# Changing the Aerospace Design Paradigm with FUN3D

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and the
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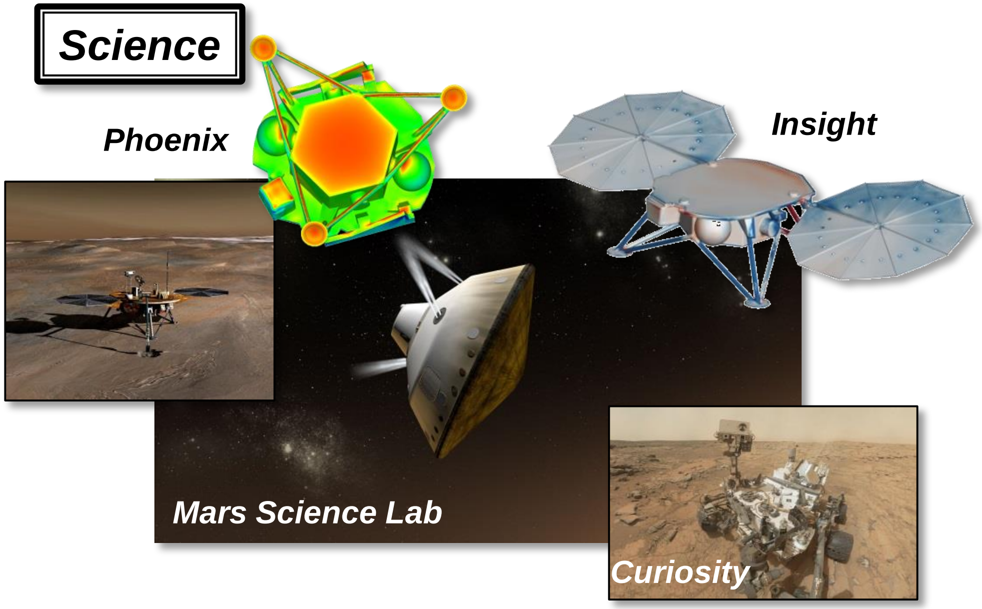
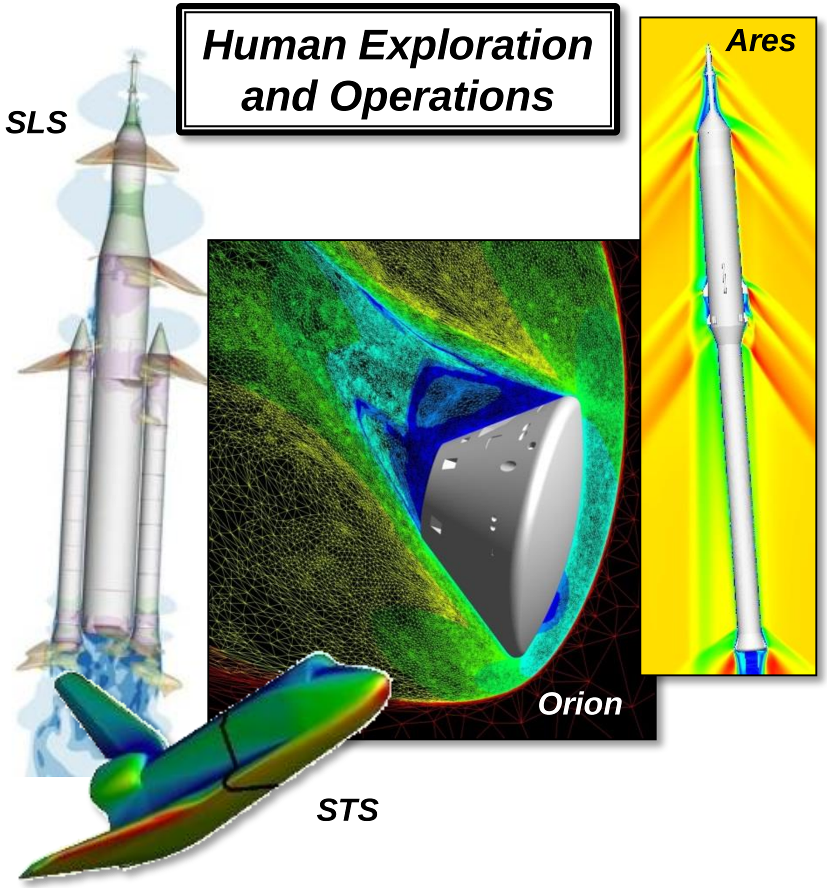
*http://fun3d.larc.nasa.gov*

FUN3D
Fully Unstructured Navier-Stokes

# Across NASA Missions

*FUN3D supplies critical physics-based aerodynamics for a broad range of applications across all Mission Directorates*




*"The FUN3D team has developed a capability that continues to find new and unique applications of significant importance to the agency."*

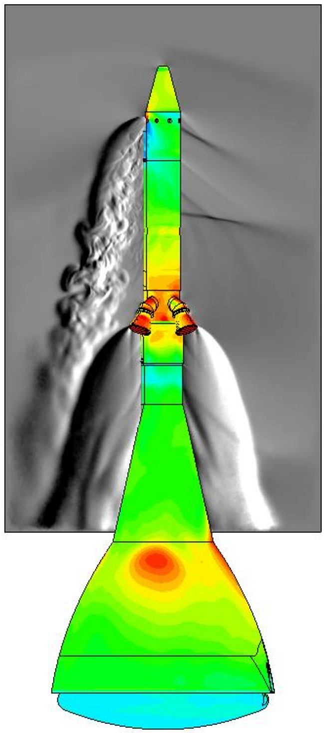
*- Dave Schuster*
*NASA Technical Fellow for Aerosciences*
*NASA Engineering and Safety Center*

FUN3D
Fully Unstructured Navier-Stokes

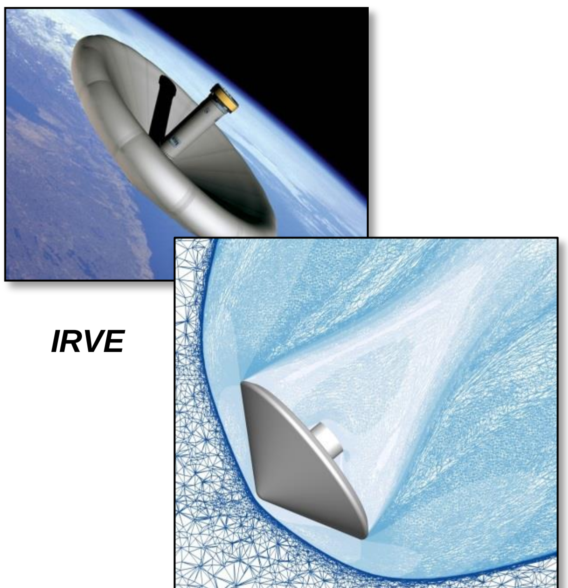
# Across NASA Missions

## Space Technology

Launch Abort

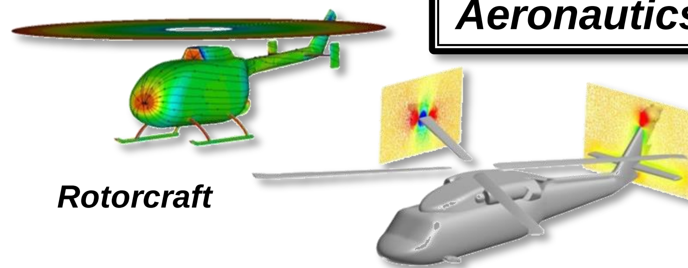


Supersonic Retropropulsion

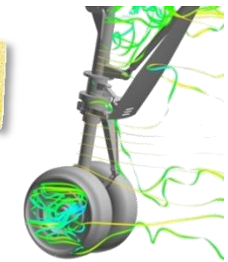


IRVE

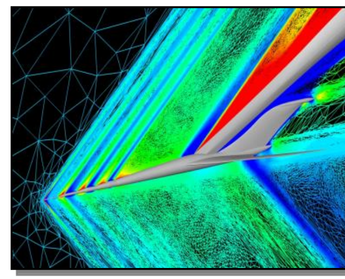
## Aeronautics Research



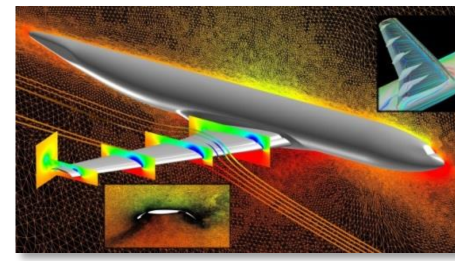
Rotorcraft

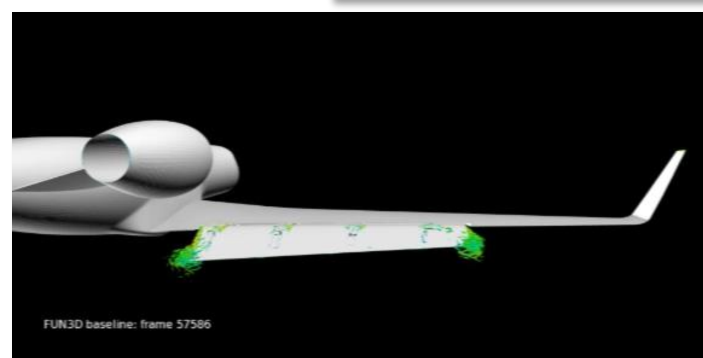


Sonic Boom Mitigation



Airframe Noise






*Due to increased demand from NASA scientists and engineers, FUN3D simulations now account for the single largest block of supercomputing cycles at the Agency: 12% of NAS, or approximately 200 million hours per year*

FUN3D
Fully Unstructured Navier-Stokes

# Across the Aerospace Industry

SPACEX

First private company to achieve orbit
and dock with the International Space Station
***Primary aerodynamics tool: FUN3D***

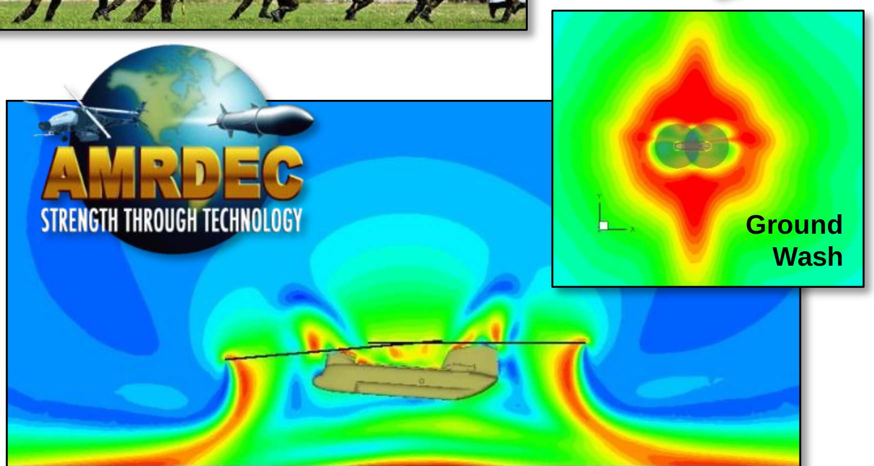
- FUN3D used for extensive analysis of Falcon 1 and Falcon 9 rockets, Dragon spacecraft
- Team consults frequently and provides new features and capabilities as requested

*"The FUN3D software suite and development team have enabled SpaceX to rapidly design, build, and successfully fly a new generation of rockets and spacecraft."*

*- Justin Richeson*
*Manager, SpaceX Aerodynamics*

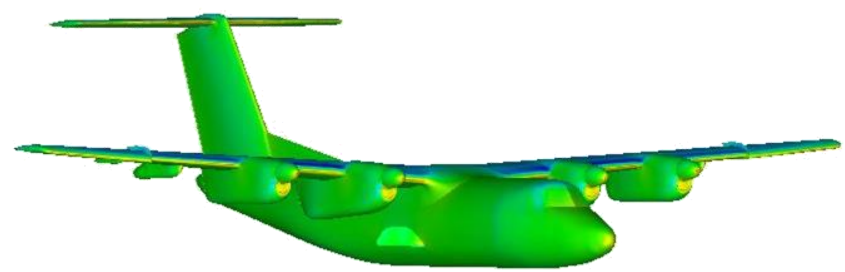
# At the Department of Defense

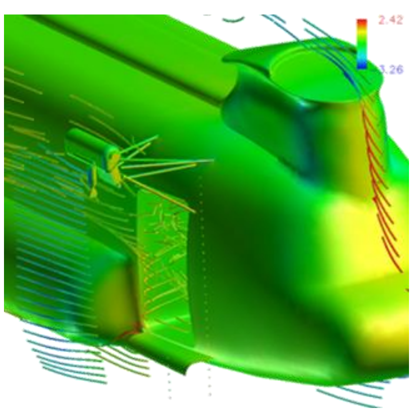





**AMRDEC at Redstone Arsenal**

- **Troop safety:** airworthiness qualification
- **Dramatic cost savings:** fewer tunnel & flight tests
- Fast-paced environment analyzing & certifying vehicle and weapons systems for operational deployment
- Intense demand for timely results on massive computing systems
- Decade of use in direct support of the US warfighter



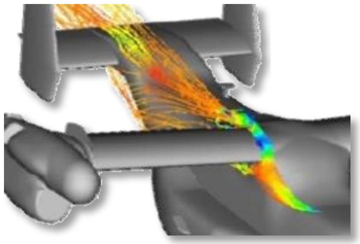


**Air Force Research Labs at WPAFB**

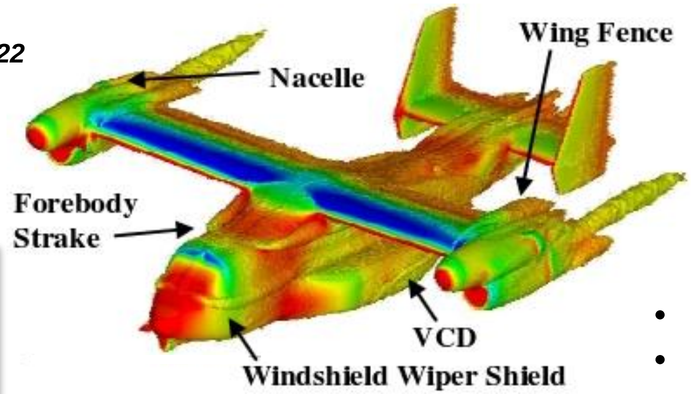
- Funded on-site training workshop (20 students)

AIR FORCE RESEARCH LABORATORY

# At the Department of Defense



*V-22*




**NAVAIR at Patuxent River**

- Hosted on-site training workshop
- Hired two recent Georgia Tech PhD graduates
  - FUN3D development for theses

# Other Government Agencies

- Gordon Bell Prize awarded to FUN3D / ANL / LLNL team
  - Most prestigious award in High Performance Computing community

- Joint collaboration improving fuel efficiency for 18-wheeler trucks
- Covered by print and TV news
- Simulations performed on Jaguar
  - The world's most powerful supercomputer at the time

- Reduced wind turbine noise while maintaining performance

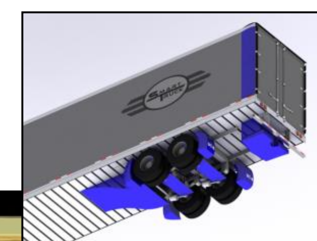
# Outside Aerospace

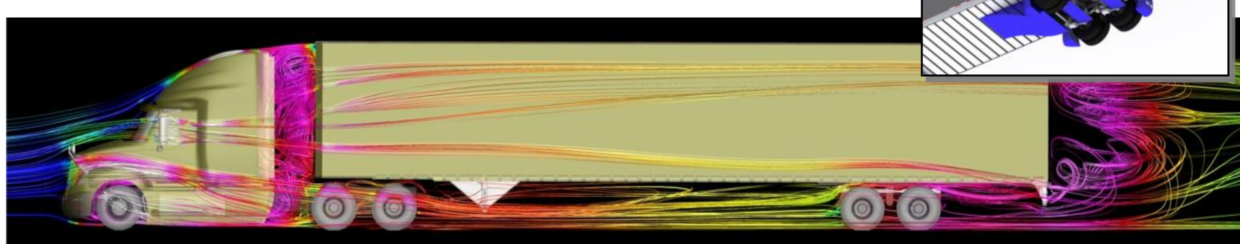
BMI Corporation

SmartTruck

- Used FUN3D on world's largest supercomputer to perform the most advanced truck simulations ever attempted
- Developed add-on kits that improve fuel mileage by as much as 11%
- Spin-off company has sold over 40,000 units

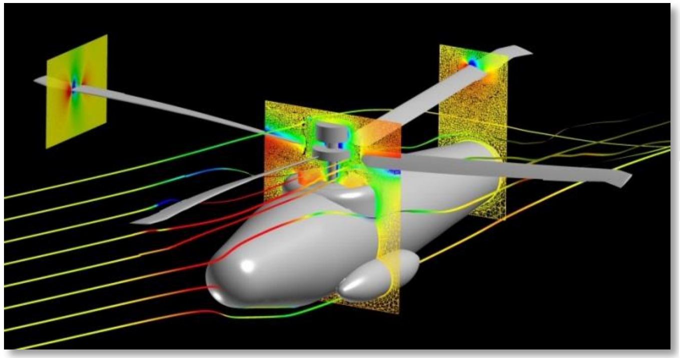
*"FUN3D is a national asset."*
*- Mike Henderson,*
*BMI Founder*



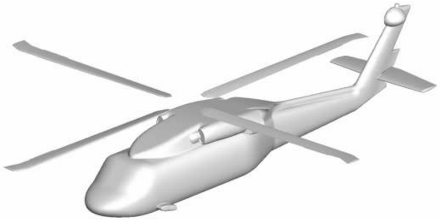


# Across Academia

- Over 50 students have interned with the team or conducted thesis work using FUN3D: 20 MS and PhD theses generated
- Graduates with hands-on FUN3D experience are highly sought after

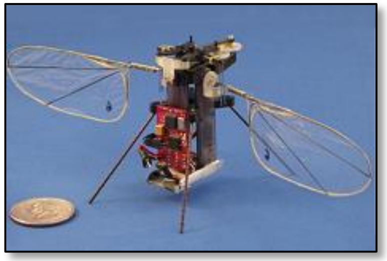


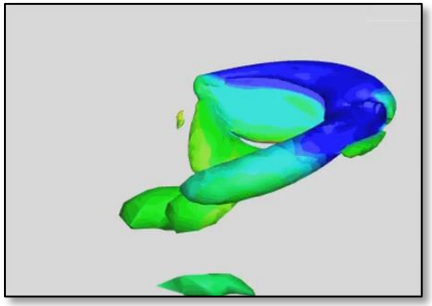
Georgia Tech has played a significant role in modeling vehicles with moving parts, such as helicopters



*"FUN3D is a vital national resource…the investment that NASA has made has generated at least a hundredfold in return on investment…"*

*- Dr. Marilyn Smith, Georgia Tech*





North Carolina A&T has used FUN3D to optimize biologically-inspired micro-air vehicles for the US Army

# Customer Perspective

- Support
  - Multiple E-mail lists
    - Developer support (private list - CS monitor around clock)
    - Users
    - News
- Documentation
  - User manual: NASA/TM-2014-218179
  - Website
    - Up-to-date
    - Real-time development status
- Training
  - Multiple requests for on-site workshops
  - Streaming of previously-recorded workshops from website
  - Tutorials available on website
- Progressive software development practices
  - Automated regression testing ensures quality
  - Practices adopted by other organizations

*"…the FUN3D team's responsiveness has made working on different coasts and time zones a non-issue, and their on-site training session was a great educational event."*
*- Justin Richeson, SpaceX*

*"It is my belief that the FUN3D project should be held up as an example of software development at NASA done well."*
*- Kevin Fogleman, AVID LLC*

*"A software product is only as good as the team behind it. Here, the FUN3D team is incomparable to any other development team that I have ever worked with in my thirty-five years of computational experience."*
*- Dr. Marilyn Smith, Georgia Tech*

FUN3D

Fully Unstructured Navier-Stokes

# The Navier-Stokes Equations

$$\frac{\partial(\mathbf{Q}V)}{\partial t} + \oint_{\partial V} (\mathbf{F}^* - \mathbf{F}_v) \cdot \hat{\mathbf{n}}\, dS = 0$$

$$p = (\gamma - 1)(E - \rho\frac{(u^2 + v^2 + w^2)}{2})$$

$$\frac{D(\tilde{\nu})}{Dt} = c_{b_1}[1 - f_{t_2}]\tilde{S}\tilde{\nu} + \frac{M_\infty}{\sigma R_e}[\nabla \cdot ((\nu + (1 + c_{b_2})\tilde{\nu})\nabla\tilde{\nu} - c_{b_2}\tilde{\nu}\nabla^2\tilde{\nu})]$$
$$- \frac{M_\infty}{Re}\left[c_{w_1} f_w - \frac{c_{b_1}}{\kappa^2} f_{t_2}\right]\left[\frac{\tilde{\nu}}{d}\right]^2 + \frac{Re}{M_\infty} f_{t_1} \Delta U^2$$

$$\mathbf{F}^* = \begin{bmatrix} \rho(u - W_x) \\ \rho u(u - W_x) + p \\ \rho v(u - W_x) \\ \rho w(u - W_x) \\ (E + p)(u - W_x) + W_x p \end{bmatrix} \hat{\mathbf{i}} + \begin{bmatrix} \rho(v - W_y) \\ \rho u(v - W_y) \\ \rho v(v - W_y) + p \\ \rho w(v - W_y) \\ (E + p)(v - W_y) + W_y p \end{bmatrix} \hat{\mathbf{j}} + \begin{bmatrix} \rho(w - W_z) \\ \rho u(w - W_z) \\ \rho v(w - W_z) \\ \rho w(w - W_z) + p \\ (E + p)(w - W_z) + W_z p \end{bmatrix} \hat{\mathbf{k}}$$

$$\mathbf{F_v} = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{yx} \\ \tau_{zx} \\ u\tau_{xx} + v\tau_{xy} + w\tau_{xz} - q_x \end{bmatrix} \hat{\mathbf{i}} + \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \\ \tau_{zy} \\ u\tau_{yx} + v\tau_{yy} + w\tau_{yz} - q_y \end{bmatrix} \hat{\mathbf{j}} + \begin{bmatrix} 0 \\ \tau_{xz} \\ \tau_{yz} \\ \tau_{zz} \\ u\tau_{zx} + v\tau_{zy} + w\tau_{zz} - q_z \end{bmatrix} \hat{\mathbf{k}}$$

$$\tau_{xx} = \frac{2}{3}\frac{M_\infty}{Re}(\mu + \mu_t)\left(2\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} - \frac{\partial w}{\partial z}\right) \qquad \tau_{xy} = \tau_{yx} = (\mu + \mu_t)\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \qquad q_x = -\frac{M_\infty}{Re(\gamma - 1)}(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t})\frac{\partial T}{\partial x}$$

$$\tau_{yy} = \frac{2}{3}\frac{M_\infty}{Re}(\mu + \mu_t)\left(2\frac{\partial y}{\partial y} - \frac{\partial u}{\partial x} - \frac{\partial w}{\partial z}\right) \qquad \tau_{xz} = \tau_{zx} = (\mu + \mu_t)\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) \qquad q_y = -\frac{M_\infty}{Re(\gamma - 1)}(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t})\frac{\partial T}{\partial y}$$

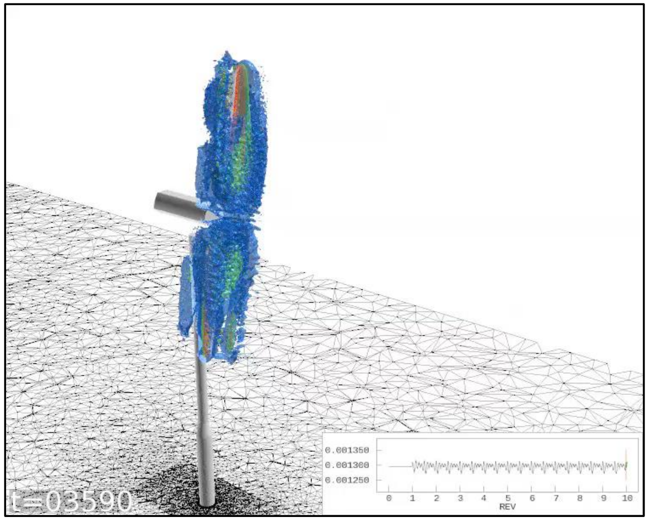
$$\tau_{zz} = \frac{2}{3}\frac{M_\infty}{Re}(\mu + \mu_t)\left(2\frac{\partial w}{\partial z} - \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right) \qquad \tau_{yz} = \tau_{zy} = (\mu + \mu_t)\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) \qquad q_z = -\frac{M_\infty}{Re(\gamma - 1)}(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t})\frac{\partial T}{\partial z}$$

- Traditional CFD tools solve for the flow field and associated output parameters, such as drag on an aircraft
- Software to do this is typically ~50,000 lines of code

# Design With CFD

- The Navier-Stokes equations are solved forward in time to give information about the flow field (lift, drag)
- For design, we need to know how the flow field is sensitive to a change in design parameters (chord, sweep)
- Perturbing each parameter, computing the flow field, and differencing the output to obtain sensitivity is intractable for multiple variables

- An auxiliary set of adjoint equations are obtained by differentiating the governing equations
- Adjoint equations are solved backward in time to determine which parameters impact a given output and how
- This provides efficient sensitivity analysis for all inputs simultaneously



# The Adjoint Equations



$$\begin{aligned}&\mathbf{C}_s^n\circ\left[a\frac{\mathbf{Q}_s^n-\mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t}\circ\mathbf{V}_s^n+c\frac{\mathbf{I}_s^n\mathbf{Q}^{n-2}-\mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t}\circ\mathbf{I}_s^n\mathbf{V}^{n-2}\right.\\&\left.+d\frac{\mathbf{I}_s^n\mathbf{Q}^{n-3}-\mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t}\circ\mathbf{I}_s^n\mathbf{V}^{n-3}\right]\\&+\mathbf{R}^n+((\mathbf{I}_s^n\mathbf{Q}^{n-1})\circ\mathbf{C}_s^n+\beta\bar{\mathbf{C}}_s^n)\circ\mathbf{R}_{\mathrm{GCL}}^n=0\end{aligned}\qquad\text{(A1)}$$

Proceeding as before, the Lagrangian can be written as

$$\begin{aligned}L(\mathbf{D},\mathbf{Q},\mathbf{X},\mathbf{\Lambda},\mathbf{\Lambda}_g)&=f\Delta t+\sum_{n=1}^{N}[\mathbf{\Lambda}_g^n]^T\mathbf{G}^n\Delta t\\&+\sum_{n=1}^{N}\left\{[\mathbf{C}_s^n\circ\mathbf{\Lambda}_s^n]^T\left[a\frac{\mathbf{Q}_s^n-\mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t}\circ\mathbf{V}_s^n\right.\right.\\&+c\frac{\mathbf{I}_s^n\mathbf{Q}^{n-2}-\mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t}\circ(\mathbf{I}_s^n\mathbf{V}^{n-2})\\&\left.+d\frac{\mathbf{I}_s^n\mathbf{Q}^{n-3}-\mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t}\circ(\mathbf{I}_s^n\mathbf{V}^{n-3})\right]\\&+[\mathbf{\Lambda}_s^n]^T[\mathbf{R}^n+((\mathbf{I}_s^n\mathbf{Q}^{n-1})\circ\mathbf{C}_s^n+\beta\bar{\mathbf{C}}_s^n)\circ\mathbf{R}_{\mathrm{GCL}}^n]\\&\left.+[\mathbf{\Lambda}_f^n]^T[\mathbf{A}^n\mathbf{Q}^n]+[\mathbf{\Lambda}_h^n]^T[\mathbf{P}^n\mathbf{Q}^n]\right\}\Delta t\\&+(f^0+[\mathbf{\Lambda}_g^0]^T\mathbf{G}^0+[\mathbf{\Lambda}^0]^T\mathbf{R}^{\mathrm{in}})\Delta t\end{aligned}\qquad\text{(A2)}$$

On time levels 1 and 2, the time derivatives are assumed to be discretized with the BDF1 and BDF2 schemes, respectively. Taking into account the dependencies on data at time levels $n-2$ and $n-3$, the adjoint equations are obtained as follows:

$S$:

$$\begin{aligned}&\frac{a}{\Delta t}\mathbf{V}_s^n\circ\mathbf{C}_s^n\circ\mathbf{\Lambda}_s^n+\left[\frac{\partial\mathbf{R}^n}{\partial\mathbf{Q}_s^n}\right]^T\mathbf{\Lambda}_s^n+[\mathbf{A}_s^n]^T\mathbf{\Lambda}_f^n+[\mathbf{P}_s^n]^T\mathbf{\Lambda}_h^n=-\left[\frac{\partial f}{\partial\mathbf{Q}_s^n}\right]^T\\&-\mathbf{I}_s^n\left\{[\mathbf{I}_s^{n+1}]^T\left[\left(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1}-\frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1}-\frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2}\right.\right.\right.\\&\left.\left.+\mathbf{R}_{\mathrm{GCL}}^{n+1}\right)\circ\mathbf{C}_s^{n+1}\circ\mathbf{\Lambda}_s^{n+1}\right]+[\mathbf{I}_s^{n+2}]^T\left[\left(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+2}\circ\mathbf{\Lambda}_s^{n+2}\right]\\&\left.+[\mathbf{I}_s^{n+3}]^T\left[\left(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+3}\circ\mathbf{\Lambda}_s^{n+3}\right]\right\}\end{aligned}$$

$F$:

$$\begin{aligned}&\left[\frac{\partial\mathbf{R}^n}{\partial\mathbf{Q}_f^n}\right]^T\mathbf{\Lambda}_s^n+[\mathbf{A}_f^n]^T\mathbf{\Lambda}_f^n+[\mathbf{P}_f^n]^T\mathbf{\Lambda}_h^n=-\left[\frac{\partial f}{\partial\mathbf{Q}_f^n}\right]^T\\&-\mathbf{I}_f^n\left\{[\mathbf{I}_s^{n+1}]^T\left[\left(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1}-\frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1}-\frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2}\right.\right.\right.\\&\left.\left.+\mathbf{R}_{\mathrm{GCL}}^{n+1}\right)\circ\mathbf{C}_s^{n+1}\circ\mathbf{\Lambda}_s^{n+1}\right]+[\mathbf{I}_s^{n+2}]^T\left[\left(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+2}\circ\mathbf{\Lambda}_s^{n+2}\right]\\&\left.+[\mathbf{I}_s^{n+3}]^T\left[\left(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+3}\circ\mathbf{\Lambda}_s^{n+3}\right]\right\}\end{aligned}$$

$H$:

$$\begin{aligned}&\left[\frac{\partial\mathbf{R}^n}{\partial\mathbf{Q}_h^n}\right]^T\mathbf{\Lambda}_s^n+[\mathbf{A}_h^n]^T\mathbf{\Lambda}_f^n+[\mathbf{P}_h^n]^T\mathbf{\Lambda}_h^n=-\left[\frac{\partial f}{\partial\mathbf{Q}_h^n}\right]^T\\&-\mathbf{I}_h^n\left\{[\mathbf{I}_s^{n+1}]^T\left[\left(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1}-\frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1}-\frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2}\right.\right.\right.\\&\left.\left.+\mathbf{R}_{\mathrm{GCL}}^{n+1}\right)\circ\mathbf{C}_s^{n+1}\circ\mathbf{\Lambda}_s^{n+1}\right]+[\mathbf{I}_s^{n+2}]^T\left[\left(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+2}\circ\mathbf{\Lambda}_s^{n+2}\right]\\&\left.+[\mathbf{I}_s^{n+3}]^T\left[\left(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+3}\circ\mathbf{\Lambda}_s^{n+3}\right]\right\}\end{aligned}$$

for $3\le n\le N$ (A3)

$S$:

$$\begin{aligned}&\frac{3}{2\Delta t}\mathbf{V}_s^n\circ\mathbf{C}_s^n\circ\mathbf{\Lambda}_s^n+\left[\frac{\partial\mathbf{R}^n}{\partial\mathbf{Q}_s^n}\right]^T\mathbf{\Lambda}_s^n+[\mathbf{A}_s^n]^T\mathbf{\Lambda}_f^n+[\mathbf{P}_s^n]^T\mathbf{\Lambda}_h^n=\\&-\left[\frac{\partial f}{\partial\mathbf{Q}_s^n}\right]^T-\mathbf{I}_s^n\left\{[\mathbf{I}_s^{n+1}]^T\left[\left(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1}-\frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1}\right.\right.\right.\\&\left.\left.-\frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2}+\mathbf{R}_{\mathrm{GCL}}^{n+1}\right)\circ\mathbf{C}_s^{n+1}\circ\mathbf{\Lambda}_s^{n+1}\right]\\&+[\mathbf{I}_s^{n+2}]^T\left[\left(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+2}\circ\mathbf{\Lambda}_s^{n+2}\right]\\&\left.+[\mathbf{I}_s^{n+3}]^T\left[\left(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+3}\circ\mathbf{\Lambda}_s^{n+3}\right]\right\}\end{aligned}$$

$F$:

$$\begin{aligned}&\left[\frac{\partial\mathbf{R}^n}{\partial\mathbf{Q}_f^n}\right]^T\mathbf{\Lambda}_s^n+[\mathbf{A}_f^n]^T\mathbf{\Lambda}_f^n+[\mathbf{P}_f^n]^T\mathbf{\Lambda}_h^n=-\left[\frac{\partial f}{\partial\mathbf{Q}_f^n}\right]^T\\&-\mathbf{I}_f^n\left\{[\mathbf{I}_s^{n+1}]^T\left[\left(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1}-\frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1}-\frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2}\right.\right.\right.\\&\left.\left.+\mathbf{R}_{\mathrm{GCL}}^{n+1}\right)\circ\mathbf{C}_s^{n+1}\circ\mathbf{\Lambda}_s^{n+1}\right]+[\mathbf{I}_s^{n+2}]^T\left[\left(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+2}\circ\mathbf{\Lambda}_s^{n+2}\right]\\&\left.+[\mathbf{I}_s^{n+3}]^T\left[\left(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+3}\circ\mathbf{\Lambda}_s^{n+3}\right]\right\}\end{aligned}$$

$H$:

$$\begin{aligned}&\left[\frac{\partial\mathbf{R}^n}{\partial\mathbf{Q}_h^n}\right]^T\mathbf{\Lambda}_s^n+[\mathbf{A}_h^n]^T\mathbf{\Lambda}_f^n+[\mathbf{P}_h^n]^T\mathbf{\Lambda}_h^n=-\left[\frac{\partial f}{\partial\mathbf{Q}_h^n}\right]^T\\&-\mathbf{I}_h^n\left\{[\mathbf{I}_s^{n+1}]^T\left[\left(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1}-\frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1}-\frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2}\right.\right.\right.\\&\left.\left.+\mathbf{R}_{\mathrm{GCL}}^{n+1}\right)\circ\mathbf{C}_s^{n+1}\circ\mathbf{\Lambda}_s^{n+1}\right]+[\mathbf{I}_s^{n+2}]^T\left[\left(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+2}\circ\mathbf{\Lambda}_s^{n+2}\right]\\&\left.+[\mathbf{I}_s^{n+3}]^T\left[\left(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+3}\circ\mathbf{\Lambda}_s^{n+3}\right]\right\}\end{aligned}$$

for $n=2$ (A4)

$$\begin{aligned}S:\ &\frac{1}{\Delta t}\mathbf{V}_s^n\circ\mathbf{C}_s^n\circ\mathbf{\Lambda}_s^n+\left[\frac{\partial\mathbf{R}^n}{\partial\mathbf{Q}_s^n}\right]^T\mathbf{\Lambda}_s^n+[\mathbf{A}_s^n]^T\mathbf{\Lambda}_f^n+[\mathbf{P}_s^n]^T\mathbf{\Lambda}_h^n\\&=-\left[\frac{\partial f}{\partial\mathbf{Q}_s^n}\right]^T-\mathbf{I}_s^n\left\{[\mathbf{I}_s^{n+1}]^T\left[\left(-\frac{3}{2\Delta t}\mathbf{V}_s^{n+1}\right.\right.\right.\\&\left.\left.-\frac{1}{2\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1}+\mathbf{R}_{\mathrm{GCL}}^{n+1}\right)\circ\mathbf{C}_s^{n+1}\circ\mathbf{\Lambda}_s^{n+1}\right]\\&+[\mathbf{I}_s^{n+2}]^T\left[\left(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\right)\right.\\&+[\mathbf{I}_s^{n+3}]^T\left[\left(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\right)\right.\\F:\ &\left[\frac{\partial\mathbf{R}^n}{\partial\mathbf{Q}_f^n}\right]^T\mathbf{\Lambda}_s^n+[\mathbf{A}_f^n]^T\mathbf{\Lambda}_f^n+\\&=-\left[\frac{\partial f}{\partial\mathbf{Q}_f^n}\right]^T-\mathbf{I}_f^n\left\{[\mathbf{I}_s^{n+1}\right.\\&-\frac{1}{2\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1}+\mathbf{R}_{\mathrm{GCL}}^{n+1}\\&+[\mathbf{I}_s^{n+2}]^T\left[\left(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\right)\right.\\&\left.+[\mathbf{I}_s^{n+3}]^T\left[\left(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\right)\circ\mathbf{C}_s^{n+3}\circ\mathbf{\Lambda}_s^{n+3}\right]\right\}\end{aligned}$$

- The time-varying adjoint equations are considerably more complex
- Total FUN3D implementation consists of nearly 1 million lines of code
- Tremendous amount of software infrastructure required

Page 1 of 4 of the adjoint equations derived and implemented in:

*Nielsen, E.J., and Diskin, B., "Discrete Adjoint-Based Design for Unsteady Turbulent Flows on Dynamic Overset Unstructured Grids," AIAA Journal, Vol. 51, No. 6, June 2013.*

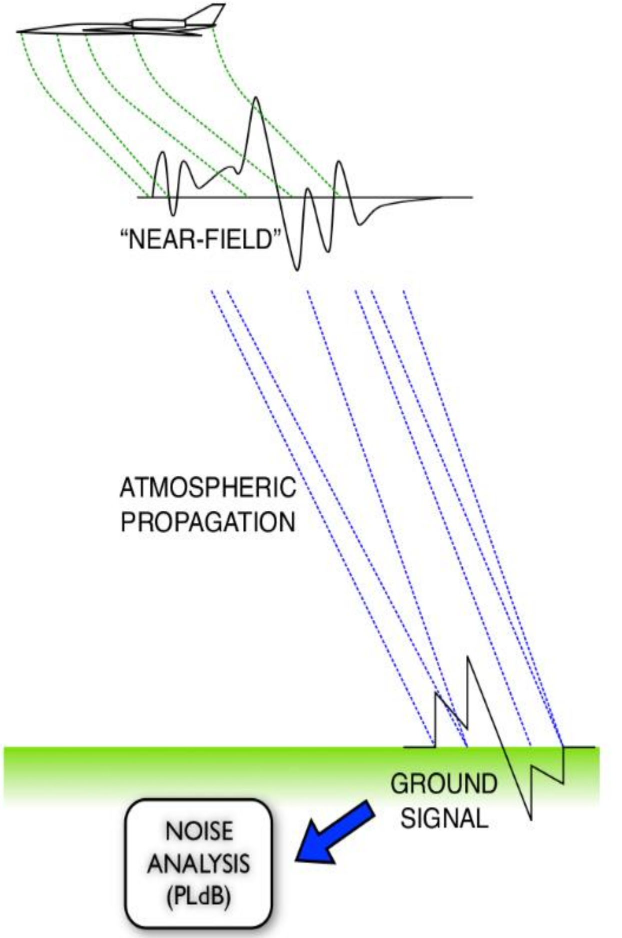
# Constant Innovation

- FUN3D is more than just an analysis tool
  - Provides sensitivity of aerodynamic outputs to thousands of design parameters at the cost of a single simulation using the adjoint approach
- Adjoint developments in FUN3D are recognized as seminal advancements in the field
  - First turbulent flow capability of its kind
  - Sensitivities for large-scale simulations using complex variables
  - Grid sensitivities via adjoint approach
  - Time-varying adjoint solution
- Impact
  - Design with high-end CFD simulations now tractable
  - Numerous organizations around the world cite FUN3D as a model for their own efforts
  - Now able to formally address MDO through collaboration with other disciplines

***Culminating work was recently awarded the 2014 H.J.E. Reid Award, Langley's highest honor for research publications***

# Enabling Physics-Based Design

- Real-world problems are governed by more than one discipline
- Formal optimization requires a sensitivity analysis of the coupled system
  - Dependent on individual sensitivities of each discipline
- For example, consider sonic boom mitigation
  - Near-field aerodynamics (CFD)
  - Long-range propagation through the atmosphere
  - Conversion to a noise metric at the ground
- CFD sensitivities represent a major component in the design of aerospace vehicles
- FUN3D provides these sensitivities for steady and time-varying flows
  - *The time-varying capability is **unique** in the world*




*High payoff for formal coupling of numerous disciplines: Aerodynamics, Structures, Materials, Acoustics, Optics…*

# Concluding Remarks

- FUN3D is an award-winning tool with broad impact and recognized as a national asset
  - Extensive use across all mission directorates
  - Assisted in vehicle design to achieve first commercial docking with ISS
  - Directly supporting the US warfighter
  - Active support, training, and documentation
- Platform for educating the next generation of scientists and engineers
  - Led to numerous graduate theses
- An innovation leader in the field of adjoint methods
  - Adjoint for time-varying turbulent flows unique in the world