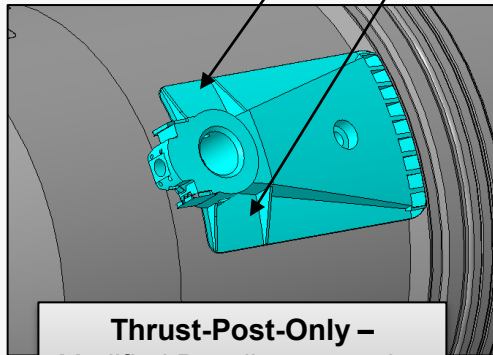
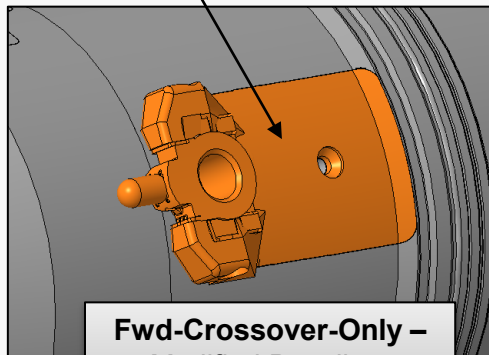
Two-sided -
March 2021
concept based
on a previous
umbilical



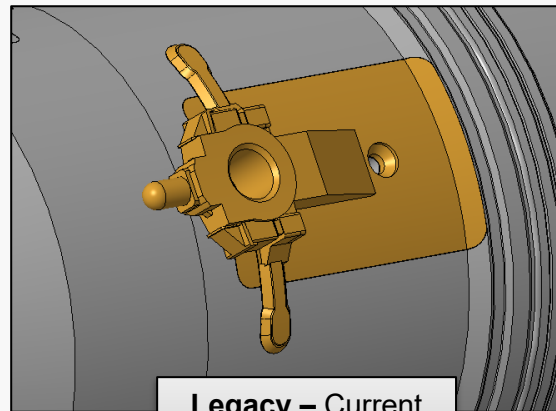
Heritage -
March 2021
concept based
on current SLS
geometry

Model Configurations - Research and reference

- *Research* designs were test-specific configurations to study the impact of specific OML features



- The *Reference* configuration was the current SLS forward attachment geometry



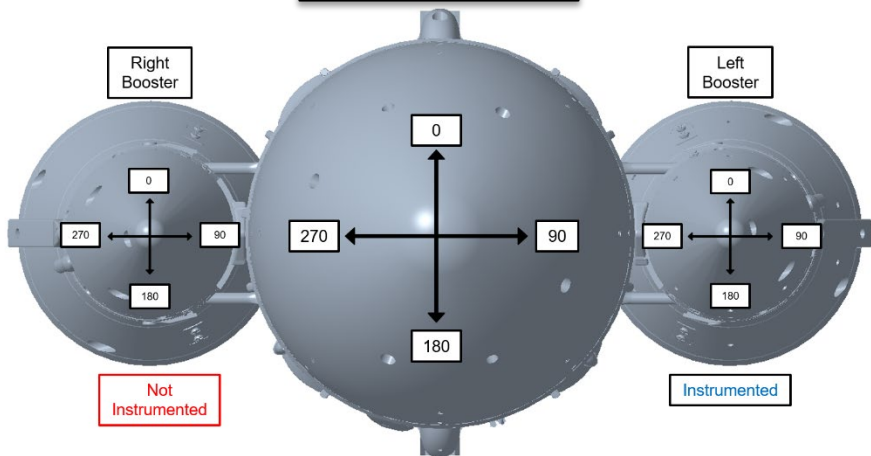


Instrumentation overview

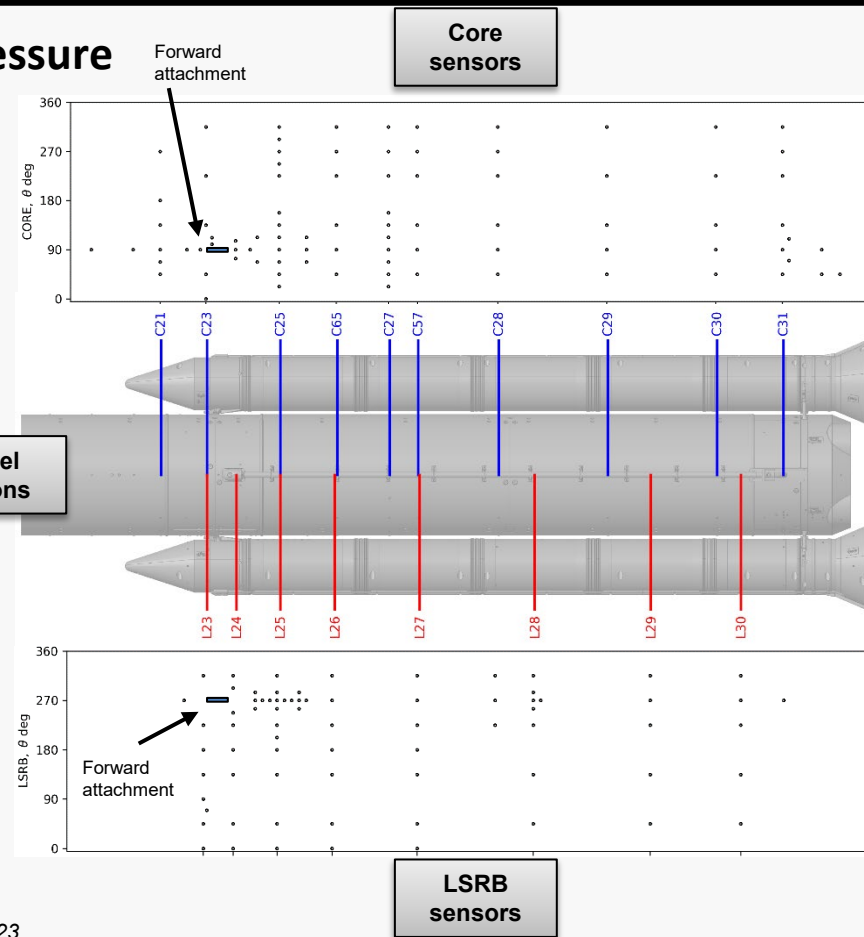
- Model was populated with Kulite unsteady pressure transducers

- 87 sensors in the core, 74 in the left solid rocket booster (LSRB)
- Model stations represent rings of sensors
- Core and LSRB model stations are *not* coincident

Model Layout



Model stations





Data sources and test operations

- **BFASTST**

- Conducted in March 2022
- Each forward attachment was tested through series of slideslip angles (β), sweeps at various angles of attack, (α) and a 55-point Mach sweep @ $\alpha = \beta = 0^\circ$
- Total of 966 runs were performed, consisting of nearly 5,000 points.



- **Ascent Transient Aerodynamics Test (ATAT)**

- Utilized as the baseline case to anchor test results
- Conducted in September 2019
- Tested many of the same parameters and conditions
 - Test article
 - Pressure sensors
 - Facility



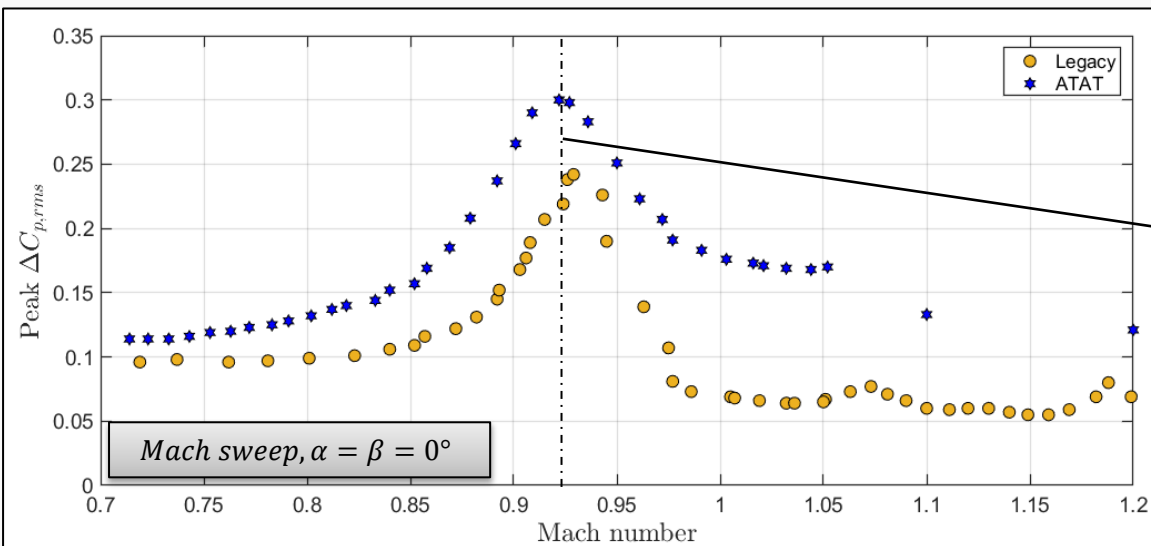
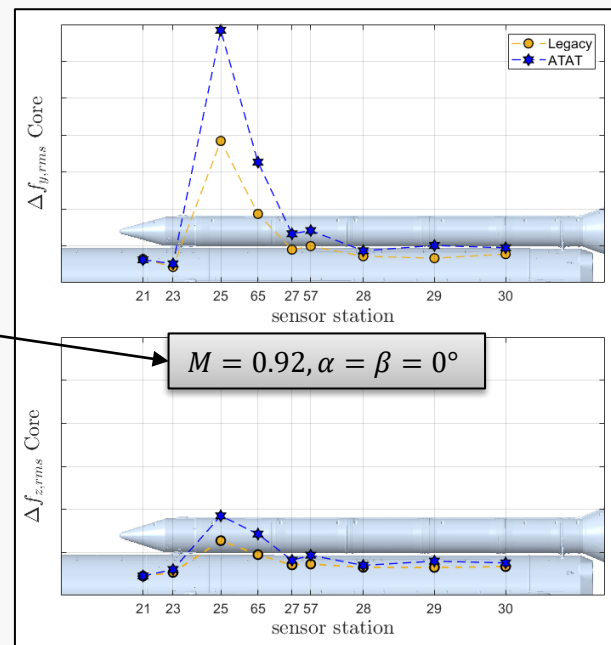


Analysis methodology

- **Fluctuating pressure environment**
 - Key metric is $\Delta C_{p,rms}$, the root-mean-square (rms) magnitude of the fluctuating component of the pressure coefficient
 - Maximum global vehicle $\Delta C_{p,rms}$: sensor with the highest value of $\Delta C_{p,rms}$ for each configuration
- **Fluctuating buffet force environment**
 - Centerline sectional buffet forcing functions (BFFs), computed by azimuthally integrating a ring of unsteady pressure time histories and assuming a unity longitudinal integration length
 - Will assess the rms of the sectional BFFs in the lateral (y) and vertical (z) directions ($\Delta f_{y,rms}$ and $\Delta f_{z,rms}$)
- **Due to the complexities in assessing spectral content of the buffet environments, the comparative frequency content is not considered**

Legacy configuration vs. ATAT

- In general, the peak core maximum $\Delta C_{p,rms}$ trends are similar
 - ATAT magnitudes consistently higher for all Mach numbers
 - Both peak maximum $\Delta C_{p,rms}$ occurs at similar Mach number, but ATAT has notably broader peak
- ATAT core sectional BFFs generally envelope those of the Legacy configuration
 - At station 25, $\Delta f_{y,rms}$ for ATAT are significantly higher
 - $\Delta f_{z,rms}$ share comparative percent differences to $\Delta f_{y,rms}$

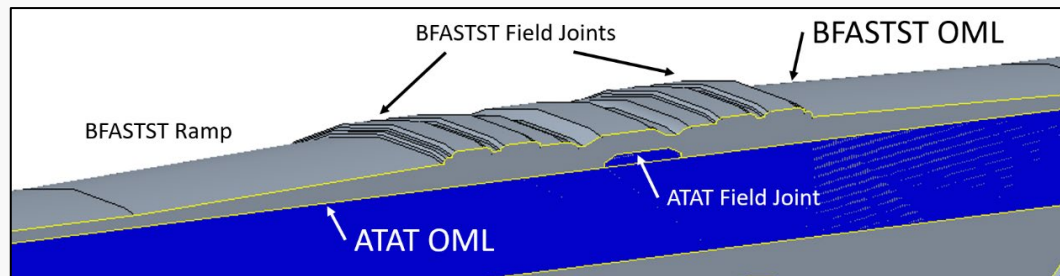




Test-to-test differences

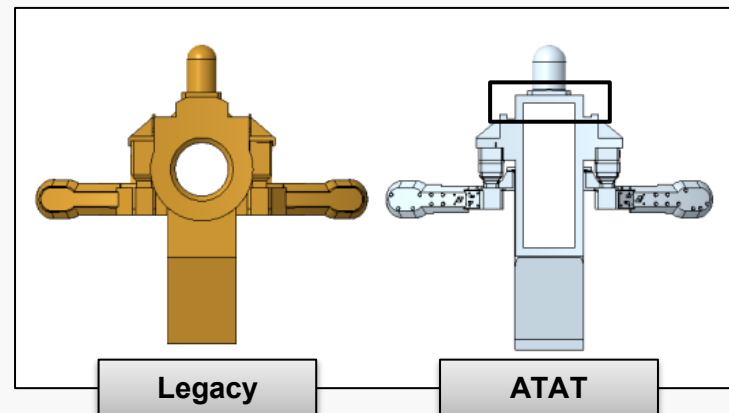
- **Booster Geometry OML has changed**

- Slight increase in diameter
- Much more pronounced field joint



- **Forward attachment geometry**

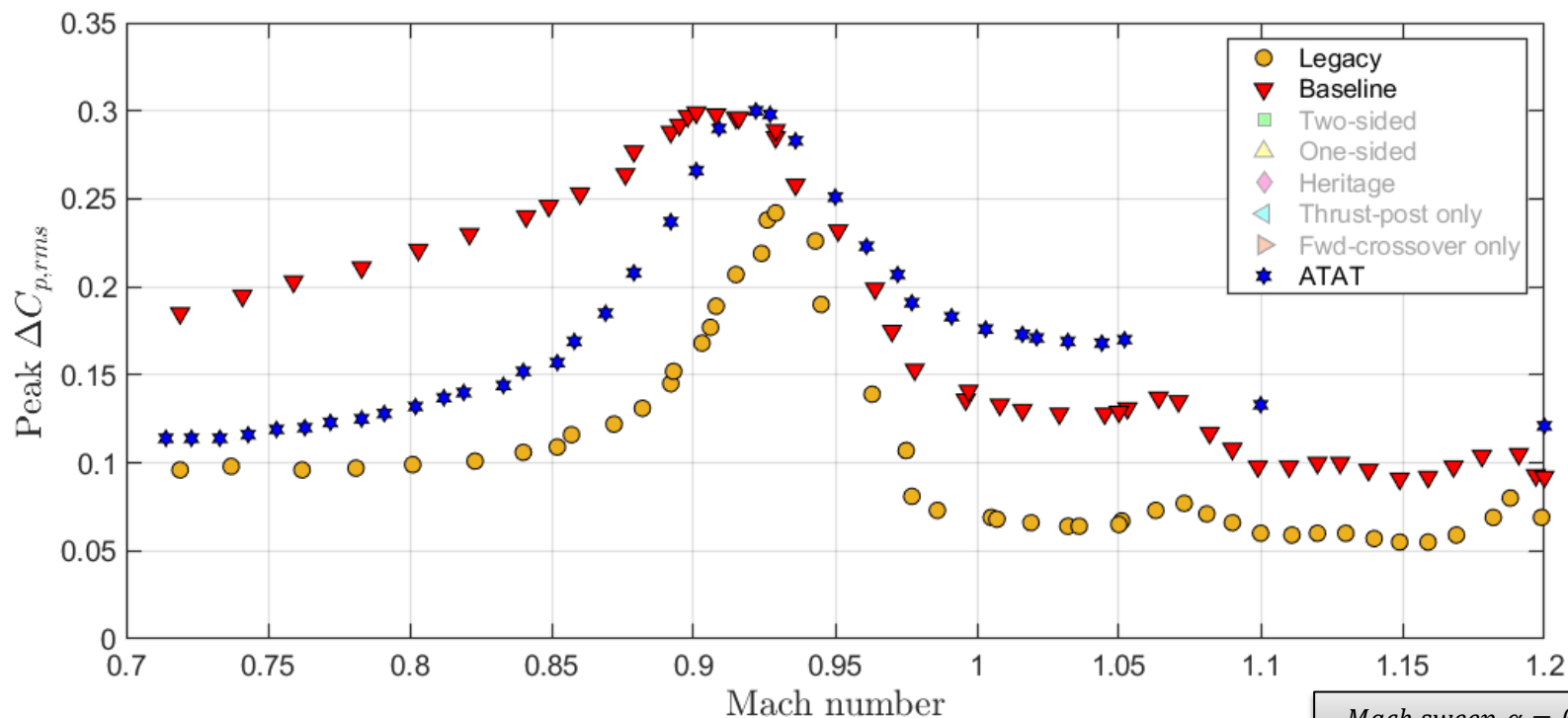
- OML differences between ATAT and the Legacy configuration
- Material differences
 - BFASTST – laser-sintered Inconel (± 0.005 in. tolerance)
 - ATAT – PLA plastic; when measured, was 0.027 in. wider than the CAD (5% increase)





BFASTST configurations maximum core $\Delta C_{p,rms}$, Baseline

- **Baseline has the highest maximum $\Delta C_{p,rms}$ of the Candidate configurations**
 - Higher than ATAT $\Delta C_{p,rms}$ despite booster OML changes



Mach sweep, $\alpha = \beta = 0^\circ$

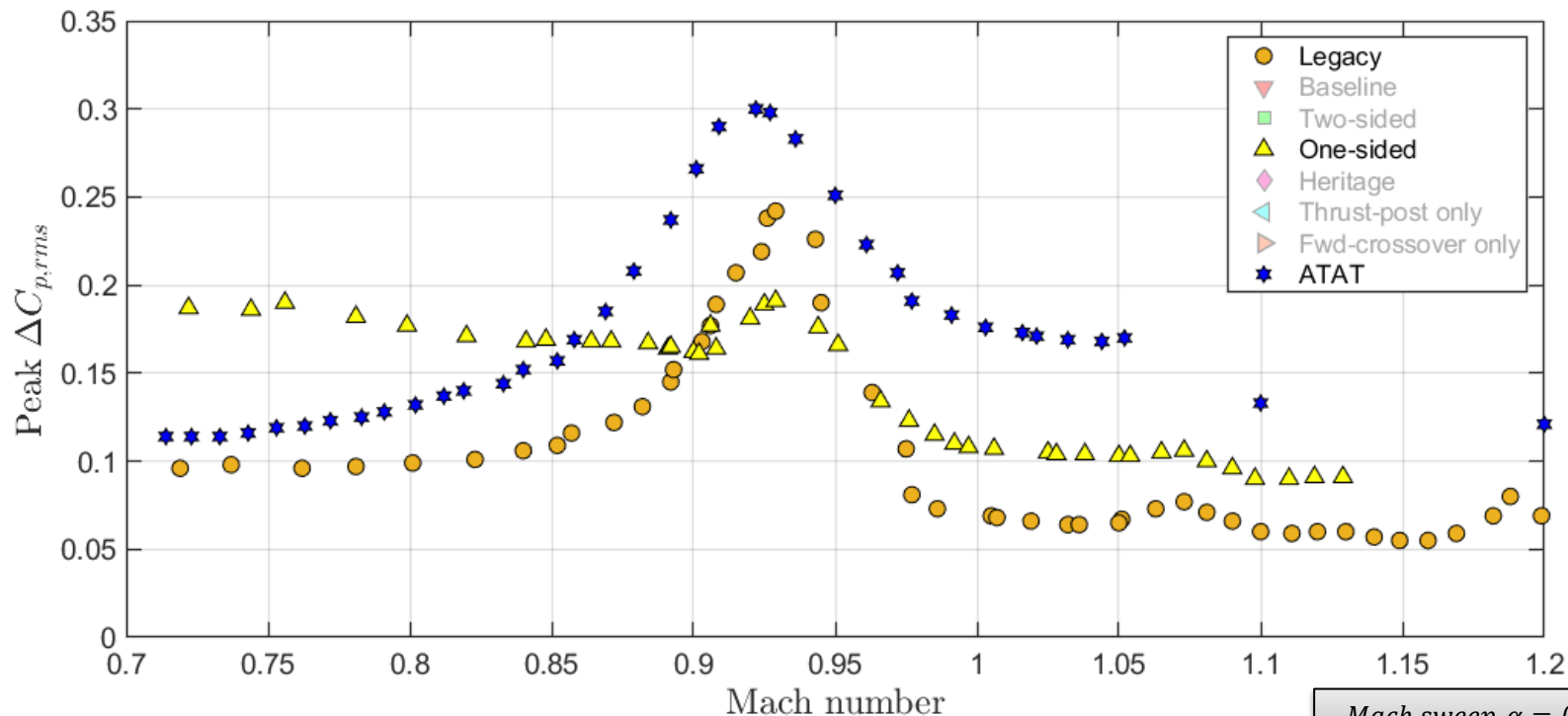


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BFASTST configurations maximum core $\Delta C_{p,rms}$, One-Sided

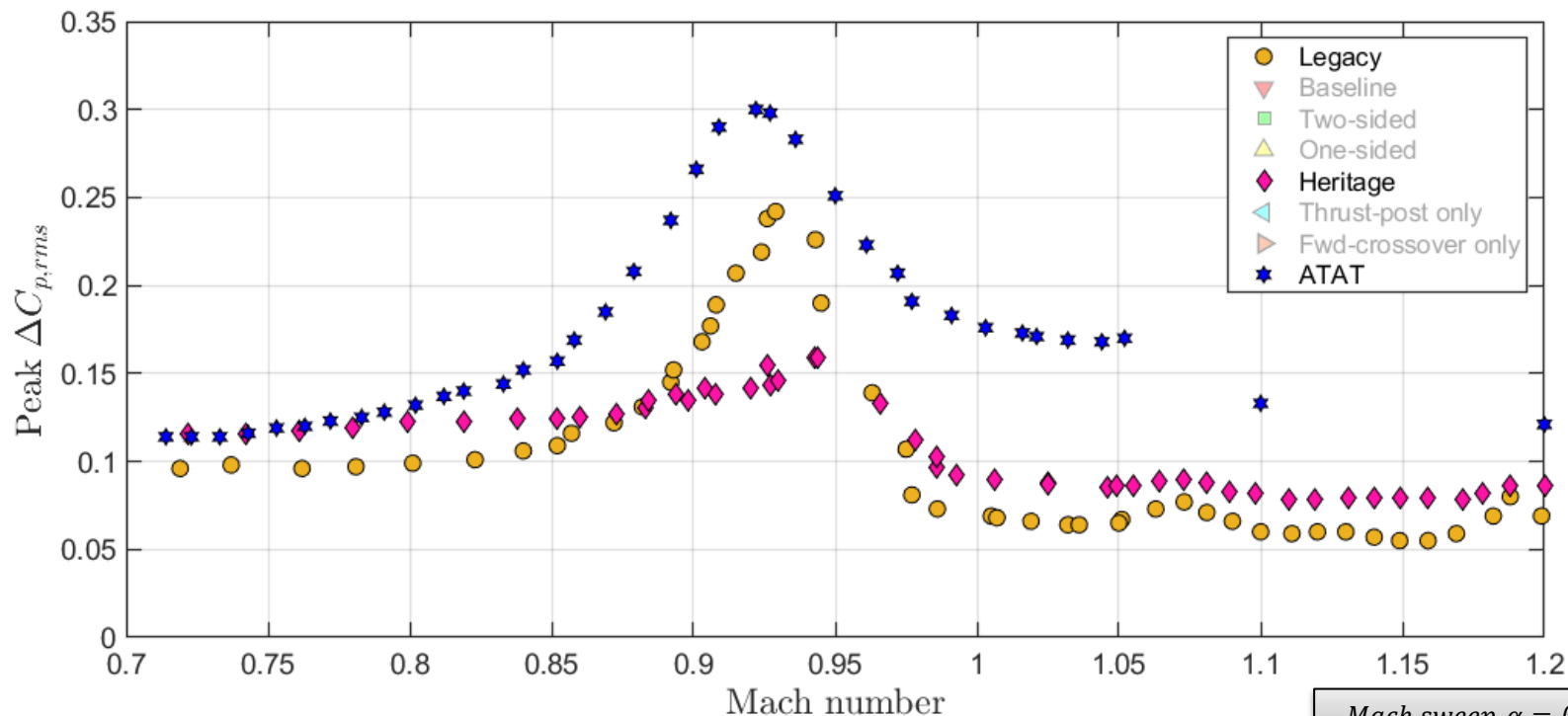
- One-Sided has lower peak maximum $\Delta C_{p,rms}$ magnitudes, but has relatively high magnitudes at lower Mach numbers





BFASTST configurations maximum core $\Delta C_{p,rms}$, Heritage

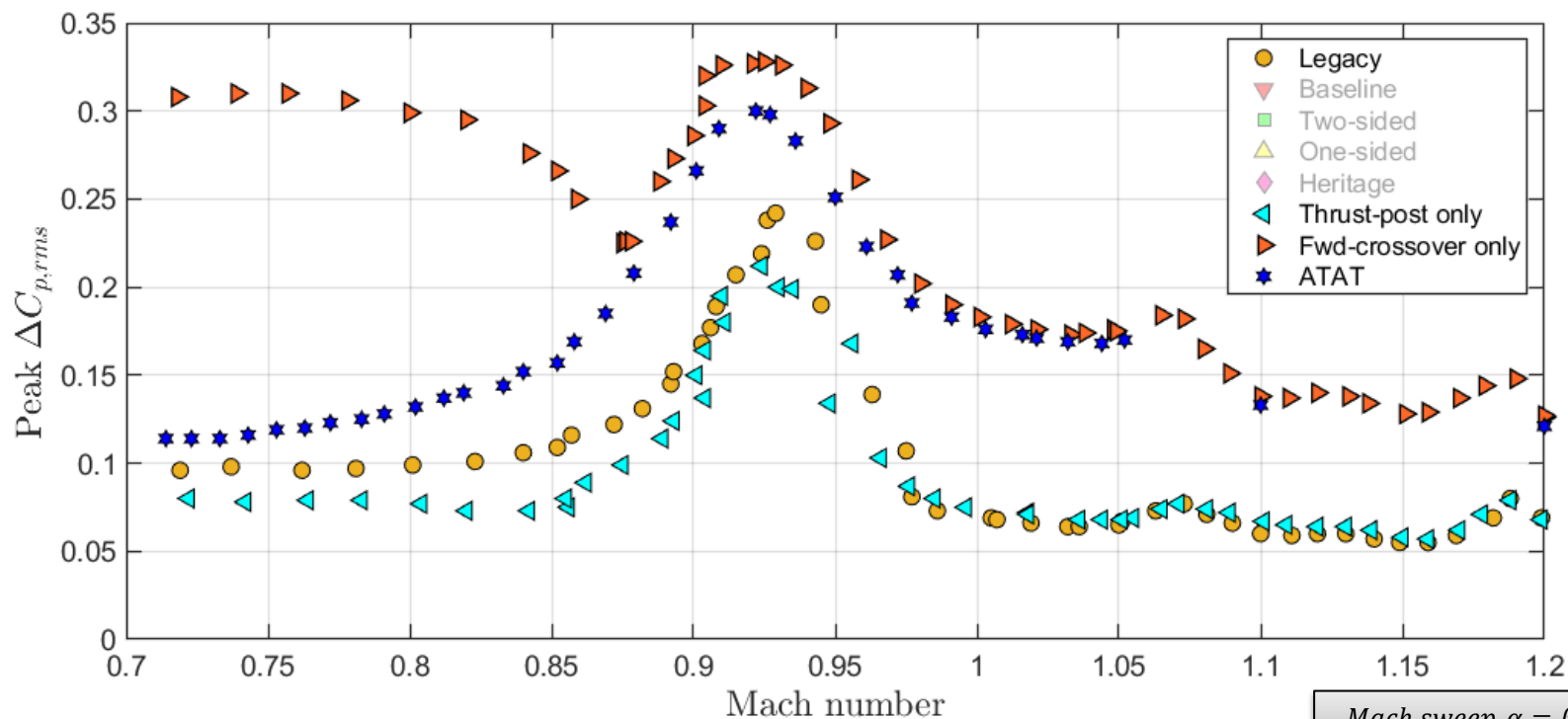
- **Heritage has the lowest maximum $\Delta C_{p,rms}$ of the Candidate configurations**
 - Concerns about missing the peak due to sensor density





BFASTST configurations maximum core $\Delta C_{p,rms}$, Research

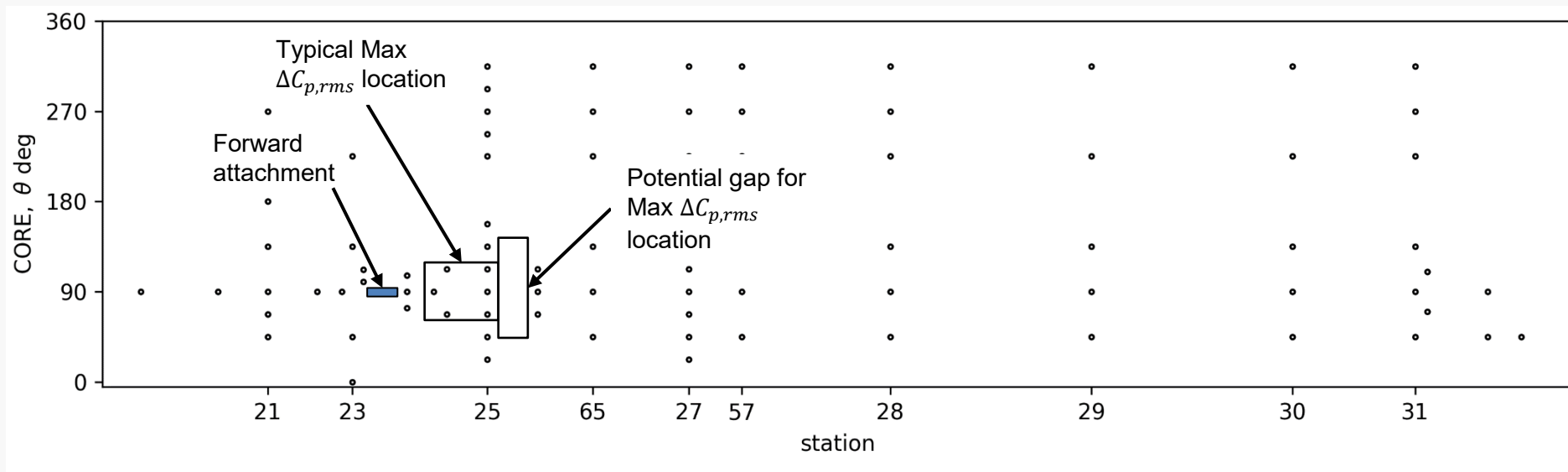
- Thrust-post-Only has lower peak maximum $\Delta C_{p,rms}$
- Fwd-Crossover-Only has the highest peak maximum $\Delta C_{p,rms}$; dip due to sensor density





Missed $\Delta C_{p,rms}$ peaks – core sensor layout

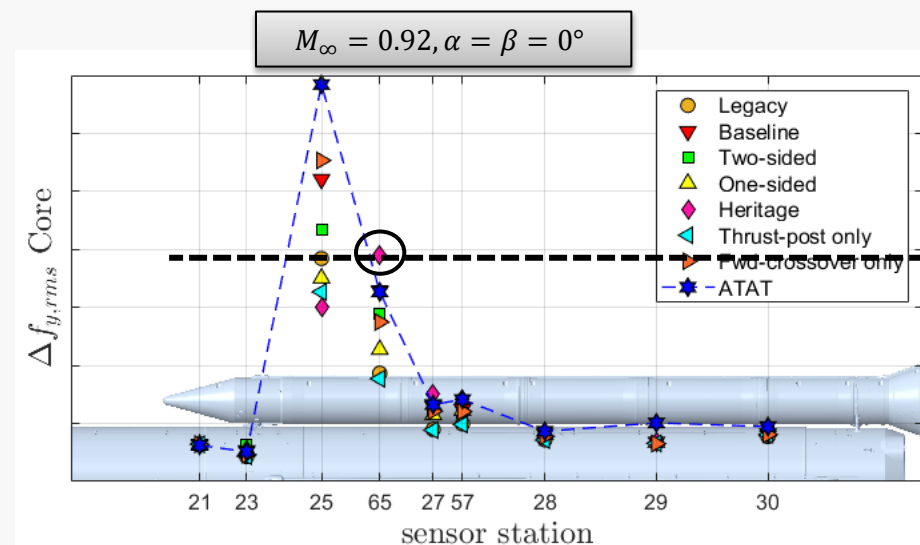
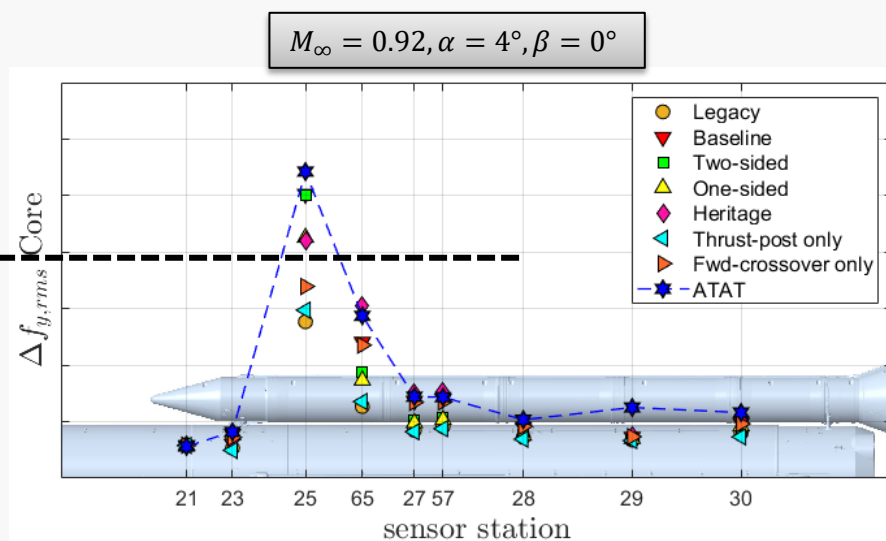
- All geometries have some sensitivity to longitudinal location of $\Delta C_{p,rms}$ with respect to Mach number
 - Since the core was not modified between tests, could not target specific locations downstream of the forward attachment





BFASTST configurations core $\Delta f_{y,rms}$

- Most designs experience higher peak $\Delta f_{y,rms}$ than the Legacy configuration when considering both $\alpha = 0^\circ$ and $\alpha = 4^\circ$ (only Thrust-Post-Only is lower)
- Heritage peak $\Delta f_{y,rms}$ could be between stations 25 and 65
 - $\Delta f_{y,rms}$ at station 65 exceeds even ATAT $\Delta f_{y,rms}$
 - Heritage has the highest levels downstream of forward attachment





General test observations

- **Lower $\Delta C_{p,rms}$ and $\Delta f_{yz,rms}$ magnitudes from the Thrust-Post-Only configuration suggest that the thrust-post reduces buffeting levels, or at a minimum does not increase buffeting**
- **Significant $\Delta C_{p,rms}$ and $\Delta f_{yz,rms}$ magnitudes from Fwd-Crossover-Only and Baseline suggest crossover width is a key parameter for affecting the magnitude and frequency of the fluctuating pressure environment**
- **Sensor placement played a large role in detecting fluctuating pressure environments and peak levels could have been missed for several of the configurations**



Conclusions

- **Presented a parametric study of forward attachment hardware geometry for the BOLE SLS booster**
- **Described the test campaign, including model development, forward attachment hardware, instrumentation, and test matrix**
- **Examined test results against a previously conducted test to establish a baseline comparison**
- **Evaluated the forward attachment geometries against the established reference case to assess not only viable designs, but provide observations on specific components of the forward attachment**



Questions

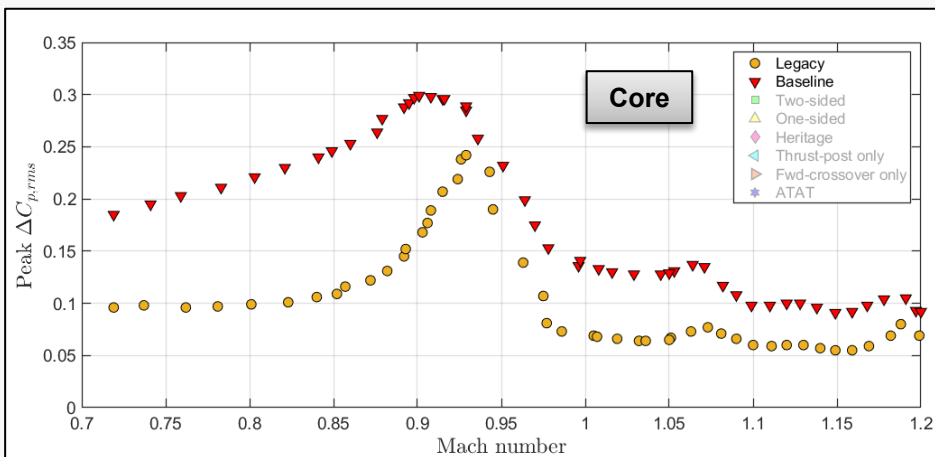
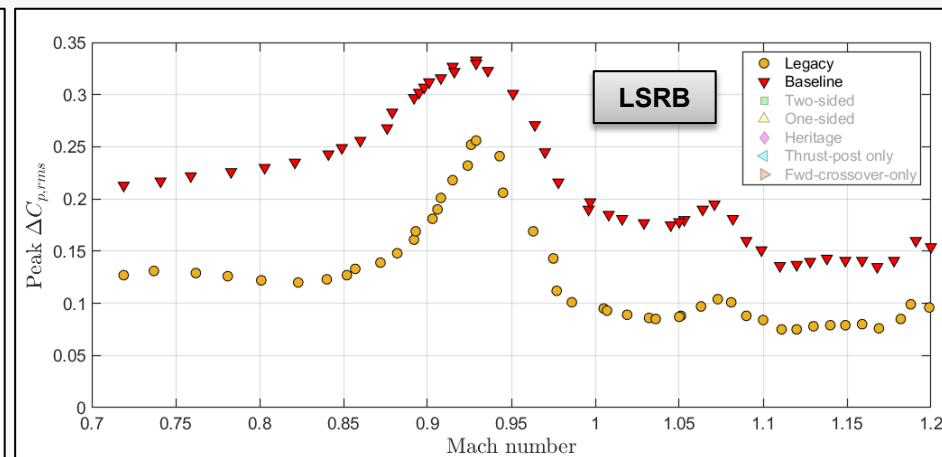


Backup



BFASTST configurations maximum $\Delta C_{p,rms}$ body comparison

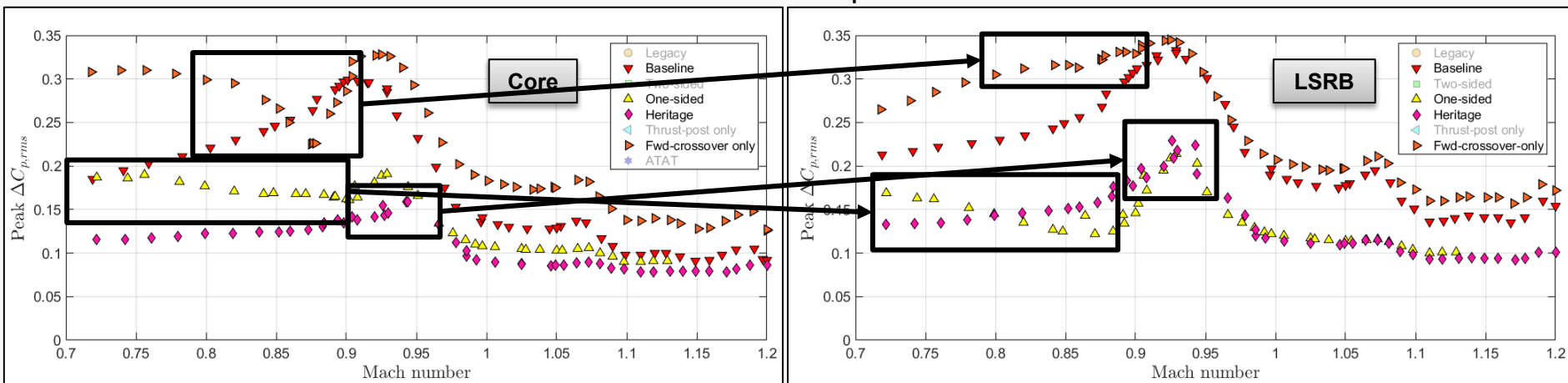
- All configurations follow approximately the same trends on Core and LSRB
 - Peak between $M_\infty = 0.92 - 0.94$
 - Drop off past $M_\infty = 0.98$
- LSRB levels are higher overall than the core due to sensor density





BFASTST configurations maximum $\Delta C_{p,rms}$ body comparison

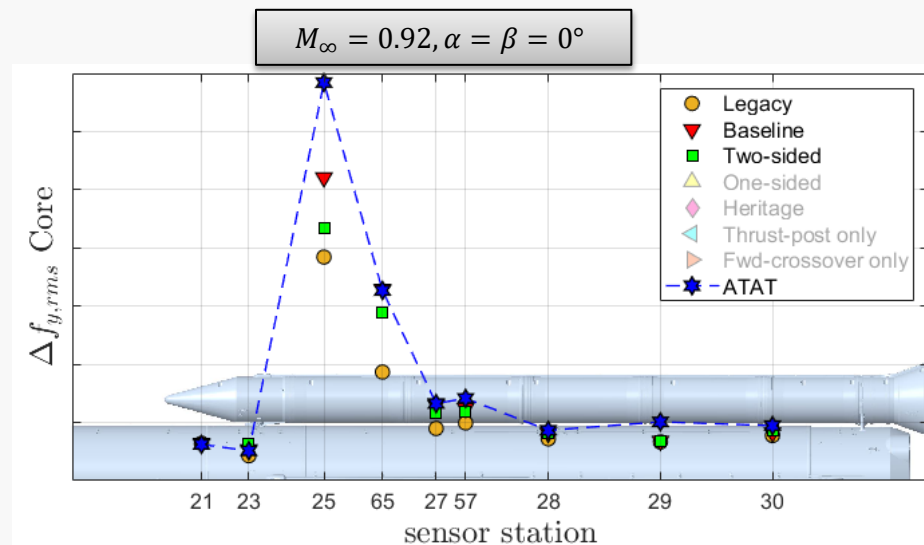
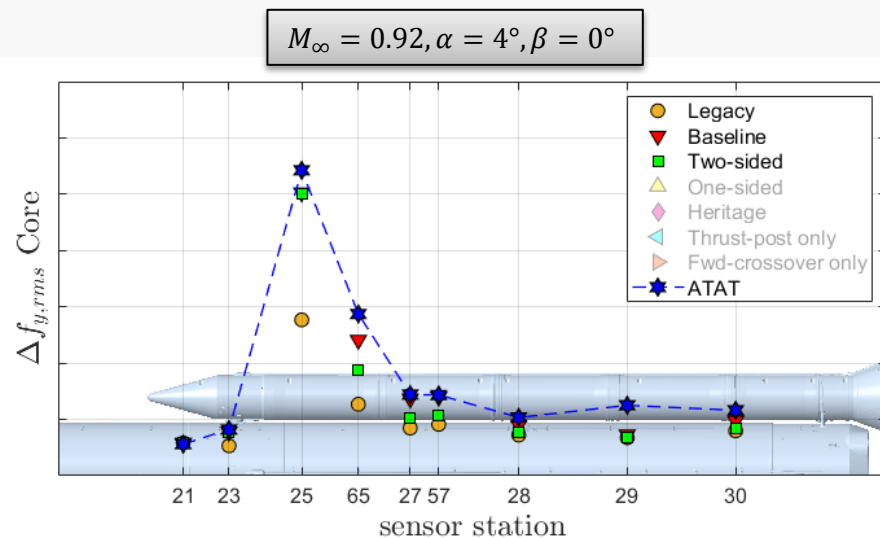
- All configurations follow approximately the same trends on Core and LSRB
 - Peak between $M_\infty = 0.92 - 0.94$
 - Drop off past $M_\infty = 0.98$
- LSRB levels are higher overall than the core due to sensor density
- Do not see “missed” maximum $\Delta C_{p,rms}$ characteristics
 - Fwd-Crossover-Only dip
 - Heritage lower peak
 - One-Sided elevated lower Mach characteristic still present





BFASTST configurations core $\Delta f_{y,rms}$

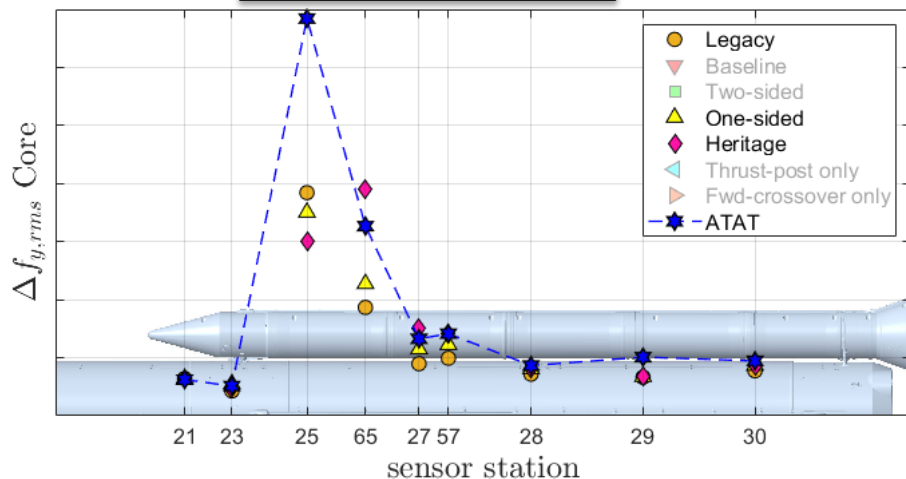
- Focus on response in lateral direction sectional forces, $\Delta f_{y,rms}$, at the peak conditions on the core, $M_\infty = 0.92$ at $\alpha = \beta = 0^\circ$ and $\alpha = 4^\circ, \beta = 0^\circ$
- Baseline and Two-Sided have higher $\Delta f_{y,rms}$ than Legacy
 - Consistent for both attitudes



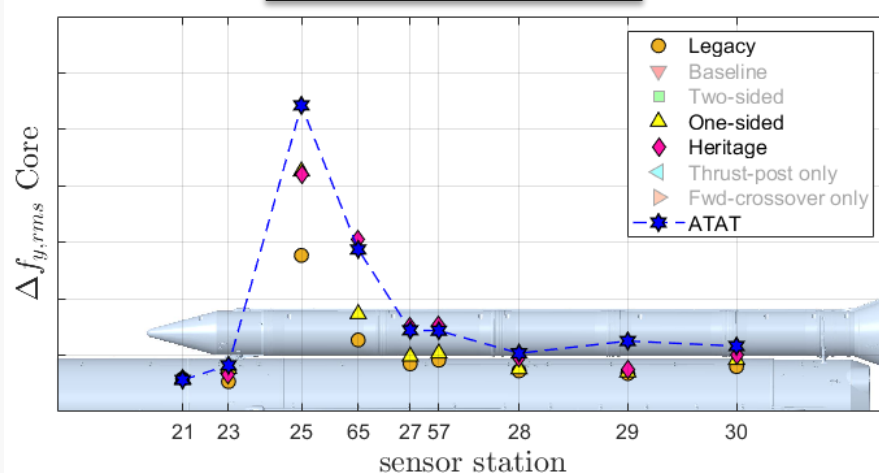
BFASTST configurations core $\Delta f_{y,rms}$ (cont'd)

- One-Sided and Heritage peak $\Delta f_{y,rms}$ similar at $\alpha = \beta = 0^\circ$ but higher at $\alpha = 4^\circ, \beta = 0^\circ$
- Heritage peak $\Delta f_{y,rms}$ could be between stations 25 and 65
 - $\Delta f_{y,rms}$ at station 65 exceeds even ATAT $\Delta f_{y,rms}$
 - Heritage has the highest levels downstream of forward attachment
 - These results coupled with the $\Delta C_{p,rms}$ could indicate a missed peak

$M_\infty = 0.92, \alpha = \beta = 0^\circ$



$M_\infty = 0.92, \alpha = 4^\circ, \beta = 0^\circ$

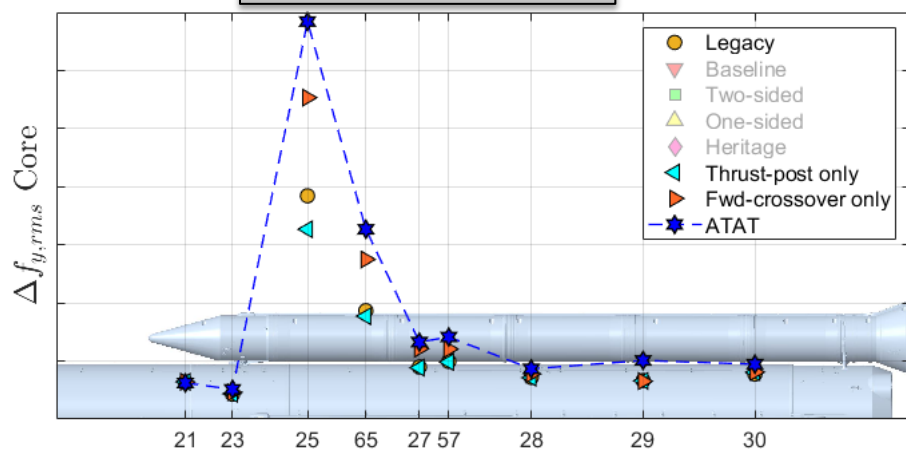




BFASTST configurations core $\Delta f_{y,rms}$ (cont'd)

- **Research Configurations consistent with $\Delta C_{p,rms}$ results**
 - Thrust-Post-Only generally has the lowest $\Delta f_{y,rms}$ longitudinally down the vehicle
 - Fwd-Crossover-Only has the highest $\Delta f_{y,rms}$

$M_\infty = 0.92, \alpha = \beta = 0^\circ$



$M_\infty = 0.92, \alpha = 4^\circ, \beta = 0^\circ$

