NSU3D Results for the Second AIAA High-Lift Prediction Workshop

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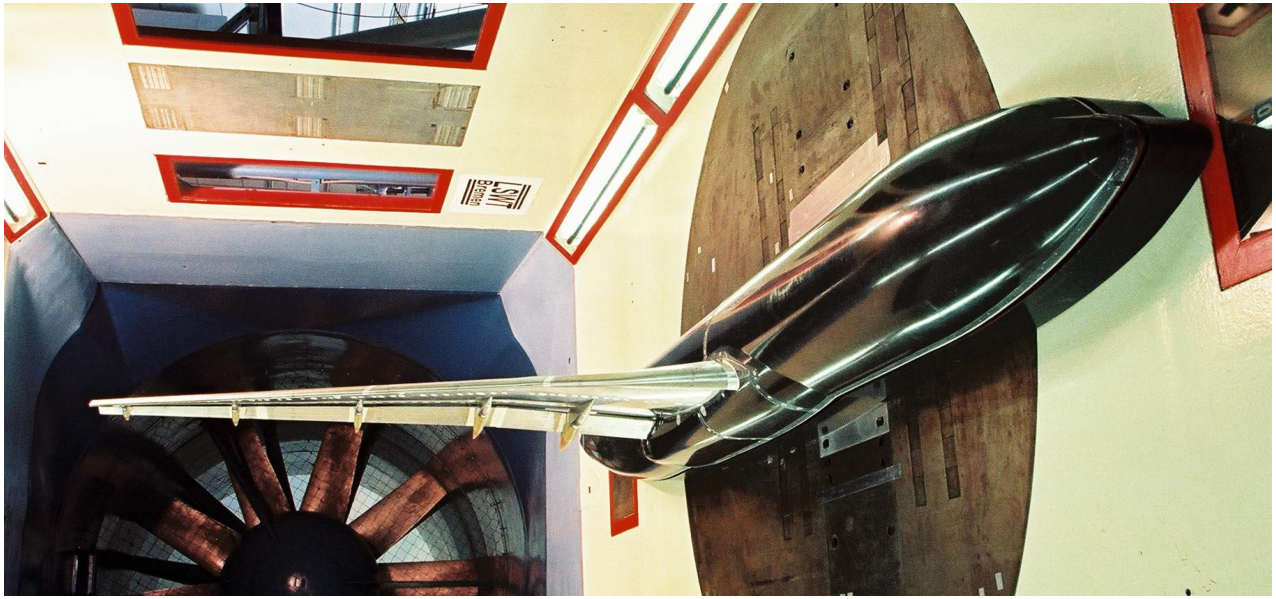
Overview

- HLPW2 geometry and test cases
- Description of unstructured meshes
- Description of NSU3D solver
- Results
  - Case 1: Grid convergence study at 7 and 16 degrees
  - Case 2a: High Re Polar Sweep
  - Case 2b: Low Re Polar Sweep
- Conclusions

Eurolift I Geometry



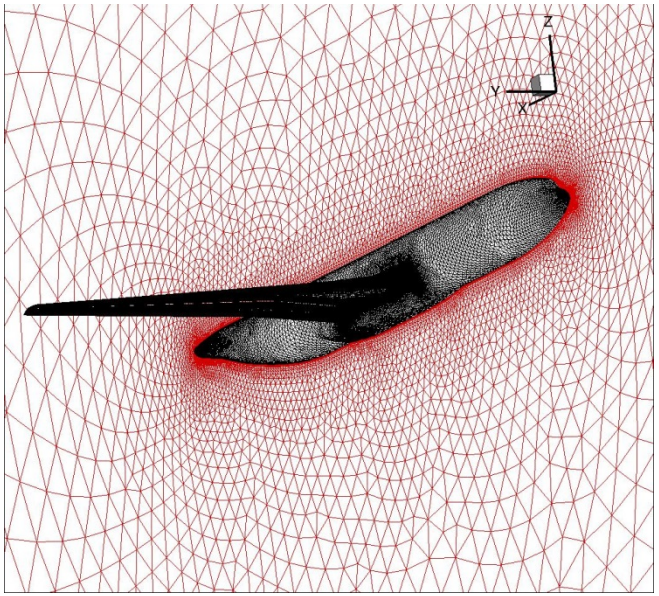
- Modern transport high lift configuration
- Increasing levels of geometric complexity
  - Mach = 0.175
  - Re = 15.1M and 1.35M
  - Case 1: No flap/slat track fairings: (7° and 16°)
  - Case 2: Alpha = 0 … post stall
  - Fully turbulent
  - Case 3 (full configuration) not computed

Unstructured Meshes

- Workshop supplied meshes
  - Unstructured Merged Node Based (D)
  - Generated by Mike Long (UW) and Mark Chaffin (Cessna)
  - Gridding guidelines
  - Fully tetrahedral Vgrids merged into mixed element meshes for NSU3D
    - Prisms in boundary layer regions

- Total of 4 meshes used
  - C,M,F: Case 1
  - M: Case 2a and 2b

Unstructured Meshes



Grid	Nodes	Tetrahedra	Prisms
Case1: Coarse	**10.2M**	13.8M	15.4M
Case1: Medium	**30.8M**	58.3M	40.8M
Case1: Fine	**76.0M**	187M	86.7M
Case 2: Medium	**41.5M**	71.4M	57.6M

NSU3D Description

- Unstructured Reynolds Averaged Navier-Stokes solver
  - Vertex-based discretization
  - Mixed elements (prisms in boundary layer)
  - Edge data structure
  - Matrix artificial dissipation
    - Option for Roe upwind scheme with gradient reconstruction
  - No cross derivative viscous terms
    - $\nabla(\mu \nabla v)$: (Similar to incompressible Full NS)
    - Option for full Navier-Stokes terms
      - Extended stencil with edge-based normal derivatives
      - Similar to most other node-based unstructured solvers

Solver Description (cont'd)

- Spalart-Allmaras turbulence model
  - (original published form)
  - Used exclusively in HLPW calculations

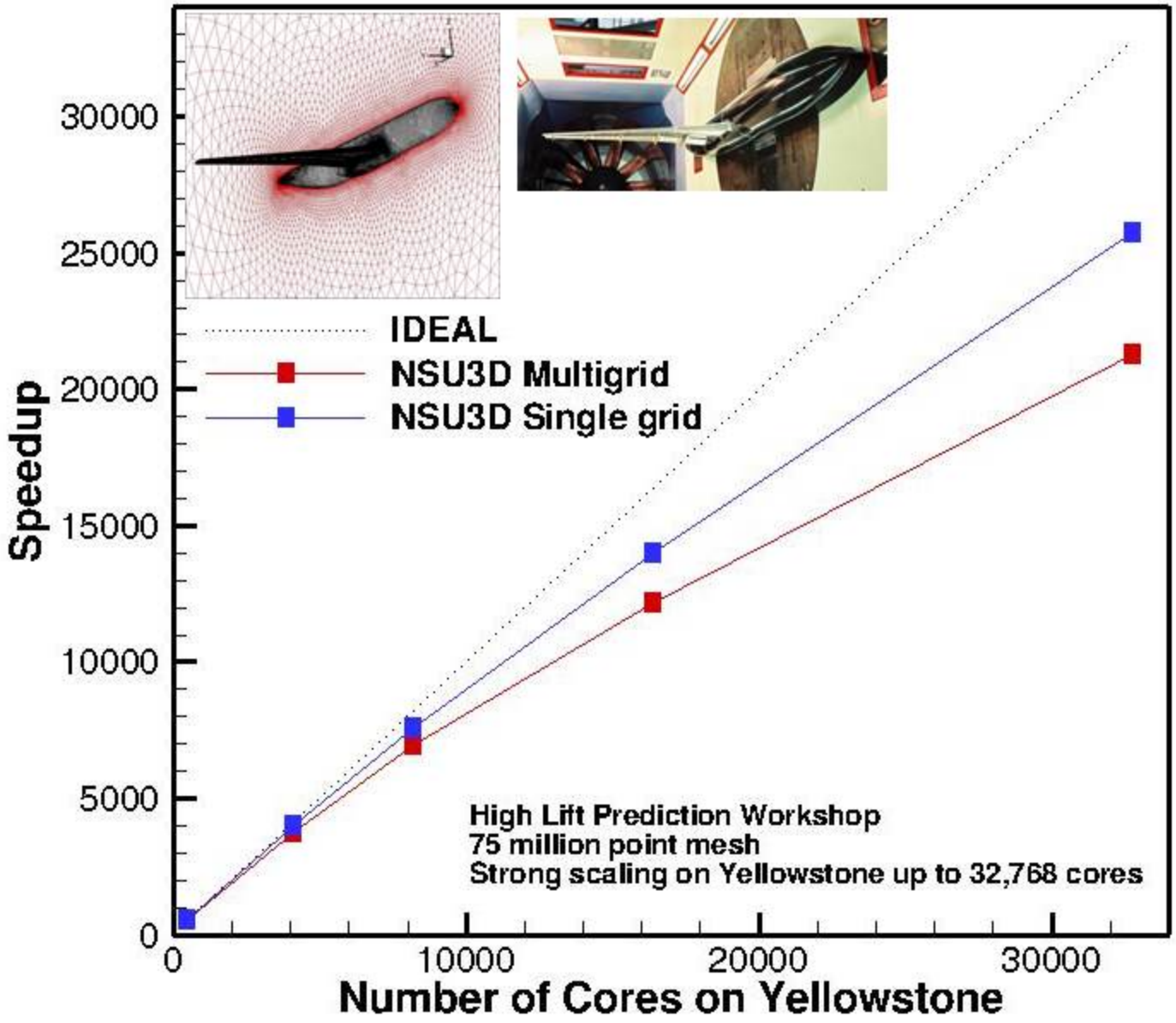
- Options for
  - Wilcox k-omega model
  - Mentor SST Model
  - Not exercised

Solution Strategy

- Jacobi/Line Preconditioning
  - Line solves in boundary layer regions
    - Relieves aspect ratio stiffness
- Agglomeration multigrid
  - Fast grid independent convergence rates
- Linear solver option
  - Multigrid or single grid
  - Line Jacobi subiterations
  - GMRES Krylov method for complete convergence

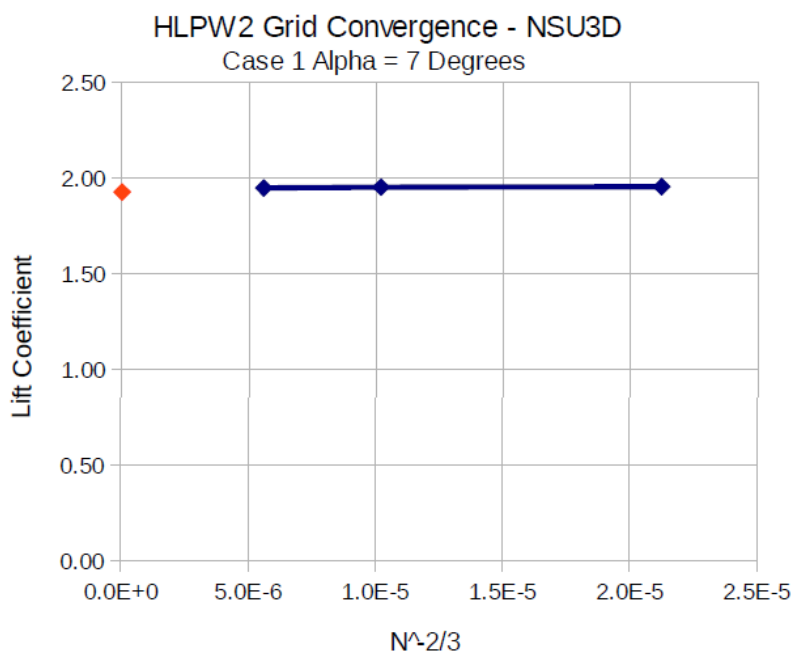
Sample Run Times

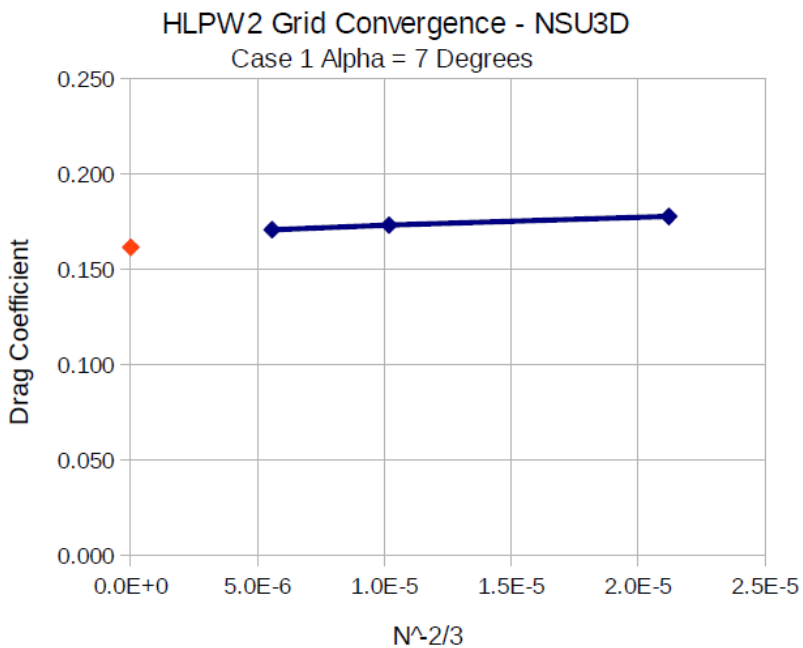
- All runs performed on Intel SandyBridge hardware (2.6GHz)
  - Good scalability up to large numbers of cores > 10,000
  - Sample timing
    - Medium mesh (Case 2) : 40M points
    - 1.7 seconds per cycle on 1024 cores
    - < 1 hour for well behaved cases
  - Run large number of iterations for other cases …


IDEAL
NSU3D Multigrid
NSU3D Single grid
High Lift Prediction Workshop
75 million point mesh
Strong scaling on Yellowstone up to 32,768 cores
Speedup
Number of Cores on Yellowstone
0
5000
10000
15000
20000
25000
30000
0
10000
20000
30000

Grid Convergence Study

Case 1: 7 degrees

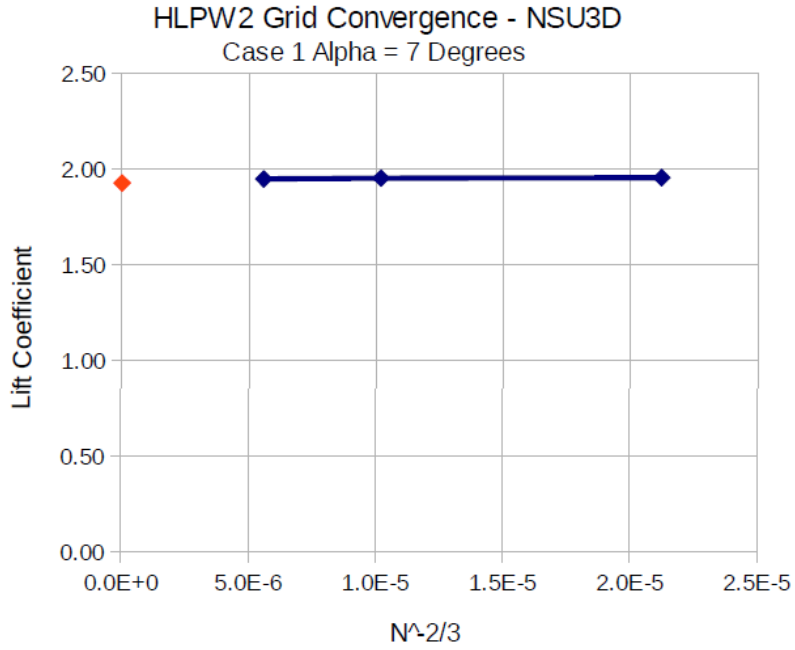


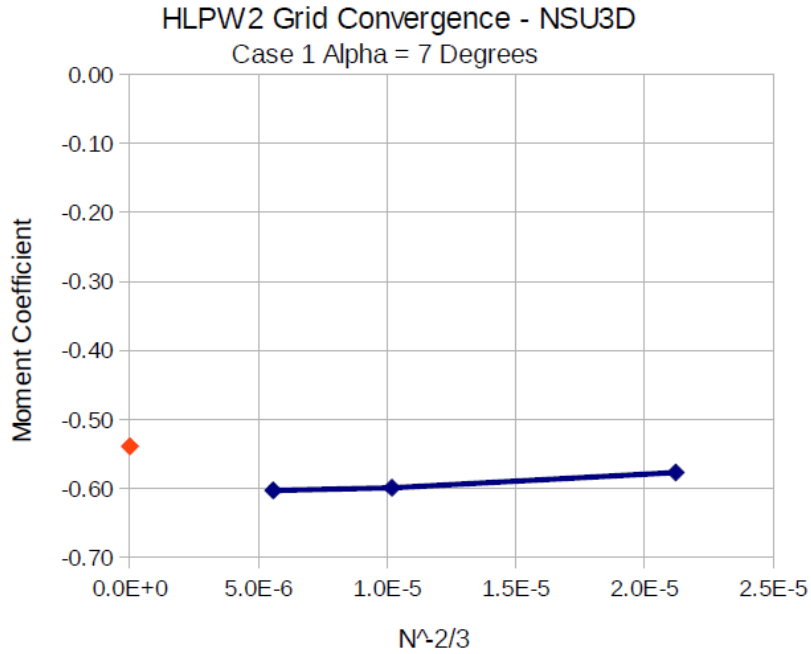


- Reasonable looking grid convergence
- Only 3 data points …

Grid Convergence Study

Case 1: 7 degrees

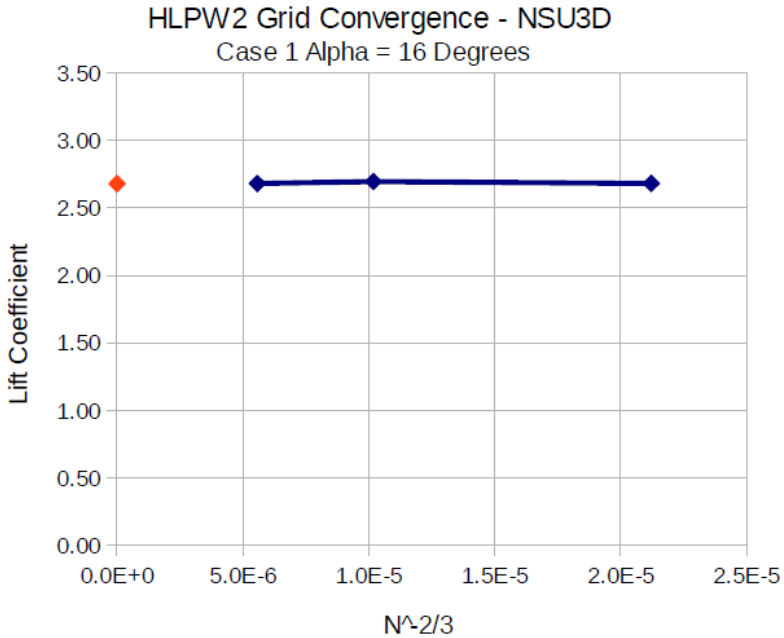


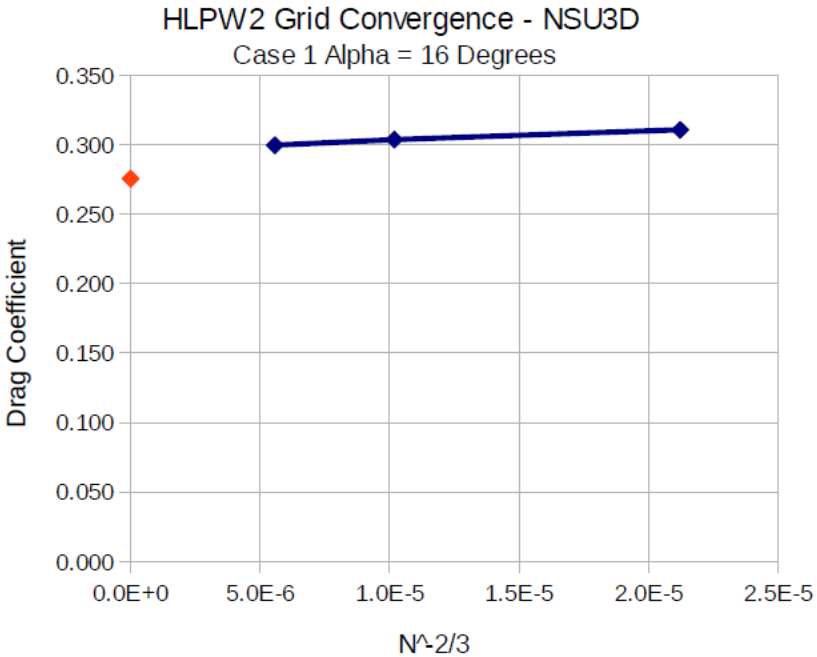


- Reasonable looking grid convergence
- Only 3 data points…

Grid Convergence Study

Case 1: 16 degrees

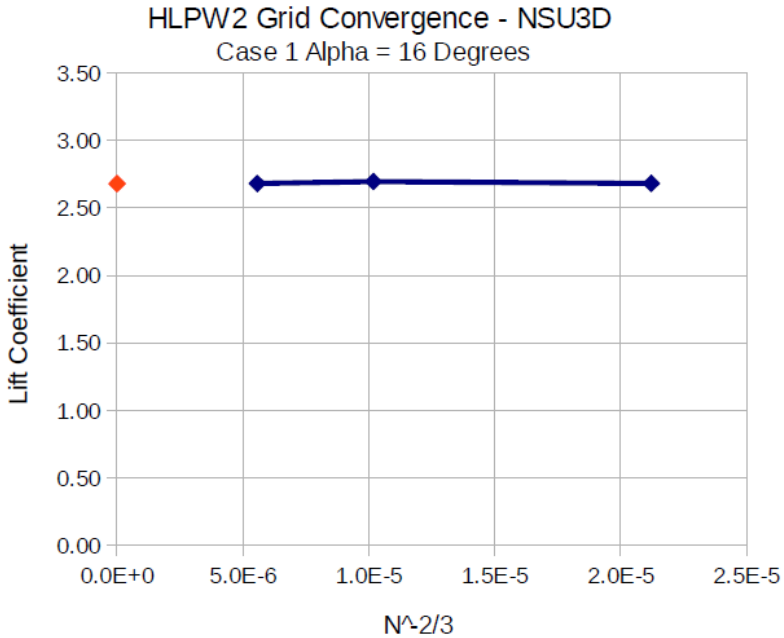


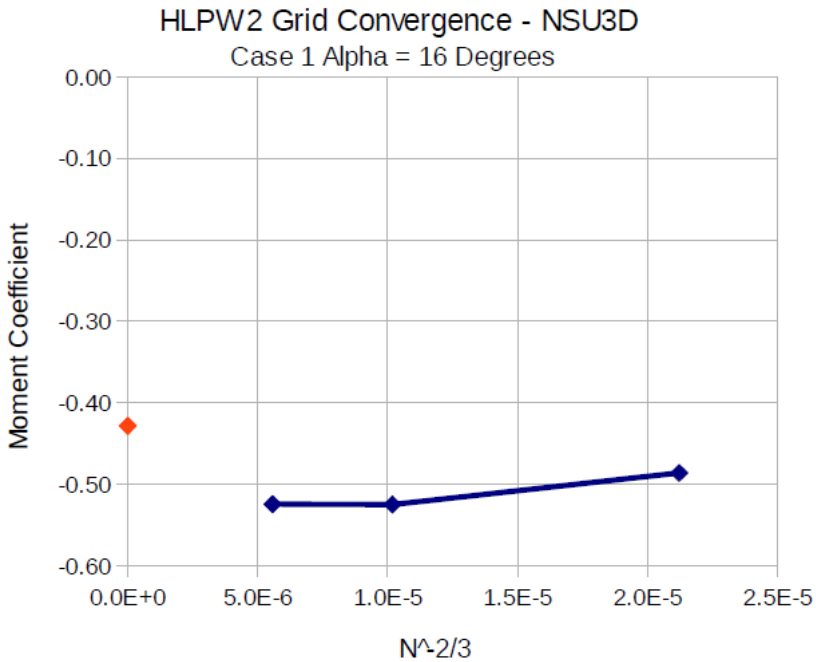


- Reasonable looking grid convergence
- Only 3 data points …

Grid Convergence Study

Case 1: 16 degrees





- Reasonable looking grid convergence
- Only 3 data points …

HLPW-2 Case 1 Alpha 7, Section 01
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-2.5
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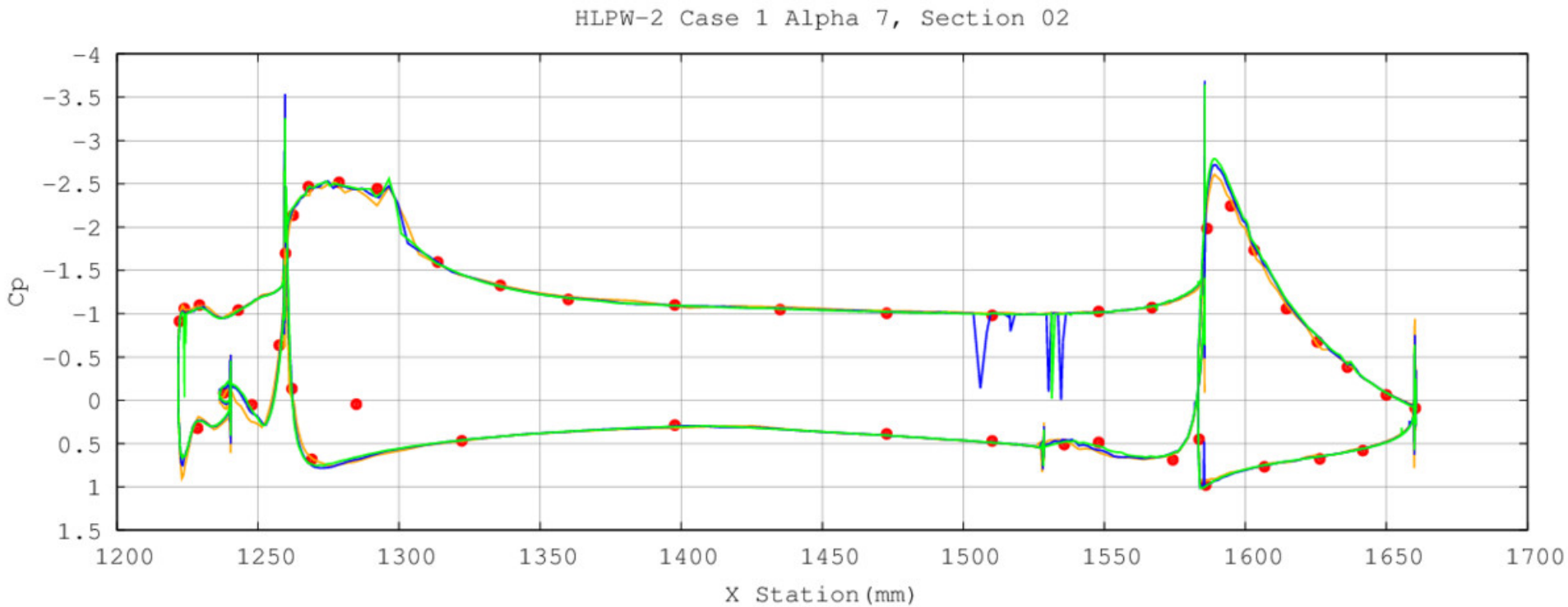
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-1
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1
1.5
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
X Station(mm)

HLPW-2 Case 1 Alpha 7, Section 04
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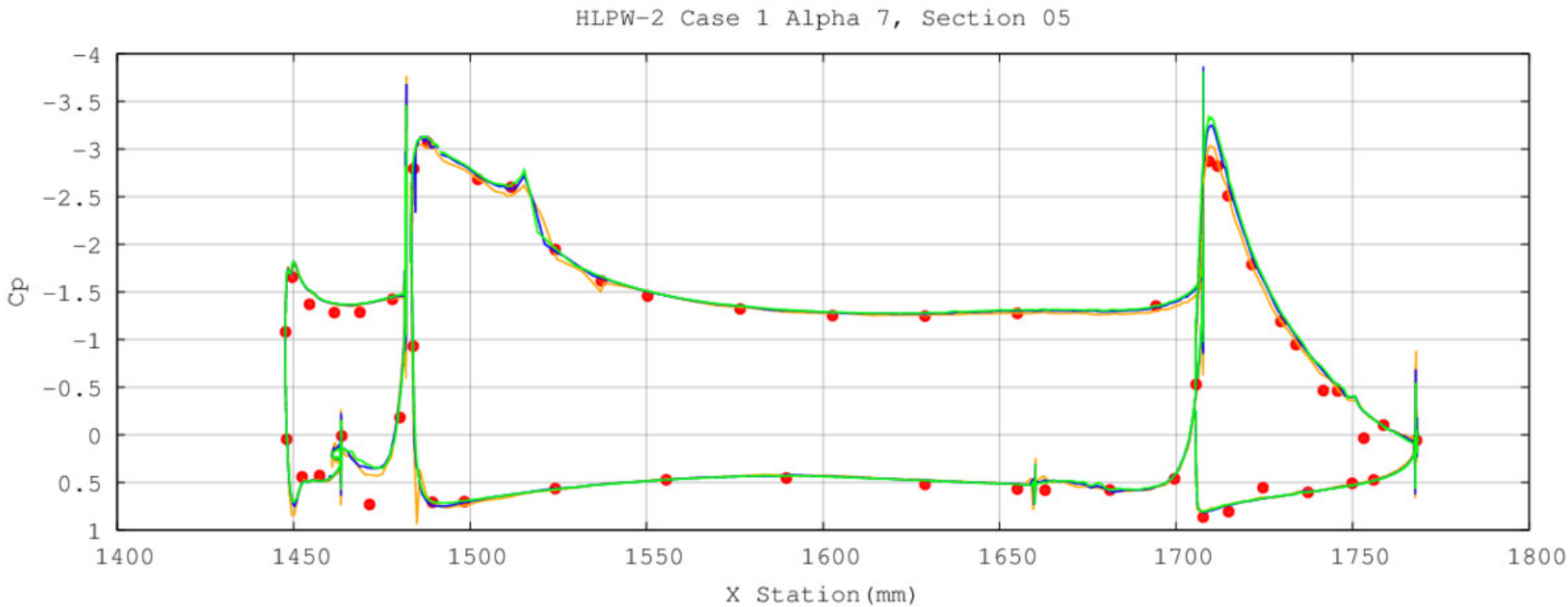
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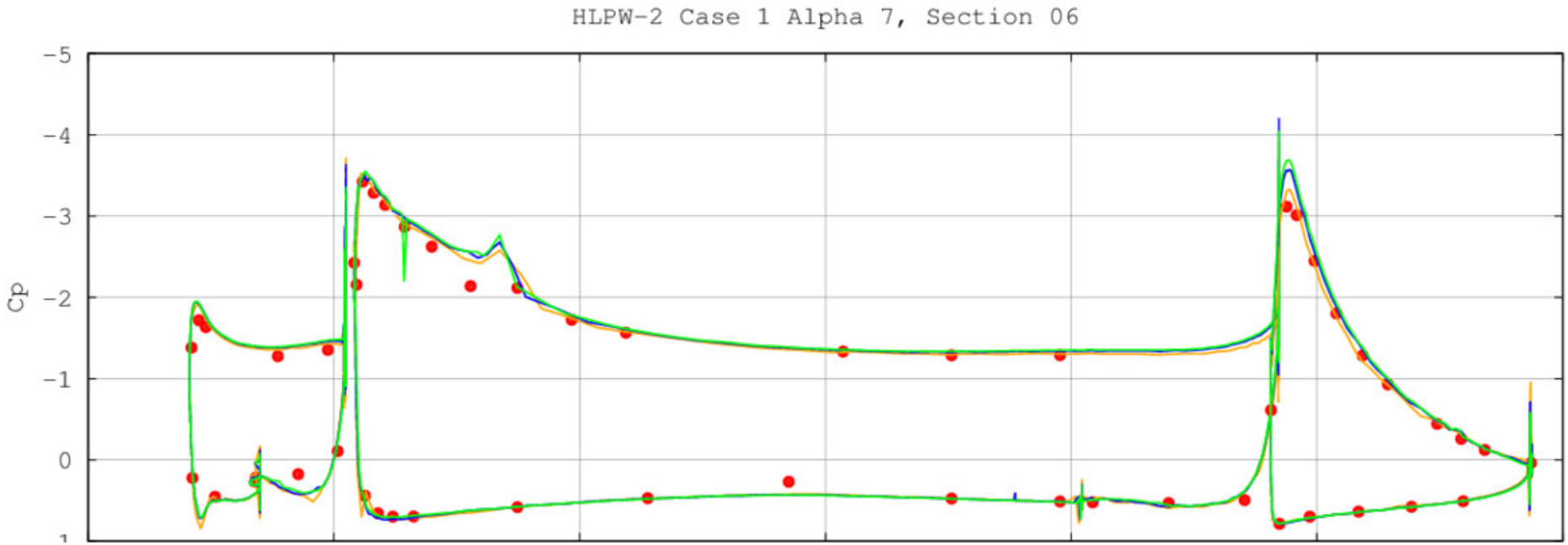
1800
X Station(mm)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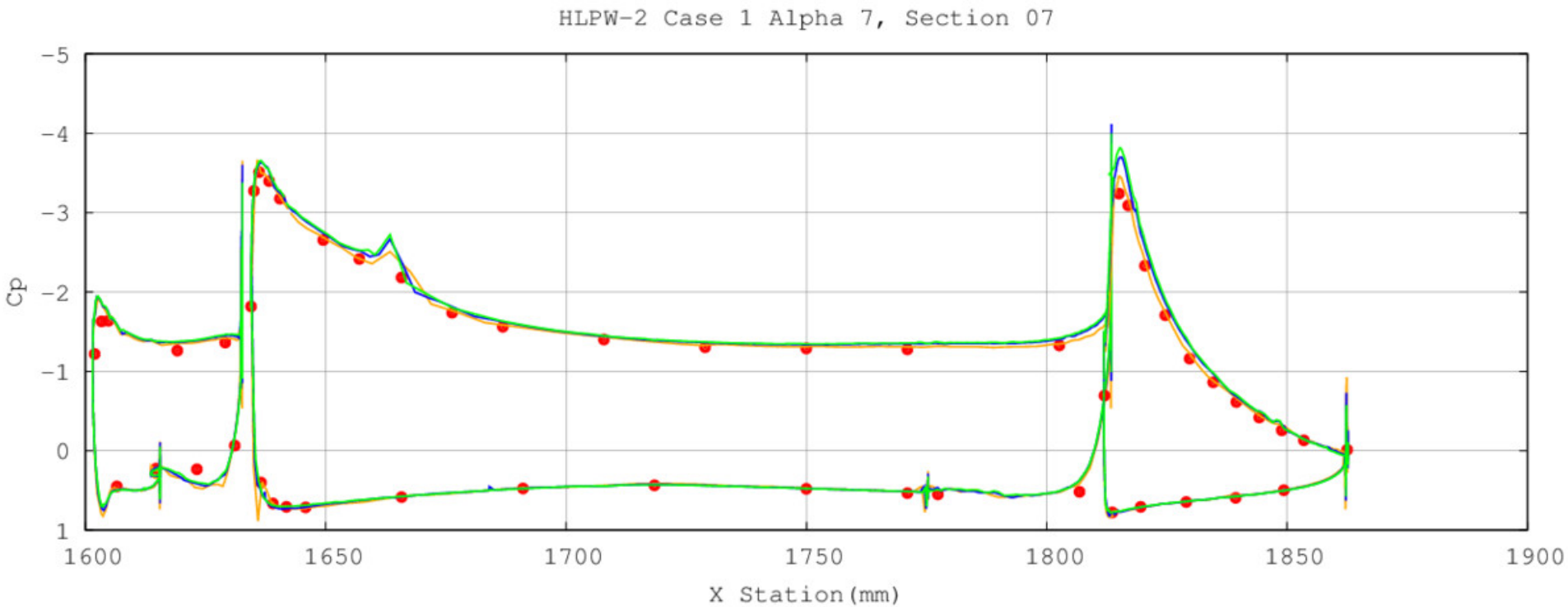
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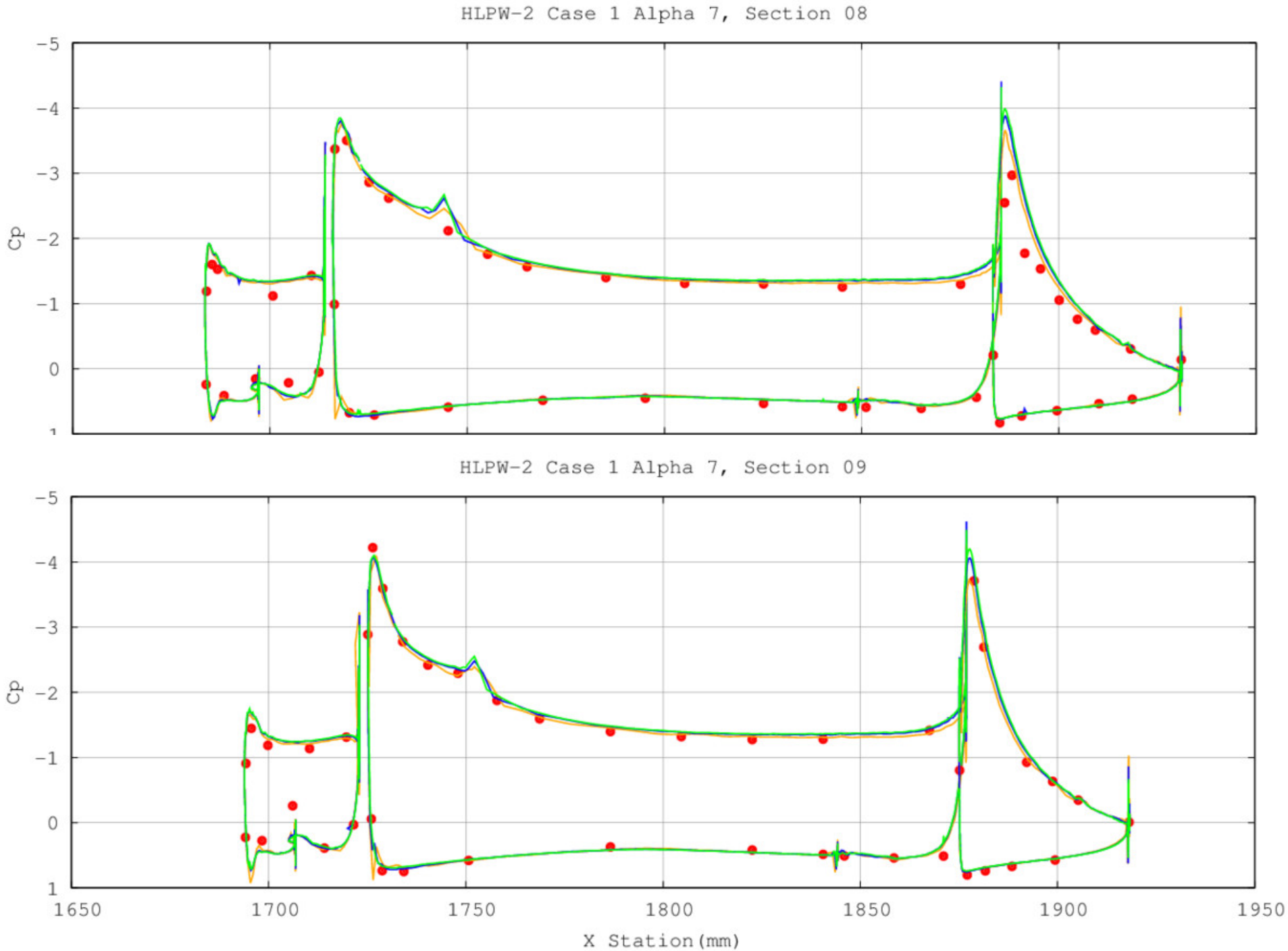
X Station(mm)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HLPW-2 Case 1 Alpha 7, Section 09
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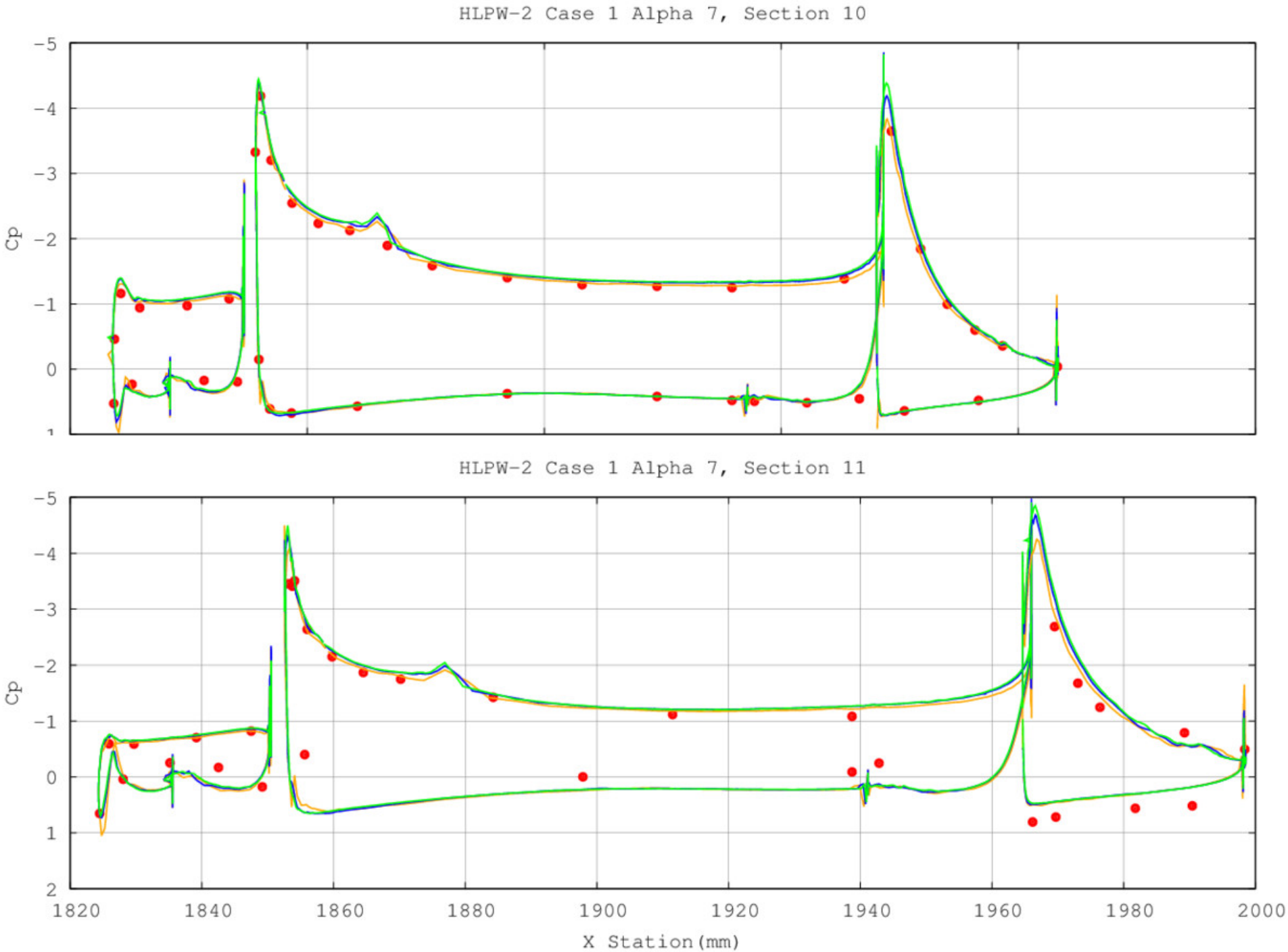
X Station(mm)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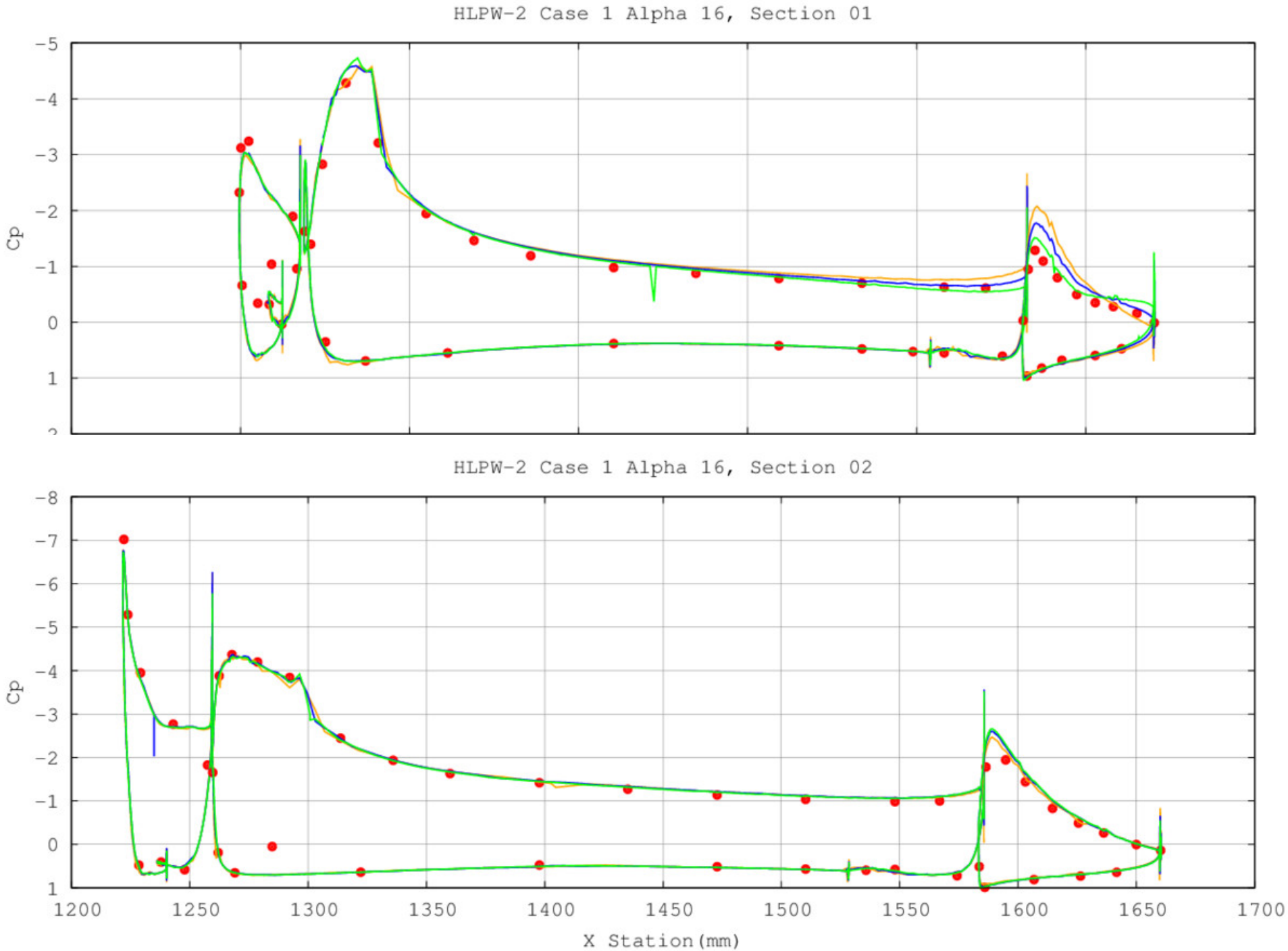
X Station(mm)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HLPW-2 Case 1 Alpha 16, Section 02
Cp
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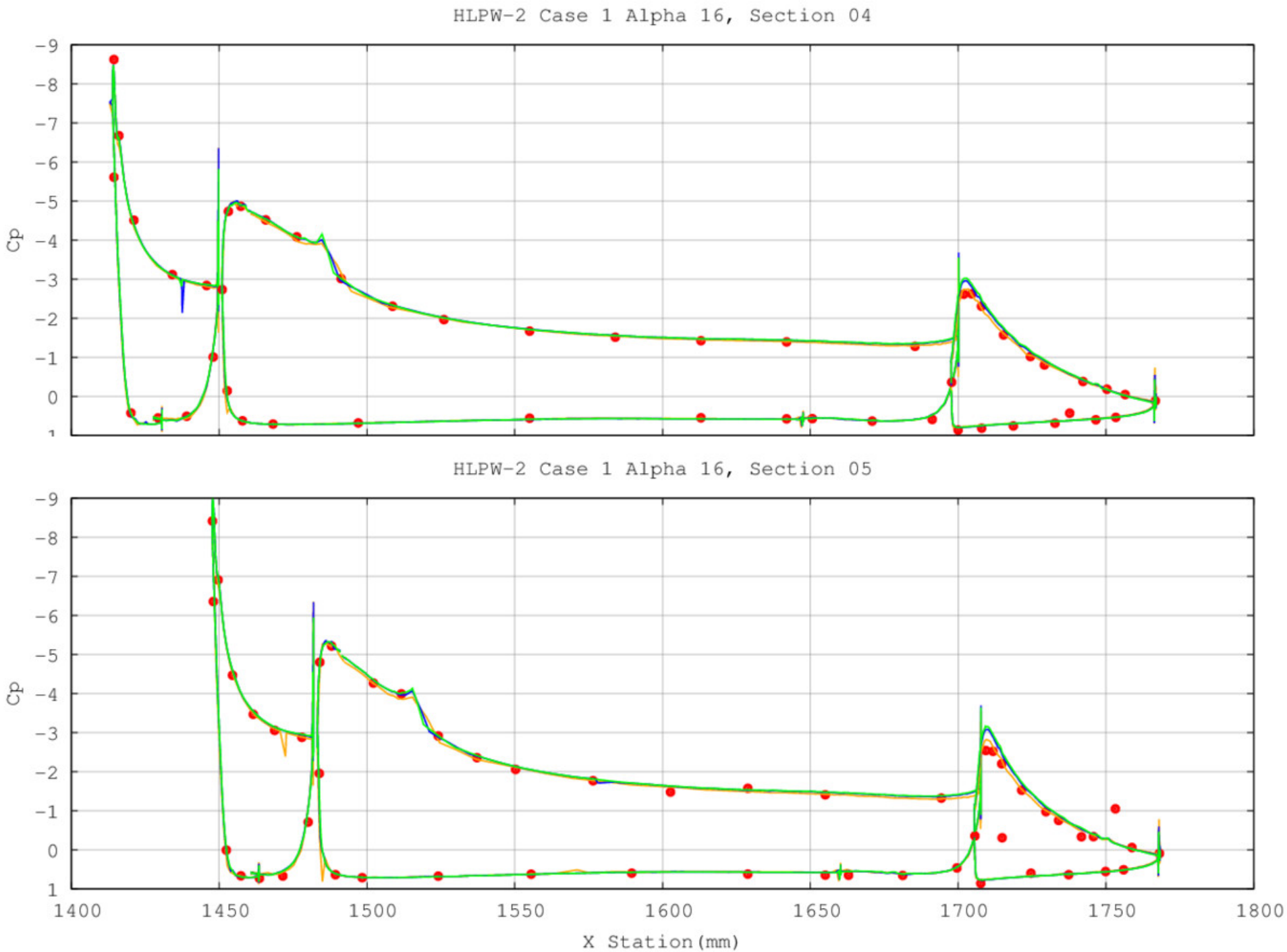
1700
X Station(mm)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Cp
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-8
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-2
-1
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1
HLPW-2 Case 1 Alpha 16, Section 05
Cp
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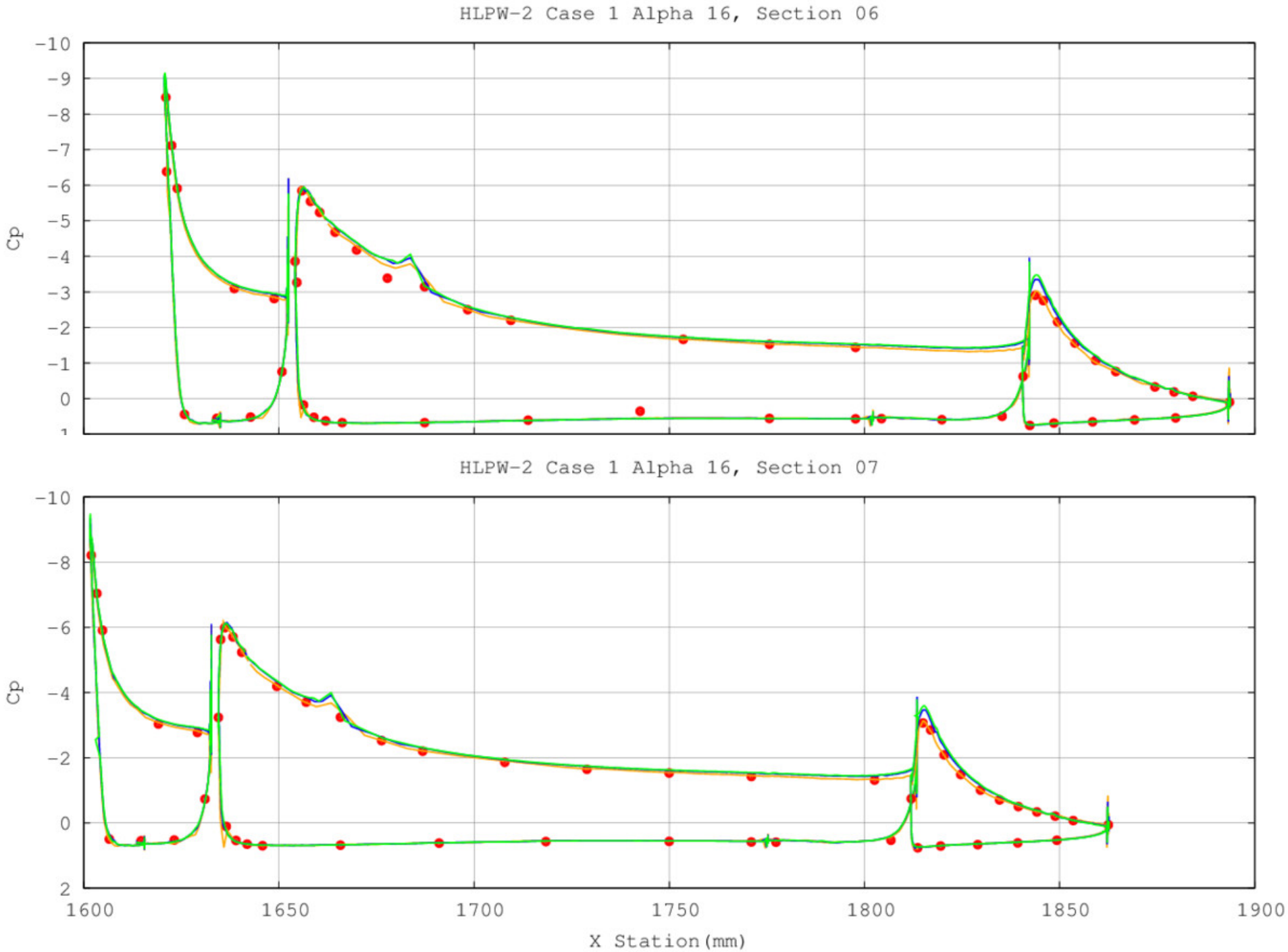
X Station(mm)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Cp
-10
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HLPW-2 Case 1 Alpha 16, Section 07
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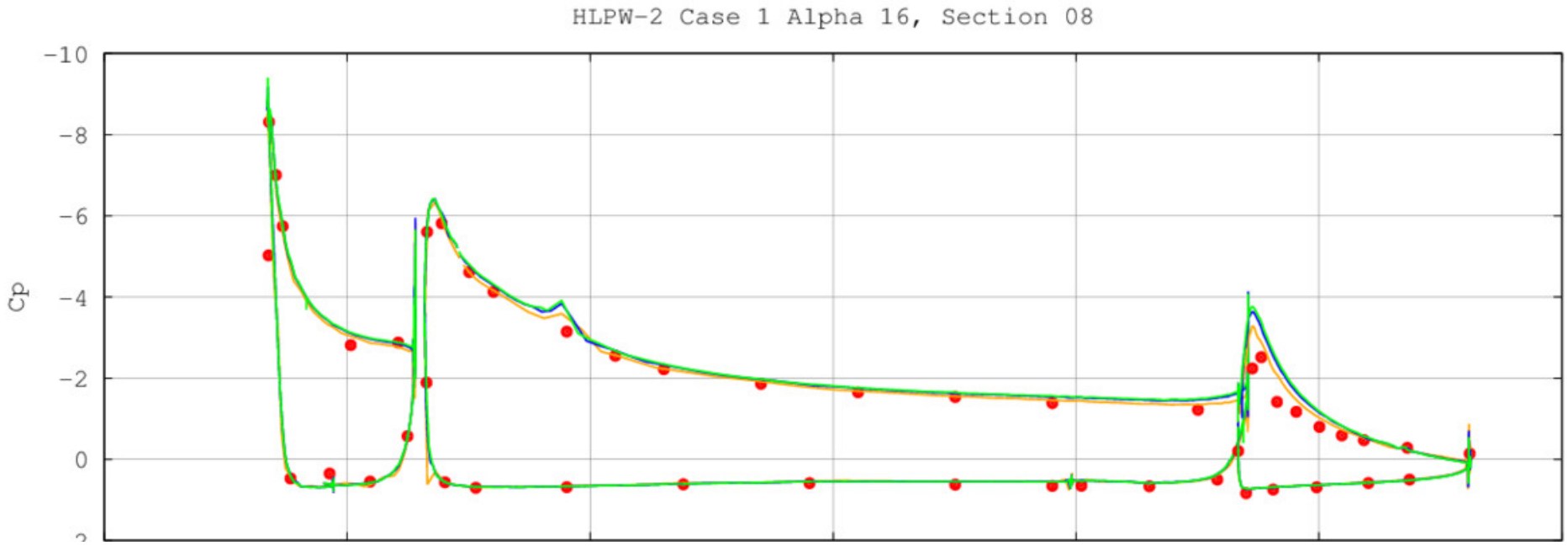
X Station(mm)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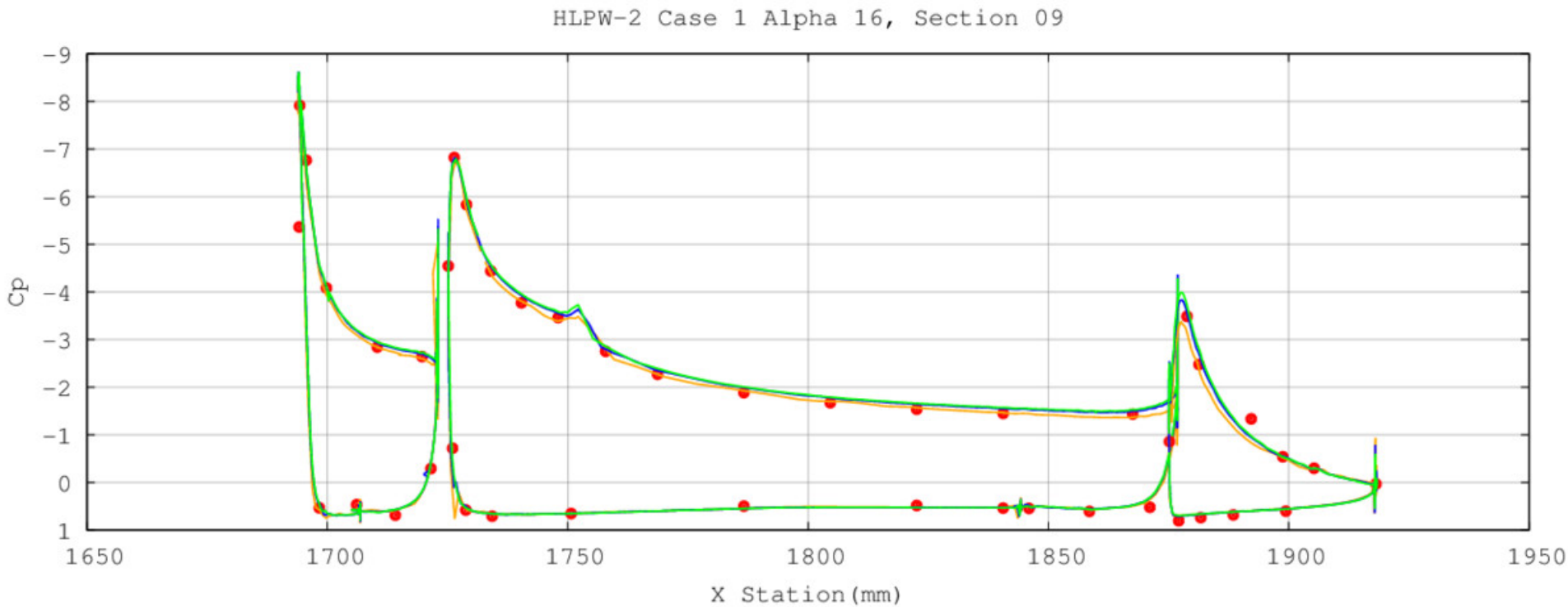
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-8
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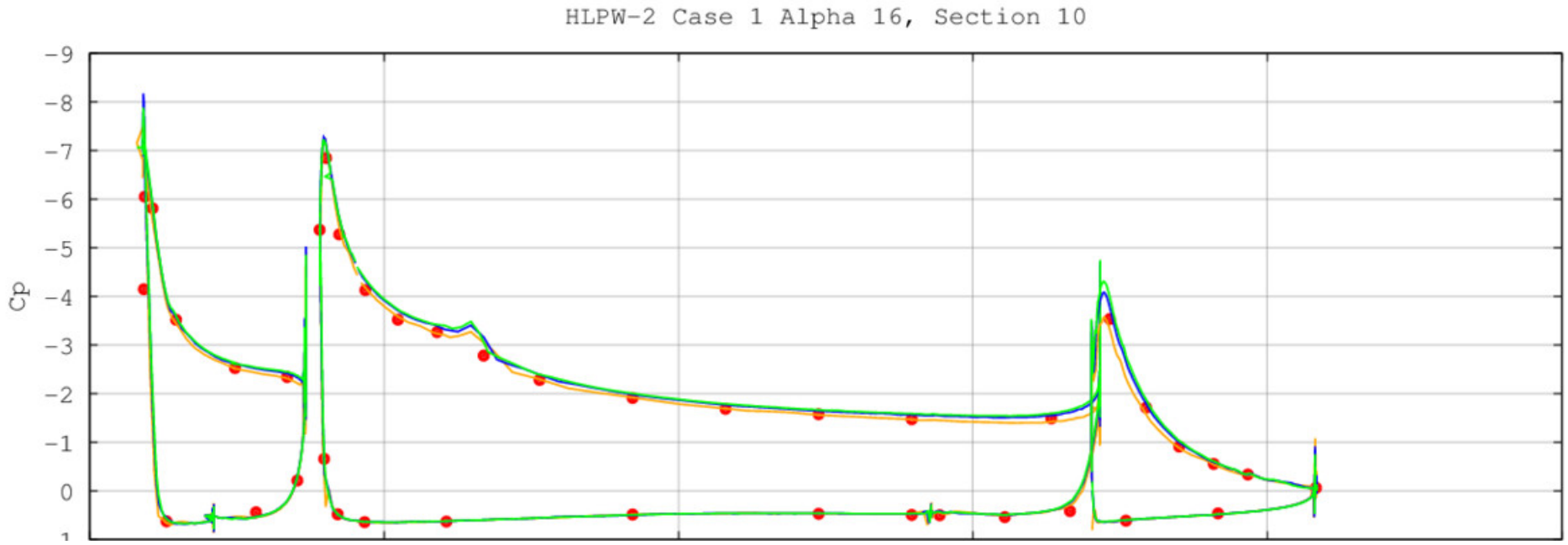
X Station(mm)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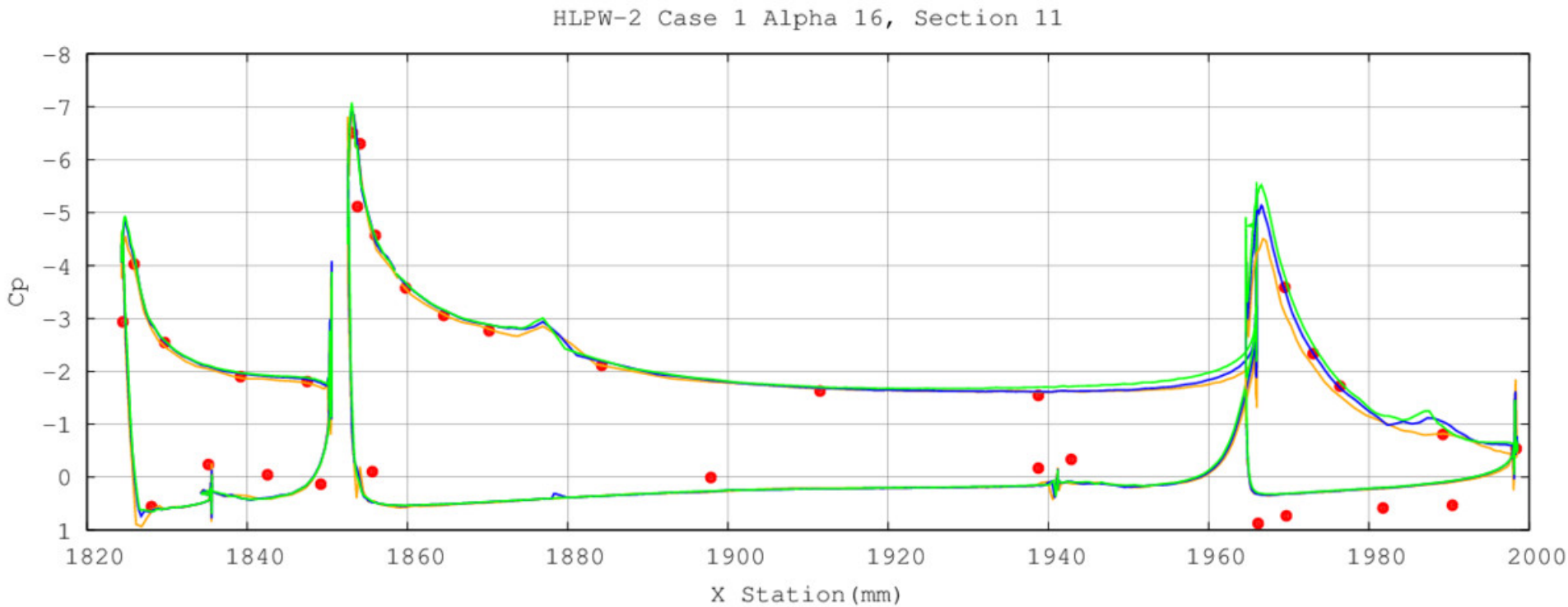
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1820
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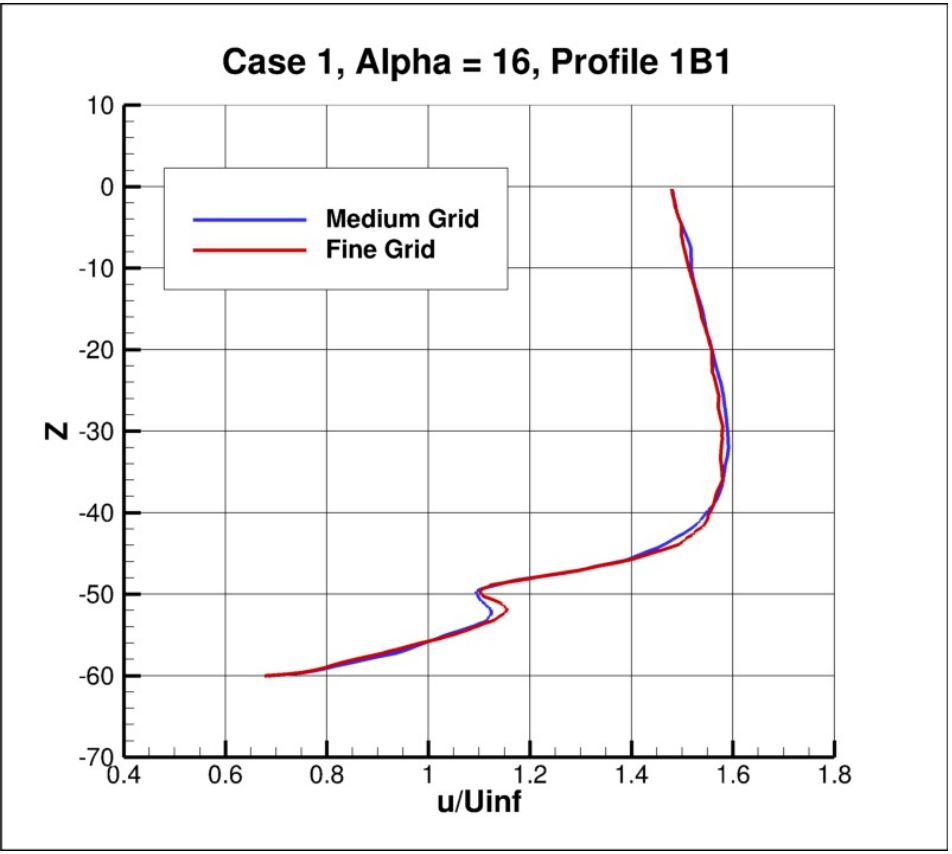
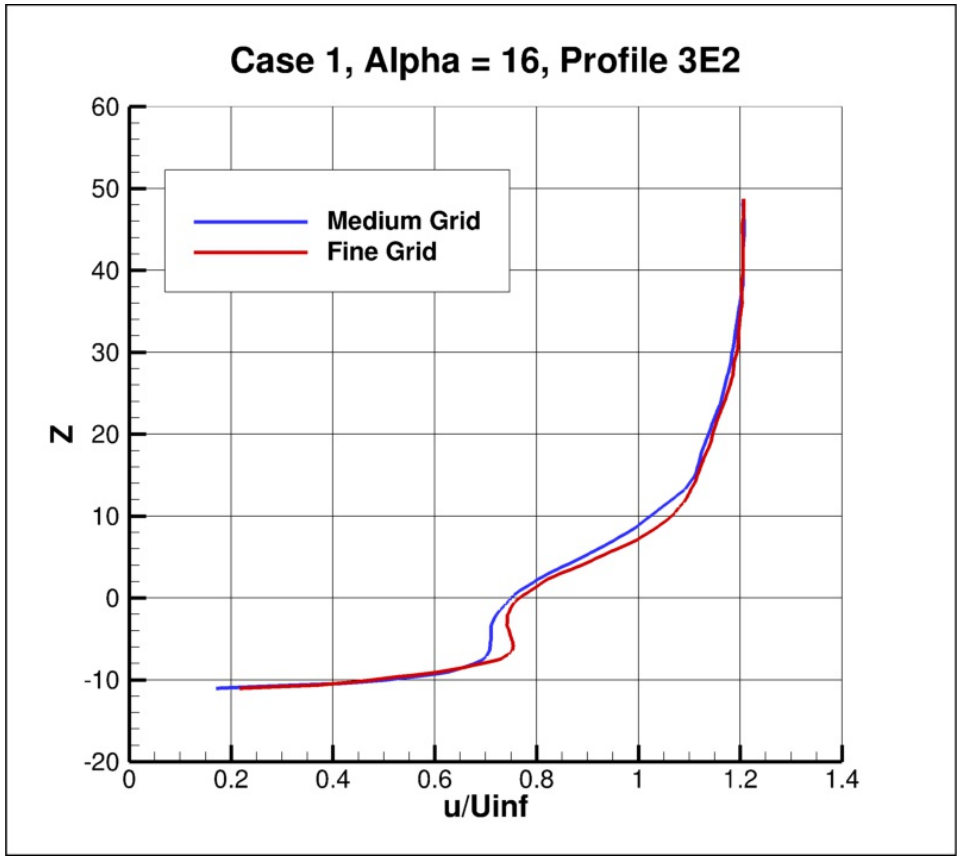
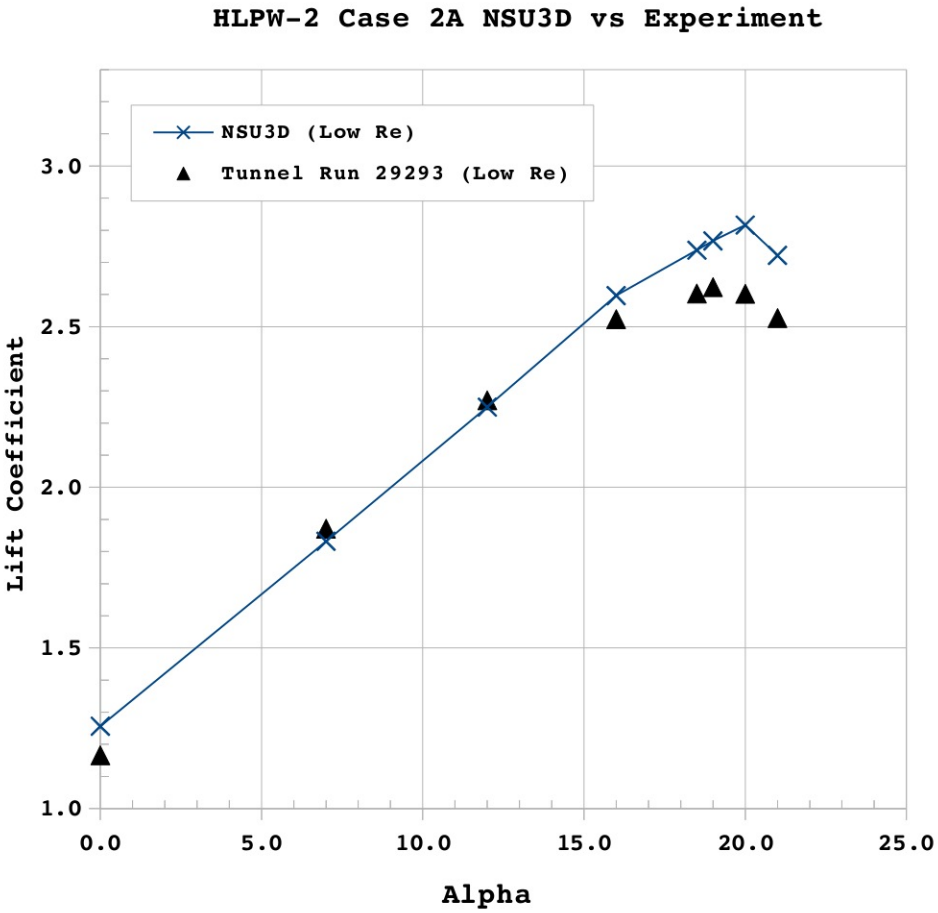
1900
1920
1940
1960
1980
2000
X Station(mm)

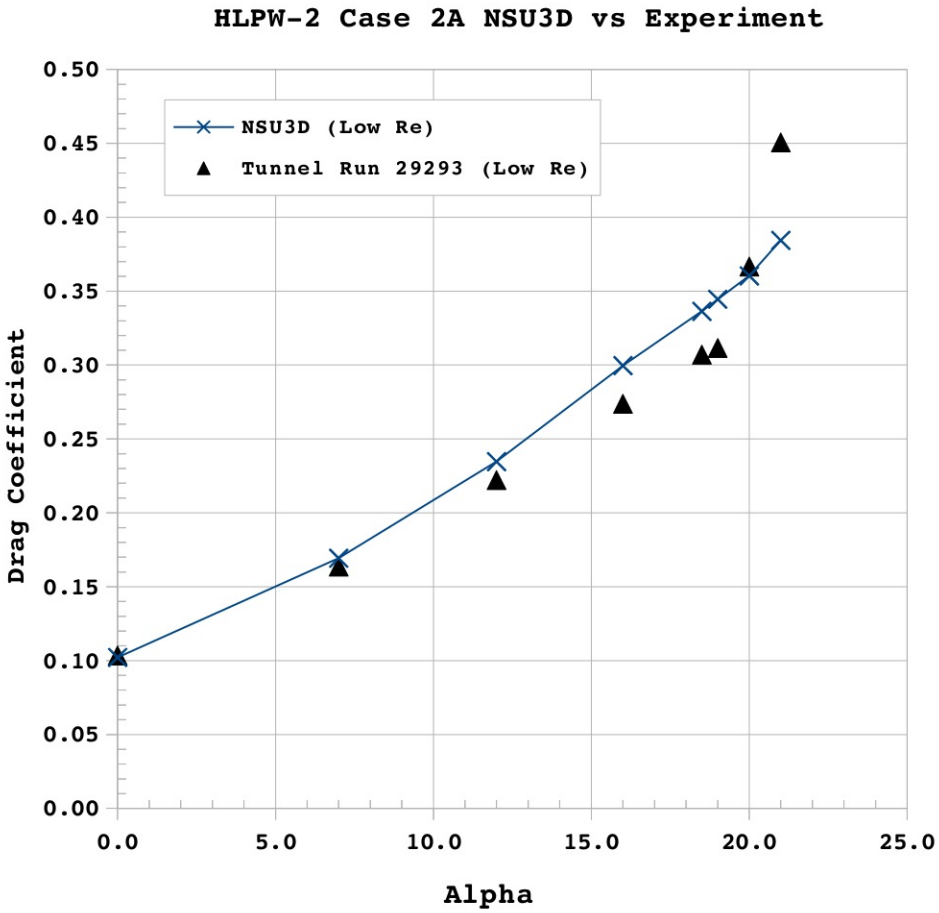
Sample Velocity Profiles





CASE 2A: Incidence sweep





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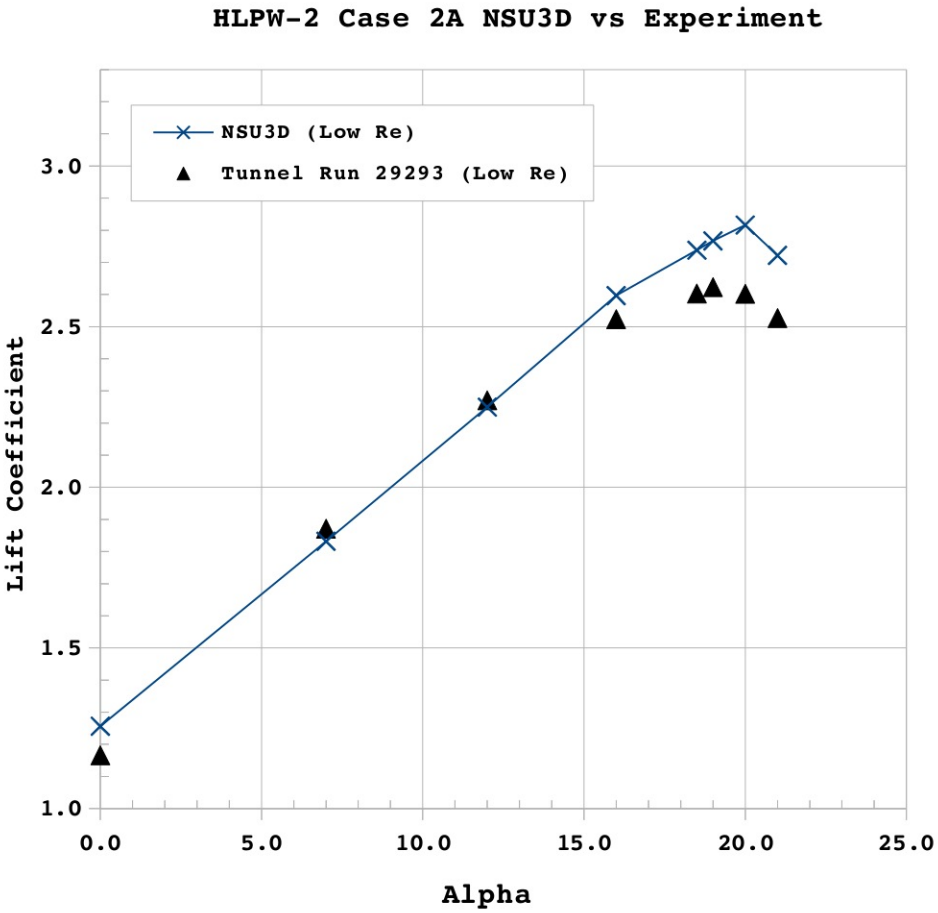
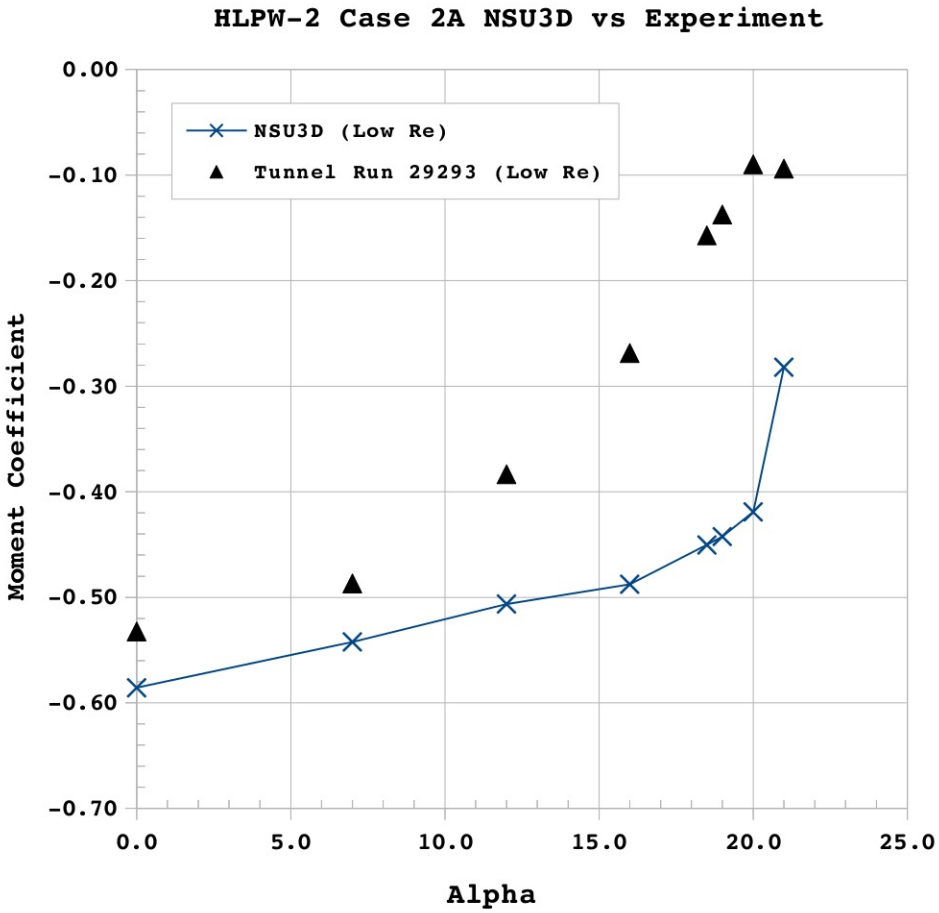
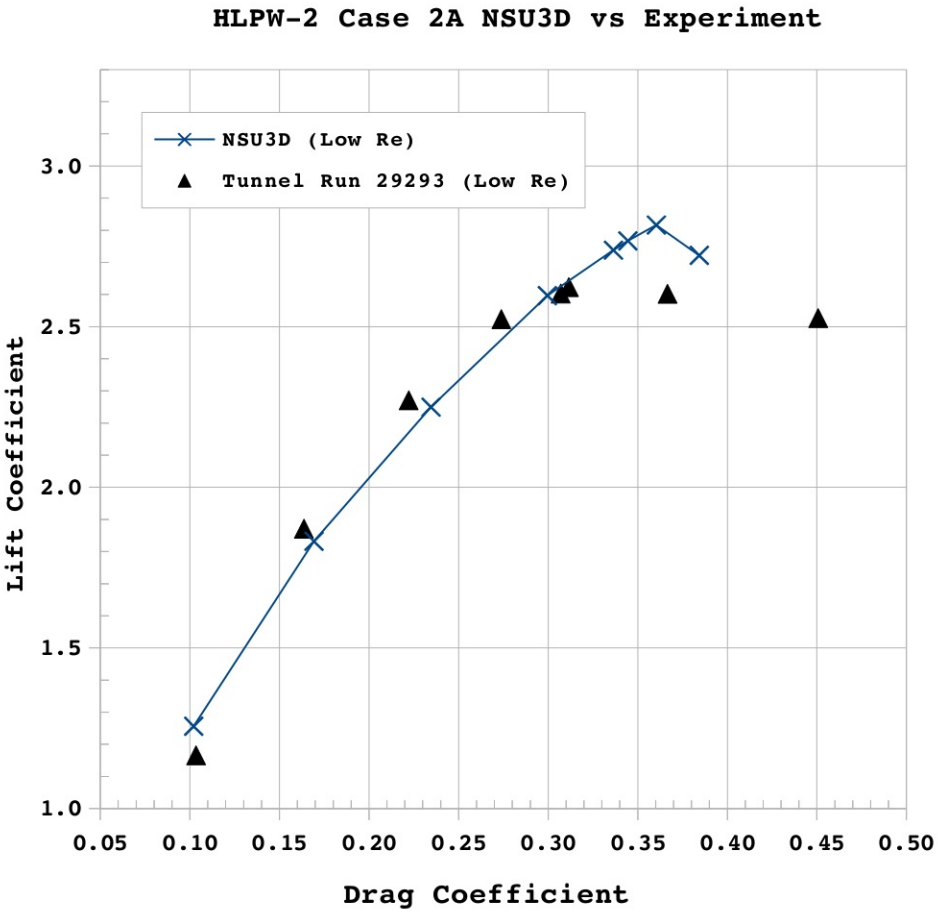
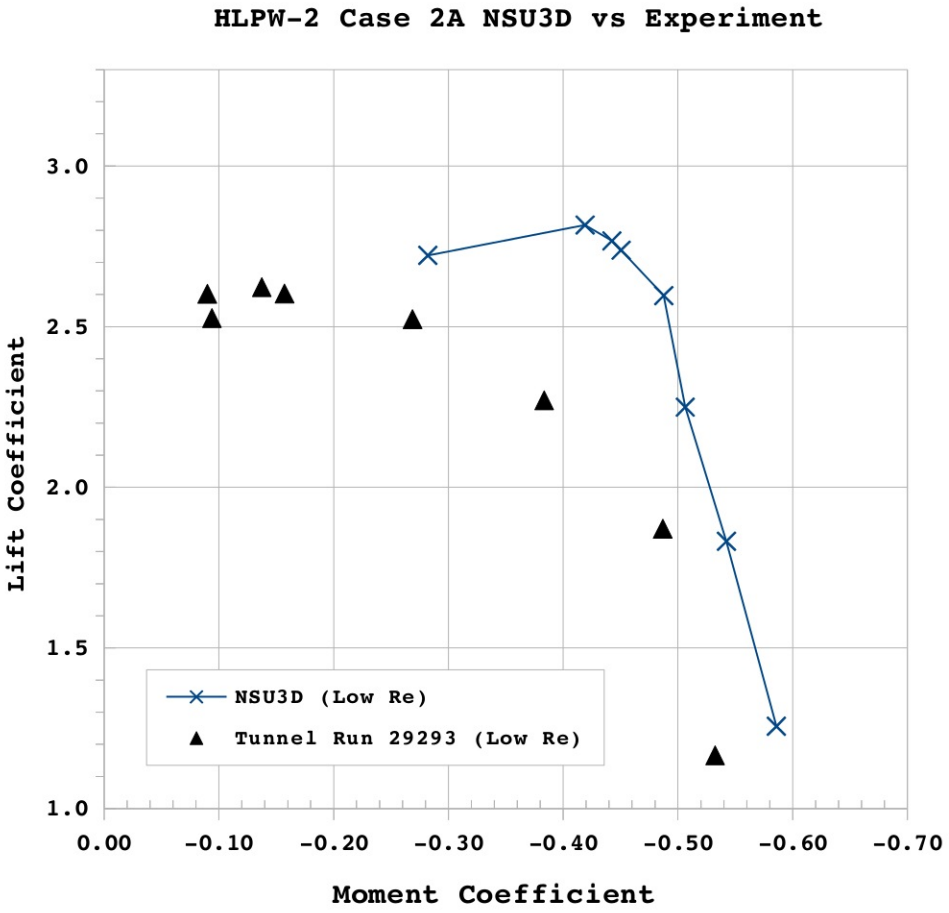


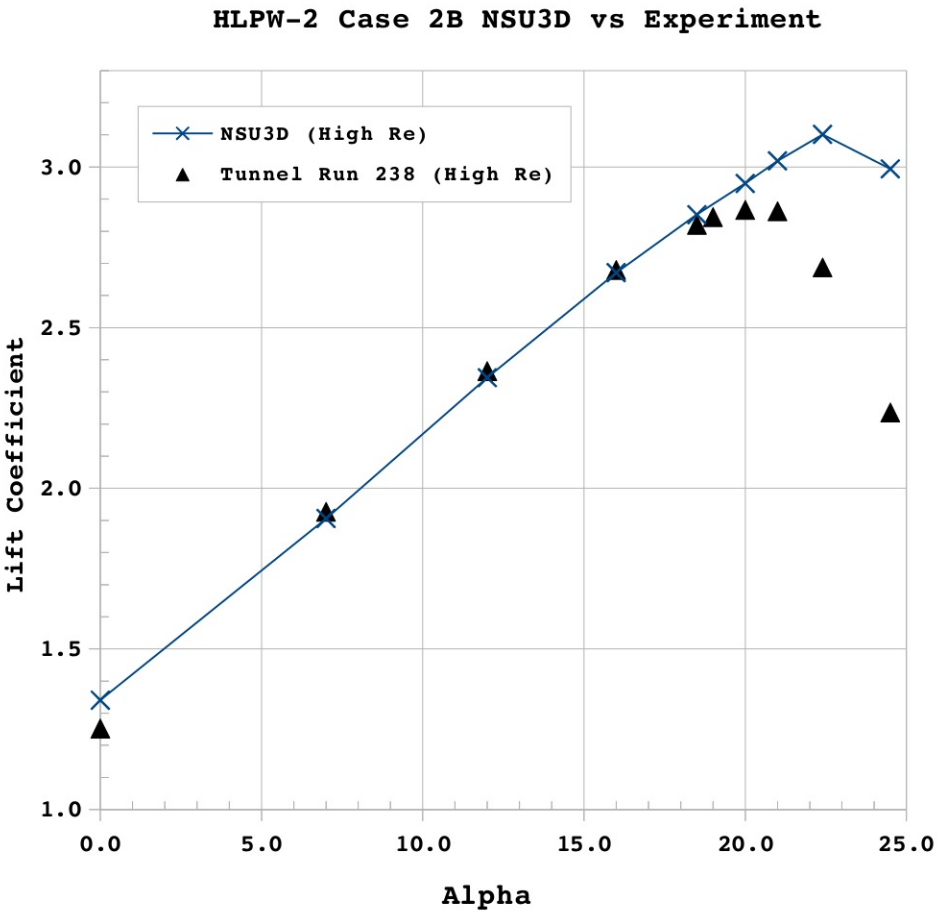


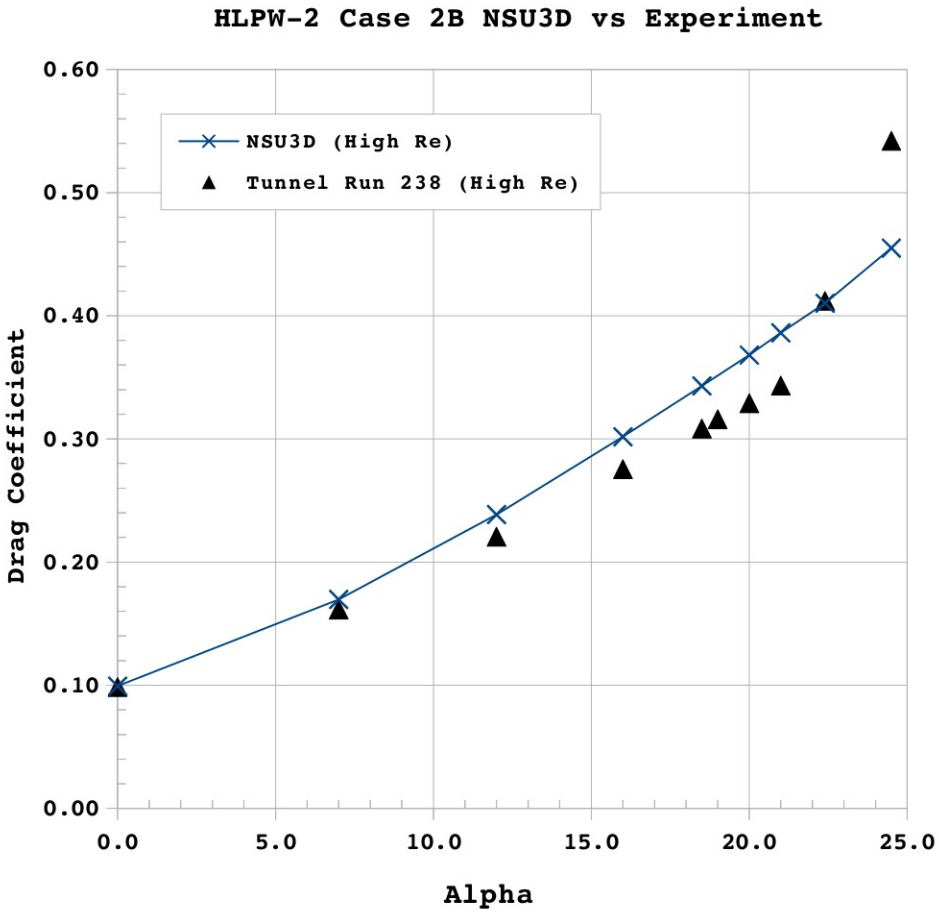
CASE 2A: Incidence sweep



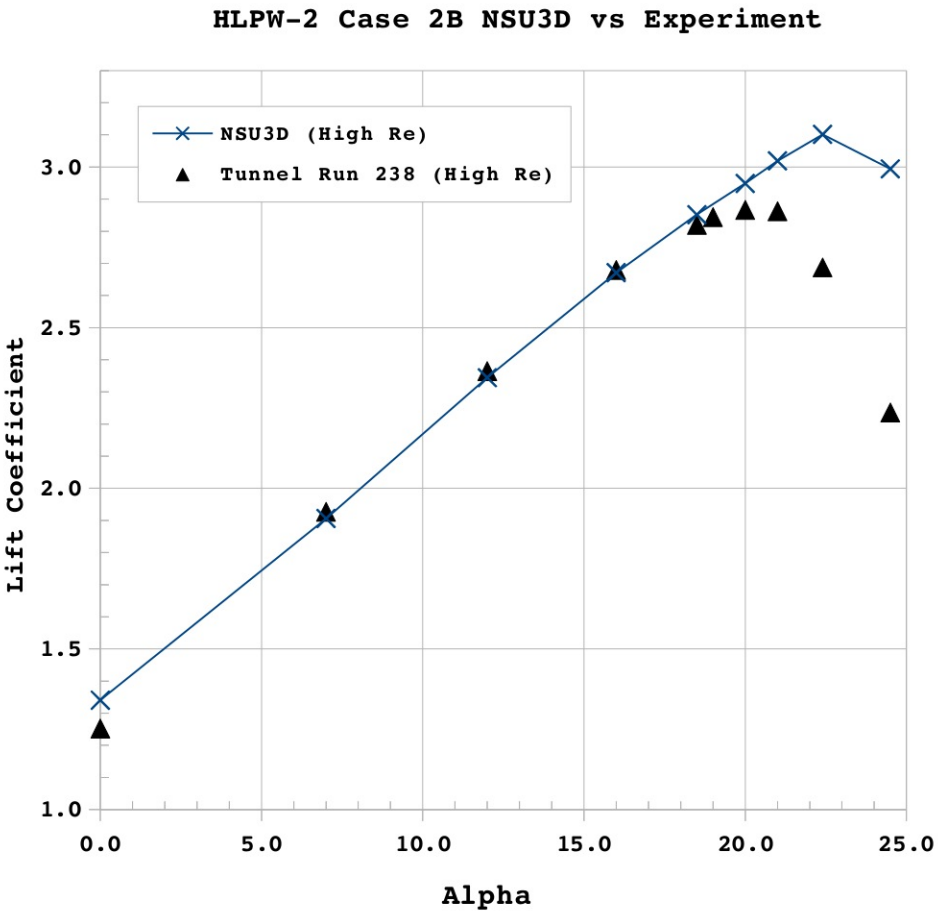


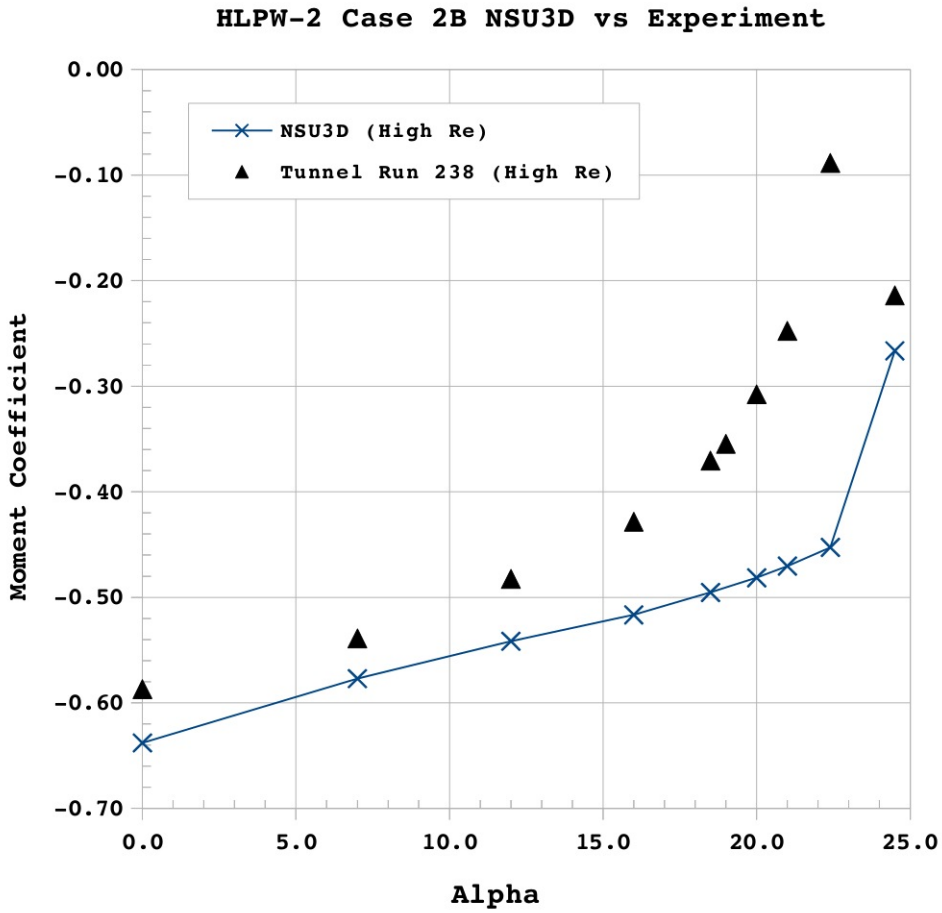
CASE 2B: Incidence sweep



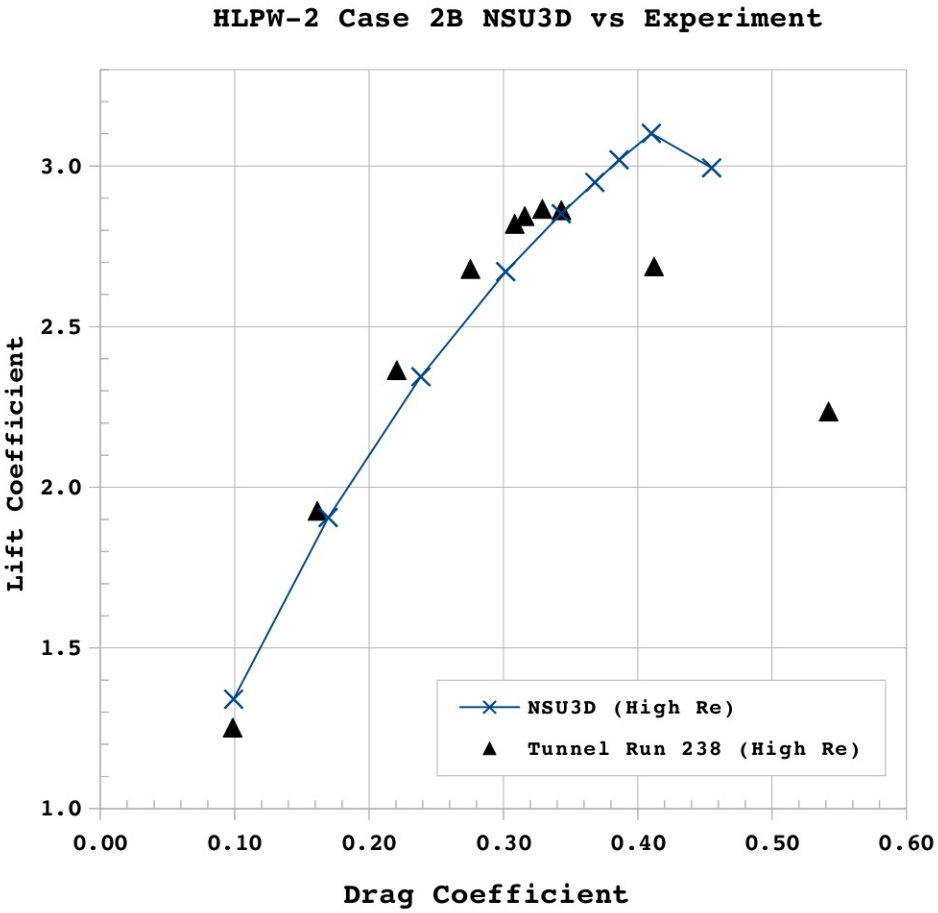


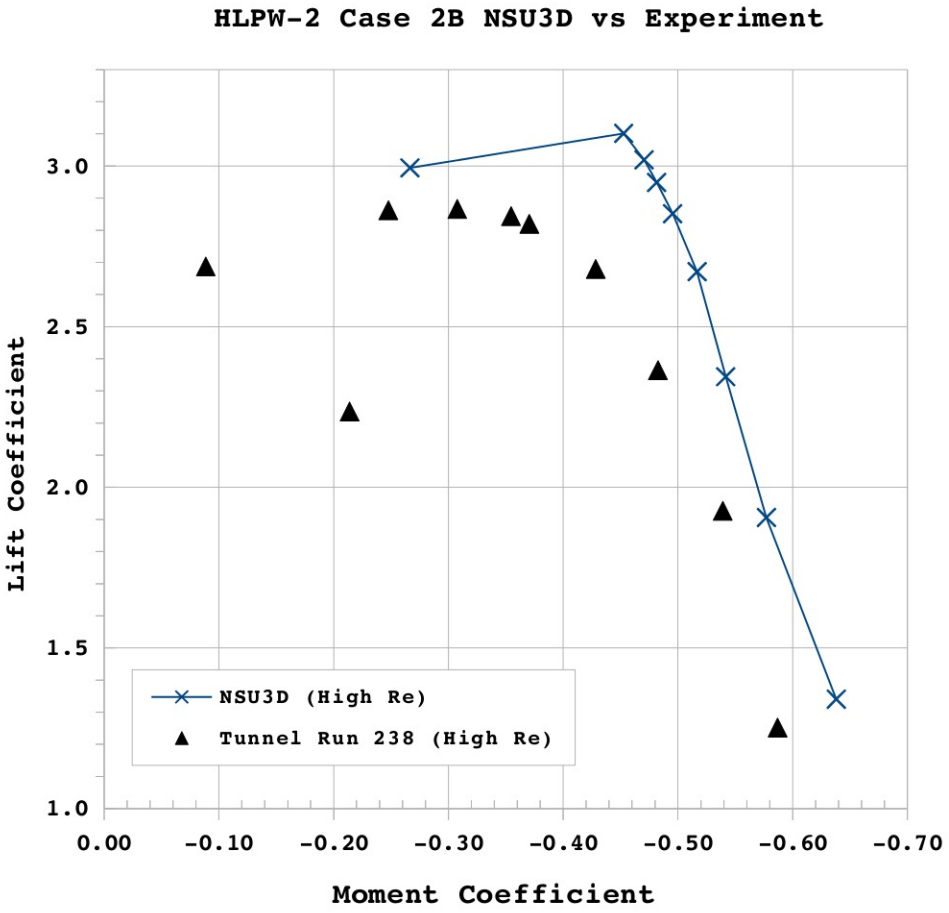
CASE 2B: Incidence sweep

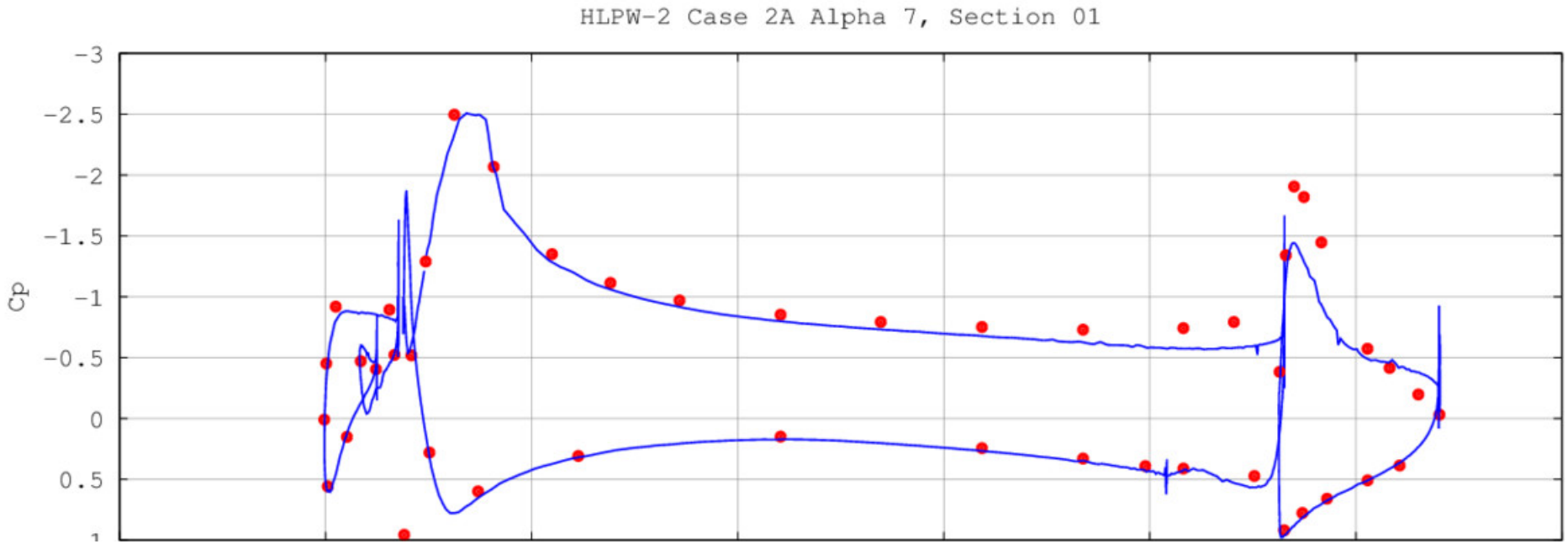




CASE 2B: Incidence sweep



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-2
-1.5
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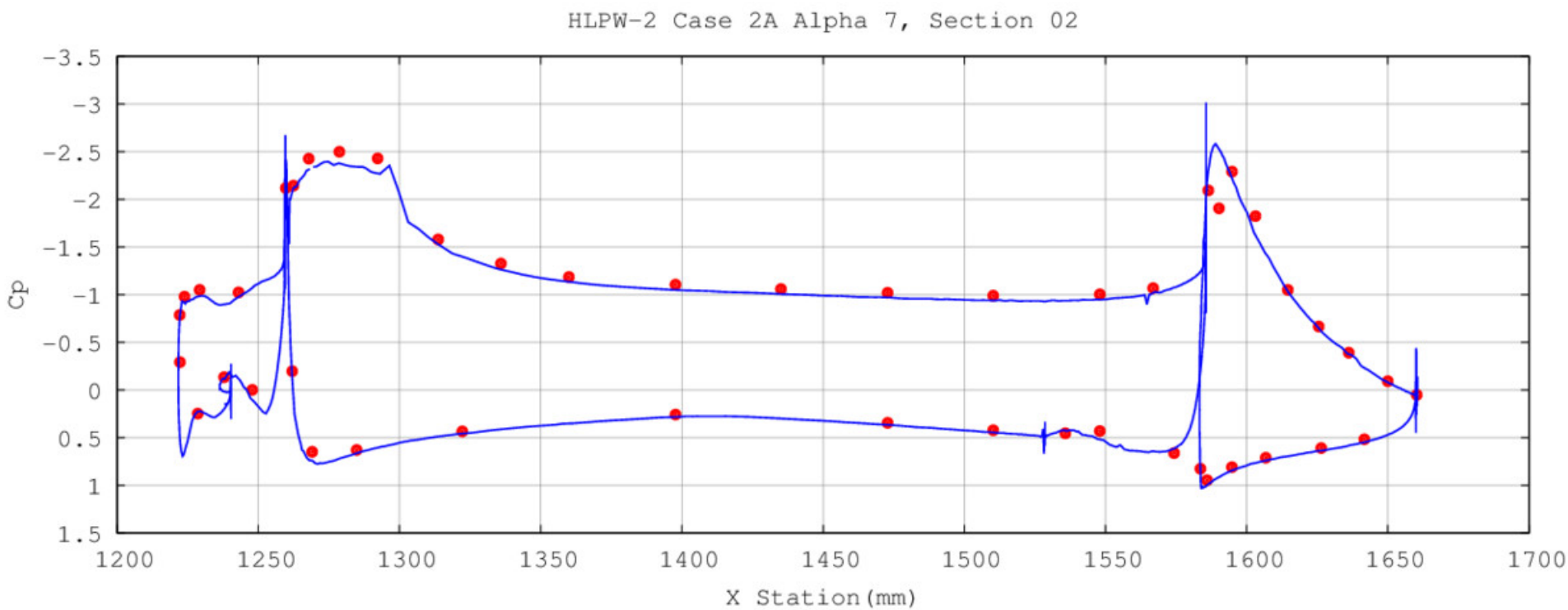
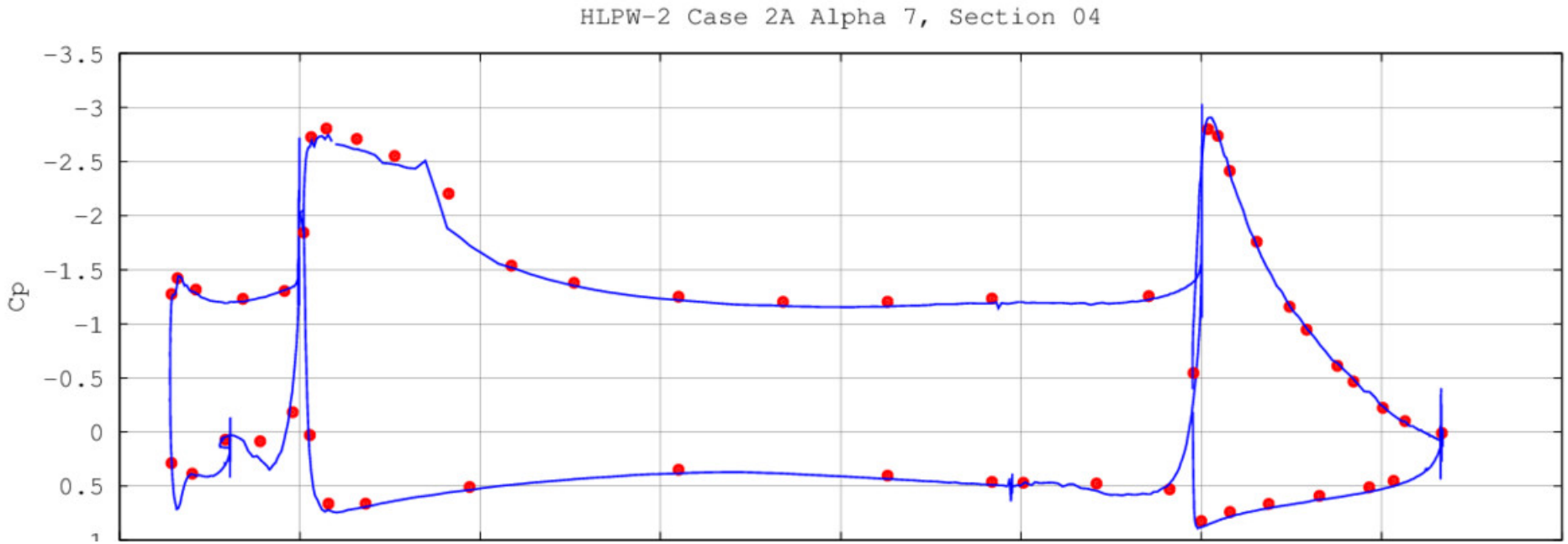
0.5
1


HLPW-2 Case 2A Alpha 7, Section 02
Cp
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
X Station(mm)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-1
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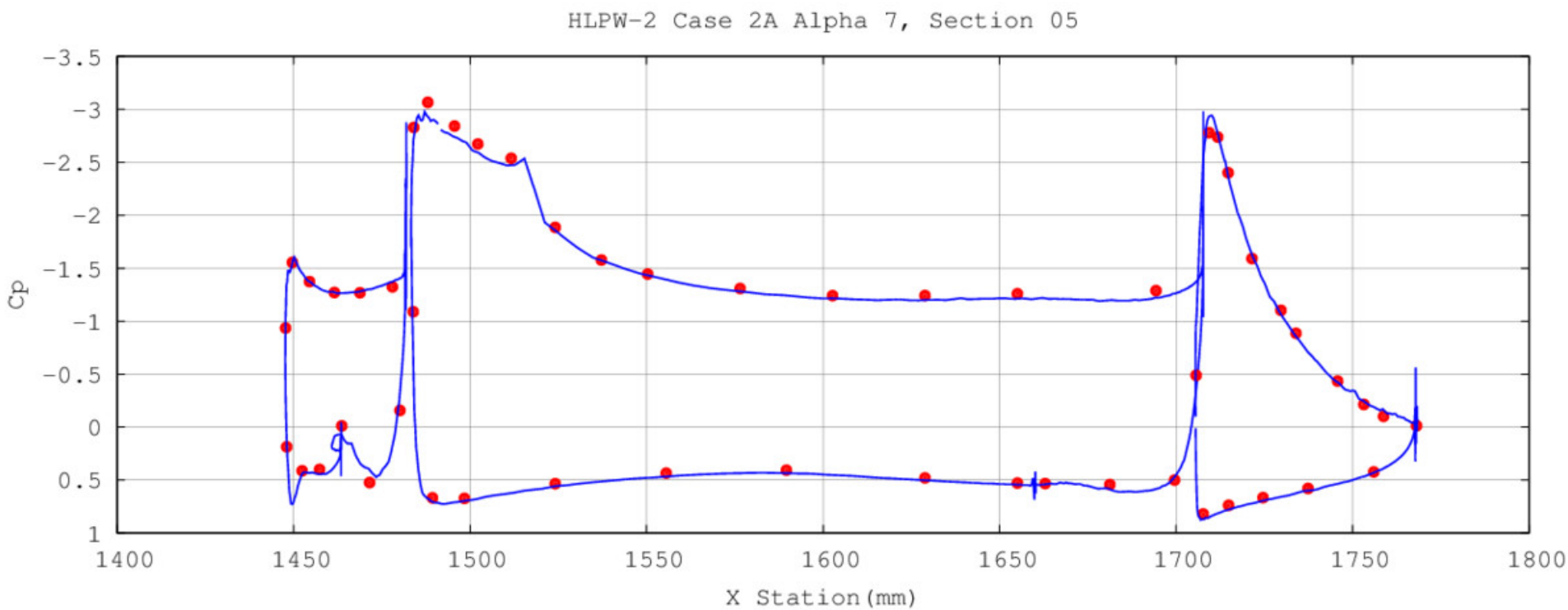
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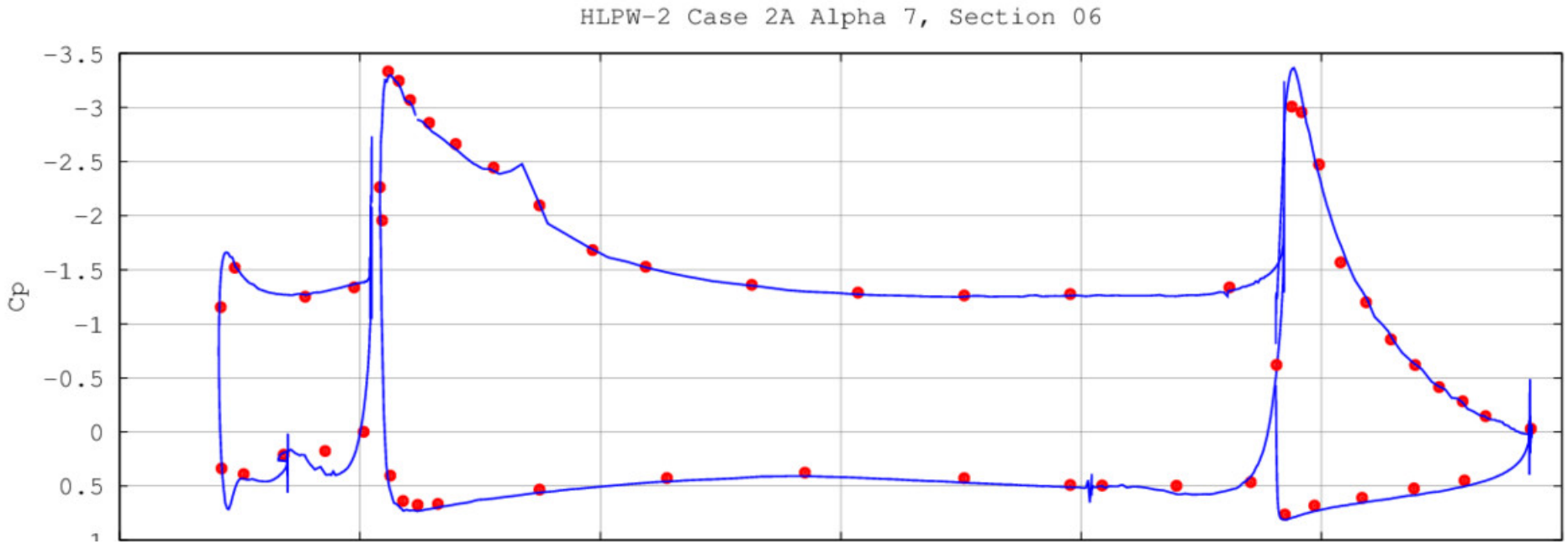
X Station(mm)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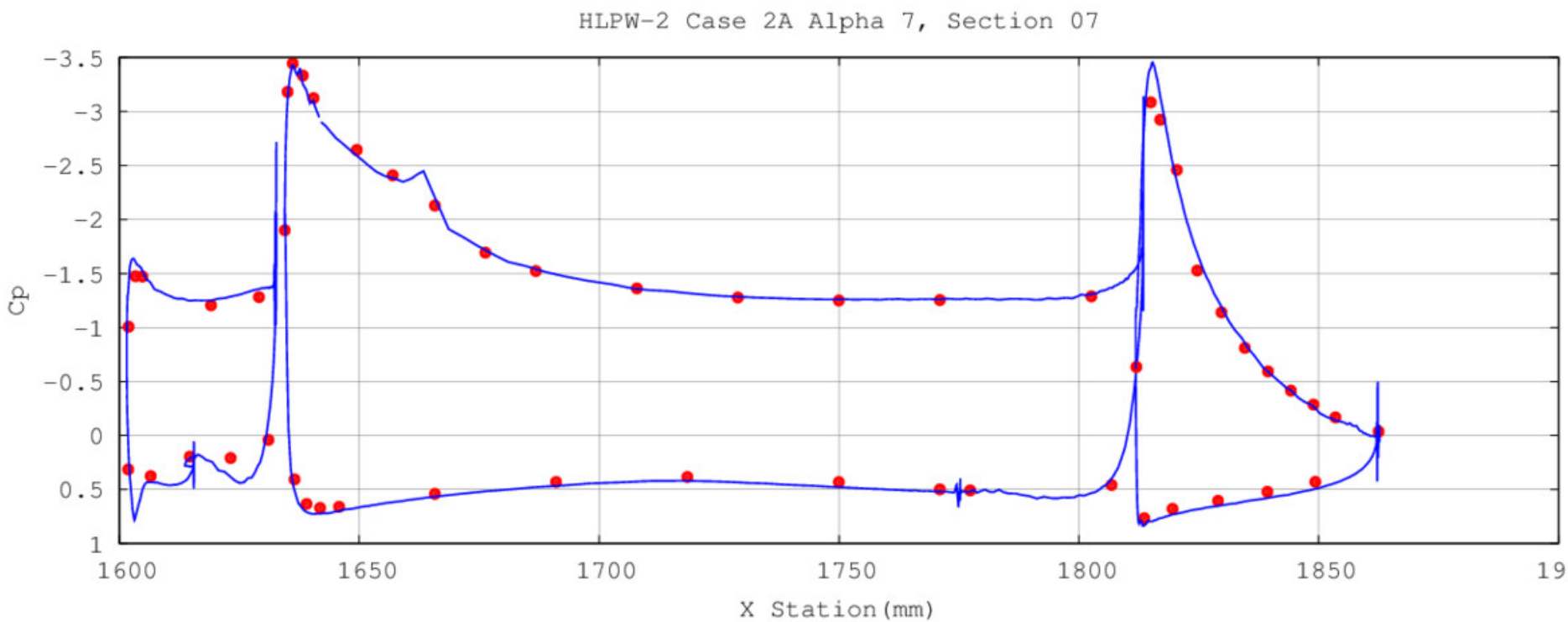
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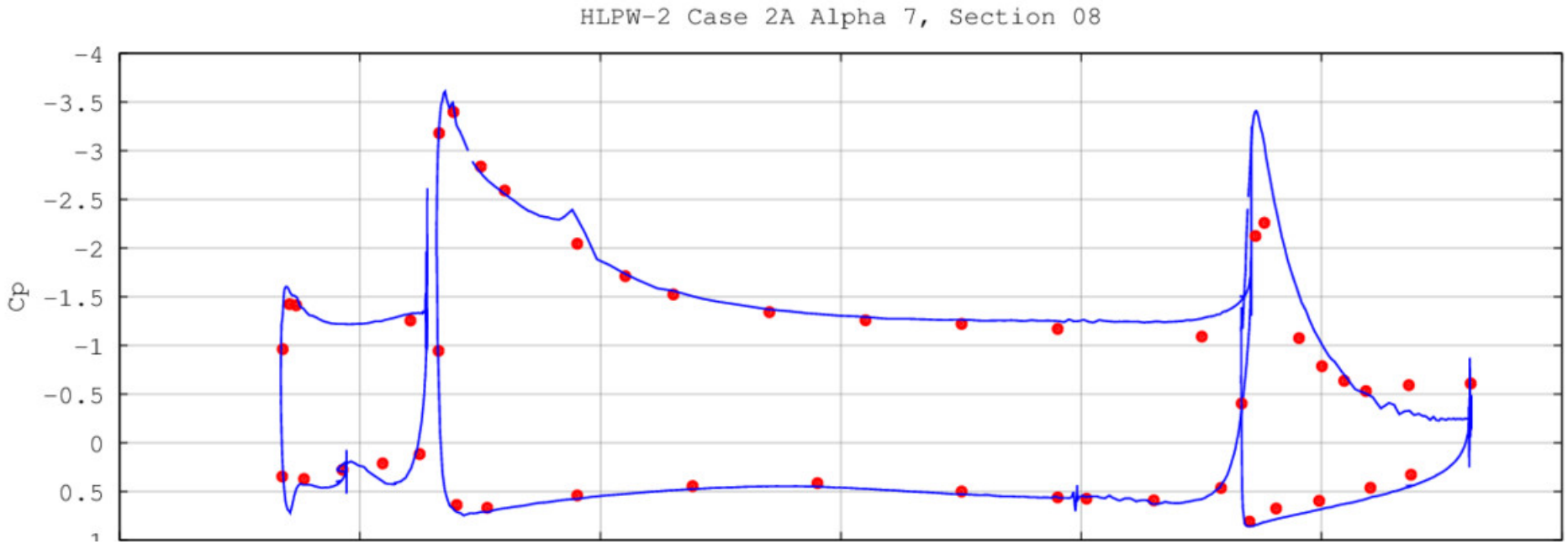
X Station(mm)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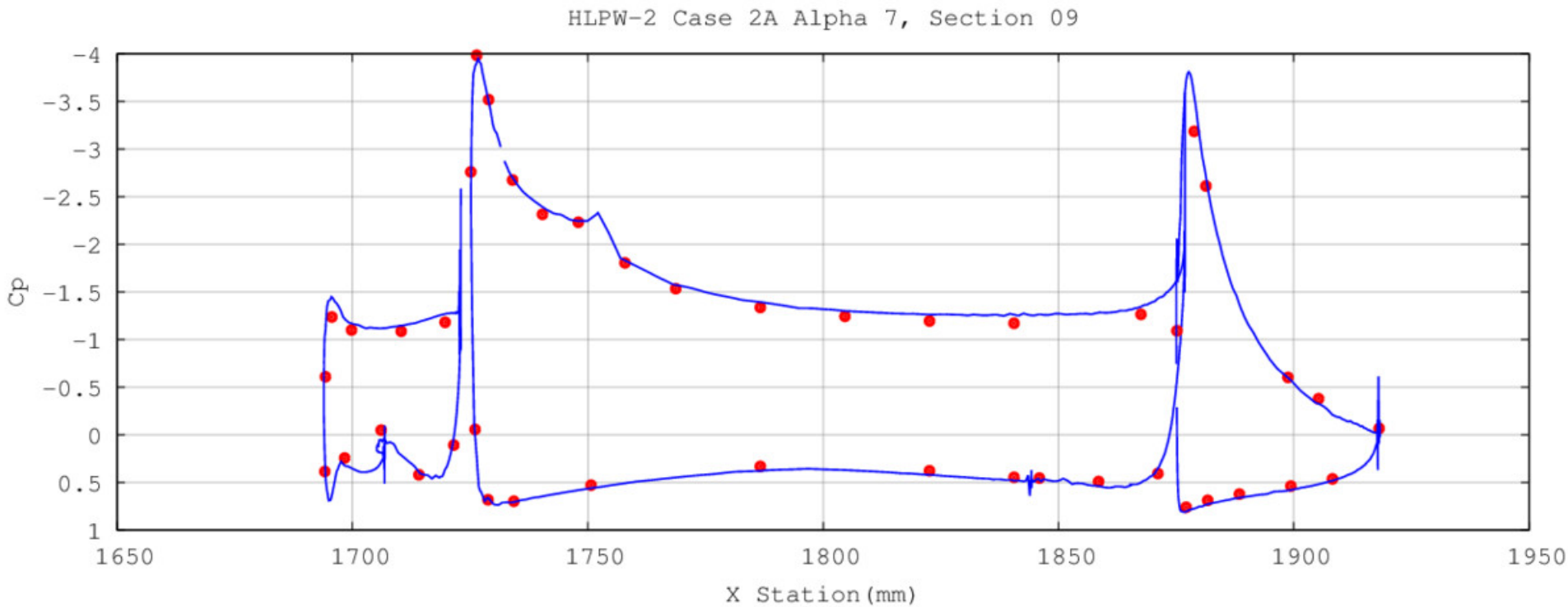
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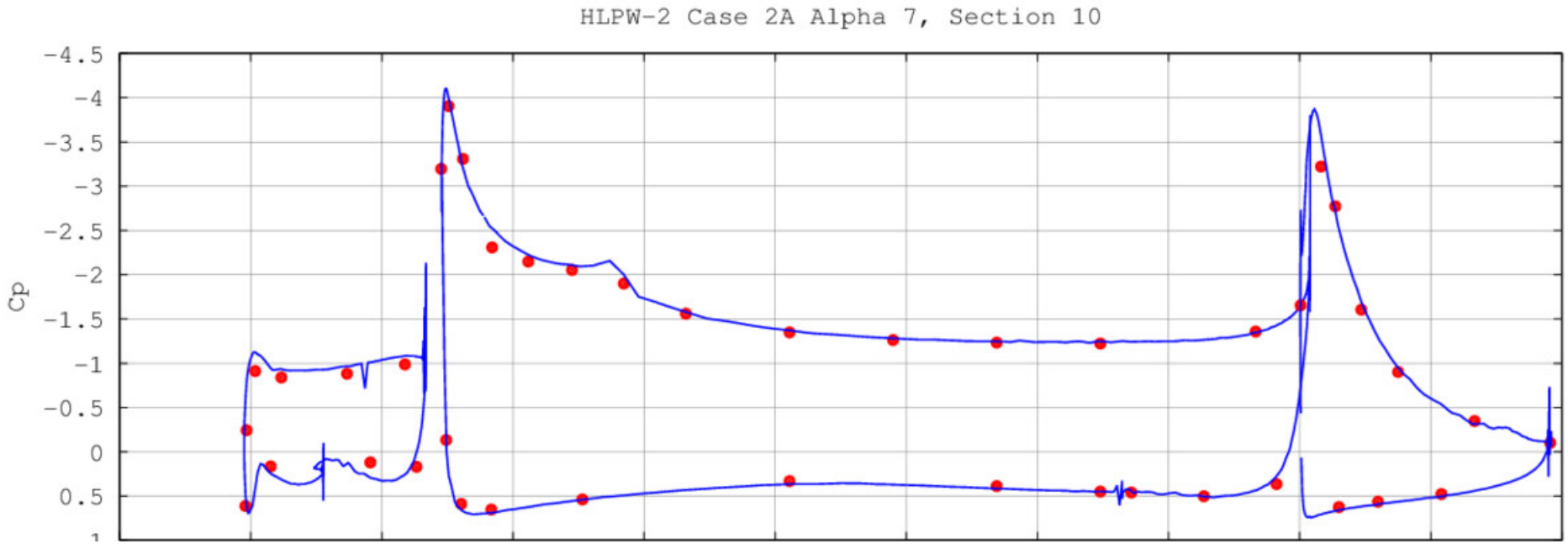
X Station(mm)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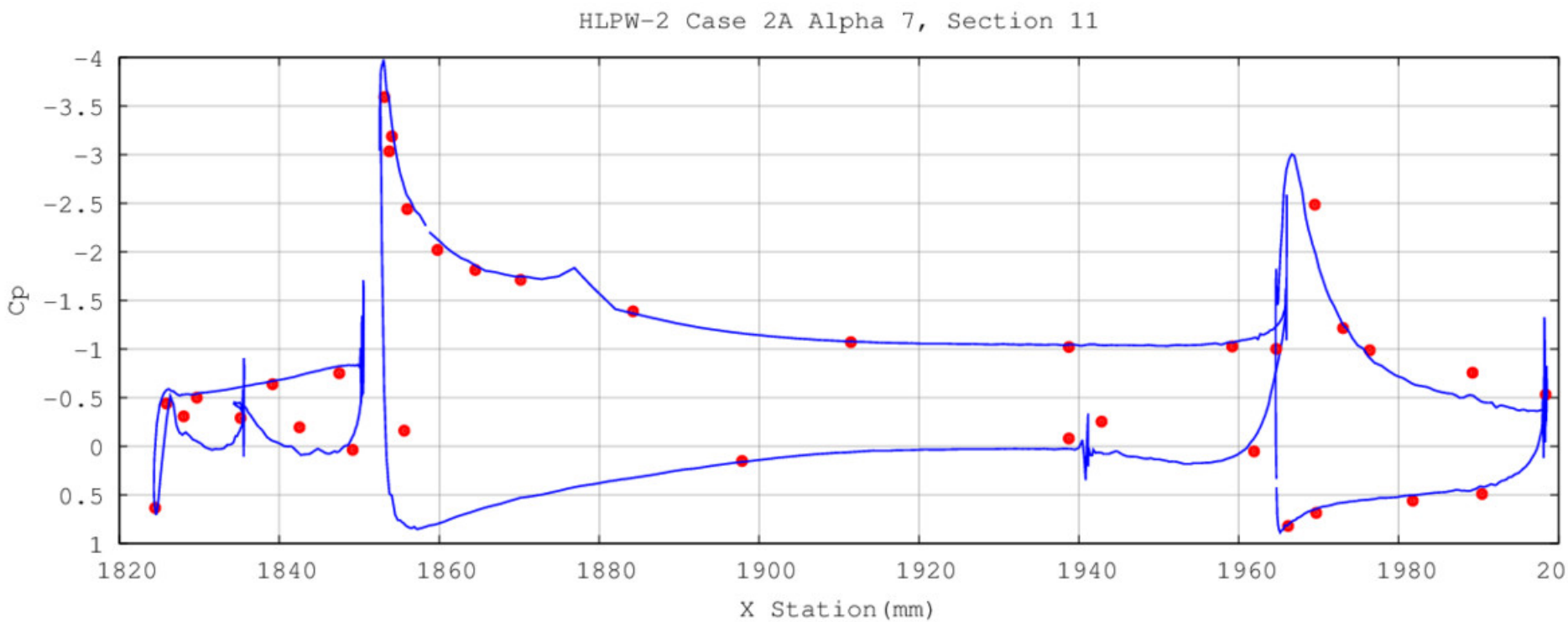
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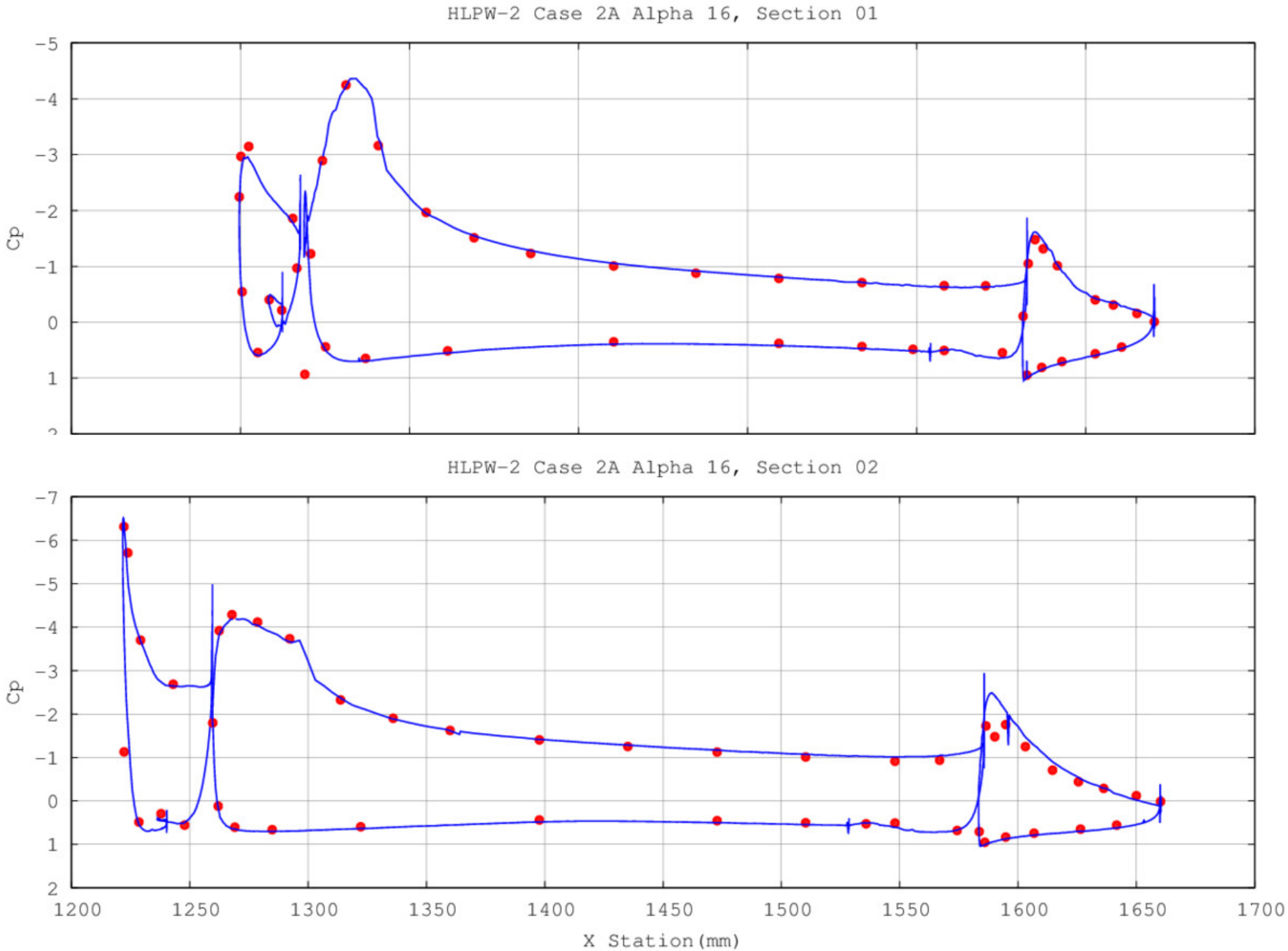
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Cp
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-4
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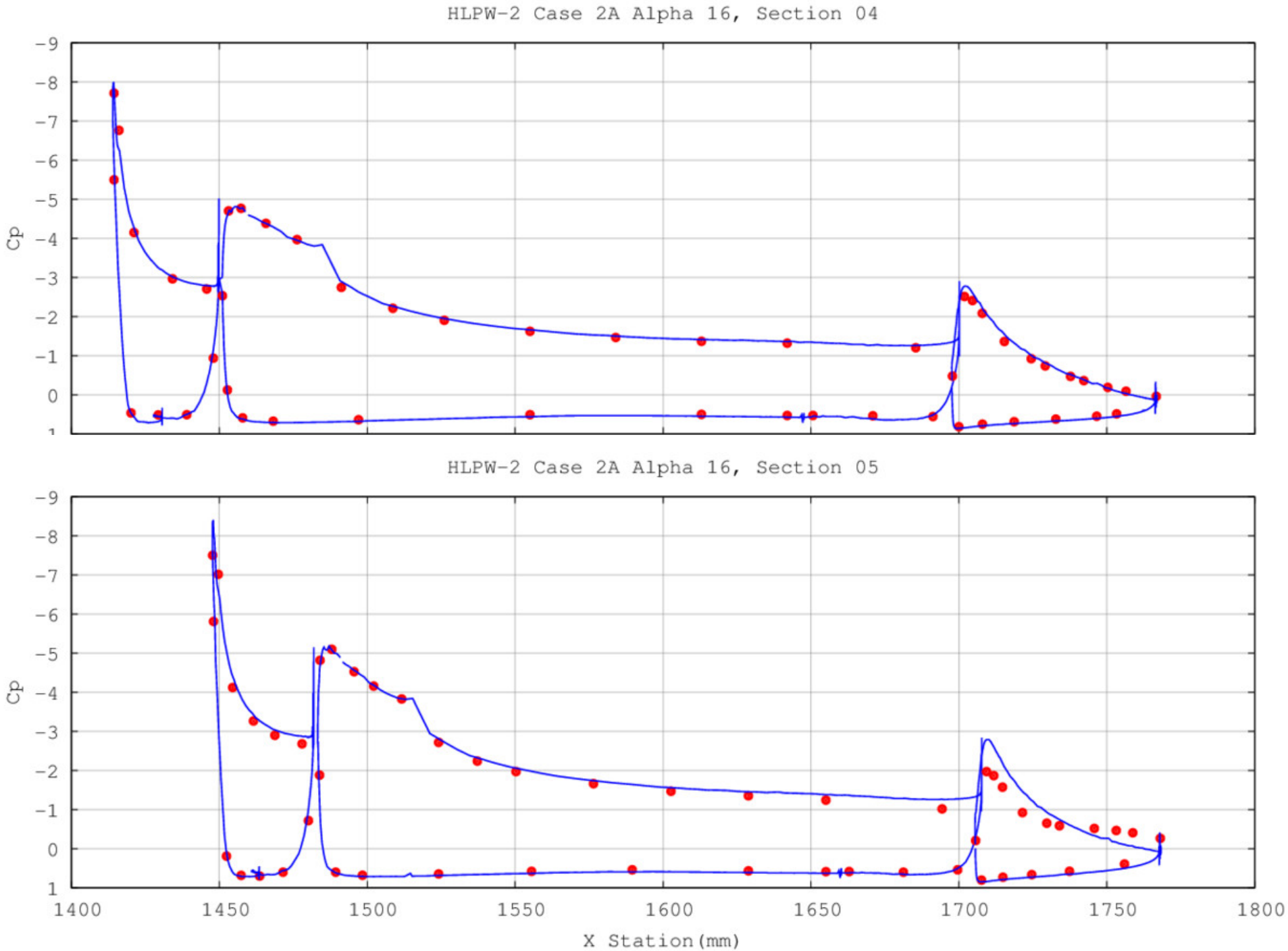
X Station(mm)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Cp
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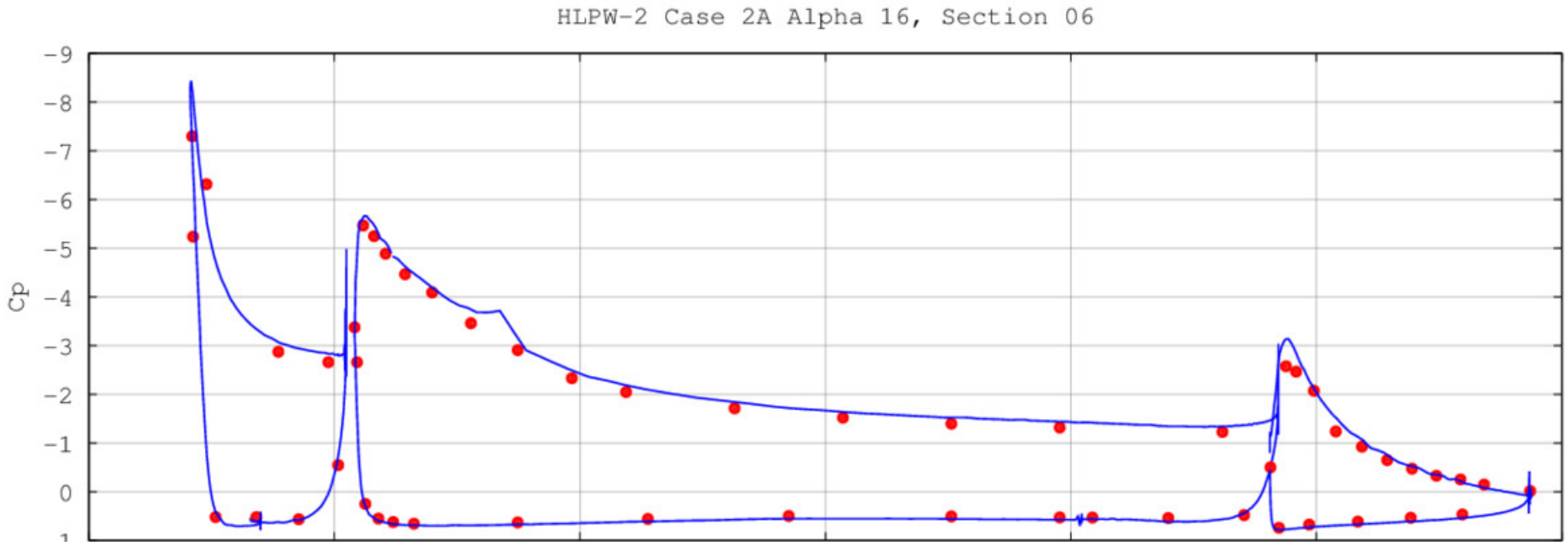
X Station(mm)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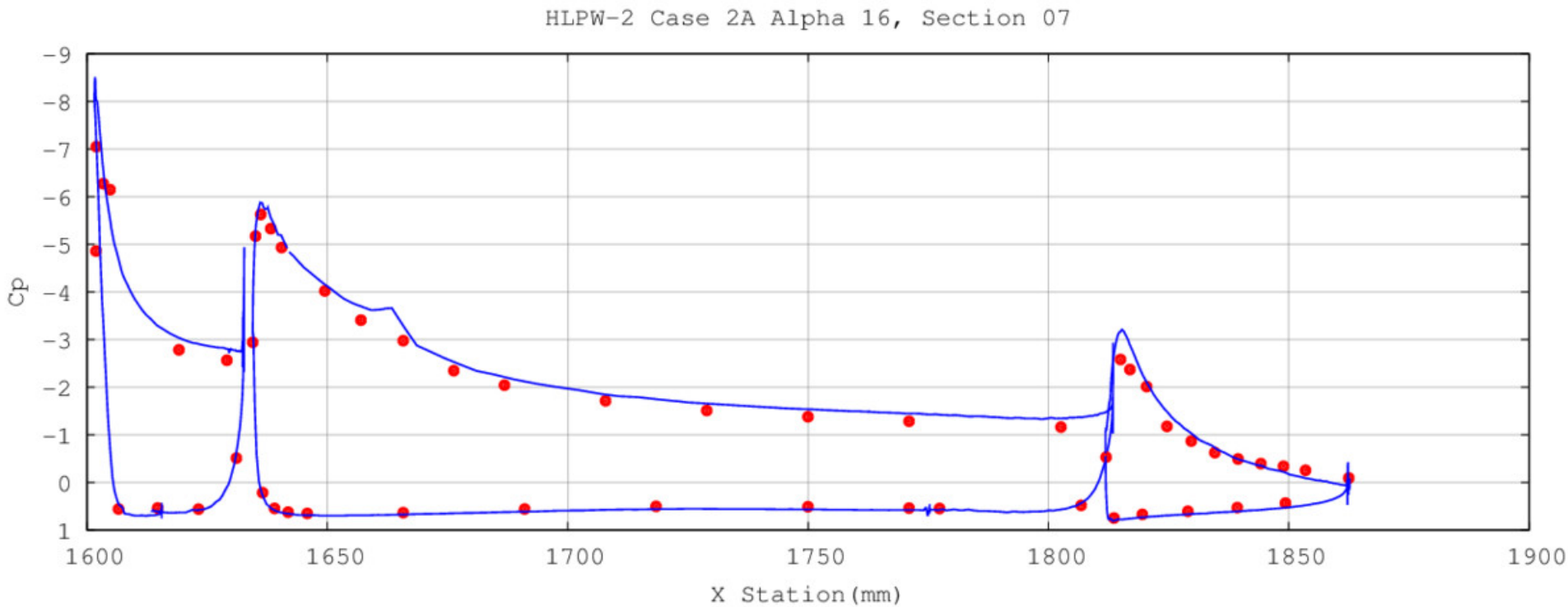
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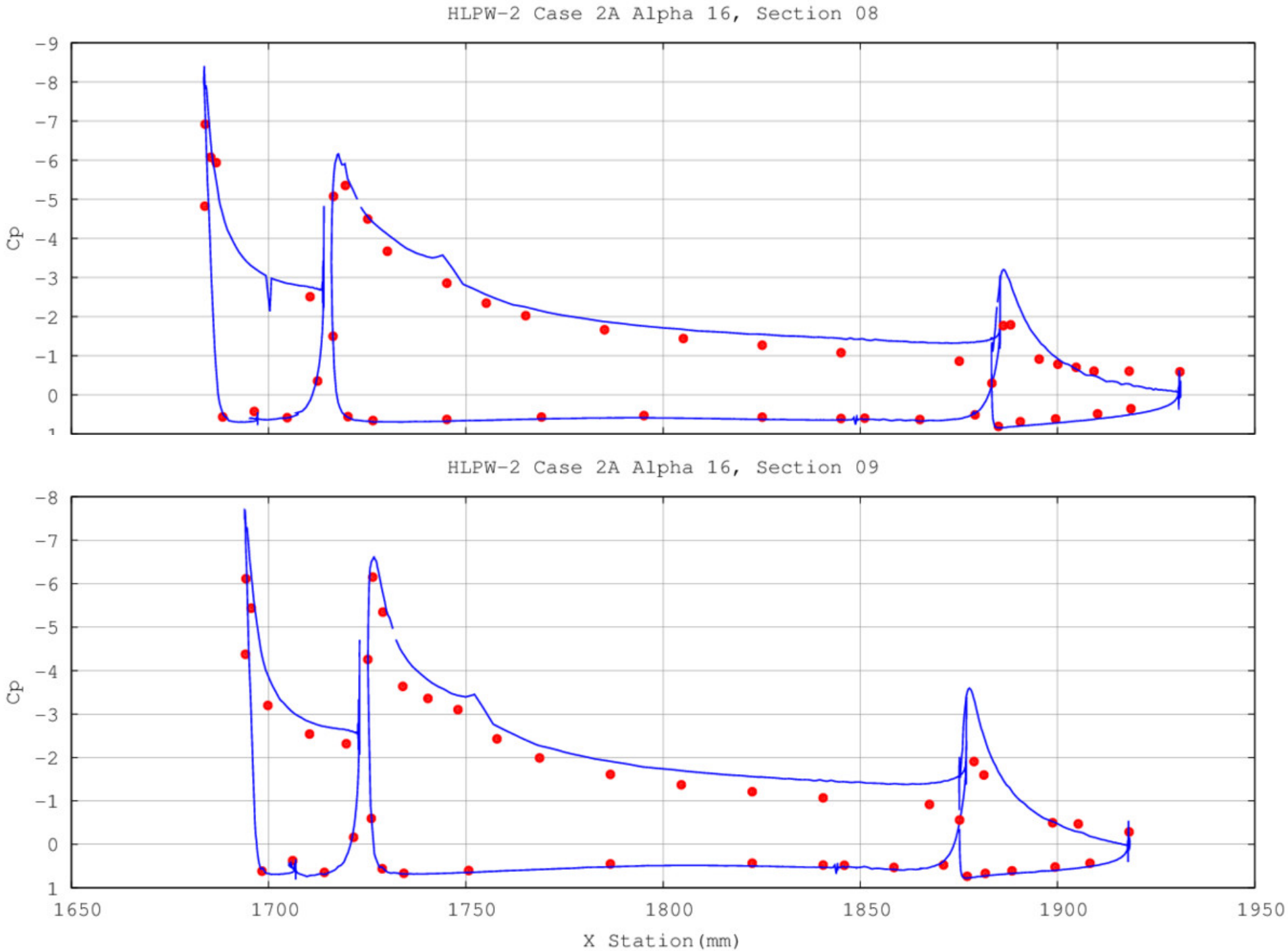
X Station(mm)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HLPW-2 Case 2A Alpha 16, Section 09
Cp
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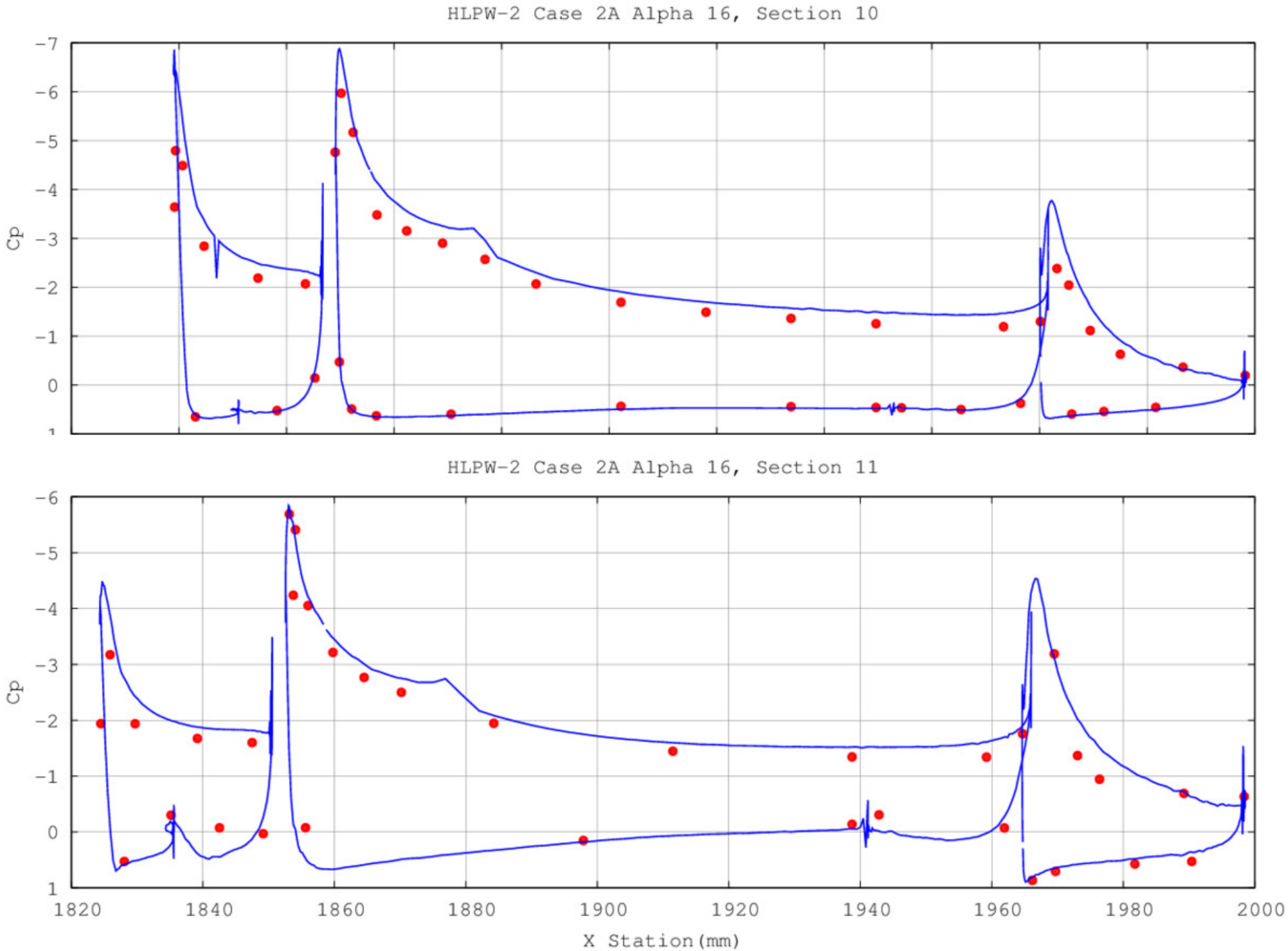
X Station(mm)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HLPW-2 Case 2A Alpha 16, Section 11
Cp
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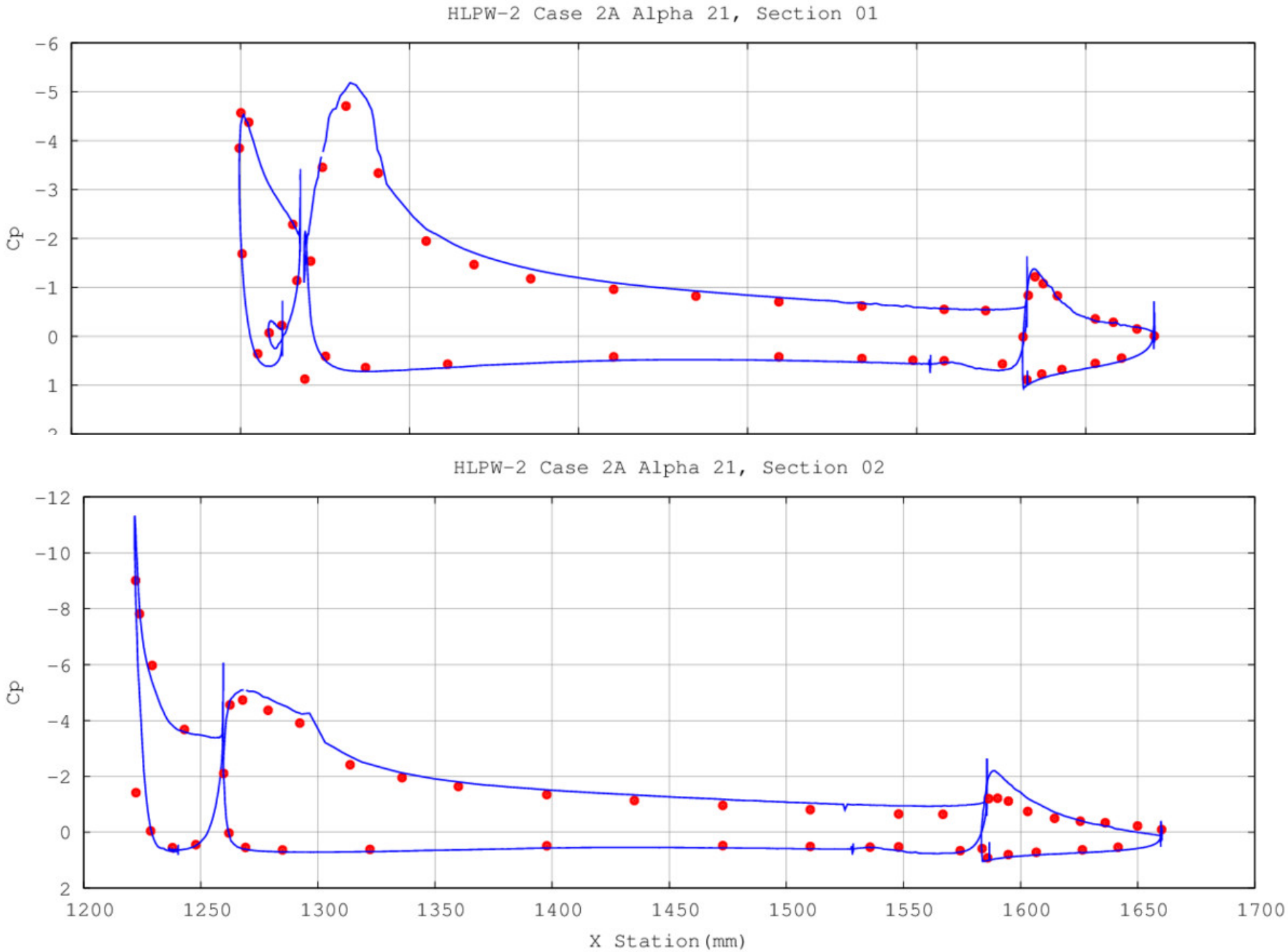
X Station(mm)


HLPW-2 Case 2A Alpha 21, Section 01
Cp
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HLPW-2 Case 2A Alpha 21, Section 02
Cp
-12
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-6
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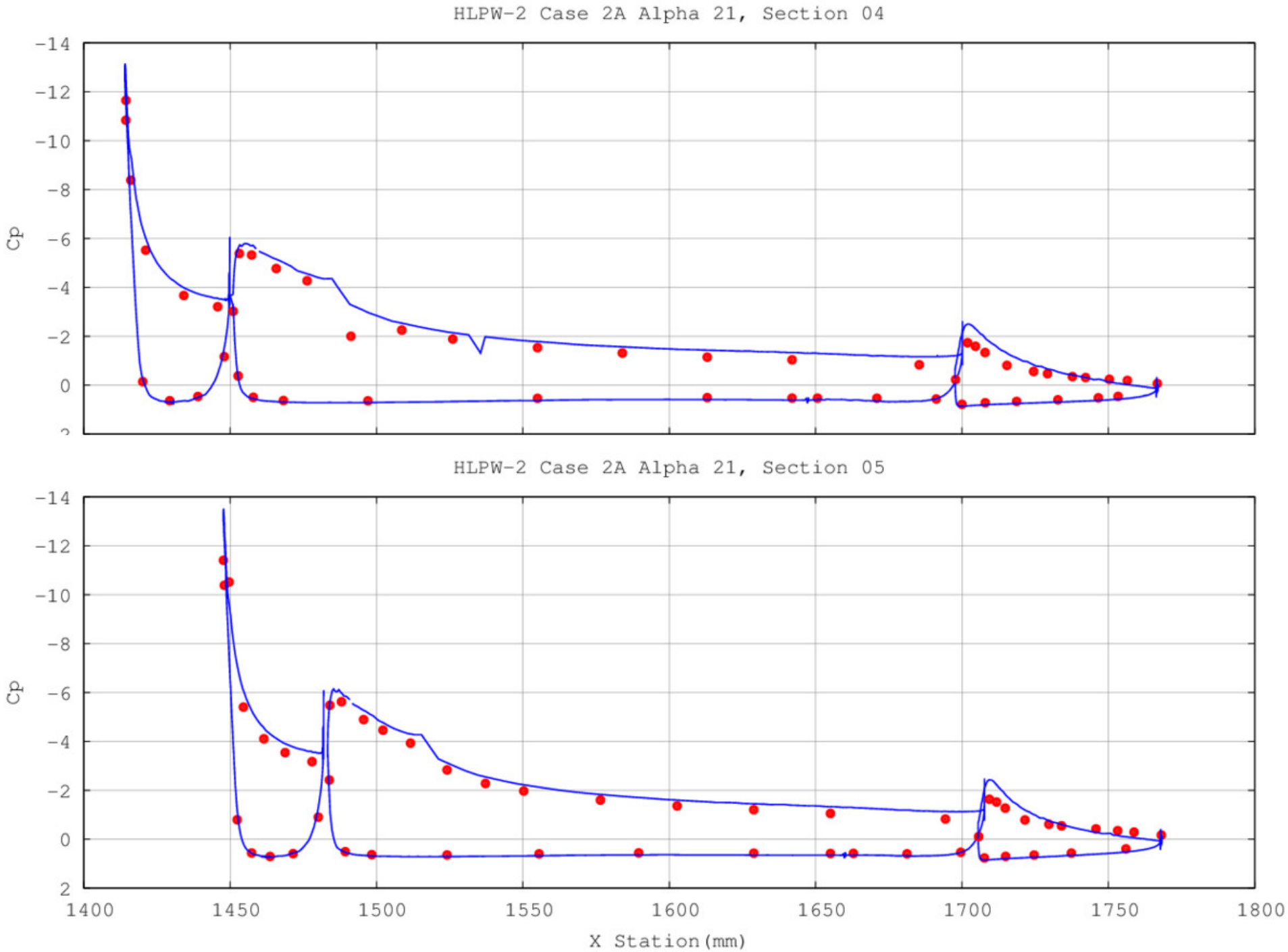
X Station(mm)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HLPW-2 Case 2A Alpha 21, Section 05
Cp
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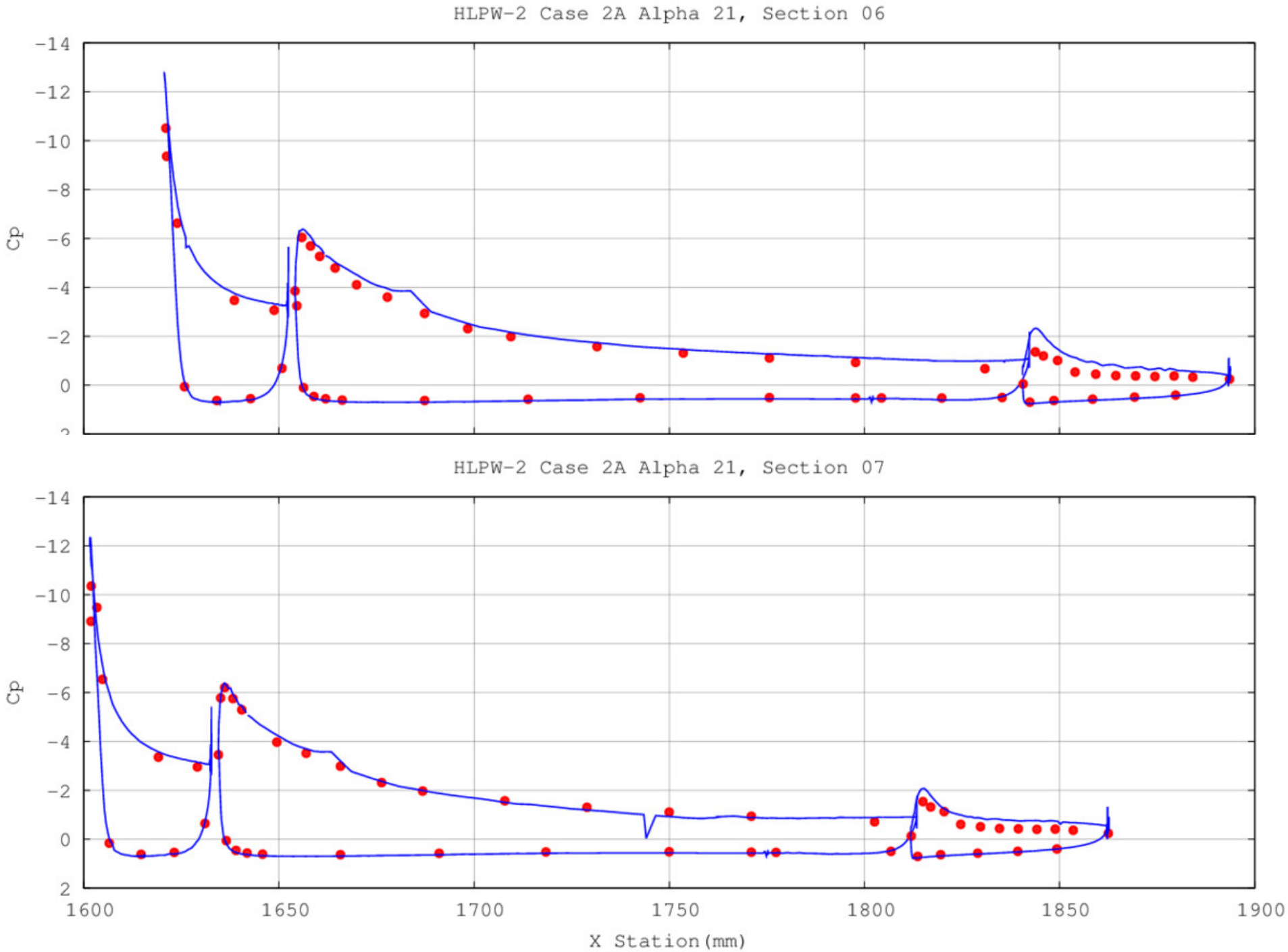
X Station(mm)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HLPW-2 Case 2A Alpha 21, Section 07
Cp
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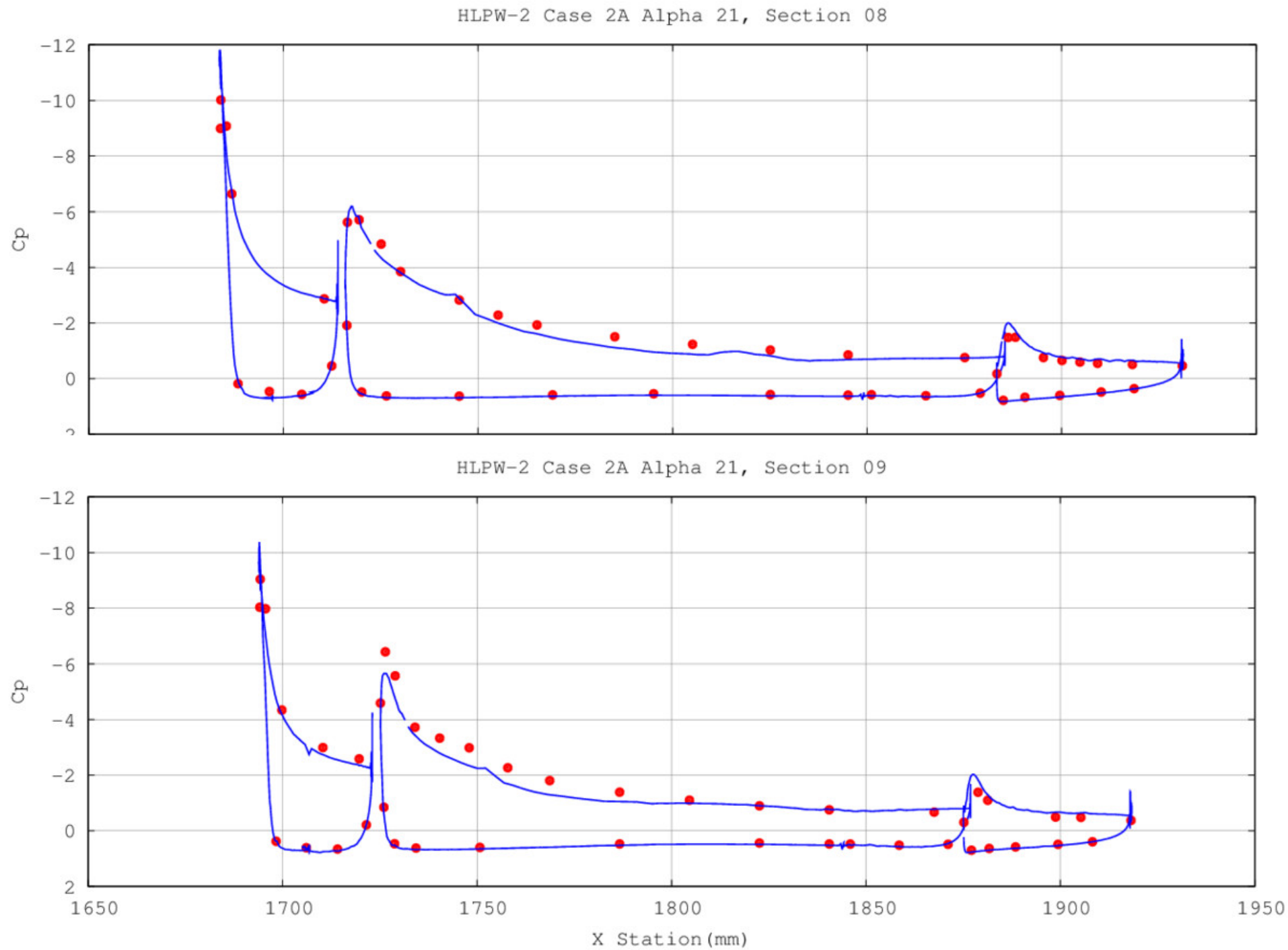
X Station(mm)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HLPW-2 Case 2A Alpha 21, Section 09
Cp
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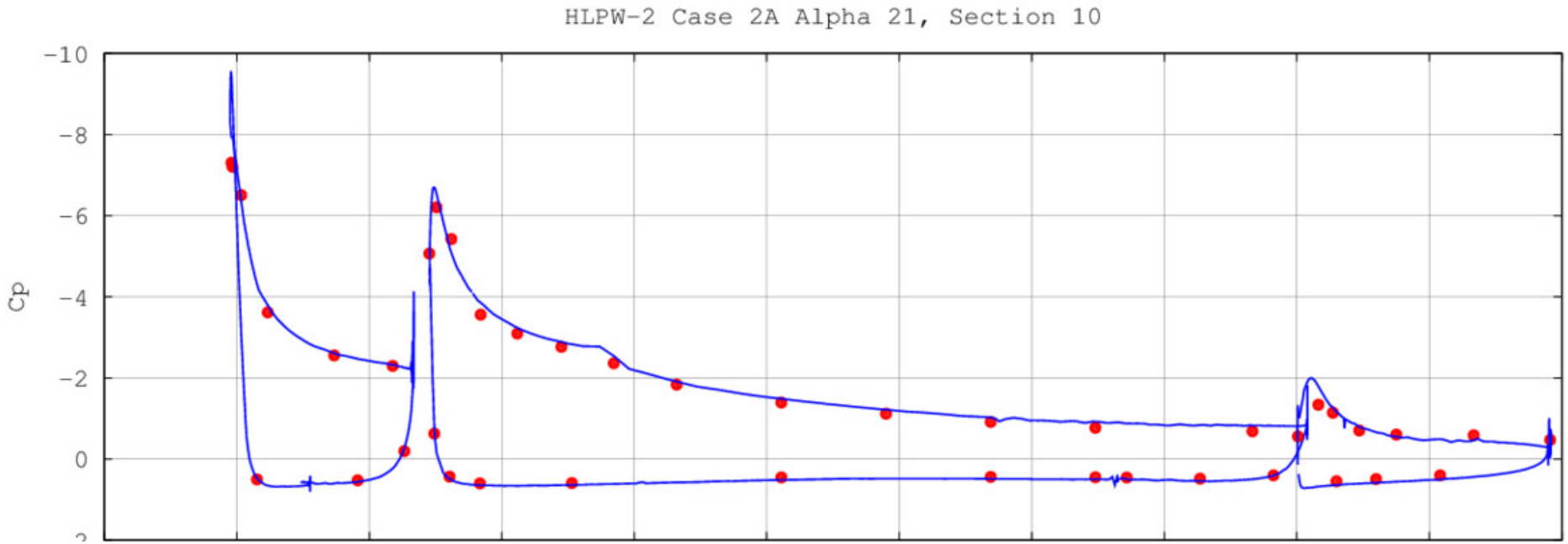
X Station(mm)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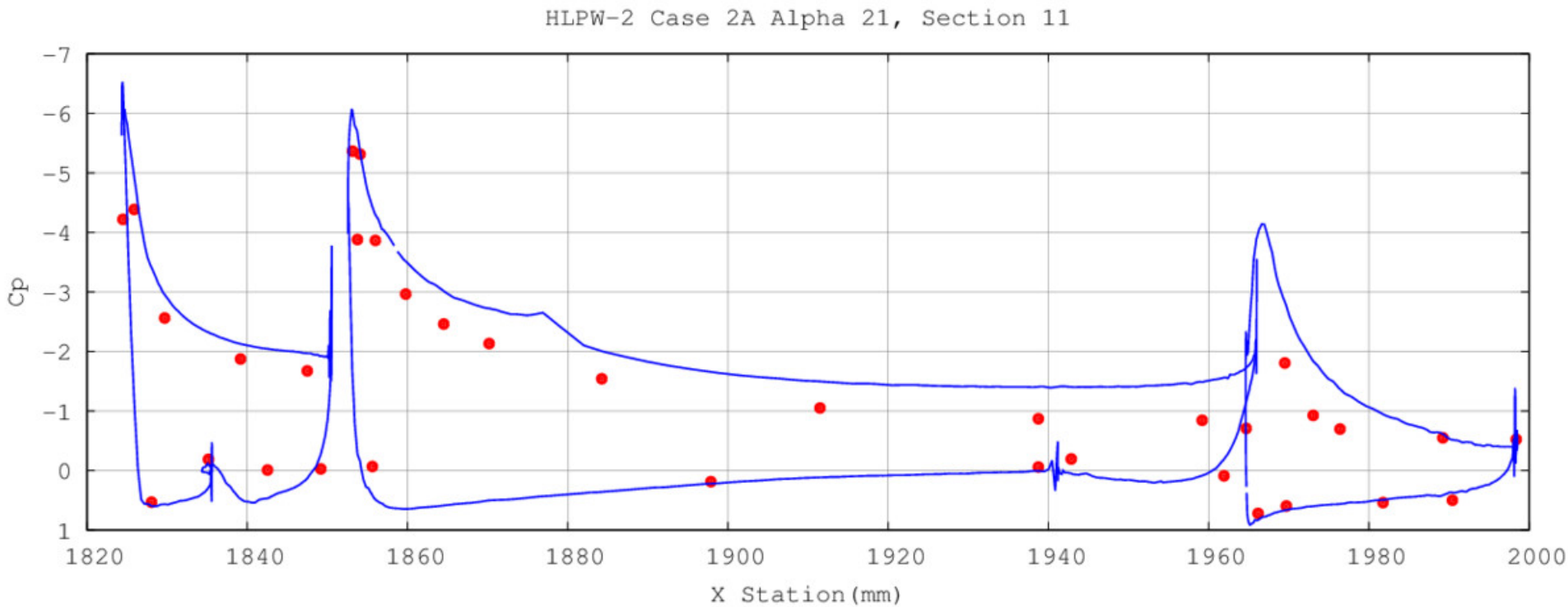
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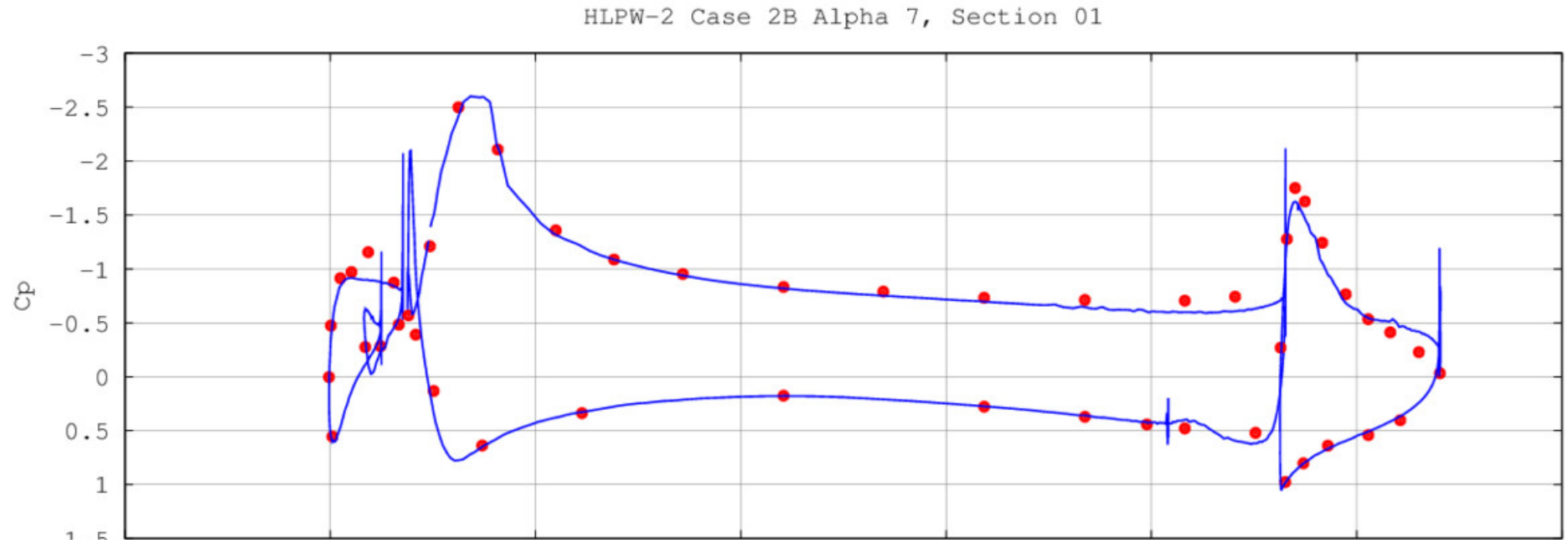
X Station(mm)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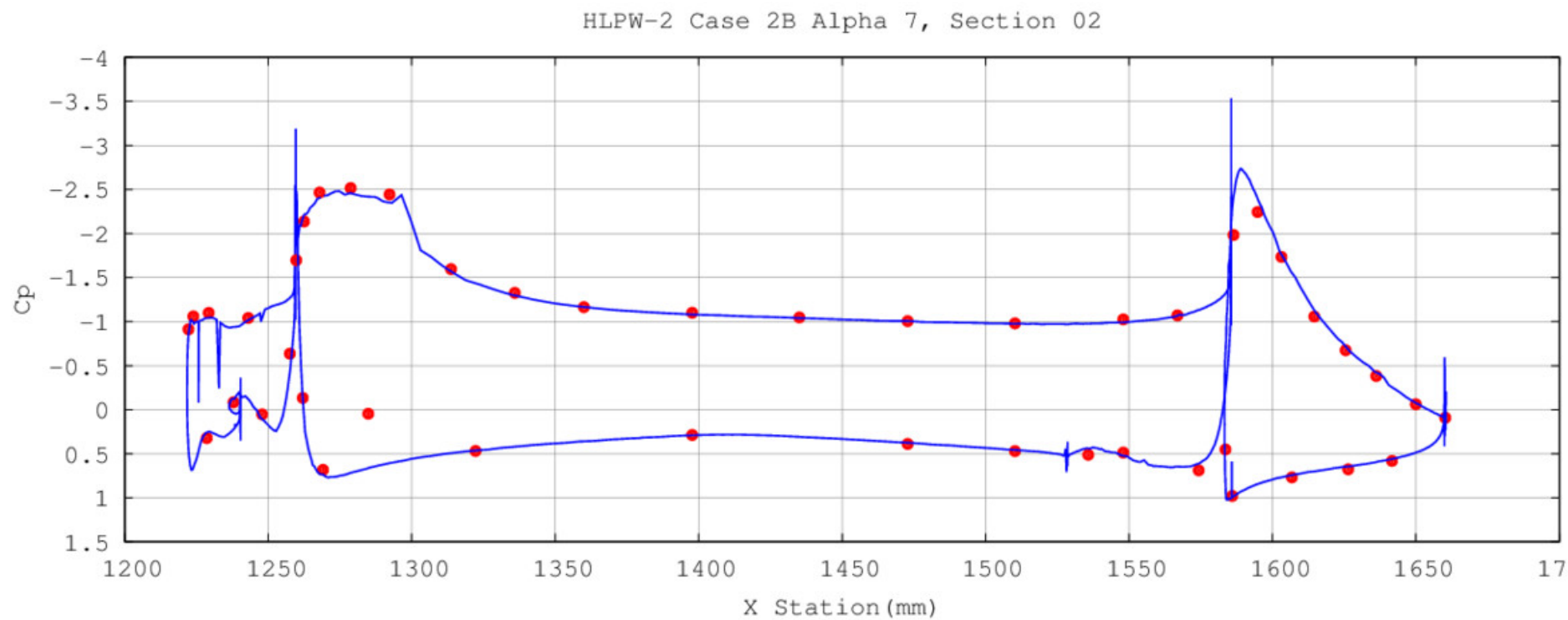
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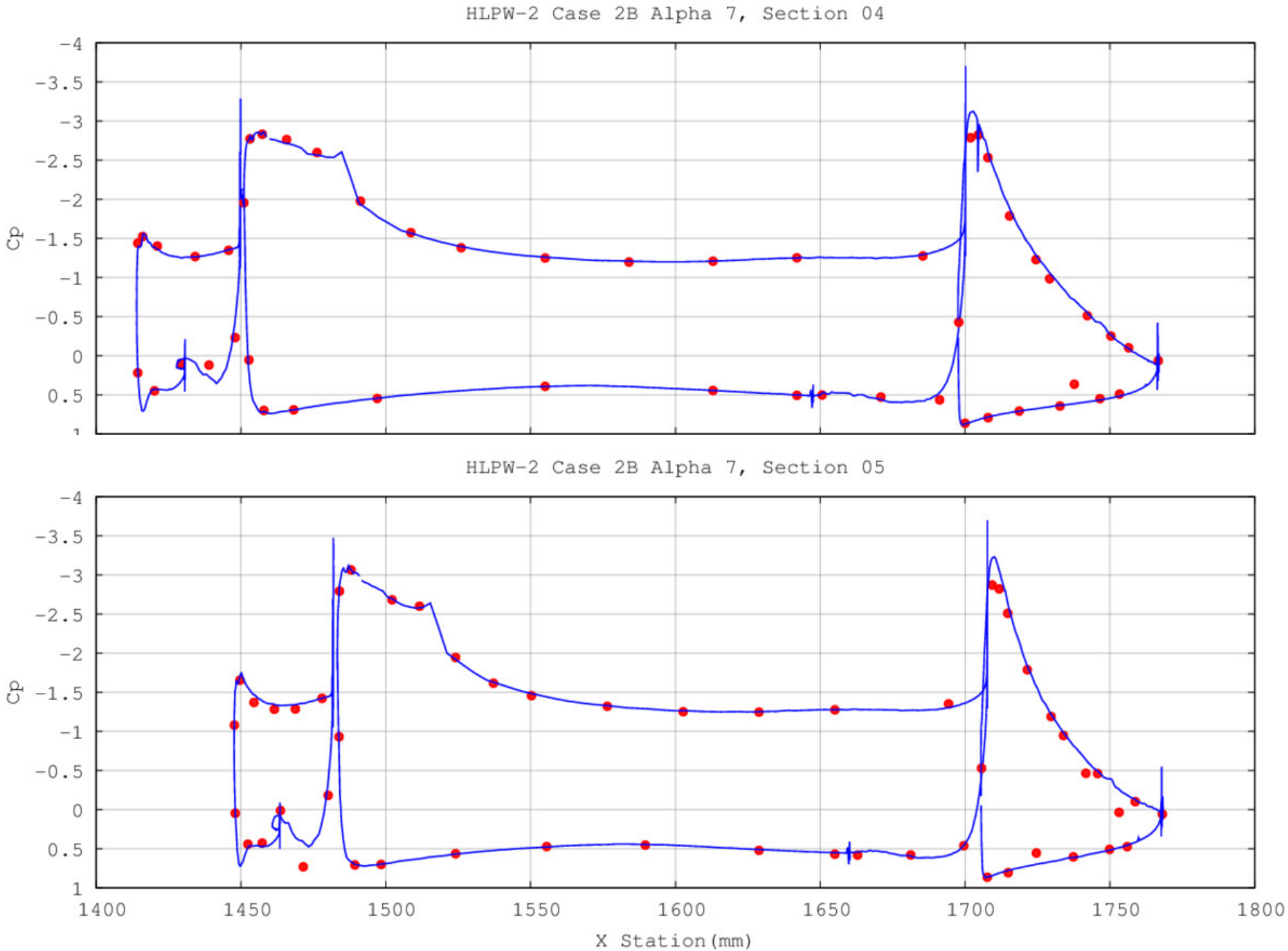
1700
X Station(mm)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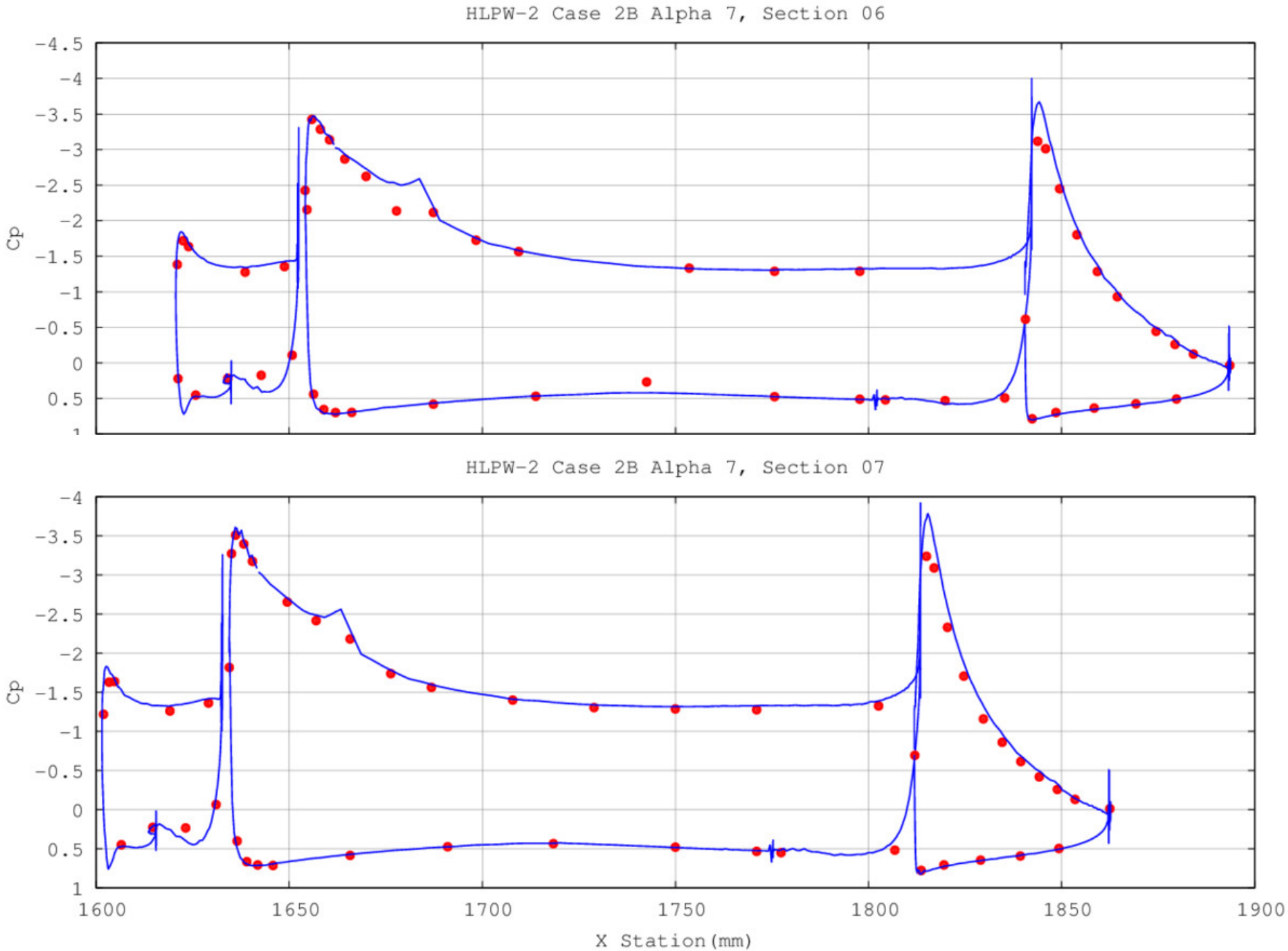
X Station(mm)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HLPW-2 Case 2B Alpha 7, Section 07
Cp
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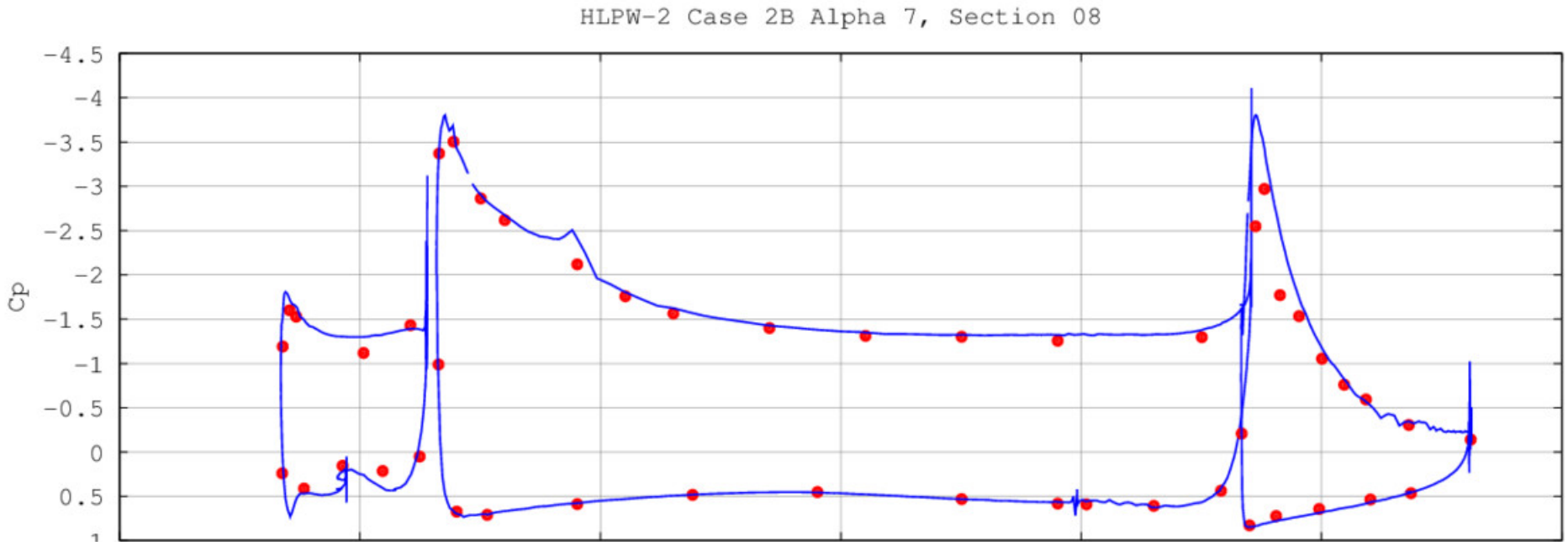
X Station(mm)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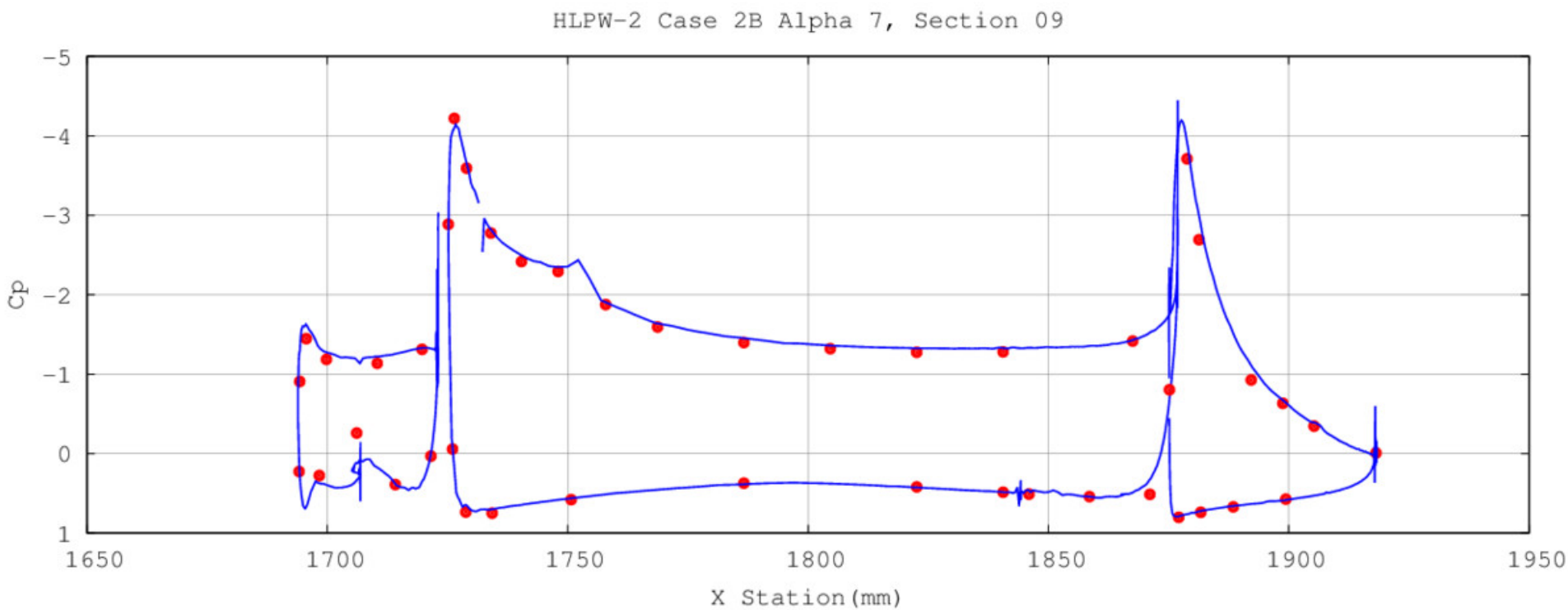
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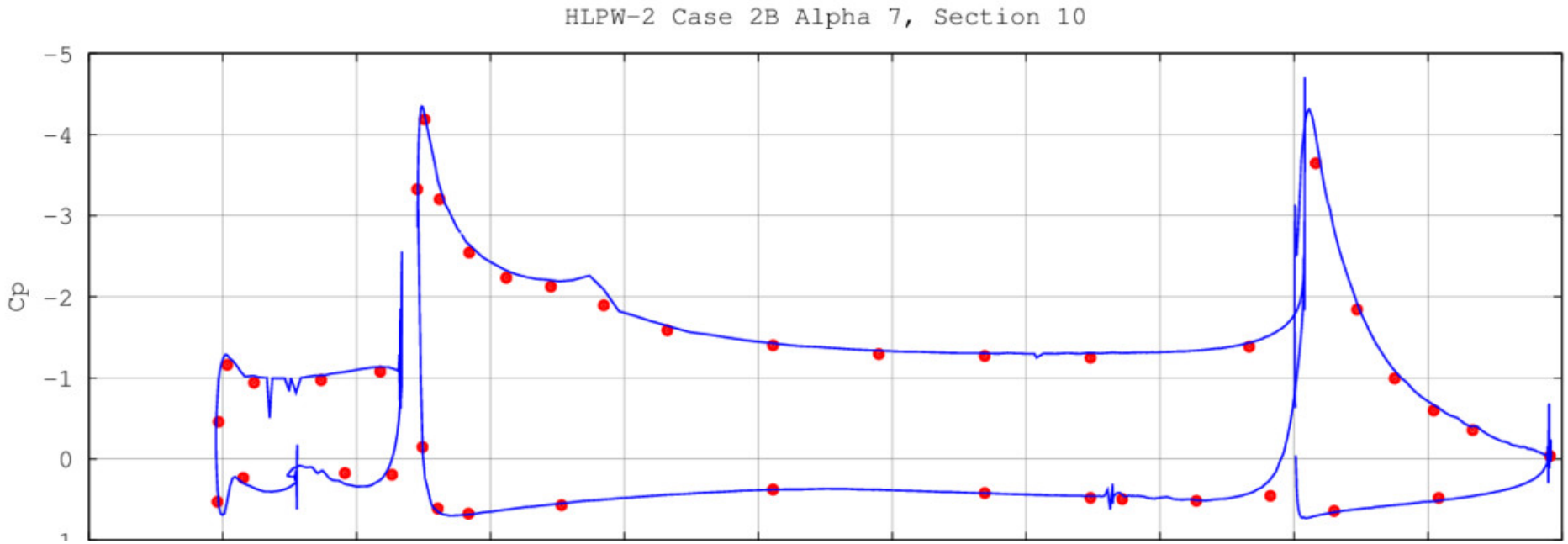
X Station(mm)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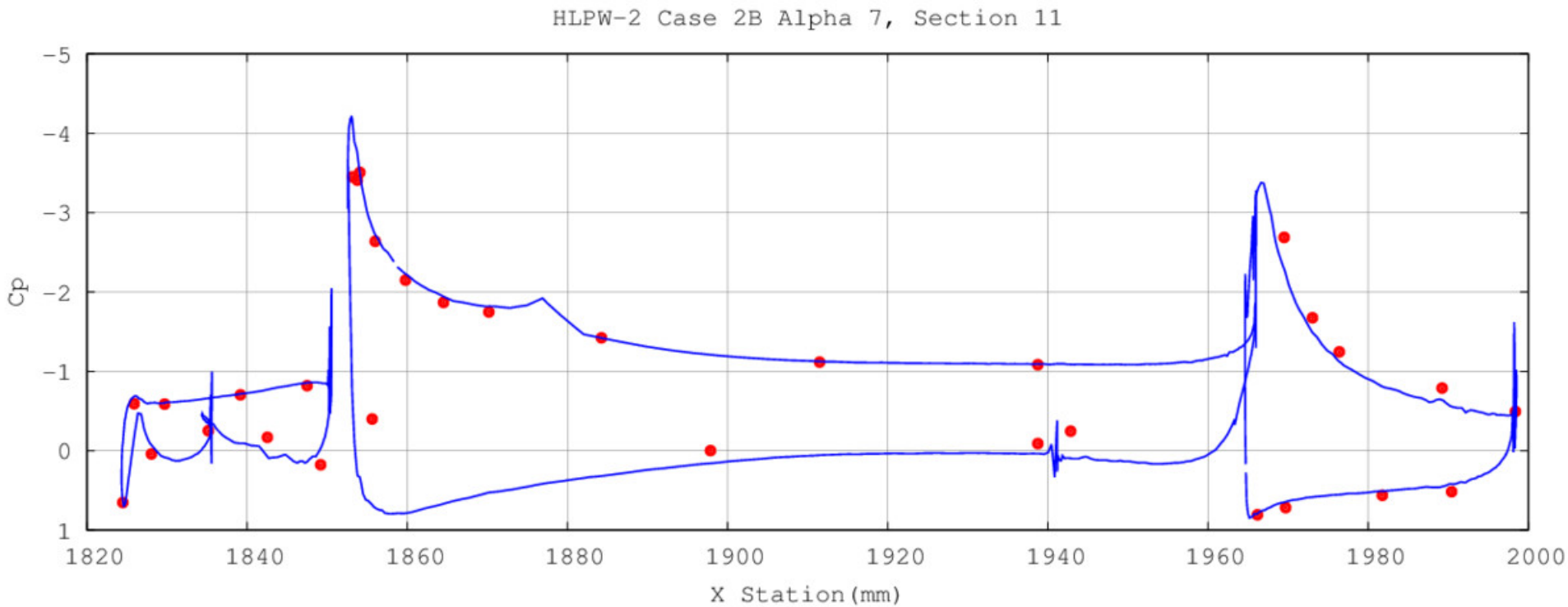
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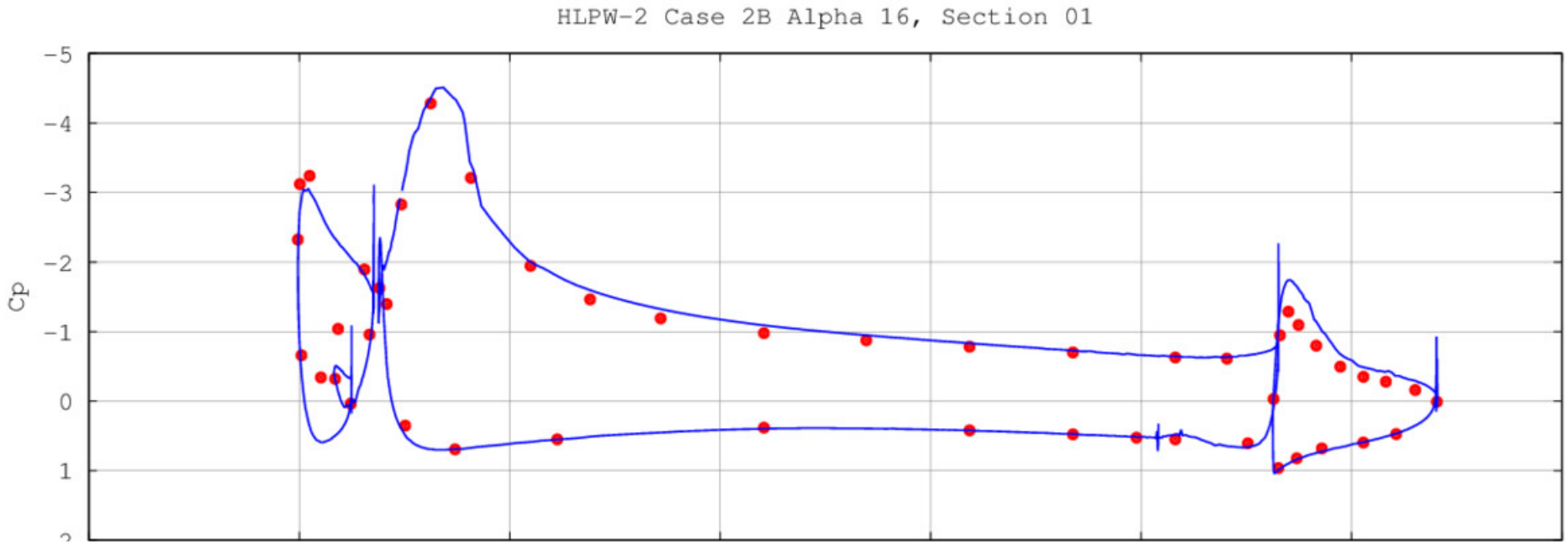
X Station(mm)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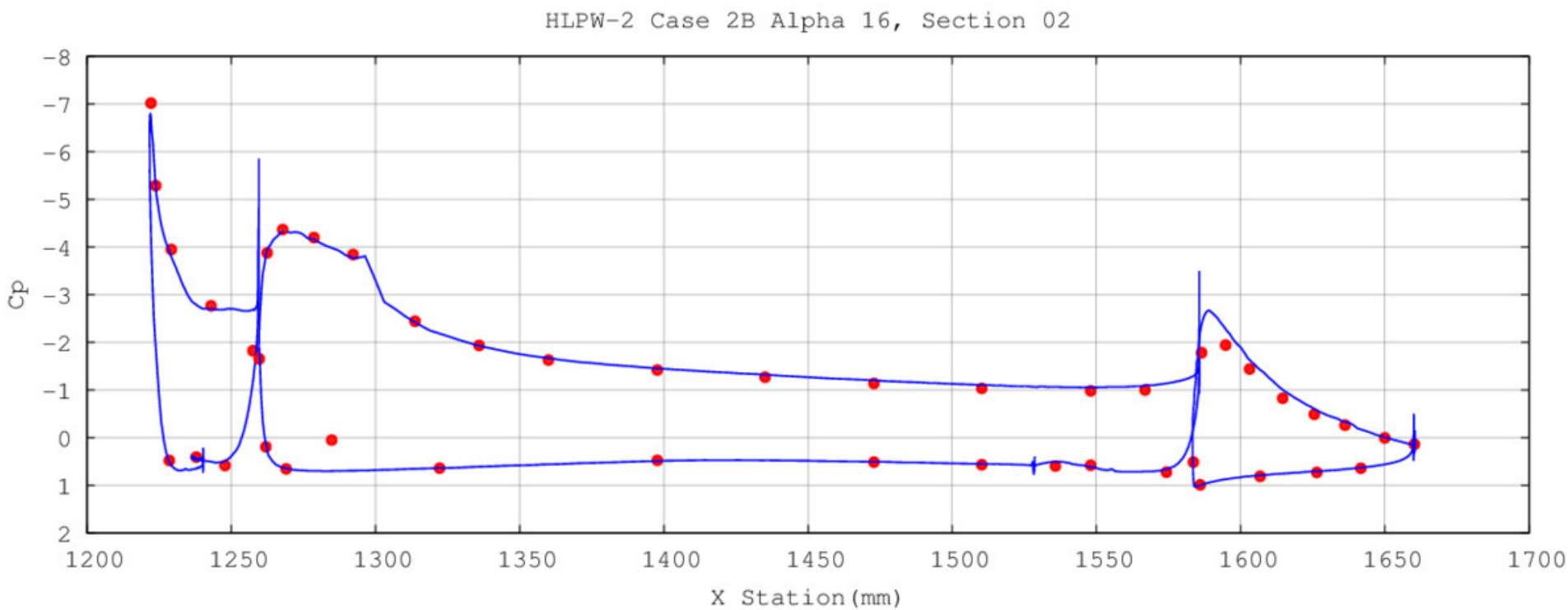
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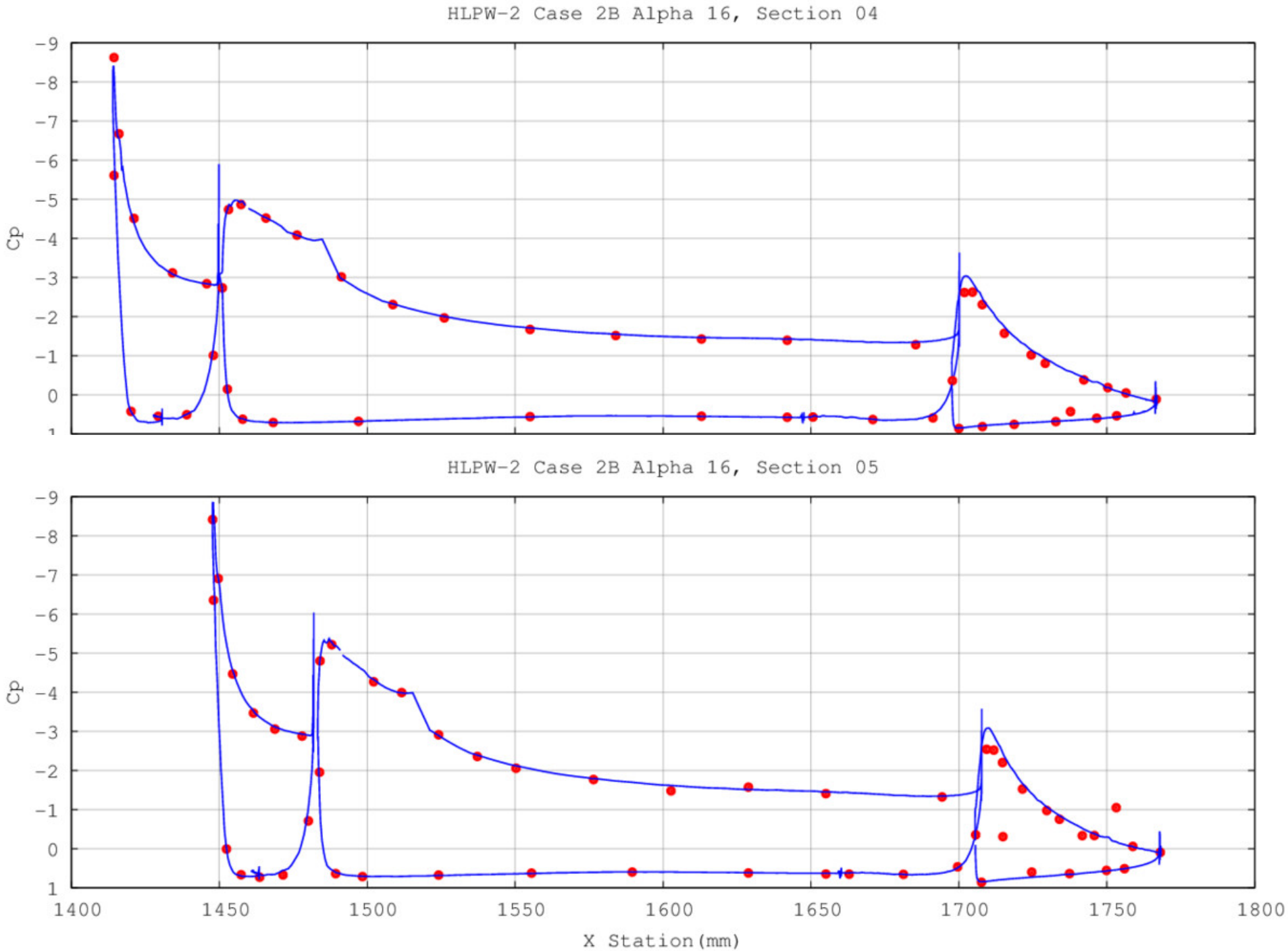
X Station(mm)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HLPW-2 Case 2B Alpha 16, Section 05
Cp
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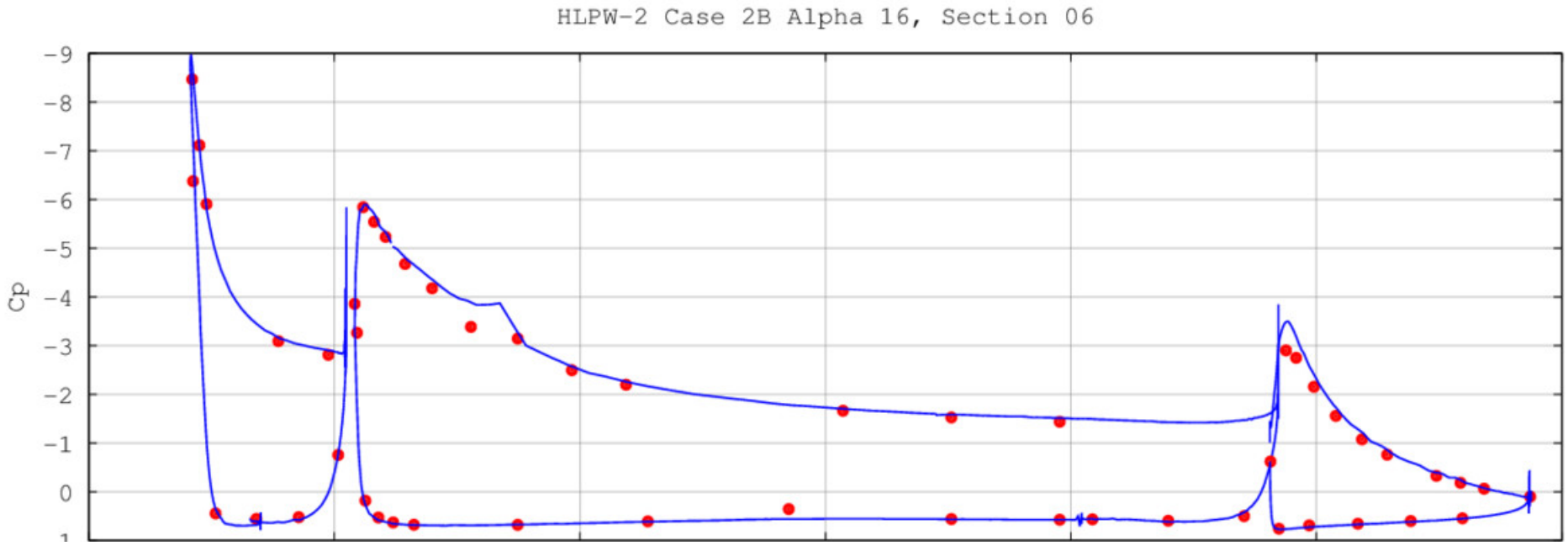
X Station(mm)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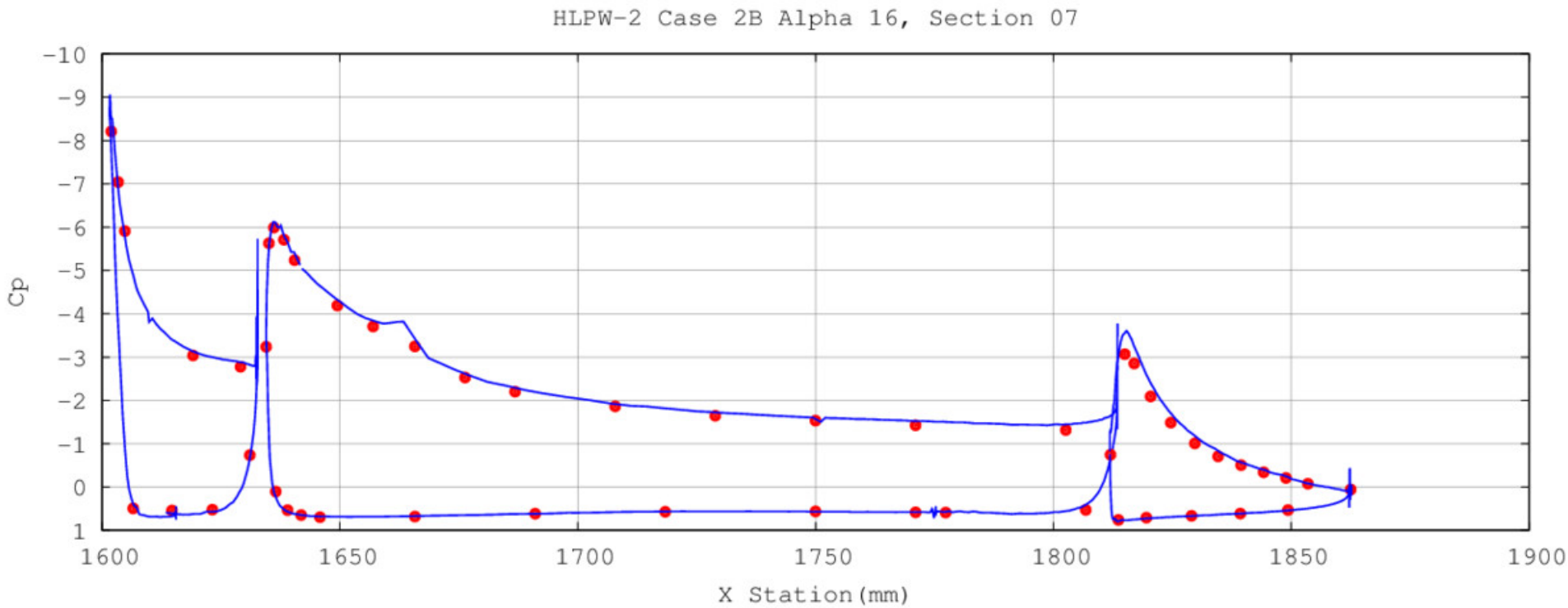
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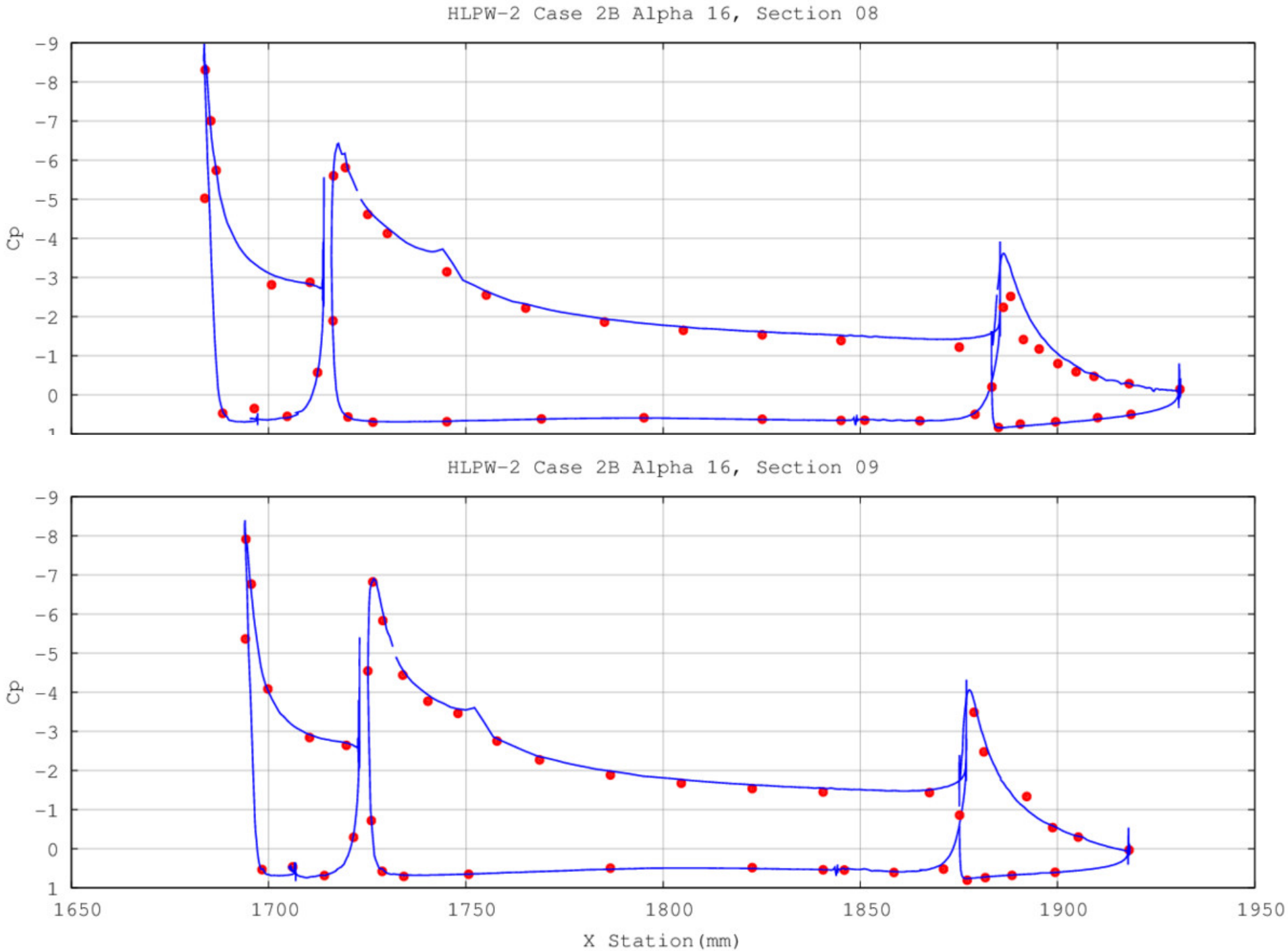
X Station(mm)


HLPW-2 Case 2B Alpha 16, Section 08
Cp
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HLPW-2 Case 2B Alpha 16, Section 09
Cp
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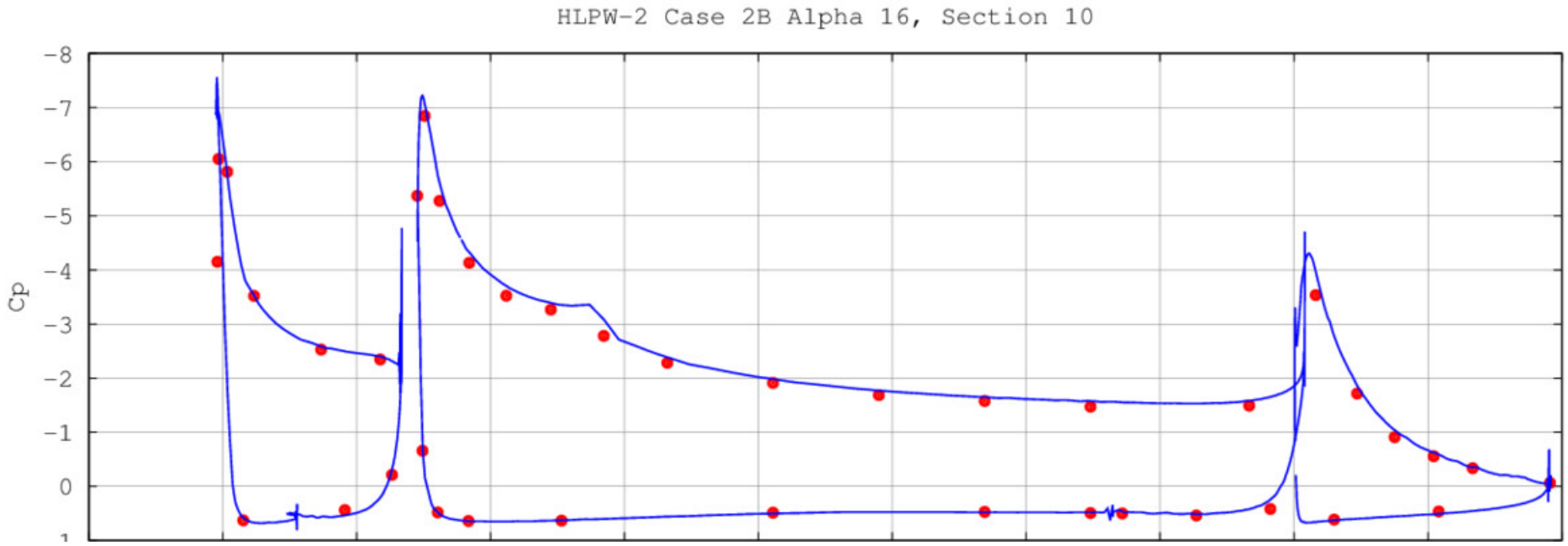
X Station(mm)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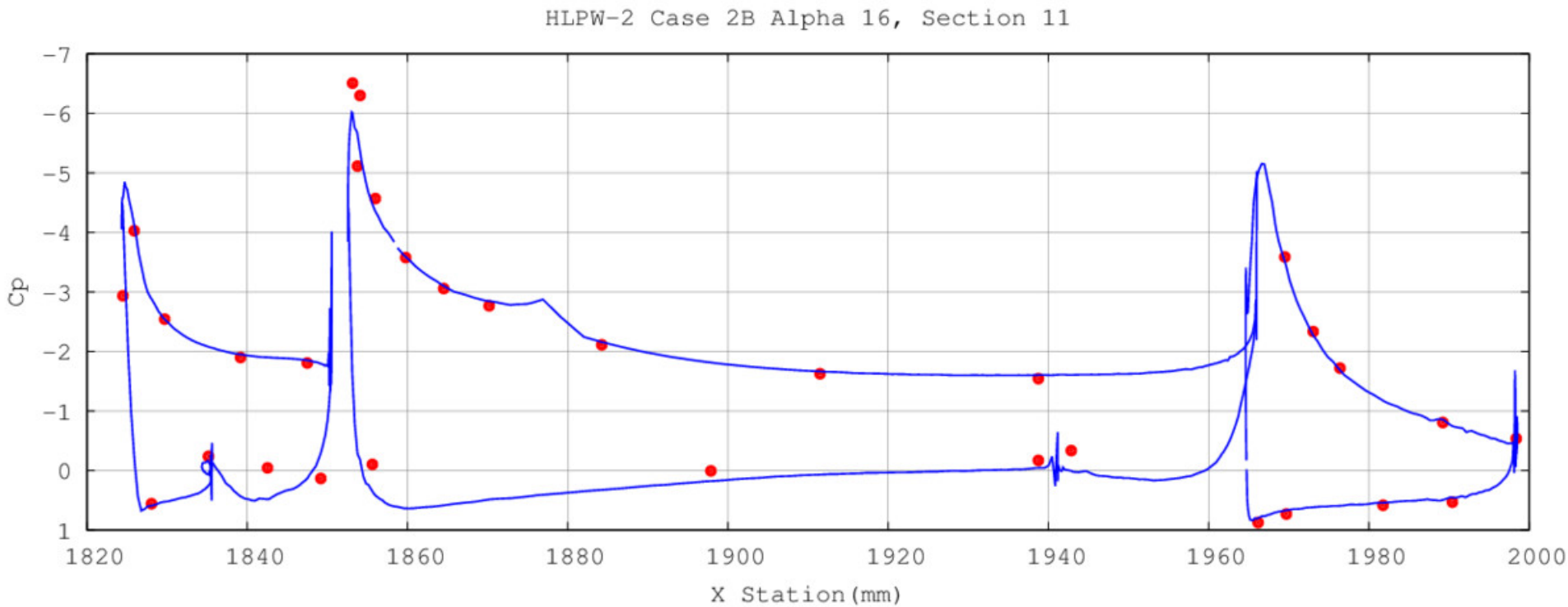
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Cp
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1880
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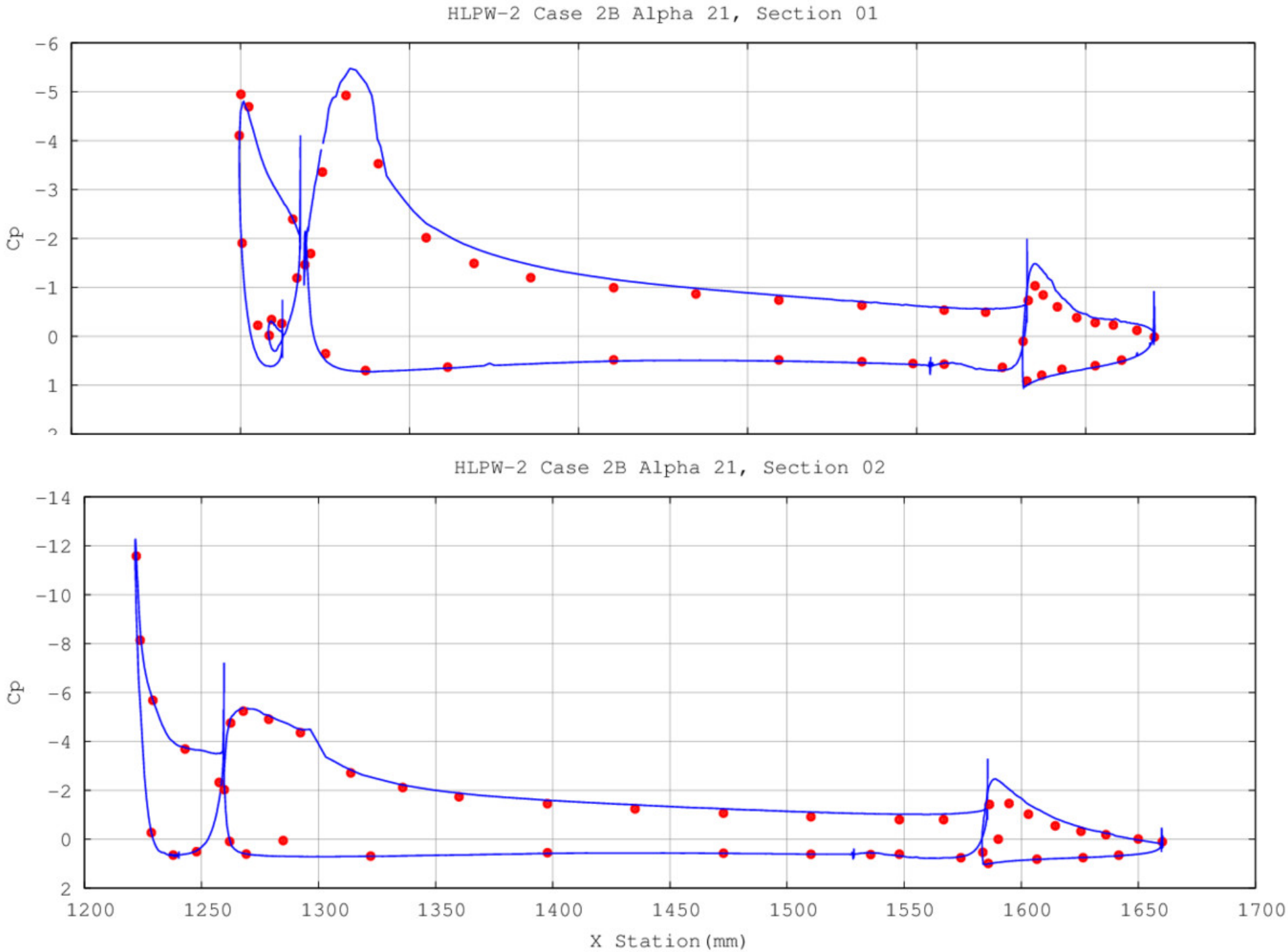
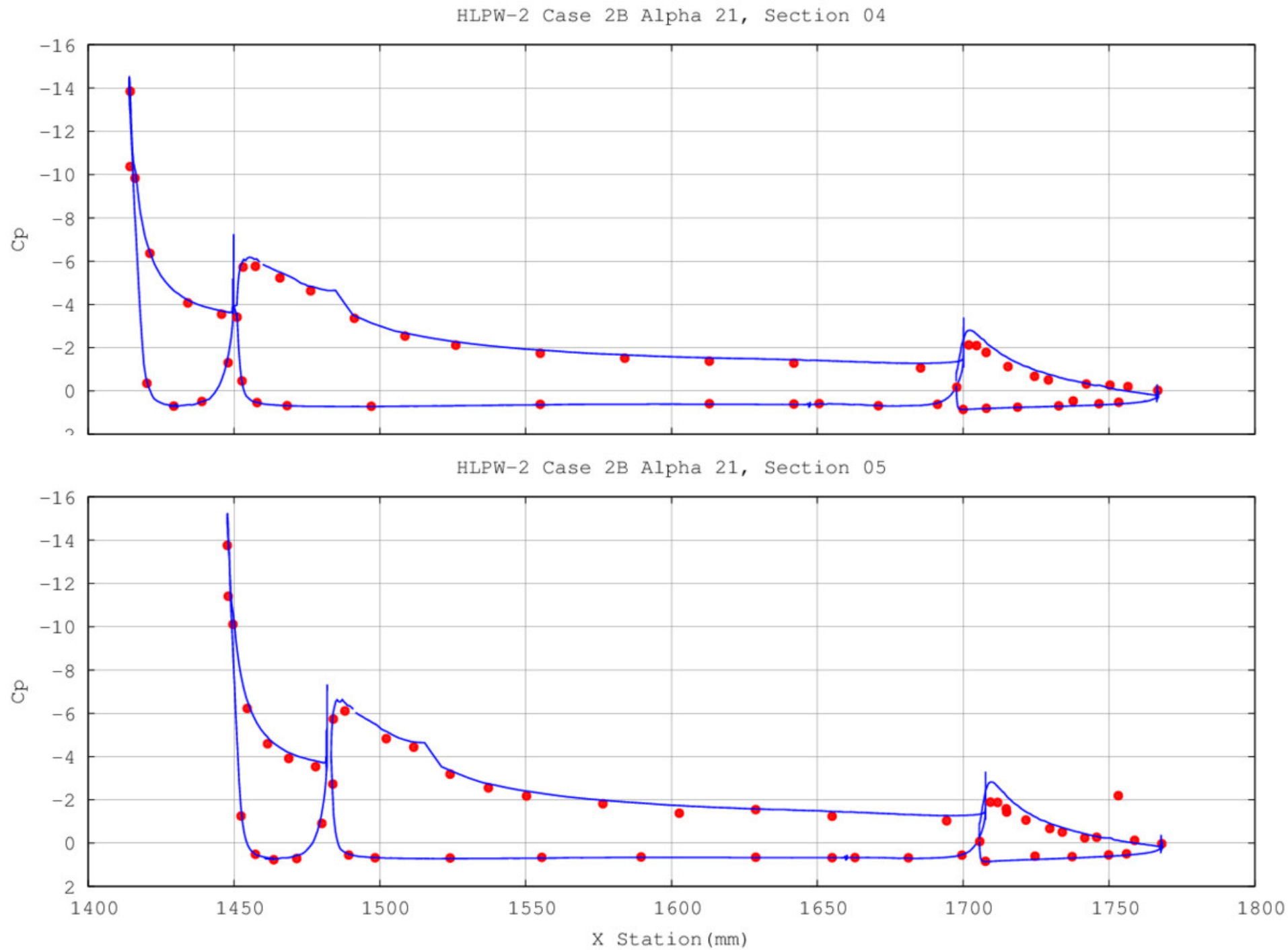
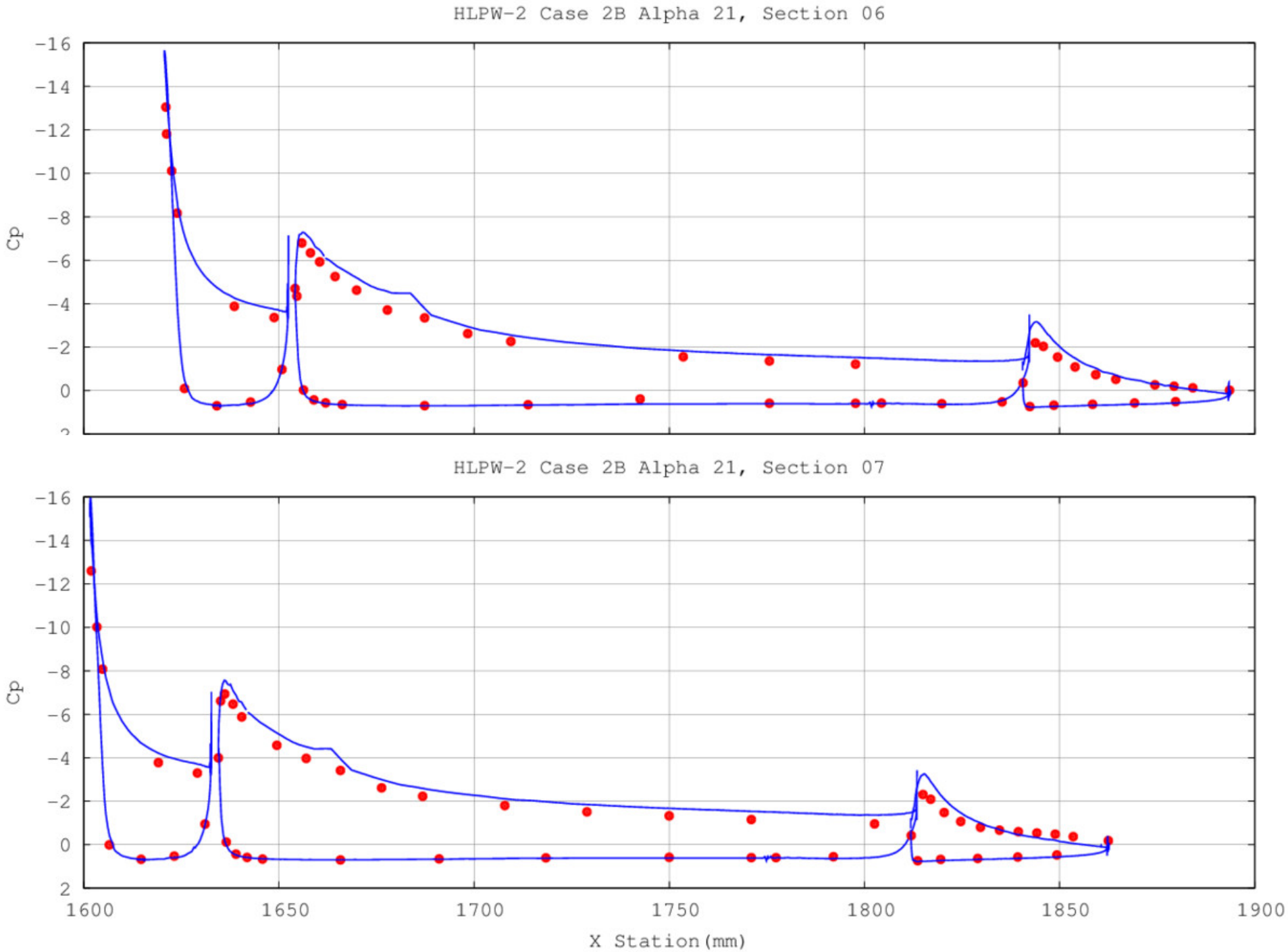
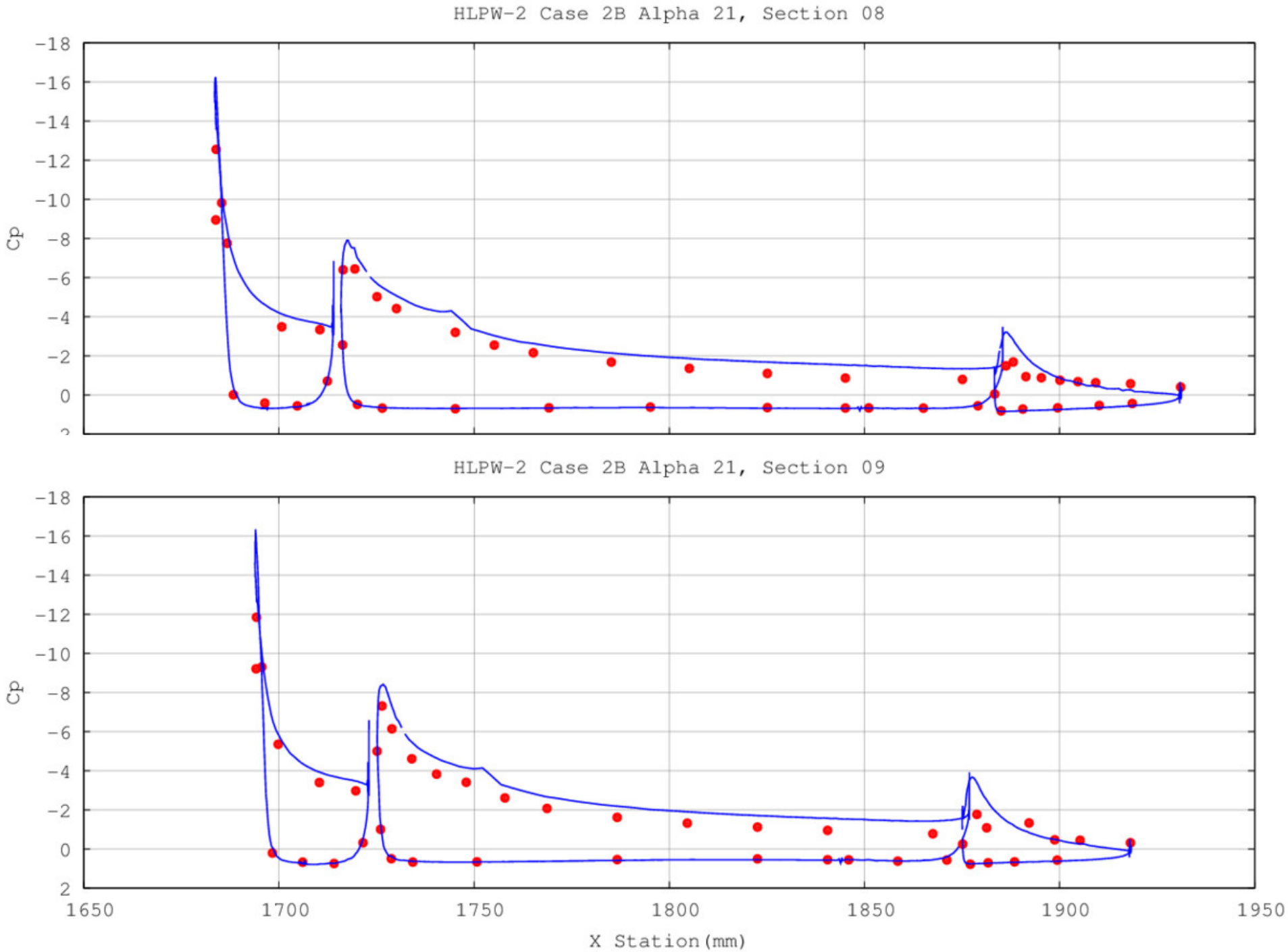
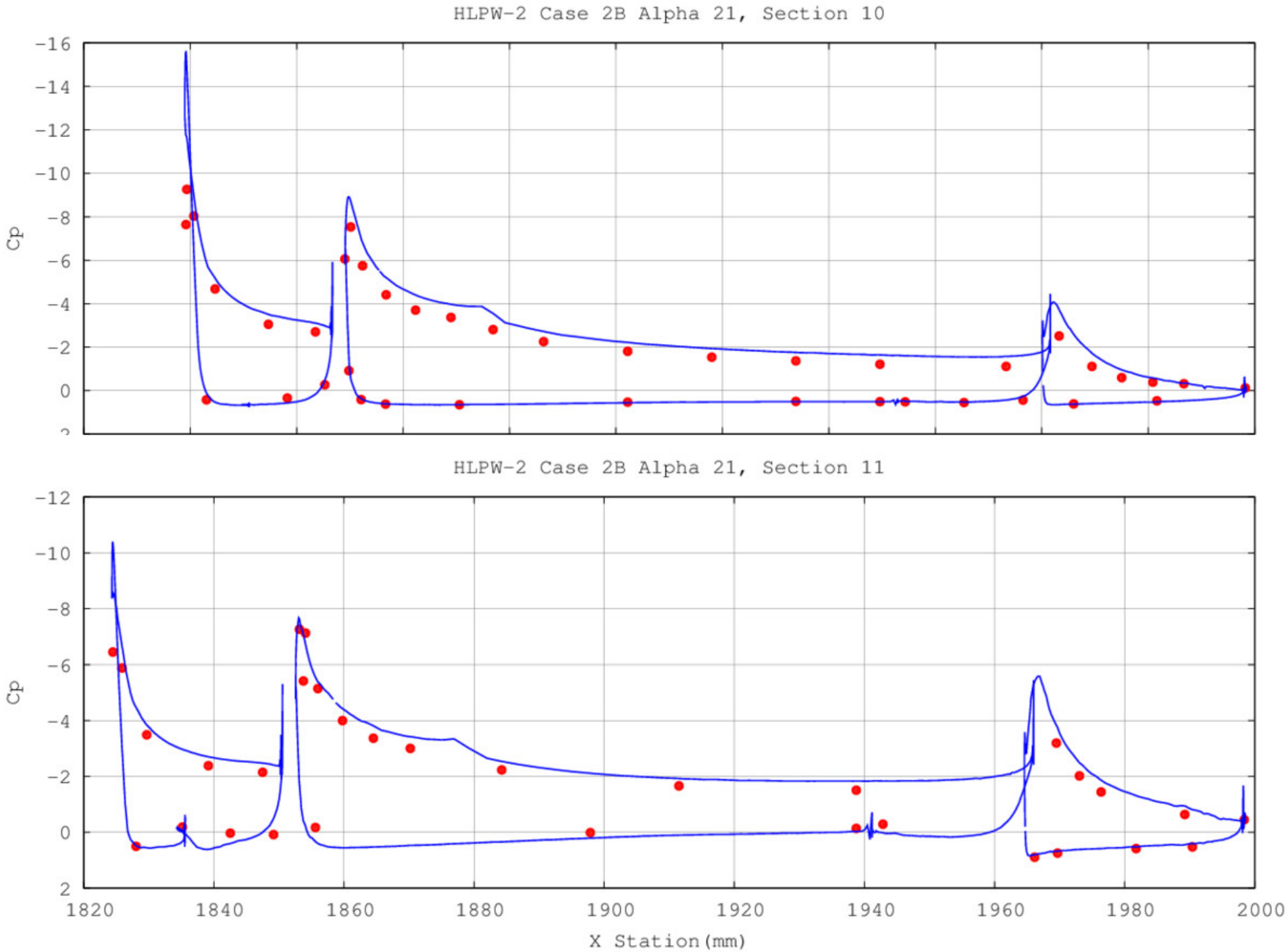
1960
1980
2000
X Station(mm)

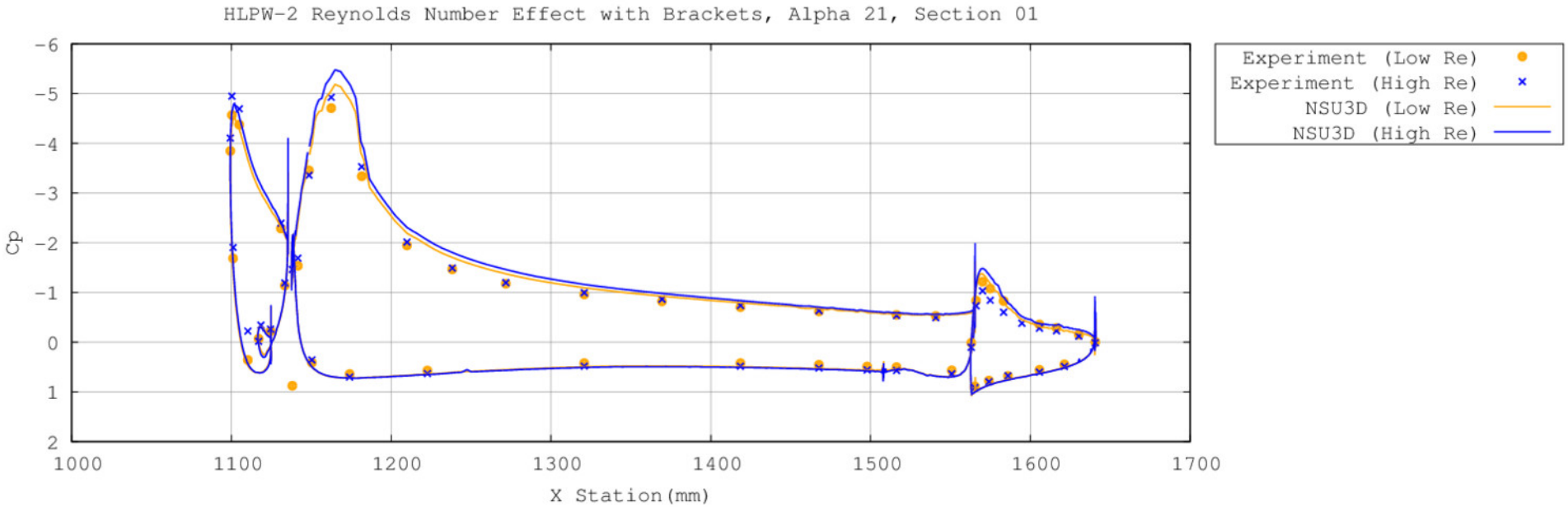

HLPW-2 Case 2B Alpha 21, Section 01
Cp
-6
-5
-4
-3
-2
-1
0
1
HLPW-2 Case 2B Alpha 21, Section 02
Cp
-14
-12
-10
-8
-6
-4
-2
0
2
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
X Station(mm)

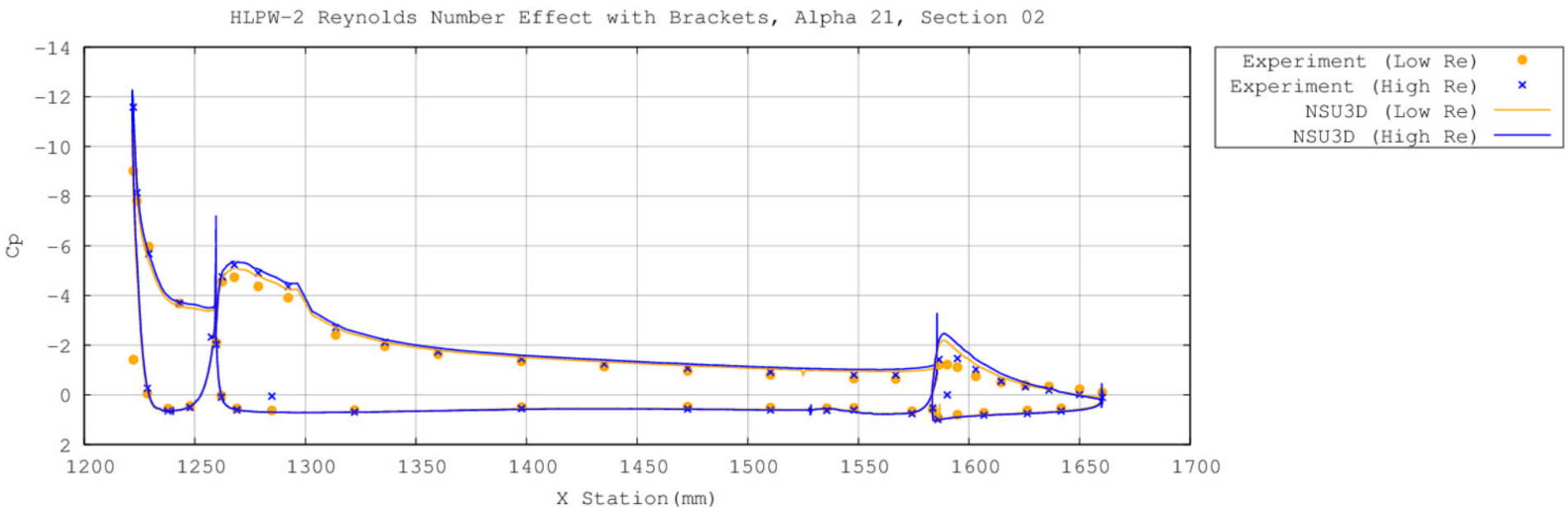

HLPW-2 Case 2B Alpha 21, Section 04
Cp
-16
-14
-12
-10
-8
-6
-4
-2
0
2
HLPW-2 Case 2B Alpha 21, Section 05
Cp
-16
-14
-12
-10
-8
-6
-4
-2
0
2
1400
1450
1500
1550
1600
1650
1700
1750
1800
X Station(mm)

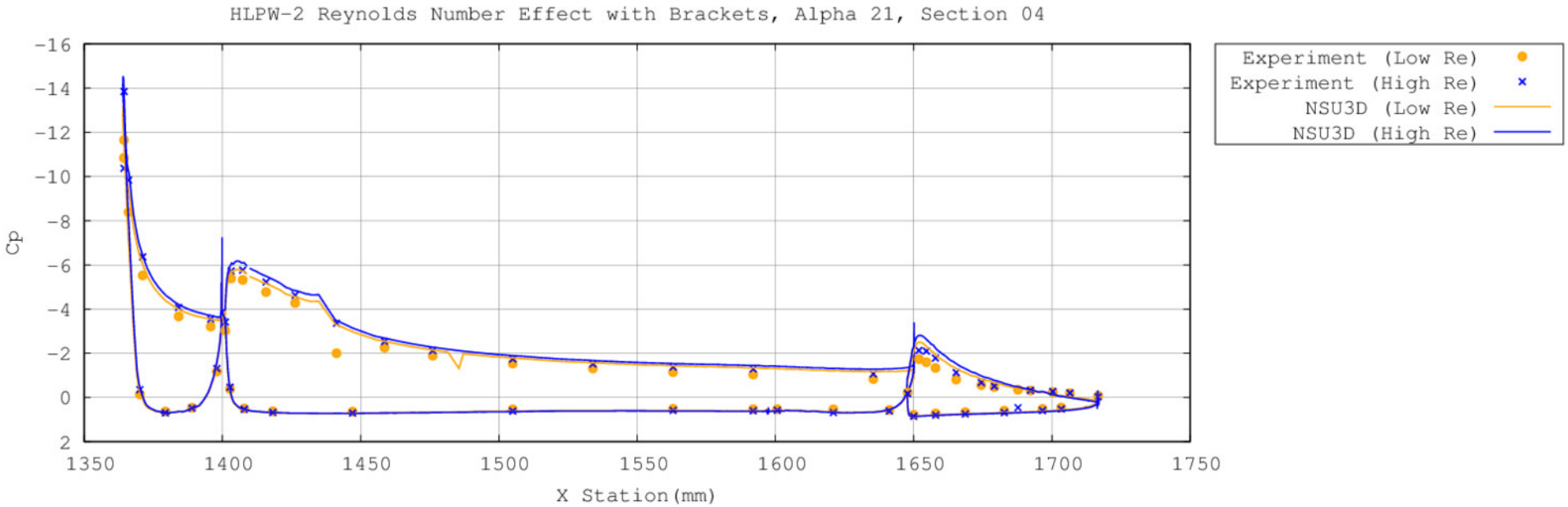

HLPW-2 Case 2B Alpha 21, Section 06
Cp
-16
-14
-12
-10
-8
-6
-4
-2
0
HLPW-2 Case 2B Alpha 21, Section 07
Cp
-16
-14
-12
-10
-8
-6
-4
-2
0
2
1600
1650
1700
1750
1800
1850
1900
X Station(mm)

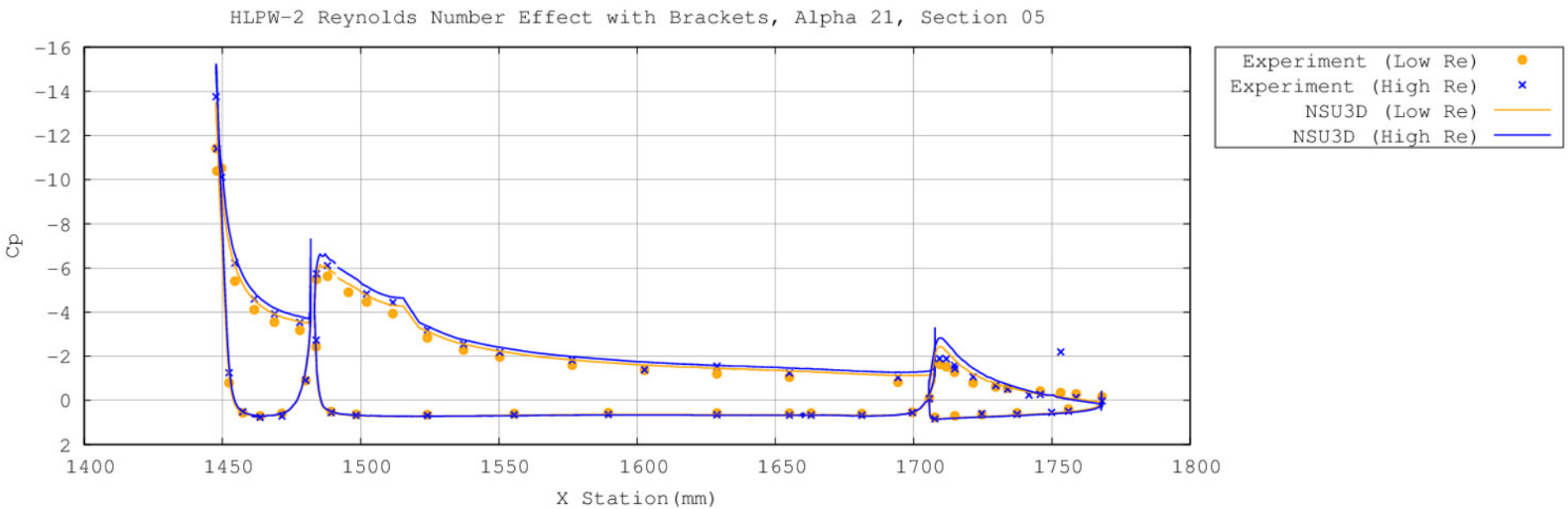

HLPW-2 Case 2B Alpha 21, Section 08
Cp
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
HLPW-2 Case 2B Alpha 21, Section 09
Cp
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
1650
1700
1750
1800
1850
1900
1950
X Station(mm)

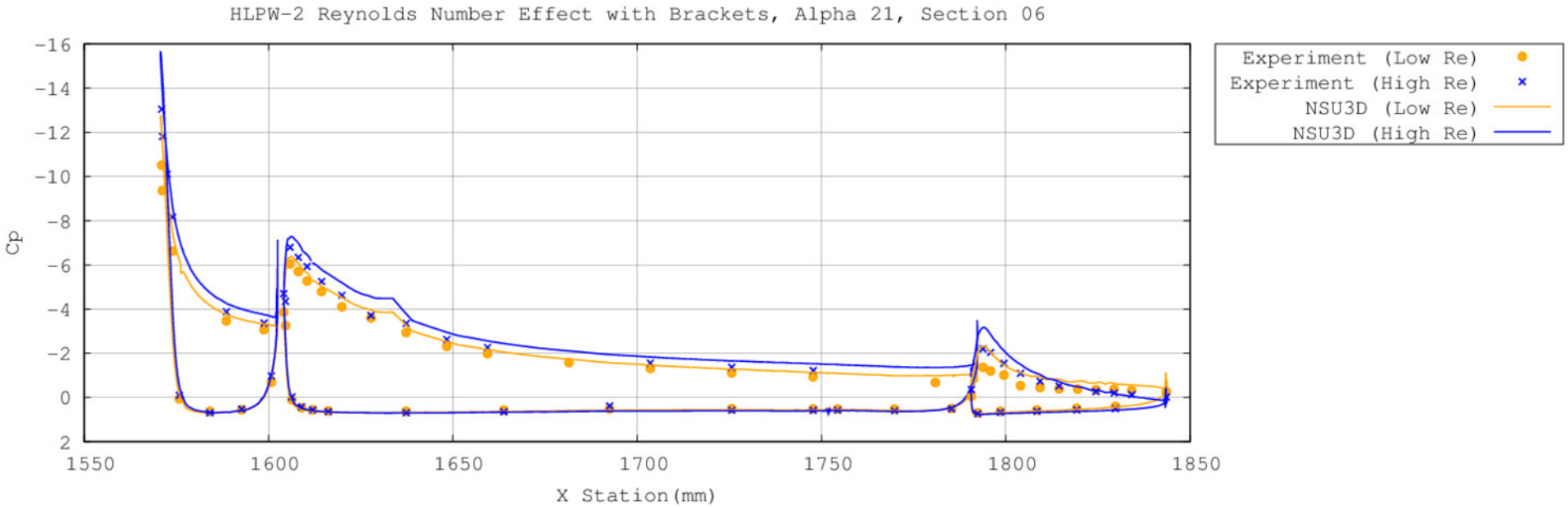

HLPW-2 Case 2B Alpha 21, Section 10
Cp
-16
-14
-12
-10
-8
-6
-4
-2
0
HLPW-2 Case 2B Alpha 21, Section 11
Cp
-12
-10
-8
-6
-4
-2
0
2
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
X Station(mm)

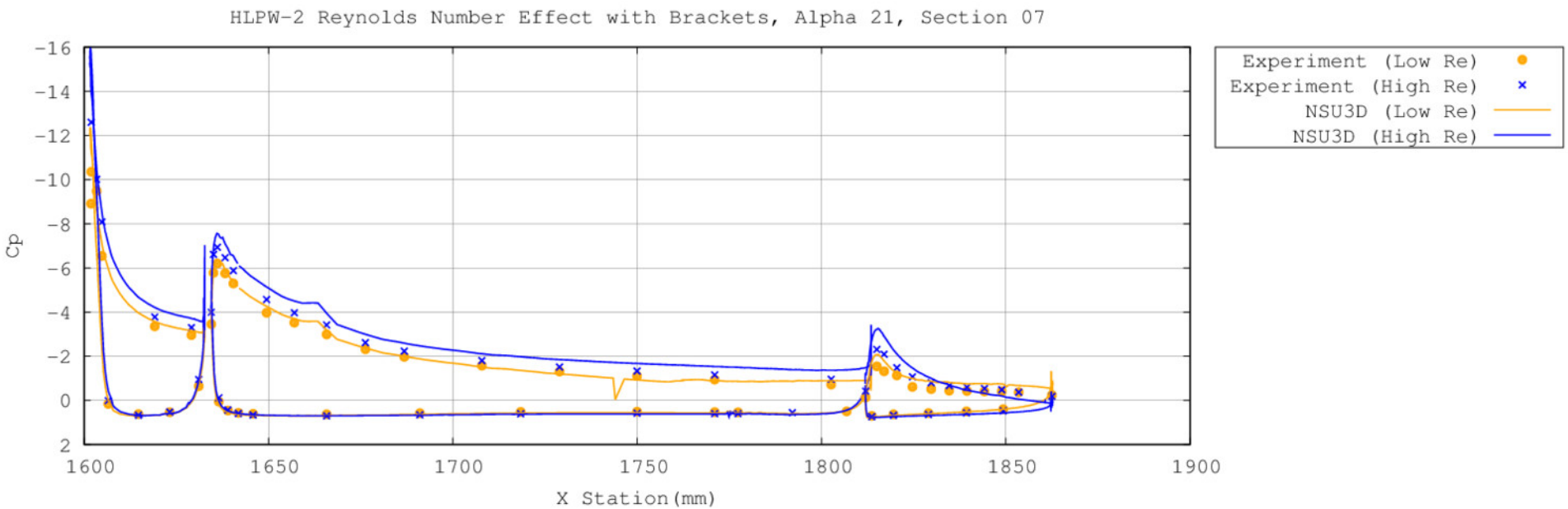

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 01
Cp
X Station(mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

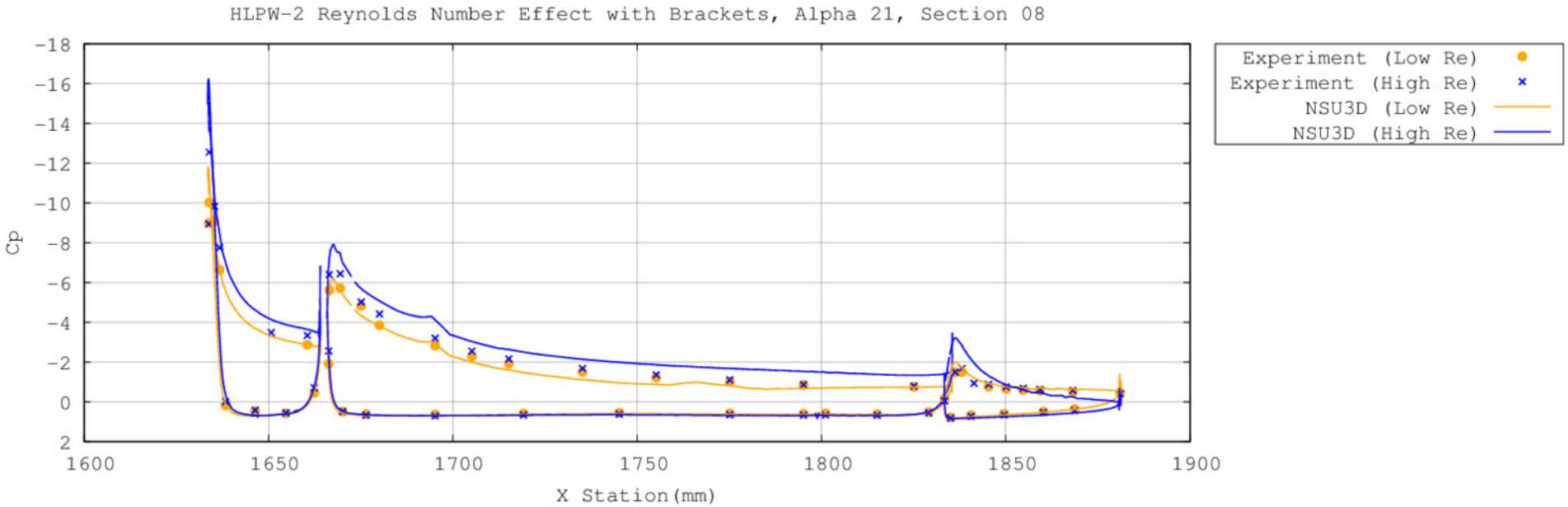

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 02
Cp
X Station(mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

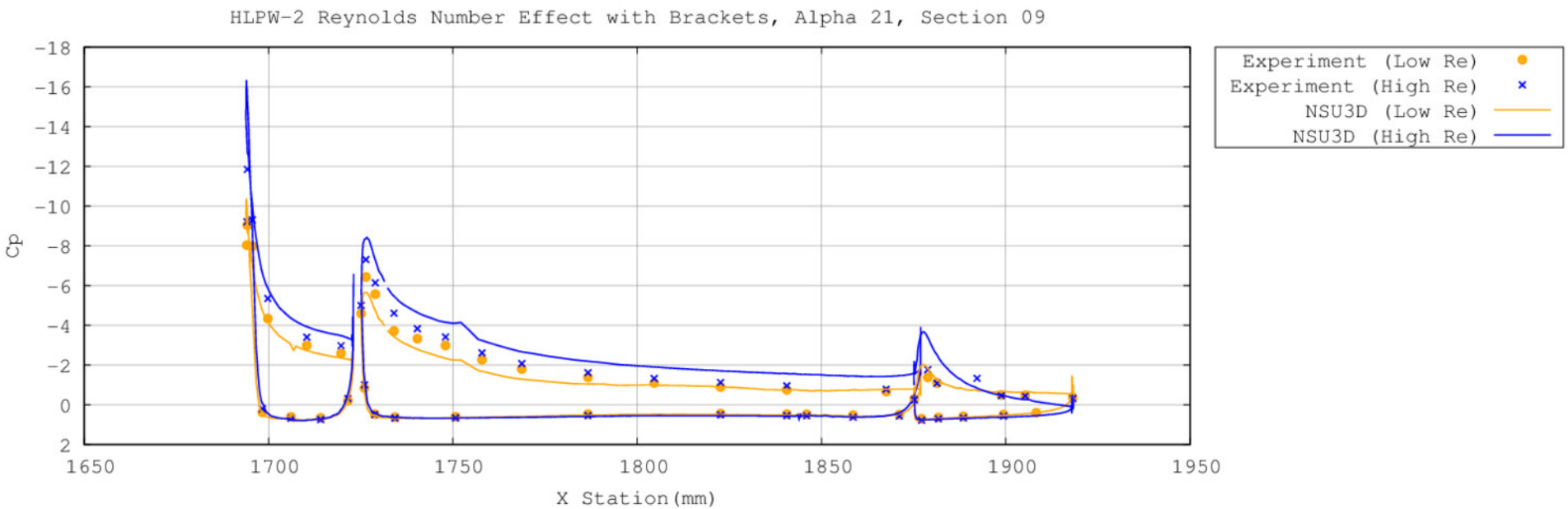

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 04
Cp
X Station (mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

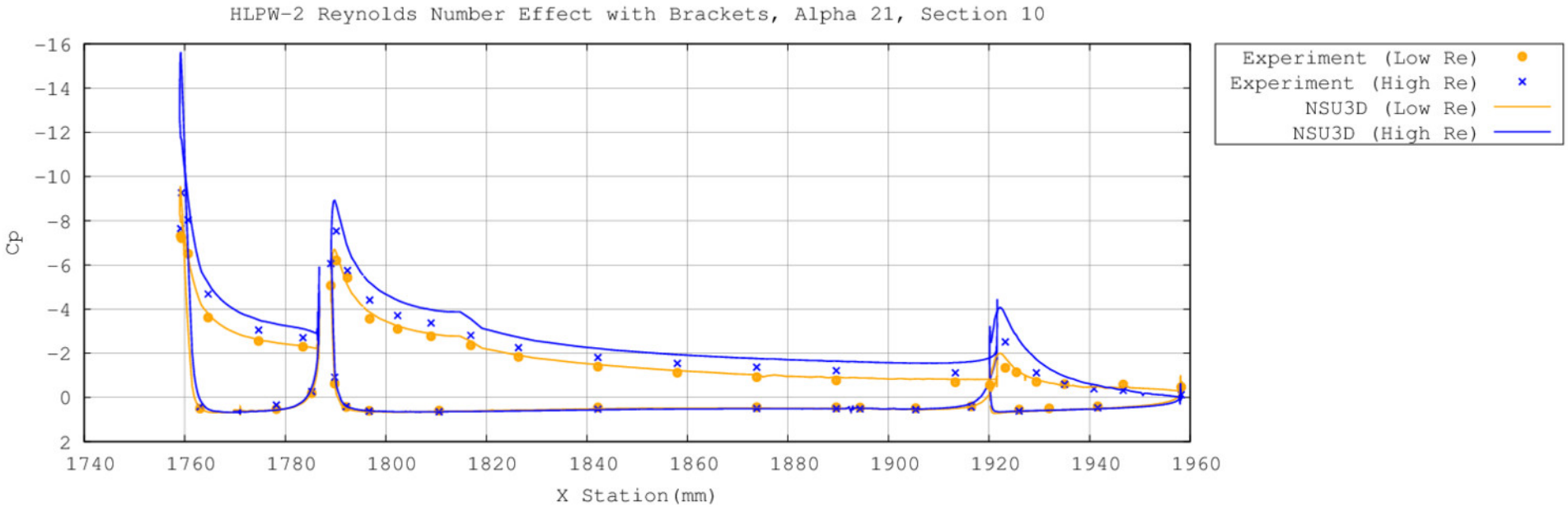

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 05
Cp
X Station (mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

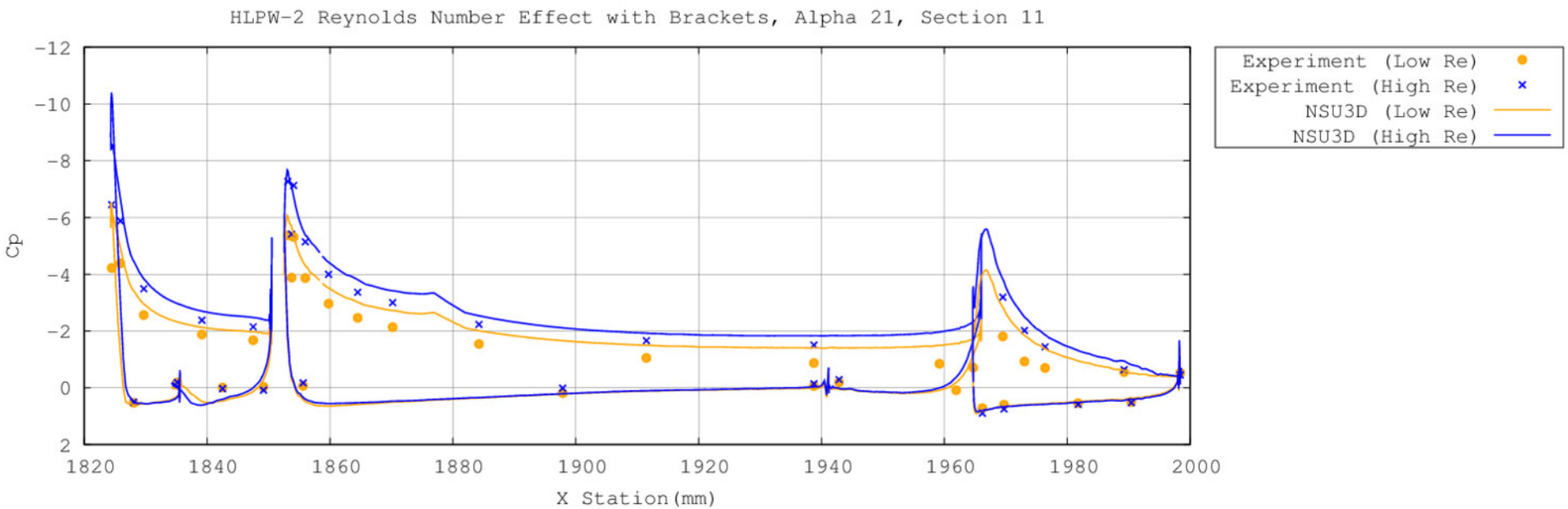

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 06
Cp
X Station (mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

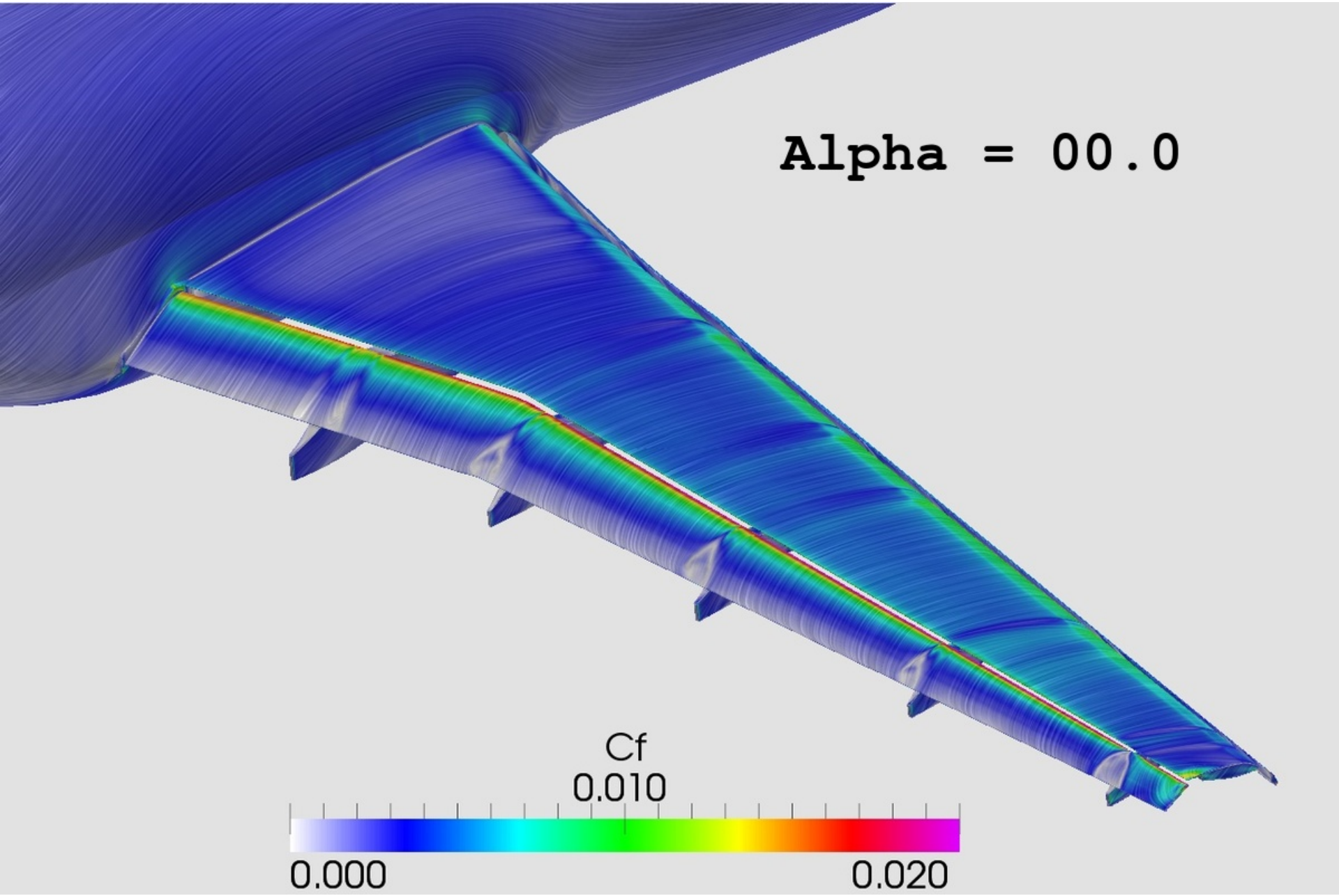

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 07
Cp
X Station (mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

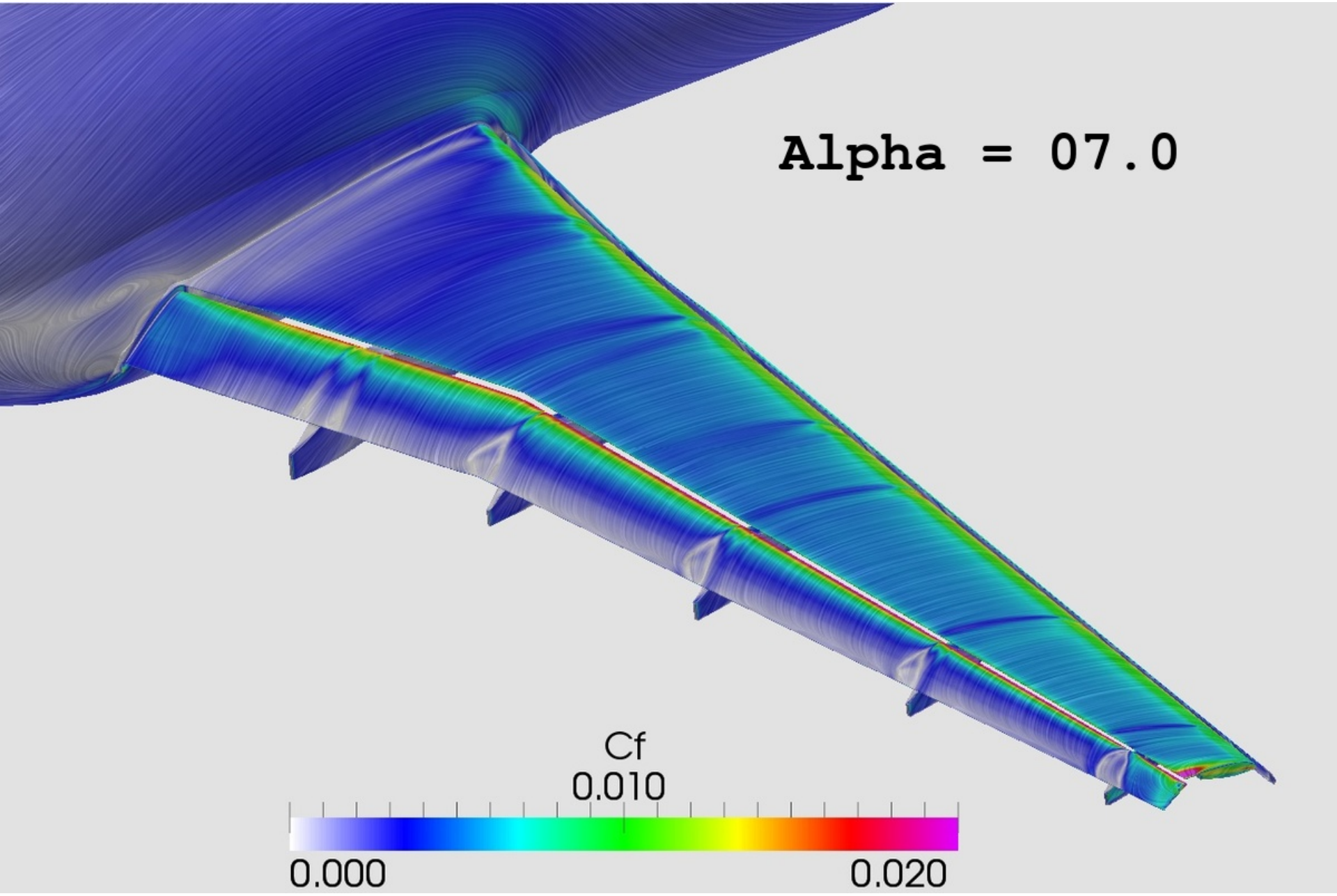

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 08
Cp
X Station (mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

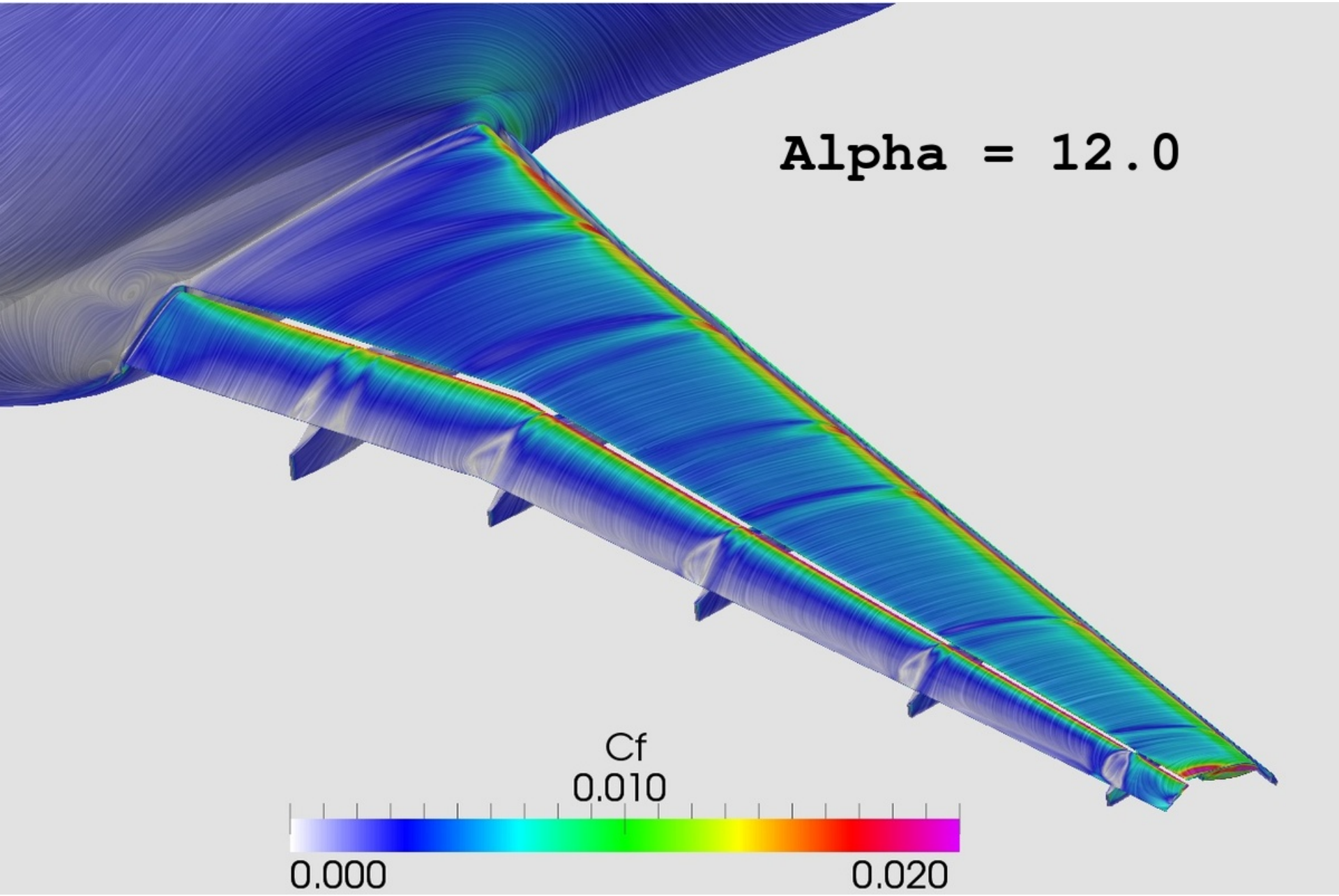

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 09
Cp
X Station (mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

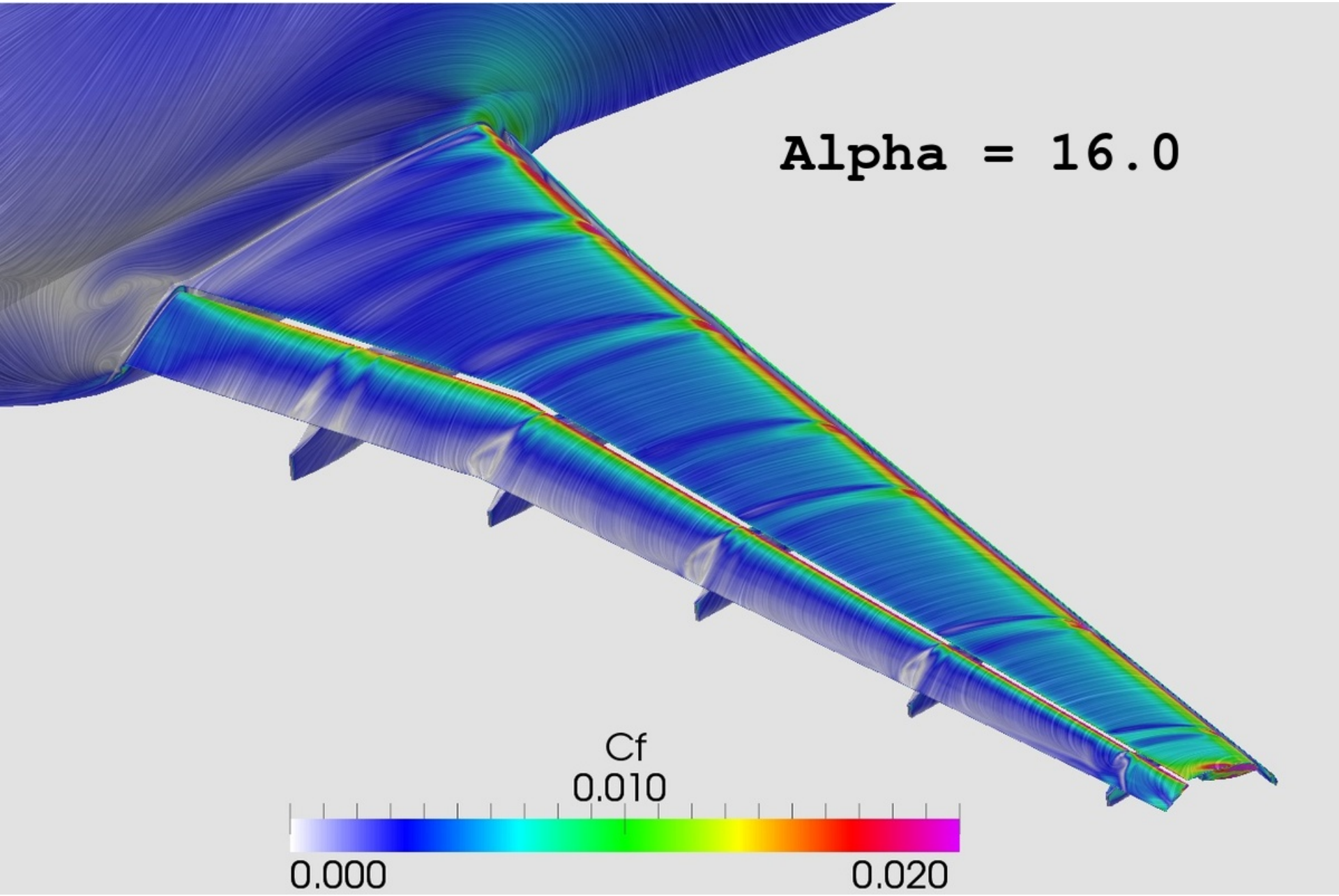

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 10
Cp
X Station(mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

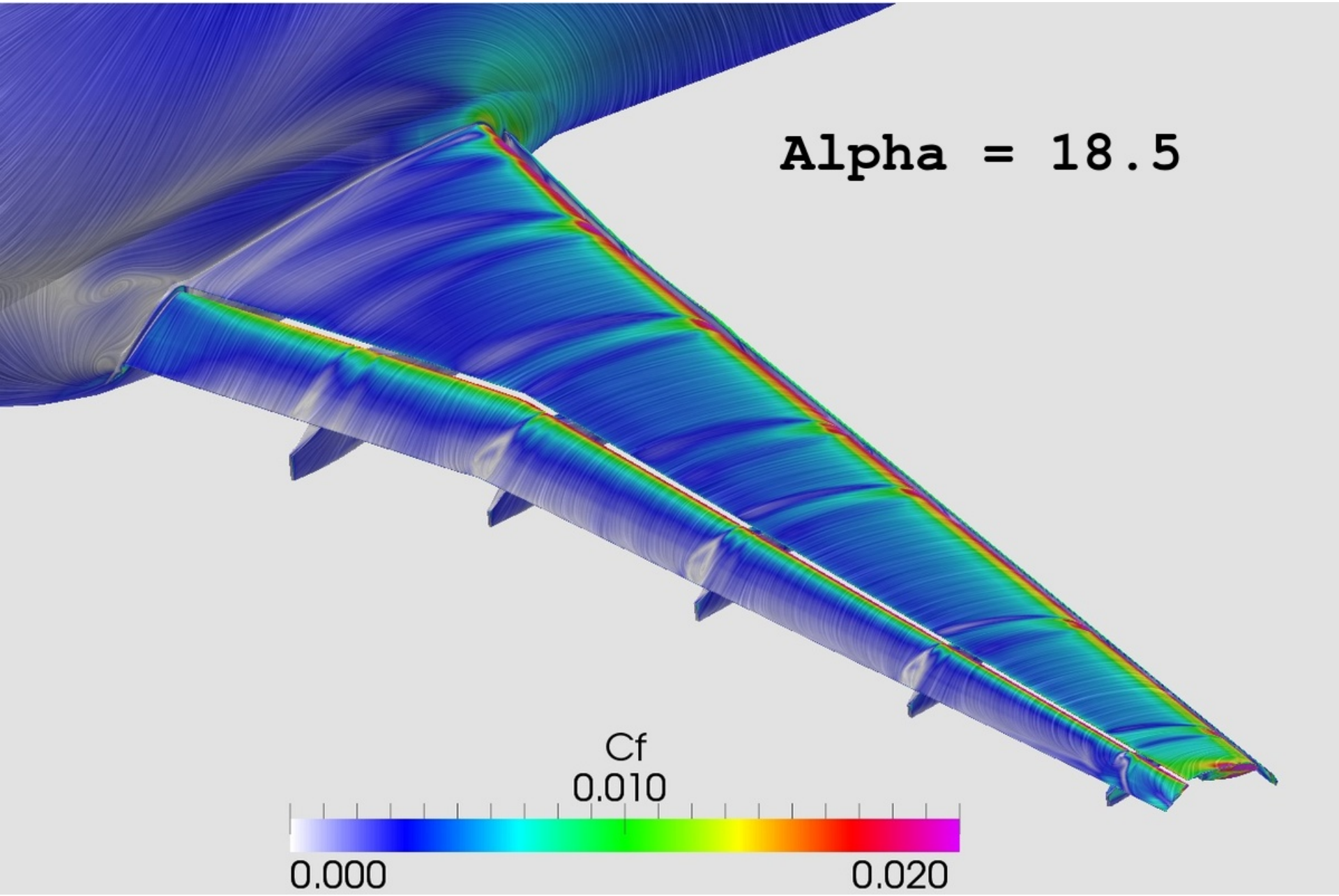

HLPW-2 Reynolds Number Effect with Brackets, Alpha 21, Section 11
Cp
X Station(mm)
Experiment (Low Re)
Experiment (High Re)
NSU3D (Low Re)
NSU3D (High Re)

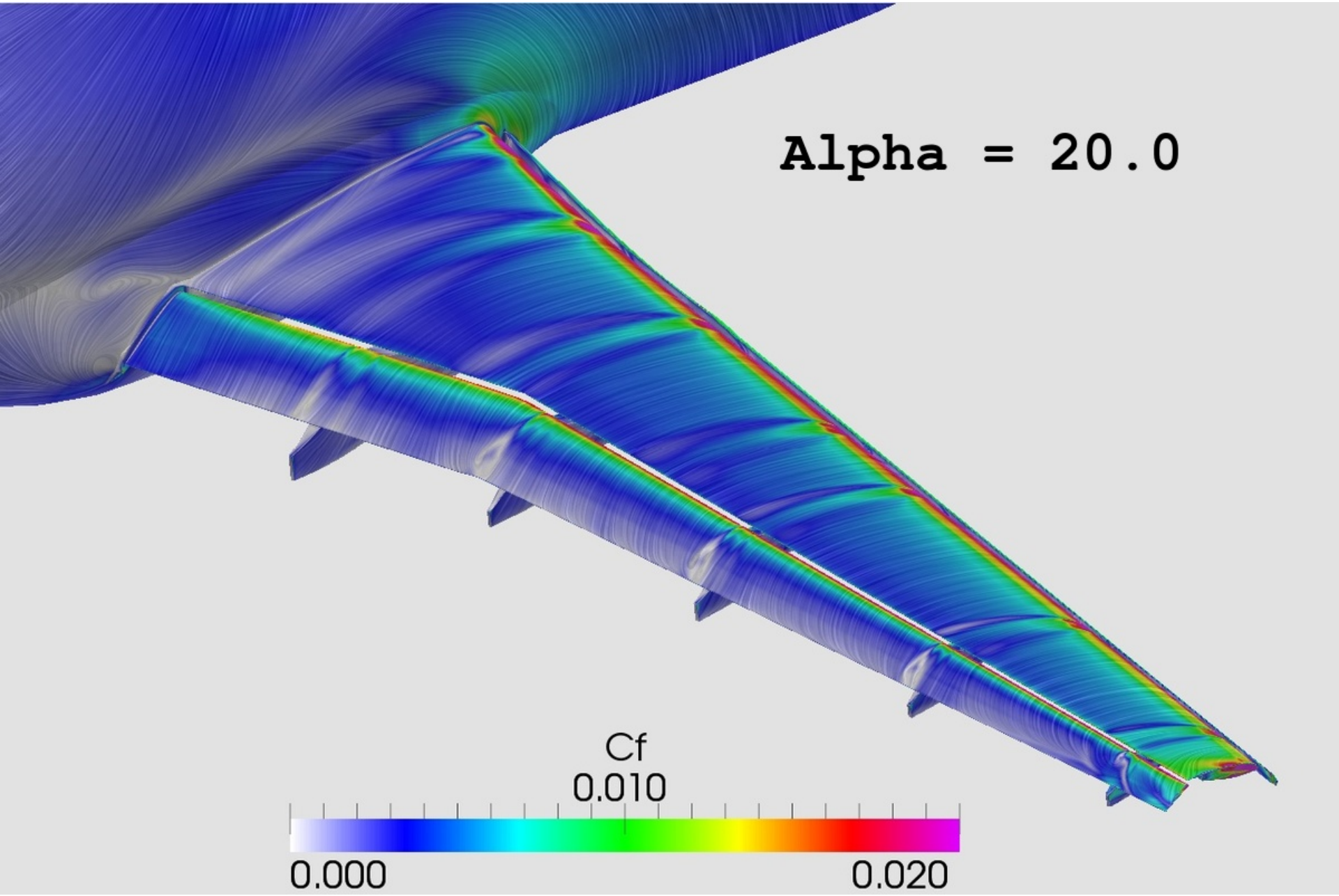

Alpha = 00.0
Cf
0.010
0.000
0.020

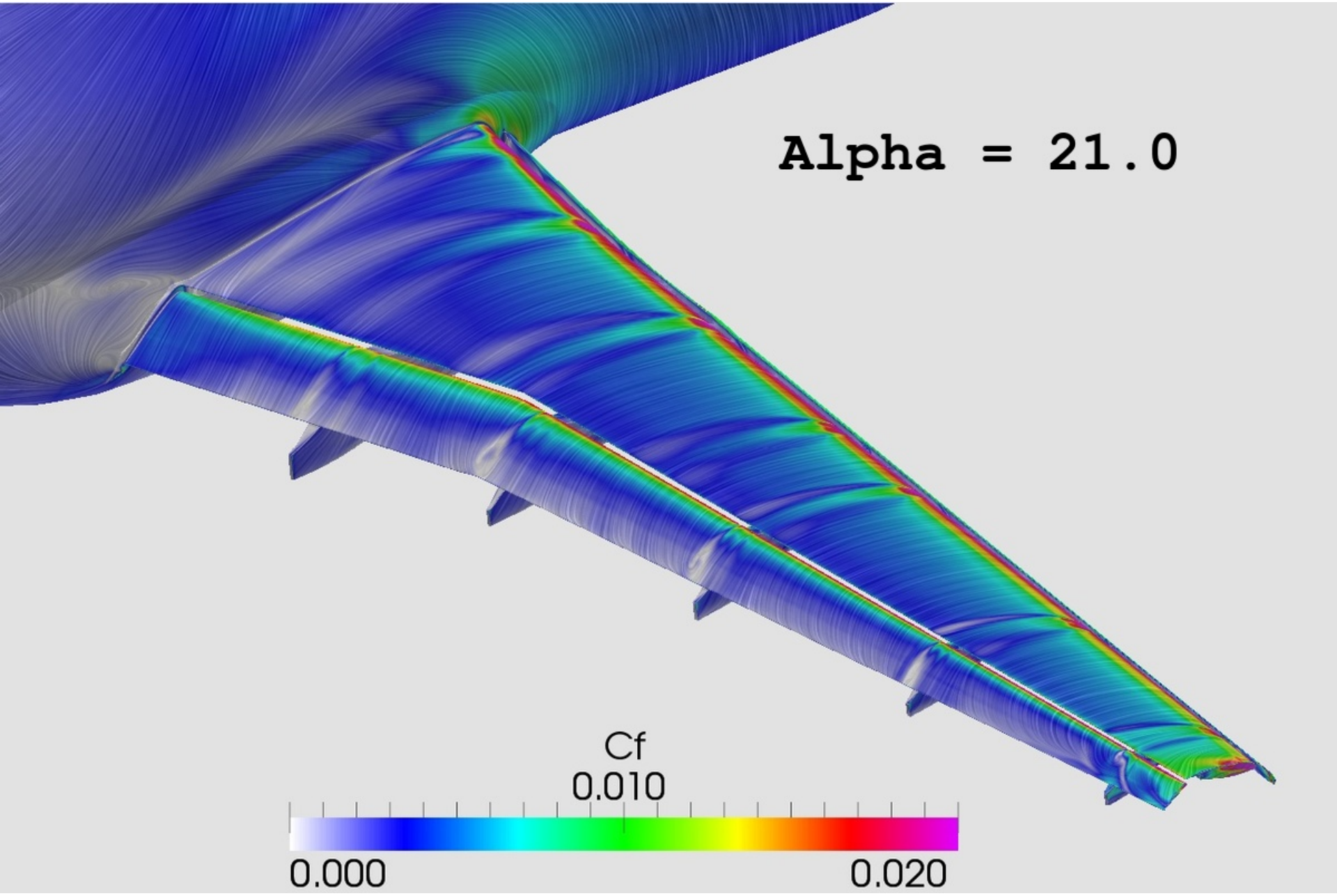

Alpha = 07.0
Cf
0.010
0.000
0.020

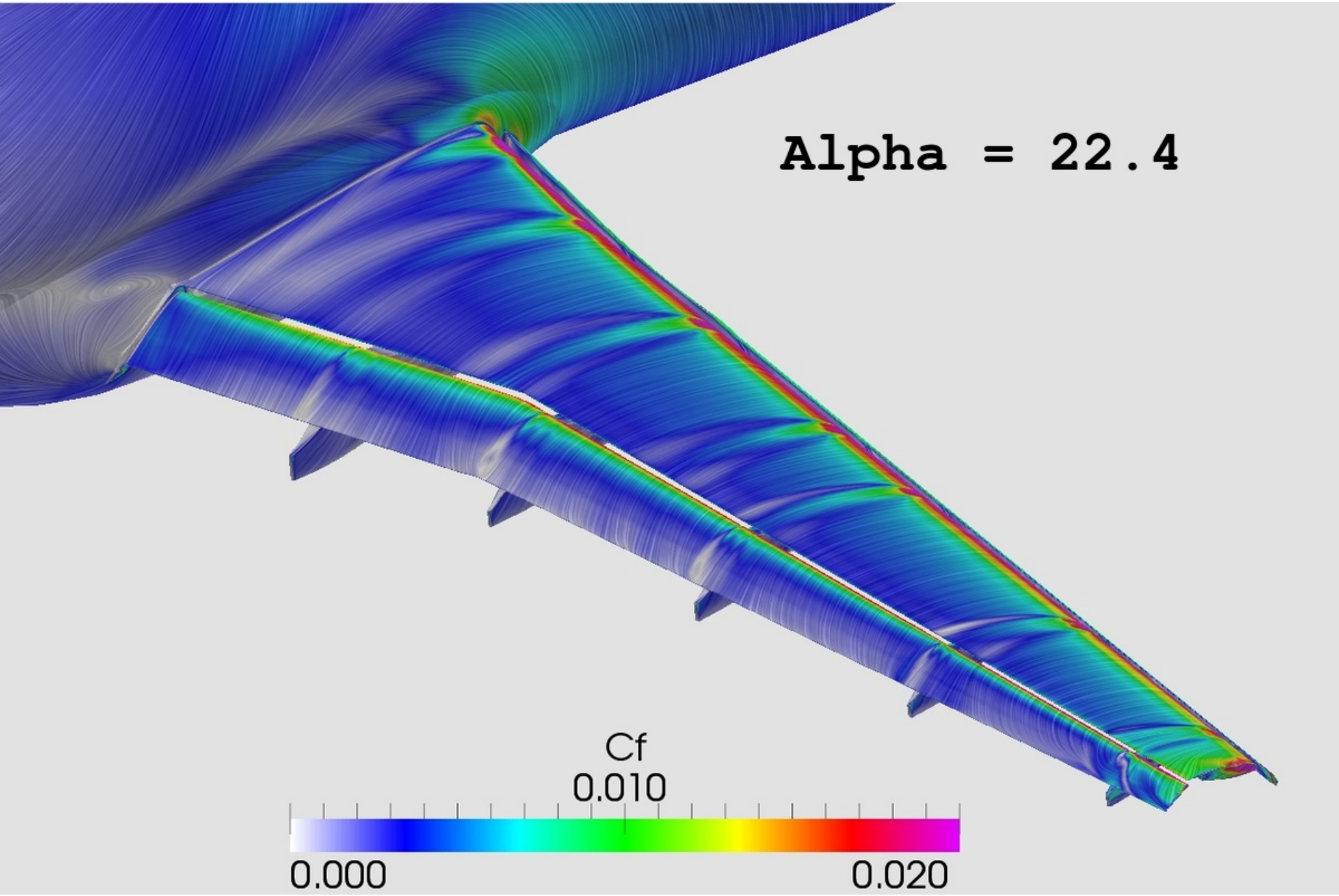

Alpha = 12.0
Cf
0.010
0.000
0.020

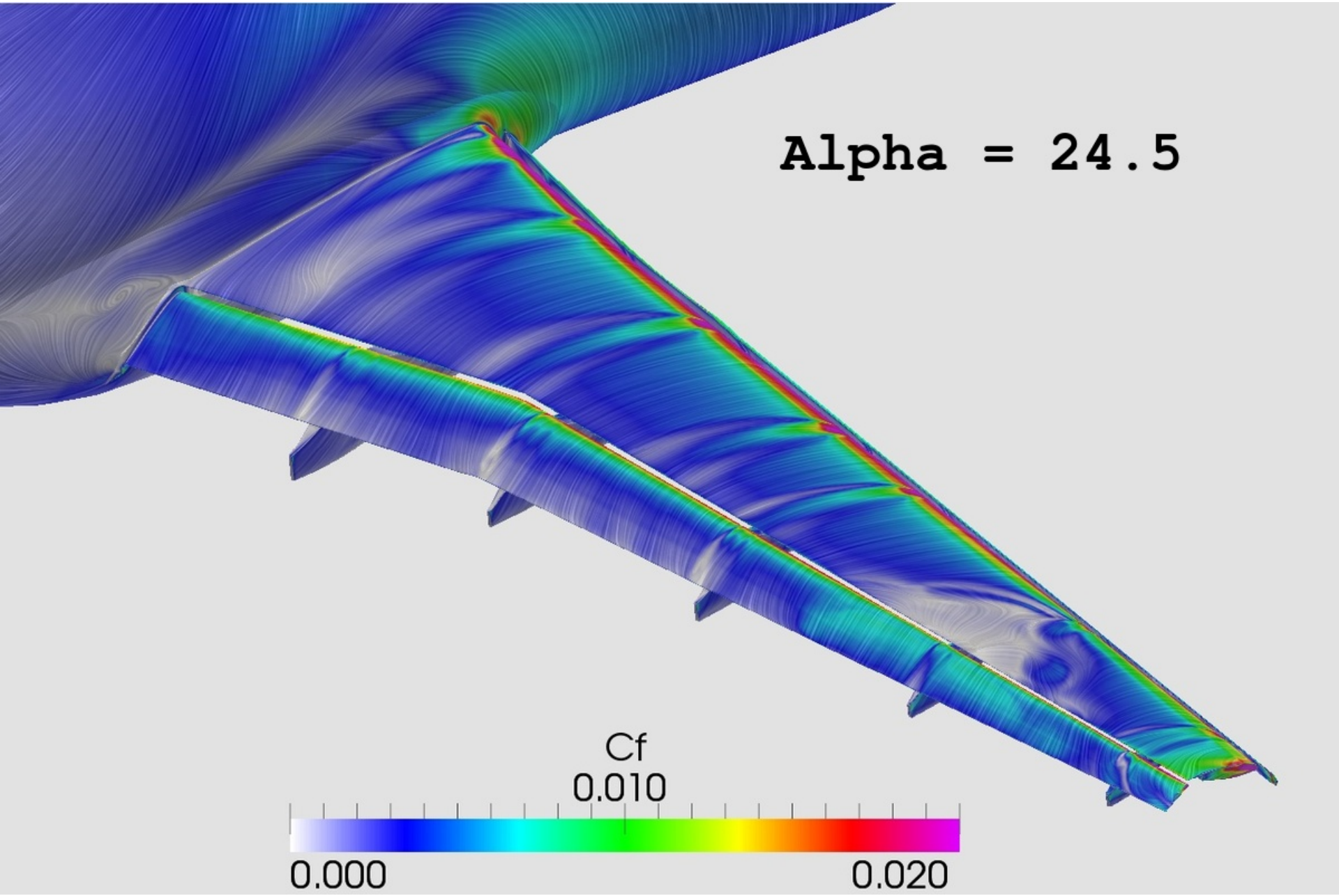

Alpha = 16.0
Cf
0.010
0.000
0.020

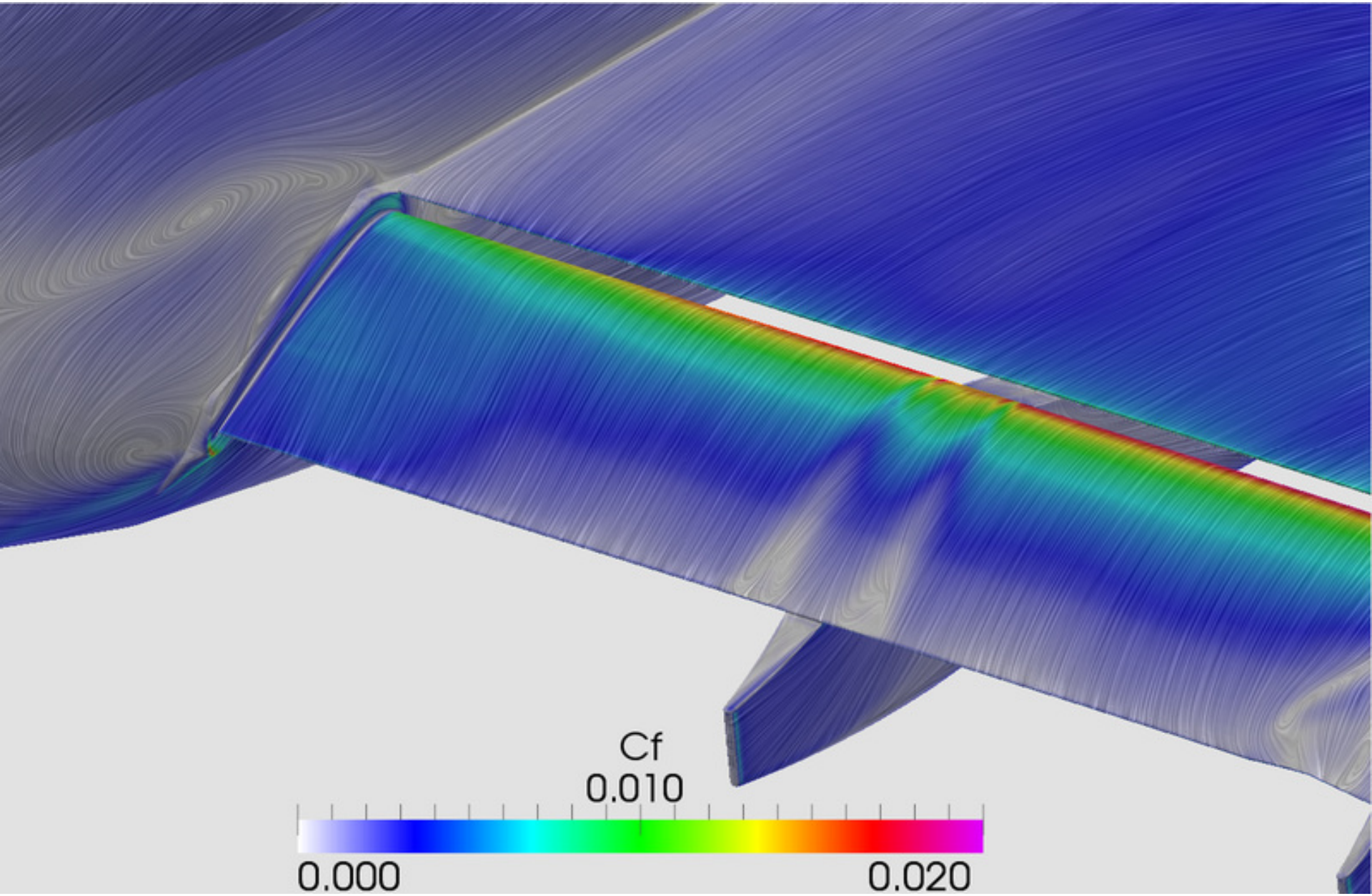

Alpha = 18.5
Cf
0.010
0.000
0.020

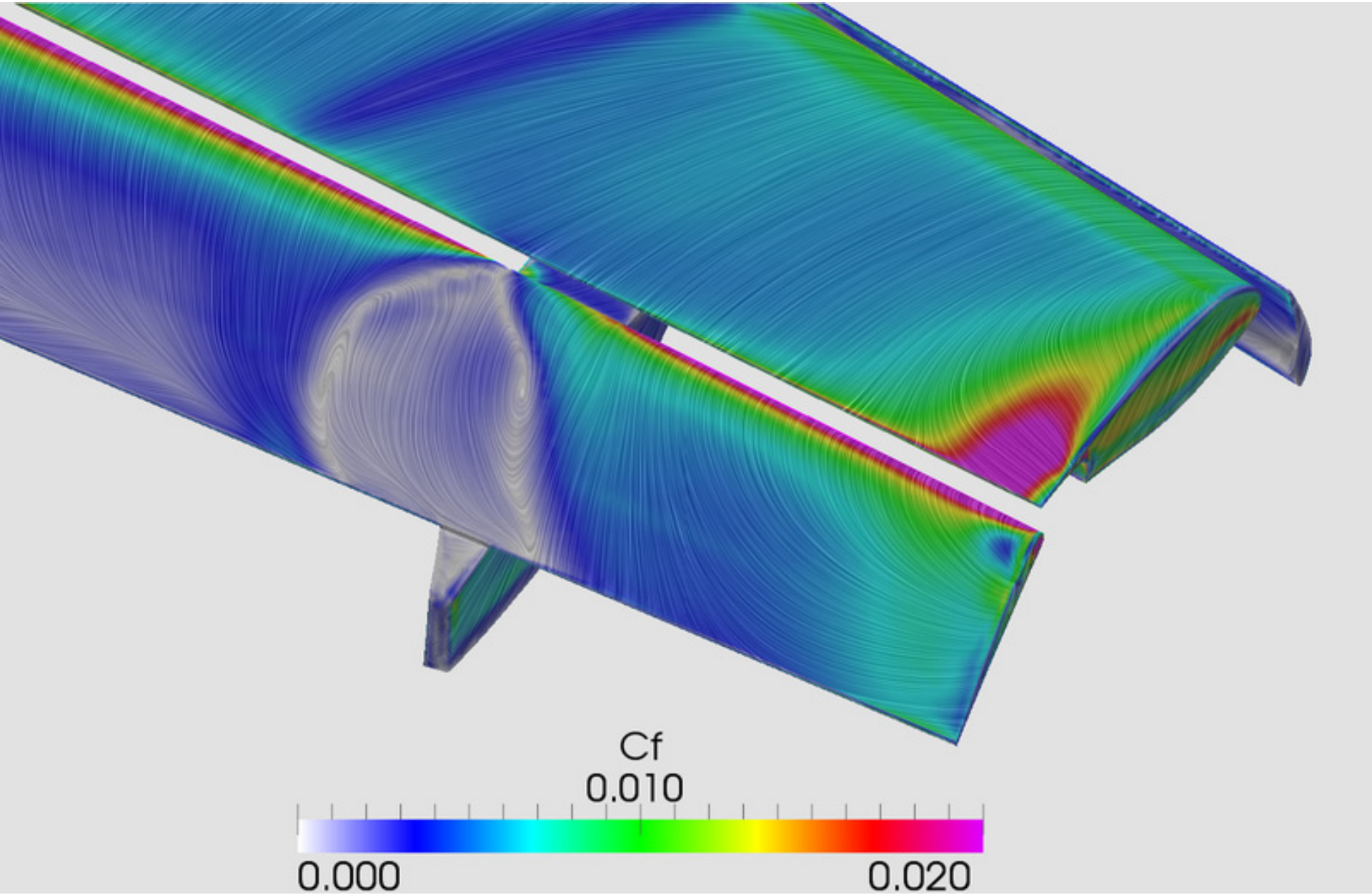

Alpha = 20.0
Cf
0.010
0.000
0.020

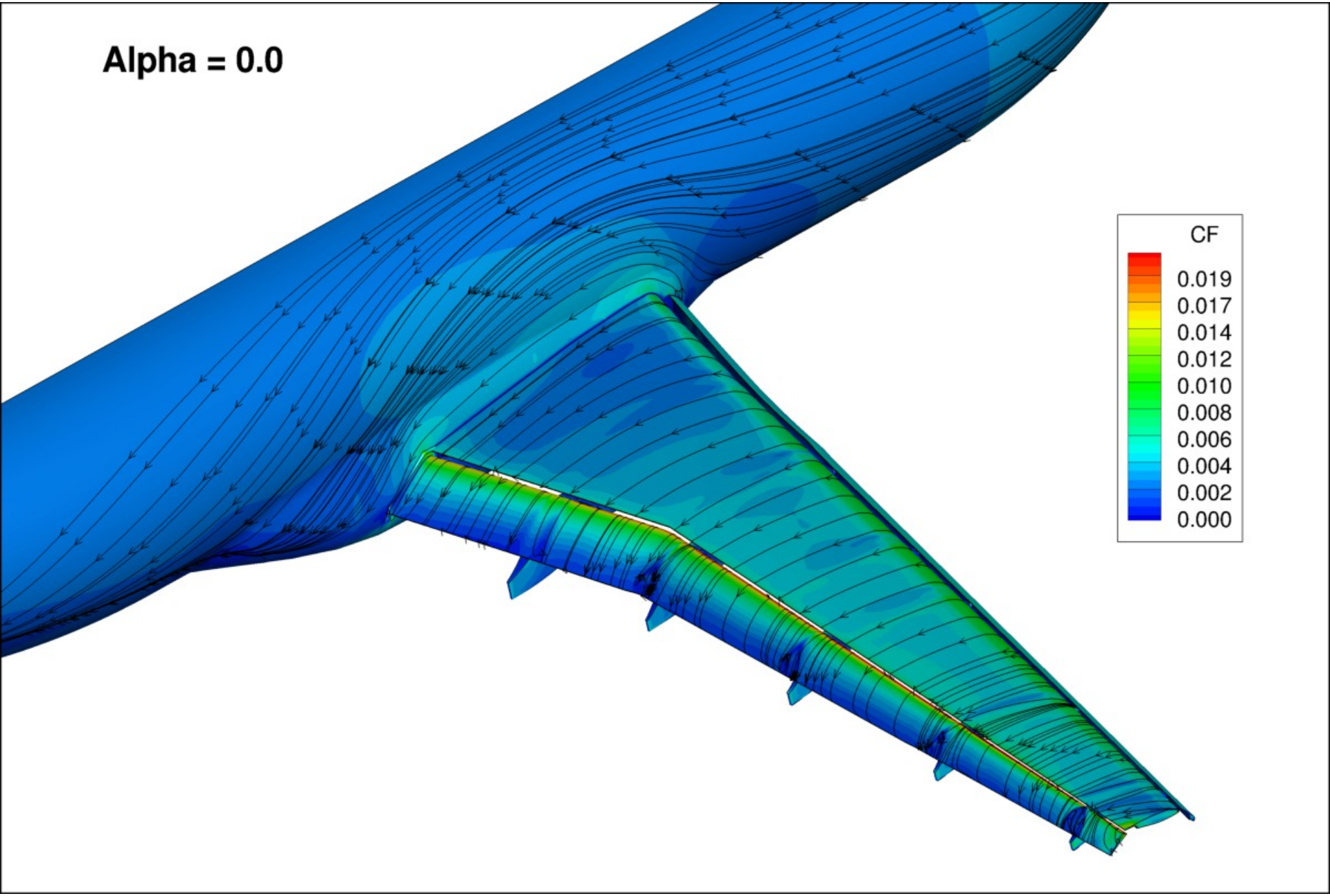

Alpha = 21.0
Cf
0.010
0.000
0.020

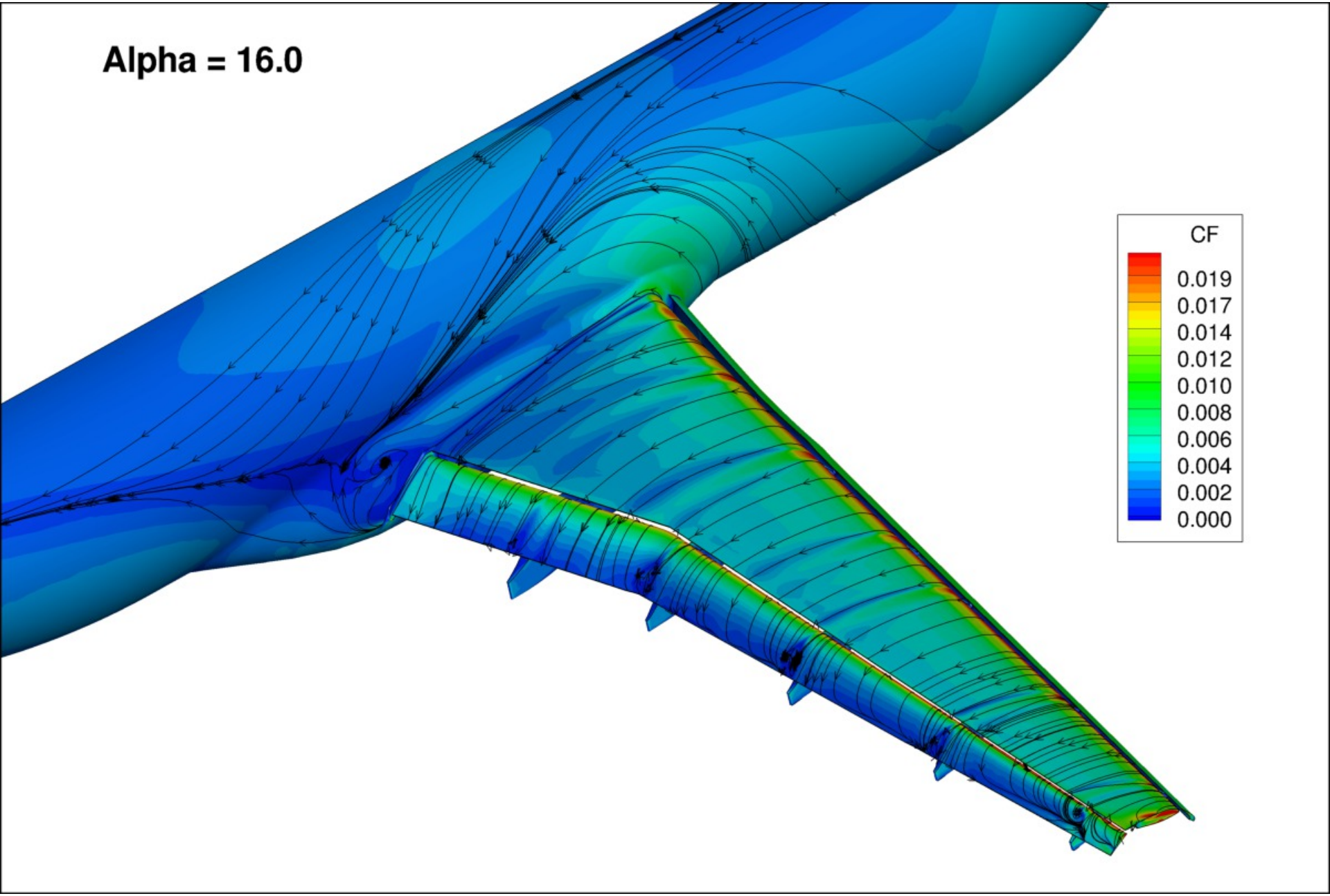

Alpha = 22.4
Cf
0.010
0.000
0.020


Alpha = 24.5
Cf
0.010
0.000
0.020


Cf
0.010
0.000
0.020


Cf
0.010
0.000
0.020


Alpha = 0.0
CF
0.019
0.017
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000


Alpha = 16.0
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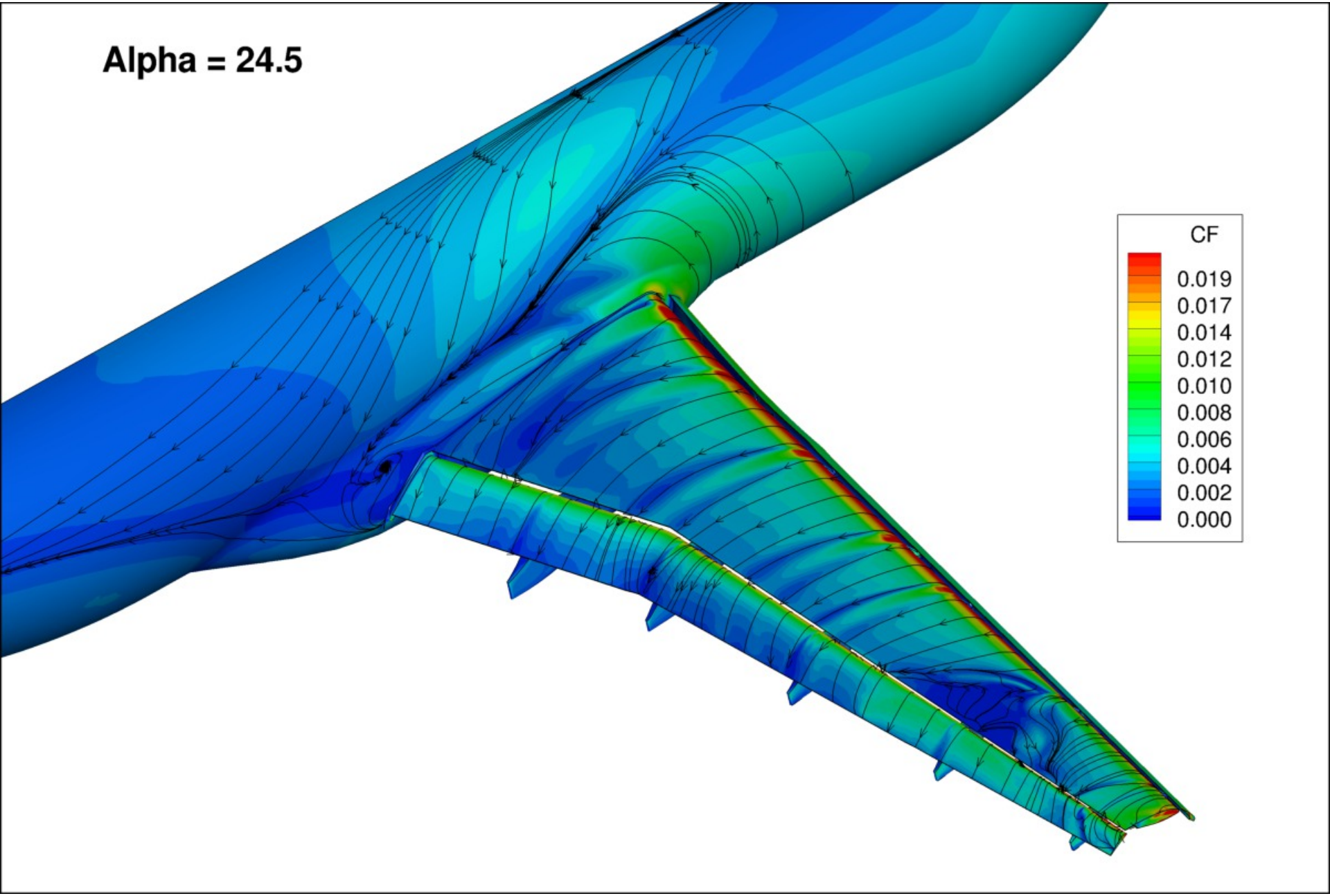
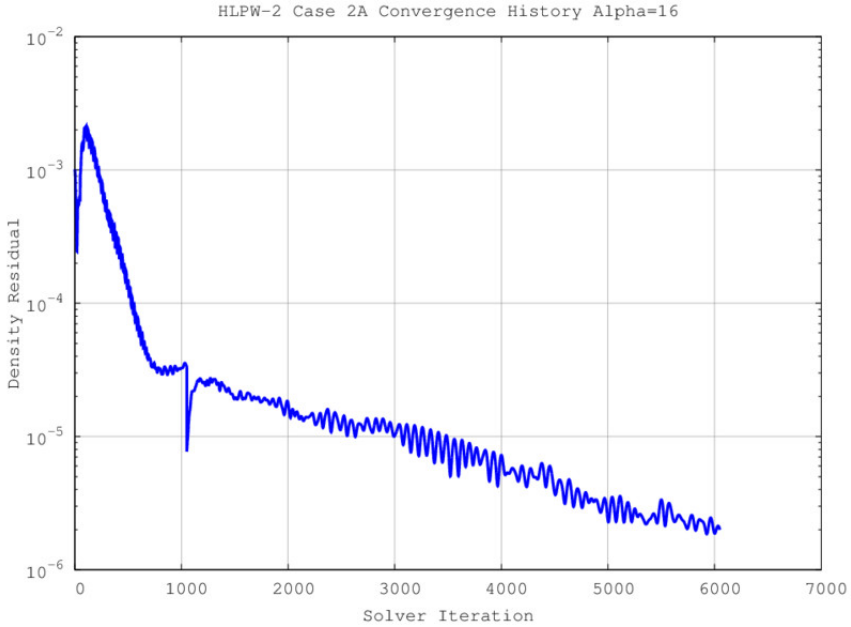
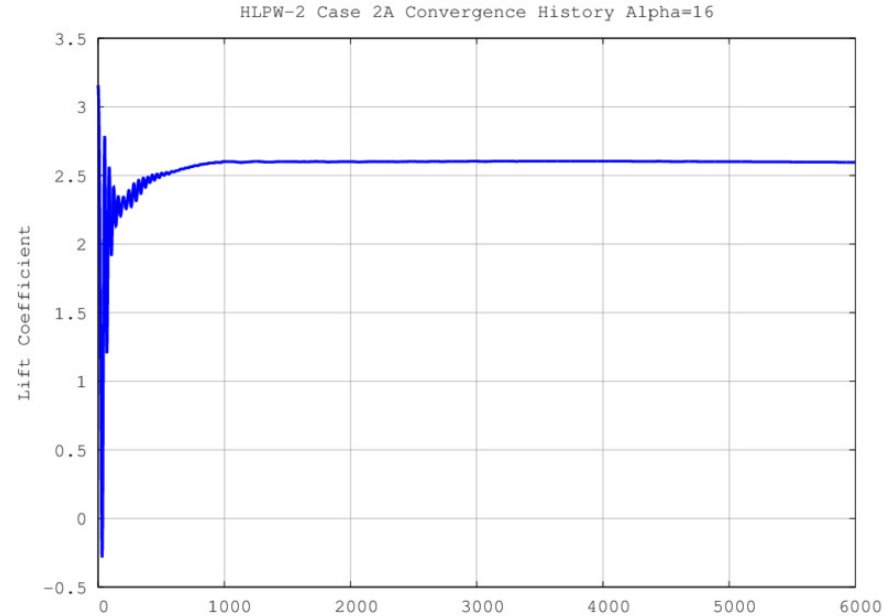
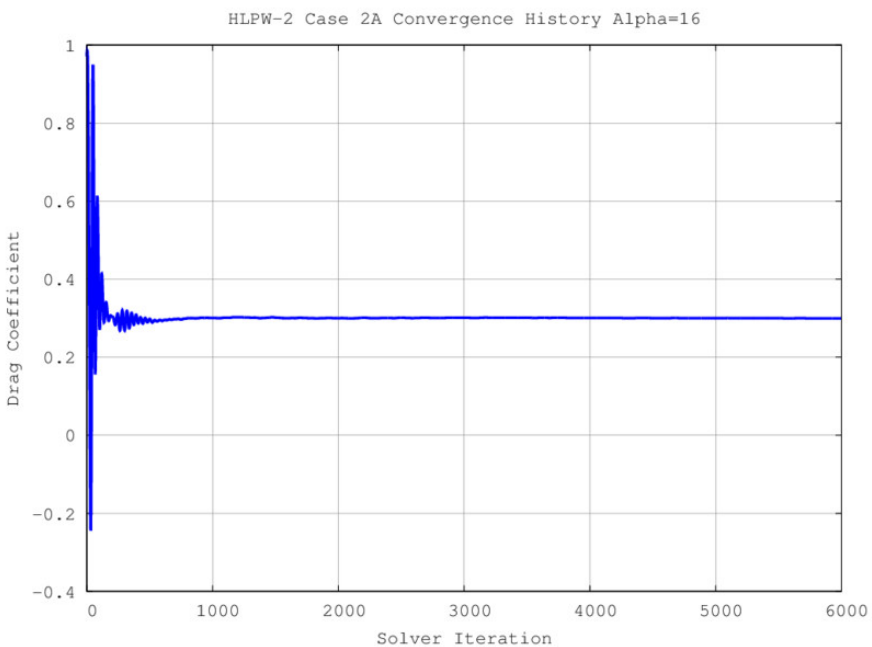
0.017
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000

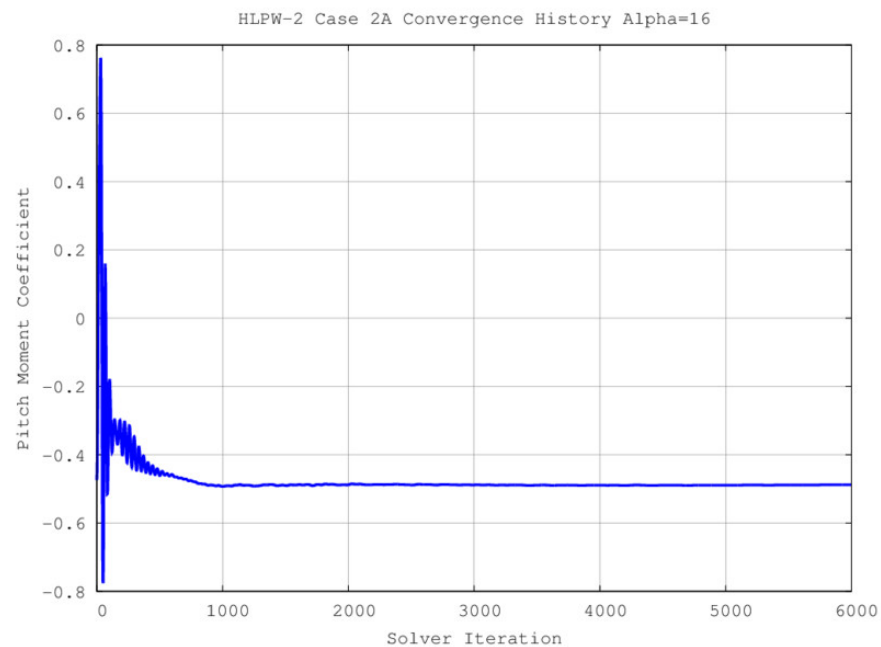

Alpha = 24.5
CF
0.019
0.017
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000

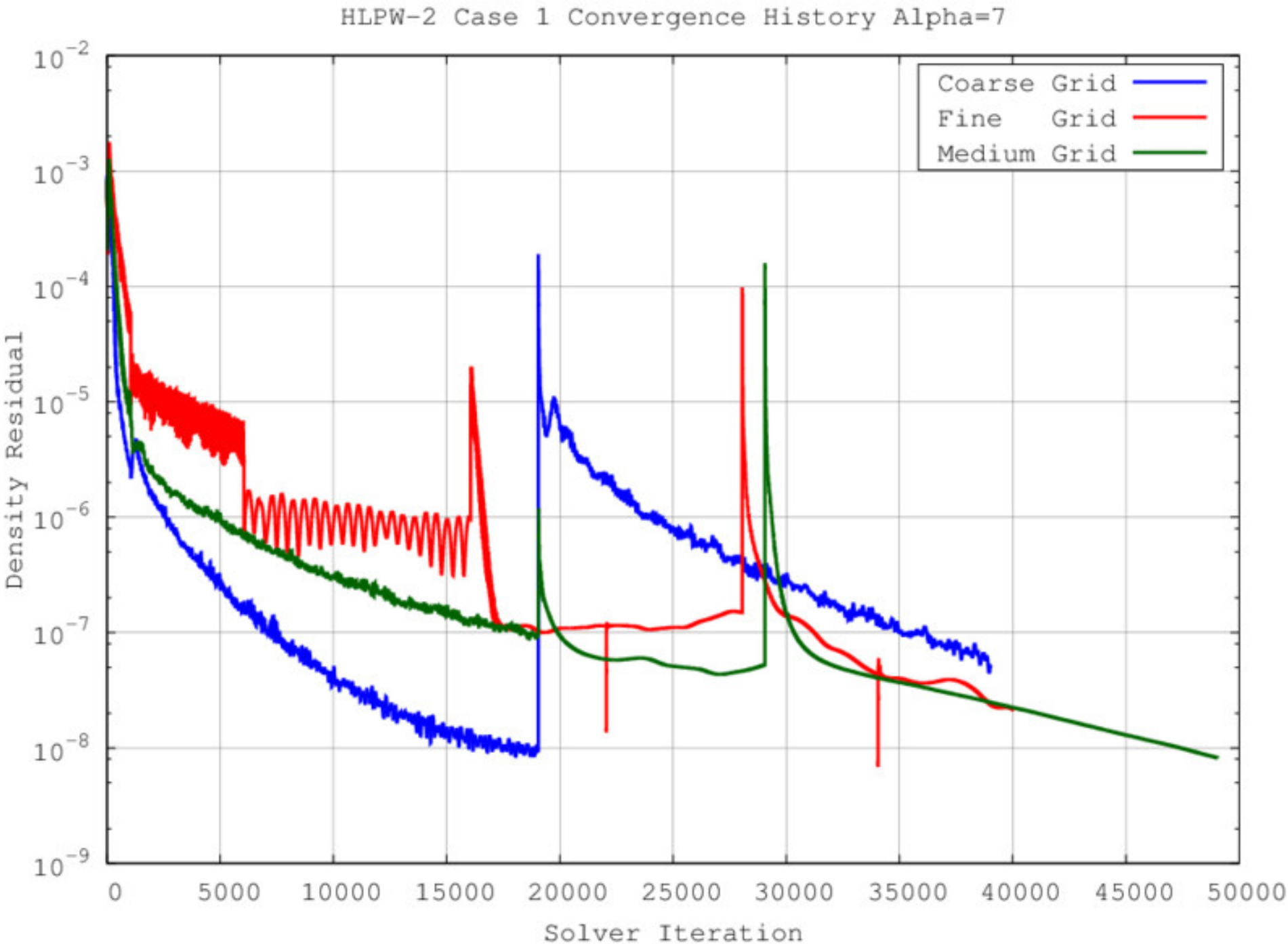
Case 2A Convergence at 16 degrees (Medium Mesh: 41M pts)

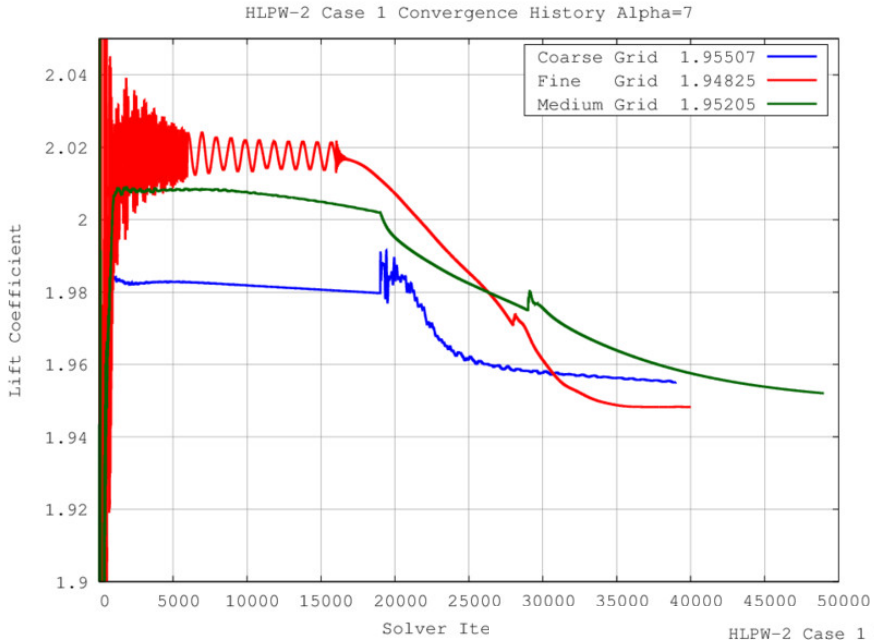


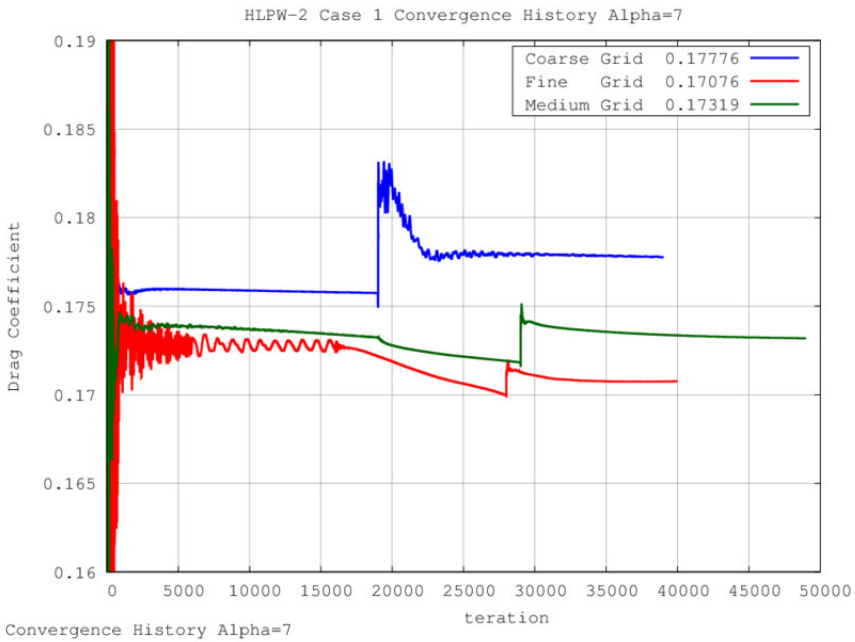


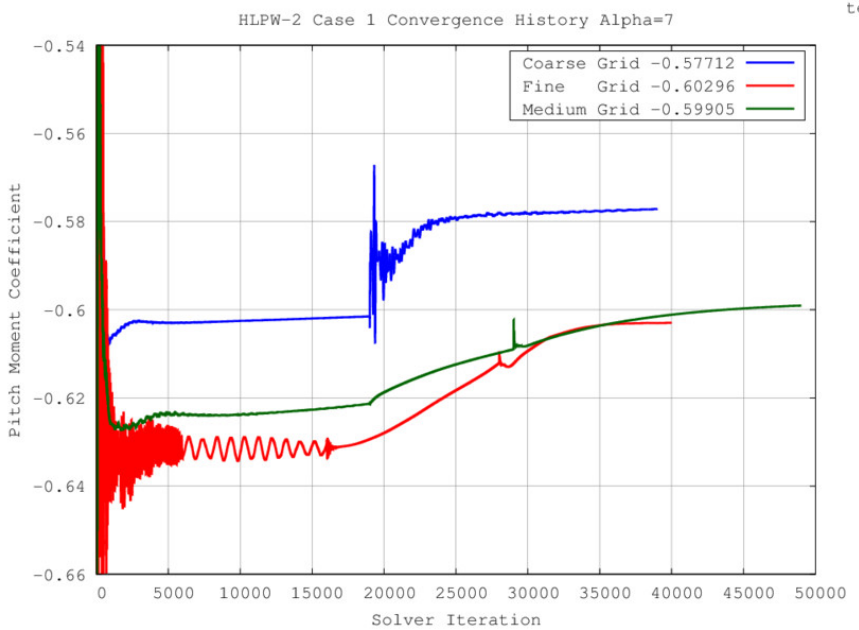


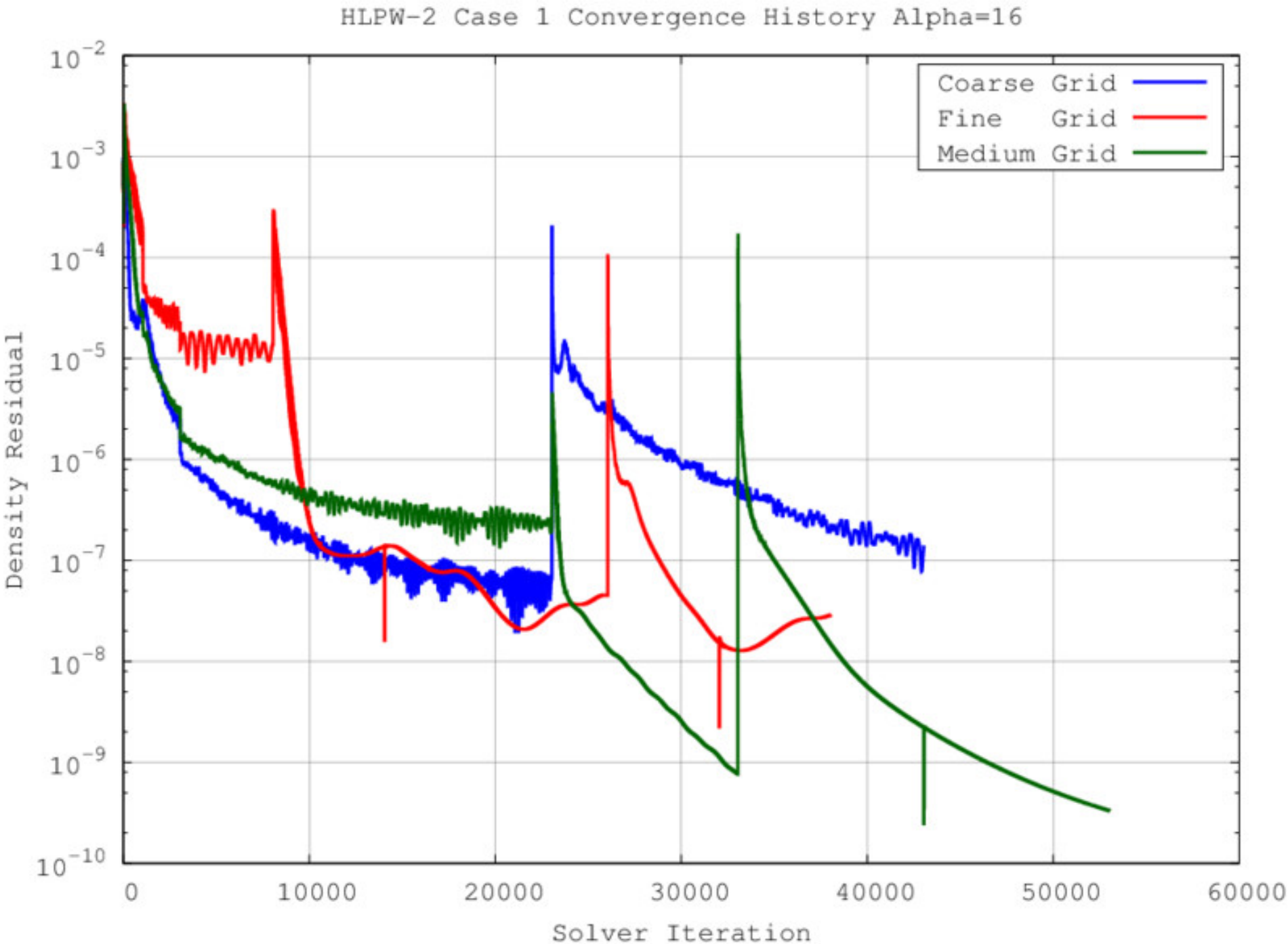


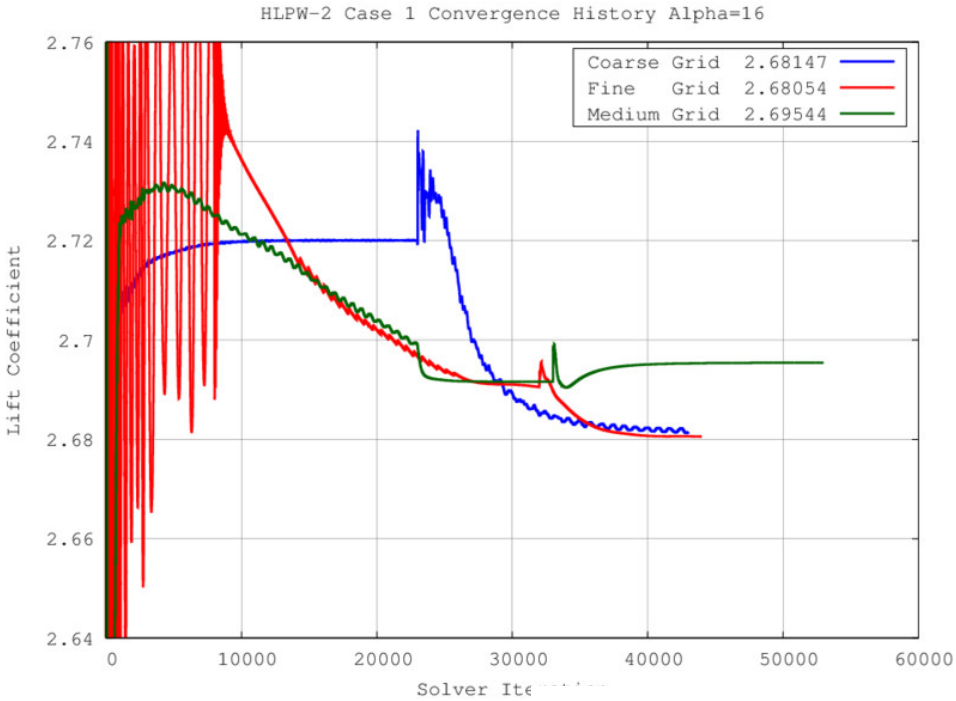

HLPW-2 Case 1 Convergence History Alpha=7
Coarse Grid
Fine Grid
Medium Grid
Density Residual
Solver Iteration
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000

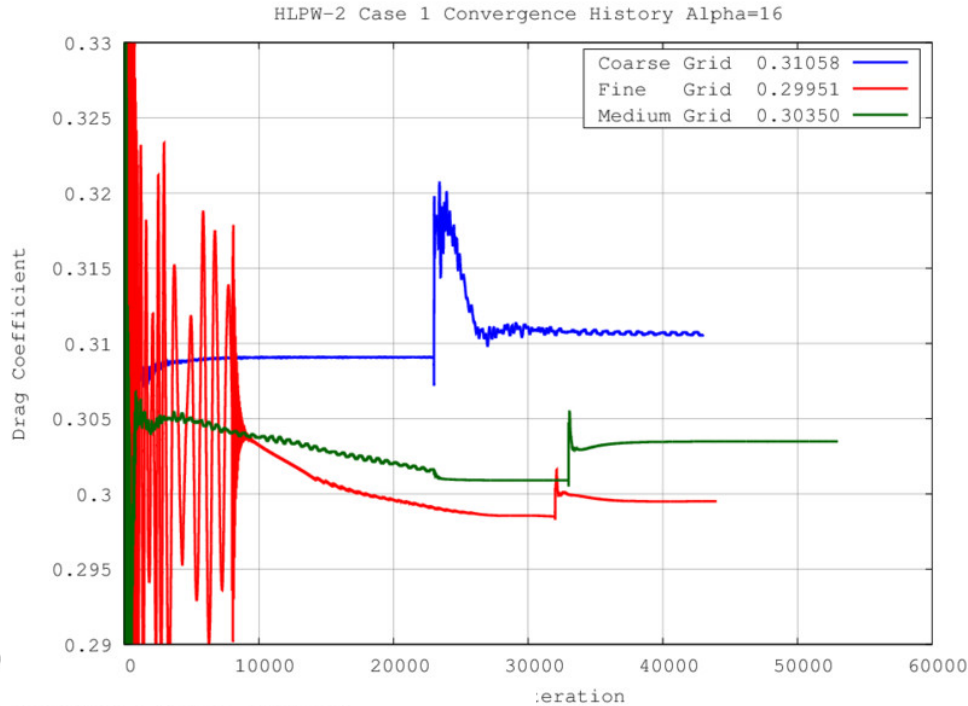

HLPW-2 Case 1 Convergence History Alpha=7
Coarse Grid 1.95507
Fine Grid 1.94825
Medium Grid 1.95205
Lift Coefficient
Solver Ite
2.04
2.02
2
1.98
1.96
1.94
1.92
1.9
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000

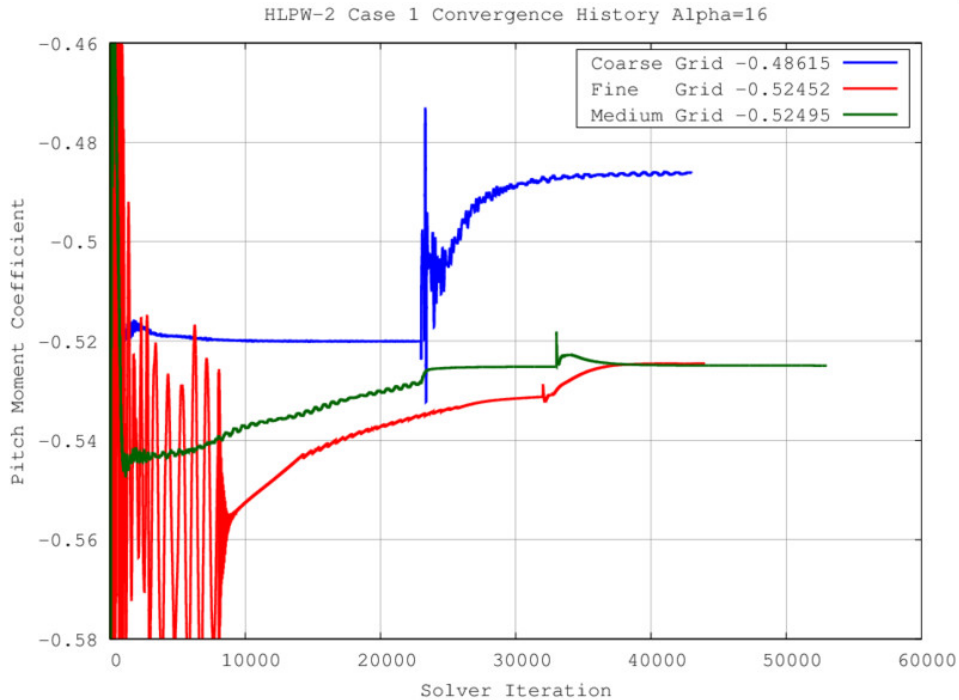

HLPW-2 Case 1 Convergence History Alpha=7
Coarse Grid 0.17776
Fine Grid 0.17076
Medium Grid 0.17319
Drag Coefficient
teration
0.19
0.185
0.18
0.175
0.17
0.165
0.16
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000


HLPW-2 Case 1 Convergence History Alpha=7
Coarse Grid -0.57712
Fine Grid -0.60296
Medium Grid -0.59905
Pitch Moment Coefficient
Solver Iteration
-0.54
-0.56
-0.58
-0.6
-0.62
-0.64
-0.66
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000


HLPW-2 Case 1 Convergence History Alpha=16
Coarse Grid
Fine Grid
Medium Grid
Density Residual
Solver Iteration
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
10000
20000
30000
40000
50000
60000


HLPW-2 Case 1 Convergence History Alpha=16
Coarse Grid 2.68147
Fine Grid 2.68054
Medium Grid 2.69544
Lift Coefficient
2.76
2.74
2.72
2.7
2.68
2.66
2.64
0
10000
20000
30000
40000
50000
60000


HLPW-2 Case 1 Convergence History Alpha=16
Coarse Grid 0.31058
Fine Grid 0.29951
Medium Grid 0.30350
Drag Coefficient
0.33
0.325
0.32
0.315
0.31
0.305
0.3
0.295
0.29
0
10000
20000
30000
40000
50000
60000


HLPW-2 Case 1 Convergence History Alpha=16
Coarse Grid -0.48615
Fine Grid -0.52452
Medium Grid -0.52495
Pitch Moment Coefficient
-0.46
-0.48
-0.5
-0.52
-0.54
-0.56
-0.58
0
10000
20000
30000
40000
50000
60000
Solver Iteration

Conclusions/Future Work

- Reasonable grid convergence on Case 1
  - Small variation in surface Cps with grid resolution
  - Possible slow transients in convergence history even after 8 orders of magnitude
  - Obtain machine zero converged solutions (GMRES)
- Case 2:
  - Low Re: CL_{max} value overpredicted
  - High Re: CL_{max} and stall angle overpredicted more severely
  - Significant moment discrepancies with experiment
  - Further examination of data
    - Stall mechanism
    - PIV data
- Complete additional test cases
  - Refine around CL_{max} locations (more incidences)
  - Full configuration cases