Comprehensive Exam Proposal

Moving Grids for Design CFD

Nathan Woods Ryan Starkey

Busemann Advanced Concepts Laboratory
Department of Aerospace Engineering Sciences
University of Colorado at Boulder

1 December 2011

Outline

About Me

Married Kristin Woods, 2010 Places I've lived - Georgia, Texas, Utah, Iowa, Idaho, Colorado Schools I've attended:

- Richfield High School, Richfield, Utah - 2002
- Brigham Young University, Provo, Utah - 2008, B.S. Physics
- University of Colorado, Boulder, Colorado - 2013, Ph.D. Aerospace Engineering

Research I've been involved in:

- Direct Simulation Monte Carlo (DSMC) for high-temperature gas mixtures
- Fabrication of nano-sensors for Mars missions
- Design of a miniature turbojet engine
- Development and design of far-infrared optical sensors

About Me, con't

My Interests (Technical & Otherwise):

- Theoretical & computational physics
- Complex systems & emergent behavior
- Application of advanced mathematics
- Performance home computing
- Home networking
- Running & rock climbing

Joint Strike Fighter ASTOVL Analysis

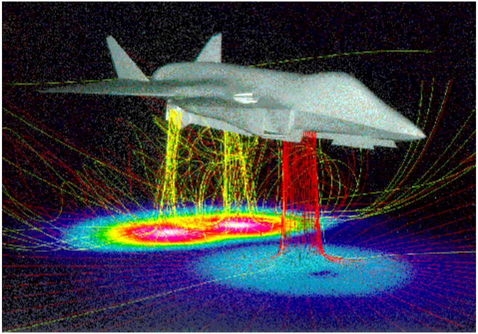


Figure: Computed streamlines of the Joint Strike Fighter B variant during vertical landing. Ground plane colored by temperature. Courtesy of Pointwise, makers of Gridgen software - http://www.pointwise.com/apps/b2jsf.shtml

Joint Strike Fighter ASTOVL Analysis

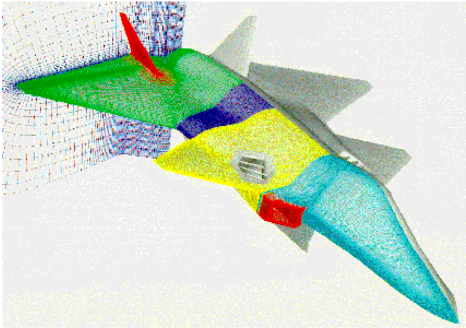


Figure: Top view of grid used in above JSF analysis, showing various structured grid blocks.

The Project Cycle

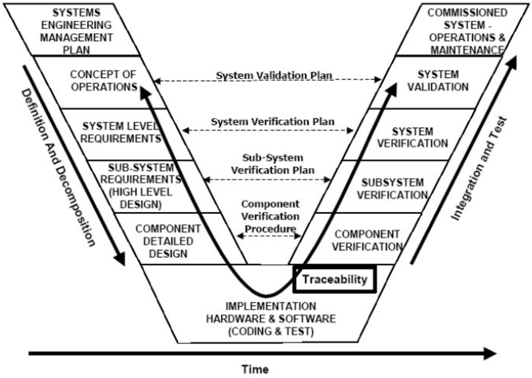


Figure: The life cycle of a project. (Wikimedia Commons)

The Project Cycle

"CFD is still not being exploited as effectively as one would like in the design process. This is partially because of the long set-up times and high costs, both human and computational, of complex flow simulations." – Antony Jameson, Stanford, 1999

"The conceptual design stage is the point where the most freedom is available to change the design... normally, advanced CFD tools aren't used until the start of preliminary design at the earliest." – William Mason, Virginia Tech, 1998

Requirements for Design CFD

Essential characteristics of a CFD design tool are:

- Short set-up times
- Low computational costs

We believe the unified coordinate system [link] will help with both of these requirements.

The Unified Coordinate System

- Lagrangian Fluid dynamics
  - Automatic grid generation
  - Can fail due to severe grid distortion
- Unified Coordinates
  - Largely preserves benefits of Lagrangian systems
  - Distortion can be controlled

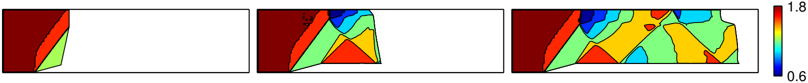


Figure: Mach contours for a transonic duct flow

Original Development of UCS

Developed by W. H. Hui[1] from from Lagrangian coordinates “I wish I had developed this at the beginning of my career, rather than at the end” - W. H. Hui, 2000, personal communication

- The time-dependent Euler equations[2][3]
- Extension to viscous flows[4]
- External flows and oscillating airfoils[5],[6]

Original Development of UCS

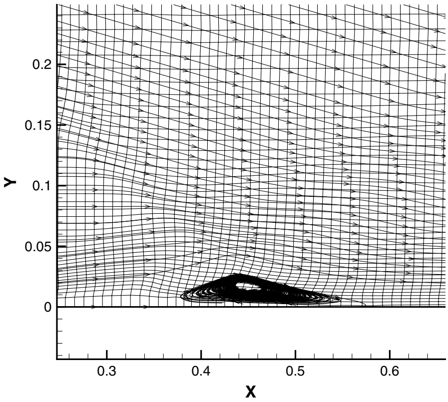


Figure: Boundary-layer separation & recirculation in Navier-Stokes equations captured by UCS[4]

Original Development of UCS

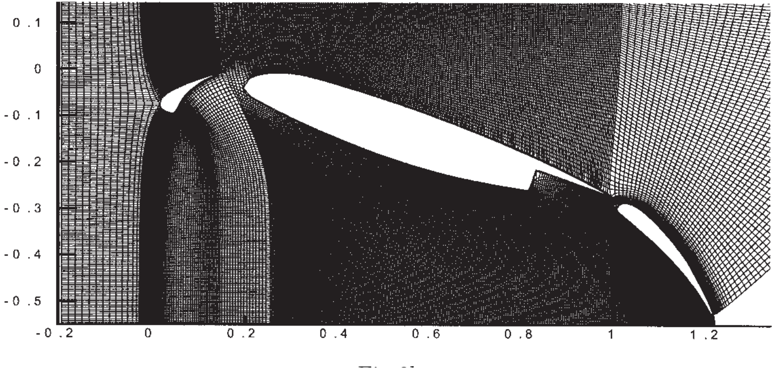


Figure: A complex unified grid generated by Hui[7]

Extensions of UCS

Applications of UCS to other systems

- Multimaterial flows[8]
- Plasma dynamics[9]
- Gas-kinetic (BGK) aerodynamics[10]

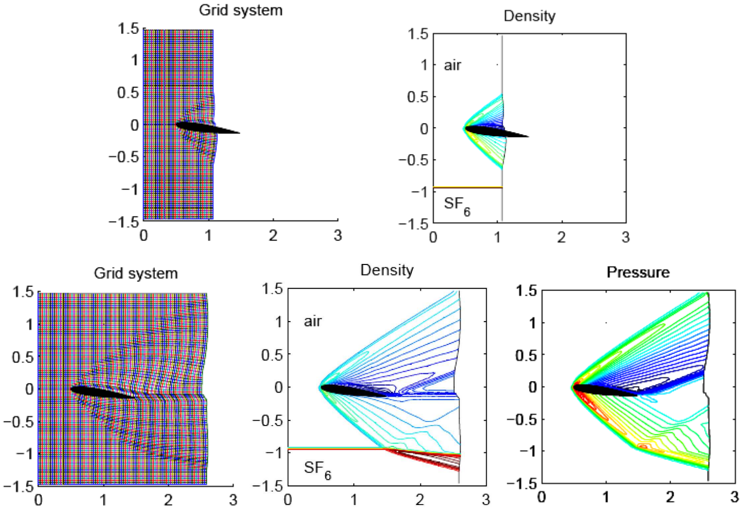


Figure 5: Mach 2.2 flow of air-SF6 over a NACA 0012 airfoil at 8° angle of attack. Flow-generated meshes and density (and pressure) contours at different times.

Extensions of UCS

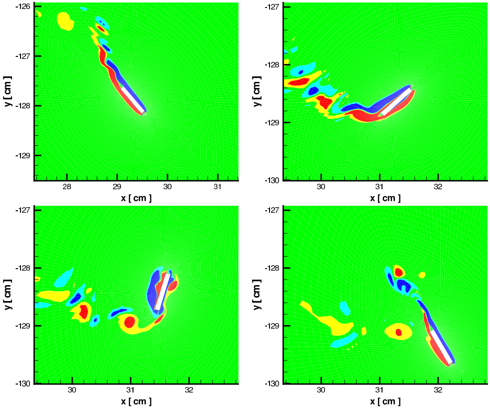


Figure: Vorticity of a freely falling plate at four instants during a full rotation[11]

Outline

The Unified Coordinate Transformation

$$\begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ U & A & L & P \\ V & B & M & Q \\ W & C & N & R \end{pmatrix} \begin{pmatrix} d\lambda \\ d\xi \\ d\eta \\ d\zeta \end{pmatrix} \tag{1}$$

The method of implementation is what separates the unified coordinate system (UCS) from the arbitrary-Lagrangian-Eulerian system (ALE).

Conservation Equations in Two Dimensions

$$\frac{\partial \mathbf{E}}{\partial \lambda} + \frac{\partial \mathbf{F}}{\partial \xi} + \frac{\partial \mathbf{G}}{\partial \eta} = 0 \tag{2}$$

$$\mathbf{E} = \begin{pmatrix} \rho J \\ \rho J u \\ \rho J v \\ \rho J e \\ A \\ B \\ L \\ M \end{pmatrix}, \mathbf{F} = \begin{pmatrix} \rho J \left(u_\xi - U_\xi\right) \\ \rho J \left(u_\xi - U_\xi\right) u + pM \\ \rho J \left(u_\xi - U_\xi\right) v - pL \\ \rho J \left(u_\xi - U_\xi\right) e + pJu_\xi \\ -U \\ -V \\ 0 \\ 0 \end{pmatrix}, \mathbf{G} = \begin{pmatrix} \rho J \left(u_\eta - U_\eta\right) \\ \rho J \left(u_\eta - U_\eta\right) u - pB \\ \rho J \left(u_\eta - U_\eta\right) v + pA \\ \rho J \left(u_\eta - U_\eta\right) e + pJu_\eta \\ 0 \\ 0 \\ -U \\ -V \end{pmatrix} \tag{3}$$

$$J = AM - BL,\ u_\xi = \frac{uM - vL}{J},\ u_\eta = \frac{Av - Bu}{J} \tag{4}$$

Controlling Grid Distortion

It is possible to preserve grid angles by requiring that U satisfy an ODE:

$$0 = \frac{\partial}{\partial \tau}\left[\cos^{-1}\left(\frac{\nabla\xi\cdot\nabla\eta}{|\nabla\xi||\nabla\eta|}\right)\right] = \frac{\partial}{\partial \tau}\left[\cos^{-1}\left(\frac{AL+BM}{\sqrt{A^2+B^2}\sqrt{L^2+M^2}}\right)\right] \quad (5)$$

$$\Rightarrow 0 = U_\eta + \frac{S^2 A}{T^2 J}(Av_\xi - Bu_\xi) - \frac{L}{J}(Av_\eta - Bu_\eta) \quad (6)$$
$$+ \left(\frac{S^2}{T^2 J}(B_\xi A + BA_\xi) - \frac{L}{JA}(B_\eta A + BA_\eta)\right)(U - u)$$

Outline

The Riemann Problem

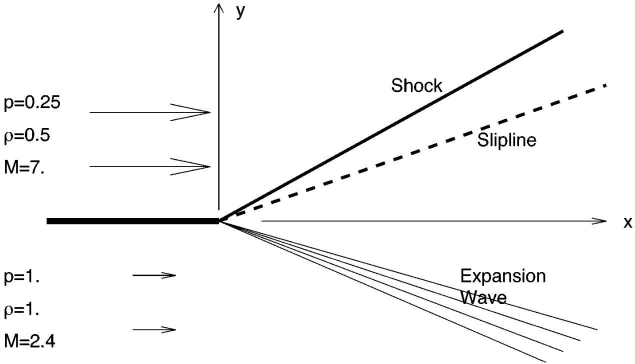
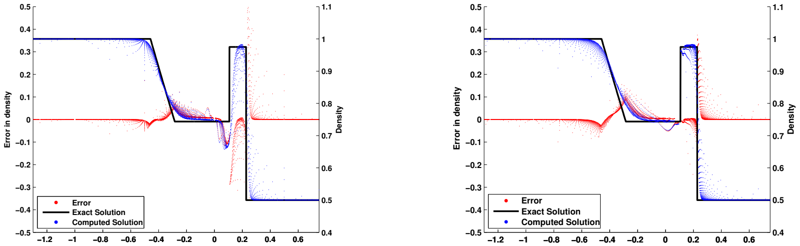


Figure: A diagram of the steady Riemann problem, as given by Hui[2]

The Riemann Problem



(a) Eulerian coordinate system

(b) Lagrangian coordinate system

Figure: The similarity solution of the Riemann problem and the corresponding error in the numerical solution, computed throughout the simulation region.

The Riemann Problem - Convergence

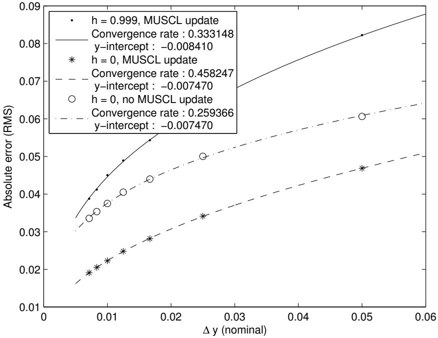


Figure: Root-mean-squared error for the riemann problem, with order of convergence *n*.

The Expansion Corner

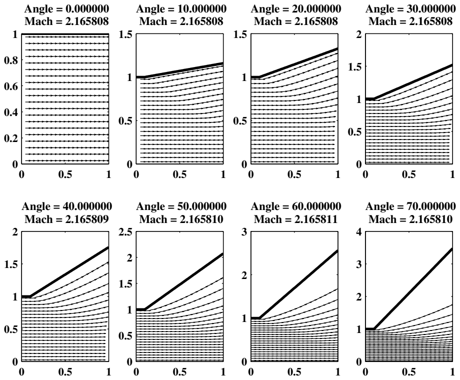


Figure: Computed streamlines for Prandtl-Meyer expansion at increasing expansion angles. Angles are given in degrees.

The Diamond Shock Train

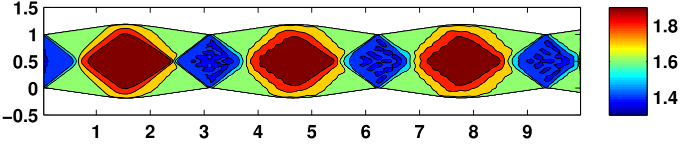
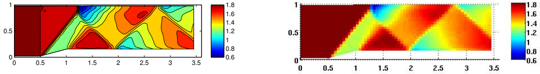
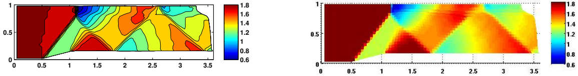


Figure: Computed Mach number for an under-expanded nozzle flow, showing the diamond-shock train

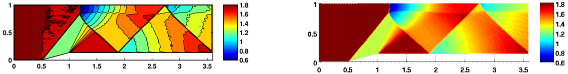
The Transonic Duct



(a) $h = 0$, nominal grid size: 72×20



(b) $h = 0.25$, nominal grid size: 72×20



(c) $h = 0$, nominal grid size: 360×100

Figure: Qualitative accuracy comparison between UCS and Eulerian simulations for a transonic duct flow. Notice the improved resolution of the slip line and the walls for the UCS solution.

Boundary-layer flow

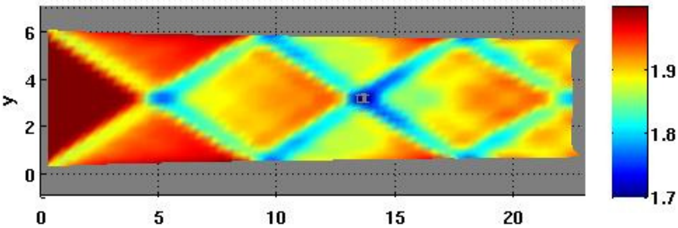


Figure: Oblique shock train produced by a turbulent boundary layer in an otherwise uniform channel

A more interesting application

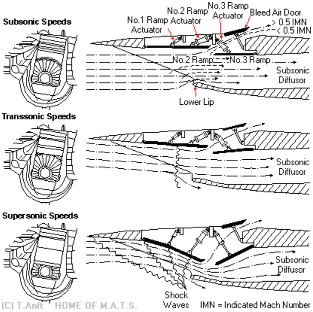
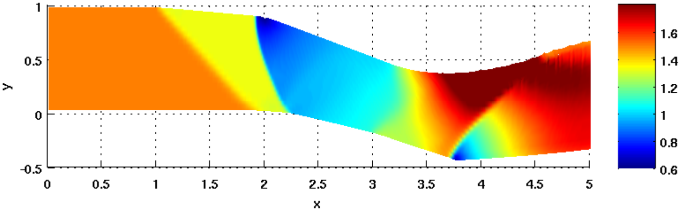


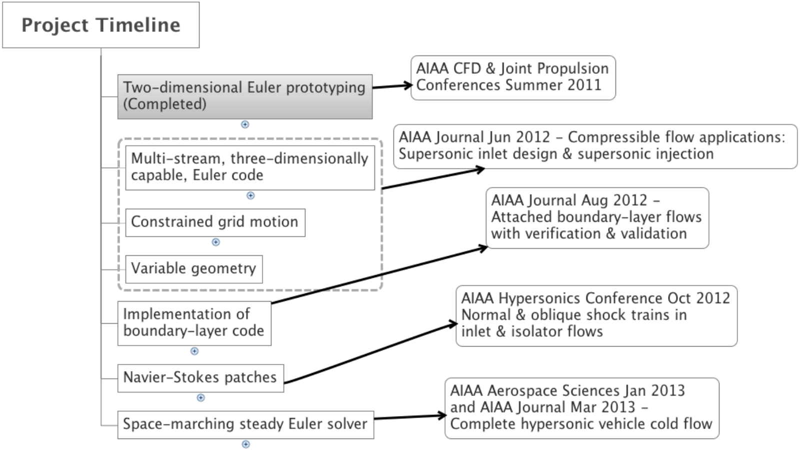
Figure: Diagram of the variable inlet geometry of the USAF F-14 Tomcat. Courtesy Home of M.A.T.S., http://www.anft.net/f-14/f14-detail-airintake.htm

A more interesting application



Outline

Timeline


Project Timeline
Two-dimensional Euler prototyping (Completed)
AIAA CFD & Joint Propulsion Conferences Summer 2011
Multi-stream, three-dimensionally capable, Euler code
Constrained grid motion
Variable geometry
AIAA Journal Jun 2012 – Compressible flow applications: Supersonic inlet design & supersonic injection
AIAA Journal Aug 2012 – Attached boundary-layer flows with verification & validation
Implementation of boundary-layer code
AIAA Hypersonics Conference Oct 2012 Normal & oblique shock trains in inlet & isolator flows
Navier-Stokes patches
Space-marching steady Euler solver
AIAA Aerospace Sciences Jan 2013 and AIAA Journal Mar 2013 – Complete hypersonic vehicle cold flow

References and Further Reading I

- Hui, W. H., “The Unified Coordinate System in Computational Fluid Dynamics,” *Communications in Computational Physics*, Vol. 2, No. 4, August 2007, pp. 577–610.
- Hui, W. H., Li, P. Y., and Li, Z. W., “A Unified Coordinate System for Solving the Two-Dimensional Euler Equations,” *Journal of Computational Physics*, Vol. 153, 1999, pp. 596–673.
- Hui, W. H. and Kudriakov, S., “A Unified Coordinate System for Solving the Three-Dimensional Euler Equations,” *Journal of Computational Physics*, Vol. 172, January 2001, pp. 235–260.

References and Further Reading II

- Hui, W., Wu, Z. N., and Gao, B., “Preliminary Extension of the Unified Coordinate System Approach to Computation of Viscous Flows,” *Journal of Scientific Computing*, Vol. 30, No. 2, February 2007, pp. 301–344.
- Hui, W. H., “A unified coordinates approach to computational fluid dynamics,” *Journal of Computational and Applied Mathematics*, Vol. 163, 2004, pp. 15–28.
- Hui, W., Hu, J., and Zhao, G., “Gridless Computation Using the Unified Coordinates,” *Computational Fluid Dynamics 2004*, edited by C. Groth and D. W. Zingg, Springer Berlin Heidelberg, 2006, pp. 503–508.

References and Further Reading III

- Hui, W., Zhao, G., Hu, J., and Zheng, Y., "Gridless Computation of Two Dimensional Flow Using the Unified Coordinates," .
- Jia, P., Jiang, S., and Zhao, G., "Two-dimensional compressible multimaterial flow calculations in a unified coordinate system," *Computers and Fluids*, Vol. 35, 2006, pp. 168–188.
- Zhilkin, A., "A Dynamic Mesh Adaptation Method for Magnetohydrodynamics Problems," *Computational Mathematics and Mathematical Physics*, Vol. 47, No. 11, 2007, pp. 1819–1832.

References and Further Reading IV

- Jin, C. and Xu, K., "A unified moving grid gas-kinetic method in Eulerian space for viscous flow computation," *Journal of Computational Physics*, Vol. 2007, 2007, pp. 155–175.
- Jin, C. and Xu, K., "Numerical Study of the Unsteady Aerodynamics of Freely Falling Plates," *Communications in Computational Physics*, Vol. 3, No. 4, April 2008, pp. 834–851.