An Efficient Approach to Collect Inlet Characterization Data

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Outline

- Motivation
- Background
- Data Reduction
- Results
- Summary

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- **Motivation**
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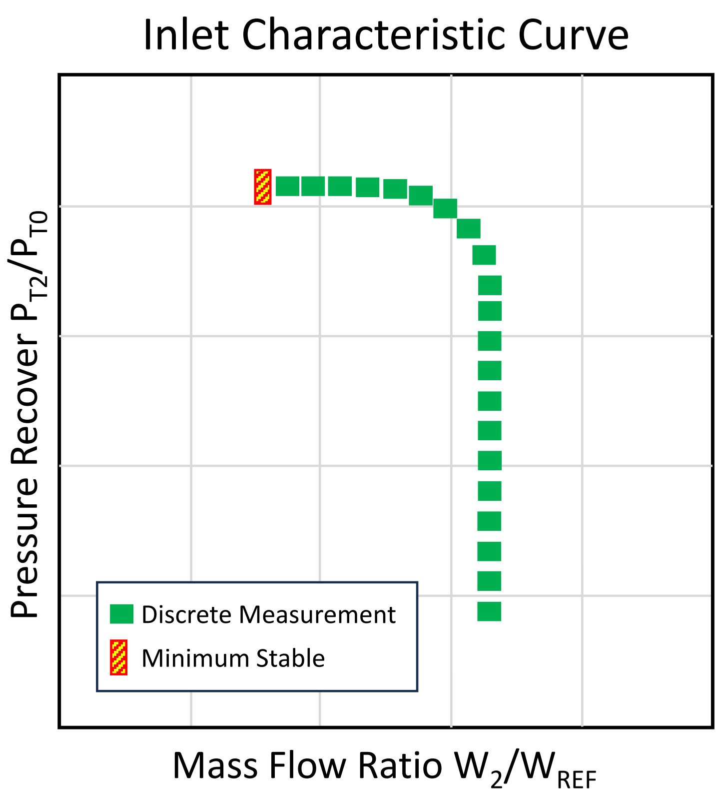
Traditional Method of Inlet Characterization

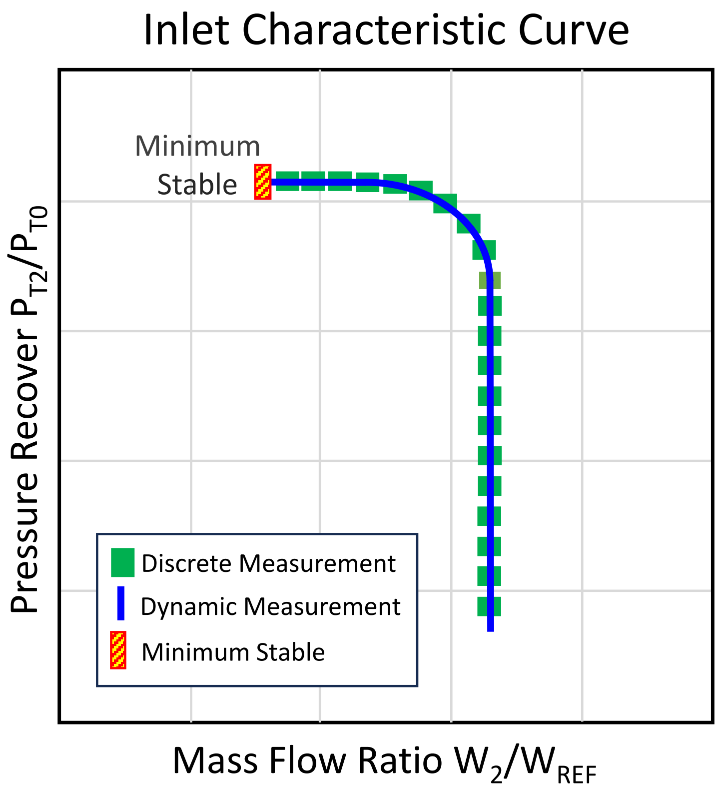
During supersonic wind tunnel experiments, actuators for inlet propulsion test articles are typically moved in discrete increments for measurement recordings that are very accurate, but slow and therefore costly.

- Move actuator to position.
- Pause to allow airflow pressure oscillations to diminish.
- Record quasi steady-state pressure measurements with electronic scanned pressure (ESP) transducers.
- Repeat…



Proposed Method of Inlet Characterization

- Use continuous (dynamic) actuator movement for faster and thus less costly measurement recordings.
  - Record pressure data as the actuator continuously moves, without stopping, through all actuator positions.
  - Within a shorter duration than necessary to measure one discrete data point, all data acquired by way of discrete process (and more) is acquired.
- However, there is a need to understand the value (accuracy and repeatability) of the dynamic measurements.
- To understand the trade-offs for moving from the previously accepted method to the proposed method, an initial study was continued and expanded using experimental wind tunnel data.



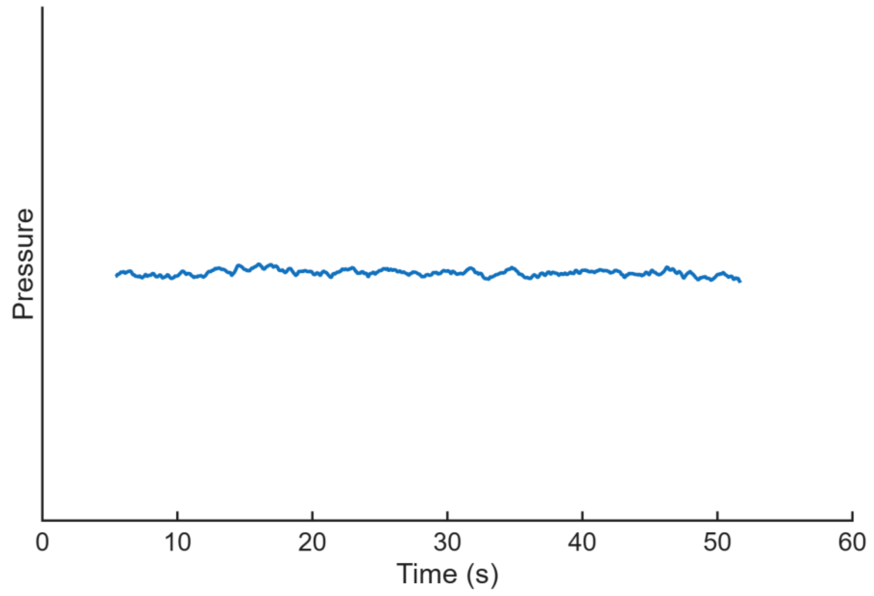
Study Approach

The study examined:

- "Flat" data agreement. Flat in reference to how the data appears graphically over a short period.
- Influence of the rate of mass flow plug (MFP) movement.
- Measurement Uncertainty.
- Effectiveness of candidate process enhancements.
  1. Rudimentary (no enhancement)
  2. Sensor Data Qualification
  3. In situ Coefficient Recalibration

More on these to follow…

Example of Flat Data



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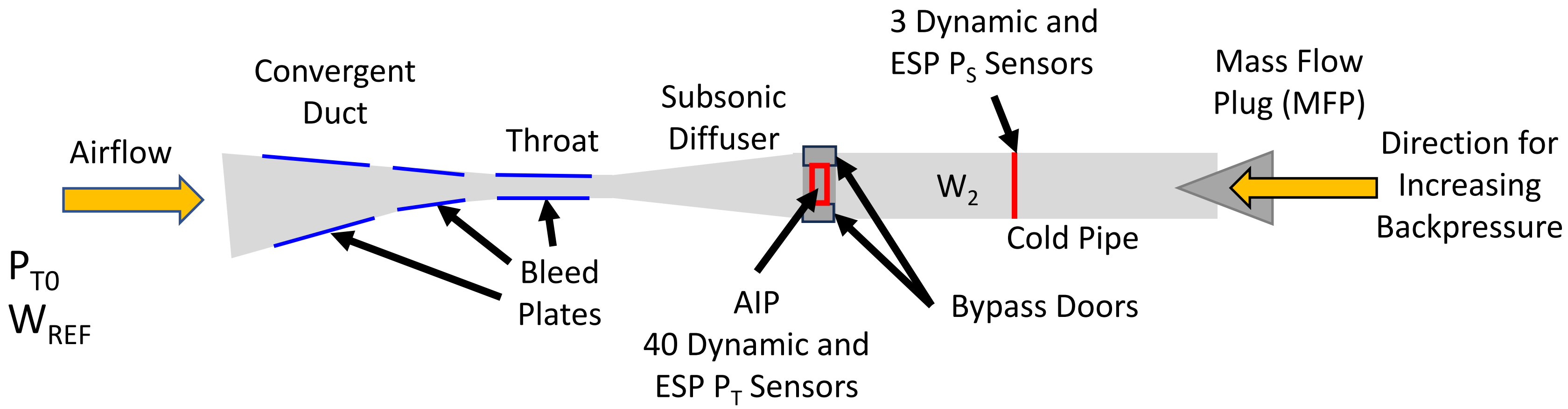
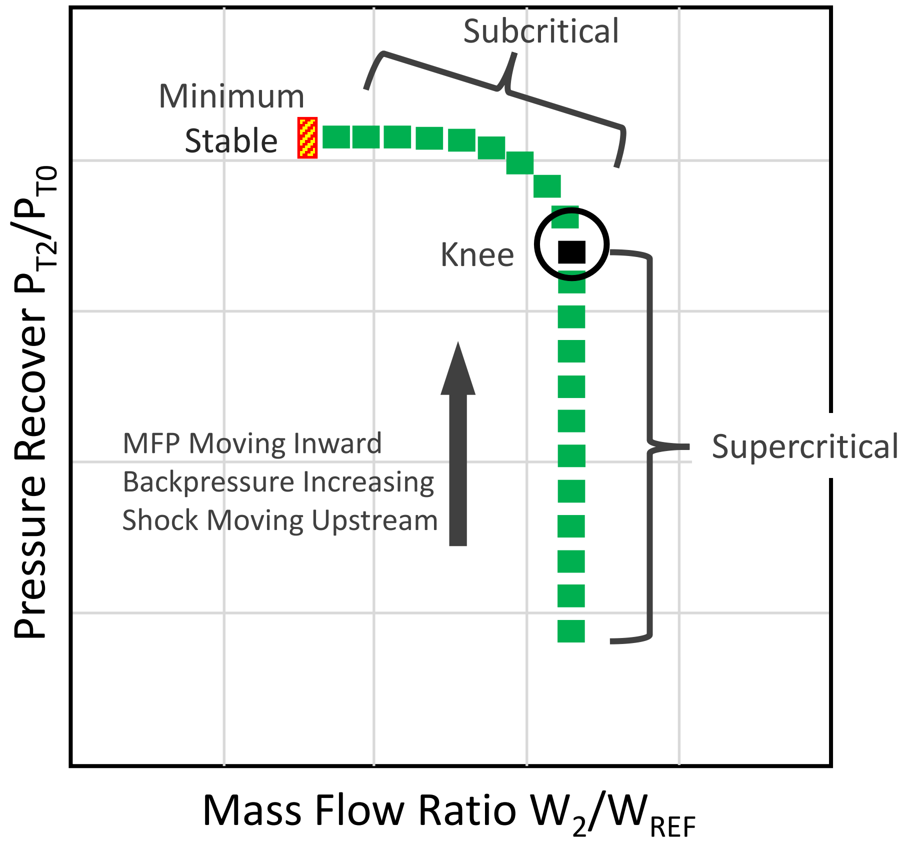
Wind Tunnel Experiments

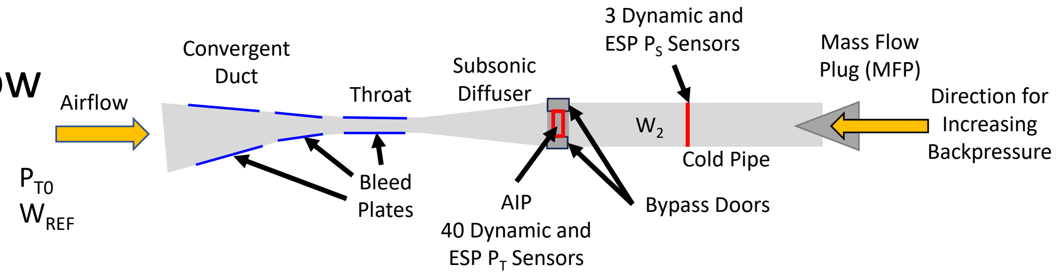
- Conducted in the NASA Glenn Research Center Abe Silverstein 10- by 10- Foot Supersonic Wind Tunnel (SWT).
- Focus was on a mixed-compression inlet system flow path.
- Relevant Actuators:
  - Mass Flow Plug – Adjusts backpressure in the subsonic diffuser.
  - Bypass Doors – Vents subsonic airflow to freestream.
- Relevant Sensors:
  - Total pressure recovery at the Aerodynamic Interface Plane (AIP).
    - 40 Prati probes – ESP and dynamic pressure sensors co-located.
  - Cold-pipe static pressures for calculated corrected airflow based on calibrated MFP position.
    - 3 static mounted ESP sensors.
    - 3 static mounted dynamic pressure sensors.



Inlet Characteristic Curves or “Cane” Curves

- Indicates inlet performance at steady-state freestream conditions and inlet geometries.
- Plots inlet pressure recovery versus mass capture ratio.
  - P_{T2} – Diffuser total pressure at AIP.
    - Average of 40 ESP sensors in Prati probes over a 5-second period.
    - Average of 40 dynamic sensors in Prati probes.
  - P_{T0} – Freestream total pressure.
  - W_2 – Cold pipe mass flow at AIP.
    - Calculated from average of 3 ESP sensors over a 5-second period.
    - Calculated from average of 3 dynamic sensors.
  - W_{Ref} – Reference airmass captured.
- Phases:
  - Supercritical – Normal shock in diffuser.
  - Knee – Normal shock over throat bleeds.
  - Subcritical – Maximum recovery.
  - Minimum Stable – Slight decrease in mass flow ratio will cause a buzz condition.

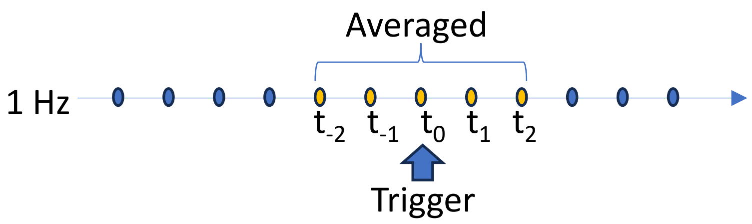




Traditional Method, Proposed Method

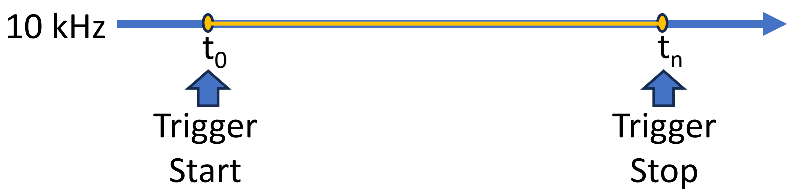
Data Acquisition

- Discrete Measurement System
  - Used low-frequency ESP sensors at aft end of tubes with front end mounted in airflow path.
  - Because of tubes, recorded quasi-steady-state data after pressure oscillations dampened.
  - Recorded all pressure and actuator positions.



- Slow Dynamic Recorder
  - Recorded at 200 Hz.
  - Used dynamic sensors.
  - Recorded all pressure and actuator positions.

- Fast Dynamic Recorder
  - Recorded at 10 kHz.
  - Used same dynamic sensors as slow dynamic recorder.
  - Recorded all pressure and actuator positions.



Data Acquisition

For the dynamic data acquisition systems:

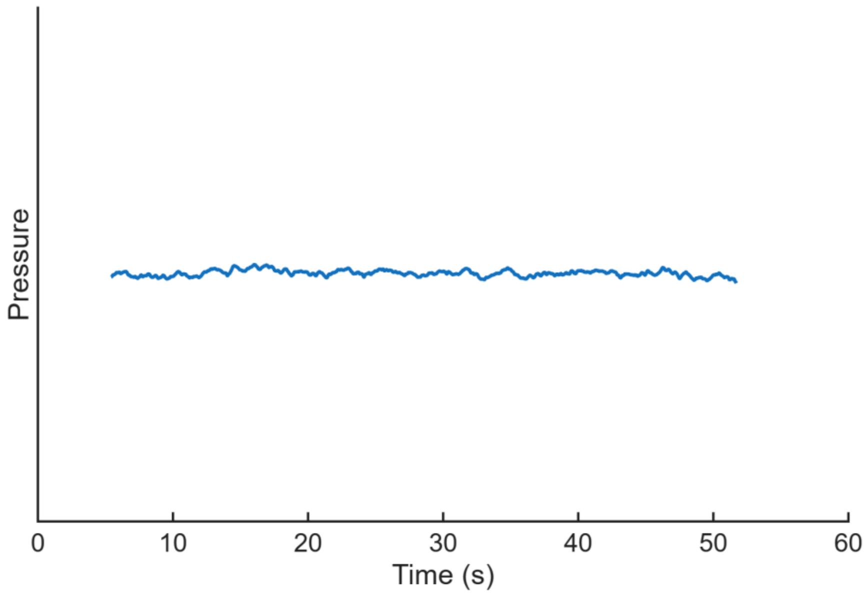
- Pressure transducers converted pressure readings to voltages, which were then transmitted to the respective data acquisition system, converted back to pressure readings and recorded.
- A calibration process determined calibration coefficient terms for each pressure transducer based on wind tunnel test section total temperature of 80° F (cold) and 250° F (hot). The calibration coefficients were the same for each dynamic data acquisition system.
- Data conditioning for each data acquisition system was done independently.

Flat Data

Each time a dynamic data acquisition system was activated, the discrete data acquisition system was also triggered.

- Often, a short duration (i.e., 30-50 seconds) dynamic recording was made while wind tunnel conditions were at steady-state (Flat Data).
- Data recorded on the dynamic system were expected to be quasi-steady-state and were verified to be.
- Data were reduced to a mean value.
- In the analysis, each flat data point was paired with the discrete data point that was recorded with it.
- Flat data from the dynamic data acquisition systems were used to compare against steady-state measurements.
  - Influence of the respective dynamic data acquisition system.
  - Effect of actuator dynamics.

Example of Flat Data



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Data Reduction Overview

- Data acquisition, calibration and recording
- Sensor Data Qualification
- Coefficient Recalibration
- Measurement Uncertainty Analysis

Sensor Data Qualification (SDQ)

- Detects and removes from consideration faulty sensor data.
- The algorithm was applied to two dynamic sensor sets.
    - 3 Cold pipe static pressure sensors.
    - 40 AIP total pressure sensors.
- For the cold pipe pressure sensors, two time-averaged relative error terms were used to compare the pressure readings of a dynamic sensor from two adjacent dynamic sensors, *i+1* and *i-1*, for *n* time steps where *k* represents each incremental time step.

$$E_{i,(i\pm1)} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left(\frac{P_{i\pm1}(k) - P_i(k)}{P_i(k)}\right)^2} \ x\ 100\%$$

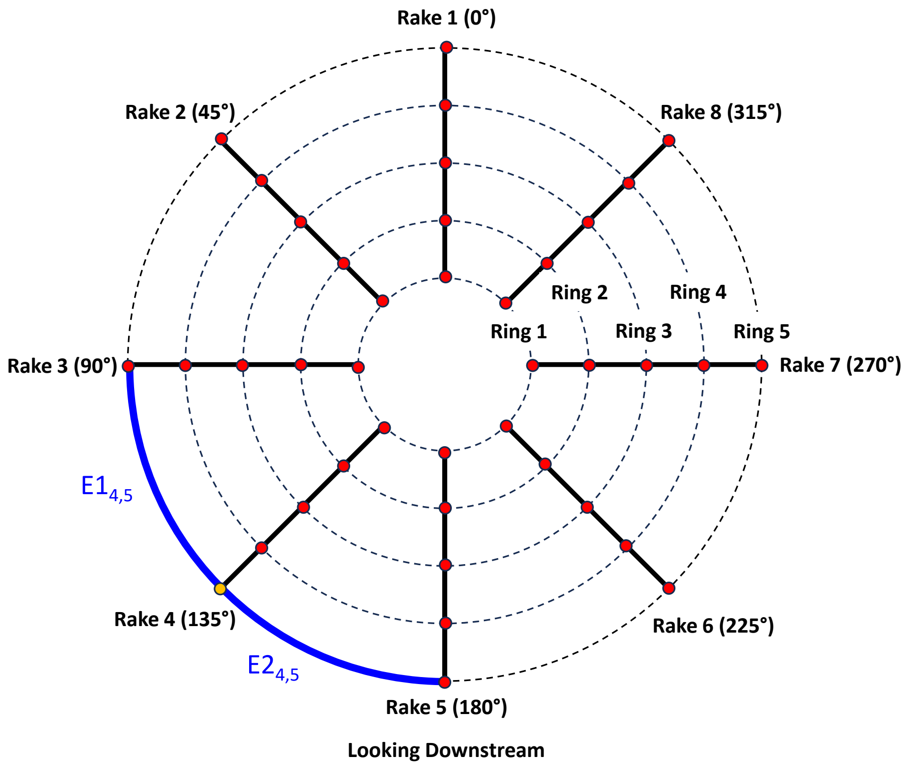
- Sensor was disqualified if both relative error terms were more than 10%.

Sensor Data Qualification (SDQ)

- Likewise for an AIP dynamic sensor on rake *i* and ring *j*, two time-averaged relative error terms were used to compare the pressure readings with two adjacent dynamic sensors, *i-1* and *i+1*, for *n* time steps where *k* represents each incremental time step.
- The sensor was disqualified if both relative error terms were more than 20%.
- The AIP rake sensor threshold for disqualification was higher because of more airflow distortion.

$$E1_{i,j} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left(\frac{P_{i-1,j}(k) - P_{i,j}(k)}{P_{i,j}(k)}\right)^2} \; x\;100\%$$

$$E2_{i,j} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left(\frac{P_{i+1,j}(k) - P_{i,j}(k)}{P_{i,j}(k)}\right)^2} \; x\;100\%$$



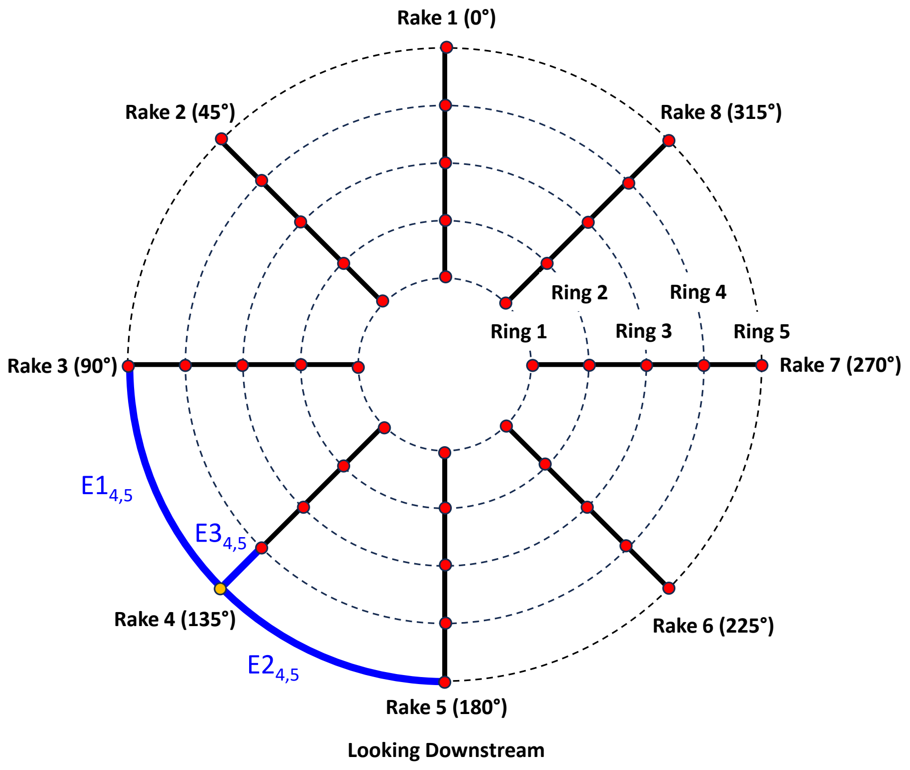
Sensor Data Qualification (SDQ)

- If one relative error term for an AIP sensor was above the threshold while the other was below, then a third evaluation was made using an adjacent sensor on the same rake.

- The adjacent rake sensor selected was the nearest towards the outside unless on Ring 5 in which case the nearest to the inside was selected.

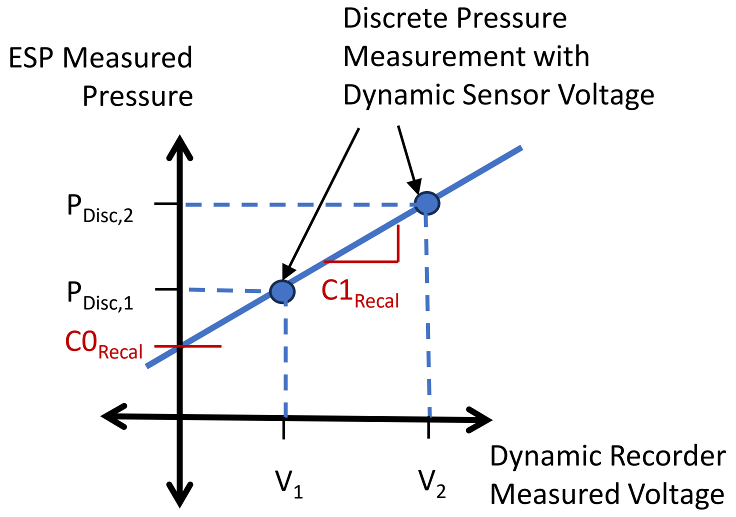
$$E3_{i,j} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left(\frac{P_{i,j+1}(k) - P_{i,j}(k)}{P_{i,j}(k)}\right)^2} \ x\ 100\%$$

- The sensor was disqualified if relative error term was more than 20%.



Coefficient Recalibration

- There were two sets of calibration coefficients for the dynamic pressure sensors.
  - Cold calibration (80° F) coefficients were typically used during tare (no wind) recordings.
  - Hot calibration (250° F) coefficients were typically used during normal wind tunnel operation.
- Two flat data files, recorded during the experiments, were used to generate new calibration coefficients ($C0_{Recal}$, $C1_{Recal}$).
- Hot calibration coefficients were used to determine the sensor voltages, which were then used with the new calibration coefficients ($C0_{Recal}$, $C1_{Recal}$) to determine the recalibrated pressure measurement values.



$$V_i = \frac{(P_{Dyn,i} - C0_{Hot})}{C1_{Hot}}$$

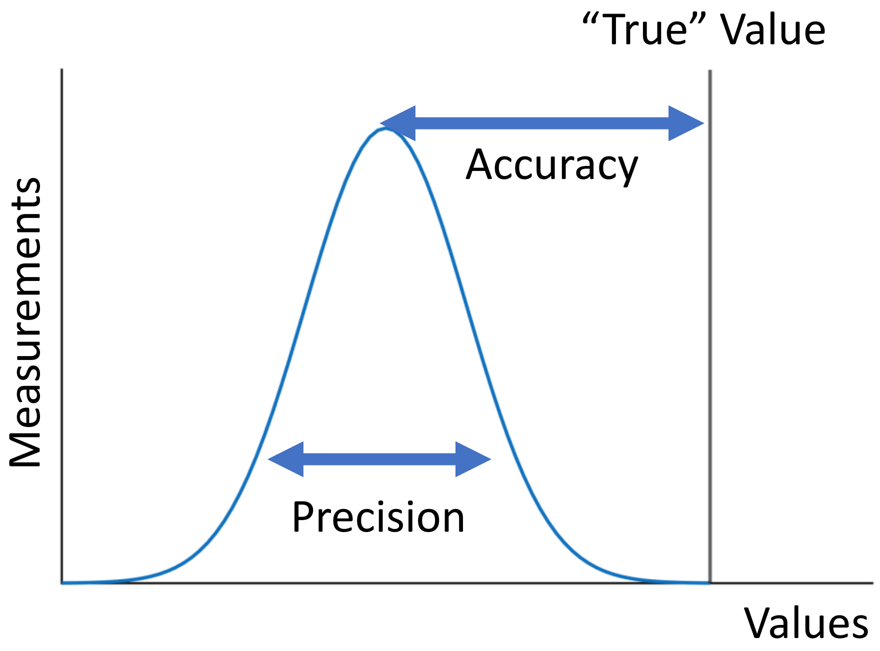
$$C1_{Recal} = \frac{(P_{Disc,2} - P_{Disc,1})}{(V_2 - V_1)}$$

$$C0_{Recal} = P_{Disc,1} - (C1_{Recal} * V_1)$$

$$P_{Recal} = C0_{Recal} + C1_{Recal}(Volts)$$

Measurement Uncertainty

- Measurement Uncertainty was studied to understand the utility of the dynamic measurement process compared to the traditional method.
- **Type A Uncertainties (Random)**
  - Unpredictable fluctuations that cause the measurement to vary positively and negatively.
  - Example sources include environmental effects or electronic noise.
  - Influences precision.
- **Type B Uncertainties (Systematic)**
  - A consistent bias that shifts measurement values in one direction.
  - Example sources include instrument calibration or experiment design.
  - Influences accuracy.



Measurement Uncertainty

- **Standard Deviation ($\boldsymbol{\sigma}$)** – A common measure of uncertainty.

$$\sigma = \sqrt{\frac{1}{(n-1)}\sum(x_i - \bar{x})^2} \quad \text{where } \bar{x} = \sum_{i=1}^{n} \frac{x_i}{n}$$

  In general, adding more samples, n, will improve the estimation accuracy of the mean value, $\bar{x}$, but will have minimal impact on standard deviation.

- **Standard Error or Standard Deviation of the Mean ($\boldsymbol{\sigma_{\bar{x}}}$)** – Calculated values of the mean, $\bar{x}$, will exhibit uncertainty due to random variations contained in the samples, x_i, it is based on. The standard deviation of the mean is:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

Standard Deviation and Standard Deviation of the Mean do not include systematic variations – only random variations.

Measurement Uncertainty Propagation

- Measurement uncertainty values may be mathematically propagated from the measured value through the data reduction process.
- Assuming measurements are **uncorrelated** (independent).
  - Addition

$$\sigma_x = \sqrt{\sigma_A^2 + \sigma_B^2}$$

  - Division

$$\left(\frac{\sigma_X}{X}\right)^2 = \left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 \quad \Rightarrow \quad \sigma_X = X\sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2}$$

Measurement Uncertainty Values

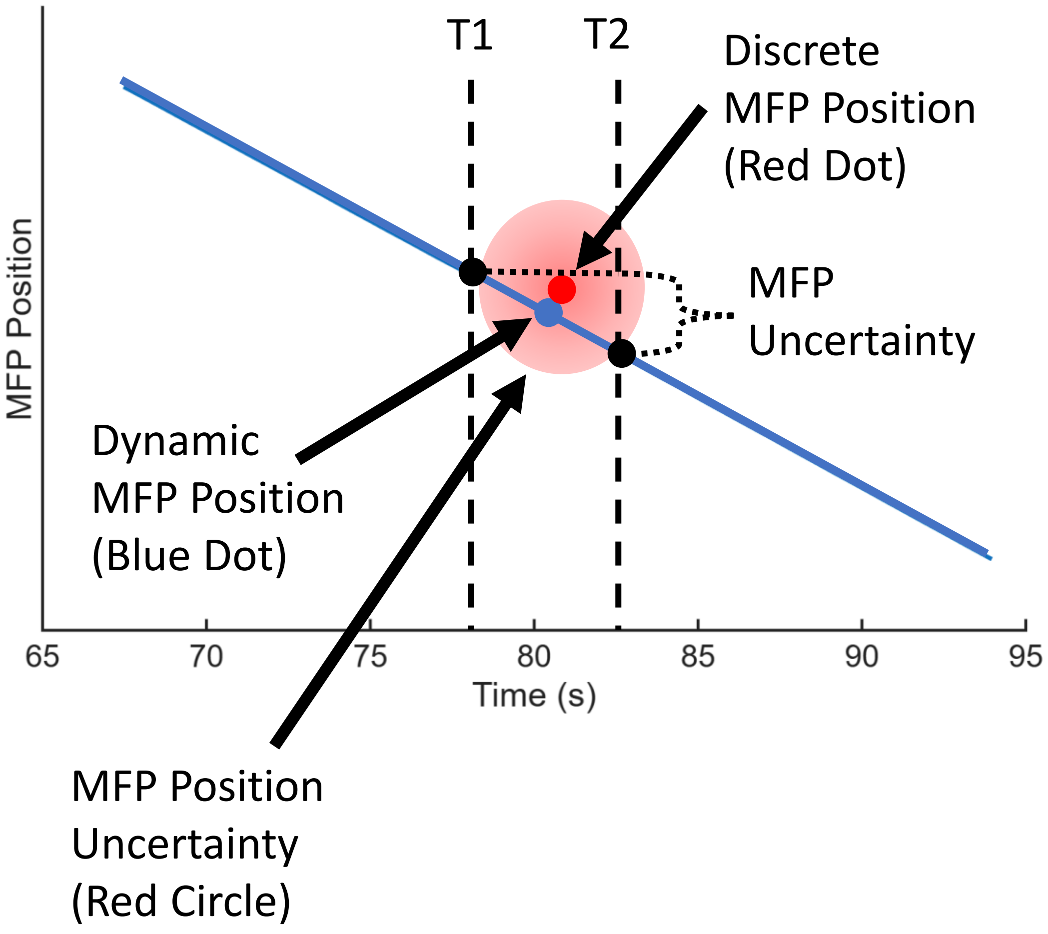
- Systematic uncertainty values were obtained from an analysis using the **M**easurement **AN**alysis **T**ool for **U**ncertainty in **S**ystems (MANTUS) on the Supersonic Wind Tunnel facility.
- The systematic uncertainty included the "instrumentation chain" from the point of measurement through to data acquisition system recording.
- Because mass flow was calculated by an algorithm, a Monte Carlo analysis was performed using the systematic uncertainty distribution of the algorithm inputs to determine its systematic uncertainty.
- Random uncertainty values were obtained from the Dynamic Nearest Neighbor measurement data.

Measurement	Systematic Uncertainty 2σ
Dynamic Pressure	0.15psi
Discrete Pressure	0.015 psi
Temperature	2.93°R
MFP Position	0.031 in
Dynamic Mass Flow	0.25 lbm/s
Discrete Mass Flow	0.06 lbm/s

Dynamic Nearest Neighbor

For each Discrete MFP position (Red Dot):

1. Find the closest Dynamic MFP position.
2. If the closest MFP Dynamic position is within the MFP uncertainty value (0.031 in.) of the Discrete MFP position, assume it is a match.
3. MFP uncertainty is used to define the period of dynamic measurements that are to be compared against discrete position.
4. Within the interval, compute the mean and standard deviation of the mean for P_{T2}, P_{T0}, W_2, and W_{REF}.
   - The mean becomes the Dynamic Nearest Neighbor value for P_{T2}, P_{T0}, W_2, and W_{REF}.
   - The standard deviation of the mean becomes the random component of the uncertainty value for P_{T2}, P_{T0}, W_2, and W_{REF}.



Cane Curve Uncertainty

- For combining the systematic and random uncertainty of P_{T2}, P_{T0}, W_2, and W_{REF} :

$$\sigma_C = \sqrt{\sigma_{Systematic}^2 + \sigma_{Random}^2}$$

- For the ratios in the inlet characterization curve plots:
  - Absolute Pressure Recovery (PR) defined as P_{T2}/P_{To}.

$$\sigma_{PR} = PR\sqrt{\left(\frac{\sigma_{C,PT_2}}{P_{T2}}\right)^2 + \left(\frac{\sigma_{C,PT0}}{P_{T0}}\right)^2}$$

  - Absolute Mass Flow Ratio (MFR) defined as W_2/W_{REF}.

$$\sigma_{MFR} = MFR\sqrt{\left(\frac{\sigma_{C,W2}}{W_2}\right)^2 + \left(\frac{\sigma_{C,WREF}}{W_{REF}}\right)^2}$$

Cane Curve Analysis Summary

1. **Filtering and Down Sampling** – Allows for timely data reduction and analysis of data.
   - Slow Dynamic: Used at the recorded rate of 200Hz.
   - Fast Dynamic: Filtered and down sampled from 10 kHz to 200 Hz.
2. **Sensor Data Qualification** – Identify qualified sensors.
3. **Coefficient Recalibration** – Use recalibrated voltage-to-pressure coefficients ($C0_{Recal}$, $C1_{Recal}$) to improve accuracy.
4. **Mass Flow Calculations** – From an iterative algorithm, compute W_2 from mass flow plug position (X_{mfp}), averaged cold pipe static pressure (P_{cp}), and total temperature (T_T).
5. **Dynamic Nearest Neighbor** – Determine the mean and standard deviation of the mean for the Dynamic variables P_{T2}, P_{T0}, W_2, and W_{REF} within Discrete MFP position uncertainty.
6. **Combine Random and Systematic Uncertainties** – For Dynamic P_{T2}, P_{T0}, W_2, and W_{REF} calculate their combined uncertainty values.

Cane Curve Analysis Summary

7. **Compute Ratios** – Compute Total Pressure Recovery by normalizing P_{T2} by P_{T0} and Mass Flow Ratio by normalizing W_2 by W_{REF}. Compute their uncertainties.
8. **Report Results** – Generate cane curve plots that include measurement uncertainty for the Dynamic nearest neighbors.
9. **Compute Error Term** – An error less than 0.01 was considered good.
   - $\Delta_{W,i}$ is the difference between discrete and dynamic mass flow ratio for discrete data point *i.*
   - $\Delta_{P,i}$ is the difference between discrete and dynamic pressure recovery for discrete data point *i*.

$$error = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\Delta_{w,i}^2 + \Delta_{P,i}^2\right)}$$

For Flat data, this process was repeated. The results were added to the cane curve plots and the error terms were recorded.

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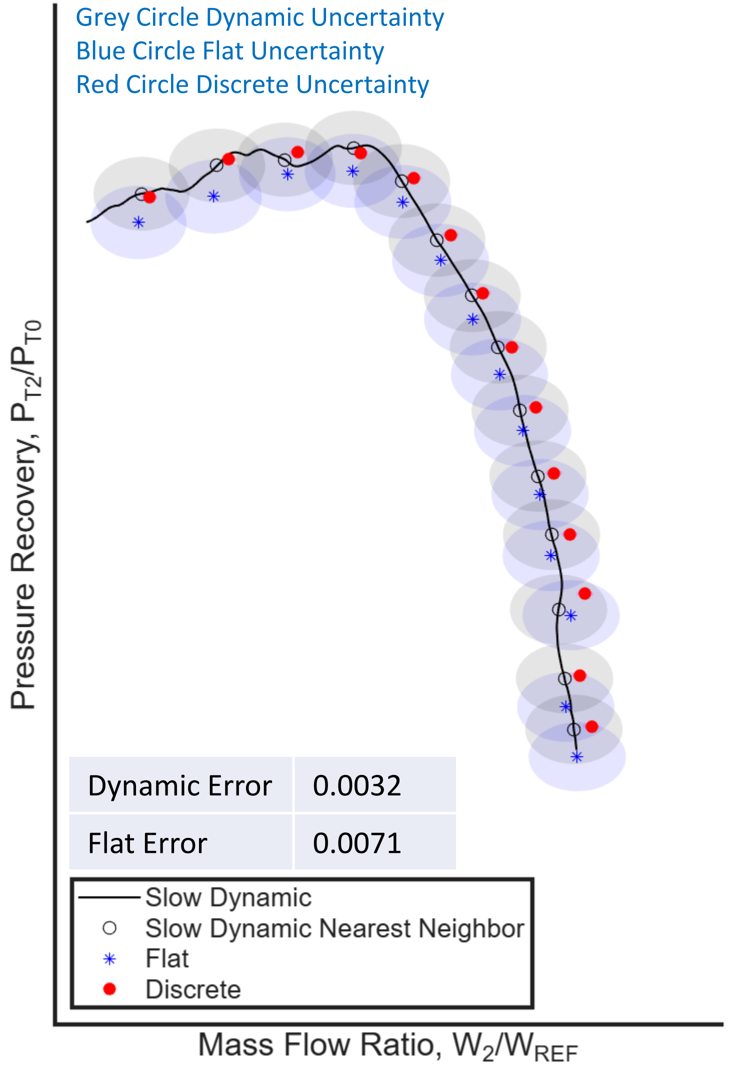
Study Approach

The study examined:

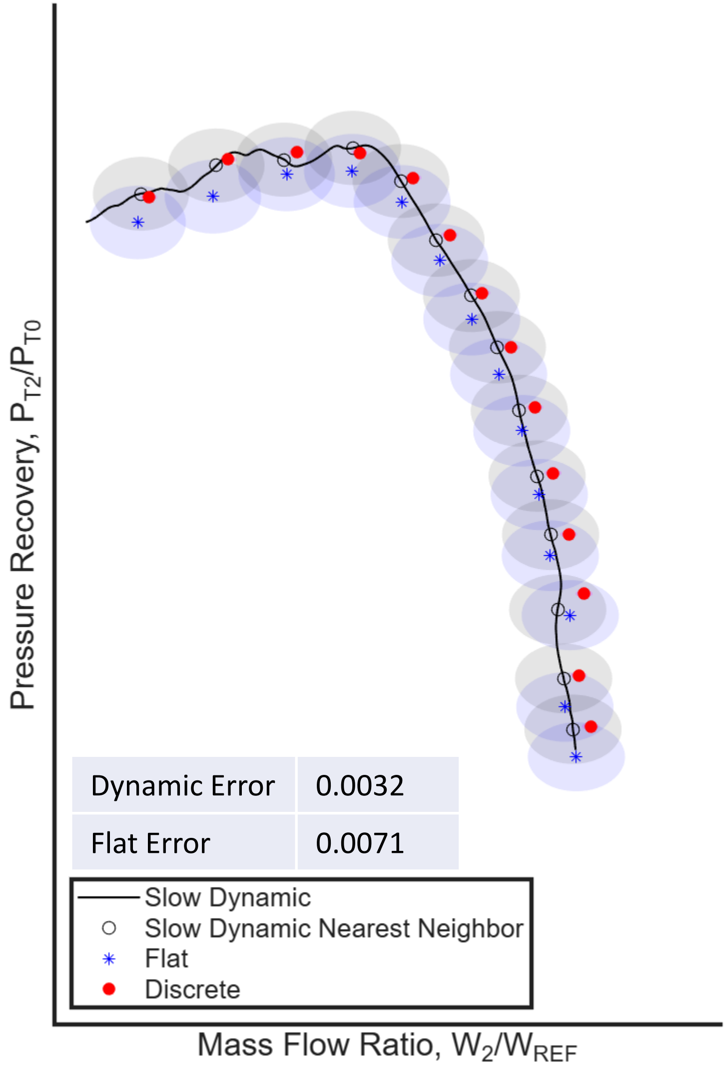
- Dynamic Error: Dynamic nearest neighbor data agreement.
- Flat Error: Flat data agreement.
- Measurement Uncertainty.
- Three rates of MFP movement:
    1. 0.16 in/s
    2. 0.20 in/s
    3. 0.26 in/s
- Process enhancements:
    1. Rudimentary (no enhancement) – To establish a baseline.
    2. Sensor Data Qualification – To identify and remove suspect sensors.
    3. Coefficient Recalibration – To recalibrate each dynamic sensor to its matching ESP sensor (i.e., the closest one).

Slow Dynamic Results for 0.16 in/s Rate of MFP Movement

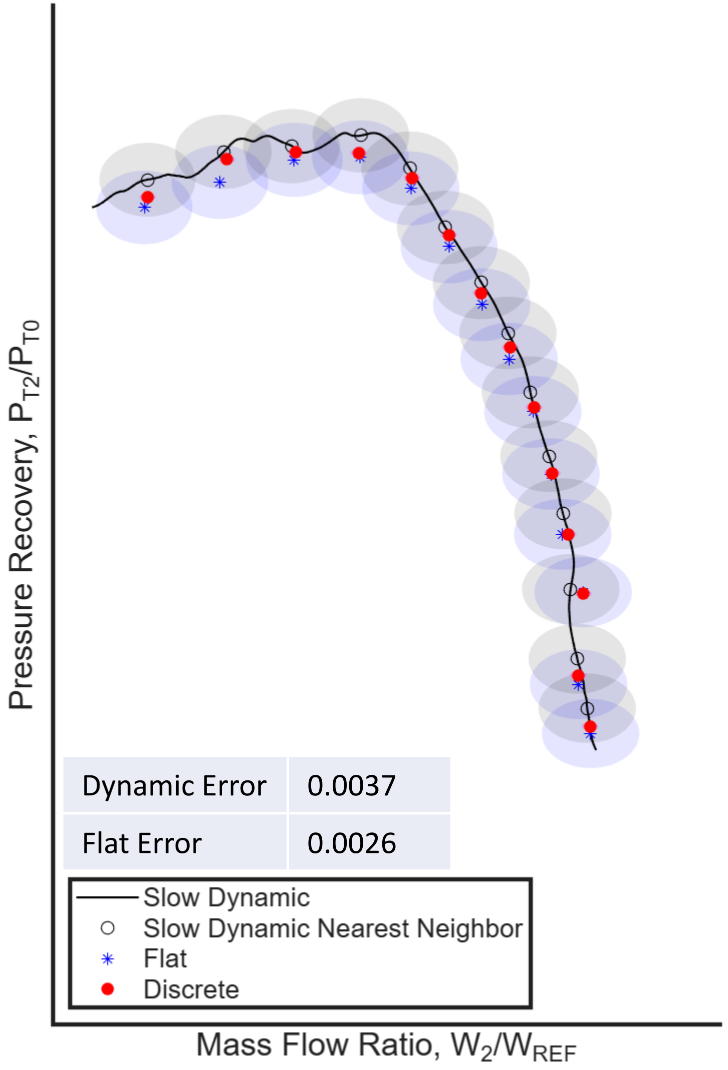
200Hz Slow Dynamic: Rudimentary
MFP Rate: 0.16 in/s



200Hz Slow Dynamic: SDQ
MFP Rate: 0.16 in/s

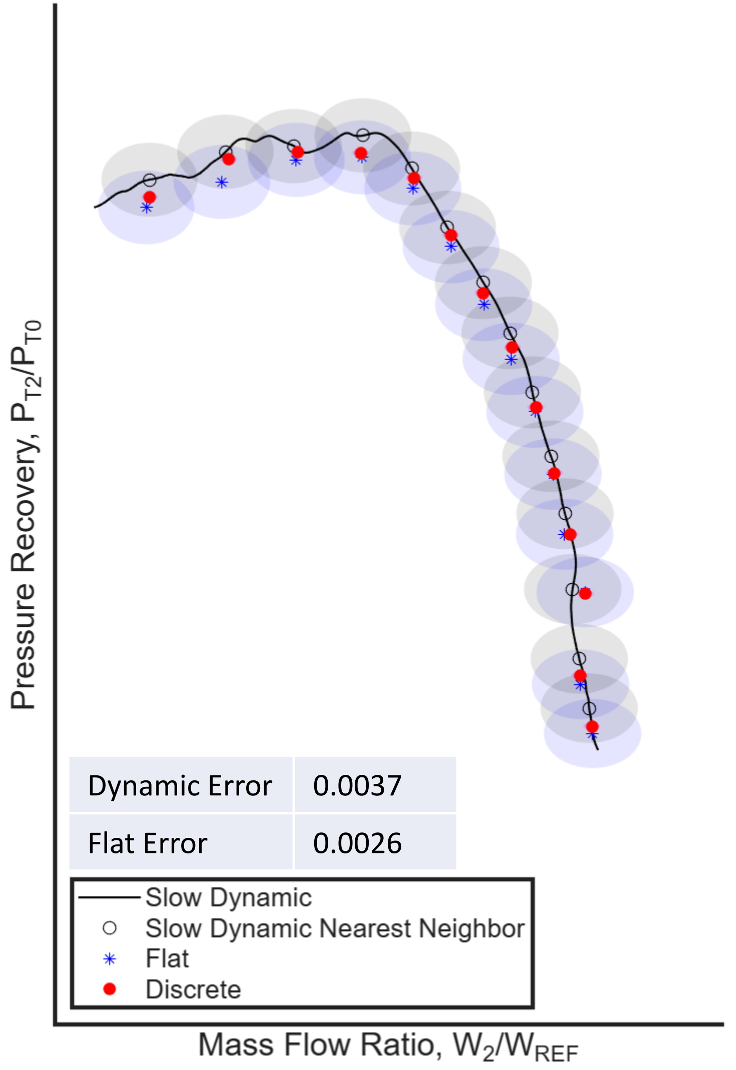


200Hz Slow Dynamic: SDQ, Recalibrate
MFP Rate: 0.16 in/s

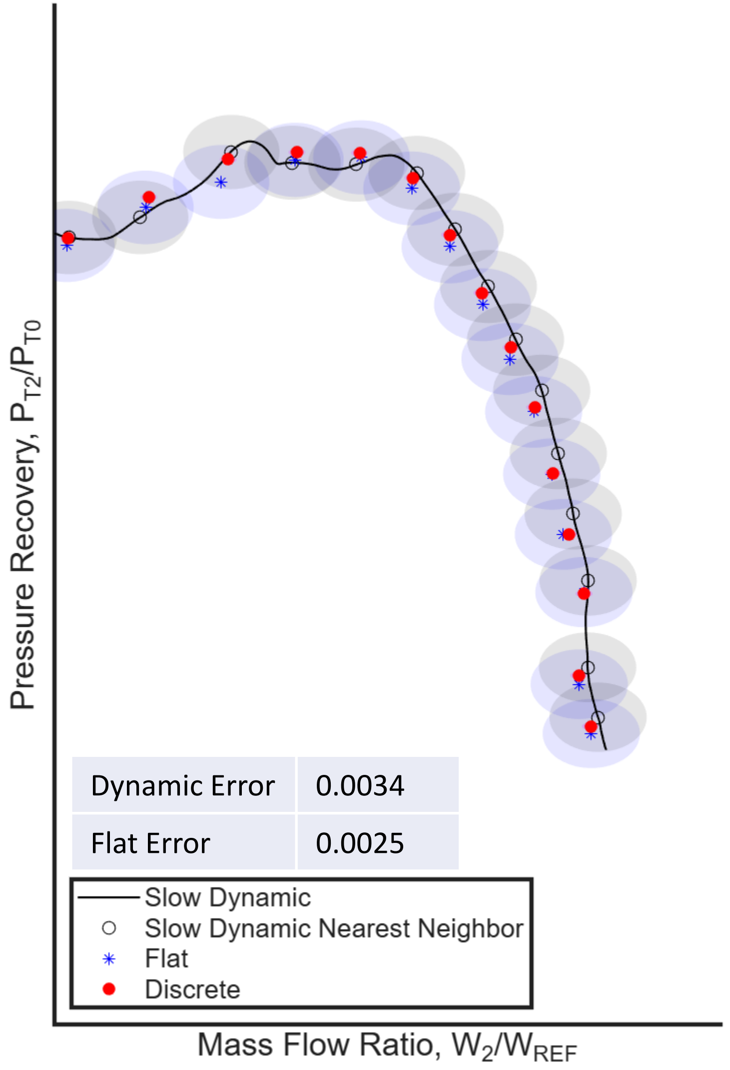


Slow Dynamic Results Summary for Each Rate of MFP Movement

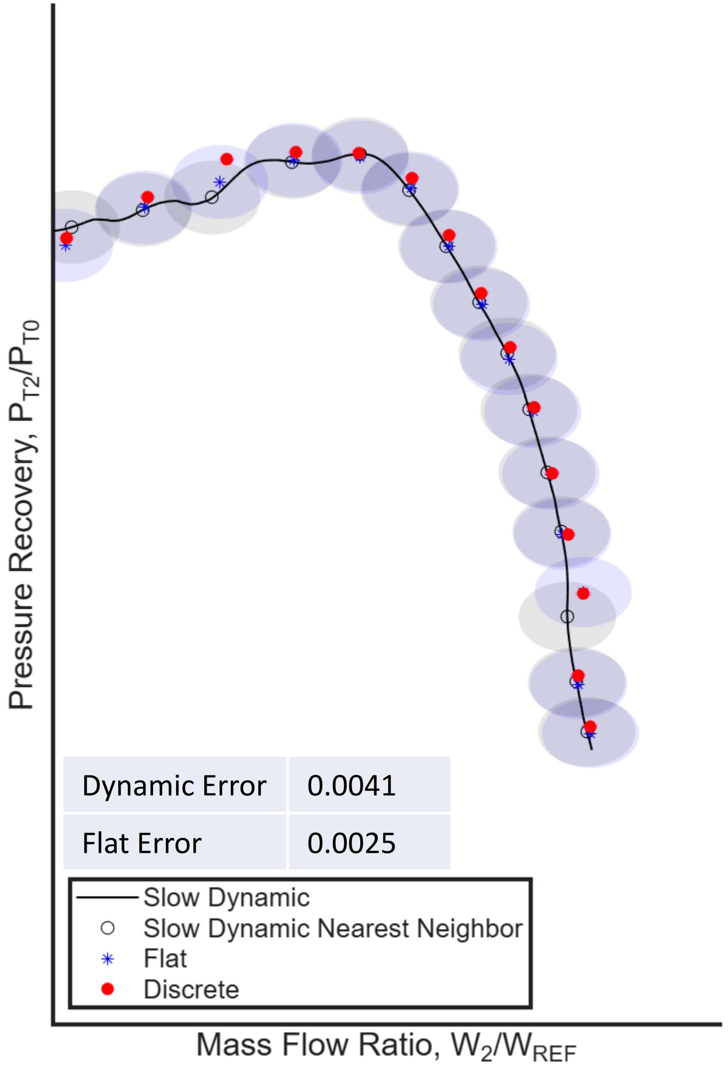
200Hz Slow Dynamic: SDQ, Recalibrate
MFP Rate: 0.16 in/s



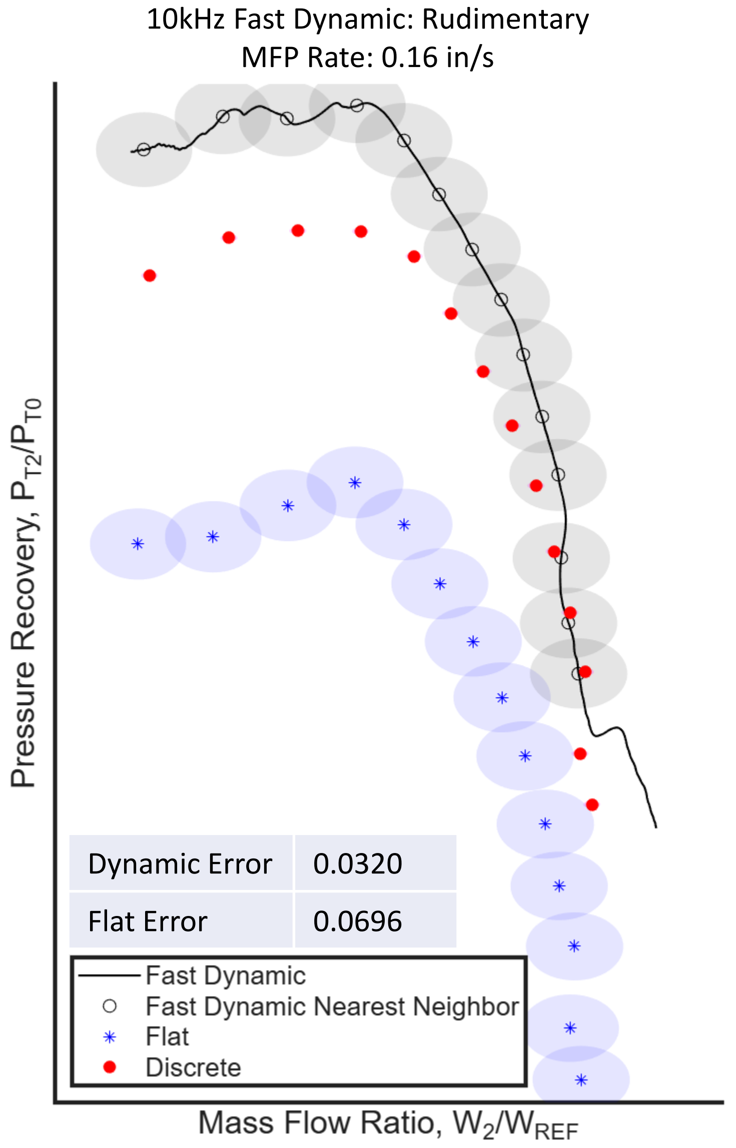
200Hz Slow Dynamic: SDQ, Recalibrate
MFP Rate: 0.20 in/s

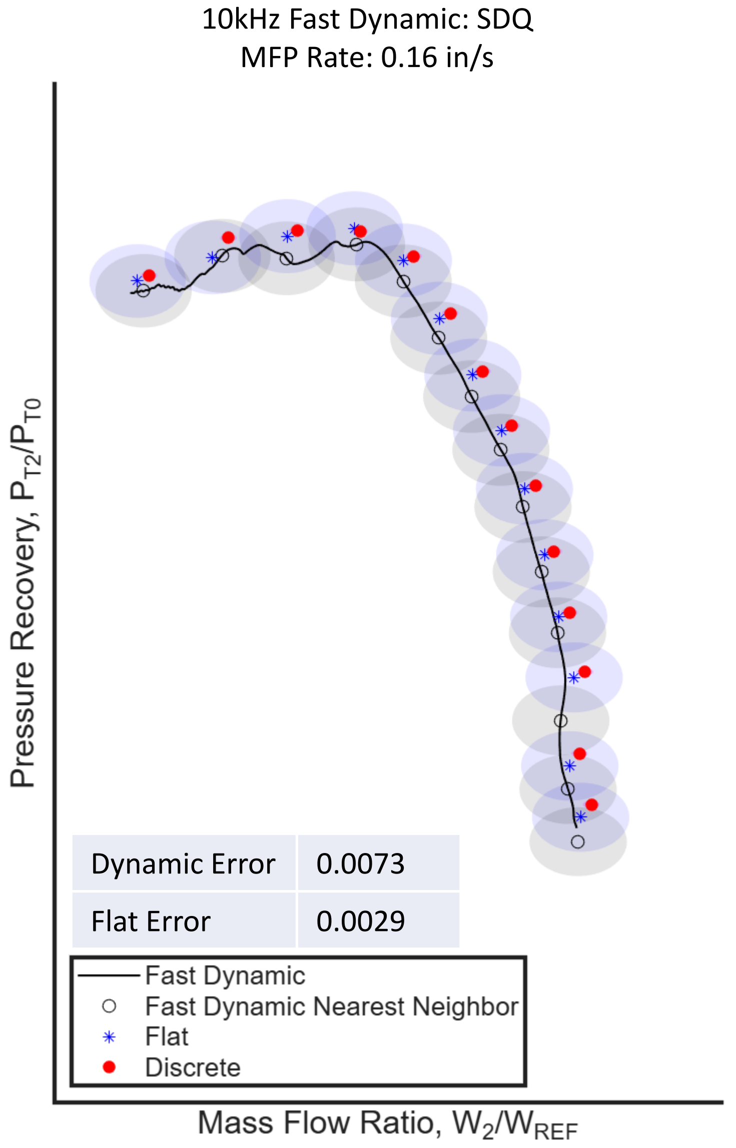


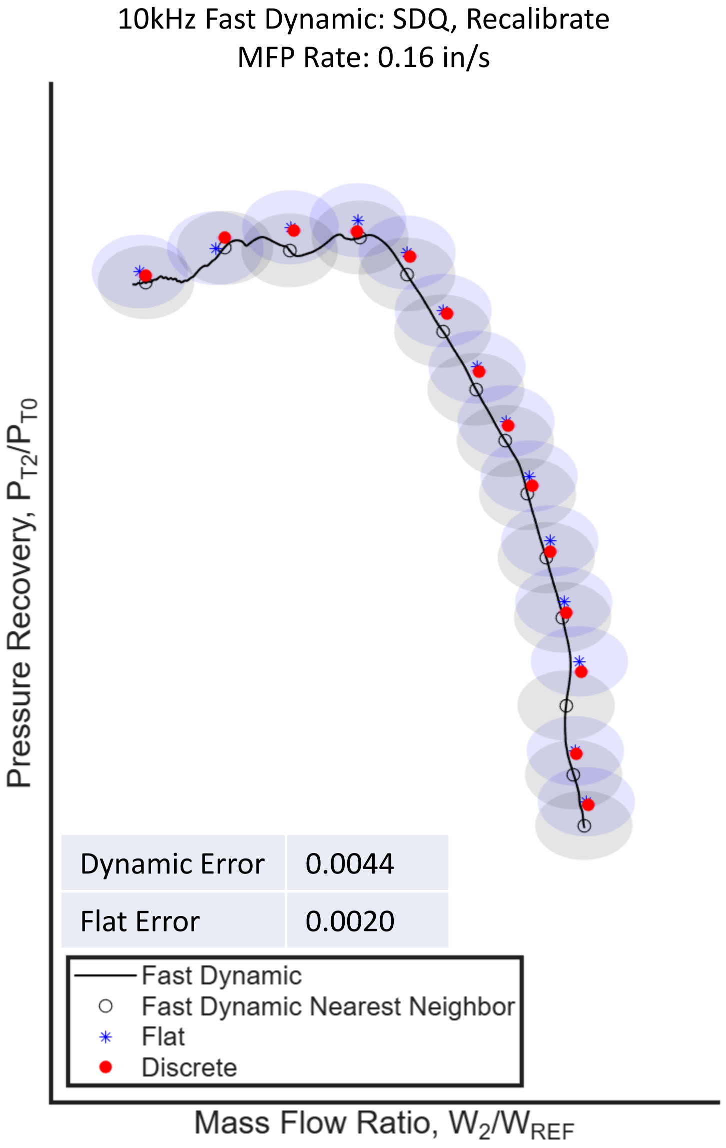
200Hz Slow Dynamic: SDQ, Recalibrate
MFP Rate: 0.26 in/s



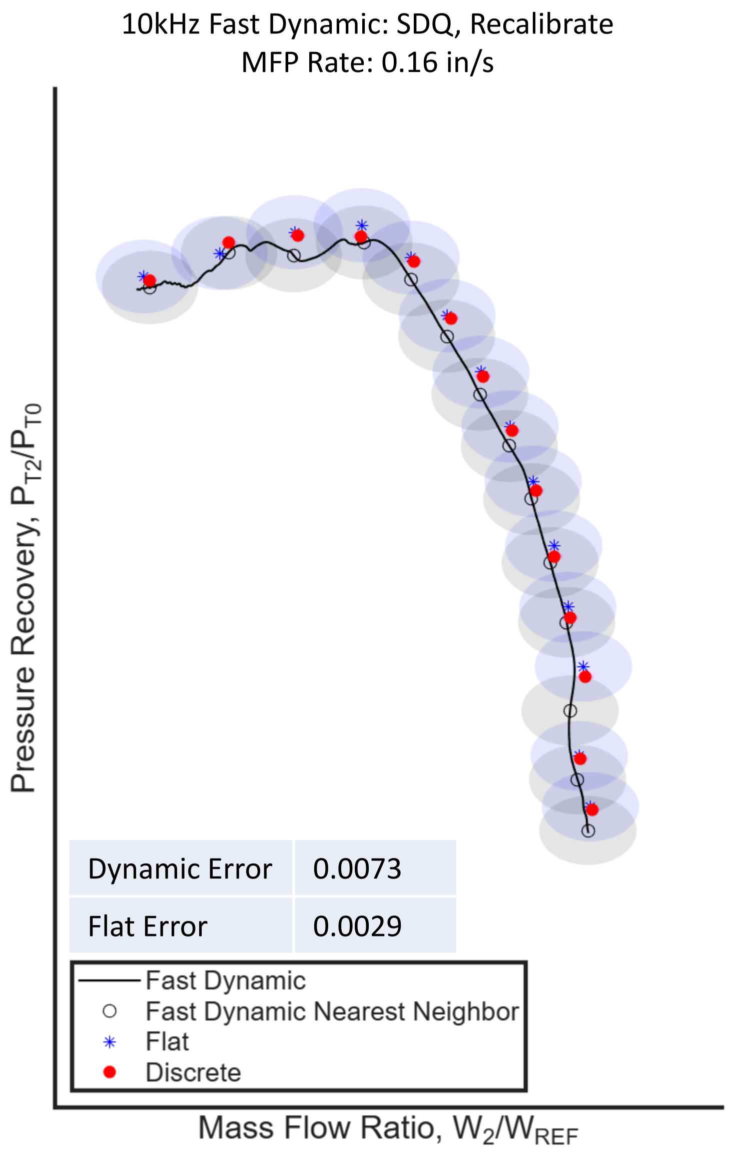
Fast Dynamic Results for 0.16 in/s Rate of MFP Movement

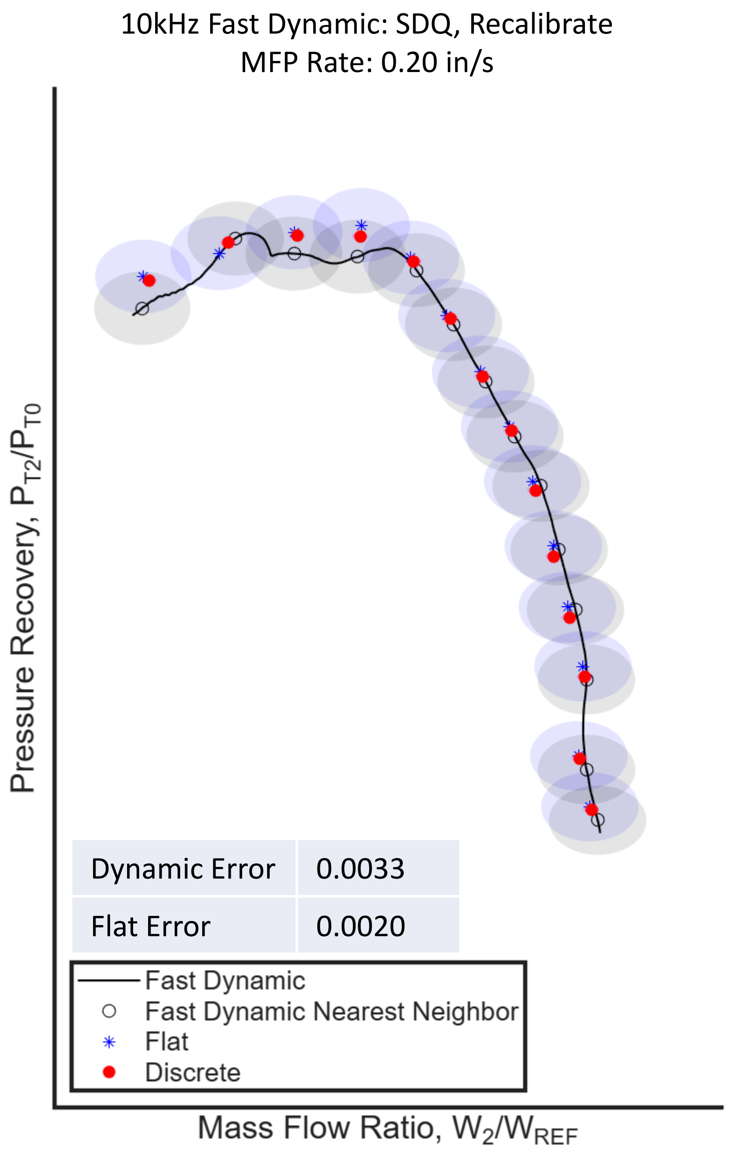


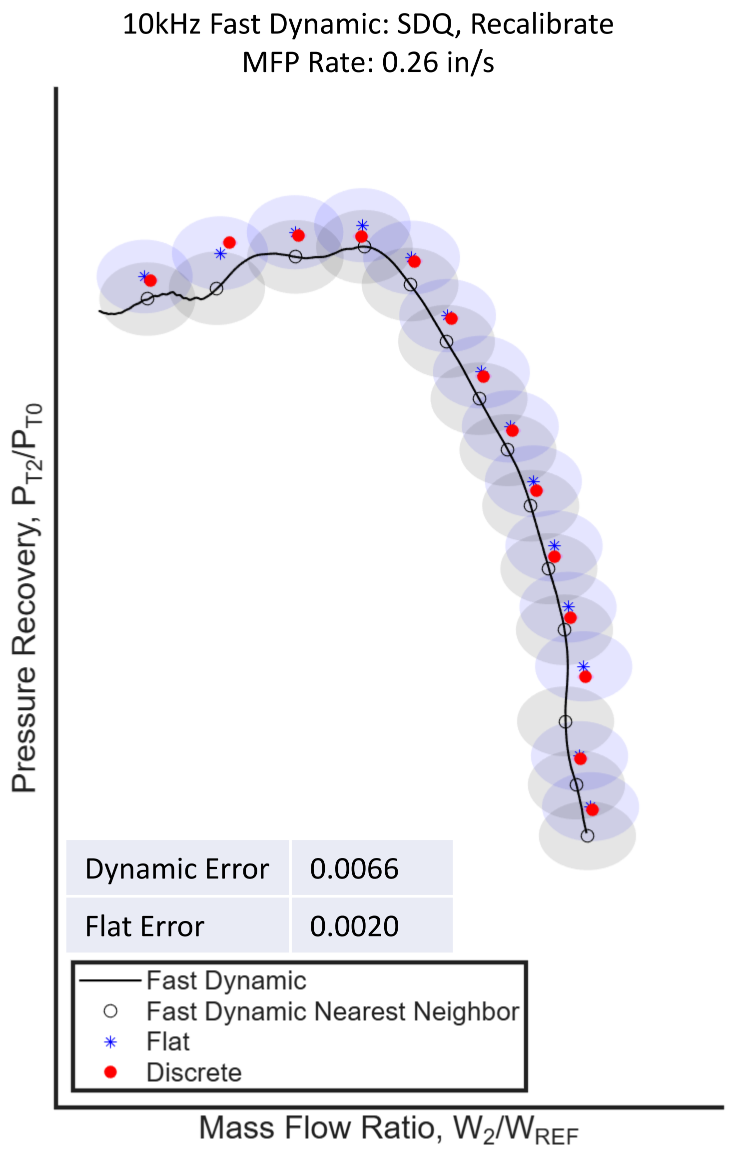




Fast Dynamic Results Summary for Each Rate of MFP Movement







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Summary

- A study was performed to determine whether dynamic data could be used to improve data acquisition efficiencies for supersonic wind tunnel analysis of propulsion inlet systems.
- Discrete and dynamic experimental data from the NASA Glenn Research Center Abe Silverstein 10- by 10-Foot Supersonic Wind Tunnel were used to construct inlet characteristic curves for a supersonic inlet.
- The study indicated that the dynamic cane curves have good agreement with a significant reduction in time to acquire data.
  - Dynamic process required about 30-60 seconds while Discrete process required about 45-60 minutes.
  - Requirements of the intended application dictates whether the agreement is sufficient.
  - At a minimum, the dynamic process could be used to explore regions of interest that can then be further examined by discrete data collection.

Acknowledgements

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Thank You