Computational fluid dynamics (CFD) plays an important role in the design and development of a vast array of aerospace vehicles, from commercial transports to space systems. With the ever-increasing computational power, usage of higher fidelity, fast CFD tools and processes will significantly improve the aerodynamic performance of airframe and propulsion systems, as well as greatly reduce nonrecurring costs associated with ground-based and flight testing. Historically, the growth of CFD accuracy has allowed NASA and other organizations, including commercial companies, to reduce wind tunnel and single-engine component tests. Going forward, increased CFD fidelity for complete vehicle or engine configurations holds the promise of significantly reducing development costs, by enabling certification by analysis. Confidence in fast, accurate CFD and multidisciplinary analysis tools allow engineers to reach out of their existing design space and accelerate technology maturation schedules. Uncertainty quantification is a key technology in enhancing confidence in the prediction capability of the computational tools. NASA’s CFD Vision 2030 Study (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf) highlighted the many shortcomings in the existing computational technologies used for conducting high-fidelity simulations, including multidisciplinary analysis and optimization, and made specific recommendations for investments necessary to overcome these challenges.

High-quality mesh generation was recognized by the Vision Study as a bottleneck in the CFD workflow as it impacts both the solution accuracy and the time to solution.
Therefore, improved mesh technology is a continued need for high-fidelity simulations and proposals are solicited in two focused areas related to the overall grid generation theme. First, adaptive mesh capabilities have been very successful in unstructured and Cartesian grid paradigms, but application to structured overset grids have been limited to mesh refinement based on solution gradients which leads to too many grid points for full-scale three-dimensional configurations. Mesh redistribution algorithms use a fixed number of grid points, and locally refine (and coarsen) the mesh to equally distribute the error. This allows the "best" solution for a fixed computation cost with respect to the defined error metric. Adaptive mesh redistribution algorithms are needed for structured overlapping grids that are robust in that given a valid structured overlapping grid system with no negative volumes, no orphan points, and a valid error-metric field, the redistributed mesh must also have no negative volumes and no orphans. The error metrics need to be based on solution and geometric gradients, solution Hessian, and adjoint-based error measures for achieving accurate lift and drag, pressure signatures, resolved turbulent kinetic energy, etc. These error-metric fields should be able to be read in and/or computed internally from an existing CFD solution. The error metric should be relevant to the CFD analysis being performed and the redistributed mesh should minimize the error with respect to the chosen metric. Finally, the cost of the redistribution algorithm (excluding the computation of the error-metric field in the case of an adjoint-based error metric) should only be a small percentage of the cost of a steady-state Reynolds-averaged Navier-Stokes (RANS) CFD solve on the structured overlapping grid being analyzed, less than 10%. Many private companies utilize NASA-structured overset grid tools such as Chimera Grid Tools and OVERFLOW, and several mesh generation software companies continue to develop and enhance their own structured grid generation capabilities. The addition of a solution- (or adjoint-) based adaptive mesh redistribution software package will have a large impact on reducing the generation of accurate overset grids, database generation, reduce uncertainty in computed solutions, and provide quantitative measures of solution error. This will impact the quality of CFD analysis being performed and lead to better products by industry.

The second focused grid-related area for which proposals are being solicited is automated and scalable mesh generation for wall-modeled large eddy simulations (WMLES). Unstructured approaches can be used to discretize highly complex flow configurations but, in addition to automation, there is a need to generate the mesh robustly and efficiently regardless of geometric complexity. The mesh quality aspect is especially critical for scale resolving simulations where numerical methods benefit significantly from element regularity and alignment. The goal of the solicited work is to encourage development of such mesh generation software that can be interfaced and integrated with NASA CFD solvers. The requirements for the solicited mesh software include: (1) it should be able to efficiently handle arbitrarily complex geometries; (2) the software should be message passing interface (MPI) parallel, scalable to billion+ cell meshes as are typical for NASA applications; (3) the mesh generation process needs to take a water-tight bounding volume definition as input, where the surface of the
Bounding volume can be marked with prescribed mesh resolution(s), in addition to any user prescribed volume refinement metrics (such as adjoint-based error metrics, prescribed volumes, etc.). Such mesh technology has the potential to drastically improve turn-around time for scale resolving simulations for complex configurations and enabling wider use of high-fidelity CFD analysis for challenging turbulent flow problems. This research effort is expected to enable NASA solvers to interface with the resulting tool. The meshing tool should be designed to perform well on the emerging high-performance computing hardware. An additional area of research may include adaptive mesh refinement while a WMLES is progressing.

Another focused area of research and development within this subtopic is the prediction of aeroelastic effects with uncertainty quantification. Application of computational aeroelastic simulations involving complex flow fields (e.g., flow separation) toward practical engineering applications is hindered by many factors beyond the large computational cost. The large volume of output data must be postprocessed nondeterministically, and new data-based methods are required to adequately understand the output, and further draw connections between the flow and events/mechanisms of interest, such as aeroelastic flutter. These methods may include machine learning, nonlinear transforms, classical parameters indicative of flutter onset (e.g., aerodynamic center location and generalized aerodynamic forces), higher-order statistical characterizations, etc. In addition to statistical flow outputs, the inputs to the flow simulations are often uncertain as well; methods are then required to propagate these uncertainties through the flow simulation in a cost-effective manner, and properly accommodate the uncertainties in the data-driven postprocessing methods. A possible and desired outcome is a toolbox of nonintrusive software that wraps around aeroelastic CFD simulations. Included in the envisioned work and products are uncertainty quantification- (UQ-) based postprocessing tools that would serve to guide an analysis team to characterize flutter onset (among other aeroelastic phenomena) in a nondeterministic manner. Phase I demonstrations of the UQ methodologies and tools on a single NASA-FUN3D flutter problem are desired. Phase II efforts would require more complete development of an automated and user-friendly toolbox. The awardees could then wrap the developed UQ tools around other CFD/aeroelastic solvers for commercialization.

In summary, proposals are being solicited in the above three focused areas under this subtopic. Successful awardees in all three research areas should note that it is NASA’s intention to use developed software tools with NASA’s CFD solvers. Therefore, fully functional application programming interfaces (APIs) will be required as deliverables.

**Expected TRL or TRL Range at completion of the Project:** 3 to 6

**Primary Technology Taxonomy:**
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Software
- Research
- Analysis

Desired Deliverables Description:

For focused area 1, the suggested research and development (including deliverable) during Phase I and II include:

Phase I:

- Single-zone demonstrations using airfoil geometry for O-grid or C-grid topologies with precomputed error-metric scalar/vector fields.
- Structured multiblock (without overset) grid for wing geometry.
- Structured overset grids for the wing geometry.
- Demonstrate capability of grid redistribution with up to 200 million grid cells within 20 minutes of wall-clock time.
- Provide an executable or an API for independent assessment by NASA teams.

Phase II:

- Collaborate with NASA team to develop API for coupled RANS-based grid adaptation.
- Assessment on four open-source complex structured grids: (1) Drag Prediction Workshop 6 (Wing-body-nacelle-pylon), (2) nozzle with baseline ramp (5th AIAA Propulsion Aerodynamics Workshop), (3) Sonic-Boom Prediction Workshop (C608 geometry), and (4) High Lift Prediction Workshop (HLPW-4).
- Demonstrate distributed memory strong scalability on grid sizes up to 1 billion with granularity at 500,000 points per core in under 5 minutes of wall-clock time.

For focused area 2, the suggested research and development during Phase I and II include:

Phase I:

- Given a bounding surface mesh (tri/quad/poly), demonstrate fully automated body-fitted polyhedral volume mesh generation for canonical geometries as proof of concept.
- Ability to export grid in CFD General Notation System (CGNS) (version greater than 4.1) file format.
- Demonstrate required cell quality metrics:
  - For each face, vector connecting the left and right cell centroids are aligned with face normal.
  - For each face, face centroid is half-way between left and right cell centroids.
• User defined refinement criteria should allow for:
  ○ Spatially varying wall-distance specified on the surface.
  ○ Minimum cell-centroid to face-centroid distance criteria specified by the user.
• Provide executable to NASA teams for preliminary testing.

Phase II:

• Demonstrations on three complex topologies: (1) HLPW-4, (2) Benchmark for Airframe Noise Computations (BANC-4) landing gear (PDCC-NLG), and (3) Multistream Chevron nozzle (TMP17) satisfying the requirements established in Phase I.
• Performance assessment on a HLPW-4 geometry:
  ○ Demonstrate distributed memory weak scaling up to 10 billion cells at better than 10 million cells per core hour.
  ○ Demonstrate strong scaling on 10 billion cells mesh up to a granularity of 100,000 cells per core.
• Demonstrate the ability to conform to a user specified set of cell centroids.
• Develop API in collaboration with NASA CFD code developers.
• Demonstrate ability to regrid based on modified refinement criteria accessible through the API.

For focused area 3, demonstrations of the UQ methodologies and tools on a single NASA-FUN3D flutter problem are desired during Phase I. Phase II efforts would require more complete development of an automated and user-friendly toolbox.

**State of the Art and Critical Gaps:**

NASA's CFD Vision 2030 Study identified several impediments in computational technologies and this solicitation addresses one of those related to application of scale resolving simulations needed for expanding the scope of application of CFD across the aircraft flight envelope, particularly in the prediction of maximum lift.

**Relevance / Science Traceability:**

Various programs and projects of NASA missions use CFD for advanced aircraft concepts, launch vehicle design, and planetary entry vehicles. The developed technology will enable design decisions by Aeronautics Research Mission Directorate (ARMD) and Human Exploration and Operations Mission Directorate (HEOMD).

**References:**

https://www.nasa.gov/aeroresearch/programs/aavp

https://www.nasa.gov/aeroresearch/programs/tacp

NASA’s CFD Vision 2030 Study: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf