Mphys: Standardizing High-fidelity Optimization with OpenMDAO

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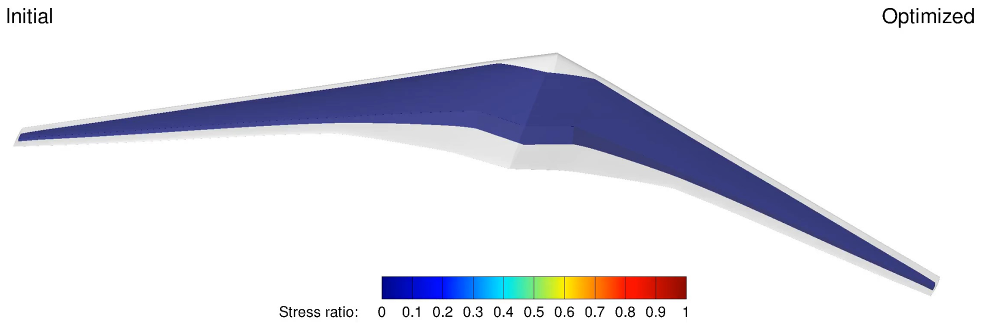
High-fidelity MDAO

High-fidelity modeling in optimization:

- More accurate analysis → fewer late-stage design modifications
- Wider range of applicability due to fewer assumptions

Roadblocks to overcome:

- Computational cost
- Automation of high-fidelity modeling
  - » Mesh generation, lack of robustness of coupling methods, …
- **Time and expertise required to develop high-fidelity MDAO capability**



State of High-fidelity MDAO

Industry performs single discipline high-fidelity optimization

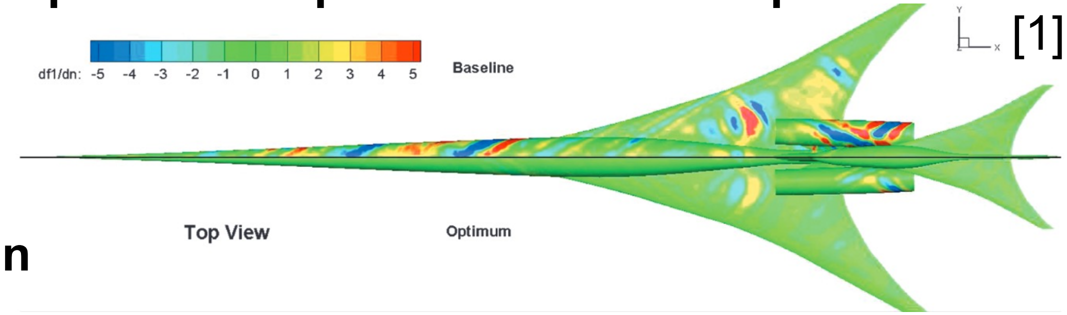
- Aerodynamic shape optimization and structural sizing
- Surrogate-based and gradient-based methods

State-of-the-art research performs high-fidelity MDAO, but the optimization problems are incomplete

- 2 or 3 disciplines
- Small subset of required design conditions and constraint types

Everyone in high-fidelity MDAO does their own implementation

- Difficult to implement and extend
- Difficult to transition research developments to industry users



[1]

$$\frac{df}{d\mathbf{x}} = \left\{ \frac{\partial f}{\partial \mathbf{x}_{A,0}} + \sum_{k=1}^{N} \left[\left(\psi_D^{(k)}\right)^T \frac{\partial \mathbf{D}^{(k)}}{\partial \mathbf{x}_{A,0}} + \left(\psi_R^{(k)}\right)^T \frac{\partial \mathbf{R}^{(k)}}{\partial \mathbf{x}_{A,0}} + \left(\psi_E^{(k)}\right)^T \frac{\partial \mathbf{E}^{(k)}}{\partial \mathbf{x}_{A,0}} + \left(\psi_L^{(k)}\right)^T \frac{\partial \mathbf{L}^{(k)}}{\partial \mathbf{x}_{A,0}} + \left(\psi_G^{(k)}\right)^T \frac{\partial \mathbf{G}^{(k)}}{\partial \mathbf{x}_{A,0}} \right] + \left(\psi_G^{(0)}\right)^T \frac{\partial \mathbf{G}^{(0)}}{\partial \mathbf{x}_{A,0}} \right\} \frac{\partial \mathbf{x}_{A,0}}{\partial \mathbf{x}} + \left\{ \frac{\partial f}{\partial \mathbf{x}_{S,0}} + \sum_{k=1}^{N} \left[\left(\psi_D^{(k)}\right)^T \frac{\partial \mathbf{D}^{(k)}}{\partial \mathbf{x}_{S,0}} + \left(\psi_L^{(k)}\right)^T \frac{\partial \mathbf{L}^{(k)}}{\partial \mathbf{x}_{S,0}} + \left(\psi_S^{(k)}\right)^T \frac{\partial \mathbf{S}^{(k)}}{\partial \mathbf{x}_{S,0}} \right] + \left(\psi_S^{(0)}\right)^T \frac{\partial \mathbf{S}^{(0)}}{\partial \mathbf{x}_{S,0}} \right\} \frac{\partial \mathbf{x}_{S,0}}{\partial \mathbf{x}}$$

CFD Vision 2030 Report:

CFD-based MDAO limited by “one-off laborious, nonstandard interfaces”

[1] Sriram K. Rallabhandi, Eric J. Nielsen and Boris Diskin, “Sonic-Boom Mitigation Through Aircraft Design and Adjoint Methodology”, Journal of Aircraft, 2014

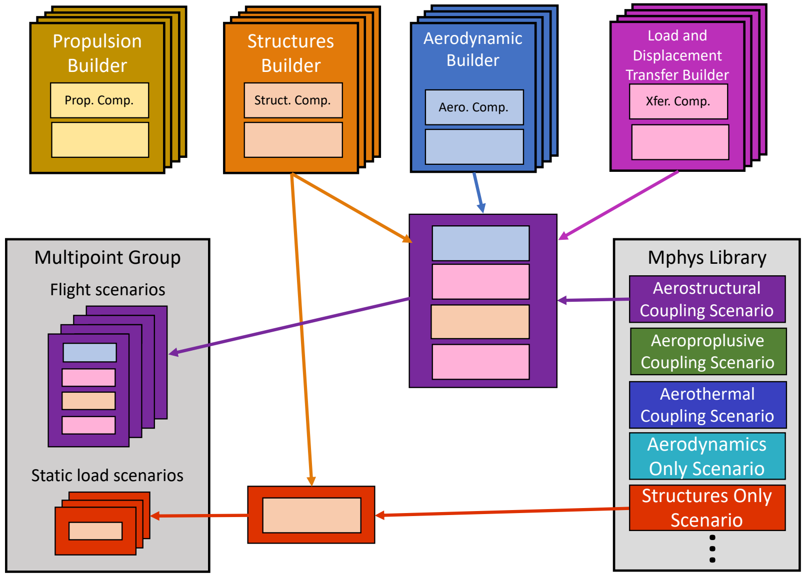
Mphys: An OpenMDAO Library

The goals are:

1. Create a modular high-fidelity MDAO environment
   - Address "one-off laborious interfaces" by standardizing interfaces and automated coupling
2. Close the gap between incomplete optimization problems in the research and industry needs

Mphys is a collaborative effort

- Open-source package developed with biweekly telecons
- Participants from:
  - Government: AFRL, NASA (LaRC, GRC, ARC)
  - Academia: Michigan, Georgia Tech, Stanford, Iowa State
  - Industry: Northrop Grumman, General Atomics

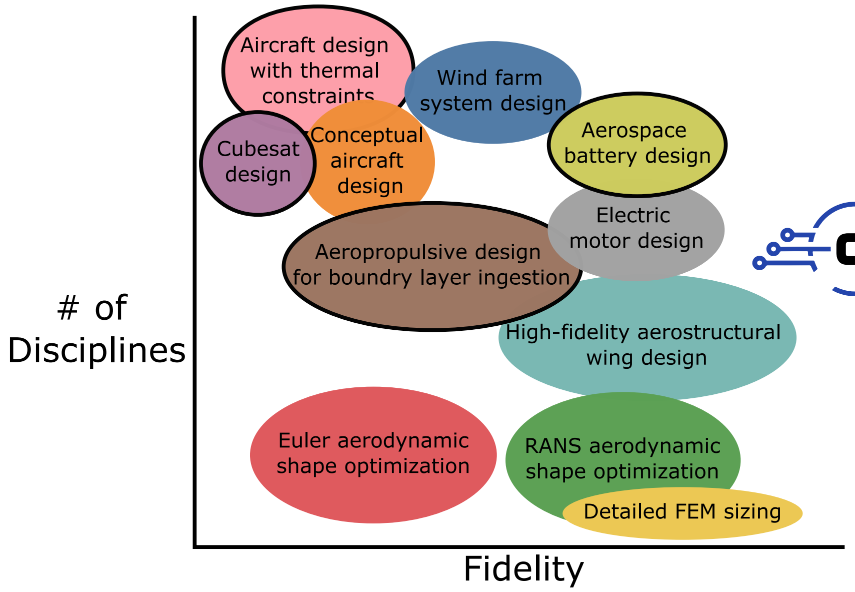


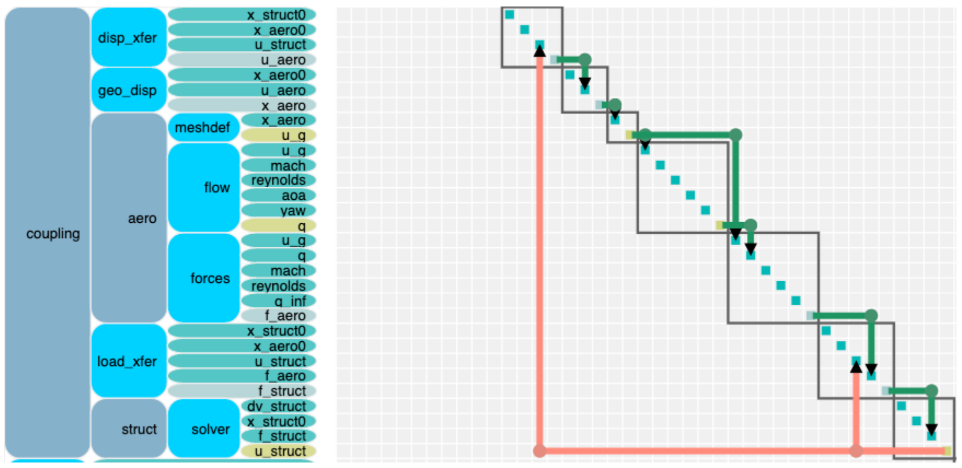
The Mphys package provides:

1. A library of standardized multiphysics problems for OpenMDAO
2. Utilities to set up optimization problems

Why use OpenMDAO for Mphys?

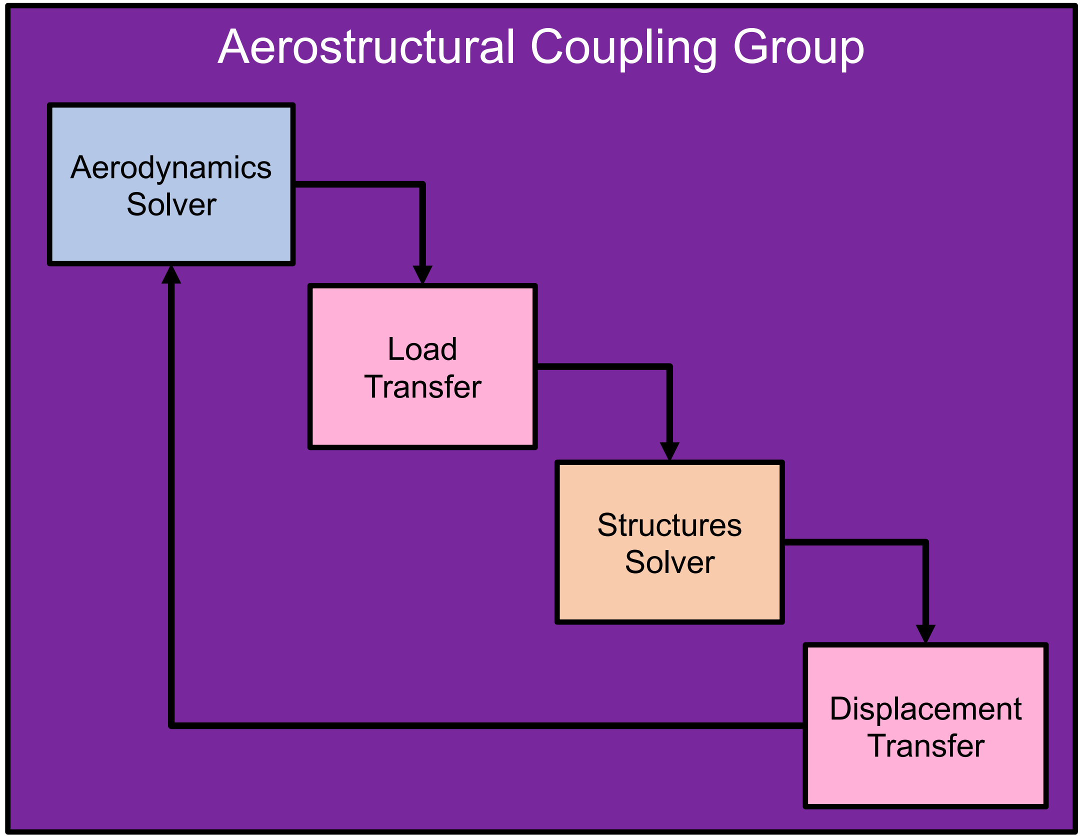
- **Automated coupled sensitivities**
  - Easier extension to new disciplines
  - Separation of responsibility and expertise
- **Ease of incorporating modularity**
- **Low barrier to entry**
  - Component development is simple for users
    - Custom objectives or constraints
  - Provides diagnostic tools for visualizing and checking a problem setup

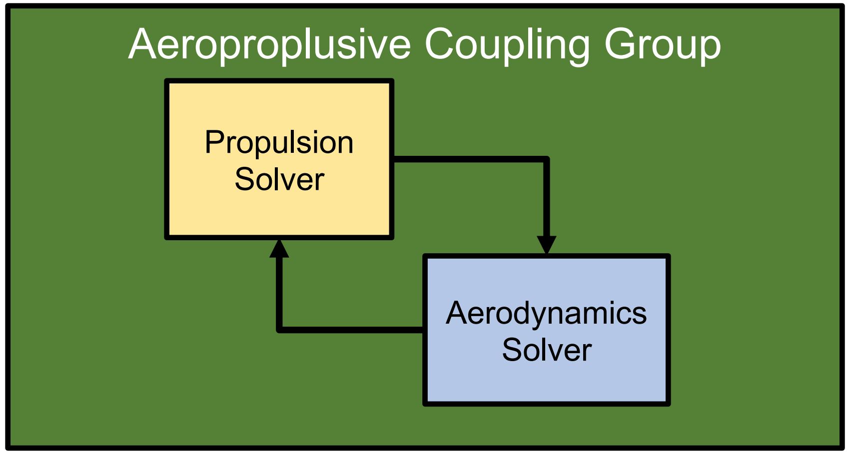




Mphys Model Hierarchy

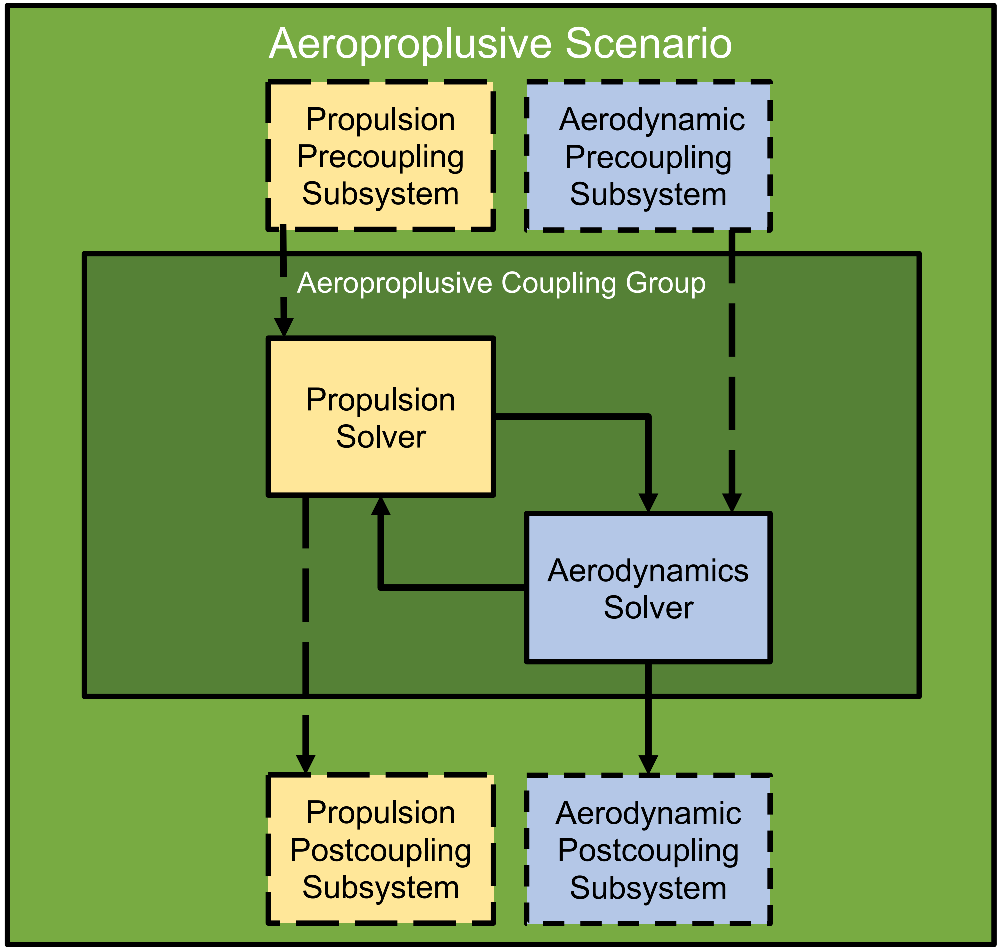
A Coupling Group represents the primary multiphysics problem

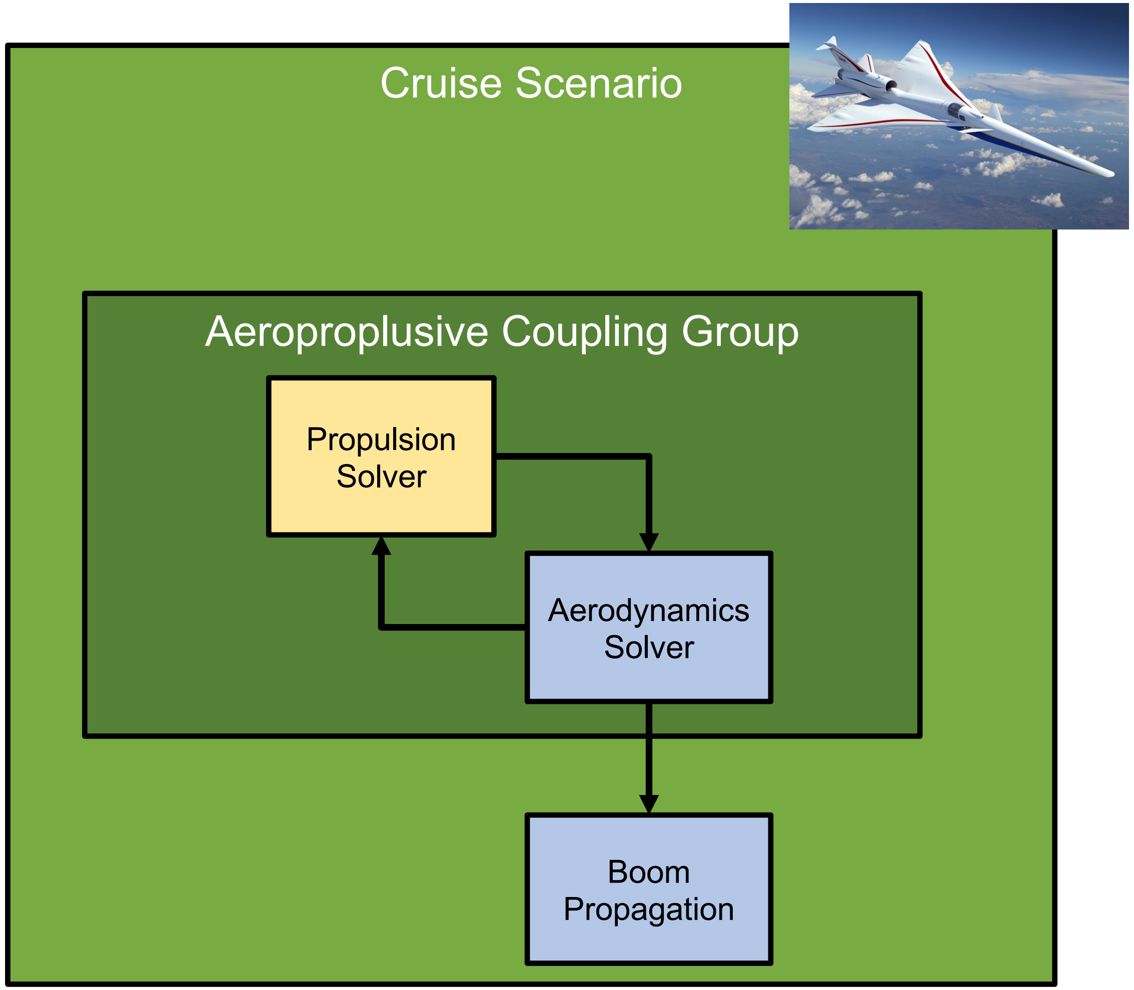




Mphys Model Hierarchy

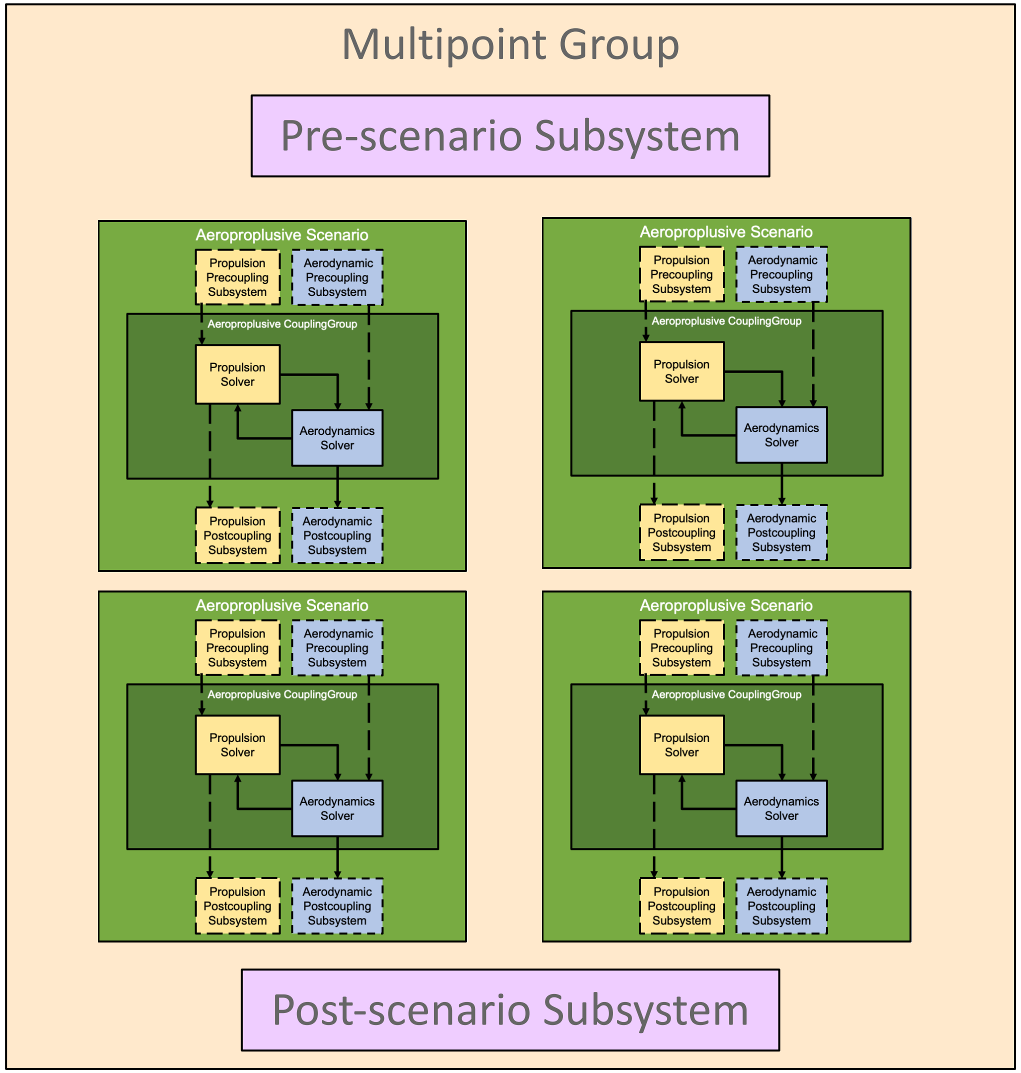
The Scenario groups hold components associated with a particular analysis condition

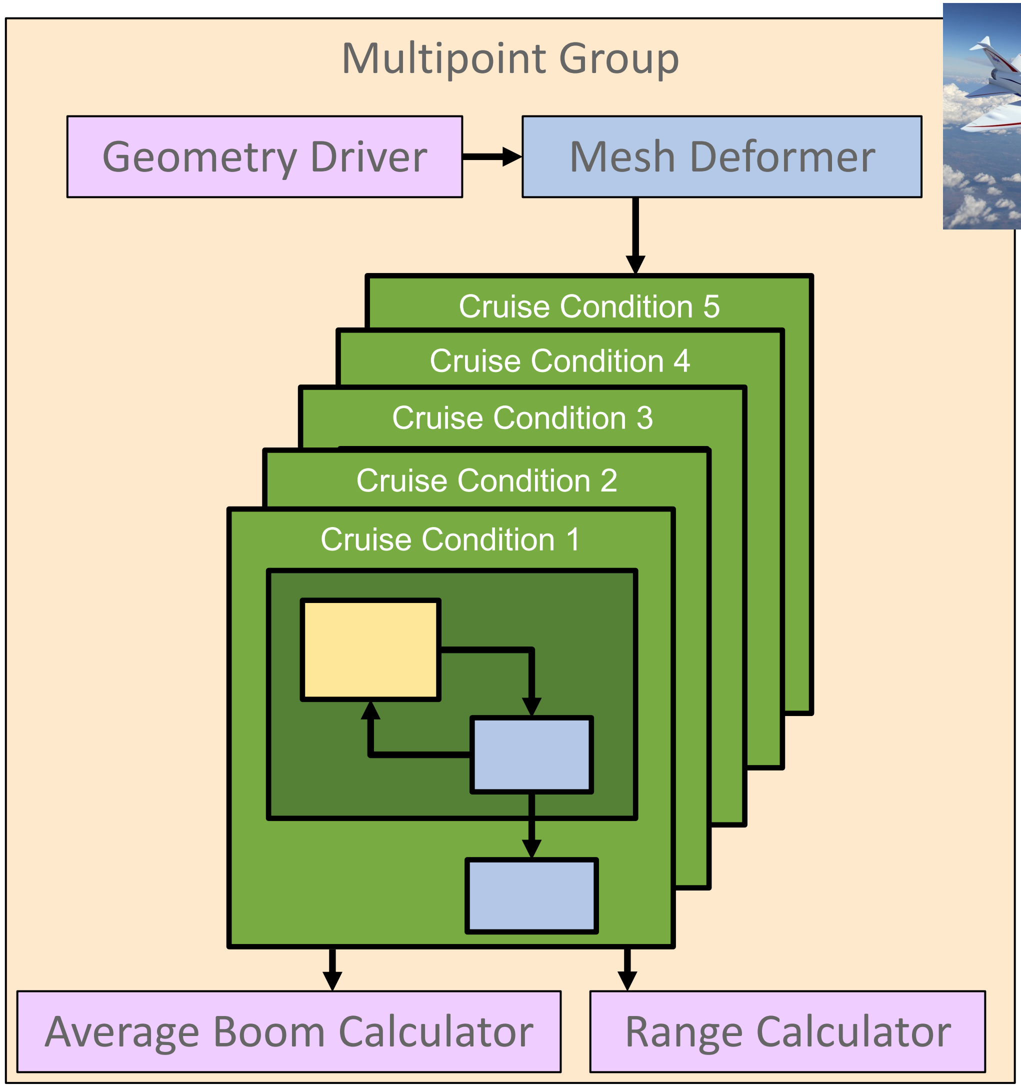




Mphys Model Hierarchy

Multipoint Groups hold a set of Scenarios and subsystems that interact with multiple Scenarios



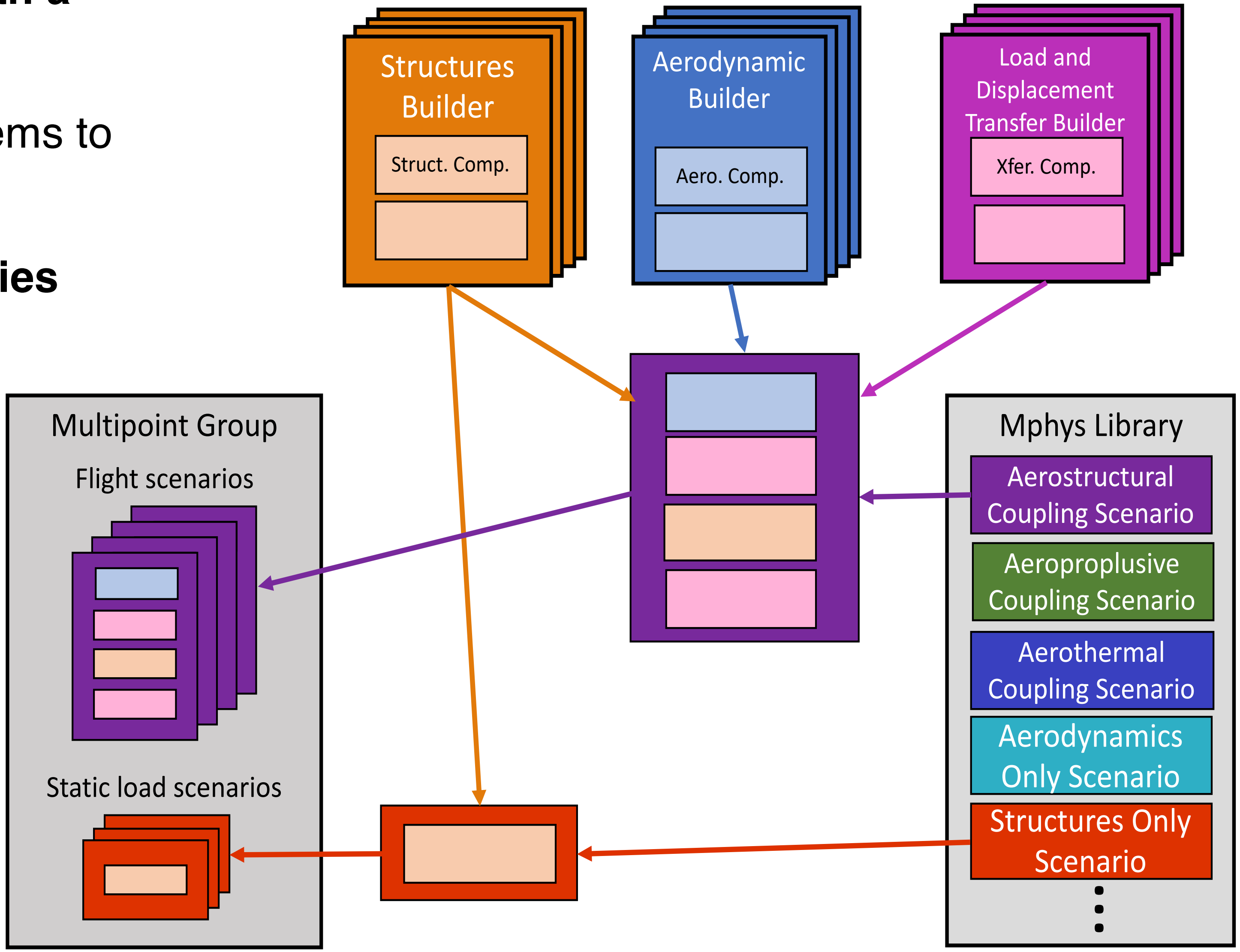


Mphys Builders

Builders are classes associated with a disciplinary solver

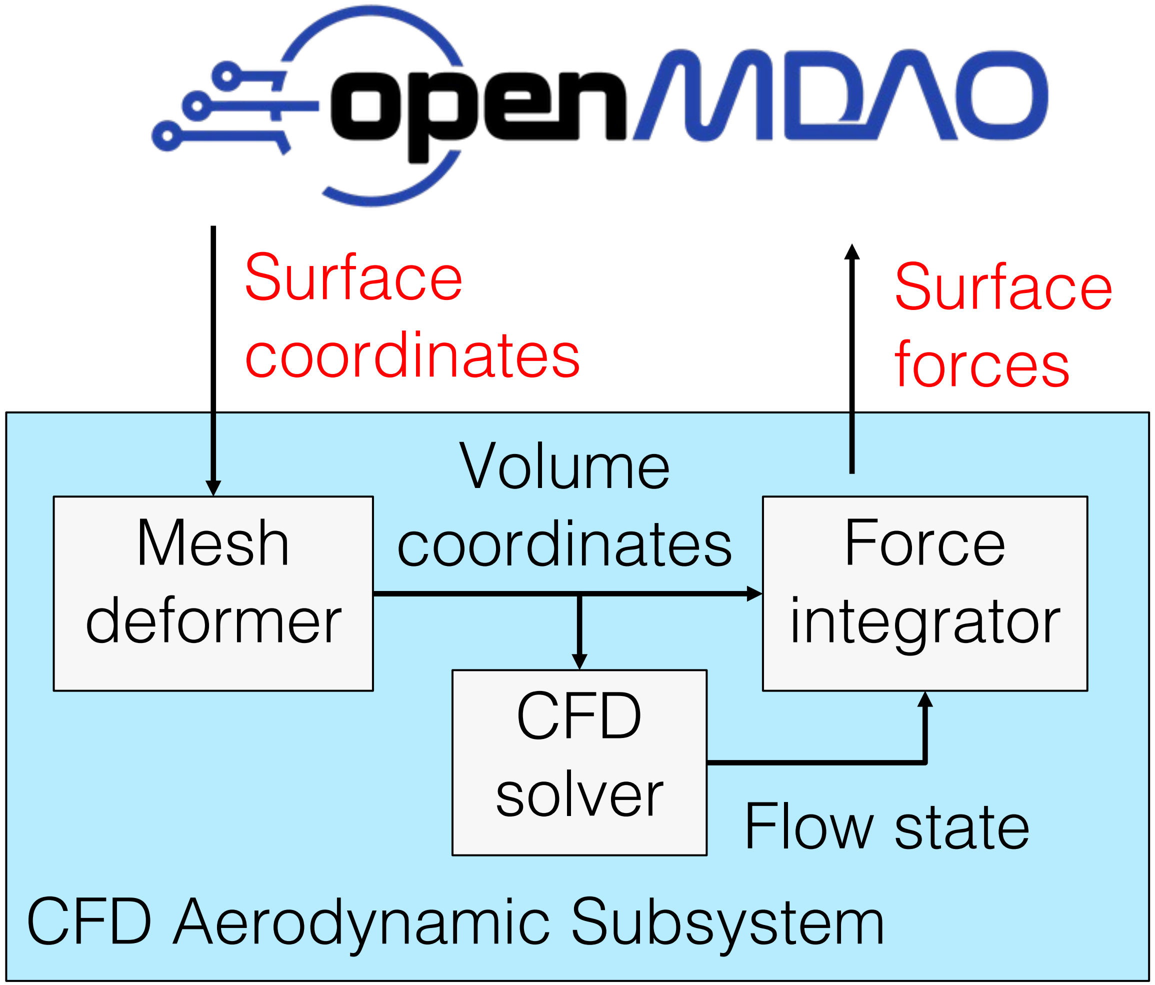
- Produce the OpenMDAO subsystems to populate the Mphys model

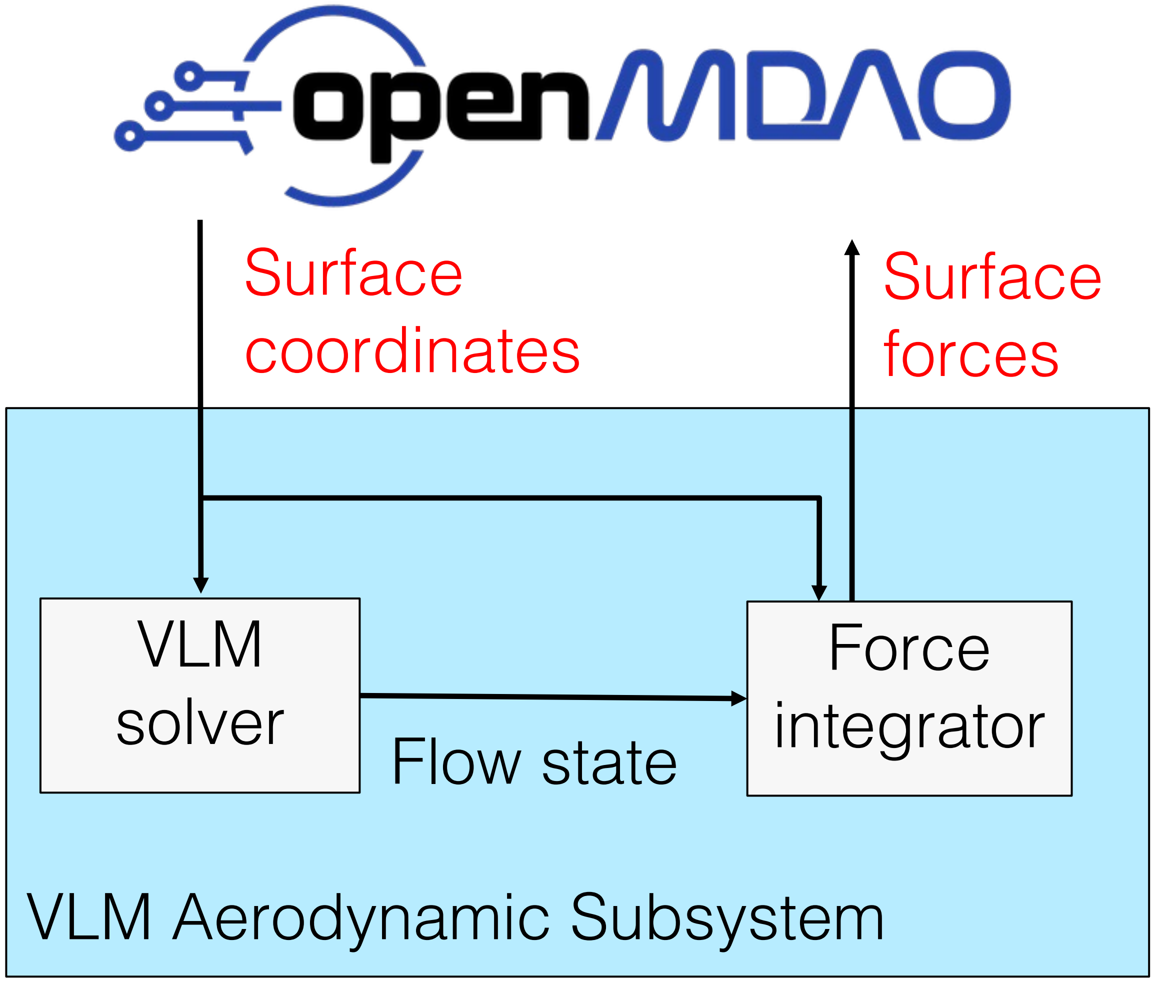
Builders + Scenario Library simplifies optimization problem setup



Standardization of Interface Definitions

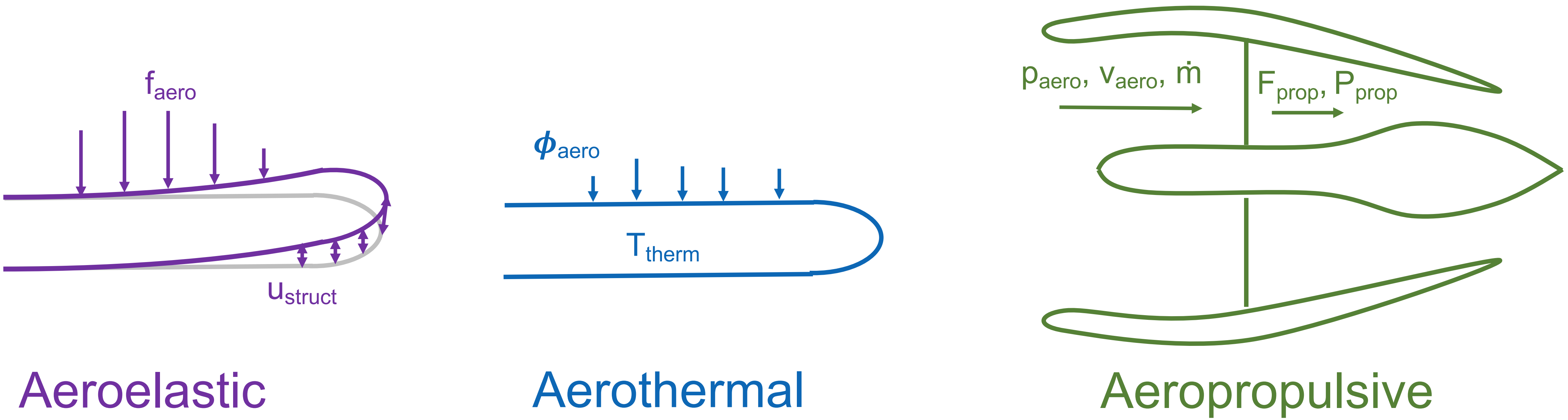
Minimum set of data to allow as many solvers to fit interface as possible





Standardized Interfaces in Mphys

- **Types of coupled problems addressed so far:**



- **Interfaces are defined as vectors of coupling states at domain boundaries**
  - Projection of these vectors from one mesh to another is handled by transfer components when necessary
  - Convention for naming of the coupling states across solvers allows modularity

Modularity with Mphys

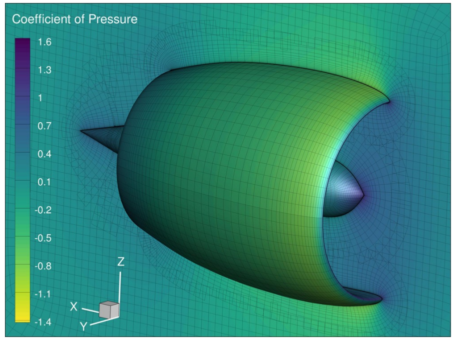
Flow Solvers:
FUN3D (SFE, FV*)
Cart3D*
ADflow
SU2*
DAFOAM
VLM
OpenAeroStruct VLM

Structural Solvers:
TACS
pyshell
Modal Structural Solver
NASTRAN*

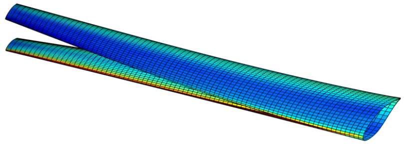
Propulsion:
pyCycle

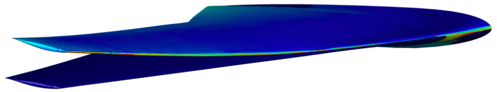
Load and Displacement Transfers:
FUNtoFEM (MELD, RBF)
Rigid Link Transfer

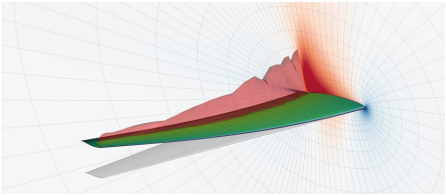
Geometry:
pyGeo (wraps OpenVSP, ESP, FFD)

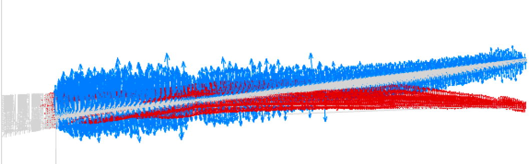


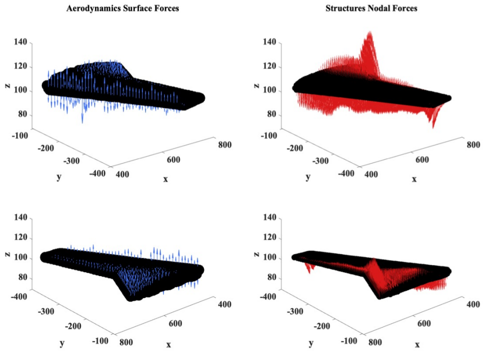
ADflow+pyCycle (Michigan)


VLM+MELD+TACS


FUN3D+MELD+TACS


ADflow+RLT+TACS (Michigan)


SU2+MELD+TACS (Stanford)

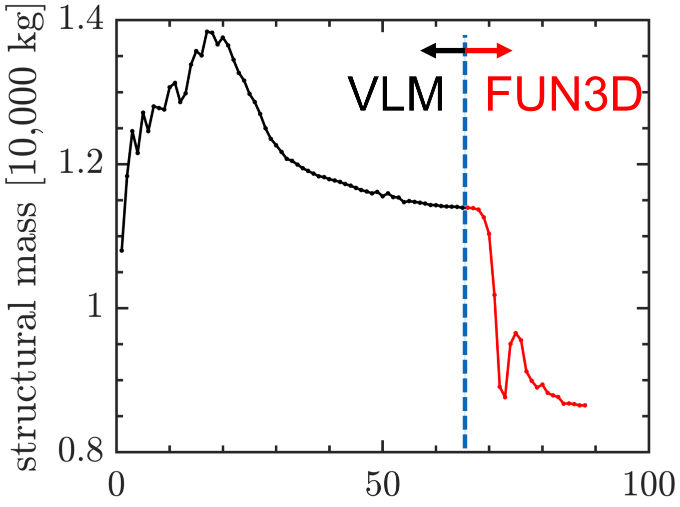


SU2+MELD+NASTRAN (Stanford)

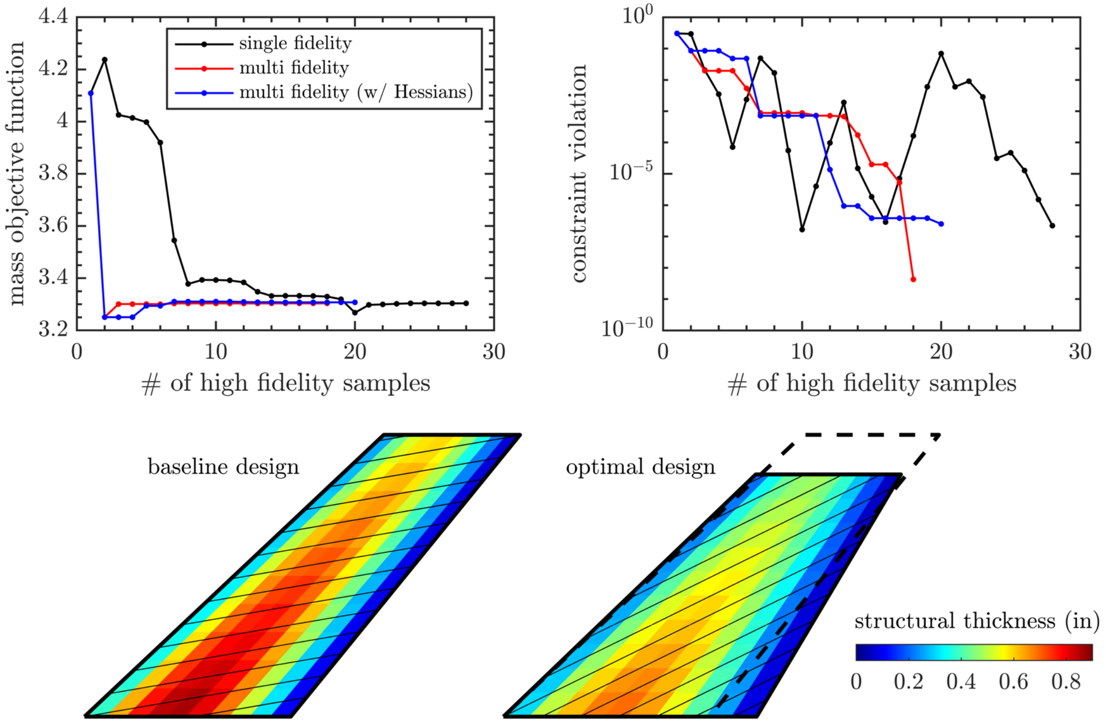
*Partially integrated

What can you do with the Modularity?

1. **Easier transfer of technology**
2. **Work out kinks in high-fidelity optimization problem with lower fidelities**
   - Scaling of DVs
   - Relative weight of competing objectives
   - Identify missing constraints
3. **UQ – swap components to see effect on analysis or optimization**
4. **Reduce cost of optimization**
   - Sequence physics during optimization
   - Multifidelity optimization



Sequencing of physics



Multifidelity flutter-constrained optimization

Aeroelastic Optimization with Physics Sequencing

Objective:

- Minimize the mass of the wingbox

Constraints at maneuver condition:

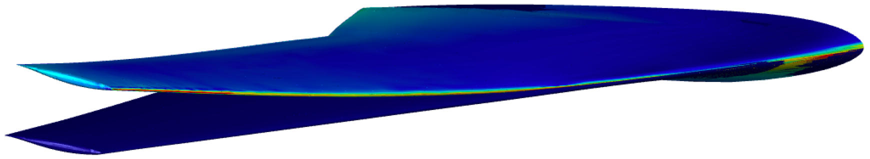
- Trim: L=2.0W
- Stress: 1.5 * KS failure < 1.0

Design variables:

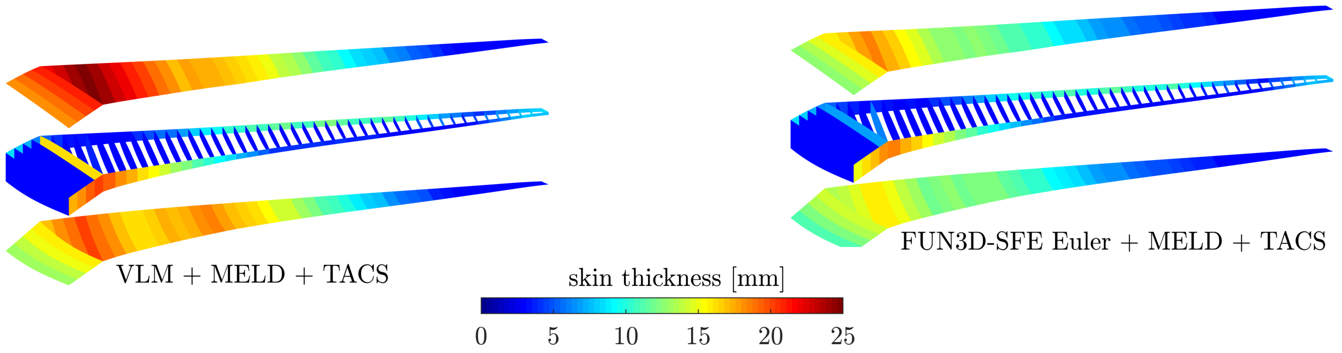
- Angle of attack (1)
- Wingbox panel thicknesses (240)

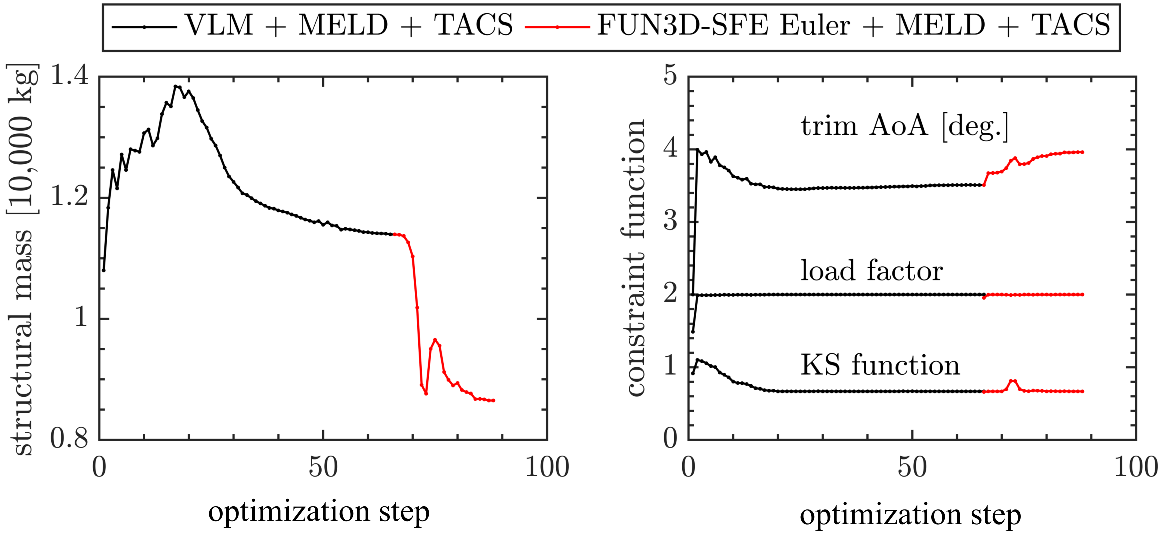
Optimization process:

1. Perform optimization with VLM
2. Use VLM result as initial condition for CFD aerodynamics



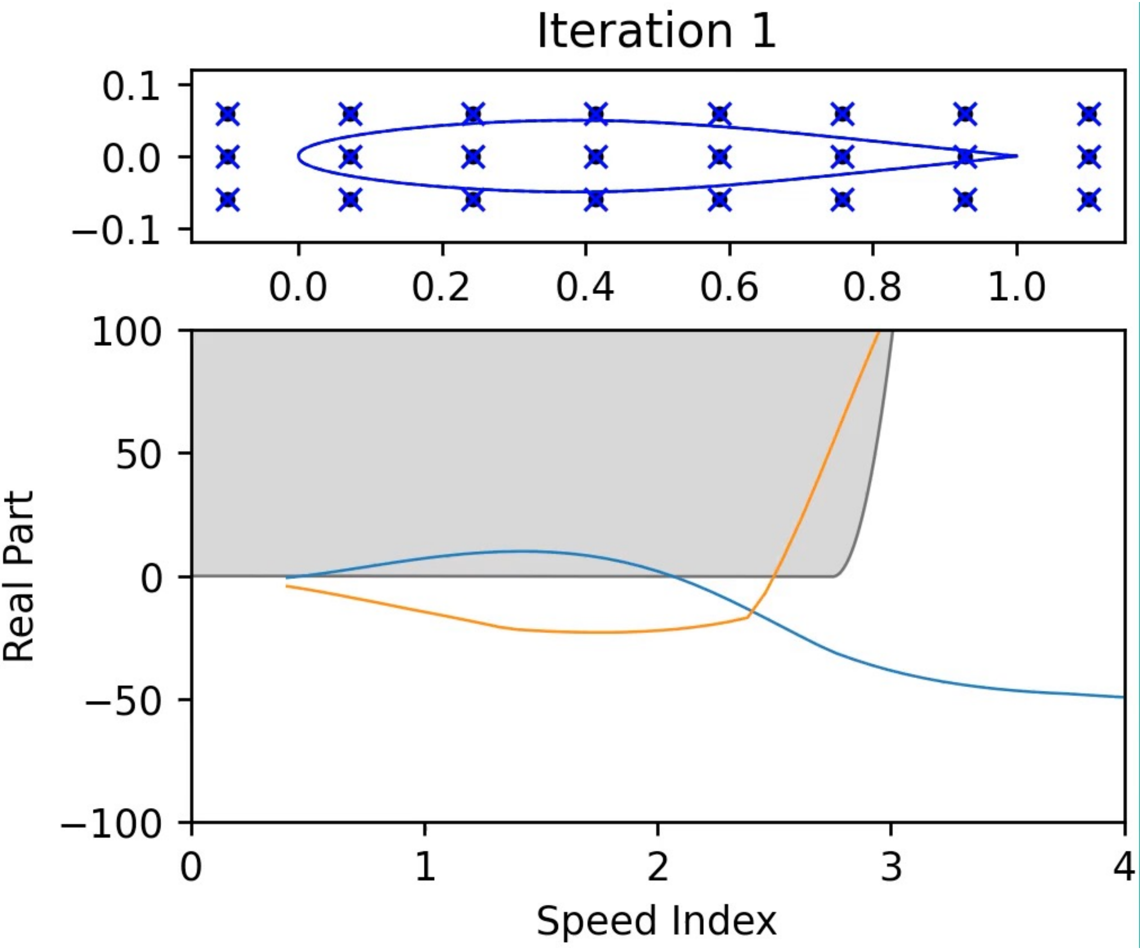
FUN3D-SFE Euler + MELD + TACS

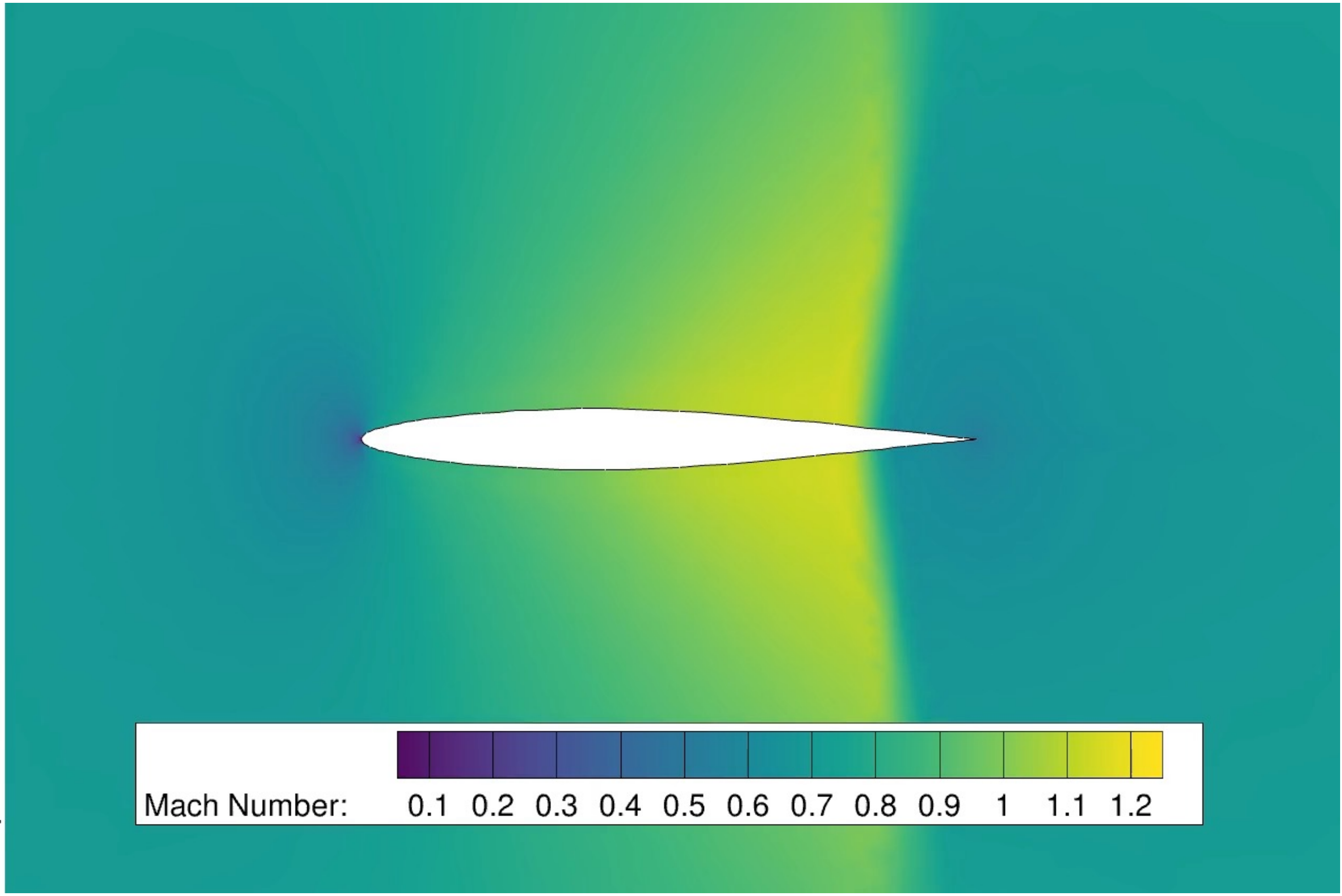




Isogai Airfoil – Flutter-Constrained Optimization

- **By changing the post-coupling groups, we can do flutter constraints**



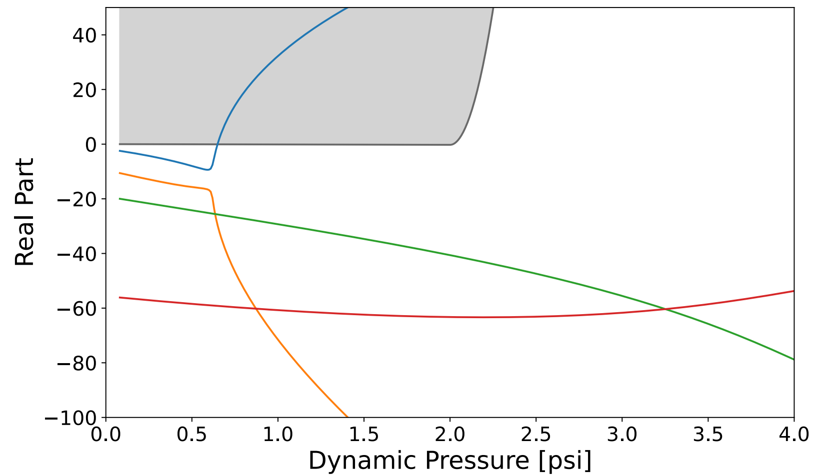


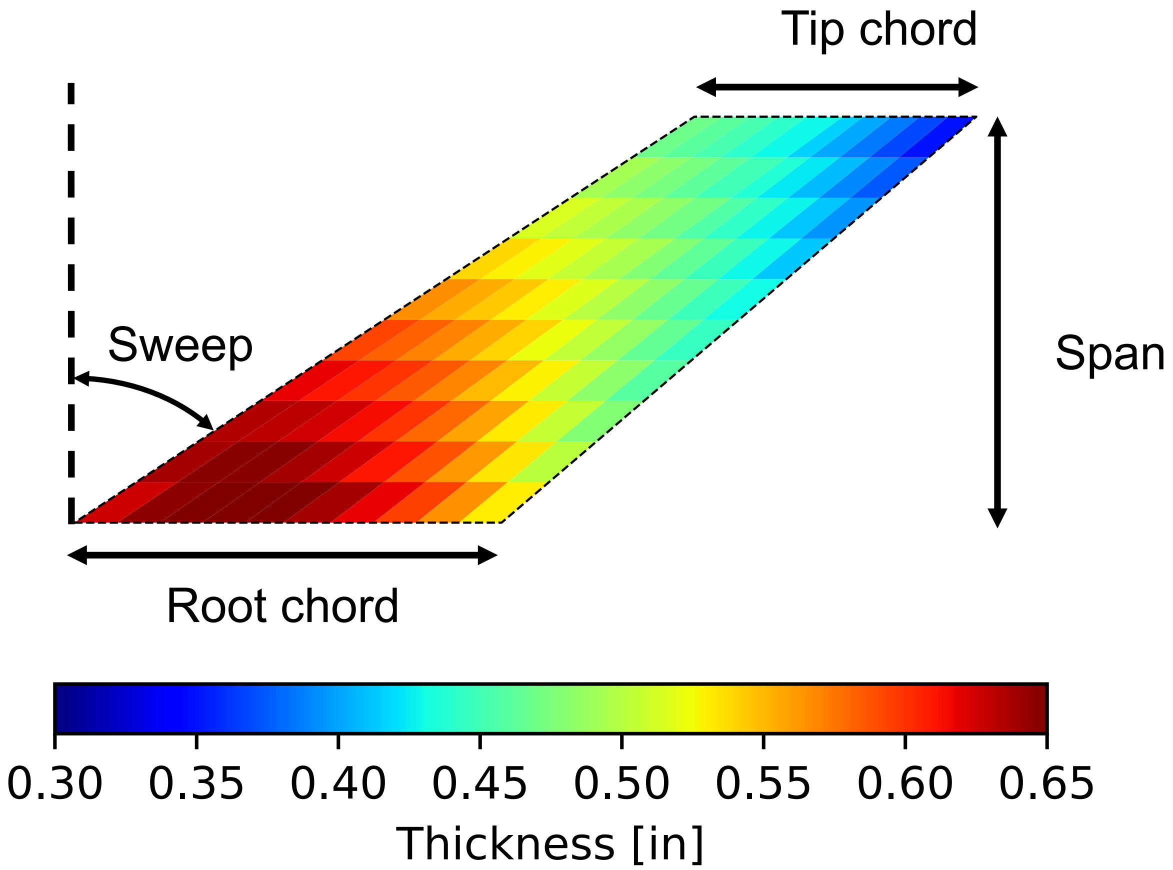
AGARD 445.6 Wing – Optimization Problem

- **Inviscid, symmetric wing at Mach 0.5**
  - Performed with LFD and Doublet Lattice Method (DLM) flutter analysis
- **Minimize the mass subject to flutter constraint and fixed planform area**

$$\begin{aligned} \min \quad & mass \\ \text{subject to:} \quad & KS_{flutter} \leq 0 \\ & A = A_0 \end{aligned}$$

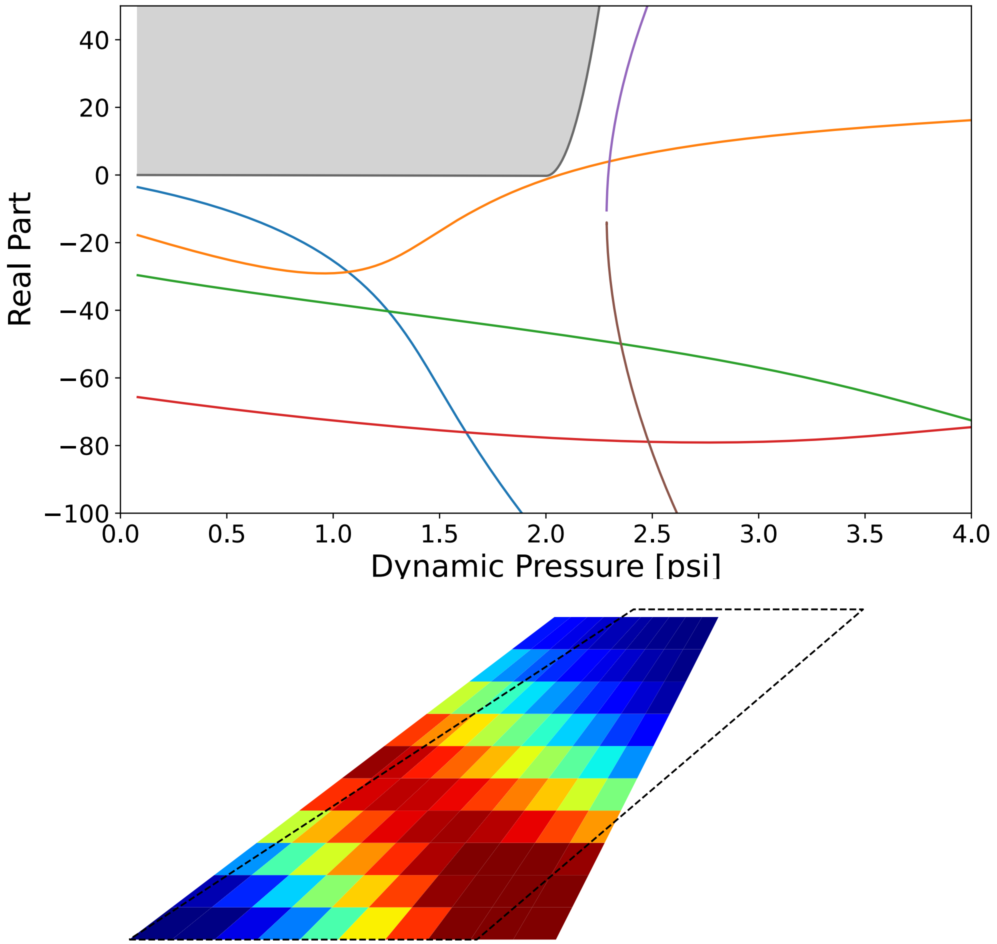
- **104 design variables**
  - 100 structural thicknesses
  - 4 geometric (affect aero. and struct. meshes)



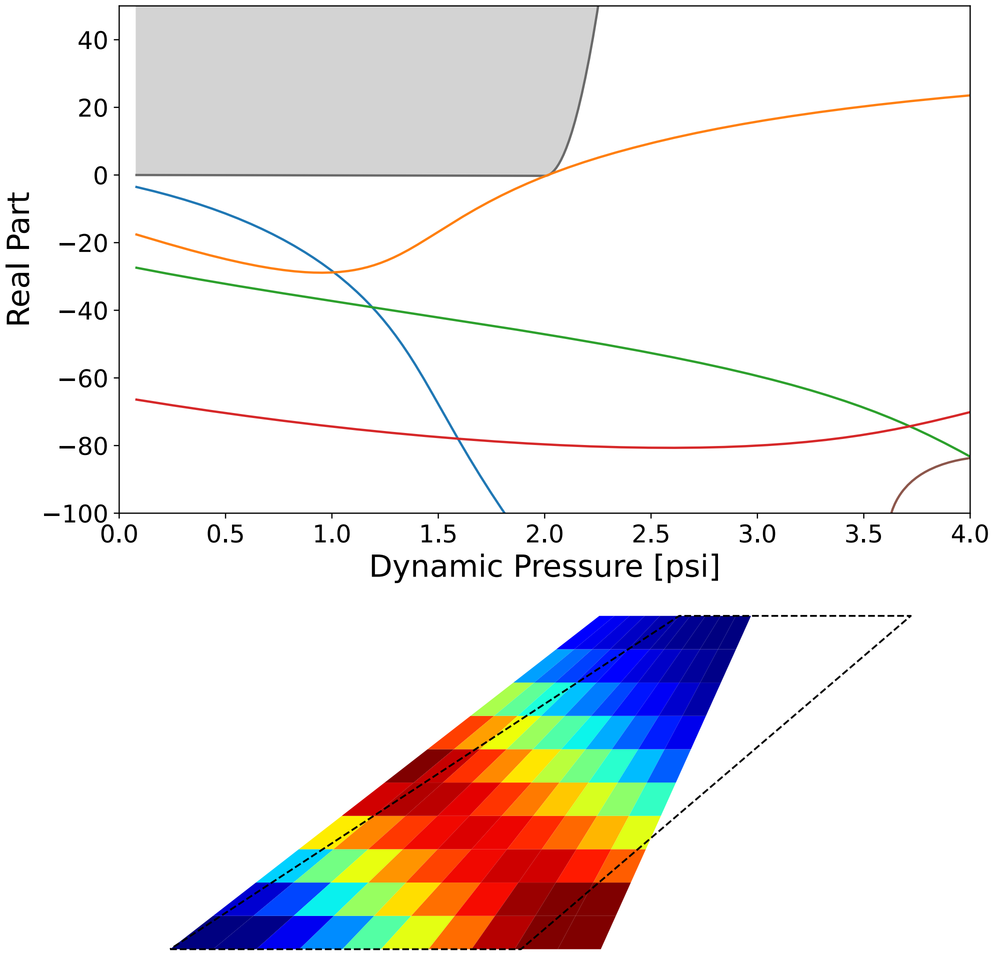


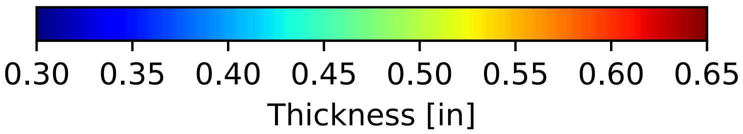
AGARD 445.6 – Optimized Designs

LFD



DLM





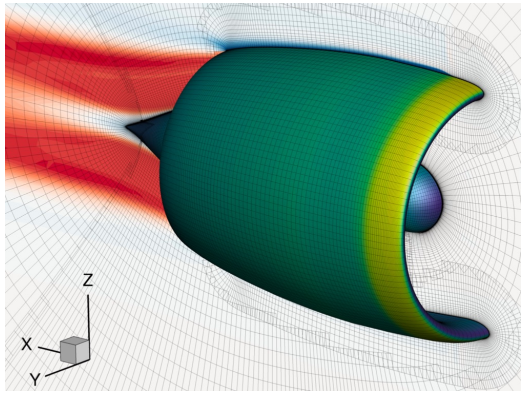
Conclusions

Mphys is a collaborative effort to standardize coupling in high-fidelity MDAO

- Participants from government, academia, and industry
- Initial disciplines being considered are aerodynamics, structures, propulsion, and heat conduction

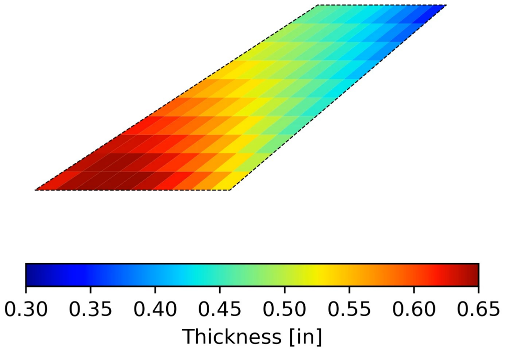
The Mphys library is an implementation of this standard

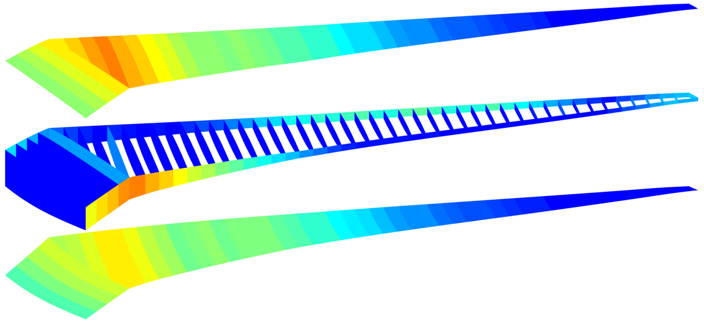
- Uses OpenMDAO for automated coupling analysis and sensitivities
- Provides utilities to simplify the optimization problem setup



Flexibility of Mphys has been demonstrated

- Analyses and optimizations of the same problems with different solvers
- Different types of multiphysics problems
- Swap different fidelities for the same discipline





Mphys Workshop

- **Learn more at the workshop tomorrow**
  - See applications of Mphys
  - See and influence future directions of Mphys
  - Virtual attendance option. For more information email me: kevin.e.jacobson@nasa.gov

Mphys: https://github.com/OpenMDAO/mphys