Generating Meshes for HiOCFD5's Challenge Cases

Steve Karman
Pointwise, Inc.

5th High Order CFD Workshop
January 6-7, 2018

Outline

- Mesh Curving Method (Unstructured)
- Cases
  - Tandem Spheres (Structured/Unstructured)
  - CRM_WB (Unstructured)
  - HL_CRM (Unstructured)
  - Rotor 67 (Unstructured)
- Meshing Philosophy
- Conclusions

Mesh Curving Method

Mesh Curving Method

1) Elevate elements to selected order.
2) Project surface nodes to true geometry.
3) Initialize interior nodes locations.
4) Apply smoothing to validate and improve quality.

Smoothing method performs optimization-based node perturbations to improve weighted cost function.

$$\mathrm{C} = \alpha C_W + \beta C_J$$

$$\alpha = \frac{MAX(1,order-1)}{order},\ \beta = 1-\alpha$$

$$C_W = \frac{V_r}{WCN} \qquad if\ J_{se} > 0, \qquad else\ C_W = J_{se}$$

$$V_r = MIN\left[1, \frac{V_p}{V_c}\right]$$

$$C_J = MIN\left[1, \frac{J_p}{J_c}\right]$$

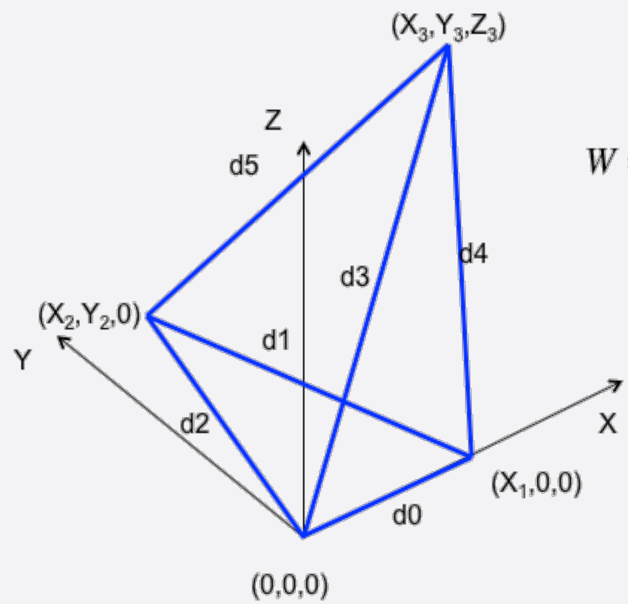
$$J = \begin{vmatrix} \sum \frac{\partial N_i}{\partial \xi} x_i & \sum \frac{\partial N_i}{\partial \xi} y_i & \sum \frac{\partial N_i}{\partial \xi} z_i \\ \sum \frac{\partial N_i}{\partial \eta} x_i & \sum \frac{\partial N_i}{\partial \eta} y_i & \sum \frac{\partial N_i}{\partial \eta} z_i \\ \sum \frac{\partial N_i}{\partial \zeta} x_i & \sum \frac{\partial N_i}{\partial \zeta} y_i & \sum \frac{\partial N_i}{\partial \zeta} z_i \end{vmatrix}$$

Weighted Condition Number

POINTWISE®
THE CHOICE FOR CFD MESHING

- Measures the conformity to a specified shape, defined by W (coordinates taken from computational mesh).
- A is the Jacobian matrix (coordinates taken from physical mesh).
- This is applied to the linear sub-elements of a higher order element.
- Value range is 0 – 1.

$$WCN = \frac{\|AW^{-1}\|\|WA^{-1}\|}{3}$$

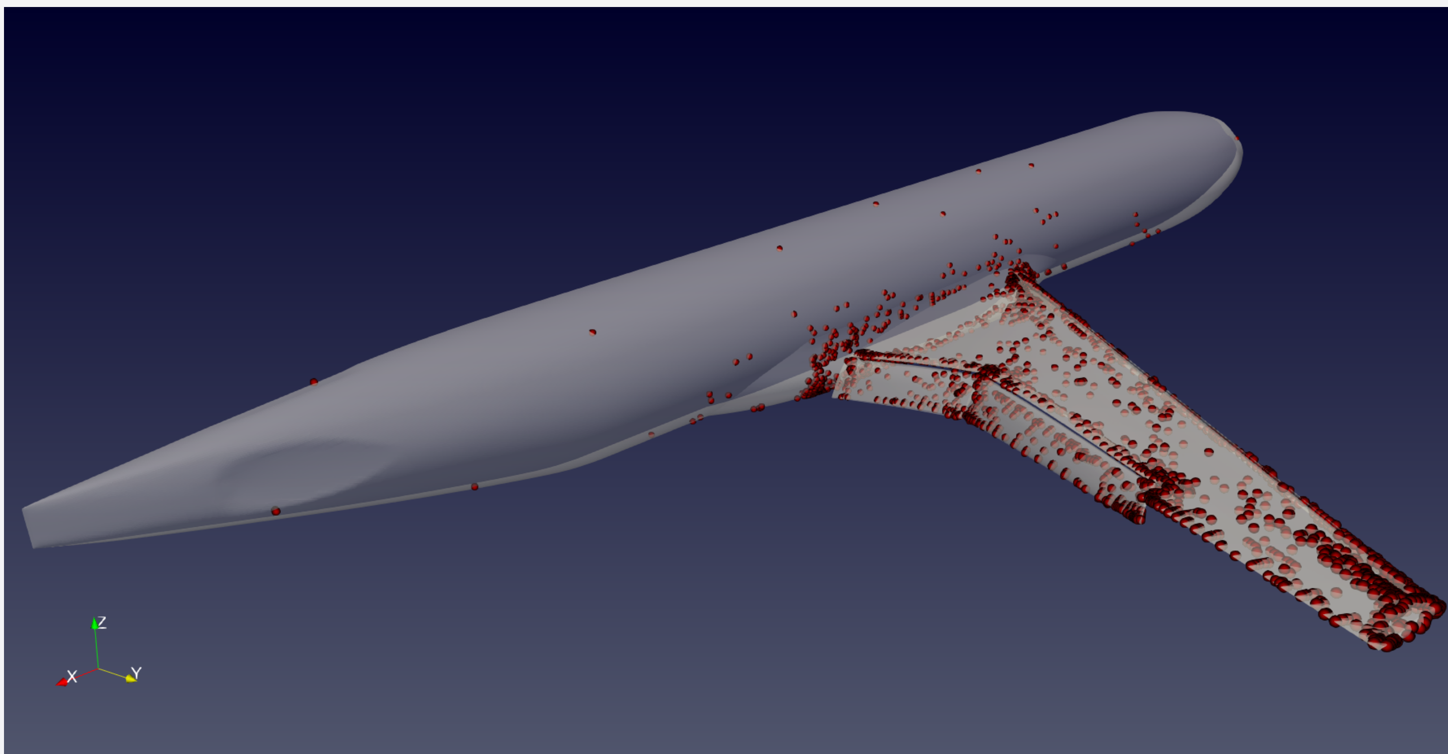


$$W = \begin{bmatrix} X_1 & X_2 & X_3 \\ 0 & Y_2 & Y_3 \\ 0 & 0 & Z_3 \end{bmatrix}$$

Latest CurveMesh Capability

POINTWISE®
THE CHOICE FOR CFD MESHING

- Incorporation of the volume ratio and second cost component eliminated negative Jacobians for more complicated cases.
- Negative Jacobians for P3 cases prior to modified method shown below.

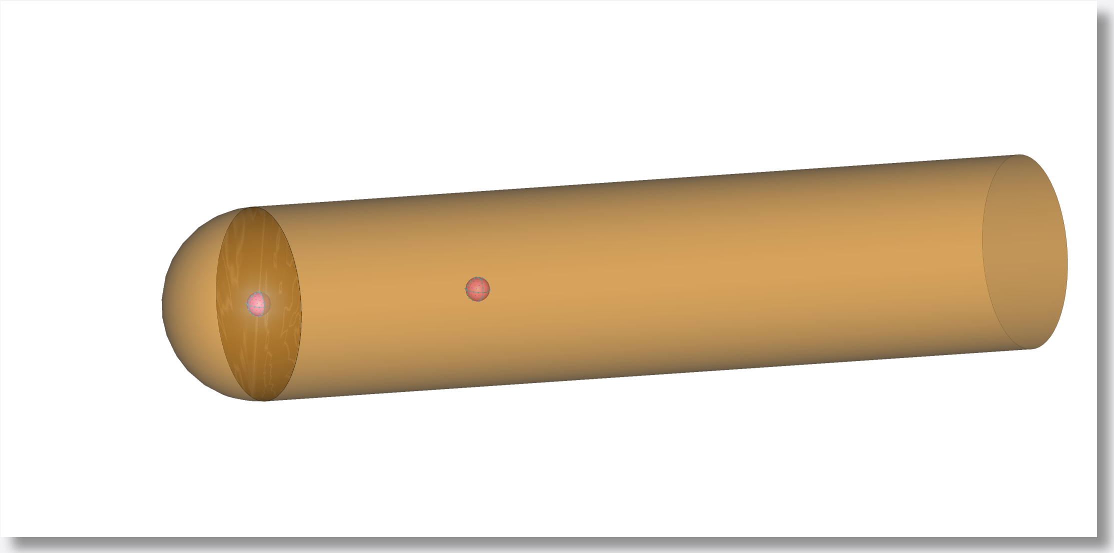


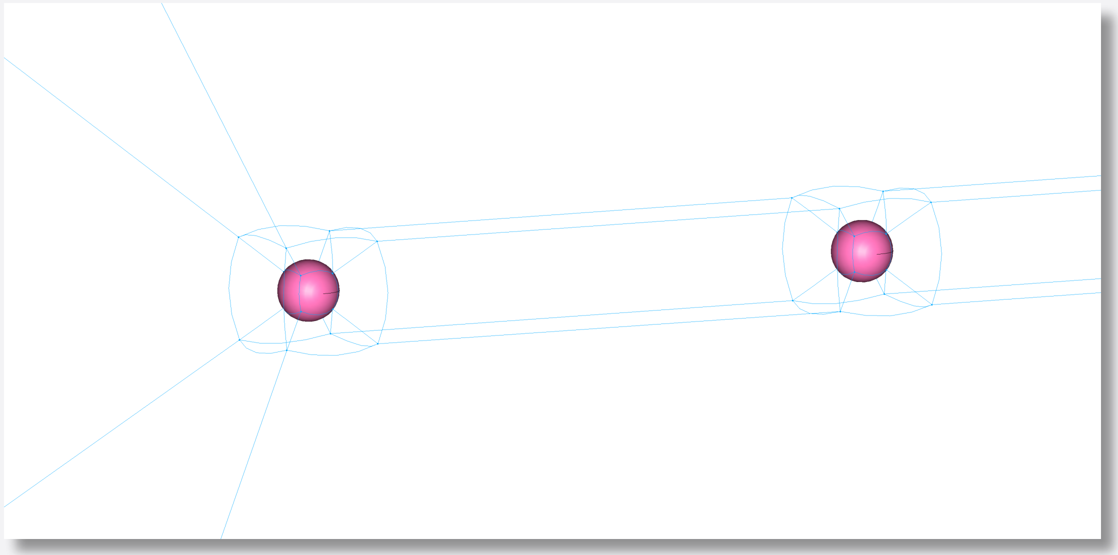
HiOCFD5 Cases

POINTWISE®
THE CHOICE FOR CFD MESHING

Tandem Spheres

- Two mesh series created
- Unstructured tetrahedra
  - Source shapes used to control resolution.
- Structured hexahedra
  - Block topology created to allow similar control.





Tetrahedral Meshes

POINTWISE® THE CHOICE FOR CFD MESHING

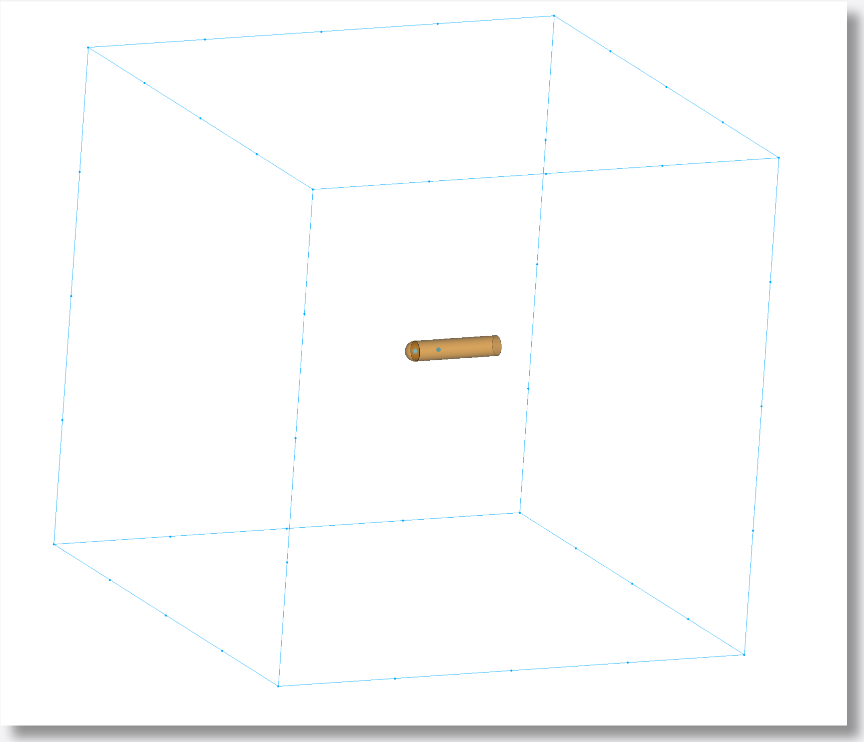
Mesh	# edge nodes	# layers	Normal spacing	Source Begin	Source End	# nodes	# tets	P2 # nodes	P3 # nodes	P4 # nodes
Mesh 0	3	6	0.0151875	0.151875	0.759375	16738	100324	133893	451792	1070759
Mesh 1	5	7	0.010125	0.10125	0.50625	41379	247951	311084	1117069	2647285
Mesh 2	8	8	0.00675	0.0675	0.3375	115436	692569	924494	3119746	7393761
Mesh 3	12	9	0.0045	0.045	0.225	358202	2152779	2871658	9693150	22975457
Mesh 4	18	9	0.003	0.03	0.15	1153576	6942991	9255896	31249954	N/A
Mesh 5	27	8	0.002	0.02	0.1	3753359	22610465	30130496	N/A	N/A
Mesh 6	41	8	0.001333	0.01333	0.06665	12463222	75127529	N/A	N/A	N/A
Mesh 7	61	8	0.000888	0.00888	0.0444	N/A	N/A	N/A	N/A	N/A

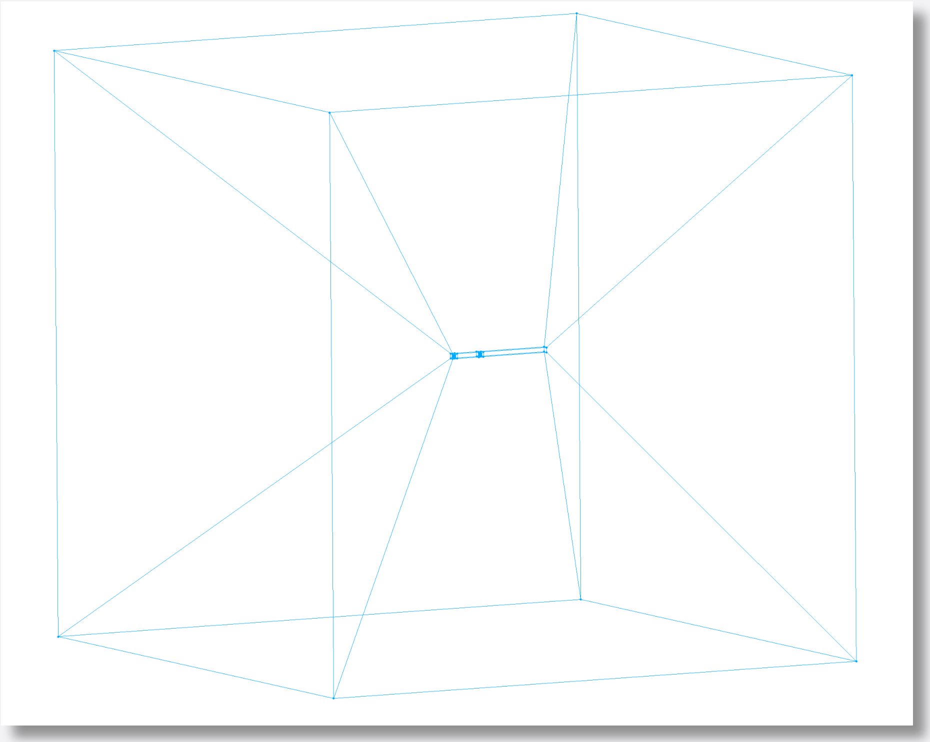
Hexahedral Meshes

Mesh	# edge nodes	# layers	Normal spacing	Nodes Between & Outer	Nodes After	# nodes	# hexes	P2 # nodes	P3 # nodes	P4 # nodes	Between SP
Mesh 0	3	6	0.0151875	11	31	7164	4000	32971	110067	259571	0.835
Mesh 1	5	9	0.010125	21	61	43180	31616	256483	861411	2037059	0.4177
Mesh 2	8	14	0.00675	41	121	255968	214284	1725947	5811516	13759755	0.2
Mesh 3	12	21	0.0045	61	181	858768	764280	6141523	20696316	49021371	0.13
Mesh 4	18	32	0.003	91	271	2888712	2674848	21461723	72361560	N/A	0.1
Mesh 5	27	48	0.002	136	406	9723294	9240504	74067991	N/A	N/A	0.0649
Mesh 6	41	72	0.001333	202	609	32978719	31891040	N/A	N/A	N/A	0.042

Mesh Topologies

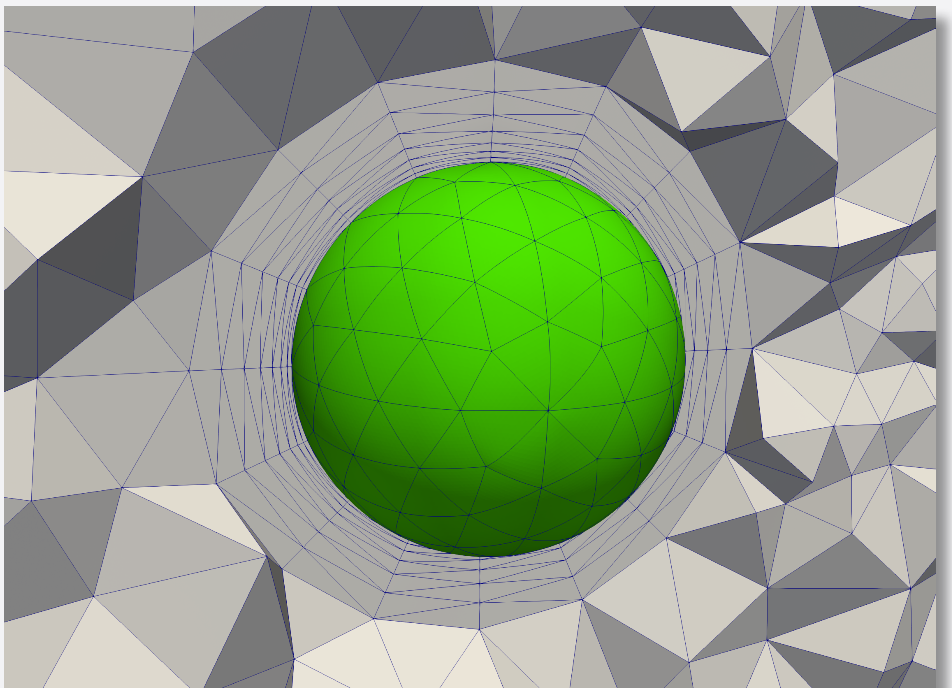
- Single block unstructured tetrahedral mesh.
  - Source shapes control resolution between and after spheres.
- Twenty block structured hexahedral mesh.

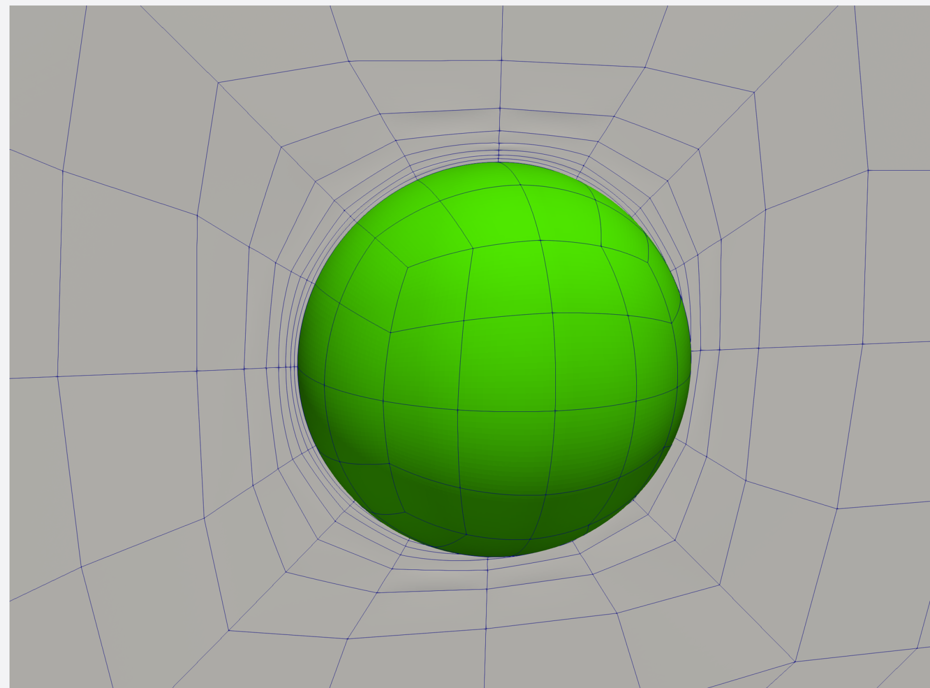




P2 Mesh 1

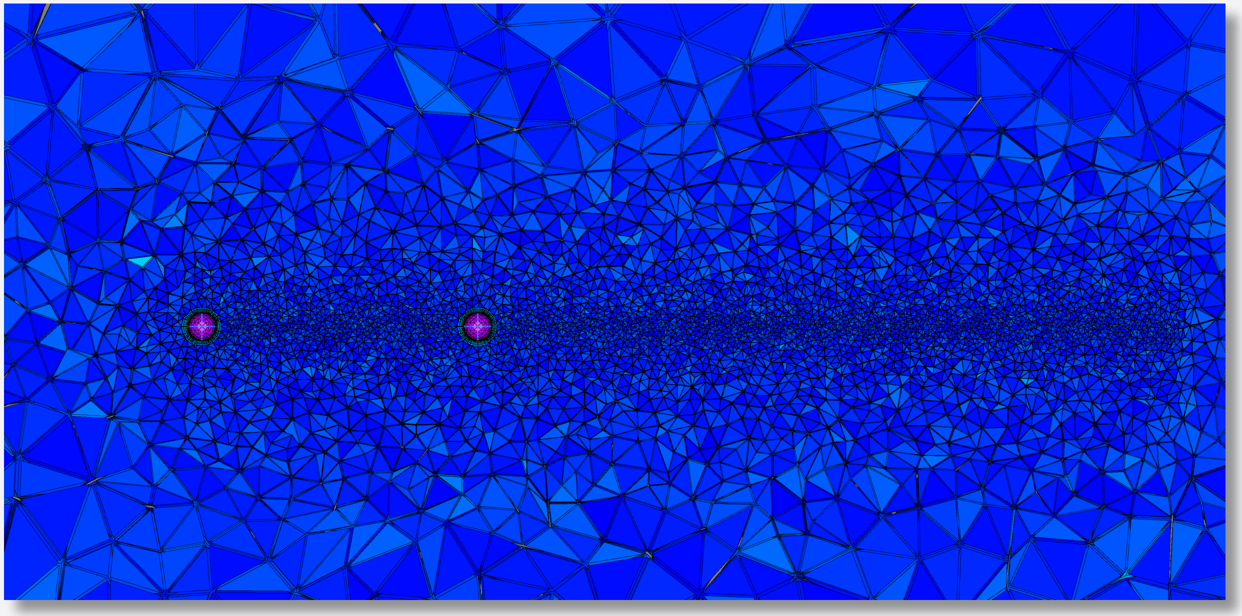
- Plotted using ParaView
  - 4 subdivision levels

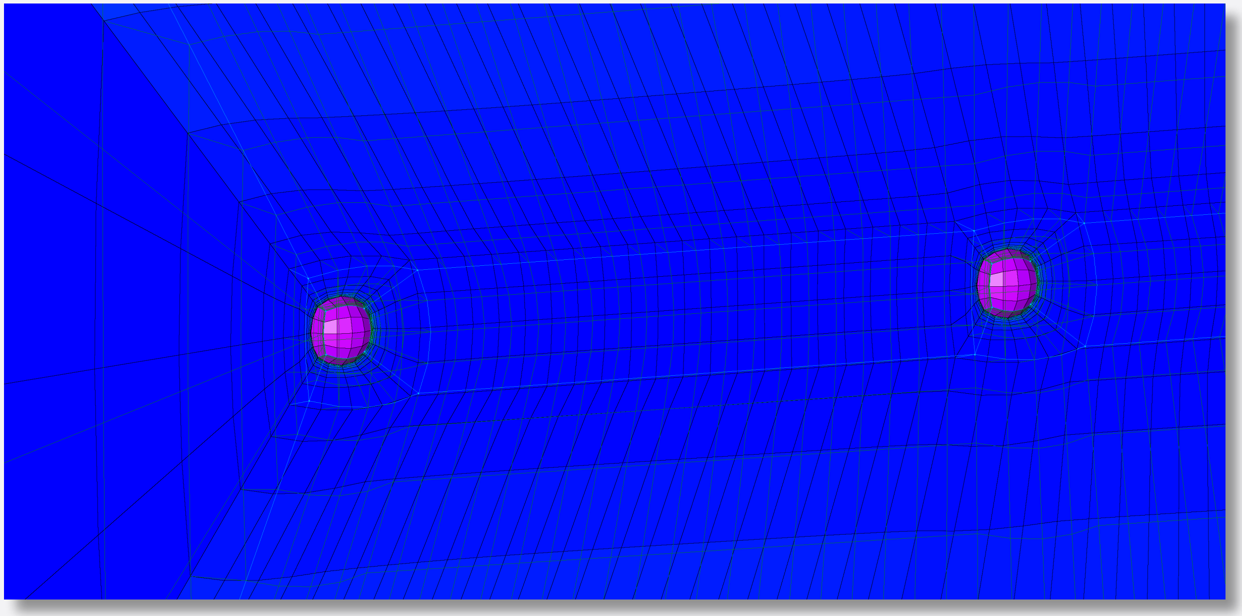




P1 Mesh 1

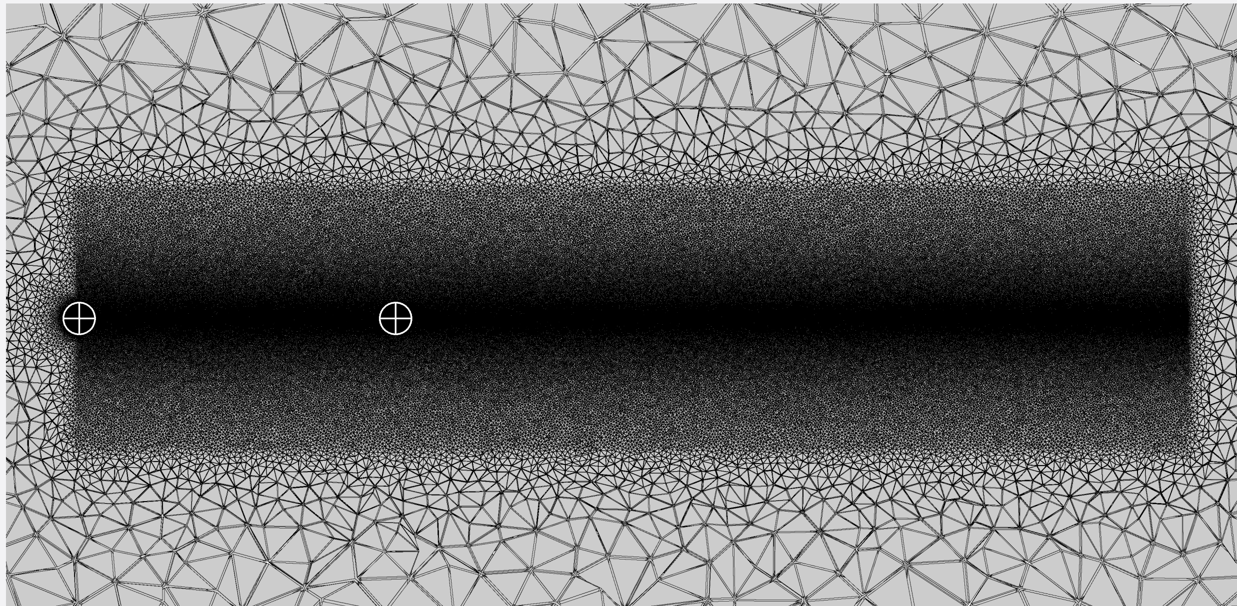
- Plotted using Pointwise

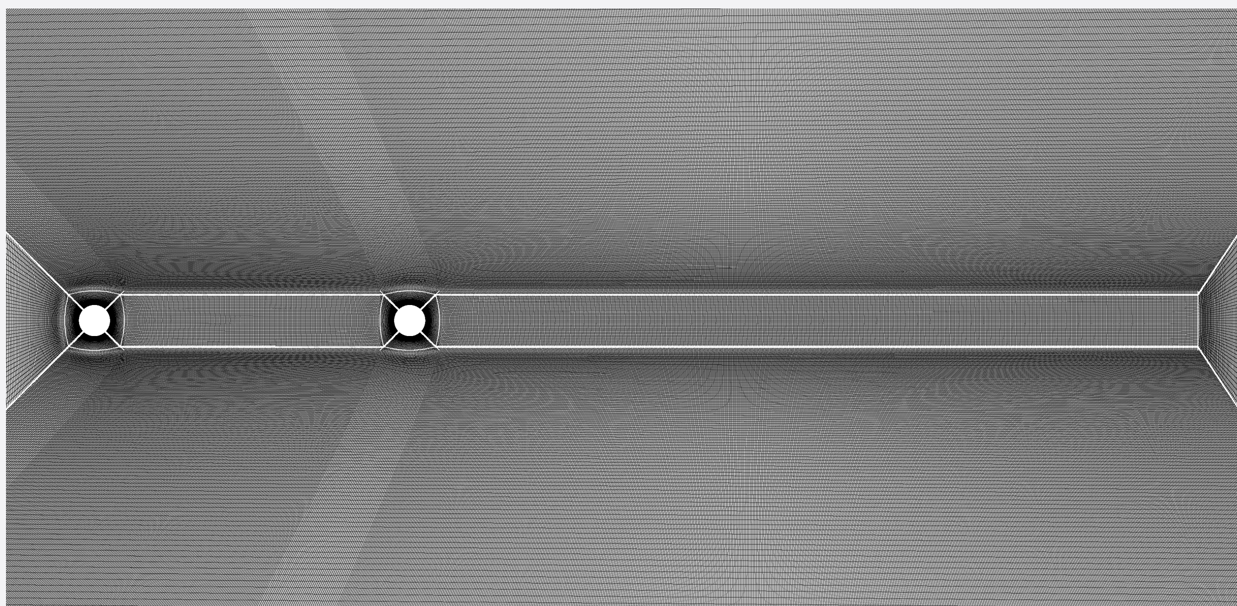




P1 Mesh 6

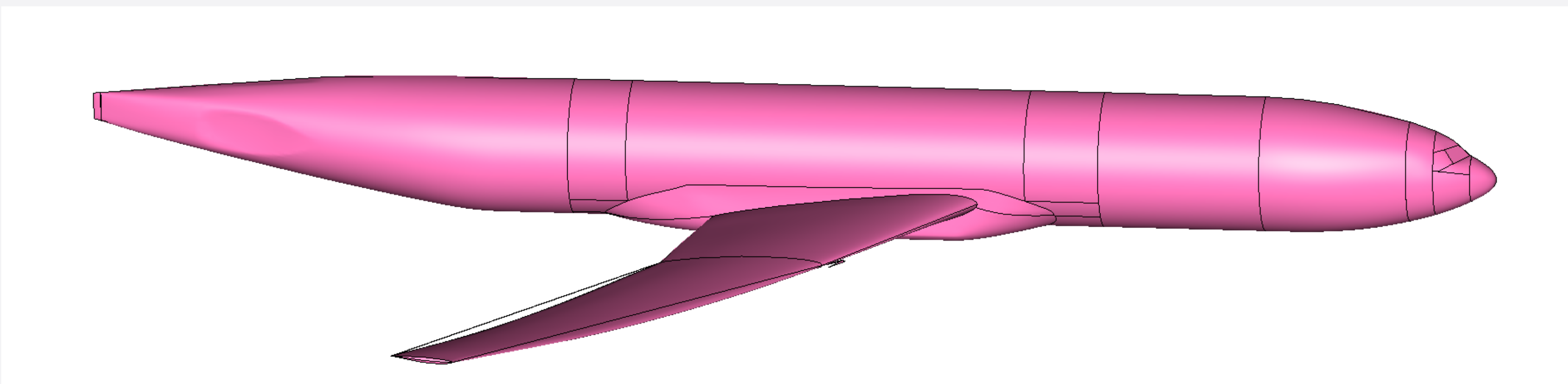
- Plotted using Pointwise





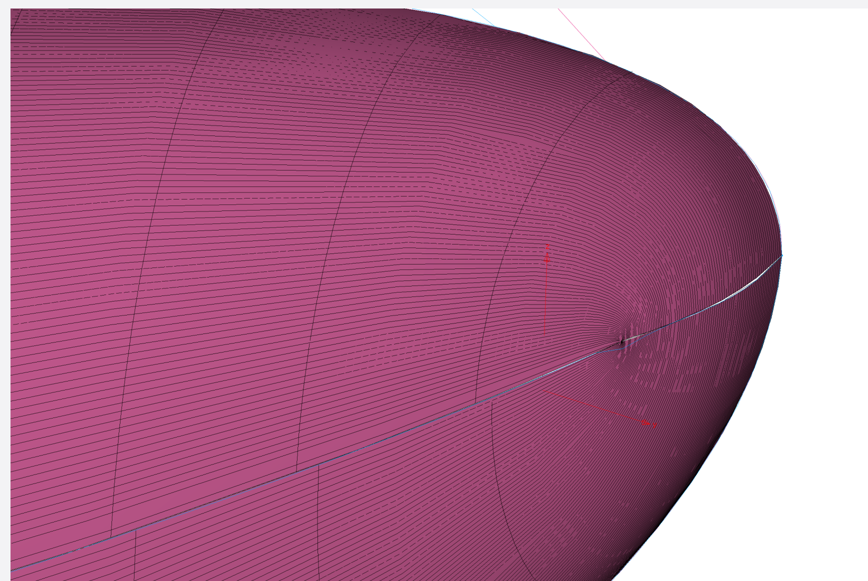
CRM-WB

- DPW 6 case
- P1 and P2 meshes for HiOCFD5
- Coarse, medium and fine (Following meshing guidelines from workshop)



Geometry Issues

- Singularities in geometry definition caused curving issues.
- Fuselage tail
- Wing tip

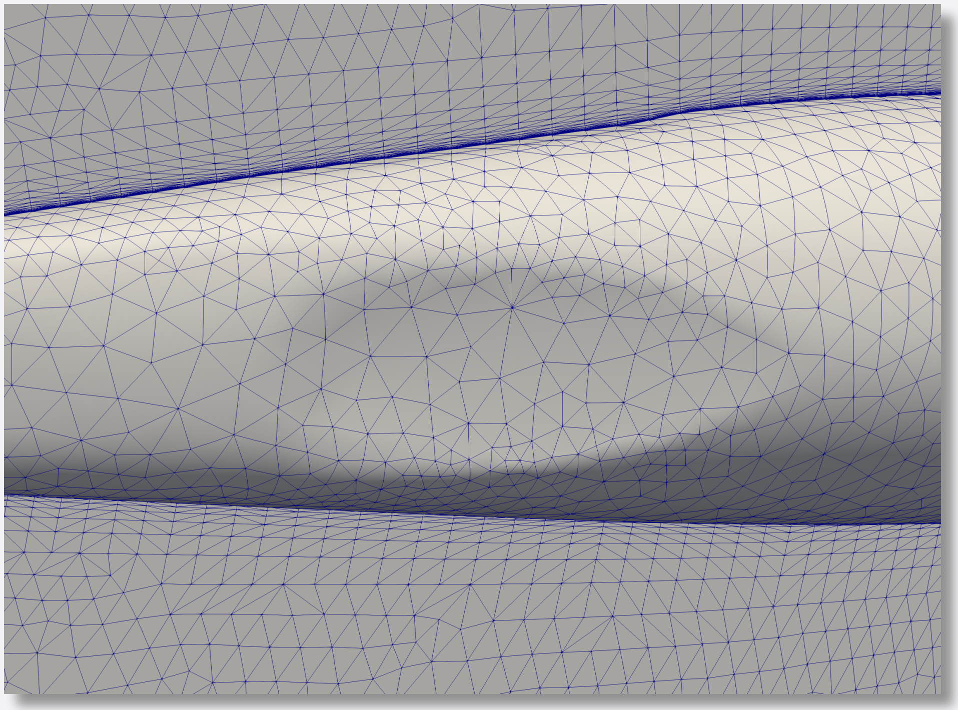


CRM-WB Mesh Series

Mesh	# Tets	P1 Nodes	P2 Nodes
Coarse	2,498,519	433,893	3,401,021
Medium	4,776,832	824,311	6,481,430
Fine	10,700,893	1,839,905	14,493,243

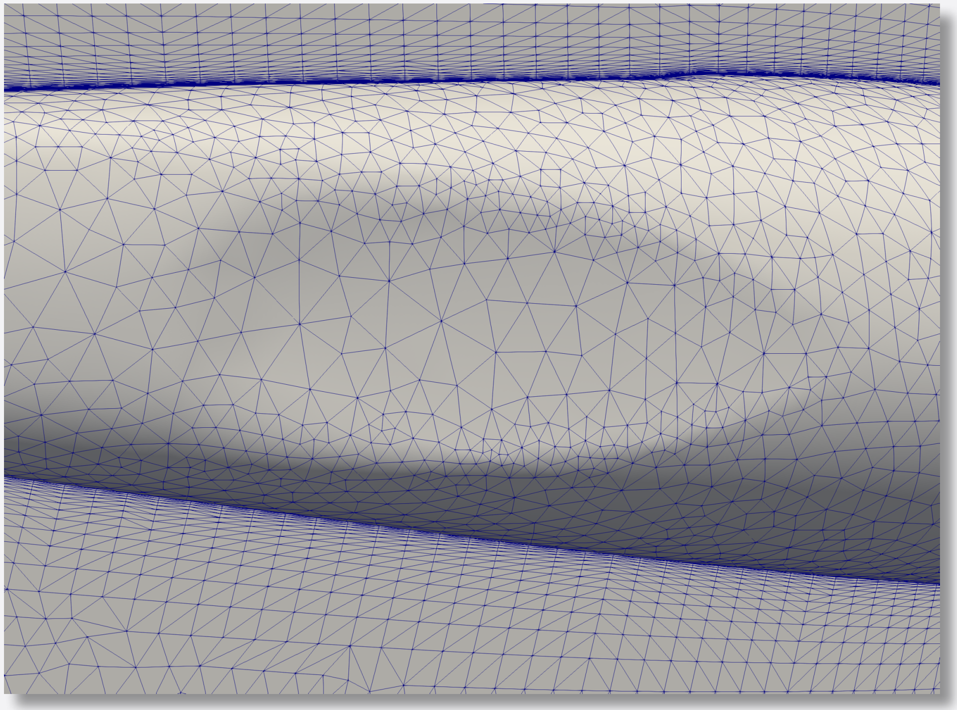
P2 Coarse & Medium

- Tail section
- Plotted using ParaView



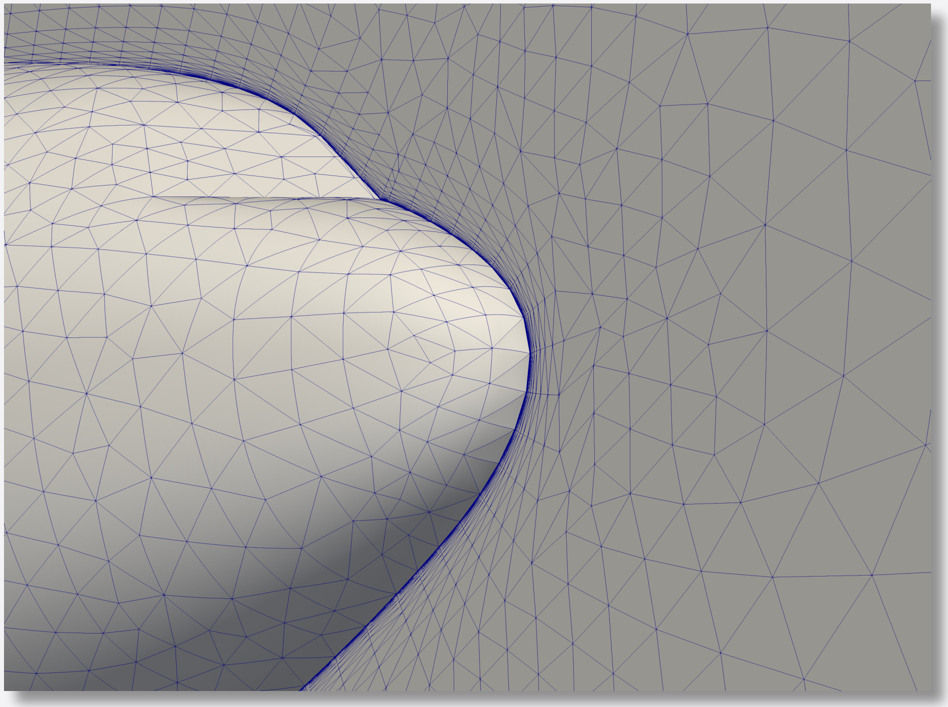
Coarse

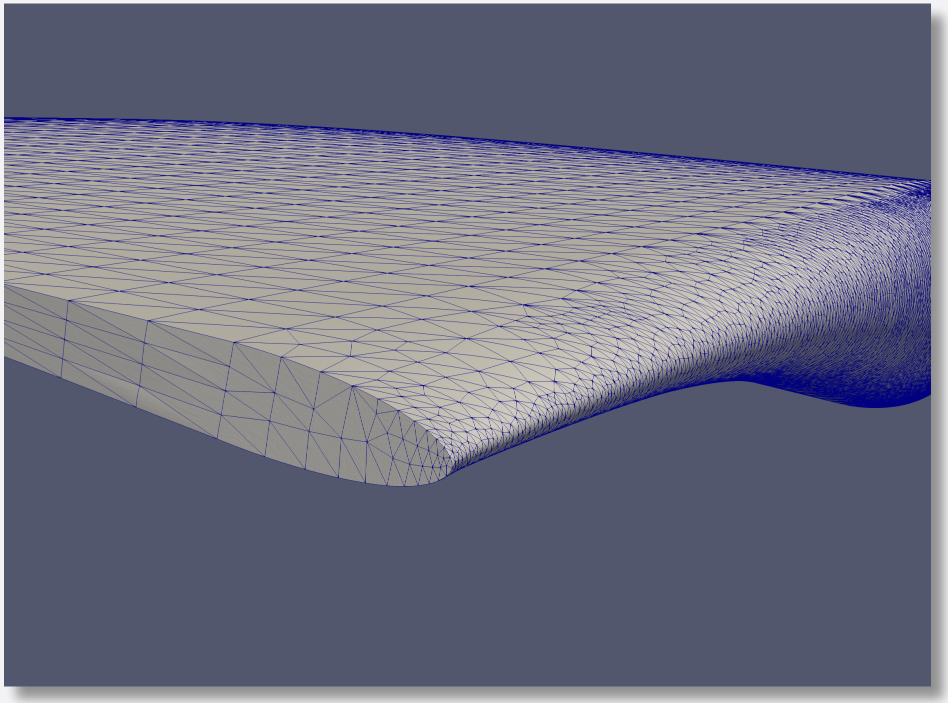
Medium



Coarse P2

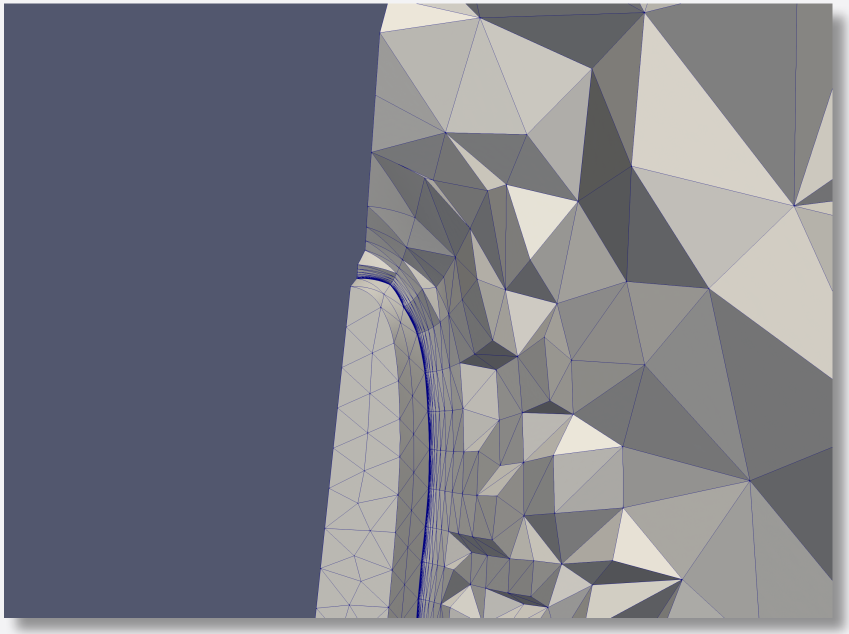
- Nose
- Wing Tip

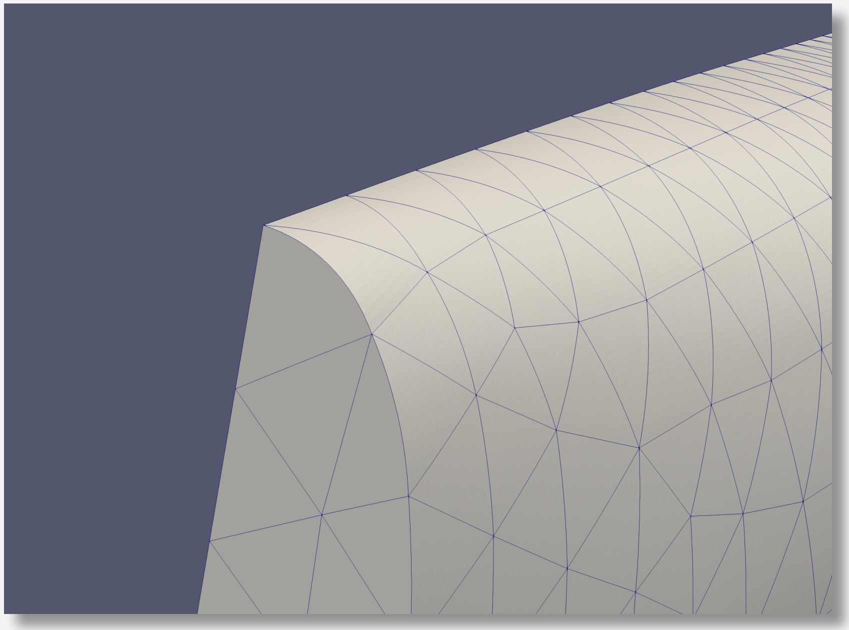


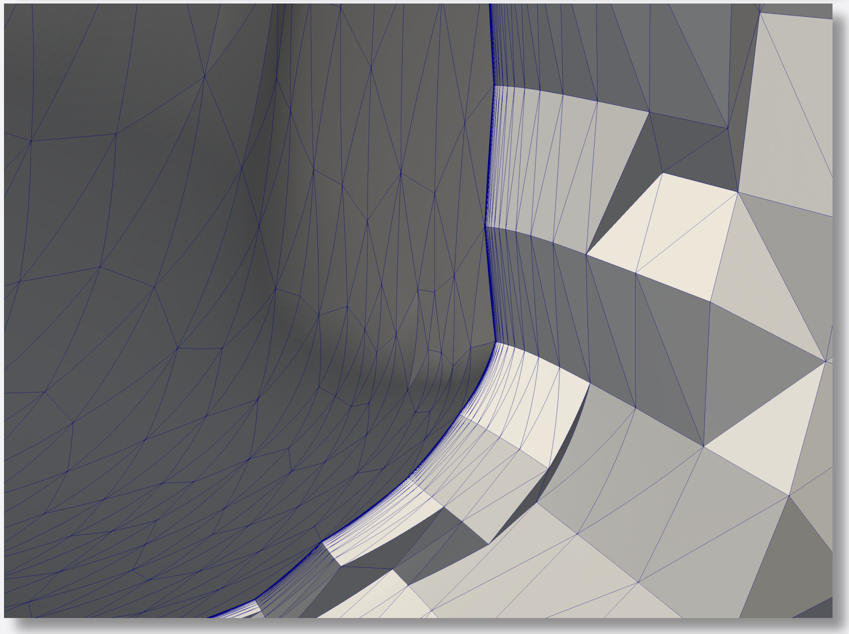


Coarse P2 Tail

- Plotted using ParaView.
- Truncated tail meshes not uploaded to HiOCFD5 website.

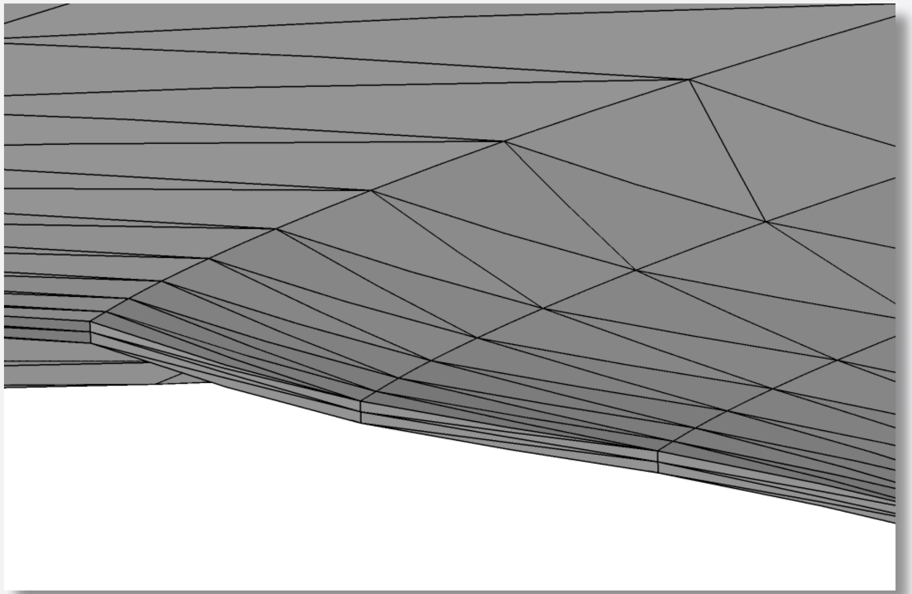


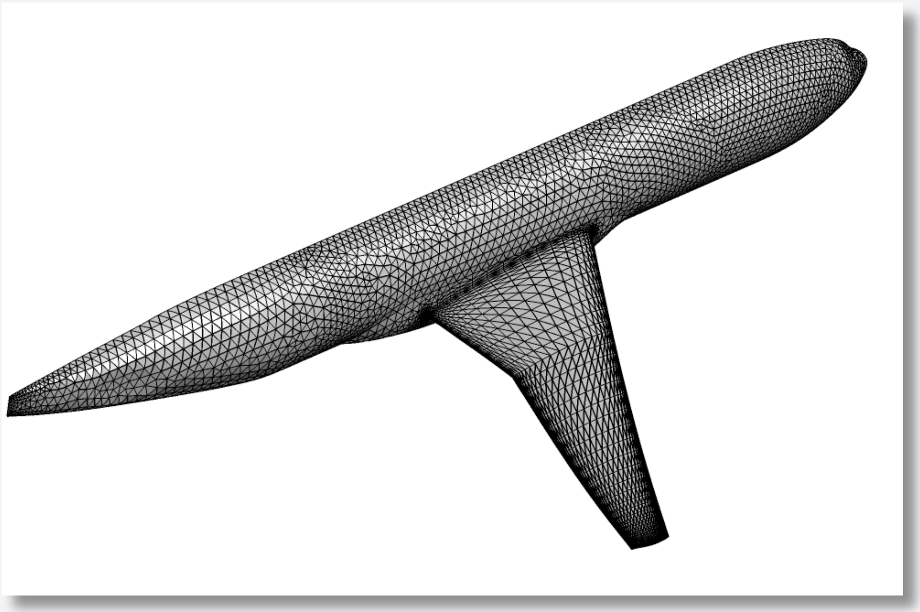


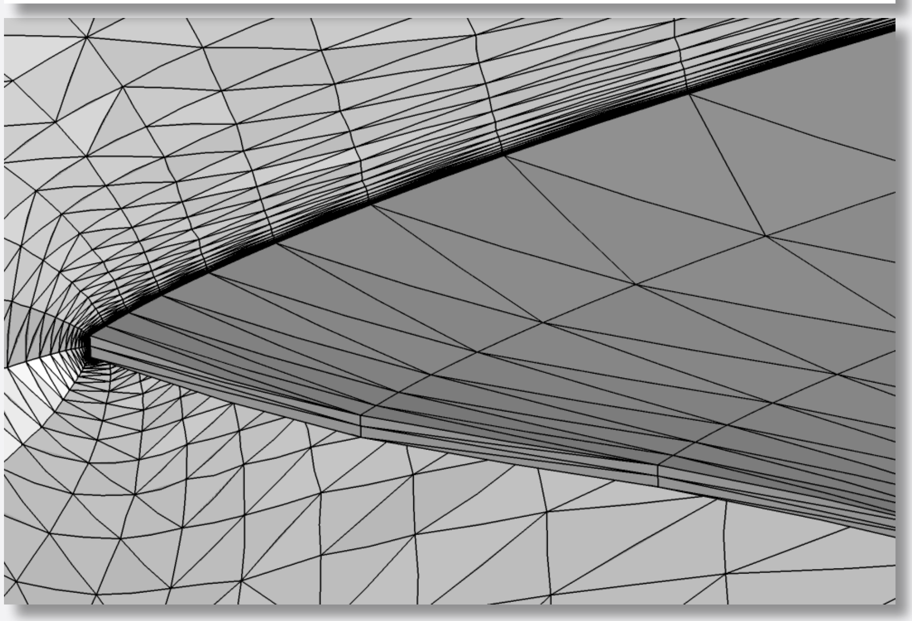


Tiny & Extra Tiny Added

- P1 and P2 all-tet meshes created in last couple of weeks.
- Coarsening reveals curved trailing edge.

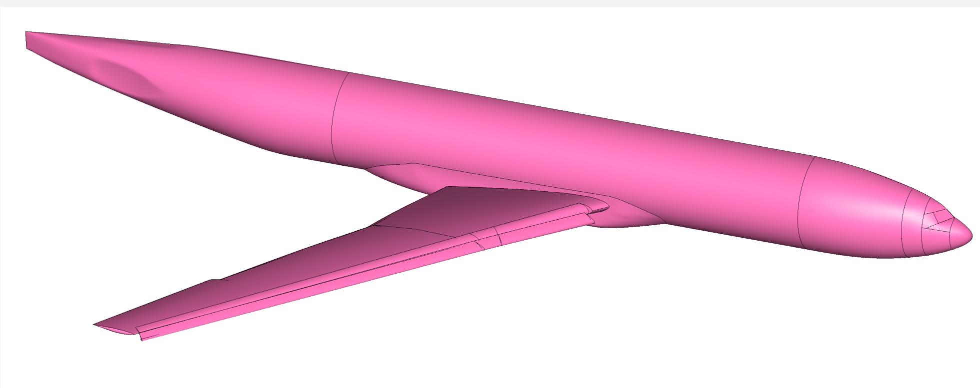


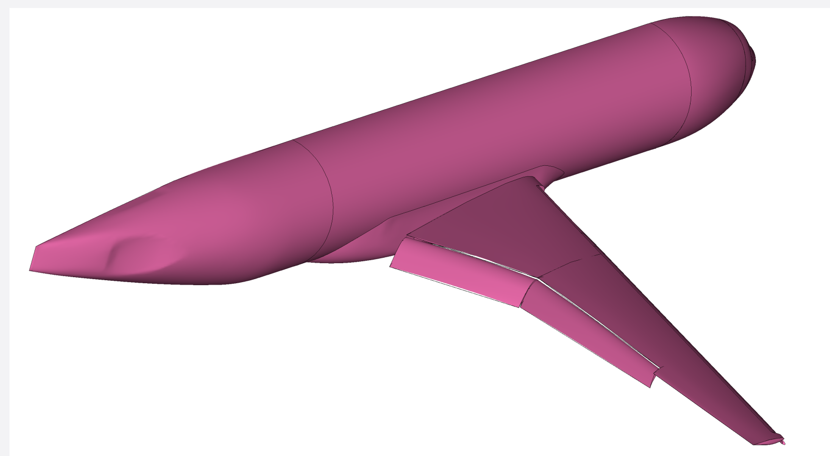




HL-CRM

- GMGW-1/HiLiftPW-3 workshop case
- Meshing guidelines provided by the two committees.





Summary of grids generated:

Case	Code(s)	Starting Geometry Model	Grid Type	Number Grid Levels
HL-CRM full gap P1	Pointwise, CurveMesh	IGES	Unstructured Tetrahedra	4
HL-CRM full gap P2	Pointwise, CurveMesh	IGES	Unstructured Tetrahedra	4
HL-CRM full gap P3	Pointwise, CurveMesh	IGES	Unstructured Tetrahedra	3
HL-CRM full gap P1	Pointwise, CurveMesh	IGES	Unstructured Prism/Tetrahedra	4
HL-CRM full gap P2	Pointwise, CurveMesh	IGES	Unstructured Prism/Tetrahedra	4
HL-CRM full gap P3	Pointwise, CurveMesh	IGES	Unstructured Prism/Tetrahedra	3

- Pointwise used to create linear meshes
  - All tetrahedral meshes created with Pointwise
  - Recombination of tetrahedra in viscous region to form prisms
  - WCN smoothing applied to eliminate extremely high included angles.
  - CurveMesh used to elevate linear meshes to produce P2 and P3 meshes

Unstructured Tetrahedra Mesh Statistics

Grid	Total Boundary Triangles	Total Boundary Quads	Total Volume Cells	Total Volume Points	Tets	Prisms	Hexes	Pyramids	Total Number of Blocks
[P1] Extra Tiny Full Gap	126266	0	5,414,279	933,440	5,414,279	0	0	0	1
[P1] Tiny Full Gap	214946	0	11,794,638	2,016,118	11,794,638	0	0	0	1
[P1] Coarse Full Gap	396224	0	32,965,522	5,591,371	32,965,522	0	0	0	1
[P1] Medium Full Gap	854744	0	98,659,138	16,654,483	98,659,138	0	0	0	1
[P2] Extra Tiny Full Gap	126266	0	5,414,279	7,344,288	5,414,279	0	0	0	1
[P2] Tiny Full Gap	214946	0	11,794,638	15,934,343	11,794,638	0	0	0	1
[P2] Coarse Full Gap	396224	0	32,965,522	44,346,372	32,965,522	0	0	0	1
[P2] Medium Full Gap	854744	0	98,659,138	132,395,472	98,659,138	0	0	0	1
[P3] Extra Tiny Full Gap	126266	0	5,414,279	24,646,827	5,414,279	0	0	0	1
[P3] Tiny Full Gap	214946	0	11,794,638	53,549,317	11,794,638	0	0	0	1
[P3] Coarse Full Gap	396224	0	32,965,522	149,230,529	32,965,522	0	0	0	1

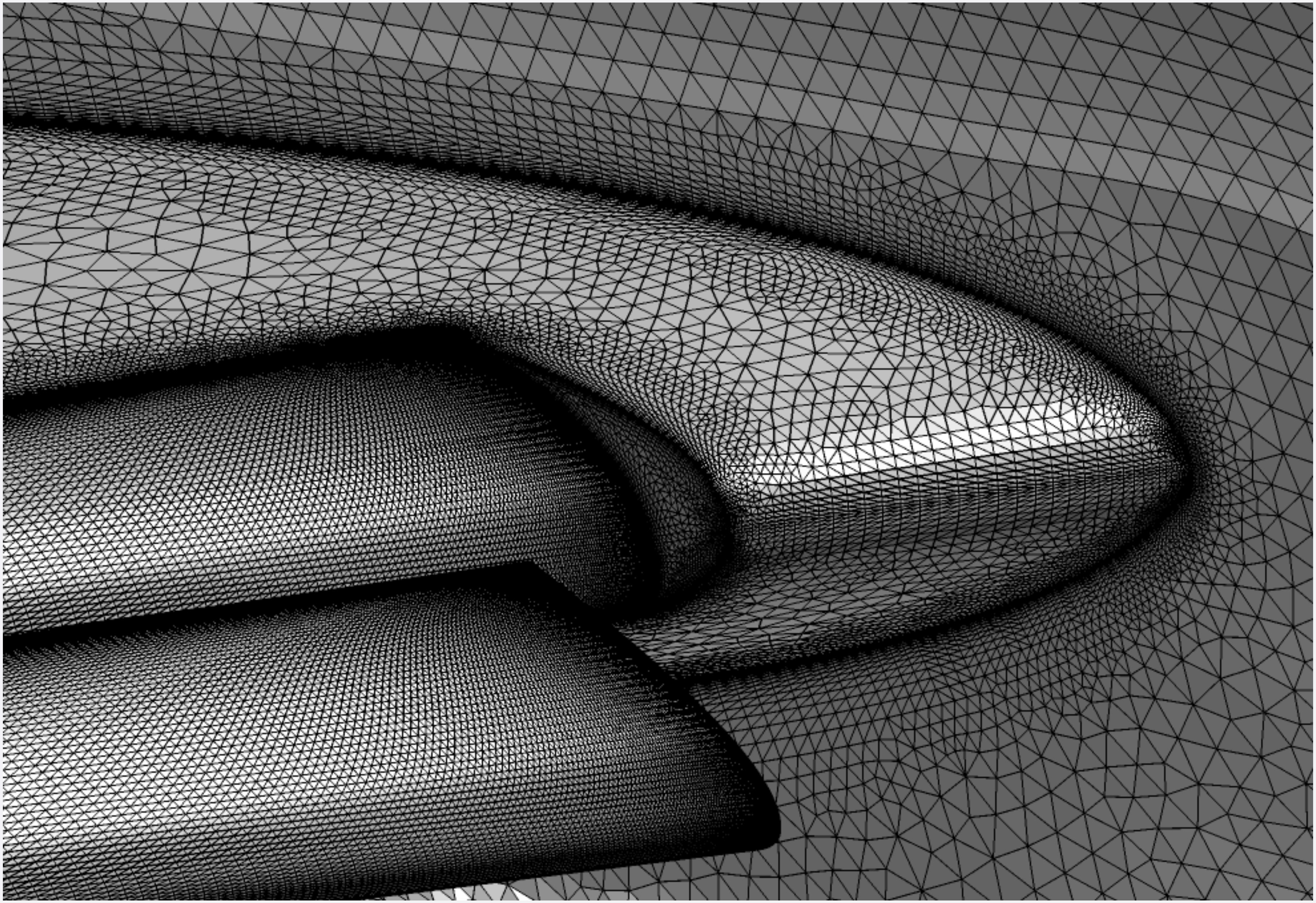
Unstructured Prism/Tetrahedra Mesh Statistics

POINTWISE®
THE CHOICE FOR CFD MESHING

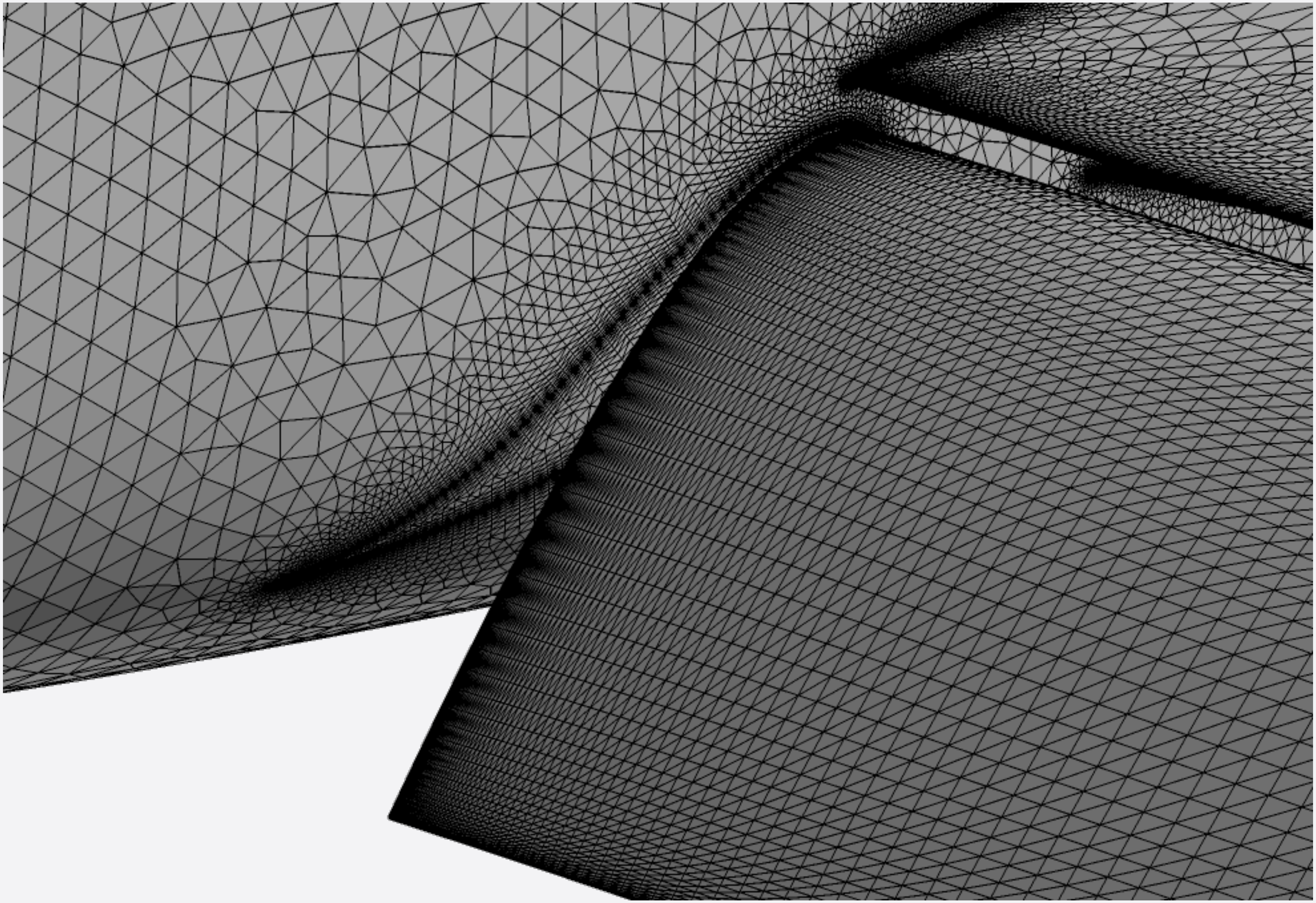
Grid	Total Boundary Triangles	Total Boundary Quads	Total Volume Cells	Total Volume Points	Tets	Prisms	Hexes	Pyramids	Total Number of Blocks
[P1] Extra Tiny Full Gap	107212	9527	2,265,022	933,440	673,419	1,557,654	0	33,949	1
[P1] Tiny Full Gap	188118	13414	4,870,427	2,016,118	1,376,337	3,430,121	0	63,969	1
[P1] Coarse Full Gap	357728	19248	12,985,896	5,591,371	2,921,314	9,915,044	0	149,538	1
[P1] Medium Full Gap	723022	65861	37,620,236	16,654,483	6,934,923	30,353,589	0	331,724	1
[P2] Extra Tiny Full Gap	107212	9527	2,265,022	7,344,288	673,419	1,557,654	0	33,949	1
[P2] Tiny Full Gap	188118	13414	4,870,427	15,934,343	1,376,337	3,430,121	0	63,969	1
[P2] Coarse Full Gap	357728	19248	12,985,896	44,346,372	2,921,314	9,915,044	0	149,538	1
[P2] Medium Full Gap	723022	65861	37,620,236	132,395,472	6,934,923	30,353,589	0	331,724	1
[P3] Extra Tiny Full Gap	107212	9527	2,265,022	24,646,827	673,419	1,557,654	0	33,949	1
[P3] Tiny Full Gap	188118	13414	4,870,427	53,549,317	1,376,337	3,430,121	0	63,969	1
[P3] Coarse Full Gap	357728	19248	12,985,896	149,230,529	2,921,314	9,915,044	0	149,538	1

Surface Mesh Pictures (Medium-P1)

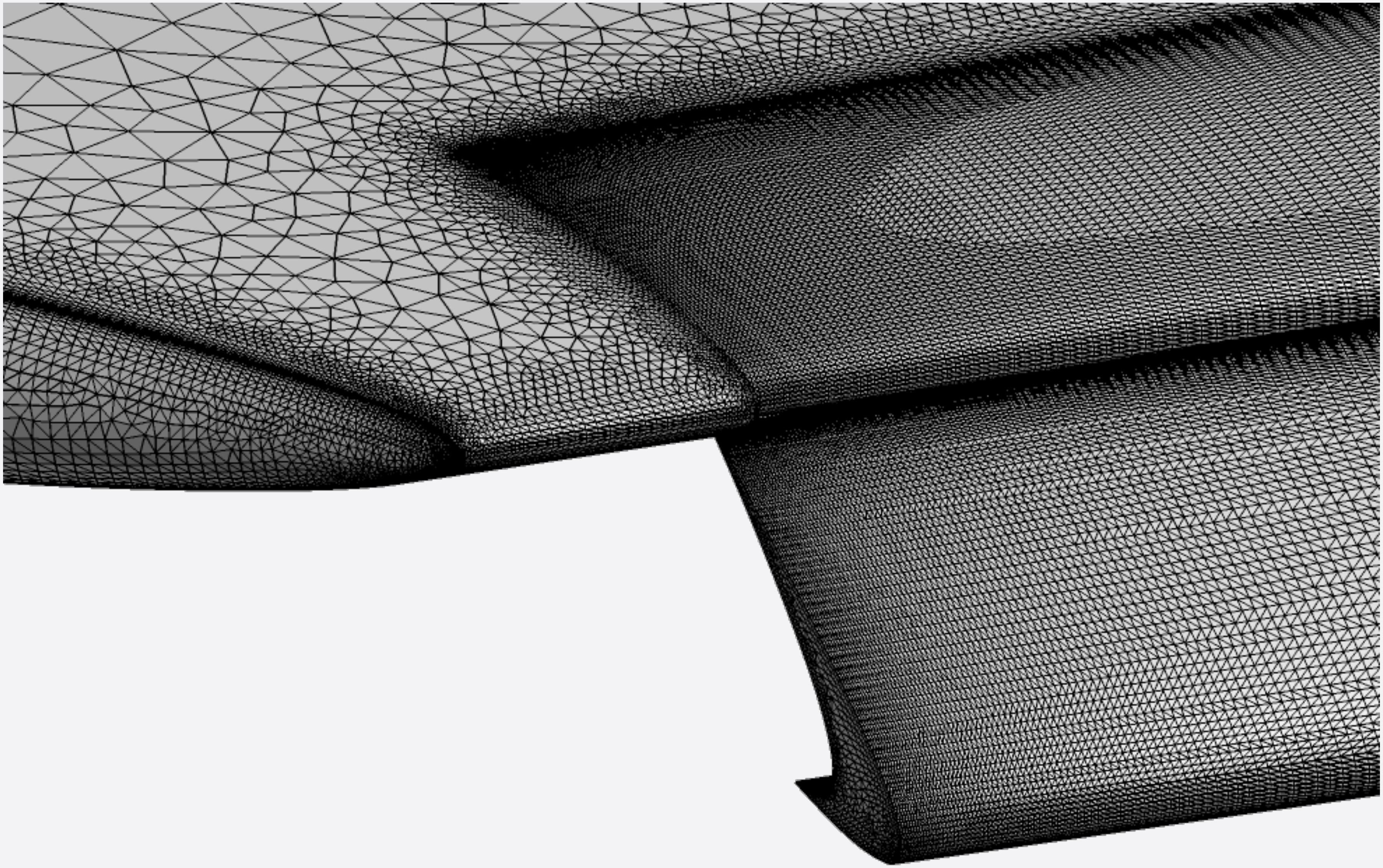
Surface Mesh Pictures (Medium-P1)



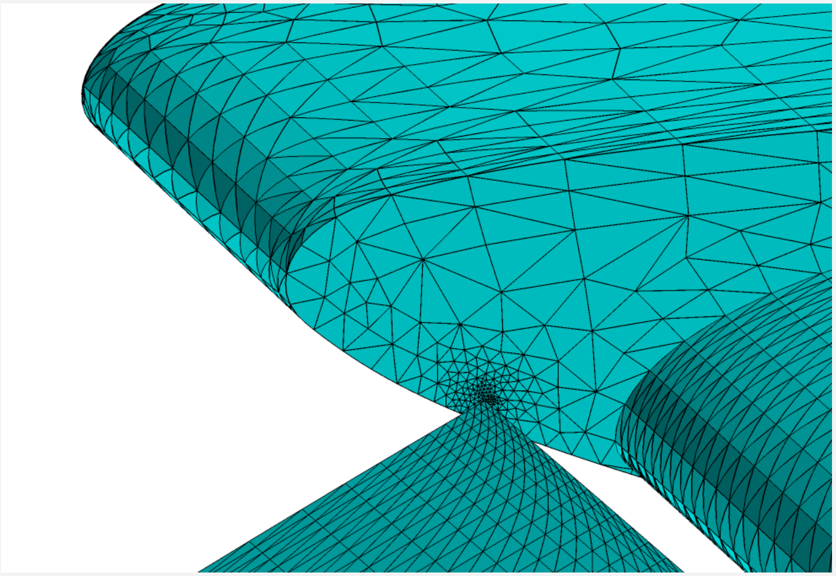
Surface Mesh Pictures (Medium-P1)

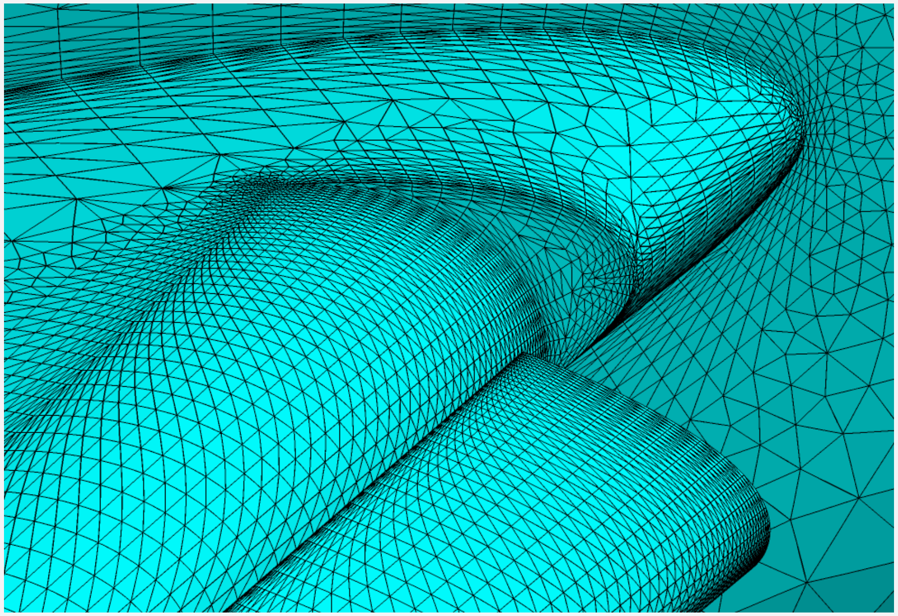


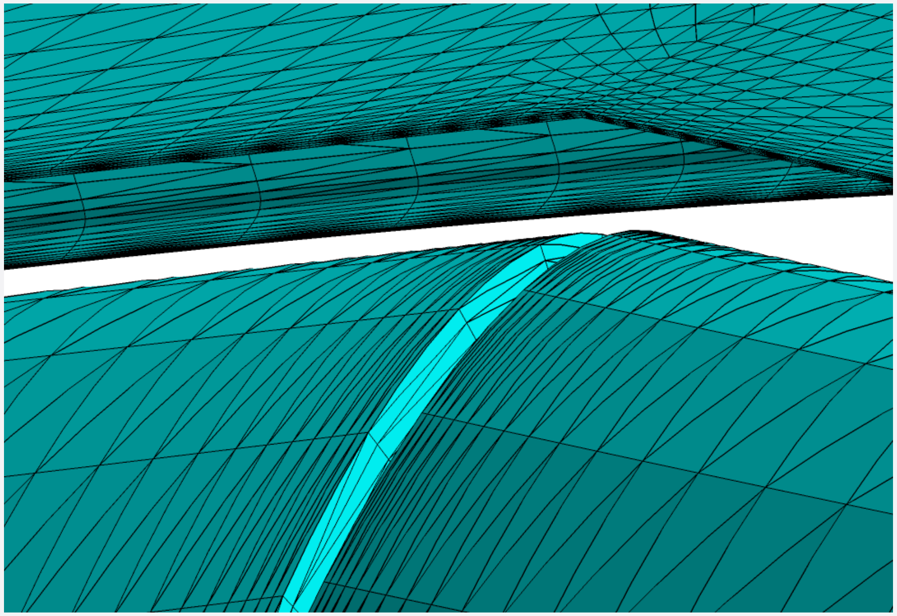
Surface Mesh Pictures (Medium-P1)



Extra Tiny P3



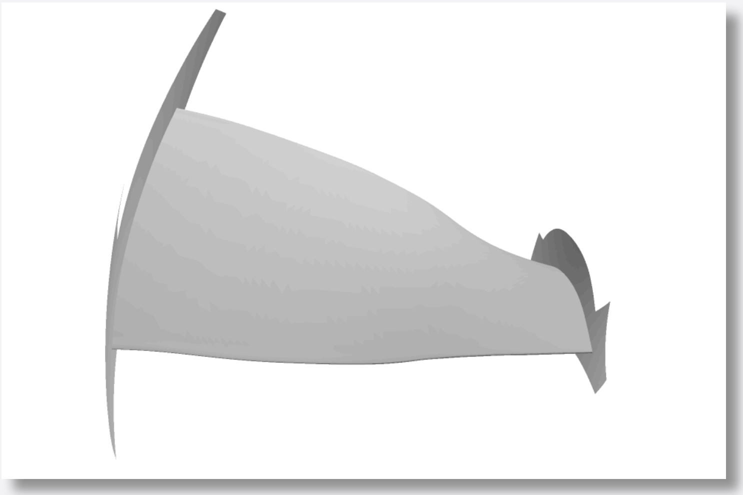


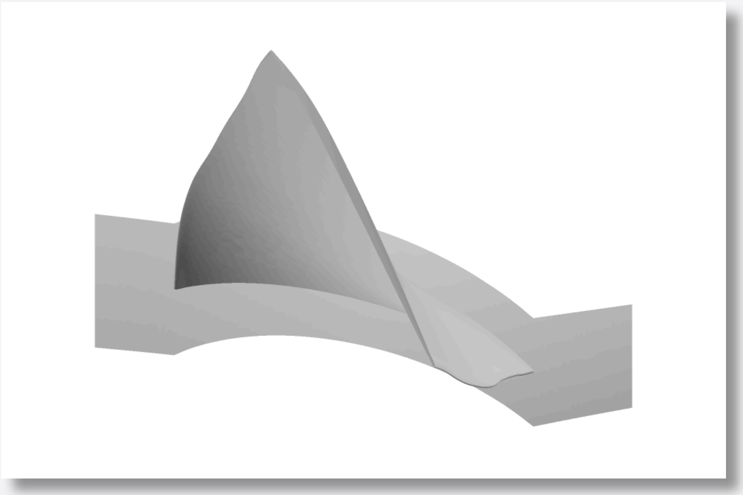


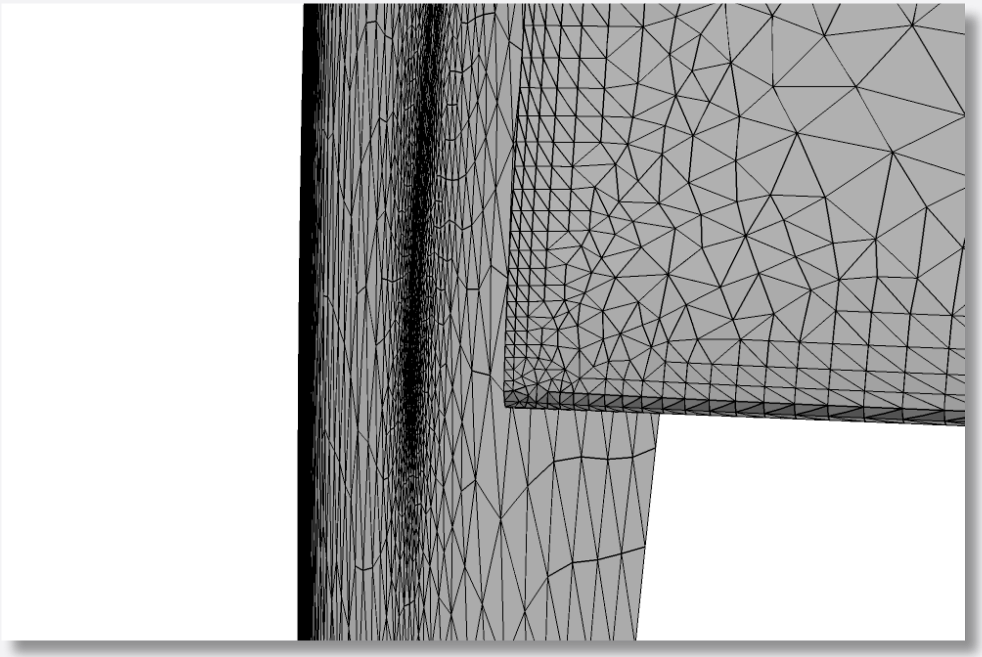
Rotor 67

- Several meshes made in an attempt to create the series.
- Issues arose with kink in geometry of blade.
  - Never completely resolved.
  - Did not have a flow solver partner with periodic boundary condition capability in higher order codes.
  - Higher priority tasks prevented work from continuing.

Geometry and Surface Mesh



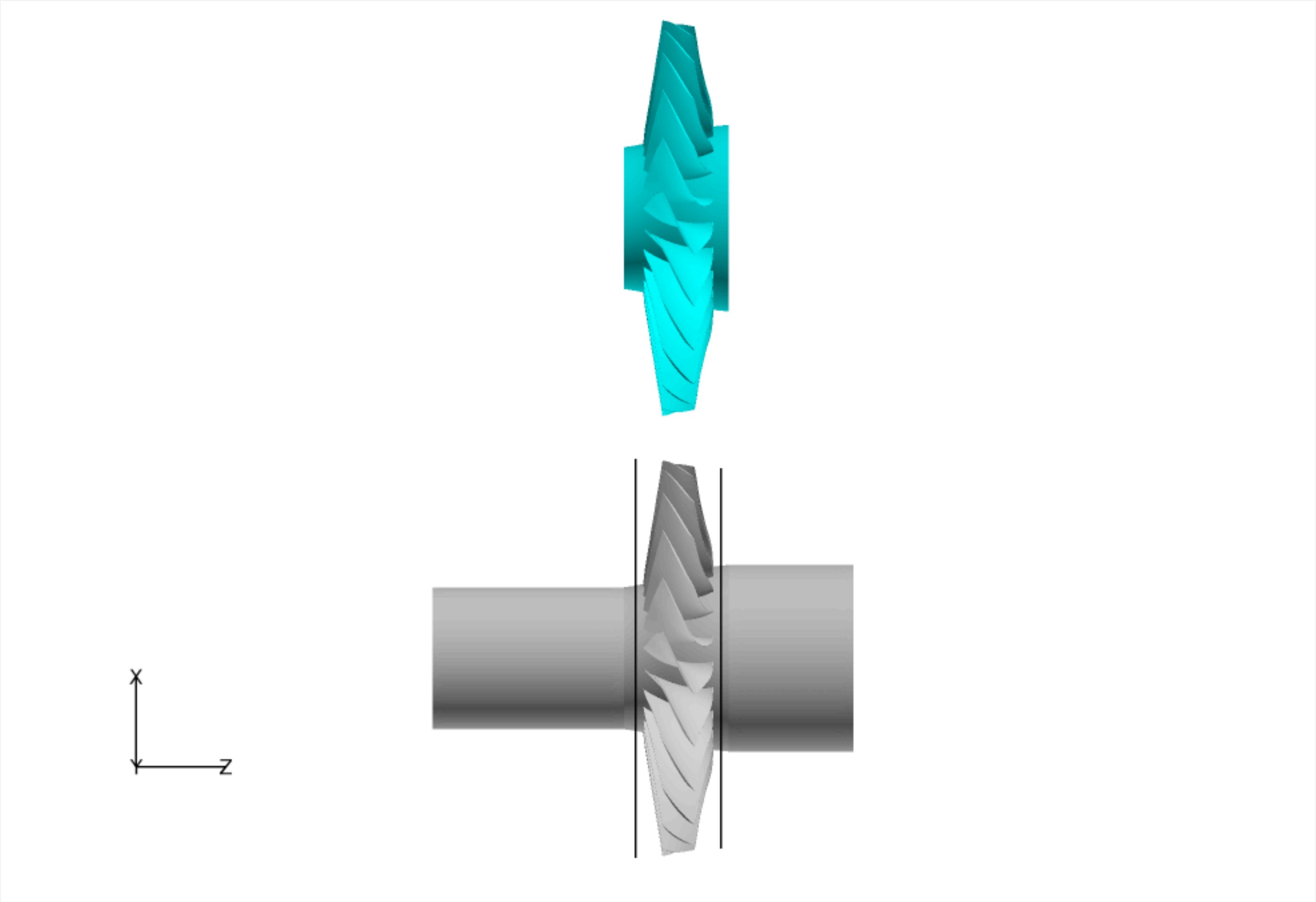




Inflow & Outflow Boundaries

POINTWISE THE CHOICE FOR CFD MESHING

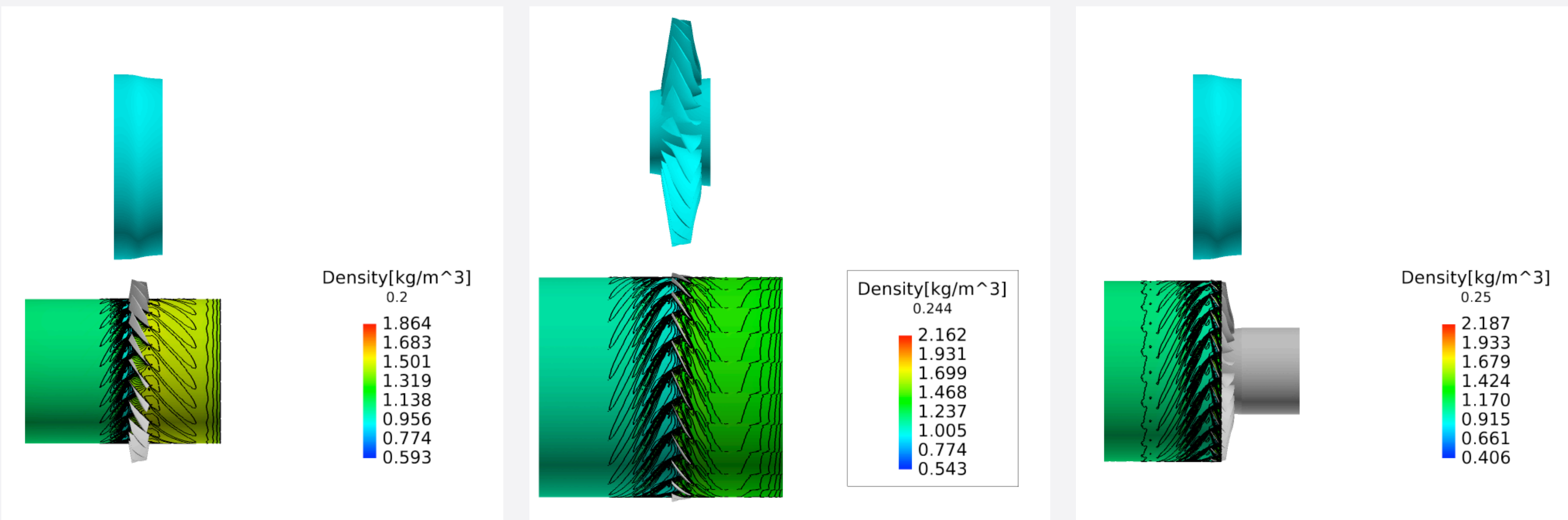
- UTC SimCenter extended the inflow and outflow boundaries and ran 2nd order linear mesh solutions.



2^{nd} Order Flow Results

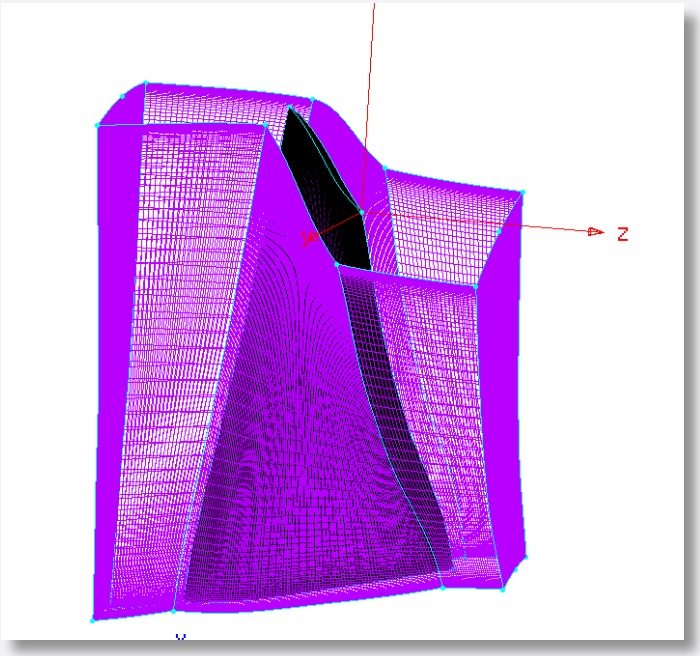
POINTWISE®
THE CHOICE FOR CFD MESHING

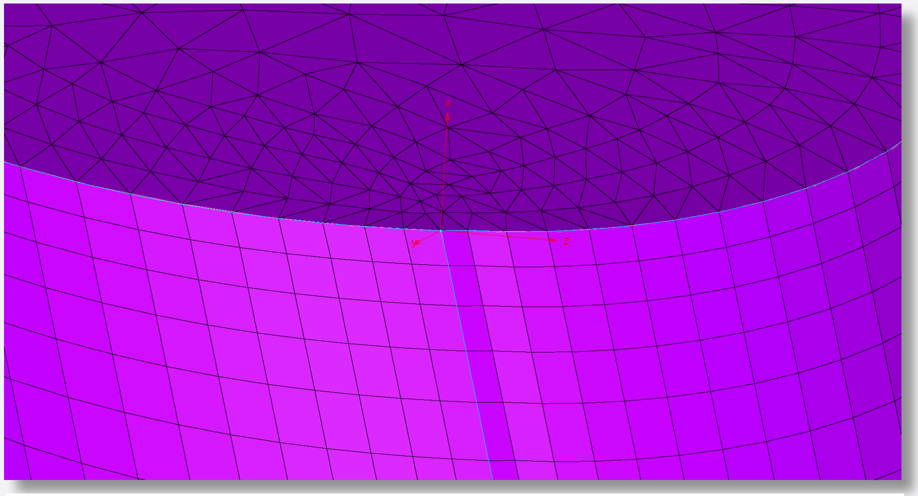
- Inflow and Outflow proximity can become an issue.

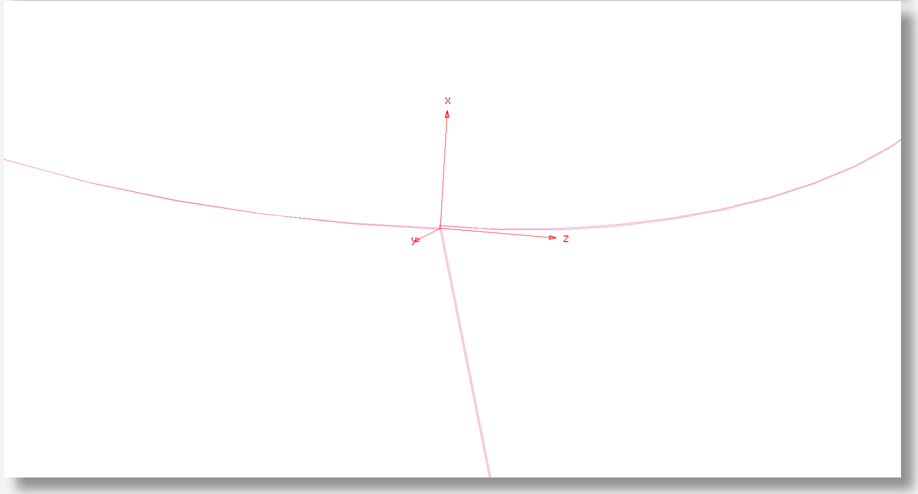


Kink in Geometry

- Uncertain whether source is original CAD or in the transfer between formats.







Meshing Philosophy

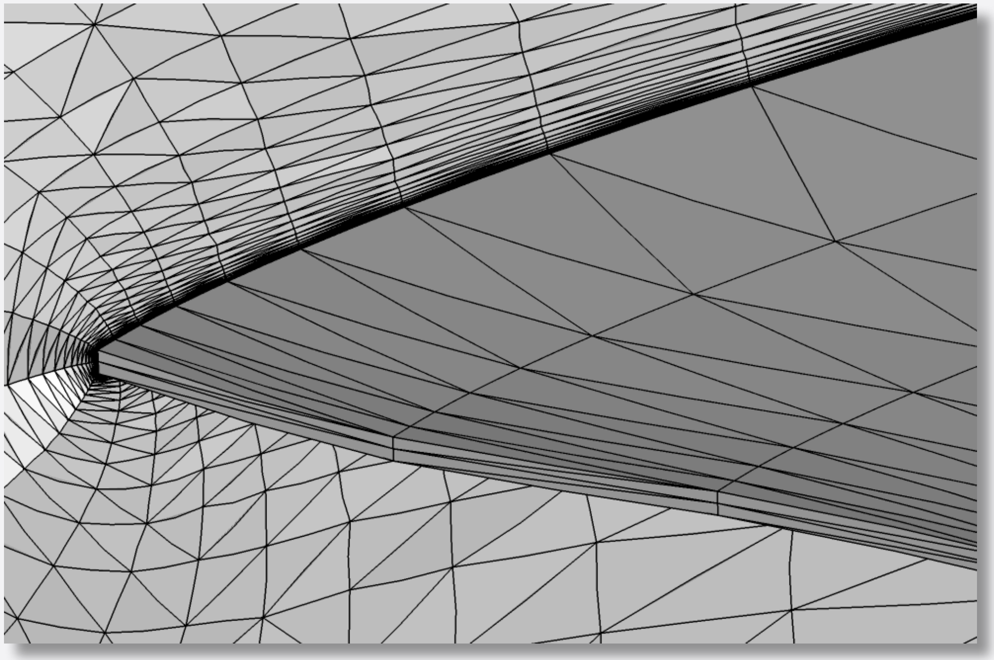
Meshing Philosophy

POINTWISE®
THE CHOICE FOR CFD MESHING

- A better quality linear input mesh will lead to successful curved mesh.
  - Strive for surface AR < 200.
  - Maintain similar spacing for edges emanating from same corner. (TE/LE Tip Root)
  - Positive linear Jacobians and max included angles α < 179.
- Resolve to sharp edges in linear mesh. Strive for reasonable resolution of curvature.
- Generating a coarse linear mesh is harder than a fine linear mesh.
- Curving a coarse mesh is much harder than a curving a fine mesh.

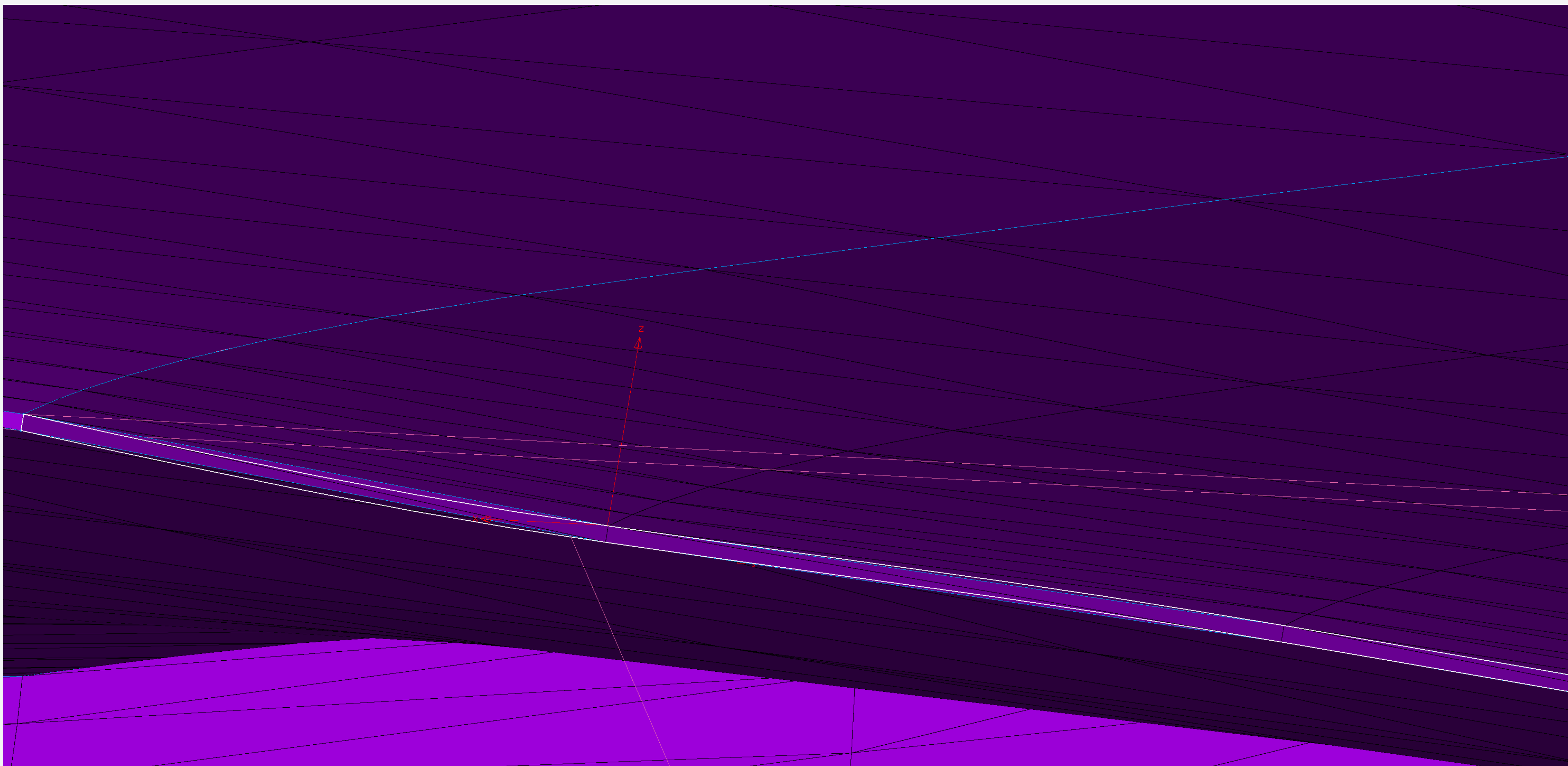
Meshing Philosophy

- Geometry sometimes dictates resolution requirements.
- Trailing edge thickness is fixed.
  - Streamwise and tangential spacing should be influenced by TE spacing.
- Curvature in multiple directions can impact the curving process.
- Tetrahedral elements in boundary layer result in extremely small included angles.
  - Prismatic elements are easier to curve.



Geometry Definition

- CRM WB Trailing edge shape is highly non-linear with multiple inflections.



Conclusions

Summary

- Mesh families with increasing resolution and order (P1, P2, P3 & P4) created for multiple HiOCFD5 cases.
- Linear mesh quality impacts higher order mesh quality.
- Singularities and kinks in the geometry definition can get exposed in the curving process.

- Future CurveMesh development will permit mixed order meshes and H-P adaptation.
  - Elevate only those elements that are necessary to resolve curvature, using the proper order (P2, P3, or P4).
  - Enforce lower order shape on edges/faces common to elements of different order.
  - On export, elevate mesh to requested order, dictated by user or solution adaptation.

Acknowledgements

- This work was partially supported by a NASA Phase I SBIR, “High Order Mesh Curving and Geometry Access”, NNX17CL83P.
- Collaboration with numerous flow solver developers has been extremely beneficial to advancing the mesh curving capabilities.