

Data Reduction and Corrections

Presentation to
AVT-328 Technical Course
Impact and Advanced Implementation of
Cryogenics in Aerodynamic Testing

Scott GOODLIFF, USA

Agenda

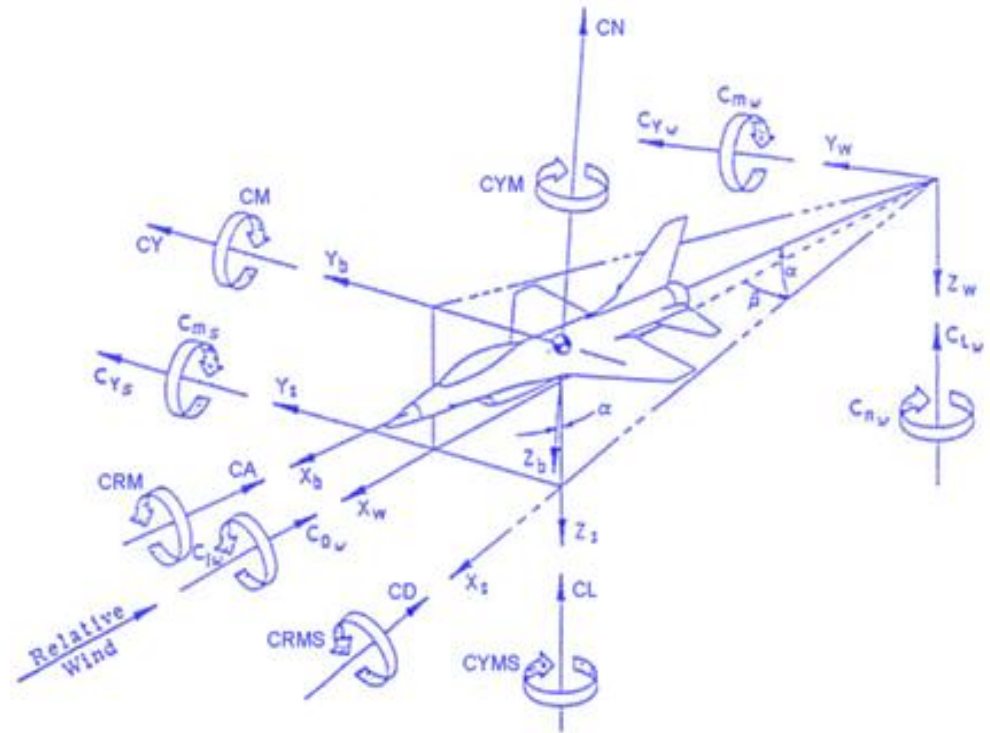
✈ General Data Reduction Process

- Overview
- Force Data Process
- Pressure Data Process

✈ Temperature-Based Corrections

- Thermal Expansion/Contraction
- Balance Temperature Corrections
- Flow Angularity
- Model Modulus of Elasticity

✈ Summary



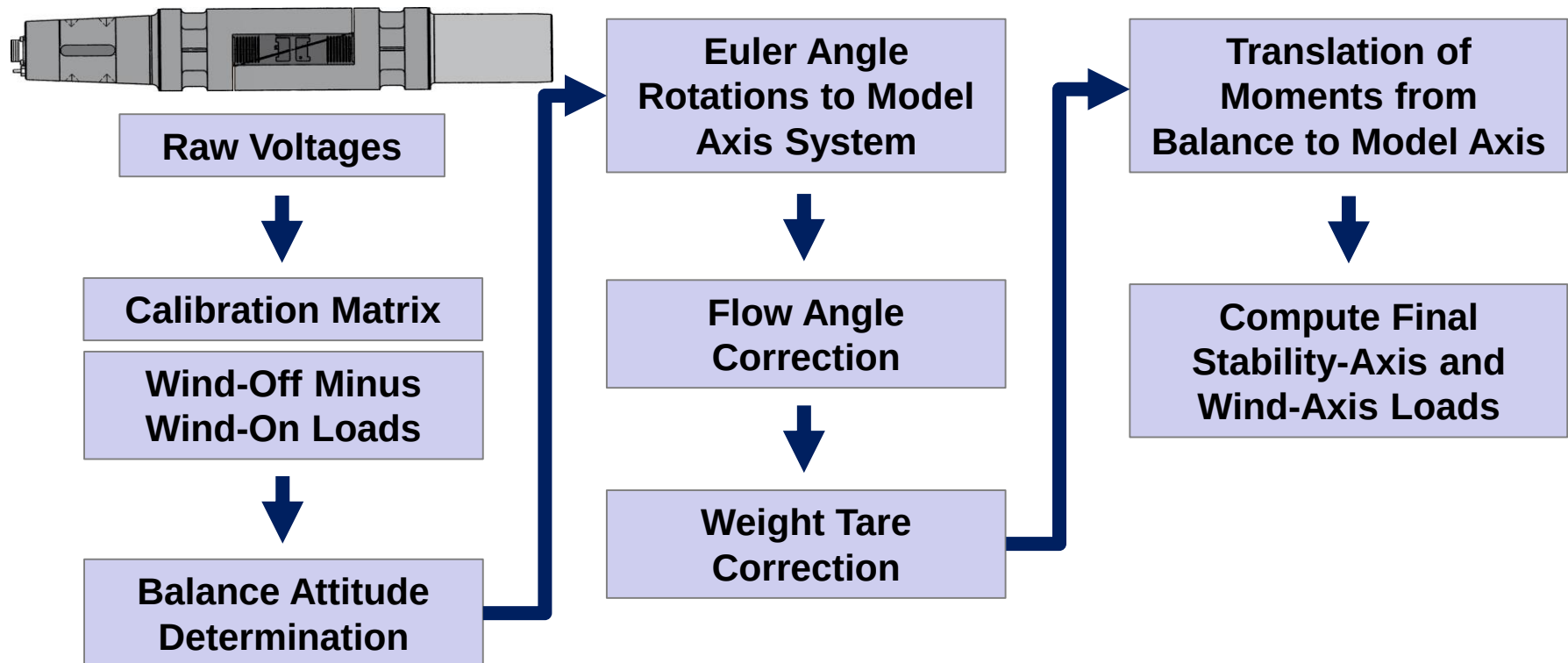
General Data Reduction Process - Overview

- ✈ Overall structure used to compute aerodynamic coefficients and pressure data similar between cryogenic facilities and other major wind-tunnel facilities
 - focus on force and pressure computations for this training
- ✈ Facilities may have proprietary data reduction processes for other acquisition techniques (i.e. video model deformation, other optical techniques)
- ✈ Data acquisition rates, acquisition methods, and data delivery mechanisms vary between facilities
 - varying acquisition and filtering hardware
 - varying computer systems and software for acquiring/processing data
 - varying software for performing computations, analysis, and plotting of reduced data

Regardless of facility differences, goal of all facilities is to produce the highest-quality data possible!

Generalized Force and Moment Data Process

- Force and moment data typically acquired using strain-gauge balance(s)
- Balance calibrated at ambient temperature and cryogenic temperatures
- Aerodynamic loads based on “delta load” methodology (wind-off minus wind-on)



Generalized Pressure Data Process

- Wing and model static pressures typically converted to pressure coefficients
- Straightforward process which normalizes the static pressure by Q (dynamic pressure)
- Applied to pressures regardless of the type of instrumentation used to measure them
- Freestream static pressure adjusted for tunnel calibration



Image: NTF

Temperature-Based Corrections

- ✈ Testing at cryogenic temperatures requires special considerations
- ✈ Instrumentation is highly sensitive to temperature changes
 - instrumentation calibrated at or near test temperature
- ✈ Model material expands and contracts at varying temperature, can be significant at cryogenic temperatures
- ✈ Tunnel geometry can change at cryogenic temperatures (facility dependent)



Image: NTF

Thermal Expansion/Contraction Corrections

- Used to correct model dimensional parameters for thermal expansion/contraction
 - model chord length
 - model reference area
 - model span
 - model volume
 - balance-to-model transfer distances
- Based on the simple principle that the model dimensions change with temperature
- Requires coefficient of thermal expansion (CTE) data for model material
 - Tobler, R. L., *"Materials for Cryogenic Wind Tunnel Testing"*, NBSIR 79-1624, May 1980
 - Wigley, David A., *"Materials and Techniques for Model Construction"*, NASA Contractor Report #172620, June 1985
- Corrections typically small, but statistically significant

Thermal Expansion/Contraction Example

- Two models to be tested in this example
 - one full span model and one semispan model
 - both models composed of VascoMax C200 stainless steel
- From Wigley in NASA CR-172620,
 - CTE is $6.10\text{E-}6$ per K @ 77K [$3.39\text{E-}6$ per °F at -321°F]
 - CTE is $8.60\text{E-}6$ per K @ 300K [$4.78\text{E-}6$ per °F at 80°F]
- Linear equation through two CTE points
 - $\text{CTE}_{\text{metric}} = 1.121\text{E-}8 * T + 5.237\text{E-}6$
 - $\text{CTE}_{\text{english}} = 3.466\text{E-}9 * T + 4.503\text{E-}6$

← T = tunnel temperature
or model temperature

Full Span Model Reference Quantities

CHORD = 6.00 in [0.1524 m]
AREA = 3.00 ft² [0.27871 m²]

*Quantities chosen
based on typical
model sizes*



Semispan Model Reference Quantities

CHORD = 12.00 in [0.3048 m]
AREA = 6.00 ft² [0.55742 m²]

Thermal Expansion/Contraction Example - Continued

- ✈ Both models tested at -250°F [116K] in this example
- ✈ Model reference quantities are adjusted using the ratio of length at cryogenic temperature to the length at ambient temperature
- ✈ Balance-to-model transfer distances are also corrected using the same ratio

Full Span Model Sample Data

$CHORD_{CORR} = 5.993 \text{ in } [0.1522 \text{ m}]$
6.000 in [0.1524 m] uncorrected

$AREA_{CORR} = 2.993 \text{ ft}^2 [0.27806 \text{ m}^2]$
3.000 ft² [0.27871 m²] uncorrected

$C_{LIFT\ CORR} = 0.5122$
0.5110 uncorrected

$C_{DRAG\ CORR} = 0.02353$
0.02348 uncorrected

Semispan Model Sample Data

$CHORD_{CORR} = 11.986 \text{ in } [0.3044 \text{ m}]$
12.000 in [0.3048 m] uncorrected

$AREA_{CORR} = 5.986 \text{ ft}^2 [0.55612 \text{ m}^2]$
6.000 ft² [0.55742 m²] uncorrected

$C_{LIFT\ CORR} = 0.4732$
0.4721 uncorrected

$C_{DRAG\ CORR} = 0.02559$
0.02553 uncorrected

**Note: Buoyancy correction not included in drag computations*

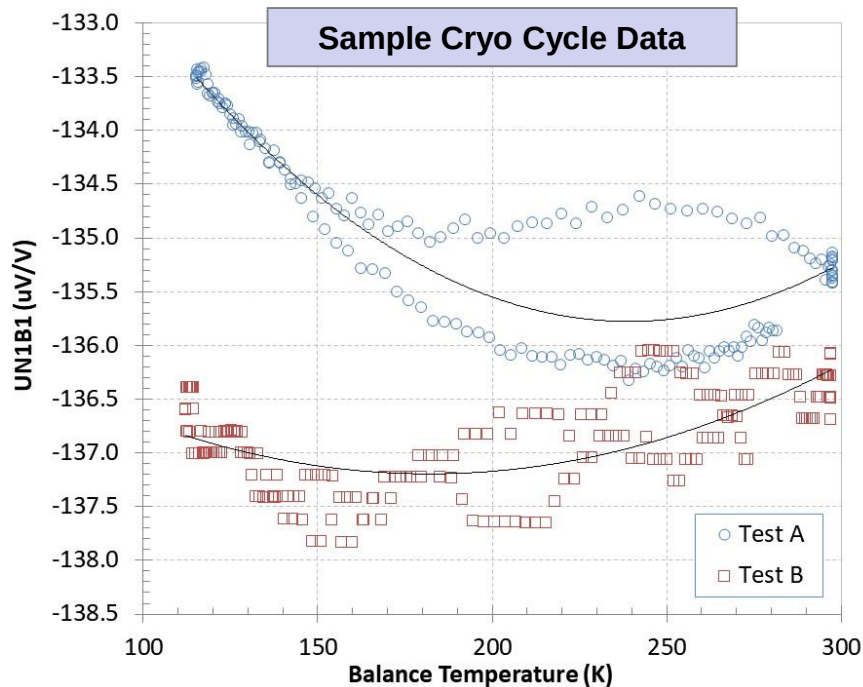
Balance Temperature Corrections

- Strain-gauge force and moment balances are very sensitive to temperature
- Calibrations completed at or near test temperatures
 - yields full calibration matrices at test temperatures and/or sensitivity shift coefficients across the temperature range
- Temperature cycle down to lowest test temperature to obtain the resultant apparent strain
 - used to correct the balance zero output back to the calibration temperature
 - completed in some facilities with the model installed on the balance in the test configuration
- Model cryo cycle completed during the pre-test phase of the campaign



Image: NTF

Balance Temperature Corrections - Continued



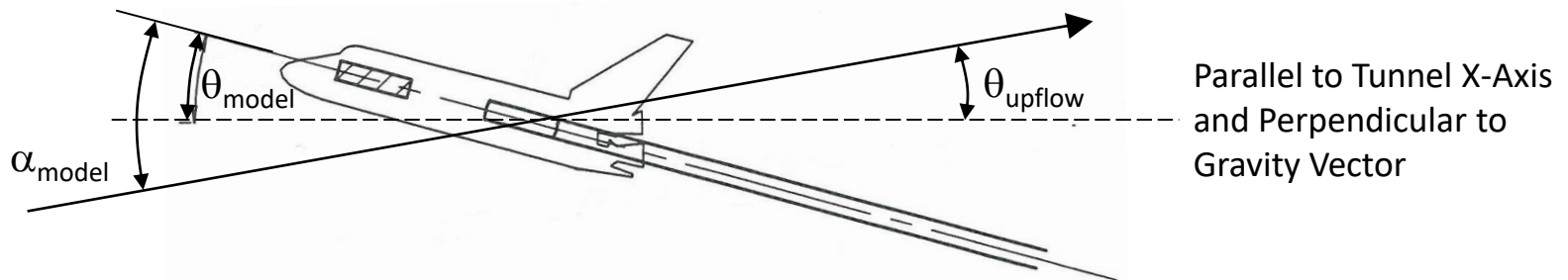
- ➔ Second order curve fit applied through data to characterize zero shift
- ➔ Possible to correct for balance thermal gradient (temperature difference across the balance)
 - typically handled by using best practices instead of a correction
 - testing with the balance in equilibrium with respect to test temperature
 - testing with near-zero thermal gradient

Two Recent Papers on Balance Calibrations

- ➔ *"Evaluation of Cryogenic Force Balance Calibration Methodologies Relative to Wind Tunnel Results"*, 11th International Symposium on Strain-Gauge Balances, Cologne, Germany, May 2018
- ➔ *"Comparative Analysis of Two Cryogenic Force Balance Calibration Systems"*, AIAA Paper 2018-4108, June 2018

Flow Angularity

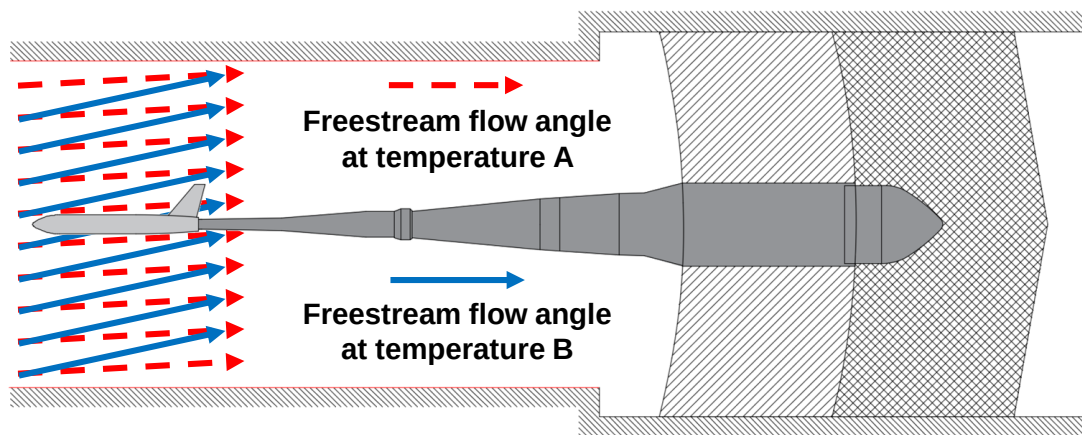
- Tunnel geometry can change at cryogenic temperatures
 - tunnel supporting structure and internal flow surfaces can expand/contract/shift
 - extremely facility dependent, may affect some facilities and not others
- Geometry changes can manifest as freestream flow angle changes in the test section



- θ_{model} → Model pitch angle typically measured by on-board model accelerometer
- θ_{upflow} → Flow angle, applied as a wind-to-gravity angle
- α_{model} → Final corrected model angle-of-attack

Flow Angularity - Continued

- ✈ Flow angle can shift even after freestream temperature has reached the target setpoint
 - tunnel structural components take longer to reach thermal equilibrium
 - several hours of “conditioning” are required at the target setpoint to allow for the structure to thermally stabilize
- ✈ Requires model upright and model inverted polars in the region where the normal force coefficient curve is the most linear
 - other methods for measuring flow angle (probes, wires, optical, etc.), point methods
 - using the model as an integrator provides more accurate measurement of apparent flow angle



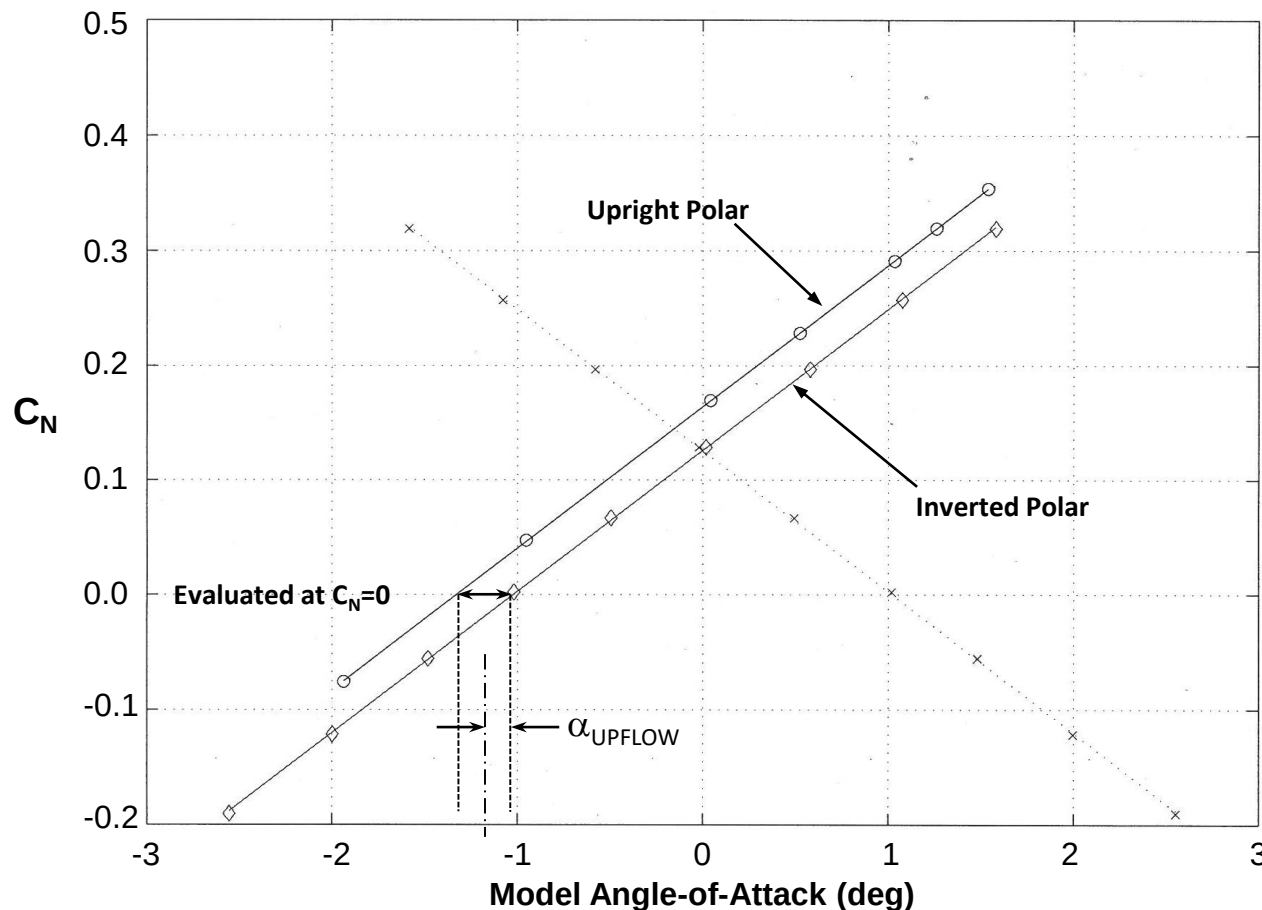
*Exaggerated example, not representative of actual flow angle strengths or directions



Can vary by test condition, facility test engineer can assist in recommendations

Flow Angularity Computation Example

- ➔ Computation method similar to many other major wind tunnels
 - parallel method used on upright and inverted C_N curves



Curvefits

$$C_N = 0.12325\alpha + 0.16366 \quad \leftarrow \text{Upright}$$

$$C_N = 0.12310\alpha + 0.12560 \quad \leftarrow \text{Inverted}$$

Evaluate at $C_N = 0$

Upright

$$0 = 0.12325\alpha + 0.16366$$

$$\alpha_{UPR} = -1.3279^\circ$$

Inverted

$$0 = 0.12310\alpha + 0.12560$$

$$\alpha_{INV} = -1.0203^\circ$$

Calculation of Upflow Angle

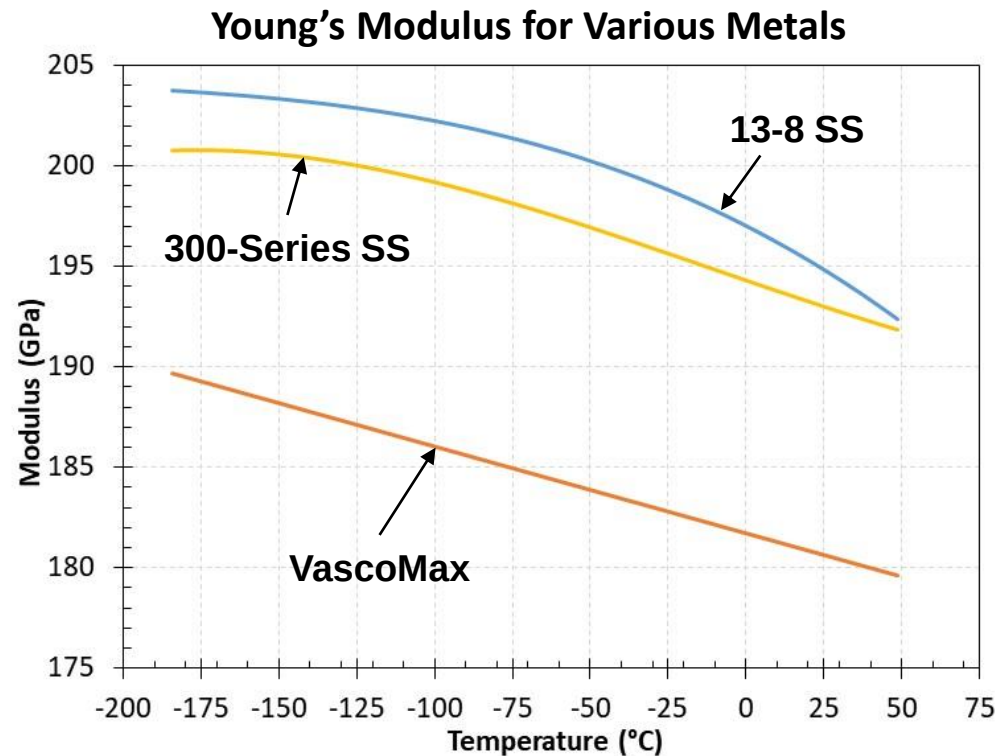
$$\alpha_{UPFLOW} = \frac{\alpha_{INV} - \alpha_{UPR}}{2}$$

$$\alpha_{UPFLOW} = \frac{(-1.0203) - (-1.3279)}{2}$$

$$\alpha_{UPFLOW} = 0.154^\circ$$

Model Modulus of Elasticity

- ✈ Pure aeroelastic studies can be completed in high Reynolds-number facilities
 - hold Mach and Reynolds number constant while varying Q
- ✈ Q/E parameter used to characterize aeroelastic condition
- ✈ Modulus of elasticity (Young's Modulus) is not constant, varies with temperature
- ✈ Important to compensate for the change in model modulus to obtain the correct aeroelastic shape at varying temperatures



Summary

- ✈ Force and moment data reduction processes are similar to other major wind-tunnel facilities
- ✈ Cryogenic testing adds another layer of corrections that need to be made
- ✈ Although some are small, goal of all corrections is to improve data quality and compensate for temperature effects

Questions / Discussion