Improved Prediction of Butterfly Valve Aerodynamic Torque through CFD: Commercial Code and SU2 Evaluation

WOODWARD

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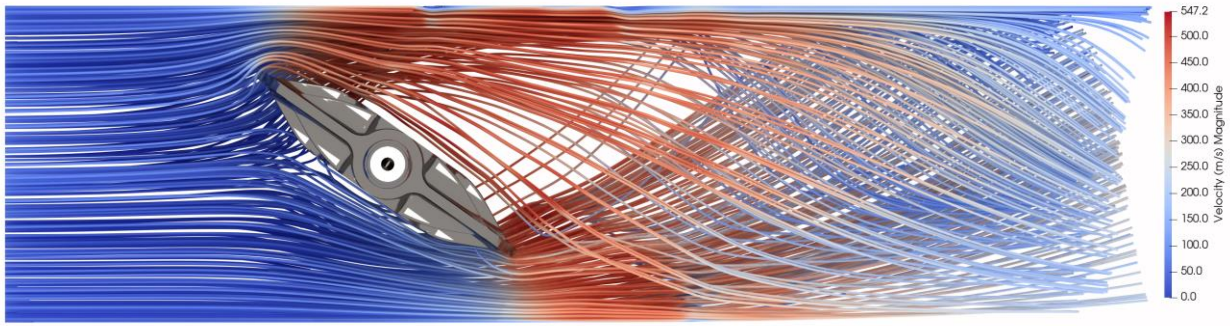
1st Annual SU2 Conference
10-12 June 2020

SU2 code

Topics

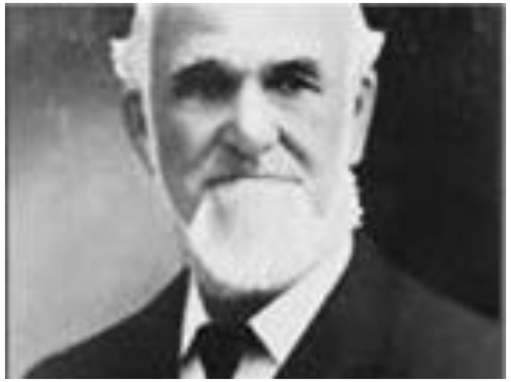


- Woodward, Inc. Introduction
- Glo-Tech II Butterfly Valve
- Aero Torque Test Data
- Empirical Model (Motivation for CFD)
- CFD
  - General strategy
  - Grid strategy
  - CFX setup
  - SU2 setup
  - Comparisons
- Looking Ahead, Future Work

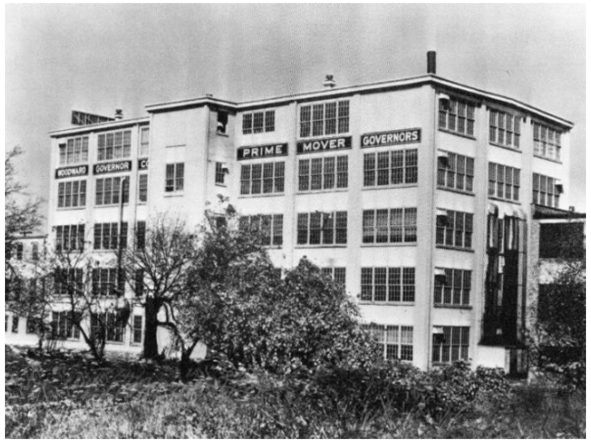
WOODWARD

Woodward, Inc.

Founded in 1870



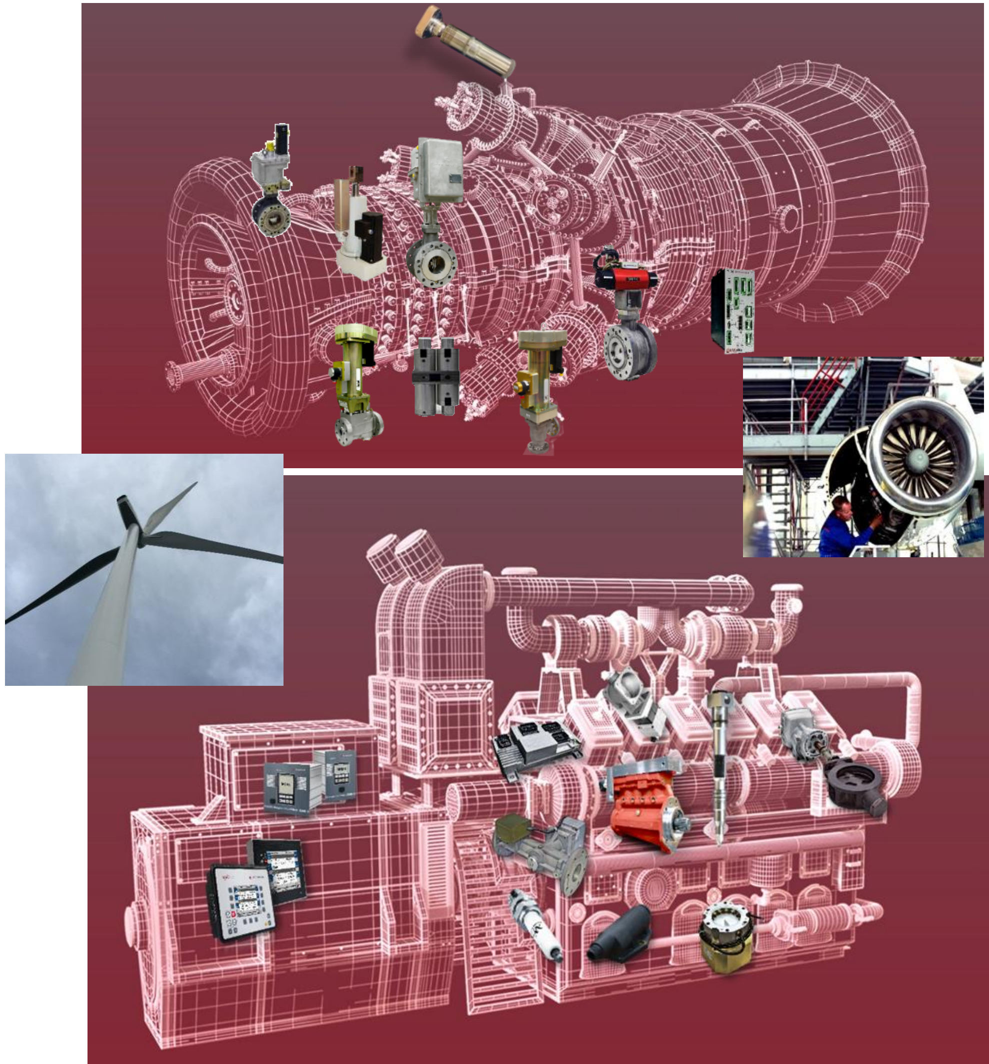
Amos Woodward



Our First Product

Waterwheel governor

Today: leading supplier of aerospace and industrial controls



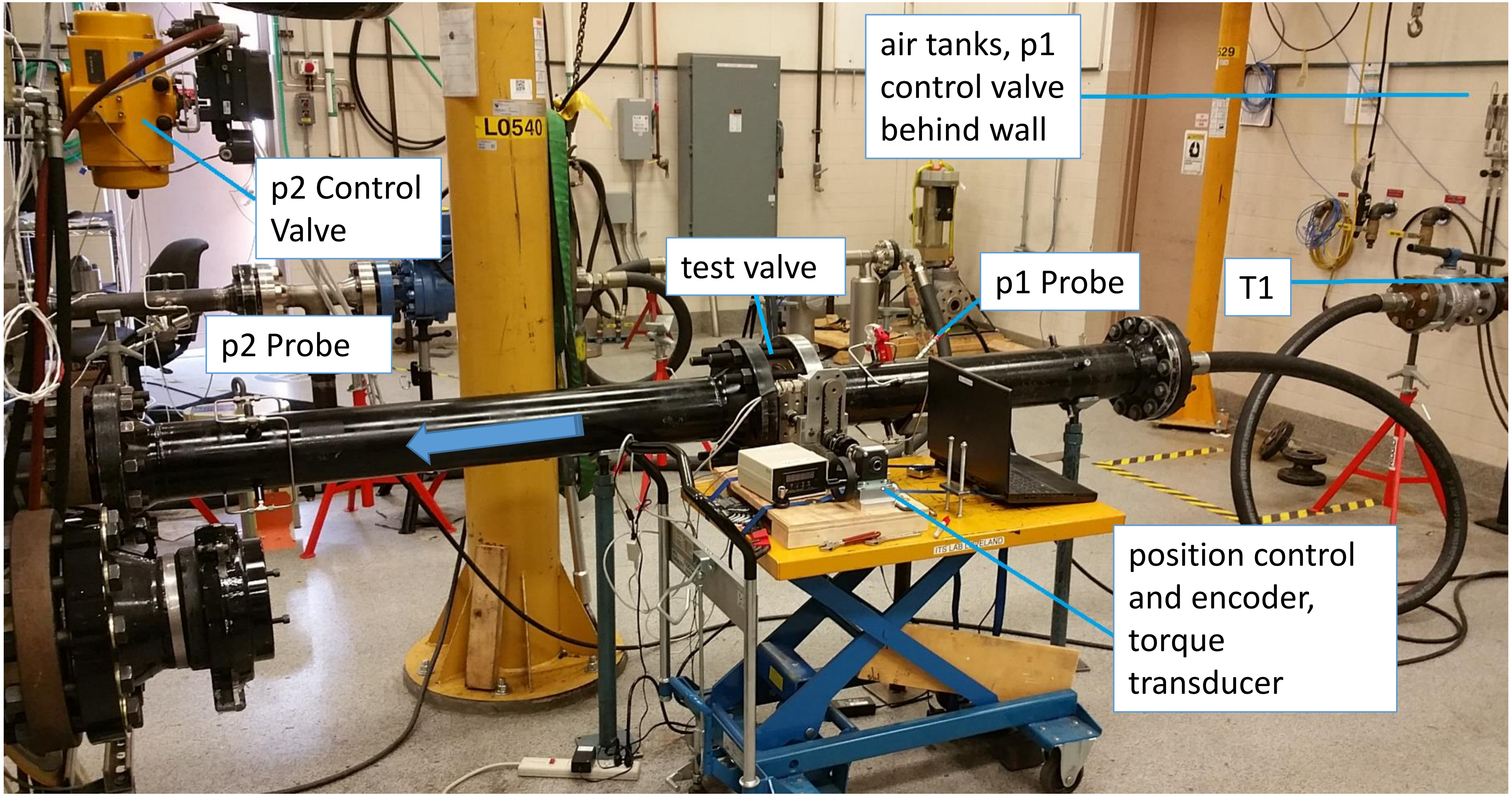
Glo-Tech II Butterfly Valve

- Exhaust gas flow control valve
  - 40 mm thru 150 mm valve bore diameters
  - Used on marine and power-gen engines
- Paired with Woodward R-Series geared actuator
  - Ability to model valve torque is critical to sizing actuator
- This study evaluated CFD for improving aerodynamic torque prediction over an empirical textbook equation
  - ANSYS CFX
  - SU2

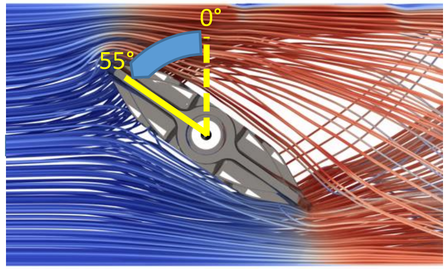
Aero Torque Test Data

- Used compressible flow test stand at Woodward, Loveland CO
- Range of inlet and outlet pressures, valve angles to generate aerodynamic torque map of valve
  - Transonic and subsonic conditions
  - Some test points exceed flow stand capacity, especially larger valves at larger angles
    - *Thus, need for modeling*
- 80 mm version of the valve family used for CFD correlation study
  - Step 1: Build confidence in CFD; good agreement with test data?
  - Step 2: Apply to extended flow conditions

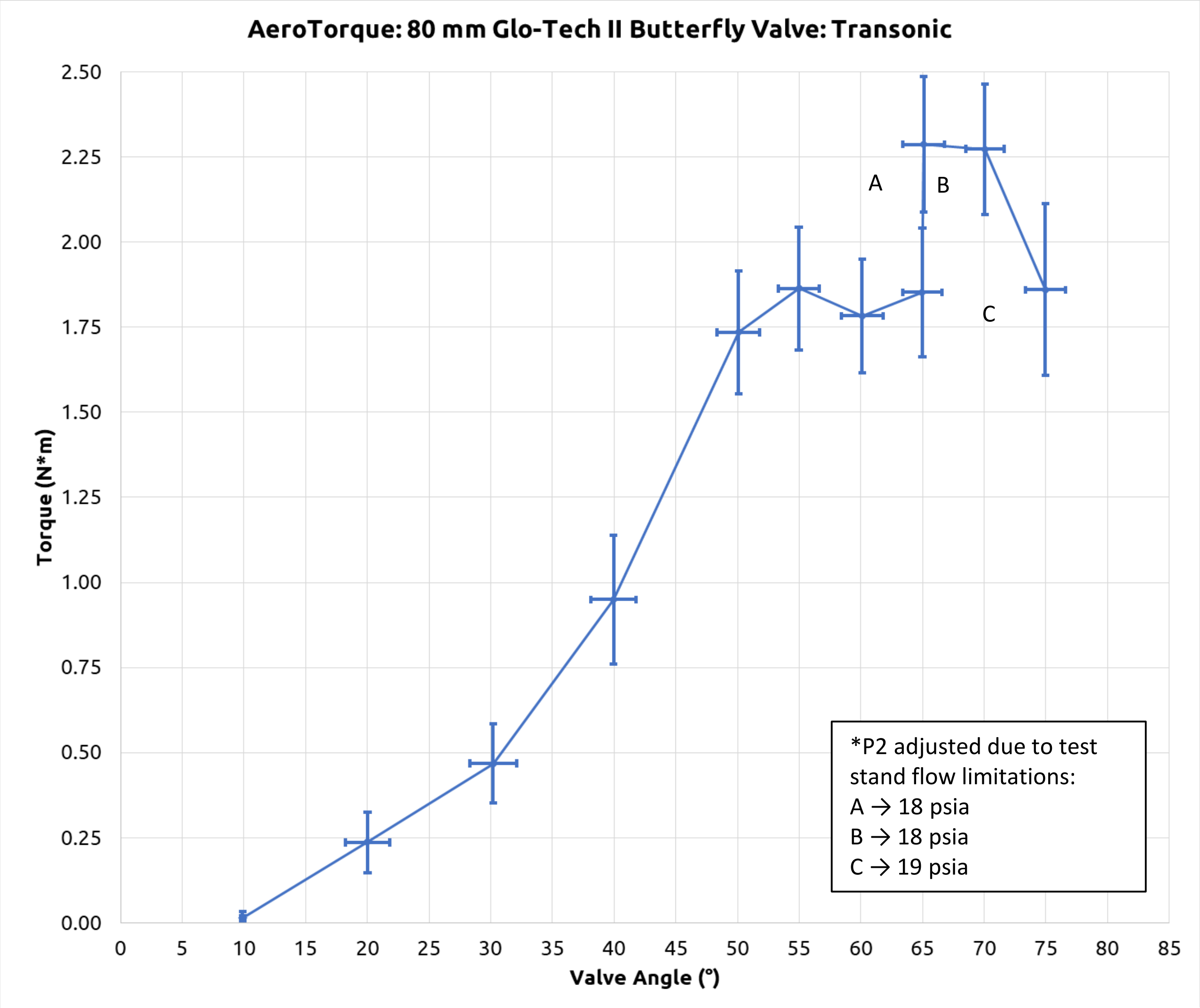
Aero Torque Test Data



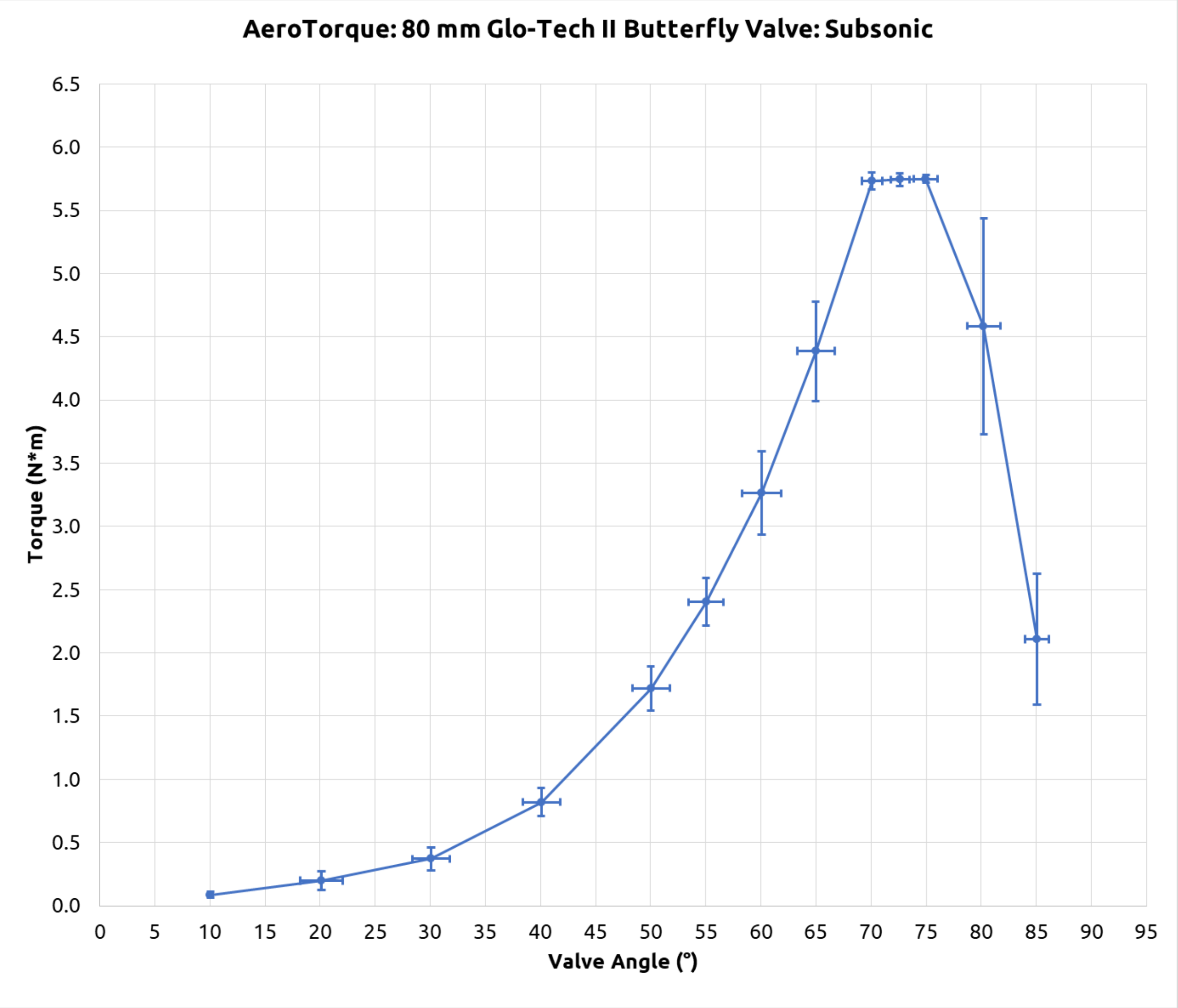
Aero Torque Test Data



Transonic conditions: 40 psia P1, 16* psia P2

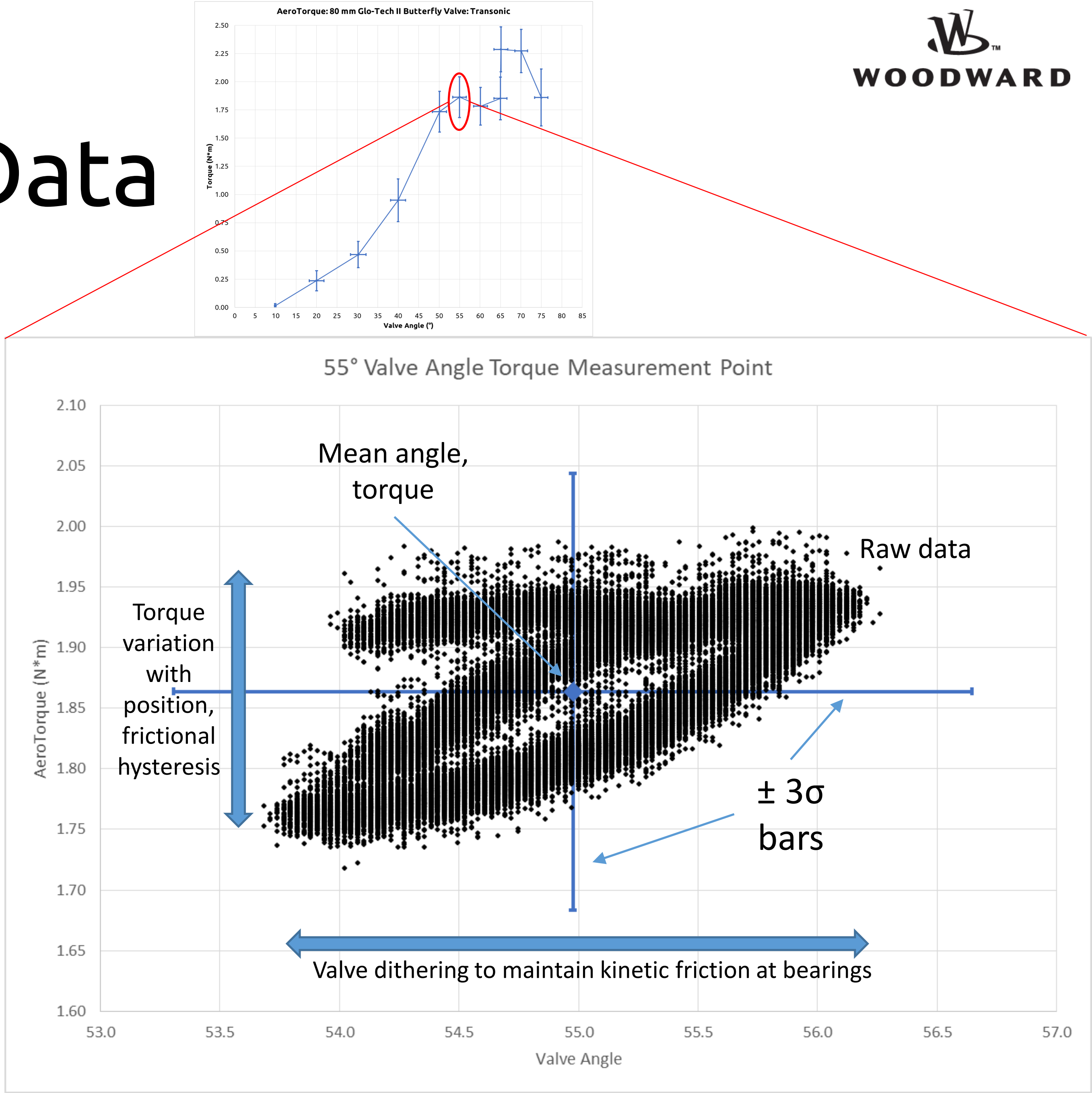


Subsonic conditions: 62.5 psia P1, 50 psia P2



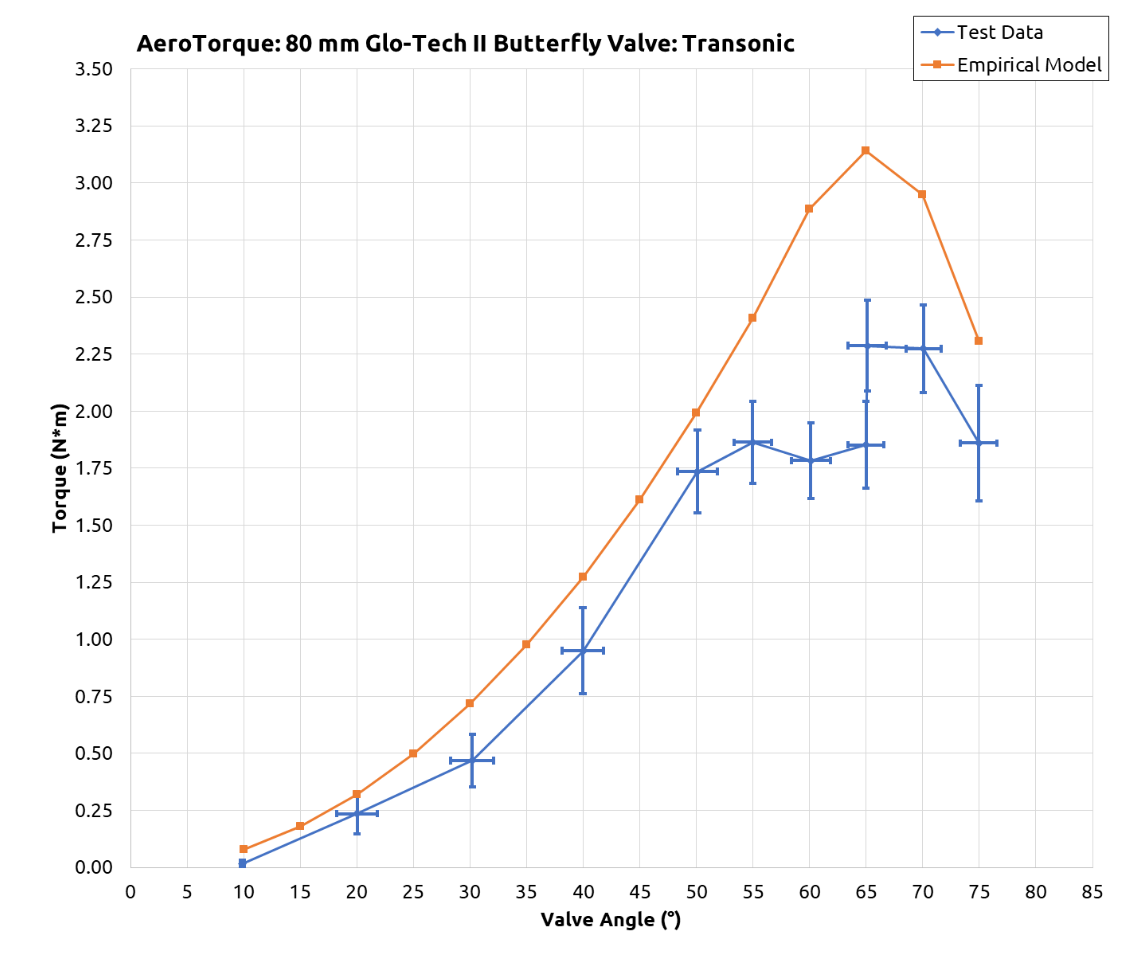
Aero Torque Test Data

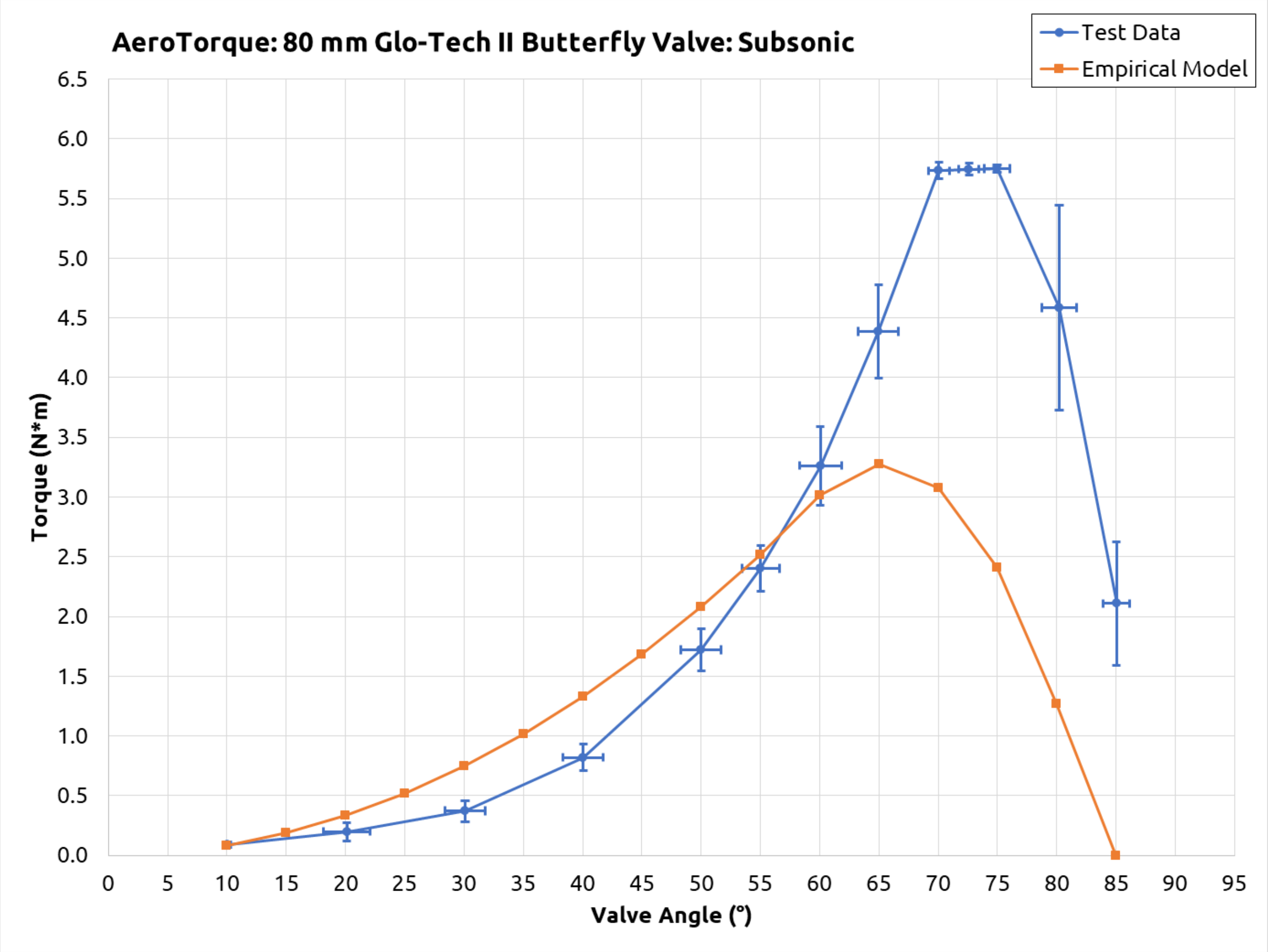
- Valves built with rolling element bearings, but to further minimize static frictional effects, plate was manually dithered ≈ ±1°
- Some points produced pronounced torque variation with this small dither, suggesting unsteady effects
- Mean values for angle and torque used to express data, with 3σ error bars shown



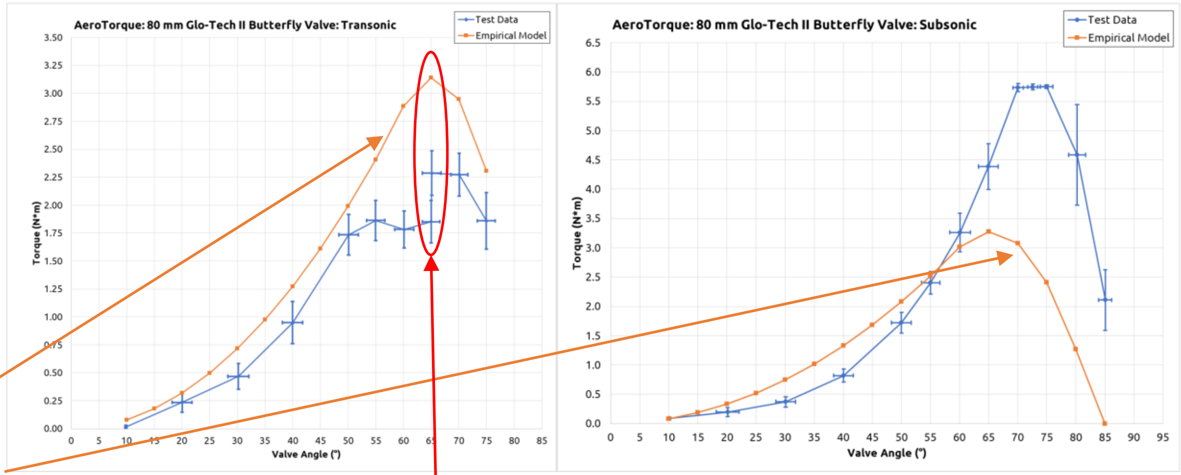
Empirical Model

- Equation for predicting torque on generic butterfly valve
  - Andersen, B. W. (2001). *The Analysis and Design of Pneumatic Systems,* Krieger Publishing Company
    - *Equation 3.3-24*
- Model previously used when test data was unavailable

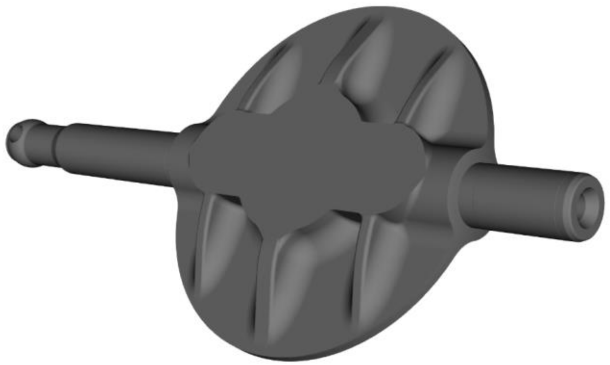




Empirical Model



- Poor accuracy
  - Over-predicts torque, transonic
  - Under-predicts torque, subsonic
  - Insensitive to downstream pressure changes, transonic
    - See Points “A, B, C” in previous slide
    - Model assumes “choked torque” behaves like choked mass flow
  - Peak-torque always predicted at 65°, but not the case here
- Poor agreement likely due to unique topology of valve plate



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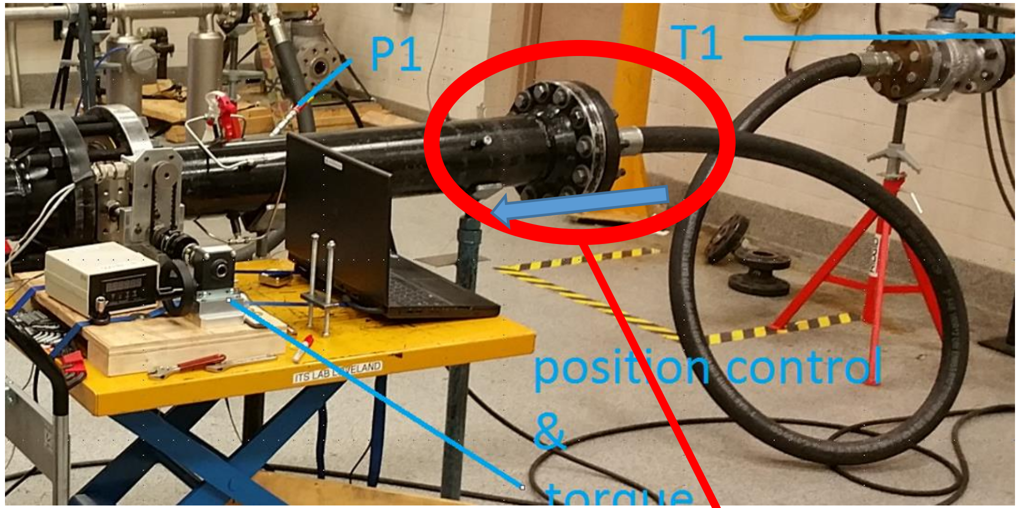
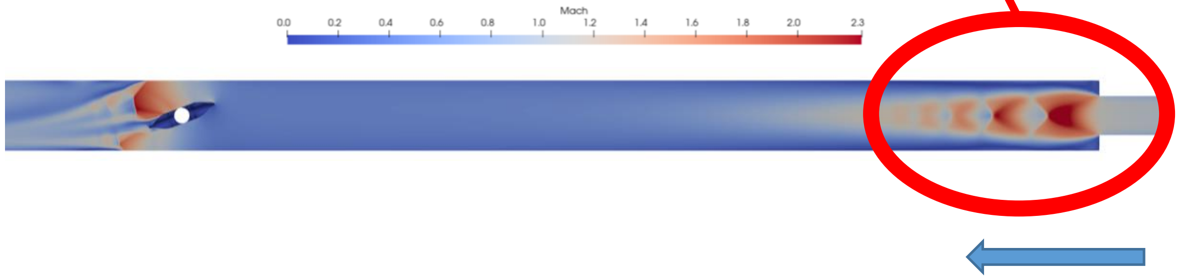
CFD - General approach

- Leverage half-symmetry
- RANS, steady, compressible
- For the purpose of comparing SU2 with CFX, avoid wall functions
  - Grid layers strive for y+ ≈ 1, 30 boundary layer cells
- Isothermal pipe walls, adiabatic plate walls
- Lesson learned from previous study: include sudden-expansion at inlet hose/pipe transition from test stand
  - Affects torque at higher valve angles
- Focus on plate angles ≥ 30°
- Grid generation in ANSYS Workbench





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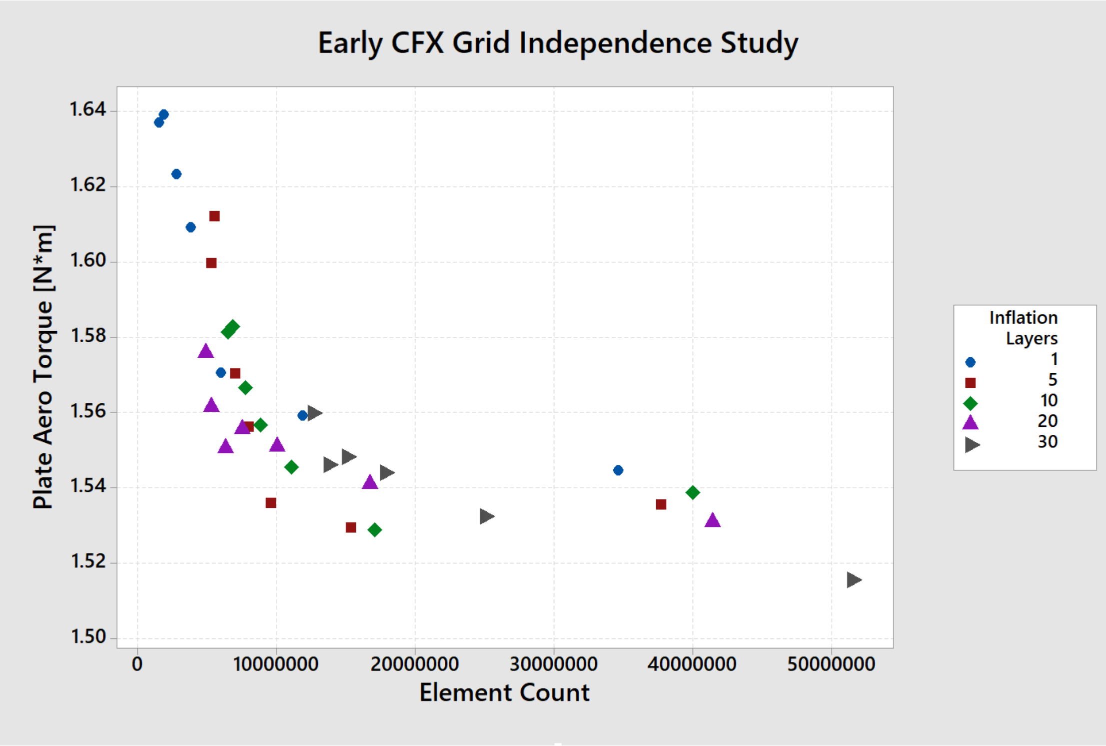
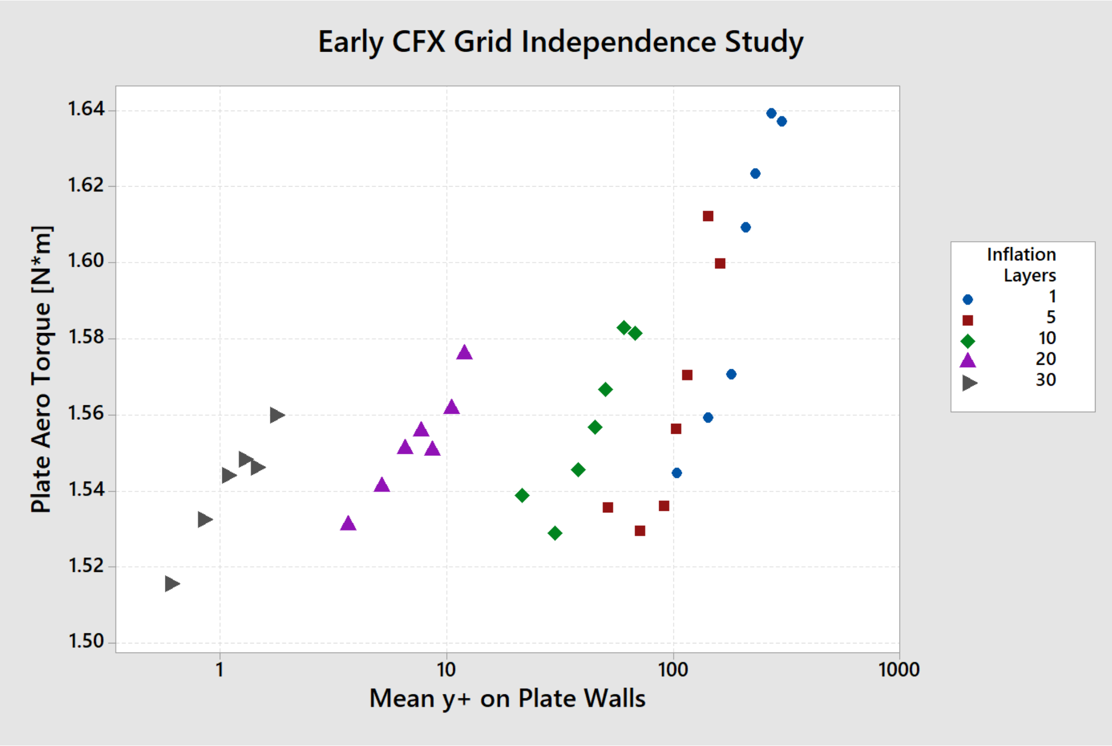
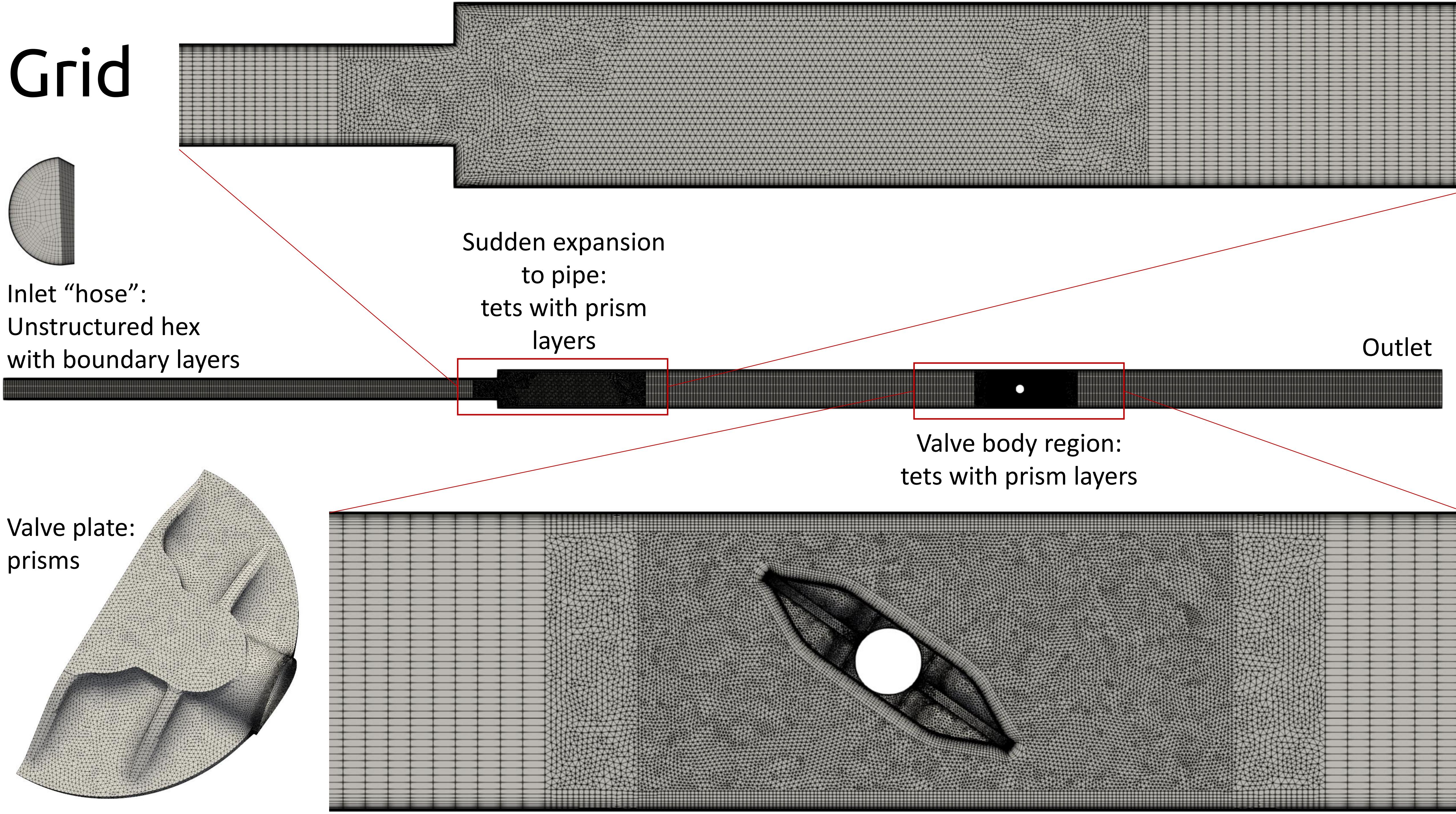
Grid: Early grid independence study

- From previous work in CFX on this geometry, ≈10e6 elements is optimal. Grid was further optimized for this study with unstructured hex in pipe regions to reduce element count

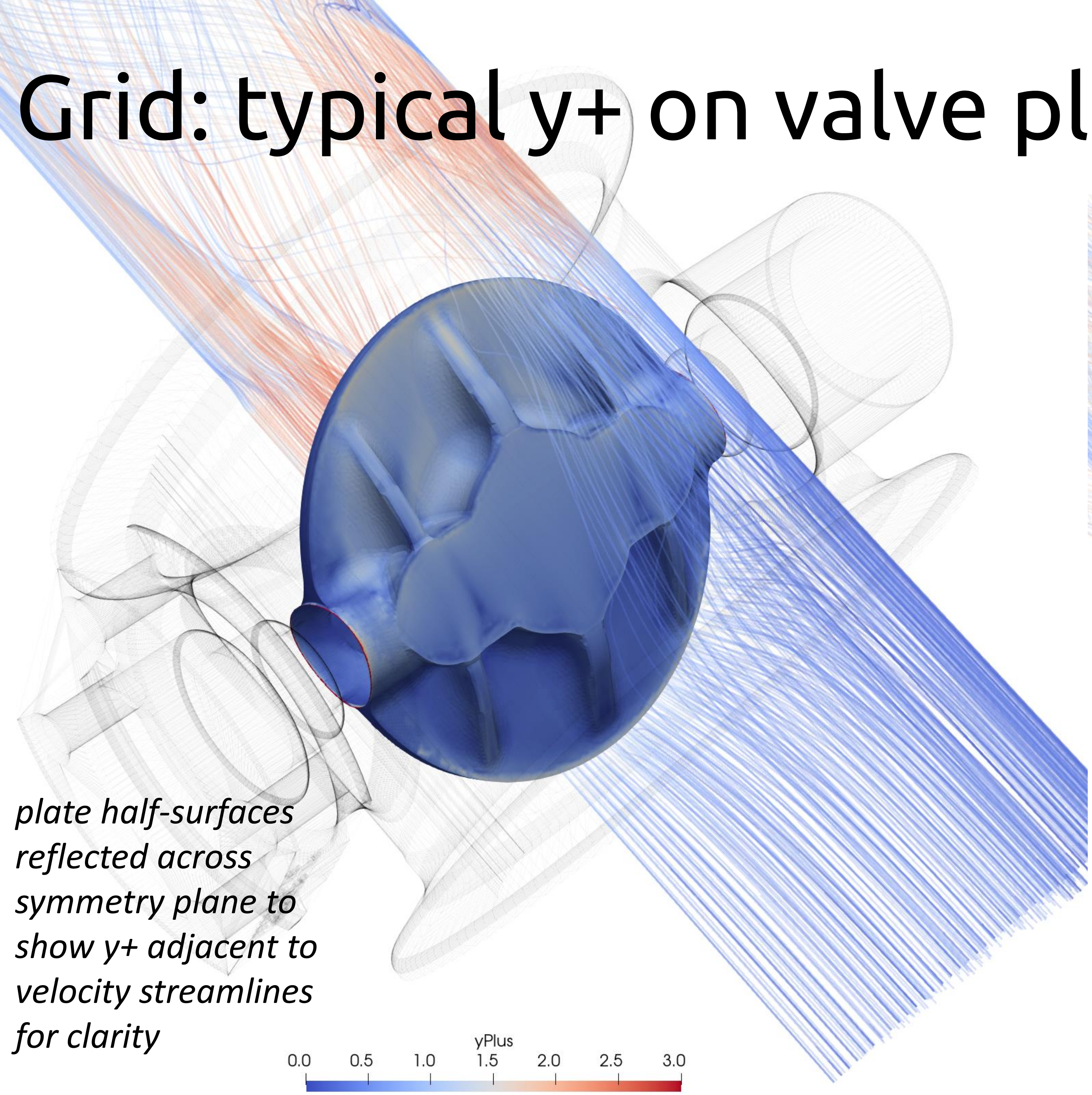




Grid


Inlet “hose”:
Unstructured hex
with boundary layers
Sudden expansion
to pipe:
tets with prism
layers
Outlet
Valve body region:
tets with prism layers
Valve plate:
prisms

Grid: typical y+ on valve plate



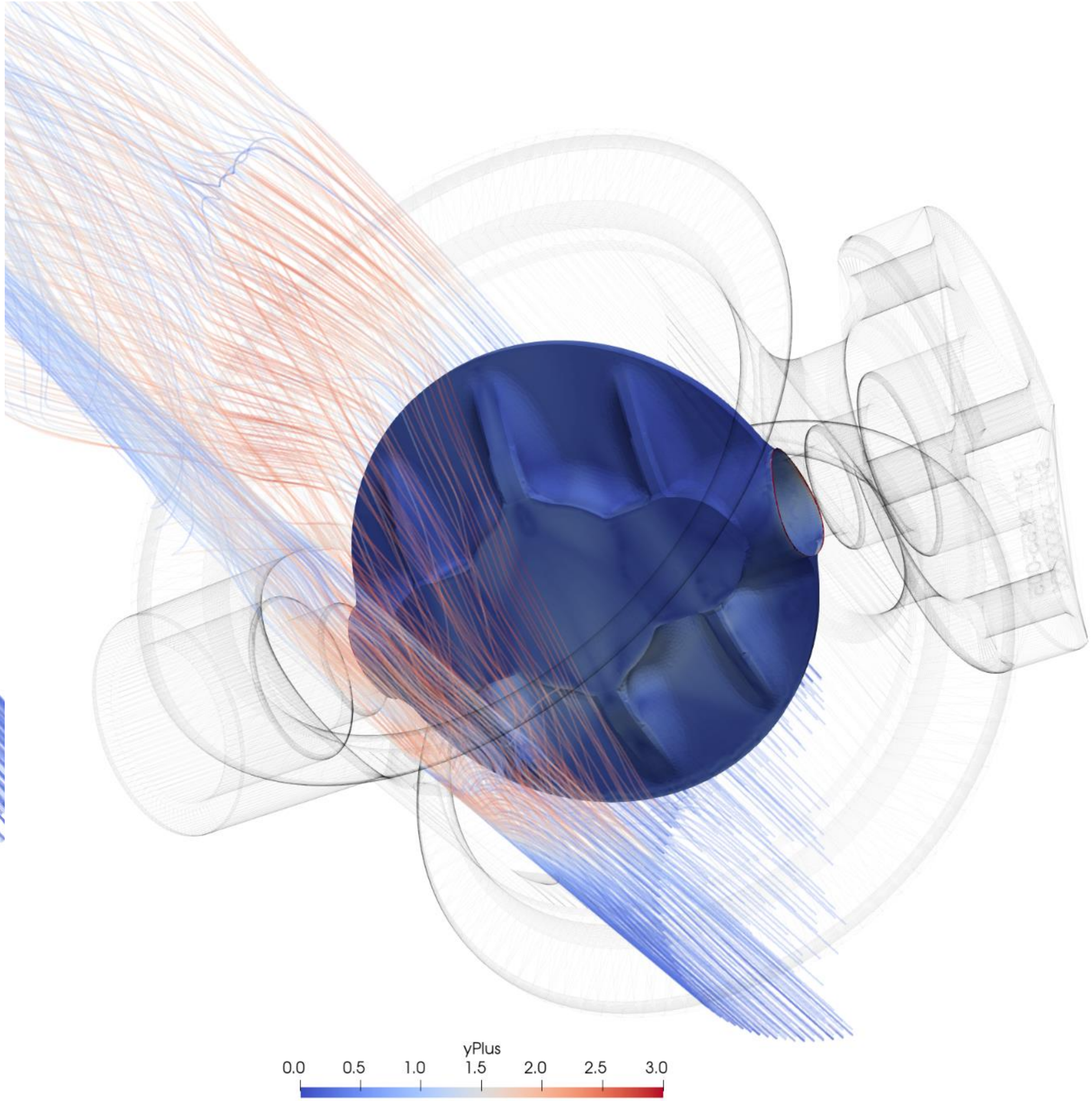
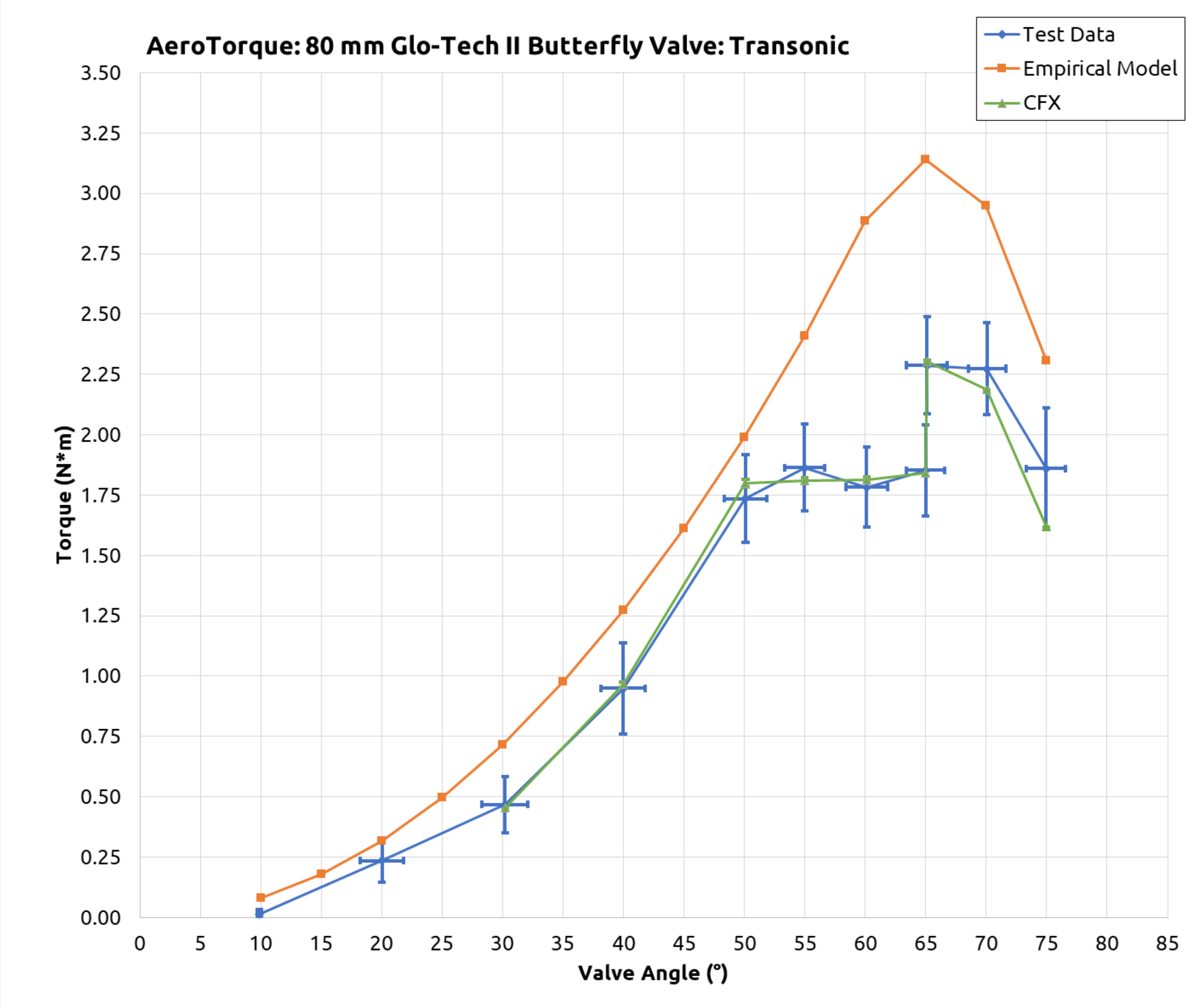


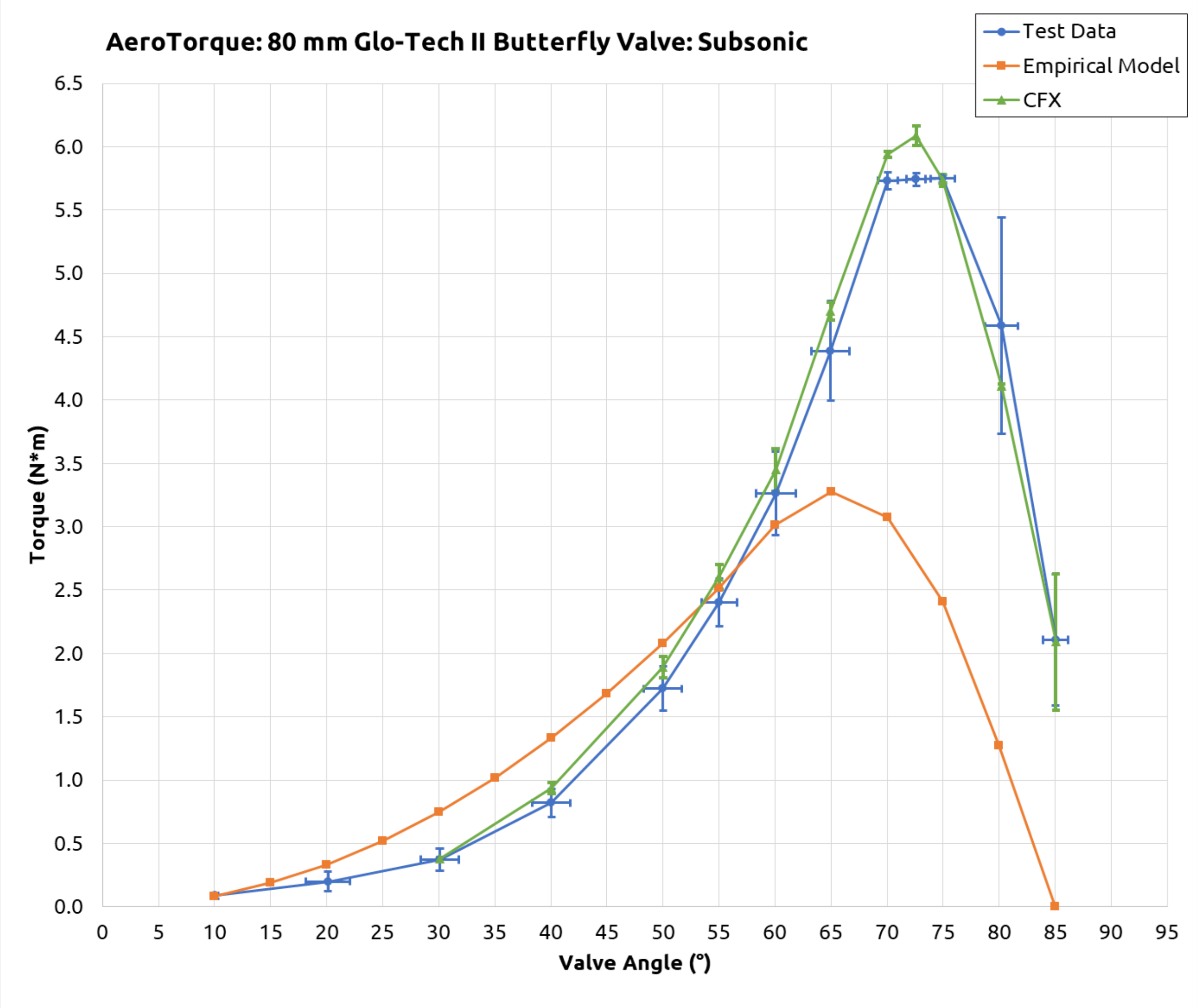
plate half-surfaces reflected across symmetry plane to show y+ adjacent to velocity streamlines for clarity

CFX Setup

- Multi-configuration
  - “Upwind” Advection O(1) initialization run, 500 iterations
  - “High Resolution” Advection O(2) finishing run, ≈ 2000 iterations
- Spalart-Allmaras turbulence model (beta feature in CFX)
  - SST often used for internal flow, but SA chosen for comparison with SU2
  - O(1) turbulence for stability
- Air as ideal gas with Sutherland viscosity model
- Total energy
- Mean ± 3σ from final 500 iterations used to report torque results
  - Quasi-attempt to capture any unsteady effects

CFX Results


AeroTorque: 80 mm Glo-Tech II Butterfly Valve: Transonic
Test Data
Empirical Model
CFX
Torque (N*m)
Valve Angle (°)
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85


AeroTorque: 80 mm Glo-Tech II Butterfly Valve: Subsonic
Test Data
Empirical Model
CFX
Torque (N*m)
Valve Angle (°)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95

CFX Conclusions

- Much improved prediction over empirical model
  - Generally within error bars of test data
  - Exceptions:
    - 75° transonic, low prediction
    - Slight over-prediction of subsonic peak torque region
- Accurately captures the transonic torque-shift at 65° when P2 is increased from 16 to 18 psia

Why Evaluate SU2?

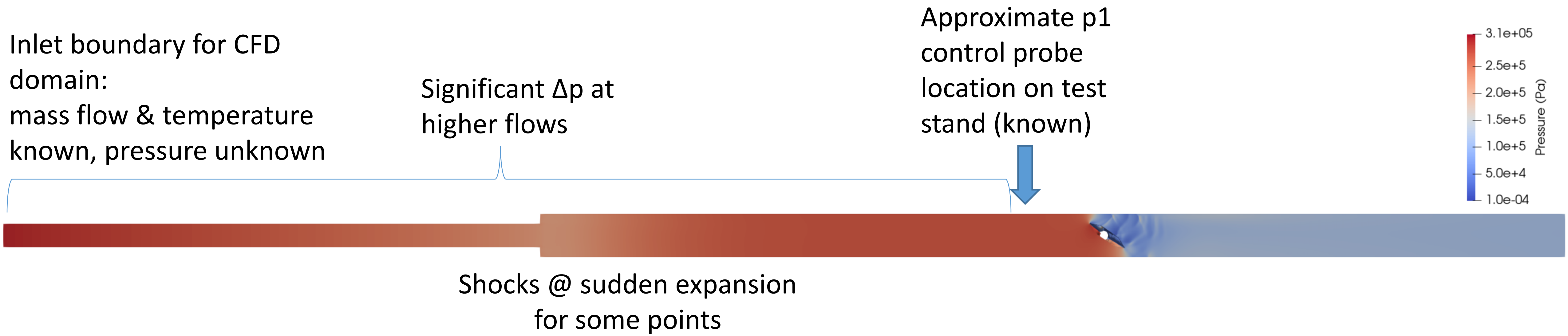
- Open-source alternative to commercial codes
- Today, steady-state RANS is still workhorse for our simulations…
  - Commercial licensing for 32-core jobs is tractable
- …but, how can our product design and insight improve as we move towards scale-resolved simulations in the future?
  - Freedom from license costs that scale with processor count is attractive
  - Ability to customize the code if/when needed
- SU2 points of interest
  - Density-based, adjoint capabilities, solver improvements in v7.0.0, FEM DG capability is interesting, active development community, documentation keeps improving, good tutorials

SU2 - Setup

- Version 7.0.0
- Used same grids as CFX runs (both codes are node-based)
- 6000 iterations
- SA turbulence model
- CFL adapt [5 $\rightarrow$ 30], 50 linear solver max iterations, 1e-3 tol
- Green-Gauss for gradient and reconstruction
- MUSCL with Venk-Wang slope limiter, O(1) turbulence w/o Limiter
- SLAU2, found to have low dissipation and good stability
- No multigrid, no low-Mach preconditioning
- Sutherland viscosity, Const. Prandtl thermal conductivity

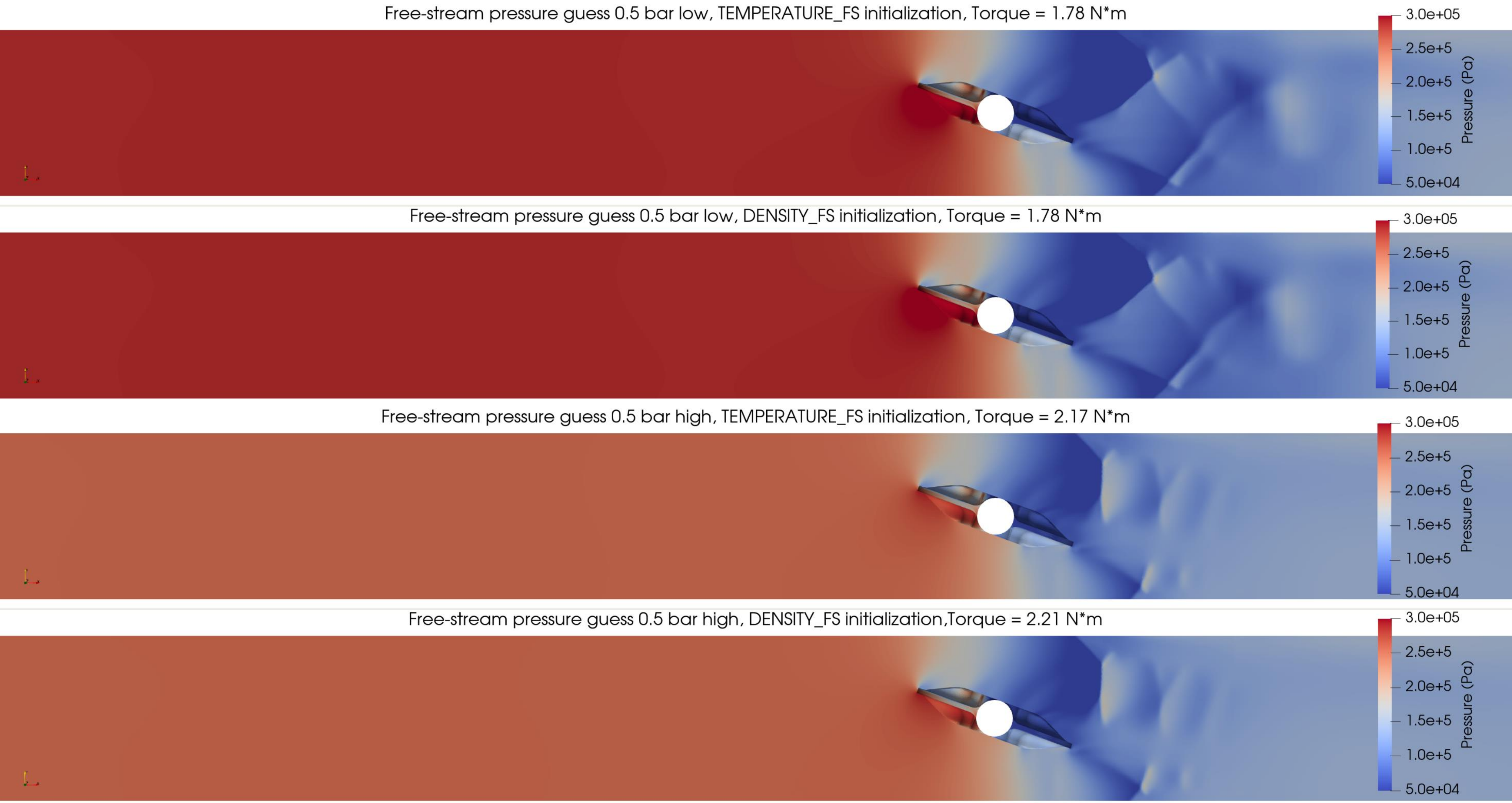
SU2 Setup

- A note about inlet boundary:
  - Normally, would use inlet total pressure boundary condition
  - However, due to effects of long inlet including sudden expansion, used a mass-flow inlet using flow data from test stand
  - Ran into a challenge with mass-flow inlet with SU2 (next slide)



SU2 Setup

- For MASS_FLOW inlet, SU2 specifies density and velocity; temperature and pressure are extracted from the domain (subsonic inlet assumed)
  - Free-stream initialization therefore is important, options are:
    - TEMPERATURE_FS → ρ_∞ calculated from P_∞, T_∞
    - DENSITY_FS → T_∞ calculated from ρ_∞, P_∞
    - To satisfy inlet boundary, free-stream initial conditions should reflect inlet hose region
  - From flow test, T_∞ is known, but P_∞ and V_∞ are unknown and thus ρ_∞ is unknown
- For this study, used the inlet conditions from CFX solutions for SU2 freestream initialization to generate robust initial conditions
- Also ran a 2x2 DOE of initialization option, and P_∞ guesses 0.5 bar too low and 0.5 bar too high vs. CFX solution (next slide)

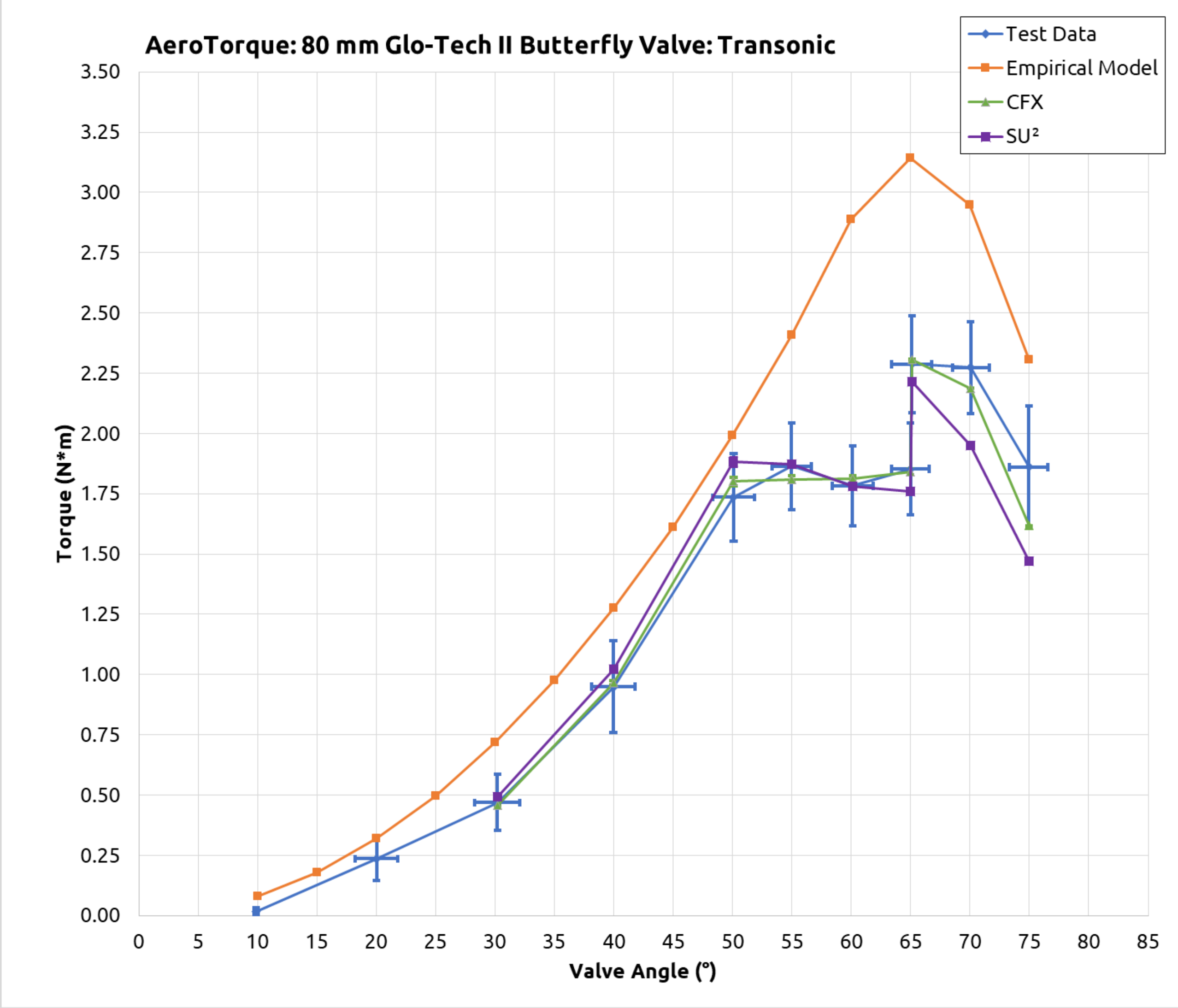


Free-stream pressure guess 0.5 bar low, TEMPERATURE_FS initialization, Torque = 1.78 N*m
Free-stream pressure guess 0.5 bar low, DENSITY_FS initialization, Torque = 1.78 N*m
Free-stream pressure guess 0.5 bar high, TEMPERATURE_FS initialization, Torque = 2.17 N*m
Free-stream pressure guess 0.5 bar high, DENSITY_FS initialization,Torque = 2.21 N*m
Pressure (Pa)
3.0e+05
2.5e+5
2.0e+5
1.5e+5
1.0e+5
5.0e+04

SU2 Setup

- ± 0.5 bar guess for P_∞ resulted in ± 0.4 N*m torque
  - 22% effect vs. mean torque at "correct" P_∞
- Negligible difference between TEMPERATURE_FS and DENSITY_FS initialization, provided all FS properties coupled to the initial P_∞ guess
- A mass flow inlet boundary with specified temperature would be useful for internal flows, such as in CFX
  - https://www.cfd-online.com/Forums/su2/151385-mass-flow-inlet-given-temperature.html
- That aside, on to the results…

SU2 Results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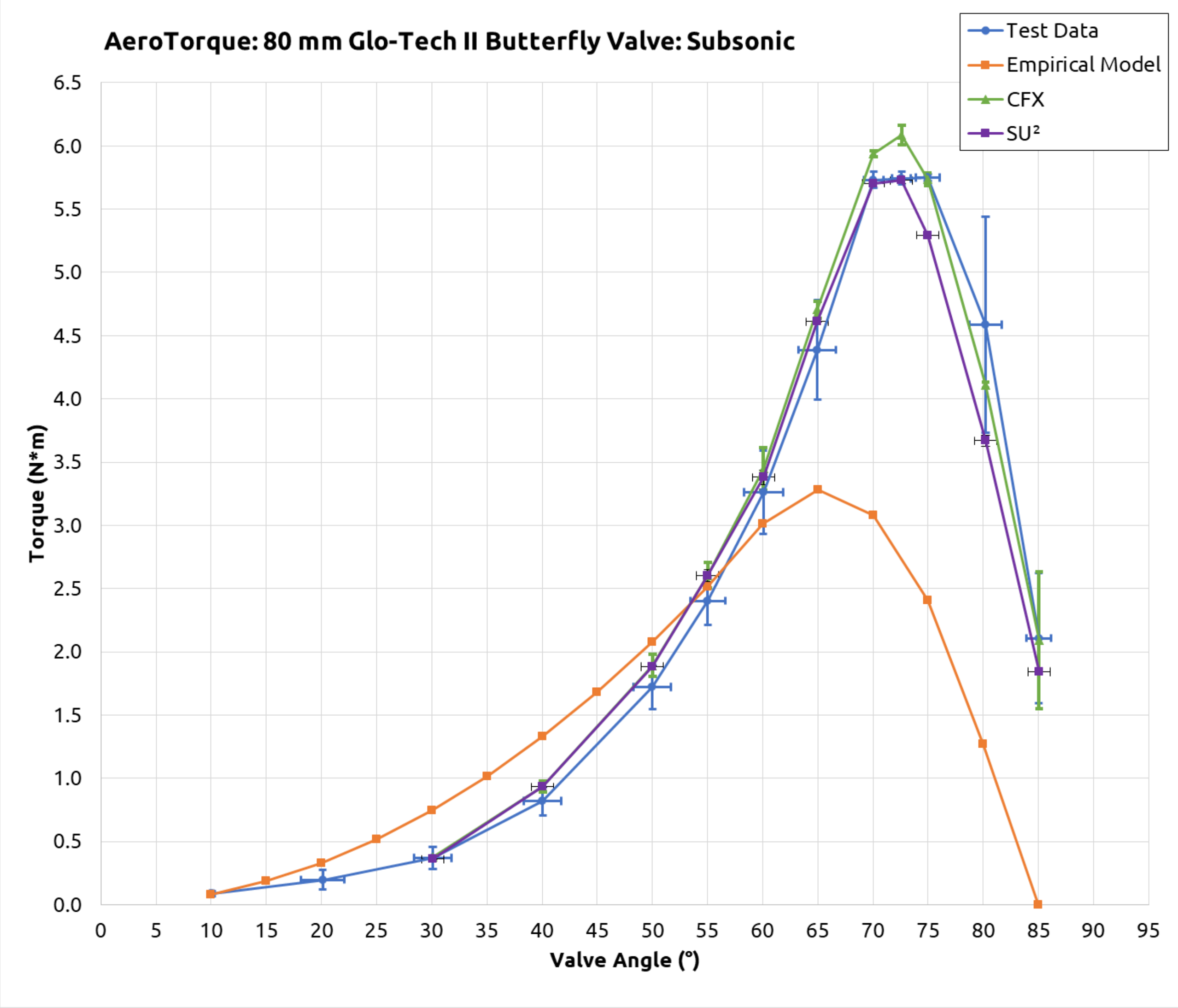
Empirical Model
CFX
SU²
Torque (N*m)
Valve Angle (°)
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85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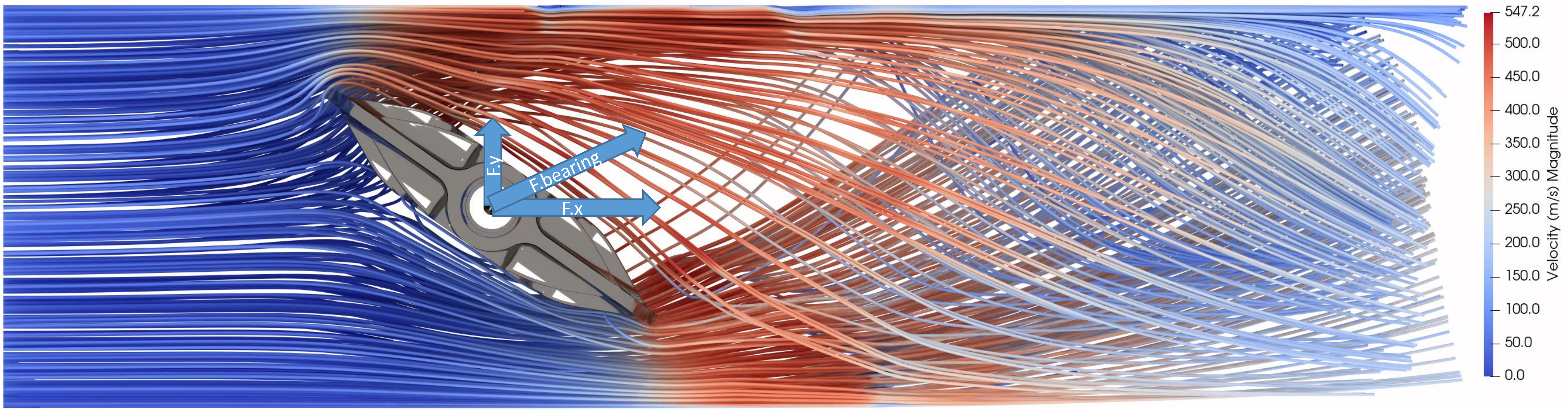
Test Data
Empirical Model
CFX
SU²
Torque (N*m)
Valve Angle (°)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95

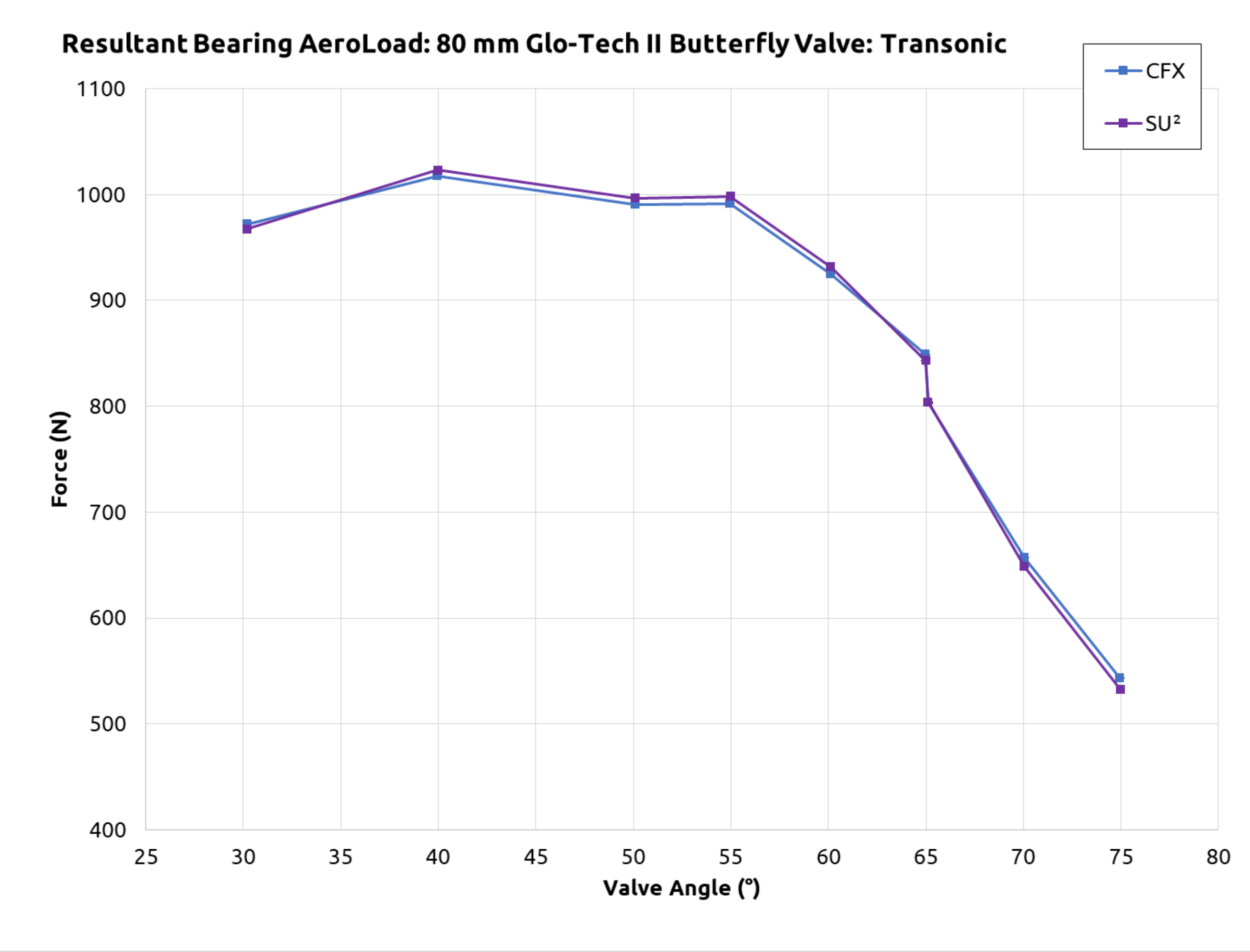
SU2 Results

- Also compared resultant force on plate
  - Used for bearing load; important for frictional torque contribution
  - No test data available for this quantity, rely solely on CFD

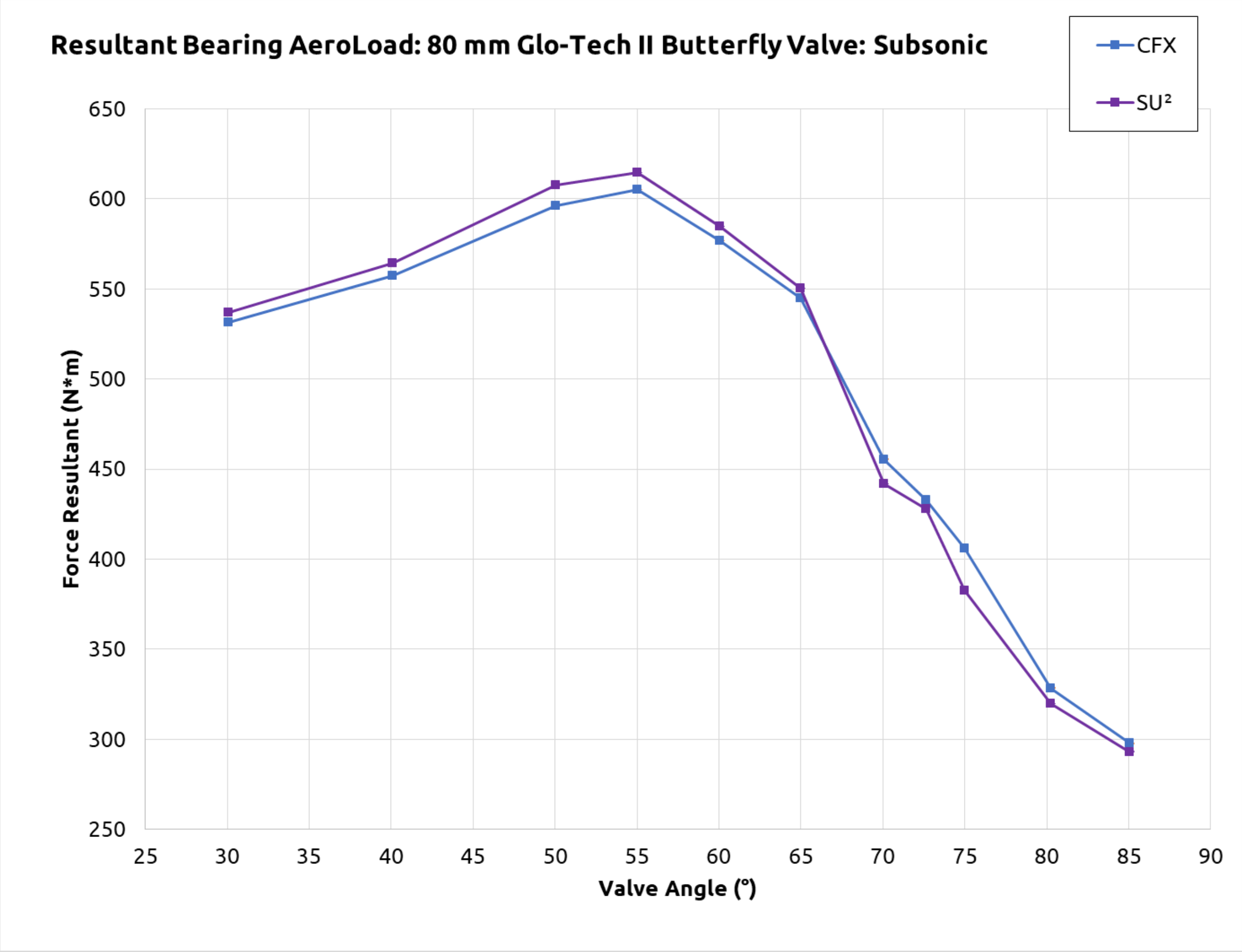


- Very good agreement between CFX and SU² (next slide)

SU2 Results



Resultant Bearing AeroLoad: 80 mm Glo-Tech II Butterfly Valve: Transonic
CFX
SU²
Force (N)
Valve Angle (°)
1100
1000
900
800
700
600
500
400
25
30
35
40
45
50
55
60
65
70
75
80

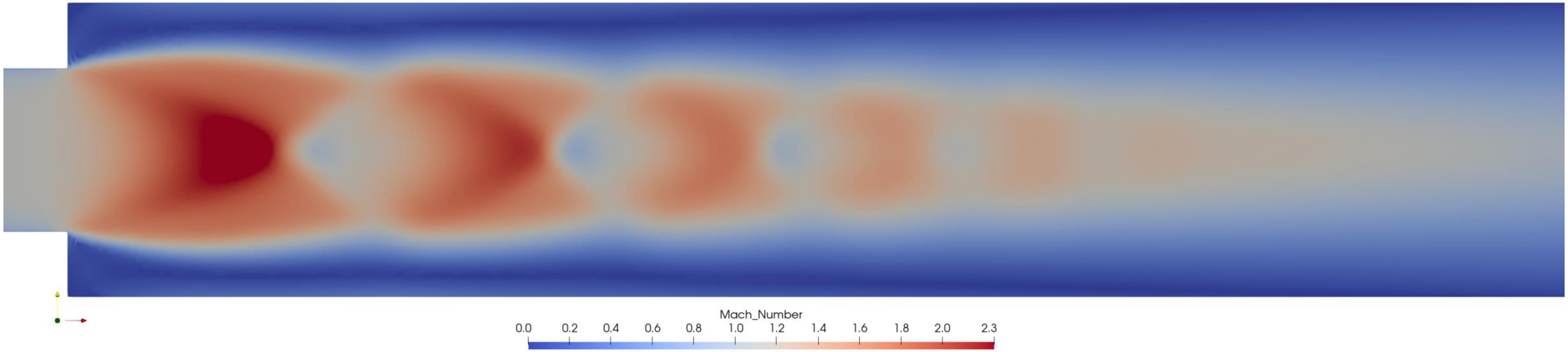


Resultant Bearing AeroLoad: 80 mm Glo-Tech II Butterfly Valve: Subsonic
CFX
SU²
Force Resultant (N*m)
Valve Angle (°)
650
600
550
500
450
400
350
300
250
25
30
35
40
45
50
55
60
65
70
75
80
85
90

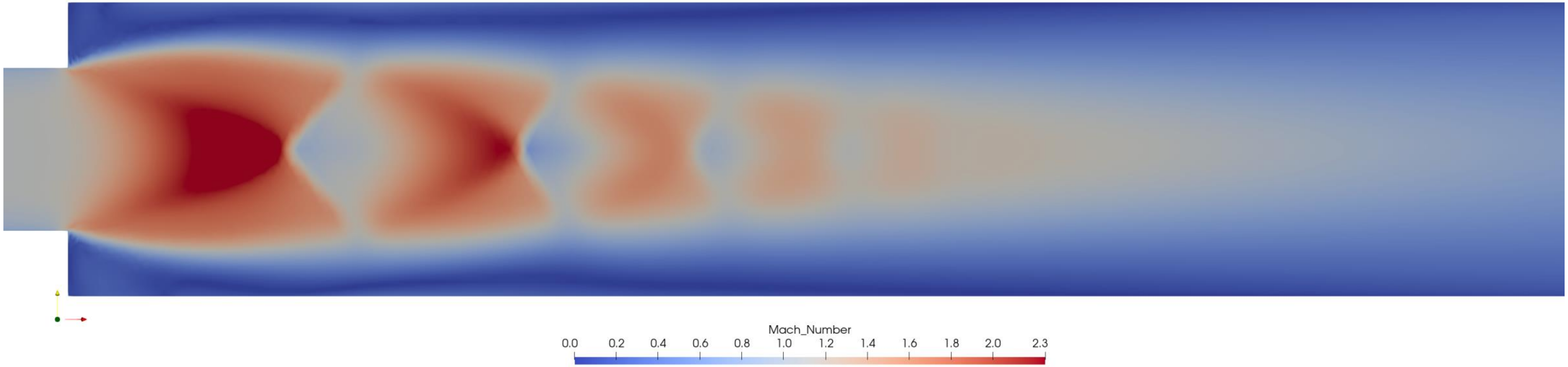
Comparative Visualizations – Sudden Expansion

WOODWARD

CFX

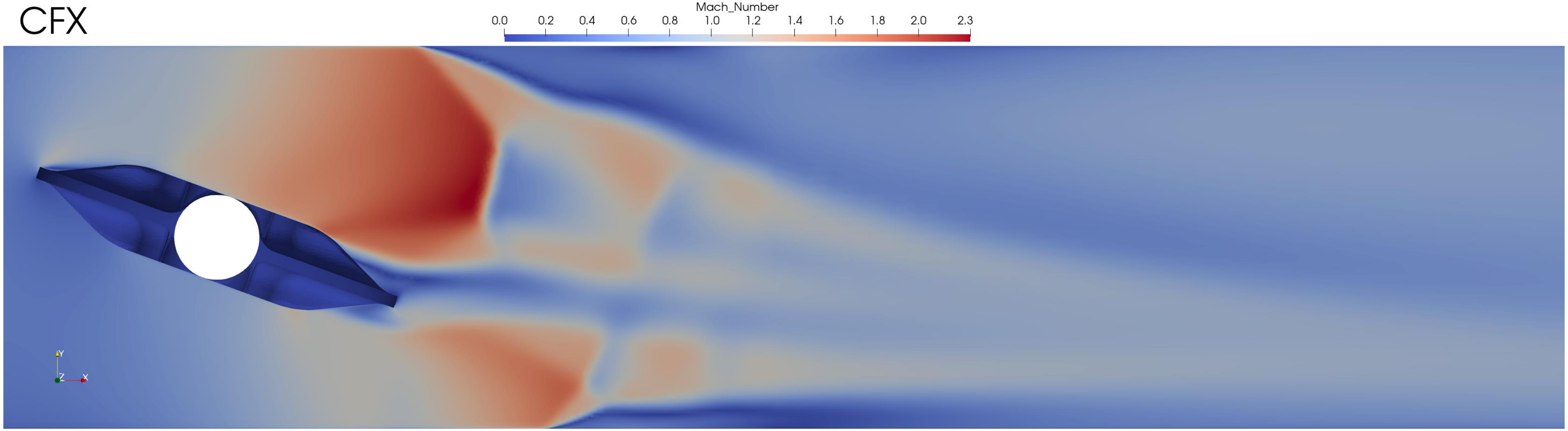


SU2

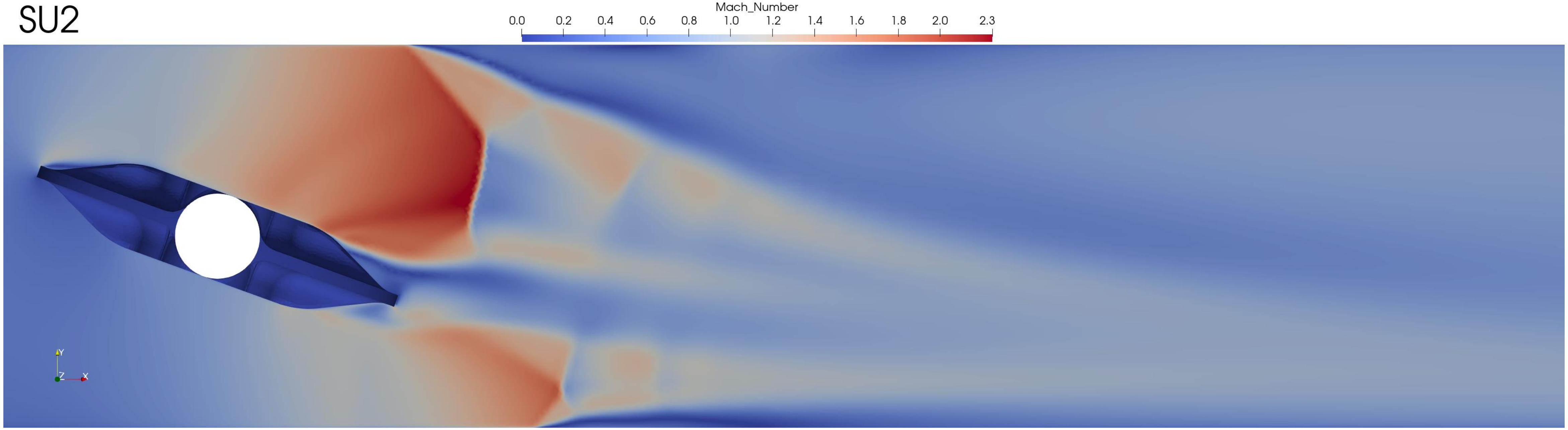


Comparative Visualizations – Plate Wake

CFX

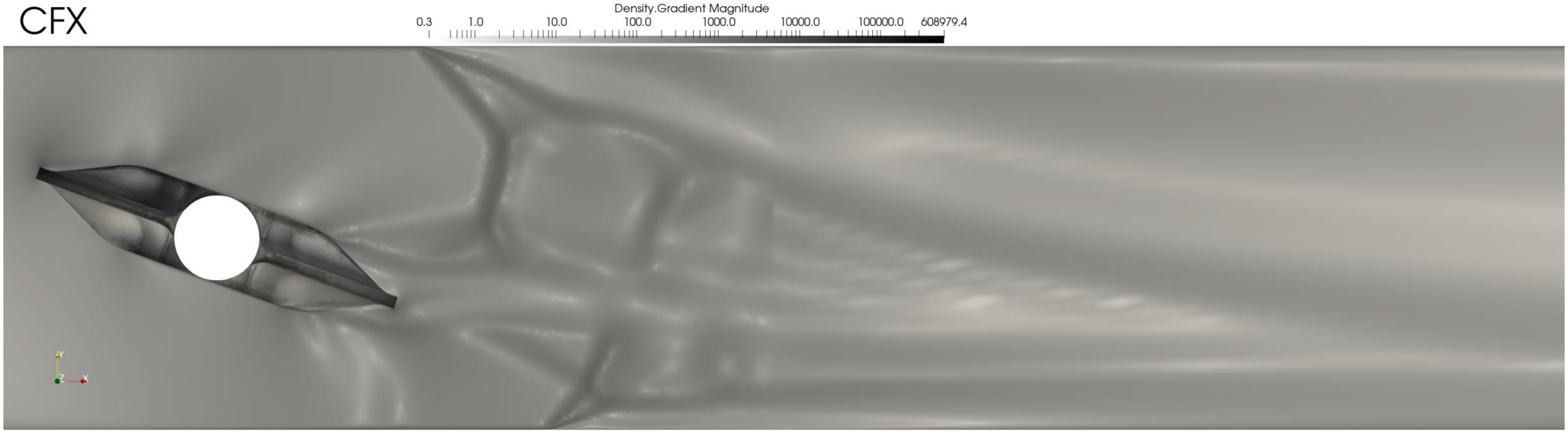


SU2



Comparative Visualizations – Plate Wake

CFX



SU2

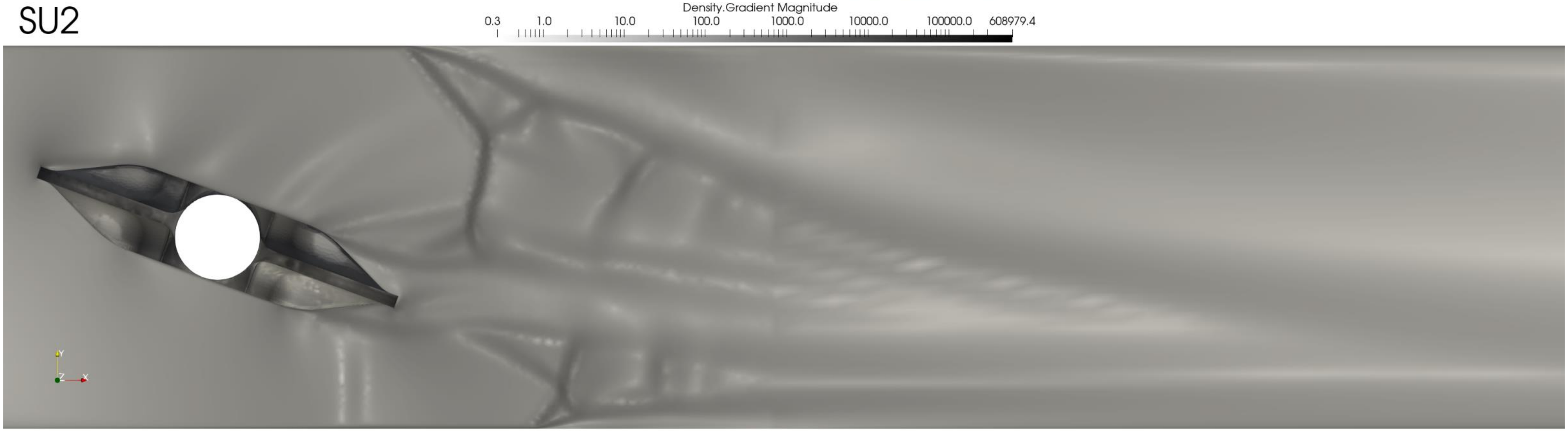


Plate Pressure, Transonic 70° Point

Possible region driving torque difference at 70°

note narrow pressure color scale

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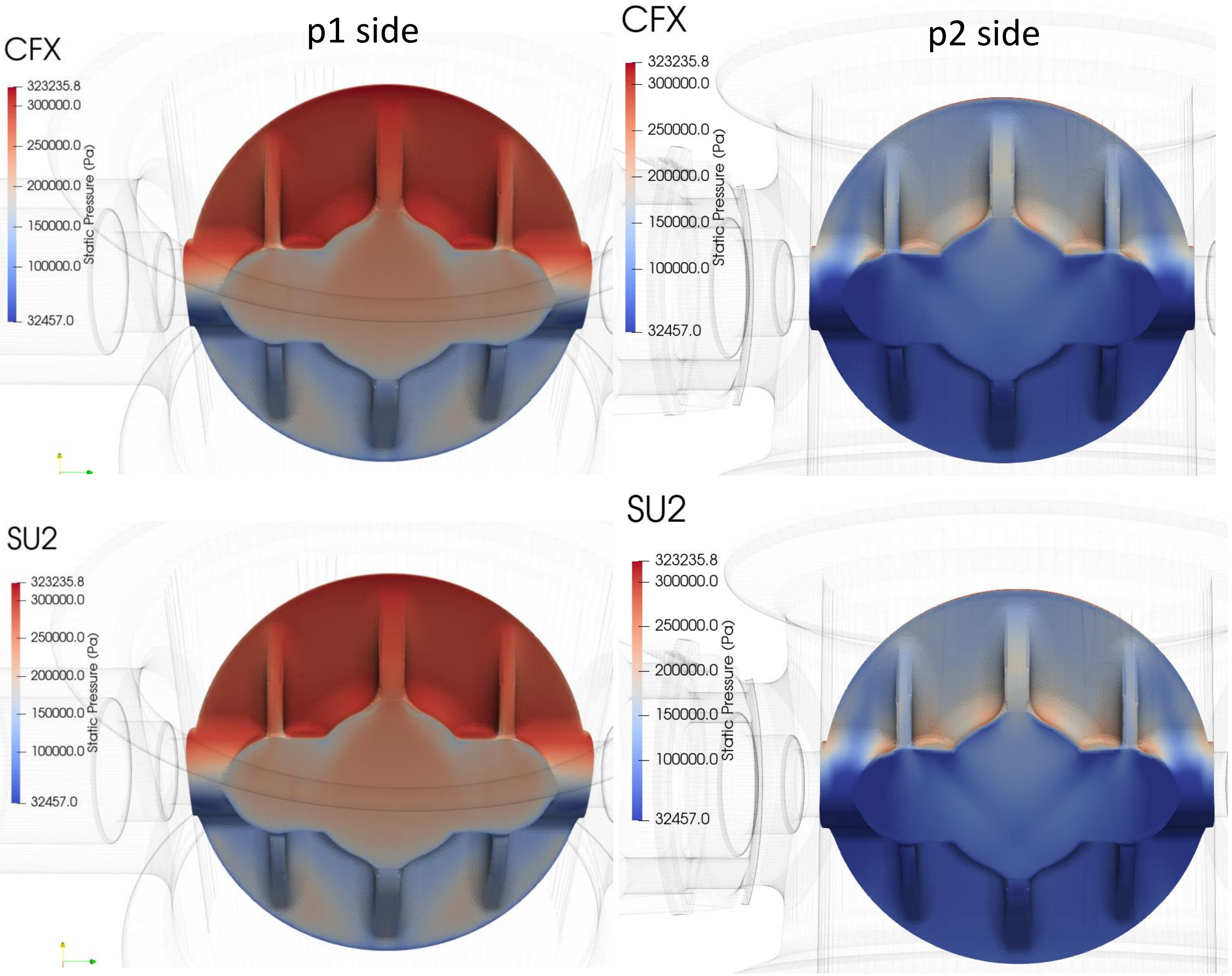

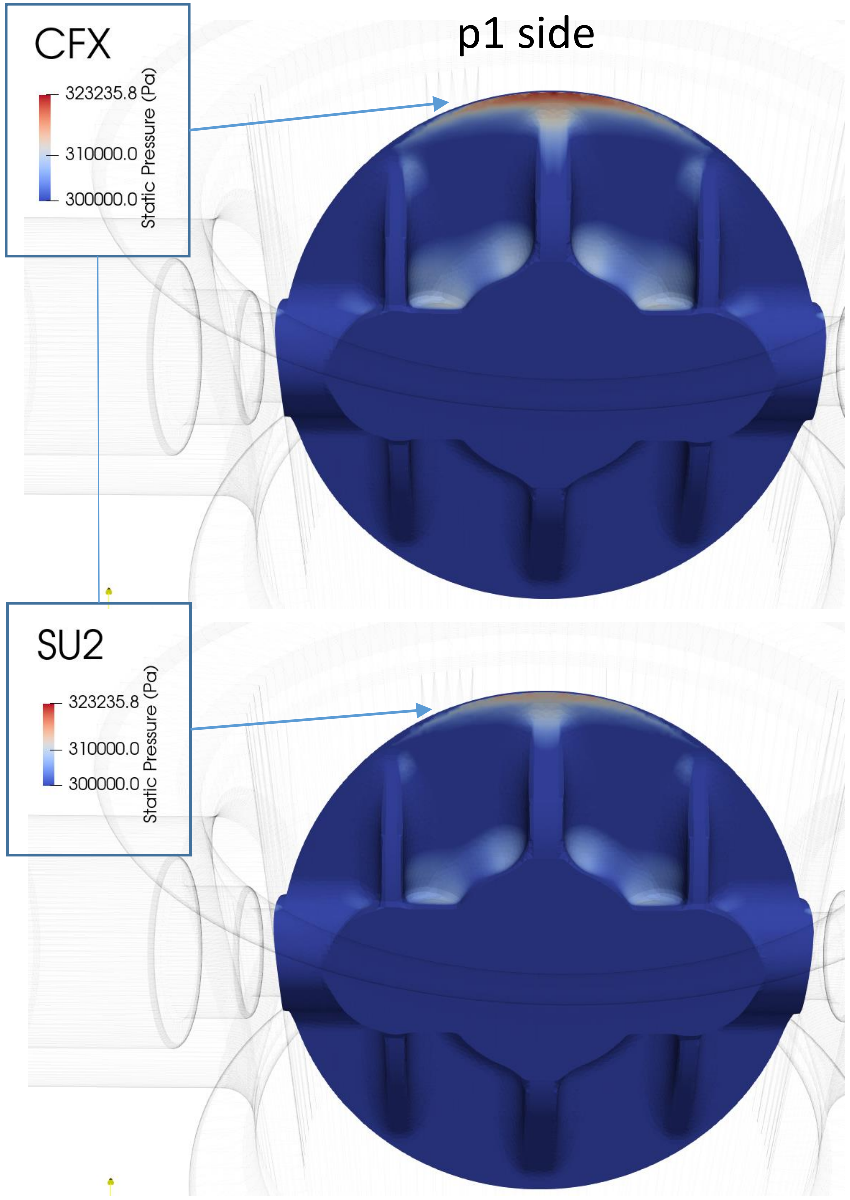

SU2 Conclusions

- Much-improved prediction over empirical model and largely inline with CFX results
  - Generally within error bars of test data
  - Exceptions:
    - 70° transonic and > 75° trans & subsonic, lower torque than CFX
  - Improved peak-torque prediction for subsonic vs. CFX
  - Accurately captures the torque-shift at 65° when P2 is increased from 16 to 18 psia
- SU2, using SLAU2, appears slightly less dissipative than CFX "High Resolution"
- SU2 produces results accurate enough for actuator sizing for valve system

Looking Ahead

- CFD can be a reliable tool for aerodynamic torque prediction of a butterfly plate, at transonic and subsonic conditions
- SU2 shown to compete well with CFX
  - Virtual “thumbs-up” to SU2 development team ☺
- Further areas of interest for SU2
  - Chasing down the high-angle torque sensitivities vs. CFX
  - Explore the adjoint capabilities: optimize geometry of plate to minimize aero torque/force?
  - Evaluate FEM DG solver – benefits/strengths/drawbacks vs FVM?
  - Scale-resolved simulations providing additional insight?

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