



AFRL-RQ-WP-TM-2017-0017

**SENSITIVITY ANALYSIS FOR MULTIDISCIPLINARY
SYSTEMS (SAMS)**

**Richard D. Snyder
Design & Analysis Branch
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**FEBRUARY 2017
Interim Report**

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1. REPORT DATE (DD-MM-YY) February 2017		2. REPORT TYPE Interim		3. DATES COVERED (From - To) 12 February 2015 to 02 February 2017	
4. TITLE AND SUBTITLE SENSITIVITY ANALYSIS FOR MULTIDISCIPLINARY SYSTEMS (SAMS)				5a. CONTRACT NUMBER In-house	
				5b. GRANT NUMBER N/A	
				5c. PROGRAM ELEMENT NUMBER 62201F	
				5d. PROJECT NUMBER 2401	
				5e. TASK NUMBER N/A	
6. AUTHOR(S) Richard D. Snyder				5f. WORK UNIT NUMBER Q1FS	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Design & Analysis Branch (AFRL/RQVC) Aerospace Vehicles Division, Air Force Research Laboratory Aerospace Systems Directorate Wright-Patterson Air Force Base, OH 45433-7541 Air Force Materiel Command , United States Air Force				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-RQ-WP-TM-2017-0017	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Aerospace Systems Directorate Wright-Patterson Air Force Base, OH 45433-7541 Air Force Materiel Command United States Air Force				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/RQVC	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RQ-WP-TM-2017-0017	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.					
13. SUPPLEMENTARY NOTES This technical memo is a series of Microsoft PowerPoint slides, comprising an interim briefing for this work effort. PA Case Number 88ABW-2016-6159; Clearance Date: 30 Nov 2016.					
14. ABSTRACT The Sensitivity Analysis for Multidisciplinary Systems (SAMS) program aims to provide the aerospace community with reliable and robust tools for the economical and accurate evaluation of sensitivities for multidisciplinary design and analysis. The program is building on the well-known and widely-used FUN3D computational fluid dynamics solver, modularizing and expanding it to include adjoint-based aeroelastic sensitivities. The aeroelastic modeling will eventually support both mode-based structural representations and time-dependent, nonlinear finite element structural dynamics. This interim report describes progress towards the goals of the program.					
15. SUBJECT TERMS aeroelasticity, multidisciplinary analysis, multidisciplinary design, adjoint method, sensitivity analysis					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	18. NUMBER OF PAGES 40	19a. NAME OF RESPONSIBLE PERSON (Monitor) Richard D. Snyder
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include Area Code) N/A

Sensitivity Analysis for Multidisciplinary Systems (SAMS)



Integrity ★ Service ★ Excellence

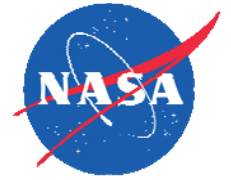
01 Dec 2016

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Multidisciplinary Science & Technology Center
Air Force Research Laboratory



AFRL-NASA Collaboration



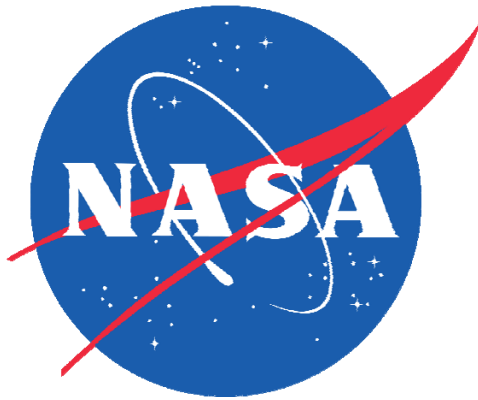
Provide
economical, accurate sensitivities
for multidisciplinary design
and analysis



Computational AeroSciences

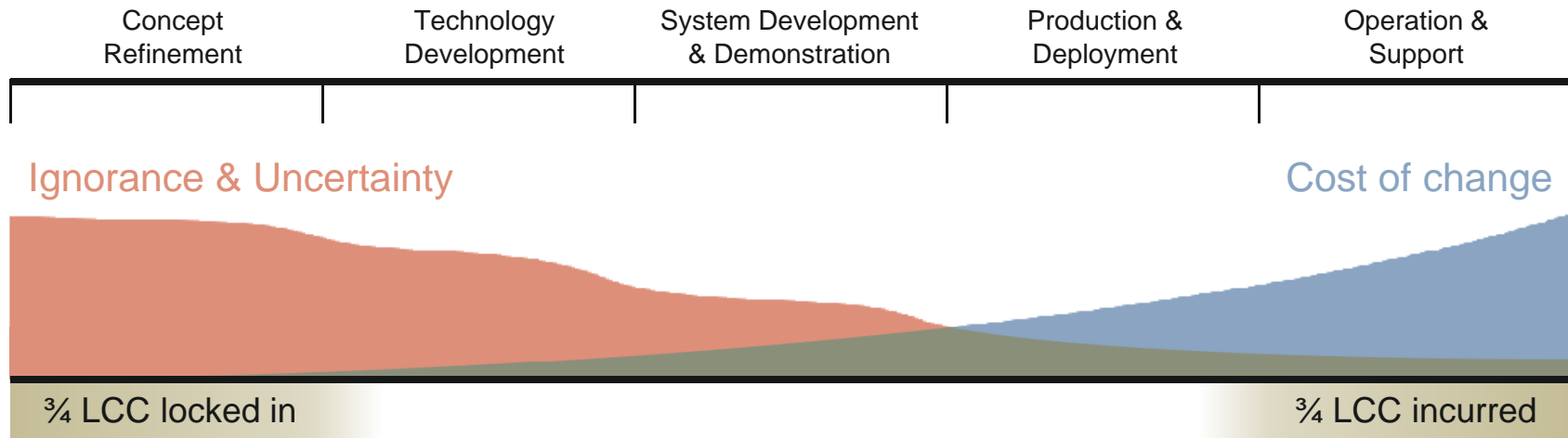
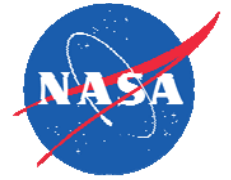


SAMS Overview





Cost & Capability

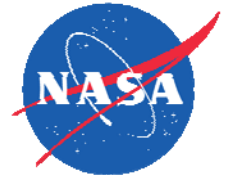


- Knowledge is most limited when majority of cost is locked in
- Limited knowledge inevitably leads to mistakes
- Changes become more expensive over time
- Correcting/accepting mistakes means cost growth and/or lost capability



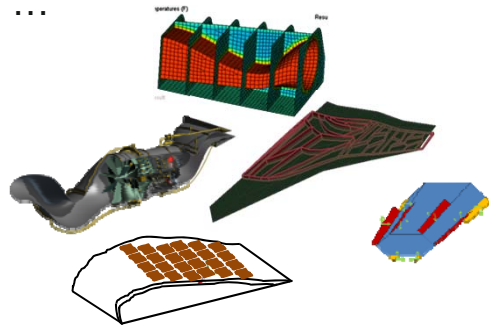


Technology Impact



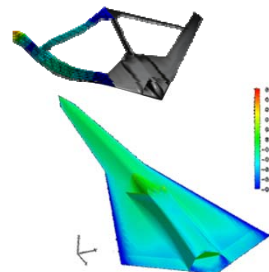
Candidate Technologies

- Aeroelastic wing
- Flutter suppression
- Third stream engine
- Advanced materials
- Thrust vectoring
- Innovative control effectors
- Directed energy
- Conformal load bearing antennas
- ...



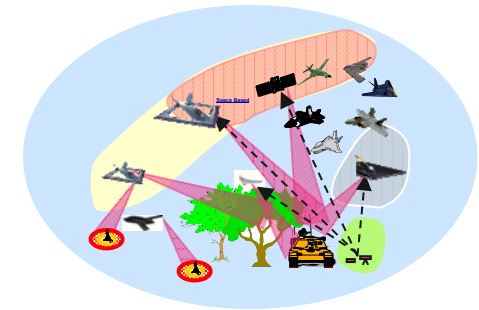
Engineering Capability

- Weight
- Drag
- Roll performance
- Yaw performance
- RCS
- Fuel efficiency
- Sensor efficiency
- ...



Mission Capability

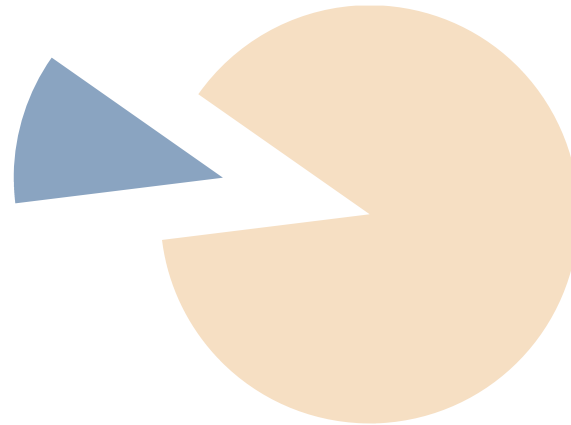
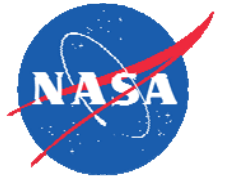
- Life cycle cost
- Survivability
- Maintainability
- Kills per \$
- IDs per \$
- ...



Use accurate physical models to obtain $\frac{\partial(\text{Mission Capability})}{\partial(\text{Technology})}$



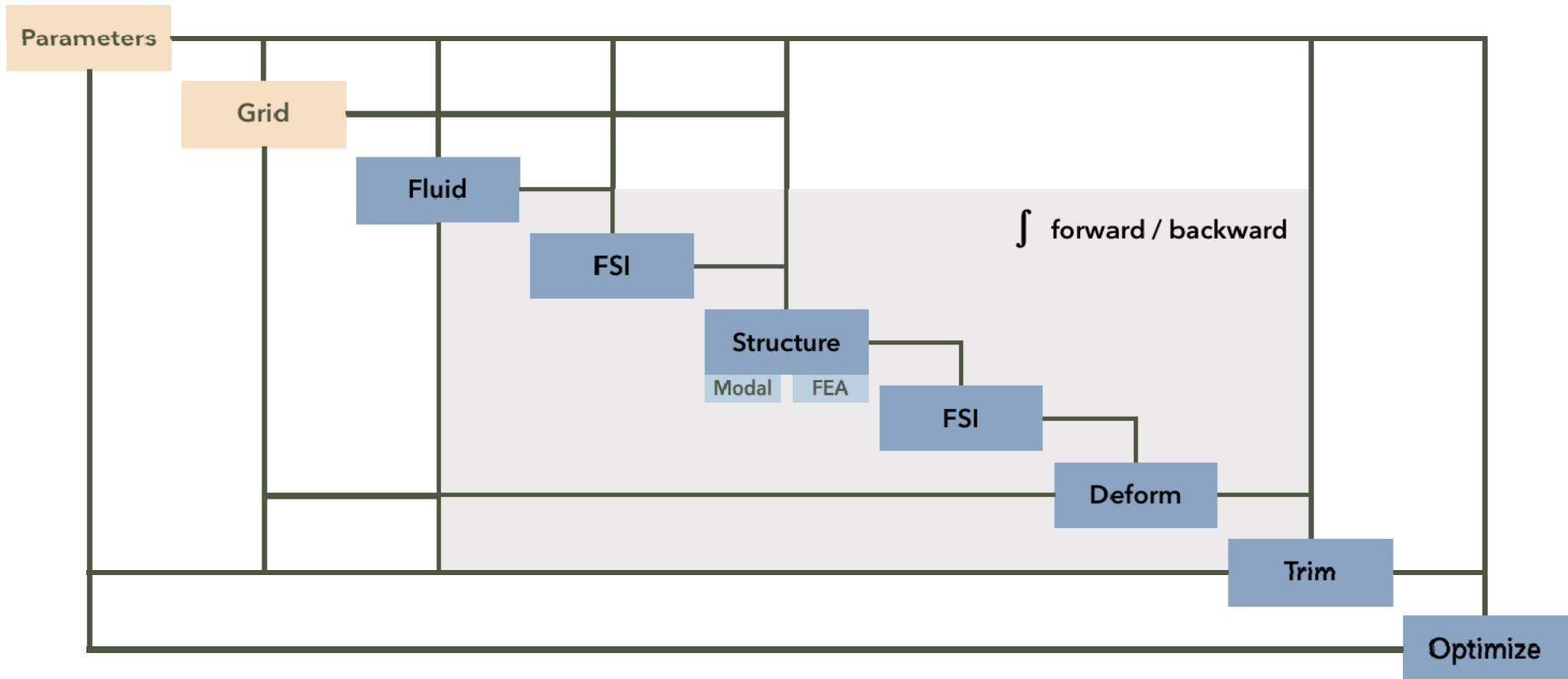
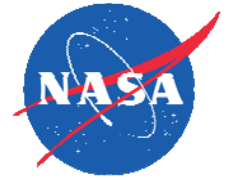
Contribution



- CFD-based analytic aeroelastic sensitivities
- Steady and transient solutions
- Nonlinear structural dynamics
- Demonstrated capability
- Enhanced FUN3D



Components



LEGEND



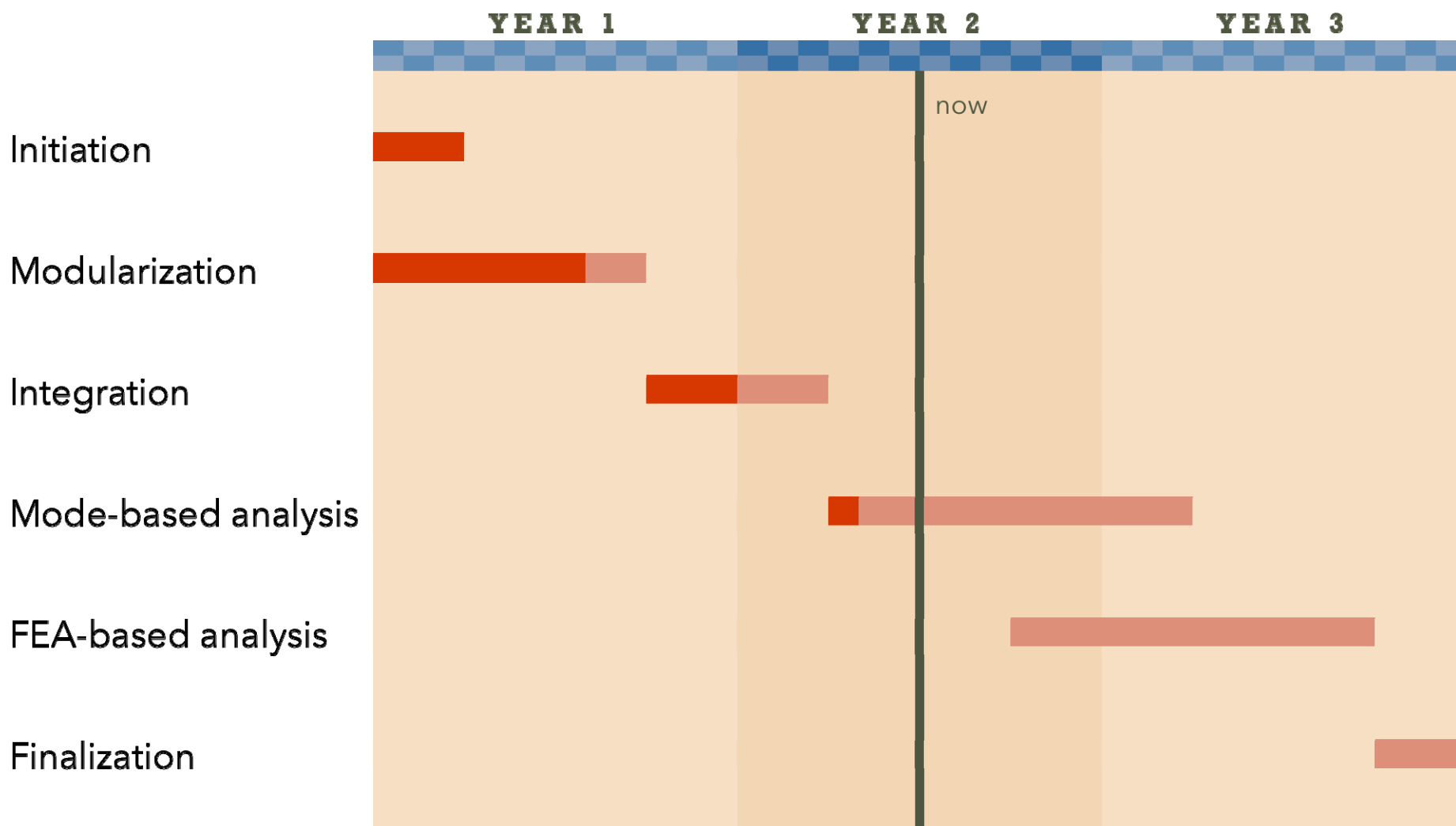
SAMS component



External component

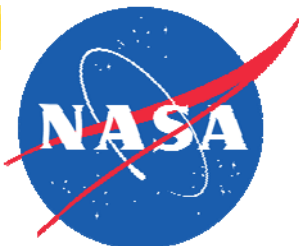
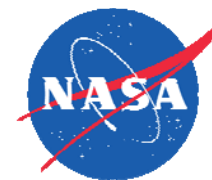


Schedule





Current and Potential Customers



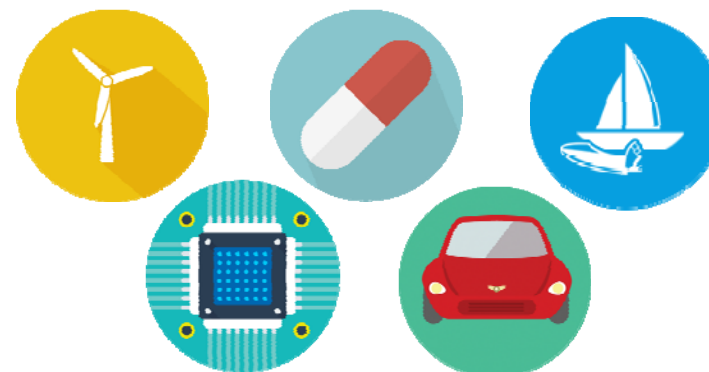
Government institutions



Academia



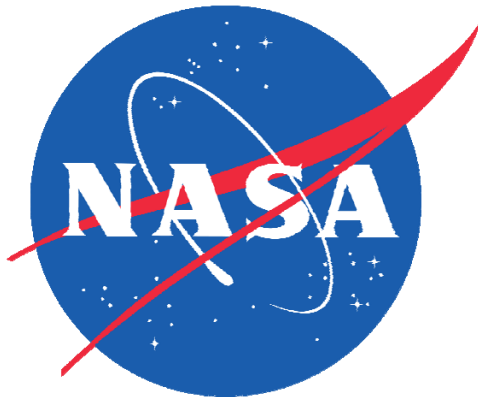
Aerospace companies



Other industries



Hermes Integration Framework





Layered Networking



Components in a multidisciplinary simulation each have their own communication requirements, driving a layered networking model

MSTC Engineering <<<or similar>>>

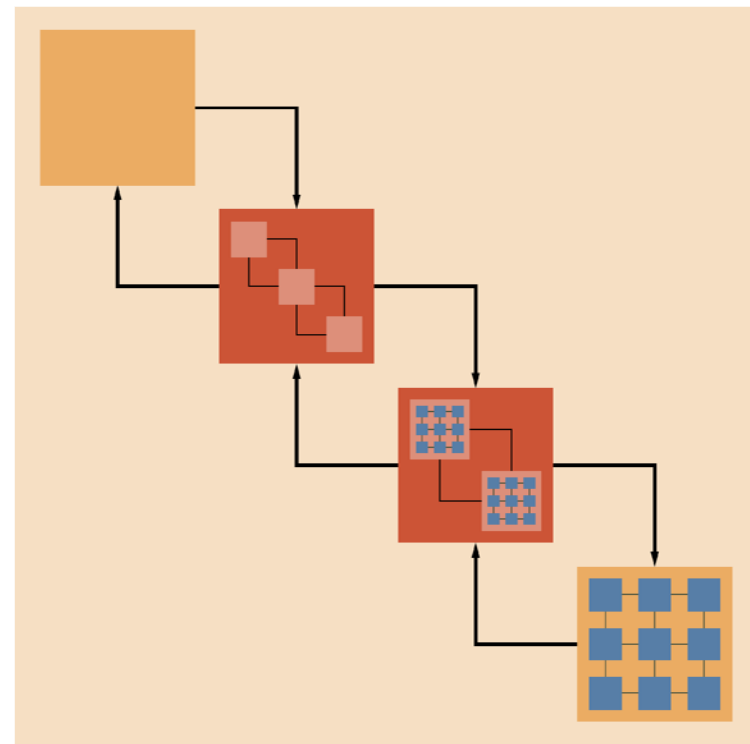
- MADO process model
- Geographically distributed components

Hermes <<<built for SAMS>>>

- Fast coupling for unsteady analysis
- Locally distributed components

MPI

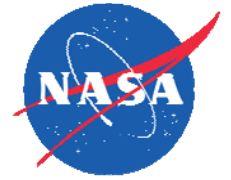
- Very fast coupling within a component
- Execution on a cluster/supercomputer



Notional N² diagram



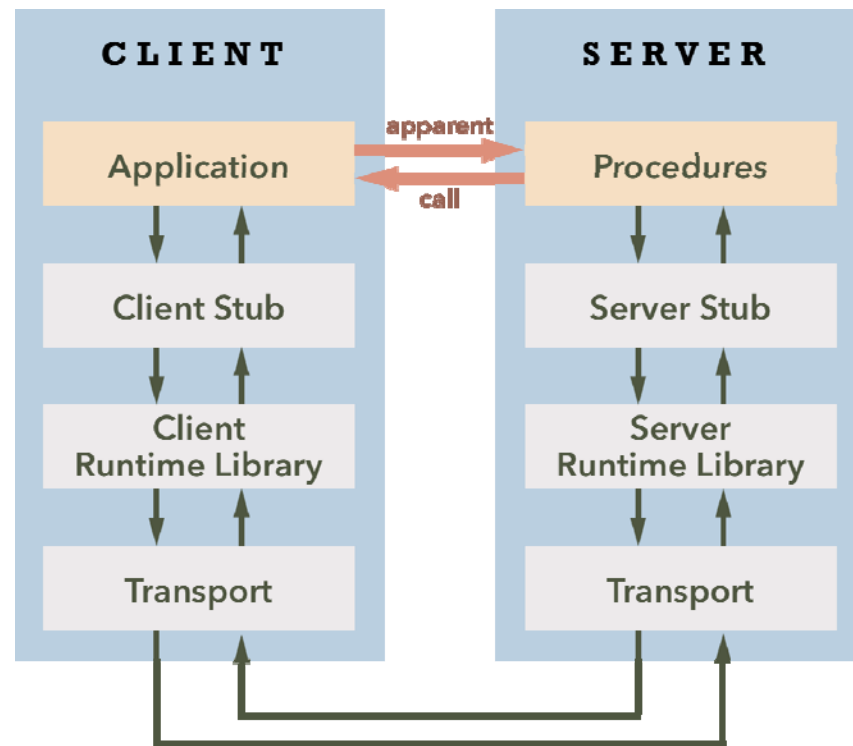
Hermes Framework



Characteristics

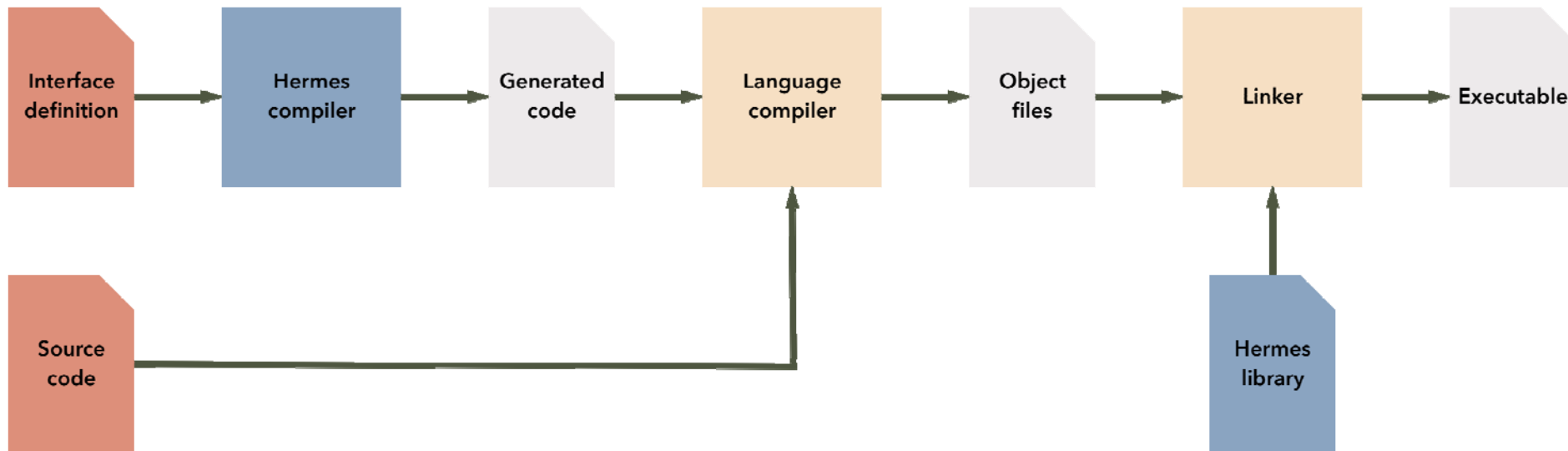
- Remote procedure calls
- Cross-language
 - C++
 - Fortran 2003
 - Python
 - ...
- Built on ØMQ
 - Client-server communication
 - Message based
 - Several transport protocols
 - Several messaging patterns

Remote Procedure Call









Process

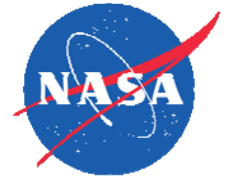


LEGEND

-  Written by a developer
-  Hermes components
-  Other tools
-  Generated files



Interface Definition



```
structure point {  
  real64 x,  
  real64 y  
}  
  
exception oops {  
  int32 code  
}  
  
interface geometry {  
  
  point centroid(vector<point> ps) throws (oops),  
  real64 distance(point p, point q)  
  
}
```

Defines a server's remotely callable procedures



Server and Client Code



Server

```
from geometry import Point, Geometry
import math
import zmq

class Server(Geometry.Server):
    def distance(self, p, q):
        dx = q.x - p.x
        dy = q.y - p.y
        return math.sqrt(dx * dx + dy * dy)
    def centroid(self, ps):
        x = sum([p.x for p in ps]) / len(ps)
        y = sum([p.y for p in ps]) / len(ps)
        return Point(x, y)

addr = 'tcp://*:49152'
ctx = zmq.Context()
srv = Server(ctx, addr, zmq.REP)
srv.serve()
srv.close()
ctx.destroy()
```

Client

```
from geometry import Point, Geometry
import zmq

addr = 'tcp://localhost:49152'
ctx = zmq.Context()
cli = Geometry.Client(ctx, addr, zmq.REQ)

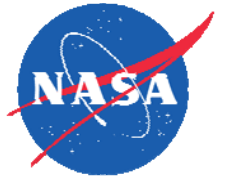
p = Point(1.2, 3.4)
q = Point(5.6, 7.8)
c = cli.centroid([p, q])
d = cli.distance(p, q)

cli.close()
ctx.destroy()
```

Developer can focus on the business logic



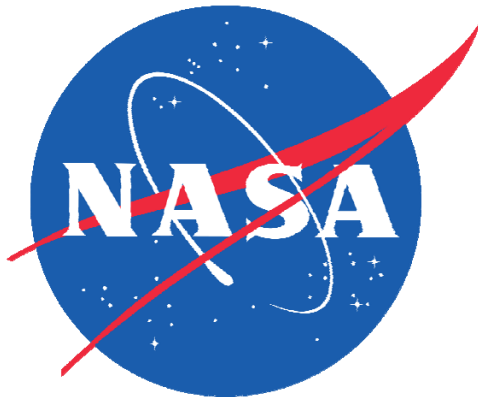
Future Directions



- Expand type support in Fortran
- Develop better documentation
- Optimize for performance
- Support more programming languages
- Asynchronous "futures" model



MAST & YAMSS Structural Solvers





MAST



Multidisciplinary Design, Adaptation, & Sensitivity Toolkit

- Elasticity, heat transfer, & compressible flow
- Adjoint solver for sensitivity analysis
- High-order finite elements
- Feature-based and goal-oriented adaptation
- MPI- and thread-based parallelism



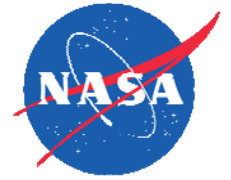
Structures



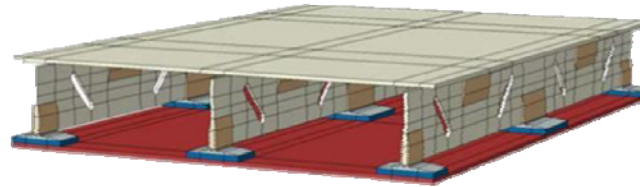
- Buckling, modal, steady, & transient problems
- Linear and nonlinear elements
- Geometric and material nonlinearities
- Can solve linear analysis about nonlinear point



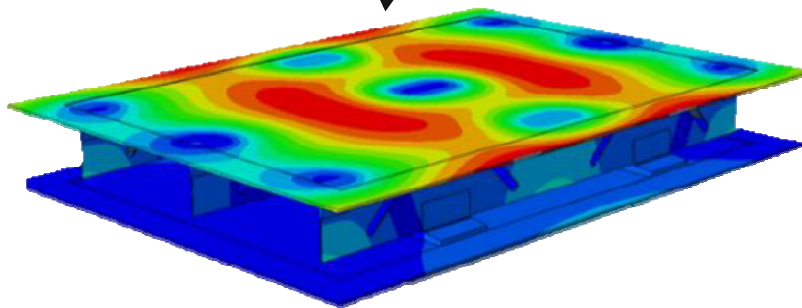
Example Application



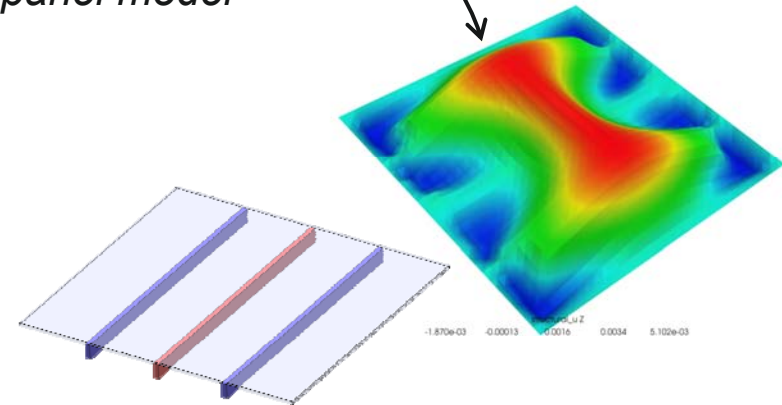
Boeing X-51



hypersonic aircraft panel model



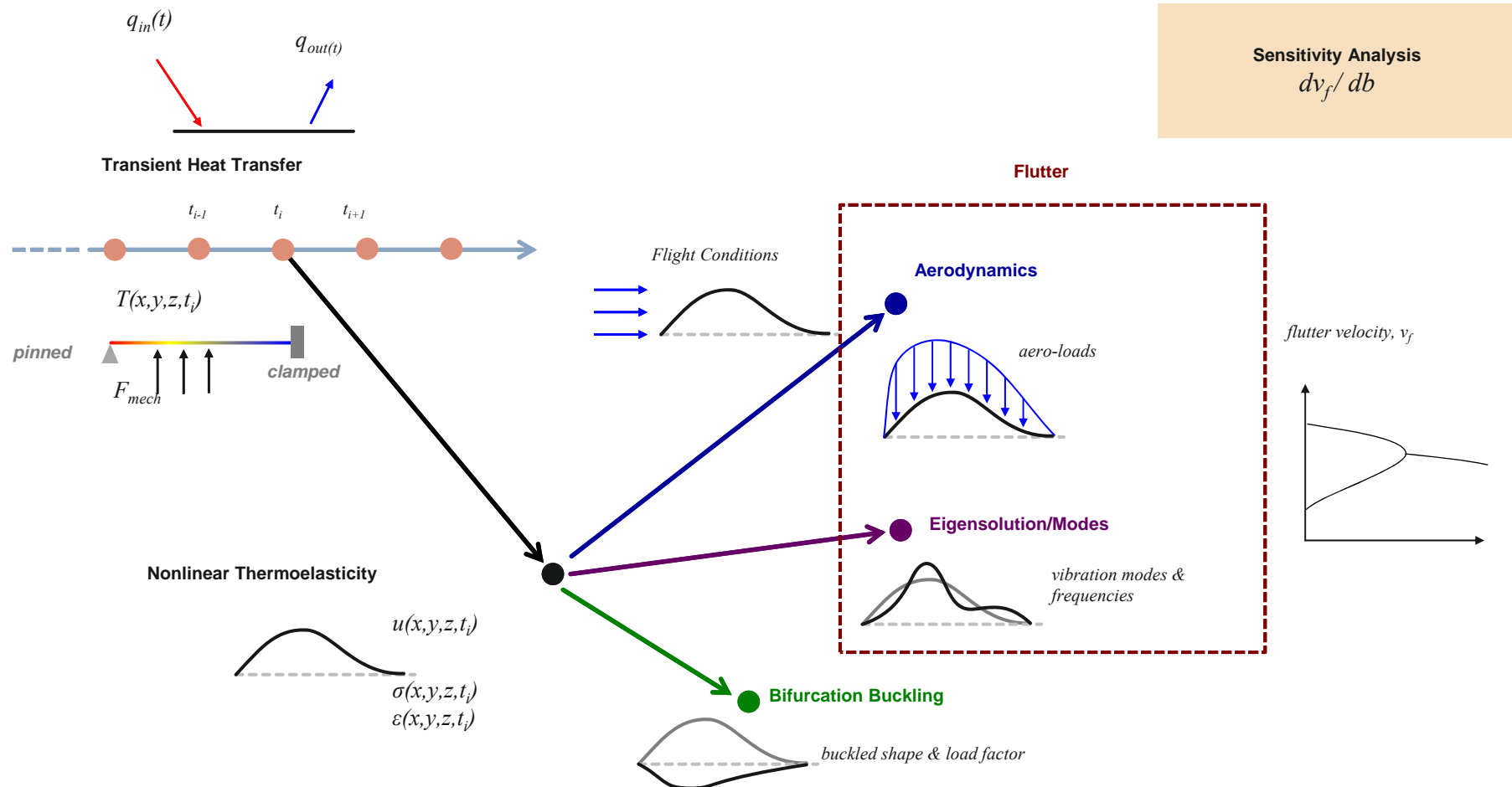
transient nonlinear thermoelasticity



panel design for transonic flutter about nonlinear equilibrium



Analyze Across Disciplines

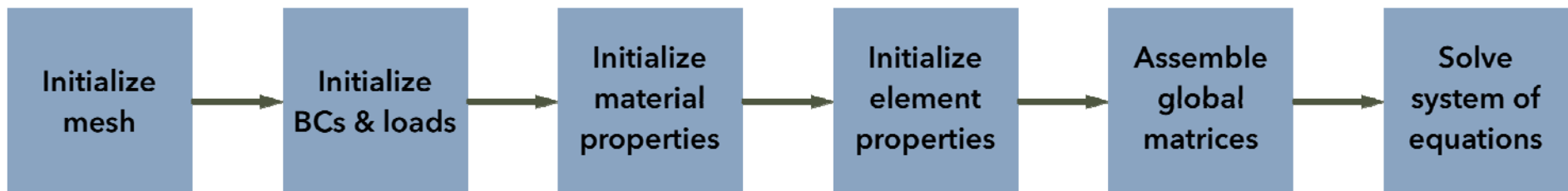




Solution Process



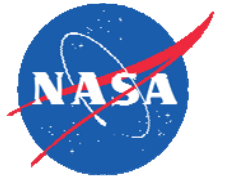
- MAST is a C++ programming library
- Steps to solve a problem:



- Currently requires writing a C++ program
- Versatile but complex approach
- Working on simpler interface for SAMS



Integration with SAMS



- Time-accurate fluid-structure interaction
- Multidisciplinary adjoint sensitivities
- Streamlined problem definition and execution
- Interface with geometry definition

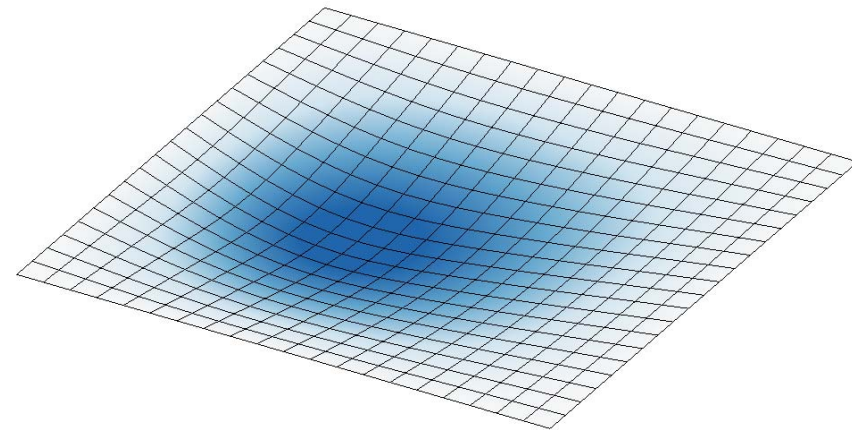
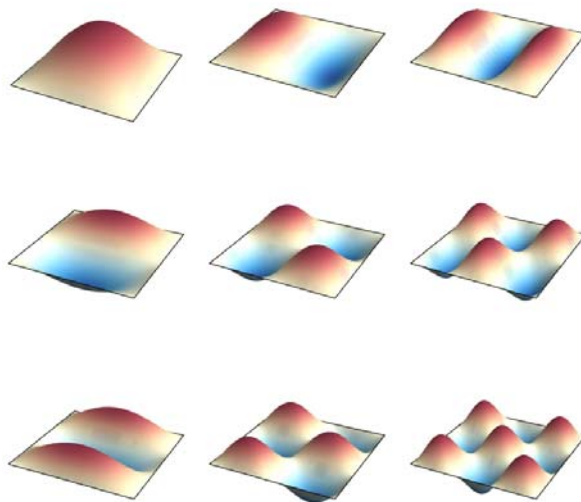


YAMSS



Yet Another Mode-based Structural Solver

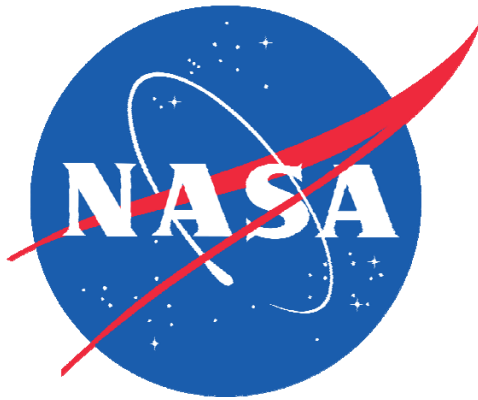
- Alternative to FUN3D modal solver
- Use to test modularity of structural solver



simply supported plate w/ sinusoidal forcing



Test Cases





Overview



Case	nD	Flow	Structure
Vortex-induced vibrations	2D	transient	spring
Airfoil with gust	2D	transient	linear beams
Turek-Hron	2D	transient	hyperelastic flag
AGARD 445.6	3D	steady	linear modes
G-Wing	3D	transient	aluminum plate
X-56A	3D	steady	built-up structure
Tailless supersonic aircraft	3D	transient	rigid

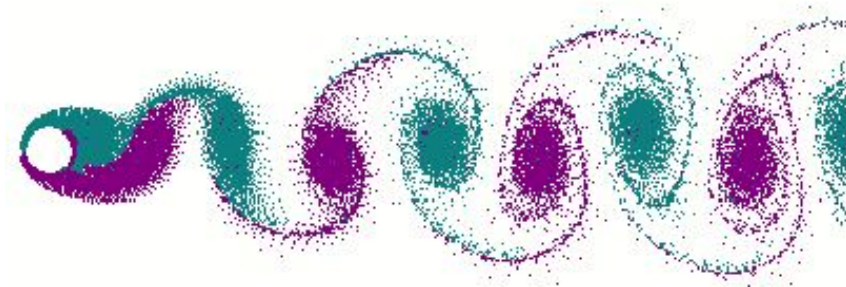
Incrementally demonstrate capability



Vortex-Induced Vibrations



- Cylinder in cross flow, free to translate or rotate
- Vortical flow may induce vibrations in cylinder
- Parameters: k , Re



References

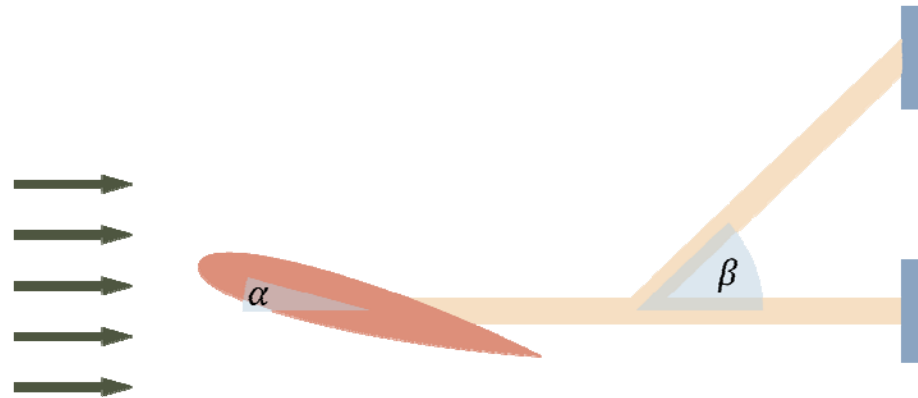
- Anagnostopoulos, P., and P. W. Bearman. "Response characteristics of a vortex-excited cylinder at low Reynolds numbers." *Journal of Fluids and Structures* 6 (1992): 39—50.
- Williamson, C. H. K., and R. Govordhan, "Vortex-induced vibrations." *Annual Review of Fluid Mechanics* 36 (2004): 413—455.



Airfoil in a Gust



- Sting-mounted airfoil in a transient gust
- Parameters: $U_{g,max}$, α , β , E



Reference

Liu, S., and R. Canfield, "Continuum shape sensitivity for nonlinear transient aeroelastic gust response." AIAA-2011-1971, *52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, 2011.

Cross, D. M., Local continuum sensitivity method for shape design derivatives using spatial gradient reconstruction. Diss. Virginia Polytechnic Institute and State University, 2014.



Turek-Hron



- Rigid cylinder with an attached elastic structure
- Flow induces deformation in elastic structure
- Parameters: Re , U , ρ , E , μ



Reference

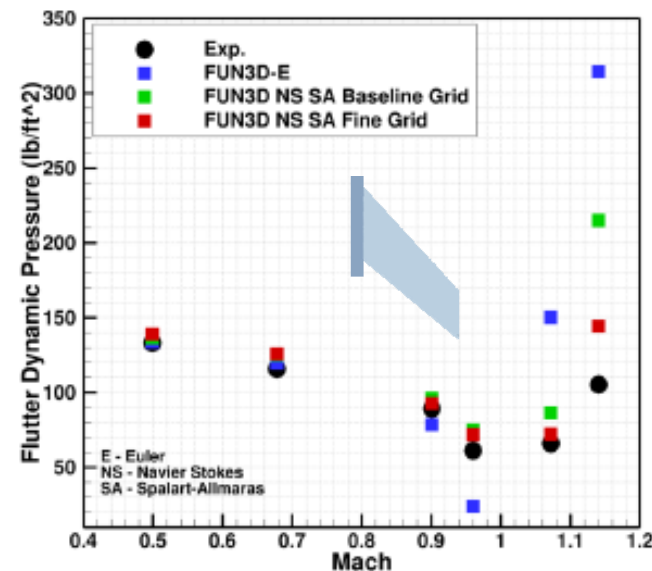
Turek, S., and J. Hron, Proposal for numerical benchmarking of fluid-structure interaction between an elastic object and laminar incompressible flow." *Fluid-structure interaction*. Springer Berlin Heidelberg, 2006, 371—385.



AGARD 445.6 Wing



- Standard aeroelastic benchmark problem
- Modal structure
- Parameters: M_∞ , p_∞



Silva et al., AIAA, 2014-0496

Reference

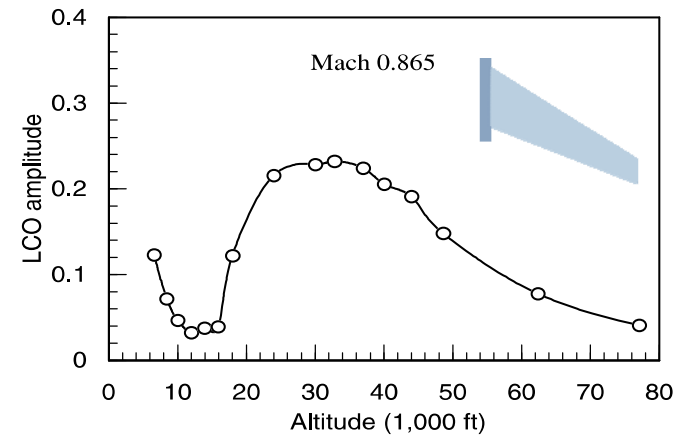
- Yates, Jr, E. C., "AGARD standard aeroelastic configurations for dynamic response. Candidate configuration I.-Wing 445.6." NASA TM 100492 (1987).
- Lee-Rausch, E. M., and J. T. Batina, "Calculation of AGARD wing 445.6 flutter using Navier-Stokes aerodynamics." AIAA-1993-3476, *11th Applied Aerodynamics Conference* (1993): 9—11.



G-Wing



- Swept transport wing
- Nonlinear structure, exhibits high-altitude LCO
- Parameters: M_∞ , h , E



Bendiksen, *J of Aircraft* 46.1

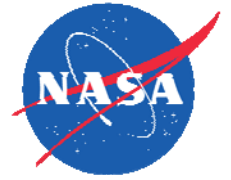
Reference

Bendiksen, O. O. "Transonic limit cycle flutter of high-aspect-ratio swept wings." *Journal of Aircraft* 45.5 (2008): 1522—1533.

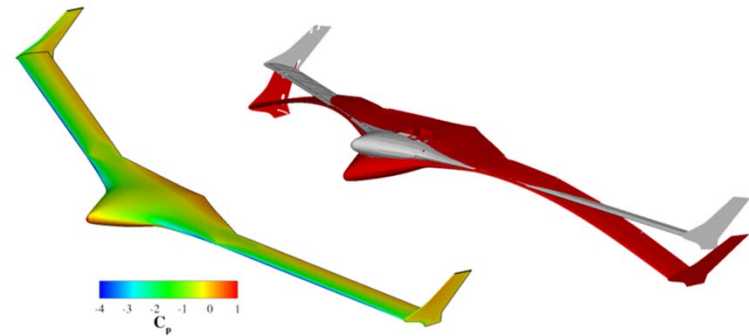
Bendiksen, O. O. "High-altitude limit cycle flutter of transonic wings." *Journal of Aircraft* 46.1 (2009): 123—136.



X-56A



- Flight-tested UAV with rigid and flexible wings
- Flutter suppression & gust load alleviation
- Parameters: M_∞ , p_∞ , K



Reference

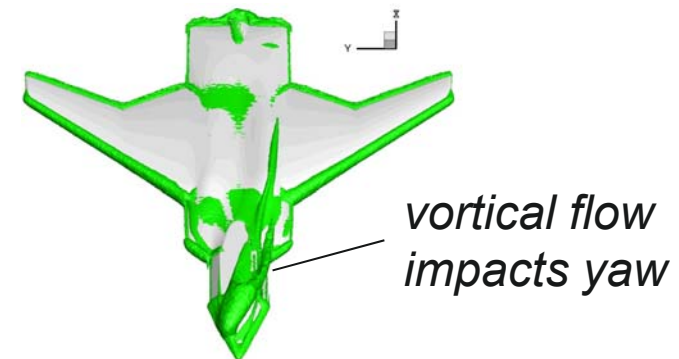
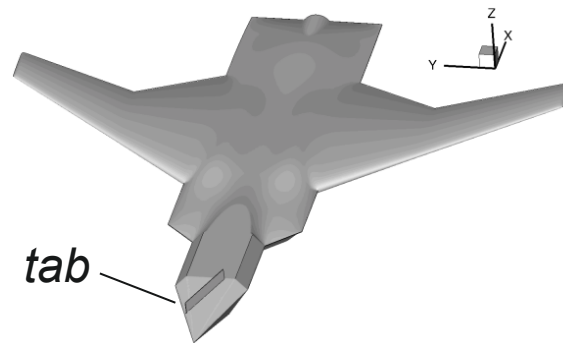
- Beranek, J., and others. "Conceptual design of a multi-utility aeroelastic demonstrator." AIAA-2010-9350. *13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference*, 2010.
- Jones, J., and C. E. Cesnik. "Nonlinear aeroelastic analysis of the X-56 multi-utility demonstrator." AIAA-2016-1799. *15th Dynamics Specialists Conference*, 2016.



Tailless Aircraft



- Tailless supersonic aircraft
- Fuselage-mounted tabs improve yaw control
- Parameters: *tab shape and position*



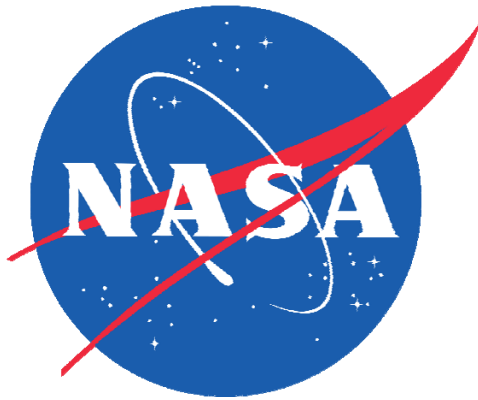
Reference

Meckstroth, C., and others. "Aerodynamic modeling techniques for efficient supersonic air vehicle multidisciplinary design optimization." AIAA-2014-3254. *32nd AIAA Applied Aerodynamics Conference*, 2014.

Meckstroth, C., and W. Blake. "Control focused multidisciplinary design optimization of tailless fighter aircraft." AIAA-2015-2324. *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2015.

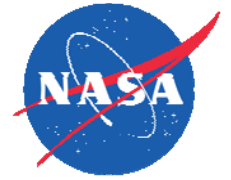



Concluding Remarks





Progress



- Major changes to FUN3D are underway
- MAST improvements are readying it for SAMS
- Integration infrastructure ready for use
- Adopting FUNtoFEM () for FSI

Next step: mode-based static aeroelasticity



Personnel



- SAMS has been understaffed
- AFRL has had two unfilled contractor positions
 1. Filled in November
 2. Currently reviewing applicants
- NASA had one unfilled position
 1. Filled in October

Behind schedule, but pace accelerating



Digital Collaboration



- Need to exchange source code and data files
- Existing "solutions" not working
 - AFRL unsuccessful getting full access to LaRC GitLab
 - NASA unsuccessful getting accounts to AFRL ELSZ
- Large file transfer mechanisms do work
 - But not good for collaboration

Digital collaboration remains a significant problem