

# Mesh Generation for the NASA High Lift Common **Research Model (HL-CRM)**

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Four types of CFD meshes (multi-block structured, unstructured tetrahedral, unstructured hybrid, and hybrid overset) were generated for the NASA High Lift Common Research Model (HL-CRM). Lessons learned during this experience are documented herein, from geometry processing through generation of the final volume meshes. All meshes are provided as a baseline to build a mesh family for a mesh sensitivity study for the 3<sup>rd</sup> AIAA High Lift Prediction Workshop and in the 1<sup>st</sup> AIAA Geometry and Mesh Generation Workshop.

### Nomenclature

HLPW	=	High Lift Prediction Workshop
CFD	=	computational fluid dynamics
GMGW	=	Geometry and Mesh Generation Workshop
HL-CRM	=	High Lift Common Research Model
WUSS	=	Wing Under Slat Surface
$C_{REF}$	=	Chord reference length
GR	=	Growth rate
F	=	Mesh size factor
п	=	Mesh level
<i>y</i> +	=	Dimensionless wall distance
∆y	=	Initial normal distance from wall
LE	=	Leading edge
TE	=	Trailing edge
PDE	=	Partial differential equations
TFI	=	Transfinite interpolation

# I. Introduction

he AIAA Applied Aerodynamics Technical Committee has sponsored the 3rd High Lift Prediction Workshop L (HLPW), to be held in Denver, CO, in June 2017, to assess the current capabilities of computational fluid dynamics (CFD) codes to model, simulate, and numerically predict the high-lift flow physics of a swept, medium-tohigh-aspect ratio wing aircraft in a landing/take-off configuration. Concurrently, the AIAA Meshing, Visualization, and Computational Environments Technical Committee has sponsored the 1<sup>st</sup> Geometry and Mesh Generation Workshop (GMGW), which will be co-located with the 3rd HLPW, to assess the current state-of-the-art in geometry preparation and mesh generation for aircraft and spacecraft of interest to AIAA constituents. The High Lift Common Research Model (HL-CRM) geometry will be used for a mesh convergence study by the 3<sup>rd</sup> HLPW and will also serve as the case study for the 1<sup>st</sup> GMGW. The focus for the 1<sup>st</sup> GMGW will be to identify and document where technology, software, and best practices can be improved for geometry processing and mesh generation of the HL-CRM. As part of this effort, a baseline set of medium meshes of different element types were generated as candidate meshes for workshop participant use. Key problem areas found during geometry processing and mesh generation are discussed in the following sections to highlight lessons learned.

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### **II.** Geometry Description

The configuration studied by both workshops, the High Lift Common Research Model (HL-CRM), was based on the Common Research Model of a high speed configuration that has been used in numerous experimental and numerical simulations<sup>1</sup>. The high lift configuration originally contained inboard and outboard leading edge slats as well as inboard and outboard single-slotted flaps as well as a pylon and nacelle. For the purposes of the workshops, the pylon and nacelle were removed which necessitated reconfiguring the wing and leading edge slats. The inboard and outboard Wing Under Slat Surfaces (WUSS) and leading edge slats were combined into one WUSS and one leading edge slat respectively as seen in Figure 1. A modification was also made to the gap region between the inboard and outboard single-slotted flaps to create a consistent 1 inch gap in order to simplify mesh generation.



Figure 1. HL-CRM wing-body configuration is shown with modifications to the leading edge slat, wing under slat surface, and inboard/outboard flap gap.

# **III.** Geometry Processing

Geometry processing was performed on an IGES file<sup>2</sup> provided by the HLPW. The Pointwise<sup>®</sup> mesh generation software was used to import the IGES file and evaluate it prior to beginning mesh generation. A watertight solid model of the geometry did not exist in the IGES file, so the geometry was reviewed to determine if one could be built and with what tolerance between adjacent surface edges. To evaluate whether there would be issues in the geometry to be resolved in the solid model, the proximity of the boundaries of all adjacent surfaces in the IGES file were compared against each other as seen in Figure 2. The most notable gap in the geometry occurred between the boundaries of the inboard flap root surface and the upper and lower surfaces adjacent to it. Near the trailing edge, the distance between these surface boundary edges reached a maximum value of 0.0138. The next largest gap between adjacent surface boundaries of the aircraft with a distance of 0.007.



Figure 2. Boundary Proximity measurements for the IGES geometry show a minor gap at cockpit nose and a more significant gap at inboard flap root trailing edge.

Solid models<sup>3</sup> of the wing-body, leading edge slat, and inboard/outboard flaps were constructed in Pointwise with an edge tolerance of 0.014 as illustrated in Figure 3. The edge tolerance measurement is analogous to the boundary proximity measurement described previously. It is a measurement from point-to-point between adjacent surface boundaries of the physical distance between those points. If the measurement of points is below the tolerance specified the surfaces are designated as having a shared boundary edge. By setting the edge tolerance to a value slightly higher than the maximum boundary proximity measurement, the geometry could be assembled into completely watertight solid models.



Figure 3. Solid models of the wing-body, leading edge slat, and inboard/outboard flaps were constructed from the IGES geometry and are shown represented in magenta, dark green, blue, and light green respectively.

Further geometry processing was performed after generation of the solid models to define regions of engineering topology called quilts<sup>3</sup>. The surfaces within each solid model were assembled into quilts based on regions where additional surface meshing control was required and/or where hard feature edges existed. When the solid models were meshed further downstream in the process, a single surface mesh was created on each quilt instead of on each of the original surfaces. In Figure 4, an illustration shows the HL-CRM surfaces before and after quilt assembly. If quilt assembly was not performed, a surface mesh would have been generated on each of the colored surfaces in the image on the left. In the image on the right, the geometrical surfaces were assembled into large quilts that, in turn, defined the boundaries of the surface meshes generated later on for the HL-CRM.



Figure 4. The HL-CRM geometry is shaded to represent the surface mesh topology defined on the geometry level before (left) and after (right) quilt assembly.

## **IV.** Mesh Generation

### A. Gridding Guidelines

The goal for this study was to create baseline structured multi-block, unstructured, hybrid, and hybrid overset medium meshes based on the gridding guidelines<sup>4</sup> provided by the HLPW and supplement those guidelines with current best practices. In this endeavor, the authors aspired to create high-quality meshes which could be used to generate families of meshes for the HLPW and GMW as well as to develop a thorough understanding of how those guidelines affected the ability to generate a mesh suitable for the purposes of the workshops. The authors created meshes based on the guidelines and asked themselves these questions during the process:

- Can all guidelines be followed? If not, which ones and why?
- Should there be additional guidelines?
- Were the guidelines provided appropriate for the types of meshes generated?

The lessons learned are provided in this paper with the aim of helping shape mesh generation guidelines and best practices for future workshops and/or meshes for this particular application area. A review of the guidelines is necessary prior to discussion of the mesh generation process and will be covered in the following sections.

For all mesh types there were several parameters the meshes needed to meet dependent on what meshing level was being constructed. The farfield surface mesh location was specified to be 100  $C_{REF}$  from the body where  $C_{REF}$  for the HL-CRM measured 275.8 in. Surface cell sizes near the body nose and tail were requested to be approximately 1.0%  $C_{REF}$ . The chordwise spacing at the leading and trailing edges were set to be approximately 0.1% of the local device chord measured for each element (slat, wing, and flaps). Spanwise spacing at the root and tips were requested to be 0.1% of the semispan. Finally, the number of cells/points across the trailing edge was set based on the mesh level being generated. The coarse, medium, fine, and extra-fine mesh levels were expected to have 4, 8, 12, and 16 cells across the trailing edges respectively.

In the volume, meshes were recommended to have at least 2 layers of constant cell spacing normal to the viscous walls and to use scaled stretch ratios in the boundary layer region across mesh family levels without exceeding a value of 1.25. The stretching ratio, or growth rate (GR), calculation for each successively refined mesh could be calculated according to Eq. (1) where F is the approximate factor increase in mesh size in the normal direction and n increased for each successively finer mesh according to:

Growth Rate = 
$$GR_1^{\frac{1}{F^n}}$$
 (1)

For the purposes of the HLPW, *F* was approximately equal to 1.5. This resulted in a recommended set of growth rates of 1.25, 1.16, 1.1, and 1.07 for the coarse, medium, fine, and extra fine mesh levels respectively. The total mesh size was expected to grow by a factor of 3 between each level. For structured meshes, this translated into an increase in mesh size of *F* in each coordinate direction while maintaining a multi-griddable number of cells in the mesh. As with the growth rate and total mesh size, the y+ at the walls which controlled the initial wall spacing,  $\Delta y$ , was supposed to vary for each mesh level as well (see Table 1).

Tuble 1. Require	a y i una Ly vulues	by mean level		
Mesh Level	<b>y</b> +	Δy (in)		
Coarse	1	0.00175		
Medium	2/3	0.00117		
Fine	4/9	0.00078		
Extra-Fine	8/27	0.00052		

Table 1. Required y+ and  $\Delta y$  values by mesh level

Additional recommendations for the volume mesh included providing extra refinement in the wake regions (with flow aligned cells if possible). Of special interest was the region behind the slat and the main wing element due to the potential for interaction between the boundary layer and the convection and diffusion of wakes from upstream elements<sup>4</sup>.

#### **B.** Unstructured and Hybrid Mesh Generation

Creation of an initial triangular surface mesh on the processed geometry was performed using an automated tool within Pointwise based on an average equilateral edge length of 2.758 (1% of  $C_{REF}$ ). Additionally structured surface meshes were created and diagonalized to create 8 consistent triangular cells across the TE down the entire span of each element. Modifications were made to spanwise spacings at the root and tip as well as chordwise spacings at the

leading and trailing edges of each element to comply with the gridding guidelines described in the previous section (see Table 2).

Spacing Location	Local	Spacing	Element	Spacing
	Chord	(0.1% Local Chord)	Semispan	(0.1% Semispan)
Slat Tip LE/TE	20.88	0.0208		
Slat Root LE/TE	36.04	0.0360		
Wing Tip LE/TE	107.635	0.1076		
Wing Root LE/TE	426.73	0.427		
Inboard Flap Tip LE/TE	71.42	0.07142		
Inboard Flap Root LE/TE	71.22	0.07122		
Outboard Flap Tip LE/TE	50.75	0.05075		
Outboard Flap Root LE/TE	70.41	0.07041		
Slat Span Tip/Root			972.48389	0.9724
Wing Span Tip/Root			1036.7165	1.0367
Inboard & Outboard			712.78787	0.7128
Flap Span Tip/Root				

Table 2. Spanwise/chordwise spacings were calculated from the gridding guidelines for the medium mesh.

A review of the surface mesh quality after application of the gridding guidelines focused first on triangular cell area ratios. The highest area ratio cells occurred in the slat tip, outboard region of the WUSS, and around all element trailing edges. In the slat tip and outboard WUSS regions, the high area ratios were due to coarsely discretized surface meshes. Refining the discretization of the slat tip and outboard WUSS to a lower average equilateral edge length of 0.75 reduced the area ratios to reasonable levels. In the trailing edge regions, the high area ratios were due to the presence of isotropic triangles neighboring the anisotropic triangles on the thin trailing edge (see Figure 5).



Figure 5. Isotropic triangles on upper/lower wing and flap surface meshes were directly adjacent to trailing edge anisotropic triangles which produced high area ratios about a critical geometric feature.

Resolving the high area ratios at the trailing edges required the application of anisotropic triangles on the upper and lower surface meshes adjacent to the trailing edge. Additionally, the spacings of these cells had to match the constant cell spacing across the TE to reduce the creation of large cell size jumps in volume cells grown off the TE. For the wing and flap, the chordwise TE spacings were set to 0.025 whereas the slat chordwise TE spacing was half that value at 0.0125 for the medium level mesh. As the mesh levels (and the number of cells required across the TE) increase, the chordwise spacings will have to be adjusted to match accordingly. This deviation from the gridding guidelines for the HL-CRM was found to be one of the most significant factors that affected overall mesh quality both in the surface mesh and in the resulting volume mesh.

Further work was required at the tip of the wing to rectify a large area ratio from the TE to the wing tip surface mesh. By reducing the spanwise spacing on the wing from the guidelines value of 1.0367 to 0.1, the area ratio at the tip was reduced from 54 to approximately 5 as seen in Figure 6.



Figure 6. A comparison of cell area ratios at the wing tip trailing edge with the recommended spanwise spacing (left) and with a reduced spacing (right) is shown.

The wing root TE also suffered from similar high area ratios with the spanwise spacings recommended by the gridding guidelines. Area ratios of up to 38.6 were found at the wing-fuselage junction; this high of a value would introduce large cell size jumps in volume cells grown off this area. By reducing the spanwise spacing from 1.0367 to 0.1, the maximum area ratio at the wing-fuselage junction was reduced to approximately 3 as seen in Figure 7. Due to comparable issues with high area ratio cells at the root and tip of the slat TE, its spanwise spacings were also reduced to 0.1 to improve the quality of these transitional regions.



Figure 7. A comparison of cell area ratios at the wing root trailing edge with the recommended spanwise spacing (left) and with a reduced spacing (right) is shown.

A review of the maximum included angles of the triangular surface meshes identified significant skewness where the WUSS connected to the wing upper and lower surface in four separate locations as shown in Figure 8.



Figure 8. Tangent mesh lines near the wing tip (left) and root (right) were problematic in four separate locations.

In these regions, the bounding curves for three surface meshes were almost tangent with an angle of  $1.17^{\circ}$ . In addition to the geometrical angle limitation, in the initial surface mesh the spacings at these locations were disparate which resulted a substantial amount of skewness in the triangular cells fit into these corners. The maximum included angle for the corner cells typically exceeded a value of  $173^{\circ}$  as seen in Figure 9. To resolve this issue, the spacings in both the chordwise and spanwise direction at this juncture had to be assigned to the same value. Additionally the first mesh points out of the corner were physically set to the same location to force a right-angle anisotropic cell out of the corner instead of a squashed anisotropic cell (see Figure 9).



Figure 9. A close-up view of tangent mesh lines identified in Figure 8 is shown. Highly skewed triangular surface cells (left) were found and corrected (right) in the WUSS - Wing surface mesh junction.

In the WUSS-wing juncture seen in Figure 9, an additional quality issue existed because the cells had a very high area ratio of approximately 100. This, like the small included angle, was considered a geometrical limitation as refining the mesh to reduce the area ratio to reasonable levels would produce a mesh that would be impractical in size. High surface mesh area ratios can translate into high volume ratios in the anisotropic boundary layer region and beyond which can be undesirable to some CFD solvers. In this case, the high area ratios in the corner did translate into volume cell size ratios of over 100 once anisotropic tetrahedra were marched off the surface for the boundary layer mesh.

Once surface mesh quality and adherence to surface meshing guidelines was met, a comparison of surface meshes across gap regions was performed. The viscous boundary layer mesh is a product of the T-Rex anisotropic meshing algorithm<sup>5</sup> which advances points on the surface front. In gap regions, colliding fronts must be stopped locally with the region between fronts filled by a modified Delaunay mesh. In order to preserve mesh quality in the gap regions, the surface mesh on colliding fronts must be compatible, i.e., of similar grid density. There were several gap areas which could potentially be affected:

- Inboard flap and fuselage gap [Figure 10(a), Figure 11(a)]
- Inboard and outboard flap gap [Figure 10(b), Figure 11(b)]
- Inboard/outboard flap leading edges and the wing over flap surfaces (WOFS) [Figure 10(c), Figure 11(c)]
- Outboard flap and wing gap [Figure 10(d), Figure 11(d)]
- Slat trailing edge and WUSS [Figure 10(e), Figure 11(e)]



Figure 10. A top down view of all gaps that required special surface mesh treatment are shown. Surface mesh lines are not shown for increased visibility.



Figure 11. Certain gaps in the geometry required special treatment of the surface meshes in those regions. Close-ups are provided of each gap.

In the regions illustrated in Figure 11, if the surface meshes across the gap did not have similar or identical distribution of points and thus cell sizes, the resulting boundary layer mesh grown into the gap region would have dissimilar cell sizes and locations introducing skewness into the isotropic region between the growing fronts.

Different techniques were used in the gaps to improve point and cell matching depending in the situation at hand. In the inboard flap root and fuselage gap shown in Figure 11(a), the flap root surface mesh point distributions were copied and replicated in the fuselage surface mesh directly across the gap. The resulting surface meshes were not identical across the gap but the variation in maximum cell size was < 7%. Minimum cell size was not compared between the surface meshes because the values ranged from  $1.9e10^{-4}$  to  $2.2e10^{-4}$  and existed predominantly at the TE where the gap was on the order of 26 inches wide. At these values, the growth of volume cells off the surface meshes in this region would stop locally due to isotropy long before the fronts met in the gap region.

The inboard flap tip and the outboard flap root surface meshes shown in Figure 11(b) were similar but not identical in shape. To ensure that the meshes had similar characteristics, the mesh point distributions, the average cell edge lengths, and the maximum allowable cell edge length were matched between the two meshes. The resulting surface meshes had a variation in maximum cell size of approximately 12%. This same technique was used to address the outboard flap tip and wing surface meshes seen in Figure 11(d).

Initial treatment of the surface meshes in Figure 11(c) and (e) involved growing anisotropic triangles off the LE of each element with the chordwise spacing specified in the gridding guidelines. The triangular cells were grown with a growth rate, or stretching ratio, of 30% and then compared to the surface mesh across the gap. With these parameters, the surface meshes across the gaps had the largest disparities in shape, orientation, and cell size. Most of the disparity in cell size was due to the number of cells required across the TEs of each element. Cells on each TE were equally spaced and had an average vertical spacing of 0.025 and 0.0125 for the wing and slat respectively. The cells on the elements behind the TEs typically had much larger cell sizes (70x larger between slat TE and WUSS) and shapes (anisotropic vs. isotropic triangles) which would have led to significant volume cell skewness being generated in the gap regions. Since the number of cells across the TEs was a fixed requirement, the most reasonable solution available was to modify how the leading edges of the WUSS and flaps were meshed to reduce the difference in cell size and shape. Anisotropic triangles were grown further in the chordwise direction from the LE of both the WUSS and the flaps by reducing their growth rate to 5%. This created layers of cells that were the same shape (anisotropic triangles) of the TE cells and were closer in average cell size. In the case of the slat TE and the WUSS, their gap surface meshes average cell size difference was reduced from a factor of 70 to 18. A cell size difference of 18x was not ideal but was felt to be sufficient for the simulation. Similar results were seen for the wing TE and flap LE surface mesh modifications.

Once the surface mesh modifications were complete, the T-Rex meshing algorithm was used to generate layers of tetrahedra from the completed surface mesh based on several key parameters for the medium-level mesh. All HL-CRM surface meshes were selected to grow anisotropic layers of tetrahedra in the boundary layer with an initial wall spacing of 0.00117. The gridding guidelines requested two constant layers of cells immediately off the wall in the boundary layer region. For these meshes, this requirement could not be met and a geometric growth rate of 1.16 was applied from the first cell off the wall. Cell advancement stopped locally when isotropy was reached, a collision with the advancing cell and an approaching front or boundary occurred, if the advancing cell's dihedral or faces contained a maximum included angle greater than 175°, or if neighboring cells had stopped locally in the previous layers and continued advancement of the current cell would introduce skewness. Cells which had not achieved isotropy and stopped advancing because of a collision or the non-advancement of neighboring cells had one additional layer of vertices (not cells) advanced into the volume past the point of the last cell. This additional set of vertices acted as seed points for the isotropic tetrahedra that were used to fill the remainder of the mesh volume about the HL-CRM. Adding seed points to a volume in gap/collision regions in this manner served to reduce volume ratio jumps from the anisotropic layers to the isotropic tetrahedra beyond them as well as providing additional refinement in the gaps.

A source, seen in Figure 12, was created in a swept rectangular region about the wing and through the wake region to provide additional isotropic tetrahedral refinement<sup>6</sup> in this area of interest.

![](_page_9_Picture_0.jpeg)

# Figure 12. A source was created over the wing and through the wake region to provide additional isotropic tetrahedral refinement in the volume mesh.

The source shape used a constant cell sizing throughout the specified shape based on the largest surface cell size on the wing element. Side and top views of the additional isotropic tetrahedral refinement from the source can be seen in volumetric mesh cuts in Figure 13 and Figure 14. Mesh cuts were also taken at constant Y locations along the wing span as illustrated in Figure 15 to show the refinement about the slat, wing, and flap elements as well as the boundary layer mesh grown about them for the unstructured mesh seen in Figure 16 through Figure 18.

![](_page_9_Picture_3.jpeg)

Figure 13. A side view of the HL-CRM illustrates the isotropic tetrahedral refinement from the source.

![](_page_9_Figure_5.jpeg)

Figure 14. A top down view of the HL-CRM illustrates the isotropic tetrahedral refinement from the source.

![](_page_10_Figure_0.jpeg)

Figure 15. Three constant Y locations were chosen along the wing span for mesh cuts.

![](_page_10_Figure_2.jpeg)

Figure 16. Two views of the unstructured mesh about the flap are shown at constant Y cuts for the medium HL-CRM mesh.

![](_page_10_Figure_4.jpeg)

Figure 17. Three views of the unstructured mesh about the wing are shown at constant Y cuts for the medium HL-CRM mesh.

![](_page_10_Figure_6.jpeg)

Figure 18. Three views of the unstructured mesh about the slat are shown at constant Y cuts for the medium HL-CRM mesh.

A second type of medium mesh was created by combining anisotropic tetrahedra in the boundary layer into prisms to produce a hybrid mesh containing prisms, pyramids, and tetrahedra<sup>7</sup>. Mesh cuts at constant Y locations were taken to show the distribution of cell types within the resulting hybrid mesh seen in Figure 19 through Figure 21.

![](_page_11_Picture_1.jpeg)

Figure 19. Two views of the hybrid mesh about the flap are shown at constant Y cuts for the medium HL-CRM mesh. Prisms, pyramids, and tetrahedra are displayed in green, yellow, and red respectively.

![](_page_11_Figure_3.jpeg)

Figure 20. Three views of the hybrid mesh about the wing are shown at constant Y cuts for the medium HL-CRM mesh. Prisms, pyramids, and tetrahedra are displayed in green, yellow, and red respectively.

![](_page_11_Figure_5.jpeg)

Figure 21. Three views of the hybrid mesh about the slat are shown at constant Y cuts for the medium HL-CRM mesh. Prisms, pyramids, and tetrahedra are displayed in green, yellow, and red respectively.

Final medium meshes were produced for the HL-CRM with approximately 28.4 million points for both the unstructured and hybrid mesh types. For the unstructured mesh, this translated to 168,637,521 tetrahedra. The hybrid mesh, a derivative of the unstructured mesh, had 81,190,078 cells (52% fewer total cells). Of those cells 53% were prisms created in the boundary layer region, 46.2% were tetrahedra created in the remainder of the volume mesh, and 0.8% were pyramids used to transition from exposed quads on partial prism layers to the tetrahedral volume.

### C. Hybrid Overset Generation

A hybrid overset mesh was created starting with the contiguous hybrid mesh described in IV.B. The contiguous hybrid mesh was segregated into near-body and off-body regions at a user-specified distance from the solid boundaries. For this example, the near-body mesh was defined to be within a distance of 275.8 (100% of  $C_{REF}$ ) from the geometry. The near-body and off-body regions of the hybrid mesh are illustrated in Figure 22.

![](_page_12_Picture_0.jpeg)

Figure 22. Near-body and off-body regions within the hybrid unstructured mesh were defined by a distance of  $C_{REF}$  from the geometry.

The off-body region of the hybrid mesh was removed and replaced by an automated hierarchical unstructured meshing process termed voxel meshing. The hierarchical meshing process, described in work by Karman, runs in a transformed Cartesian space<sup>8</sup>. Voxel meshing requires minimal user input consisting of a Cartesian bounding box and the maximum voxel size. Settings for this example were a bounding box of 57000 x 27500 x 55000 centered on the HL-CRM geometry and a maximum voxel size of 2500. An appropriate overset interpolation stencil between the nearbody hybrid mesh and the off-body voxel mesh was achieved by prescribing the boundary faces of the nearbody mesh as adaptation input to the hierarchical meshing process. Adaptation input faces need not be closed manifold topology as the hierarchical mesh fills the prescribed Cartesian space. The mesh size source (described above) aft of the wing provided further adaptation input. The *buffer\_layers* input parameter to the hierarchical subdivision process, set to 10 for this example, limited refinement level transition rate thereby ensuring smooth gradation of the hierarchical mesh and providing required overlap at the overset interpolation region. An optional post-processing step converted the hanging-node hierarchical mesh into a fully-connected unstructured mesh of tetrahedron, pyramid, and hexahedron elements for use with general unstructured mesh flow solvers.

![](_page_13_Picture_0.jpeg)

Figure 23. A cut through the off-body hierarchical mesh. The zoomed-out view (top) and zoomed-in view (bottom) illustrate mesh adaptation to the near-body mesh and mesh size source aft of the wing.

Overset grid assembly cuts away the portion of the off-body mesh inside the model and computes the stencil for interpolation between meshes. Overset grid assembly for the HL-CRM model was conducted within the Pointwise application through integration with Suggar++, a general purpose overset grid assembly software package<sup>9</sup>. The direct cut approach to hole cutting and overlap minimization capabilities of Suggar++ significantly reduce user interaction in the assembly process<sup>10</sup>. In addition to overset assembly definition, the integrated application allowed for visual inspection of the assembled composite mesh. Figure 24 and Figure 25 illustrate the overset interpolation fringe and donor cells used to connect the near-body and off-body meshes in the flow solver.

The overset composite mesh consisted of 51,601,882 cells, 80% of which are triangular prisms, in the near-body component mesh and 33,024,114 cells, 75% of which are hexahedra, in the off-body component mesh. Overset

assembly marked 14,908,437 hole cells inactive and 394,012 fringe cells for interpolation resulting in 69,323,547 active cells.

![](_page_14_Figure_1.jpeg)

Figure 24. Overset interpolation fringe cells (yellow) and respective donor cells (red) are shown on the nearbody mesh at ~30% span

![](_page_14_Figure_3.jpeg)

Figure 25. Overset interpolation fringe cells (yellow) and respective donor cells (red) are shown on the off-body mesh at ~30% span.

### **D. Structured Multi-Block Mesh Generation**

The baseline structured multi-block mesh was created with a total of 194 volume regions containing a total of 32,076,492 cells and 33,839,223 points. The overall topology that was constructed for the mesh as well as the topology immediately about the aircraft can be seen in Figure 26.

![](_page_15_Figure_2.jpeg)

Figure 26. The multi-block structured mesh topology is illustrated in an isometric view (left) and a close-up view (right).

For the creation of the structured multi-block mesh, the IGES CAD geometry was imported into Pointwise and meshed by a procedure different than the one previously described in III. On import, the trimmed surfaces in the CAD were promoted to quilt entities within Pointwise. As previously described, quilts are subsets of a larger solid model, and in Pointwise, represent meshing regions. This feature tends to be more useful for unstructured meshing, as in structured topologies, the mesh substantially will not have the same topology as the geometry. Therefore while there will be some match between the geometry topology and the mesh, much of the mesh boundaries will be defined by other constraints in order to define the regular computationally rectangular regions required in a structured mesh.

While generating mesh curves for the topology in the medium structured mesh, a number of surfaces in the geometry produced multiple mesh curves along a surface edge where one mesh curve was expected. Pointwise's automated tool for mesh curve creation on CAD geometry produced parametrically defined mesh curves which were continuously shaped identically to the underlying surface in the geometry. For a large number of surfaces in the provided geometry file, many more mesh curves were created along what appeared to be single surface edges than was expected.

Further information on the origin of the surfaces is necessary to pinpoint exactly why they contained multiple curves along an edge instead of one, however the most common reason for this issue is that the trimmed surfaces in the geometry file were created originally as a composite of many smaller surfaces. Therefore the fundamental definition of the surfaces contained subsets or breaks both in the surface and its edges. The end result for a parametric mesh curve creation algorithm will unfortunately be multiple mesh curves per surface edge as was experienced with the HL-CRM geometry file and as seen in Figure 27.

![](_page_16_Figure_0.jpeg)

Figure 27. A view of the outboard flap with multiple mesh curves per surface edge (left) is shown with a closeup of the mesh curves at the outboard flap tip (right).

While this result was unexpected, it was not necessarily a problem, but more of a nuisance during the meshing process. For a single surface in the geometry, 66 total mesh curves were returned where the expectation would normally be 4, one per edge. To resolve the issue, all mesh curves were created on the HL-CRM surfaces with an automatic joining option to create one mesh curve per edge. If the bending angle between adjacent mesh curves on an edge was less than 45°, those mesh curves were joined into one curve.

Aside from the surfaces which produced multiple mesh curves along an edge, only one other significant geometry concern arose for this mesh. The surface at the nose of the fuselage had a singularity in it at an xyz location of (92.5, 0.0, 198.0). Creating a parametrically defined mesh on this surface would result in mesh lines spreading undesirably after transfinite interpolation (TFI), the algebraic method used to initialize structured surfaces and volumes, was applied. However, this phenomenon was easily addressed by running Pointwise's structured partial differential equation (PDE) solver<sup>11</sup> on the surface mesh to smooth and restore the desired interior distribution as shown in Figure 28.

![](_page_16_Figure_4.jpeg)

Figure 28. An illustration of the parametric distortion of the surface mesh on the fuselage nose before (left) and after (right) being smoothed in Pointwise's elliptic PDE solver.

The geometry provided a number of features which were challenging to mesh from a topological standpoint. One feature was unrealistic and was best meshed with some slight modification made via the mesh topology itself rather than attempting to make modifications to the geometry. In general, use of creative mesh topology will allow all of these more difficult features to be resolved properly. However local clustering requirements and producing a smooth mesh required care in shaping the topology and distributing the mesh curves.

In the geometrical definition for the WUSS, shown in Figure 29, an unrealistically narrow surface was included that would not typically be produced for an as-built vehicle.

![](_page_17_Picture_0.jpeg)

Figure 29. A view of the surface adjacent to the WUSS which narrows down to a singularity in the geometry.

Additionally such a narrow feature undesirably compressed all surface meshes created on it, reaching near singularity proximity of local mesh points. Approaches to deal with such a situation in the geometry were to collapse the surface and treat it as a true singularity in the mesh or to expand the width of the surface slightly to make it more realistic and more easily meshed. Unfortunately, while mesh singularities are very easy to create, they are generally unfavorable in most flow solvers, particularly those which are fully structured. Therefore this feature of the geometry was addressed in the mesh by moving it slightly forward via the mesh topology shown in Figure 30. This produced a more mesh friendly feature which should also run better in flow solvers. The downside to this type of topological manipulation is that it did alter the geometry slightly, and a very small portion of the upper wing surface meshes adjacent to the feature no longer resided on the underlying geometry. The local shape of these surface mesh points were defined by a simple free space TFI. This result was easily achieved, while maintaining the remainder of the surface meshe.

![](_page_17_Picture_3.jpeg)

Figure 30. A topology change to move the base surface forward allowed the creation of a higher quality mesh without modification of the geometry.

Other challenging features to mesh were a result of the extended slat and flaps prominent in the high-lift configuration. Particularly of note are the gaps between slat and wing, both behind the slat and at the ends. And also of course the gaps between flaps, at the ends of the flaps and between the flaps and wing. Of these features, two in particular drove the layout of topology all along the spanwise length of both the flaps and the slat. Near the tip of the wing there was a gap between the slat and the WUSS. However, there was also an overlap of the slat TE and the innermost surface of the WUSS. In order to produce a smooth, controlled mesh, a very small volume mesh was required between the overlapping outboard surface of the slat TE and the inner side surface of the WUSS as illustrated in Figure 31.

![](_page_18_Picture_0.jpeg)

Figure 31. A small gap block was required to fill the area between the outboard slat TE surface and the inner side surface of the WUSS.

Additionally all surfaces required the near wall spacing in the gridding guidelines from IV.A., so mesh curves were necessary to control spacings adjacent to all surfaces. Because of the structured multi-block meshing restriction to keep all surface meshes and associated volume meshes computationally rectangular, this topology had to propagate the spanwise length of the slat to the inboard end, finally ending on the adjacent surfaces of the fuselage. Careful copying of the original topology and its shape was employed to maintain a quality mesh. A mixture of automated and manual techniques were used to perform this propagation which took a considerable amount of effort to complete.

Likewise, at the outboard gap between the flap and the wing, shown in Figure 32, there is a similar overlap where the root of the flap slightly overlaps the side of the wing cutout. Again, this situation required a unique local topology which persisted inboard along the spanwise length of both flaps, ending on the surface of the fuselage. As with the slat topology on the front of the wing, this topology had to be copied and modified to fit at other locations, for instance, at the gap between the inboard and outboard flaps, or it had to be recreated directly. Since there was a significant orientation change relative to the wing, much of the topology was best created directly instead of copied from other locations.

![](_page_18_Picture_4.jpeg)

Figure 32. A small gap block was required to fill the area between the outboard flap surface and an inner rear wing surface.

At the root of the wing there was a lesser meshing challenge where the gap between the inboard flap and fuselage varied widely in distance. Here the topology was relatively straightforward. However, it did include some of the topology transferred from the above described outboard gap overlap. The primary solution in this region was to overcluster the smaller portion of the gap so that the larger gap between the flap TE and the fuselage had sufficient mesh points to resolve the gap and appropriate clustering as shown in Figure 33.

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![](_page_19_Picture_0.jpeg)

Figure 33. An expanding gap block was used to fill the region between the inboard flap and the fuselage.

The proximity of both the flaps and slat to the wing, and their local geometric shapes introduced their own challenges in creating reasonable orthogonal topologies that also allowed control of the local wall clustering. Curvature of the pressure side of the slat also warranted special treatment with a local O-H style of topology shown in Figure 34.

![](_page_19_Figure_3.jpeg)

Figure 34. An O-H topology was used behind the slat in front of the wing.

Tips of wings and other control surfaces introduce complexity into the meshing process on a realistic geometry such as the HL-CRM. Traditionally, these regions are treated with a simple H style topology, an O-H style, or even sometimes with singularities, or poles, at the LE and TE. The choice of topology for these tips is usually dictated by the shape of the control surface and whether it has a sharp or blunt trailing edge, or base. Sometimes the choice of eventual flow solver can also direct the topology used on these features, among others. For this mesh, complexity elsewhere, particularly at the LE of the wing and slat, warranted keeping the tip topology as simple as possible. Therefore a simple H style surface mesh was applied as shown in Figure 35.

![](_page_19_Figure_6.jpeg)

Figure 35. An H style topology was used on the wing tip.

Furthermore, for also for simplicity and efficiency in meshing, much of the topology from the slat-wing gap was copied directly, transferred to the tip and modified to fit locally. Afterward, this updated tip topology was then again copied outboard, perpendicular to the tip, to provide quick, easy topology to block in the wing tip area and provide clustering to the tip. As in other areas of the geometry where there was significant local curvature in the geometry,

conic mesh curves were used in abundance traversing from the wing tip outboard so that they could be attached to the boundaries of the tip in as normal a fashion as possible as shown in Figure 36.

![](_page_20_Figure_1.jpeg)

Figure 36. Conic mesh curves were used in the wing tip topology to maintain orthogonality at the surface.

Final challenge areas which commonly exist in airframe geometries appeared at the nose and tail of the fuselage. For conical shaped geometry such as the nose of this fuselage, the easiest topology was a pole. However, as previously mentioned, many solvers do not perform well when singularities are included in the mesh. For this case, a common solution was applied where a rectangular surface mesh was applied to the nose itself while the remaining topology of the mesh wrapped around this in an O style fashion. Once understood and used in experience this topology is not overly challenging, but does not necessarily present itself immediately to a newcomer in the meshing field. As in the previous discussion of work on the wing tip, here conic mesh curves were heavily used to provide shaping orthogonal to the nose while still transitioning to a topology moving forward from the airframe as shown in Figure 37.

![](_page_20_Figure_4.jpeg)

Figure 37. An O-H style topology was created at the fuselage nose and propagated to the farfield.

The tail of the fuselage geometry presented its own unique challenges since it transitioned to a sharp vertical edge with a low angle relative to the symmetry plane. In order to keep the topology as simple as possible, here again the same O-H style implemented at the nose was also created, with care taken in regards to the distribution of points to the vertical mesh curve at the very tail and those attached to it above and below along the symmetry boundary as seen in Figure 38. While there is bound to be cell skewing as the tail nears the symmetry plane, over all this topology produced reasonable quality cells suitable for this location in the geometry relative to the focus of a flow solution.

![](_page_21_Figure_0.jpeg)

### Figure 38. An O-H style topology was used at the tail of the fuselage and propagated to the farfield.

While there are a number of areas in this mesh that can be discussed, one final area which should be covered is the volume meshes. Maintaining the mesh requirements, particularly wall spacing, while also managing over all cell and point count, introduced some point distribution issues on the interior of volume meshes. The initialization used for all structured volumes was the same TFI method used for unconstrained surface meshes. Generally it produced very good, orthogonal mesh quality. However distribution changes from one side to another of a volume mesh, while maintaining the guideline medium mesh wall spacing of 0.00117, caused some cells in the near wall layer to skew.

This is a prime example of where Pointwise's structured elliptic PDE solver came into play and locally remediated skewing and improved wall orthogonality without the need to adjust or add additional topology. Where necessary, skewed cells were improved with just a few iterations in the elliptic PDE solver with a Steger-Sorenson boundary control function<sup>12</sup> used to control orthogonality and spacing at the wall.

### V. Conclusions and Future Work

A set of medium baseline meshes has been generated for consideration in the 3<sup>rd</sup> High Lift Prediction Workshop and the 1<sup>st</sup> Geometry and Mesh Generation Workshop. During the mesh generation process for each type of mesh, the gridding guidelines for the HLPW were applied then evaluated to determine if they could all be followed, if additional guidelines were necessary, and if mesh type affected adherence to certain guidelines.

For the development of the unstructured, hybrid, and hybrid overset meshes, it was determined that the specification of the number of points across the trailing edges of the mesh as well as the spacings required in the chordwise and spanwise direction produced a surface mesh with undesirably high area ratios. From meshing experience, high area ratios in unstructured and hybrid meshes can lead to high volume ratios as well as volume cell skewness. For future gridding guidelines, requiring the number of cells and/or points across the trailing edge should either take precedence over the specification of chordwise and spanwise spacings or eradicate those requirements completely in an effort to produce smoother meshes with more reasonable area ratios at critical features in the geometry. Additionally, treatment of the gap regions for a high-lift configuration containing slats, wing, and flaps posed challenges on the meshing front related to reducing differences in surface meshes across the gaps. Techniques were applied that resulted in a high-quality mesh in these regions but more work could be done in the meshing arena to automate this process. Further study involving the use of these meshes in simulations for the HLPW is required to determine if the lack of this gridding guidelines requirement affects results with any significance.

For the development of the structured multi-block mesh, the primary focus from the guidelines was placed on accurate representation of the geometry and the medium level mesh wall spacing requirement of 0.00117 inches. Post processing of the mesh has revealed areas of deviation from the specified wall spacing requirement. These areas may be a result of spacing enforcement improperly applied, or could be a result of elliptic smoothing pulling points away from wall boundaries on the interior of a surface or volume mesh. This finding warrants further investigation during future revisions of the baseline mesh. While focusing on wall spacing and mesh distribution in general, the structured mesh guideline requirement for a multi-grid compliant mesh was not met. This requirement in the dimensioning of the mesh volumes will be the focus of the next revision of the mesh. Finally, qualitative review of the surface meshes has indicated they may be too coarse along the span and chord of the wing, and that skewing of the cell topology in the wing surface meshes is a concern. The latter is a result of gridline clustering flowing from the slat-wing gap at the wing tip LE to the flap-wing outboard gap at the wing TE. This type of skewing is not uncommon for these types of

features in a structured mesh. However, the skewing could be mitigated by an increase in number of grid points and additional topology. These types of changes may tend to occur naturally as a result of making the mesh multi-grid compliant. However, for the structured mesh, the guidelines might be enhanced with more specific requirements regarding this type of skewing of quadrilaterals in the interior of a surface mesh and their relative alignment with the flow direction and/or geometry.

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