Presented to:

NDIA Conference on Physics-Based Modeling in Design & Development for US Defense

November 15-17, 2011

High-Performance Computing for Rotorcraft Modeling and Simulation

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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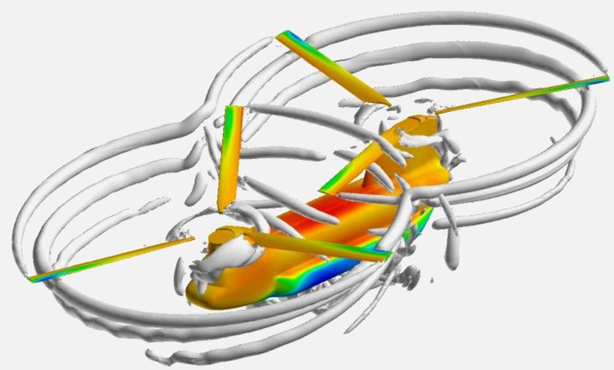
Approved for public release: AMRDEC control number FN5547

US Army Aeroflighdynamics Directorate

Located at the NASA Ames and NASA Langley Research Centers



Modeling and Simulation

Wind Tunnel Testing

From Computations to Flight !

Flight Testing

Preliminary Design

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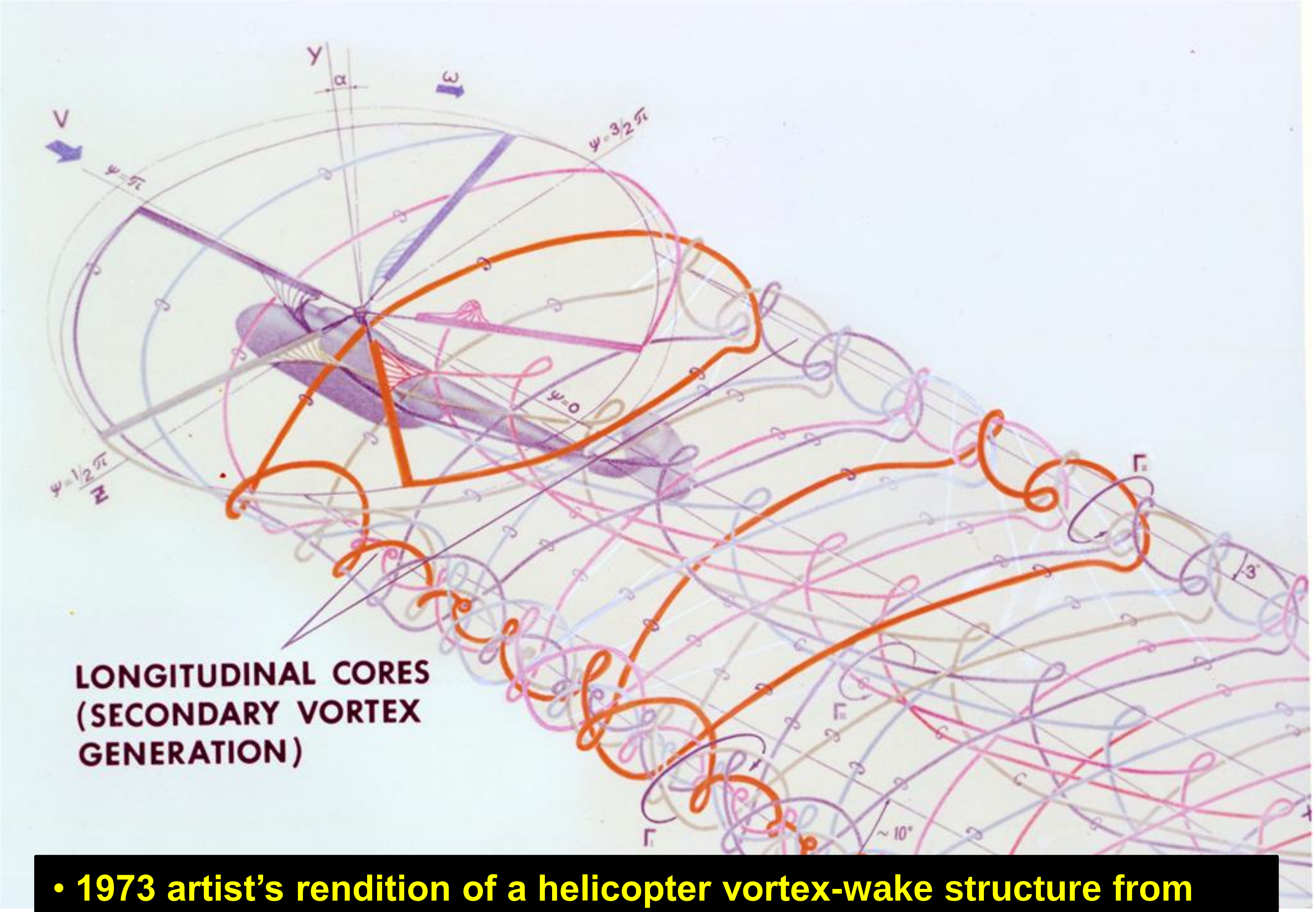
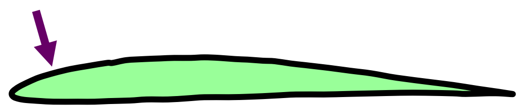
Rotary-Wing Aeromechanics



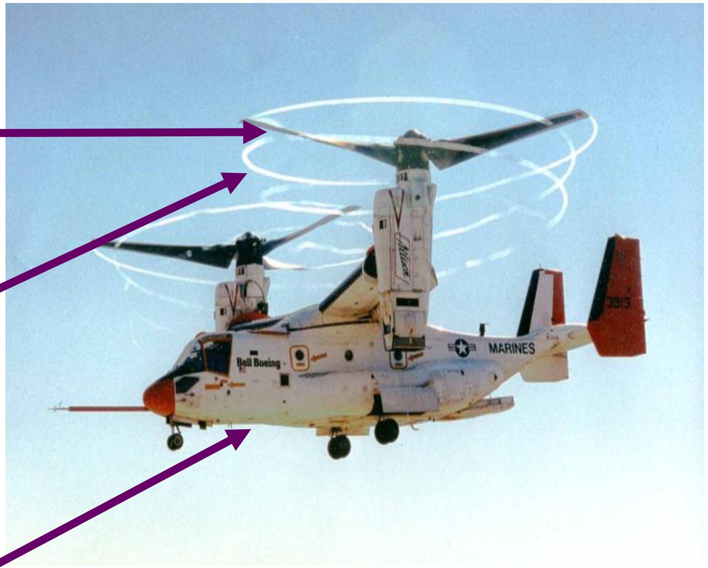
- 1973 artist's rendition of a helicopter vortex-wake structure from Aviatsiya I Kosmonautika, a monthly Soviet-era aviation magazine

Length Scale Ranges for Rotorcraft

- **Boundary layers on rotor blade surfaces (~10^{-5} blade chord lengths)**



- **Vortices in rotor wake system (~0.5 rotor blade chord lengths)**

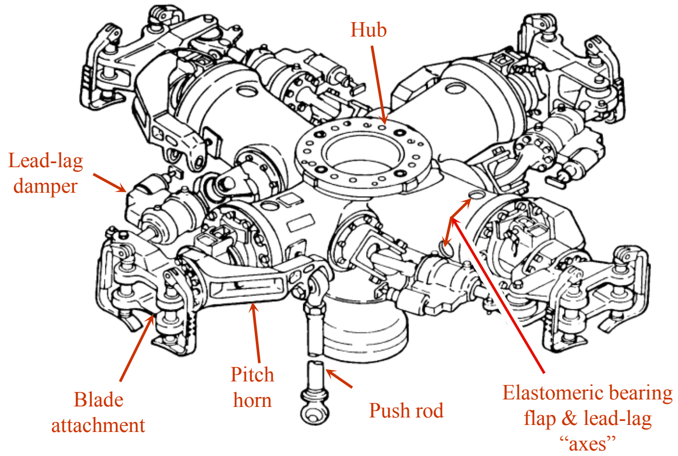


- **Vortices on rotor fuselage surface and in separated flow regions on fuselage (~10 rotor blade chord lengths)**

Rotorcraft Aeromechanics Challenges

- **Multiple length scales**
  - Large computational domain
  - Small scales in boundary layers
  - Vortical structures in wake
- **Fluid-structure coupling**
  - Rotor blade aeroelastic motion
  - Trim and pilot controls
- **Complex fluid dynamics**
  - Highly unsteady flowfield
  - Shock waves on advancing rotor
  - Dynamic stall on retreating rotor
- **Interactional aerodynamics**
  - Rotor/fuselage, main rotor/tail rotor
- **Other complexities**
  - Complex geometry
  - Bodies in relative motion

UH-60 Hub Detail



RDECOM

Recent DoD Rotorcraft Procurements

AMRDEC

RAH-66 Comanche (1983-2004)

Canceled in 2004

V-22 Osprey (1983–2005)

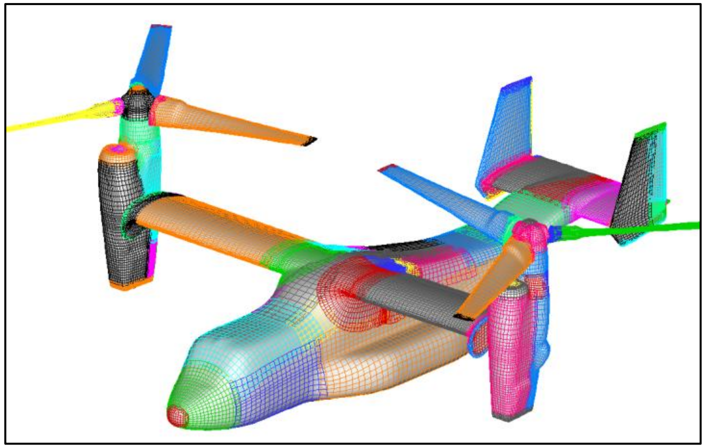
Aeromechanics Problems in Development

- **Shed vortices from hub interfered with tail control**
  - **Complete redesign of empennage in 2000**
- **Basic physics of fantail performance were poorly understood**
- **Main rotor regressive lag-mode instability**

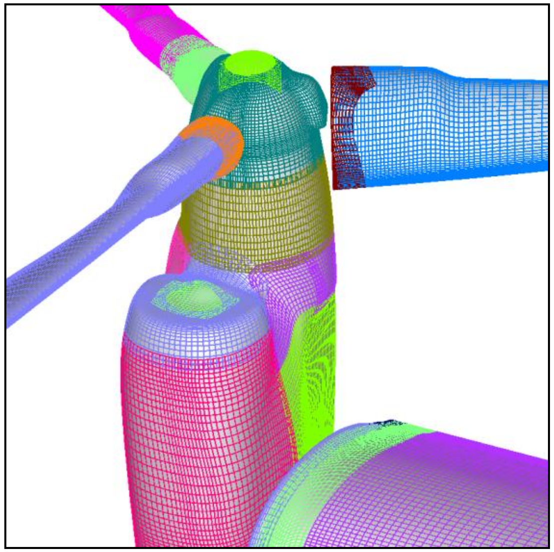
- **Control problems during rapid descent**
  - **19 Marines died in 2000 crash**
- **Poor hover performance**
- **Pitch up with 45 deg. crosswind**
- **Loss of lift with 90 deg. crosswind**

Rotorcraft Modeling in 2006

The Good:
- Basic technology developed for aerodynamic and structural dynamic couple
- Basic technology developed for computing multiple bodies in relative motion
- Basic technology developed for rotor wake capturing



The Bad:
- Painful grid generation process for complex geometries
- Painful and slow process for overlapping-grid domain connectivity
- Huge computer resource requirements for high-fidelity wake capturing
- Software was a mess



Overset structured surface grids for the V-22 Osprey

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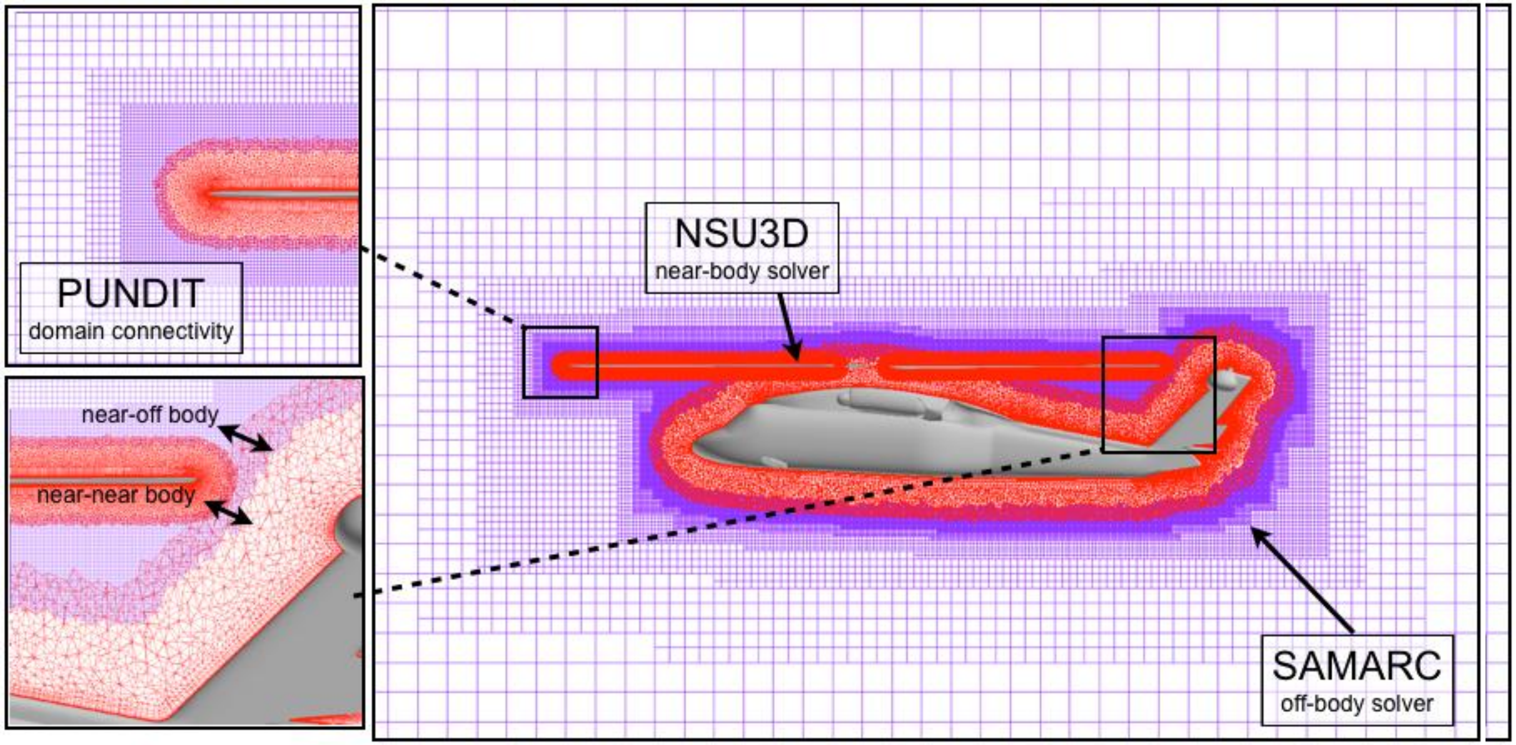
Helios Software Development

Helios Software Product

(part of CREATE-A/V)

- **Helios: Helicopter Overset Simulations**
  - **Overset is ideally suited for moving bodies**
- **Dual-mesh paradigm**
  - **Unstructured mesh in near-body**
  - **Cartesian meshes in off-body**
- **Python infrastructure**
  - **For multidisciplinary coupling**
  - **Modular and extensible**

Dual Mesh CFD Paradigm



Unstructured "near-body"

– Resolve near-wall viscous flow
– Complex geometries

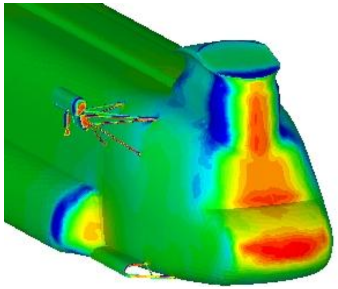
Cartesian "off-body"

– Computationally efficient
– High order accuracy
– Adaptive Mesh Refinement

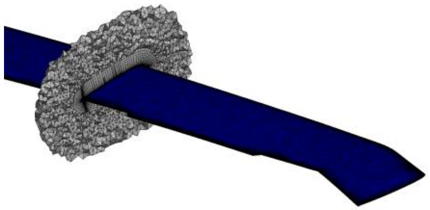
CFD Components

- **Near-body NSU3D flow solver**
  - *Developed by Mavriplis at Univ. of Wyoming*
  - General unstructured – tets, prism, hex
  - Reynolds-averaged Navier-Stokes
  - Spalart-Allmaras turbulence model
  - 2nd-Order vertex-based spatial discretization
  - 2nd-Order BDF time integration
- **Off-body SAMARC flow solver**
  - Based on NASA Ames ARC3D flow solver
  - Block structured Cartesian
  - 5th-Order spatial discretization
  - 3rd-Order explicit Runge-Kutta time
  - Solution adaptive
- **Overset Communication**
  - *PUNDIT*
  - Automated implicit hole cutting

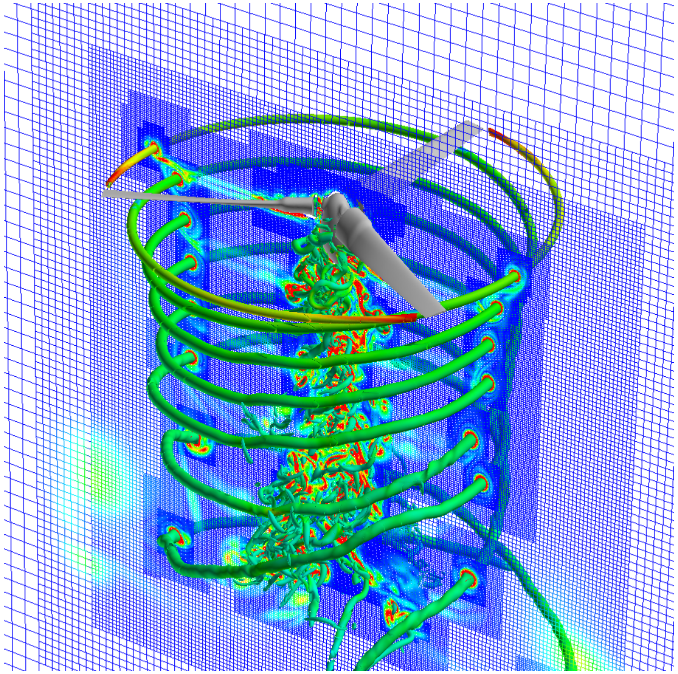
fuselage



rotor blade



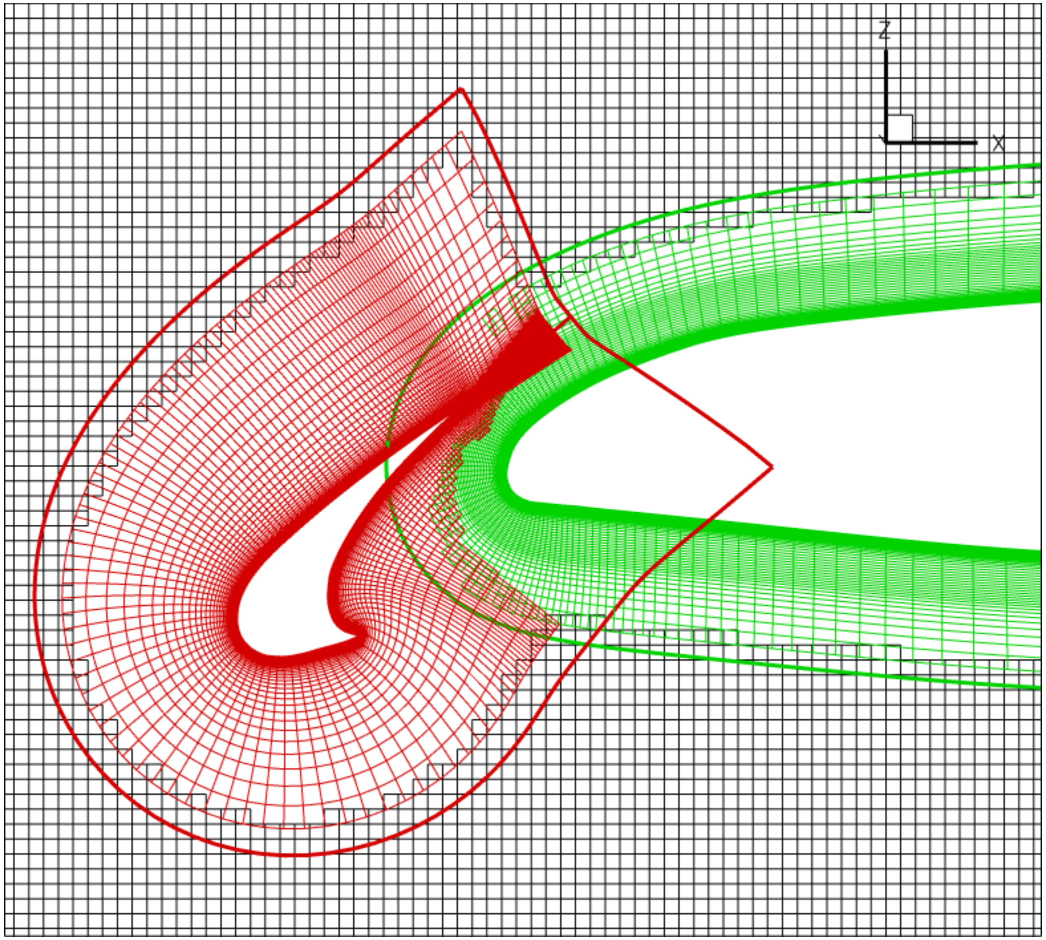
NSU3D
near-body



SAMARC
off-body

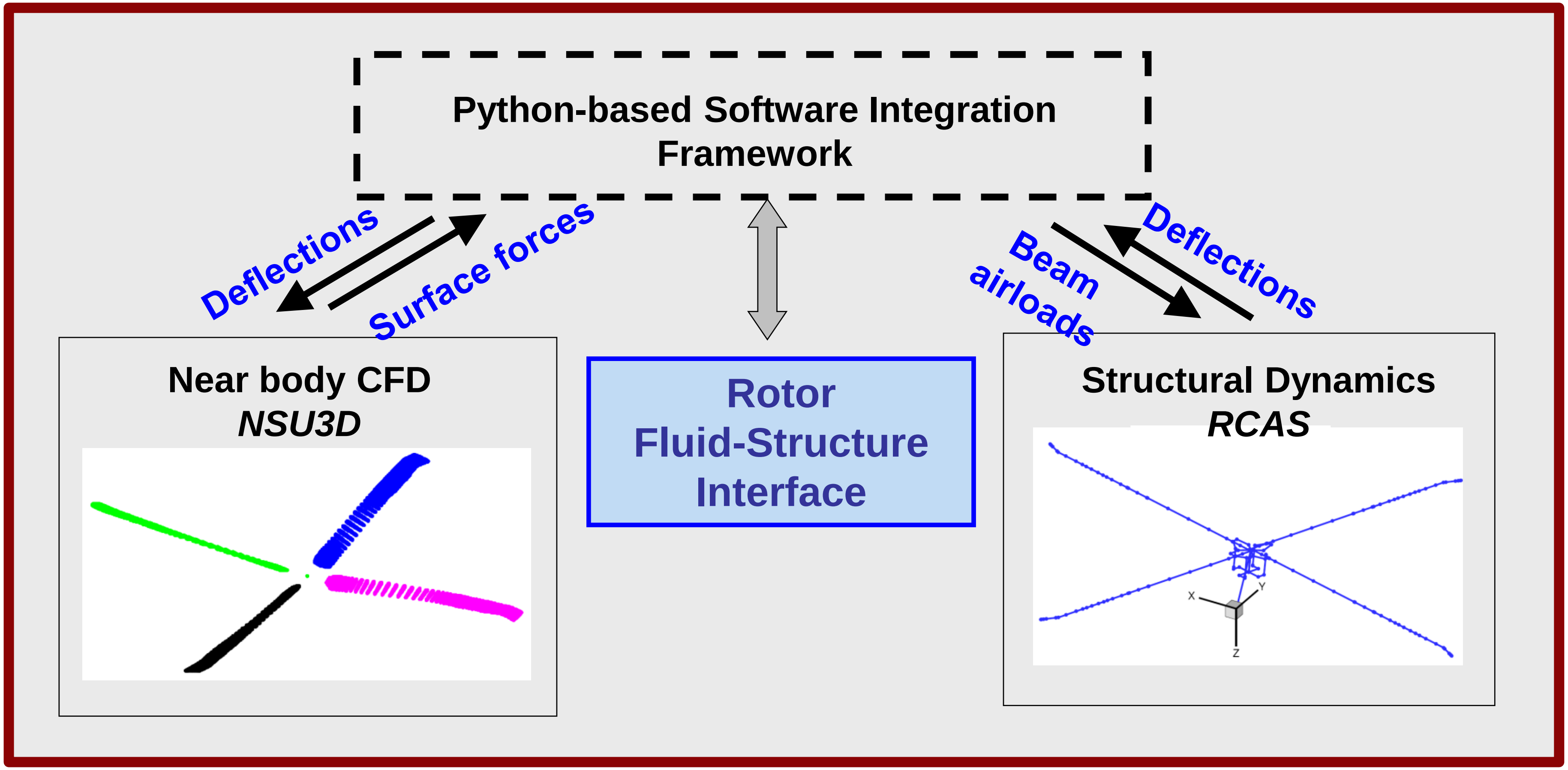
Overset Mesh Connectivity

- Parallel UNsteady Domain Information Transfer (PUNDIT)
- Manages data interpolation between near- and off-body solvers
- Implicit hole-cutting ……. automated with no required user input !!
- Constructs donor/receiver information between moving grids



Helios Fluid Structure Interface

- Near-body CFD solver computes rotor surface forces
- Structural dynamics solver receives non-linear beam airloads, computes deflections, trim angles
- Near-body grid appropriately moved/deformed



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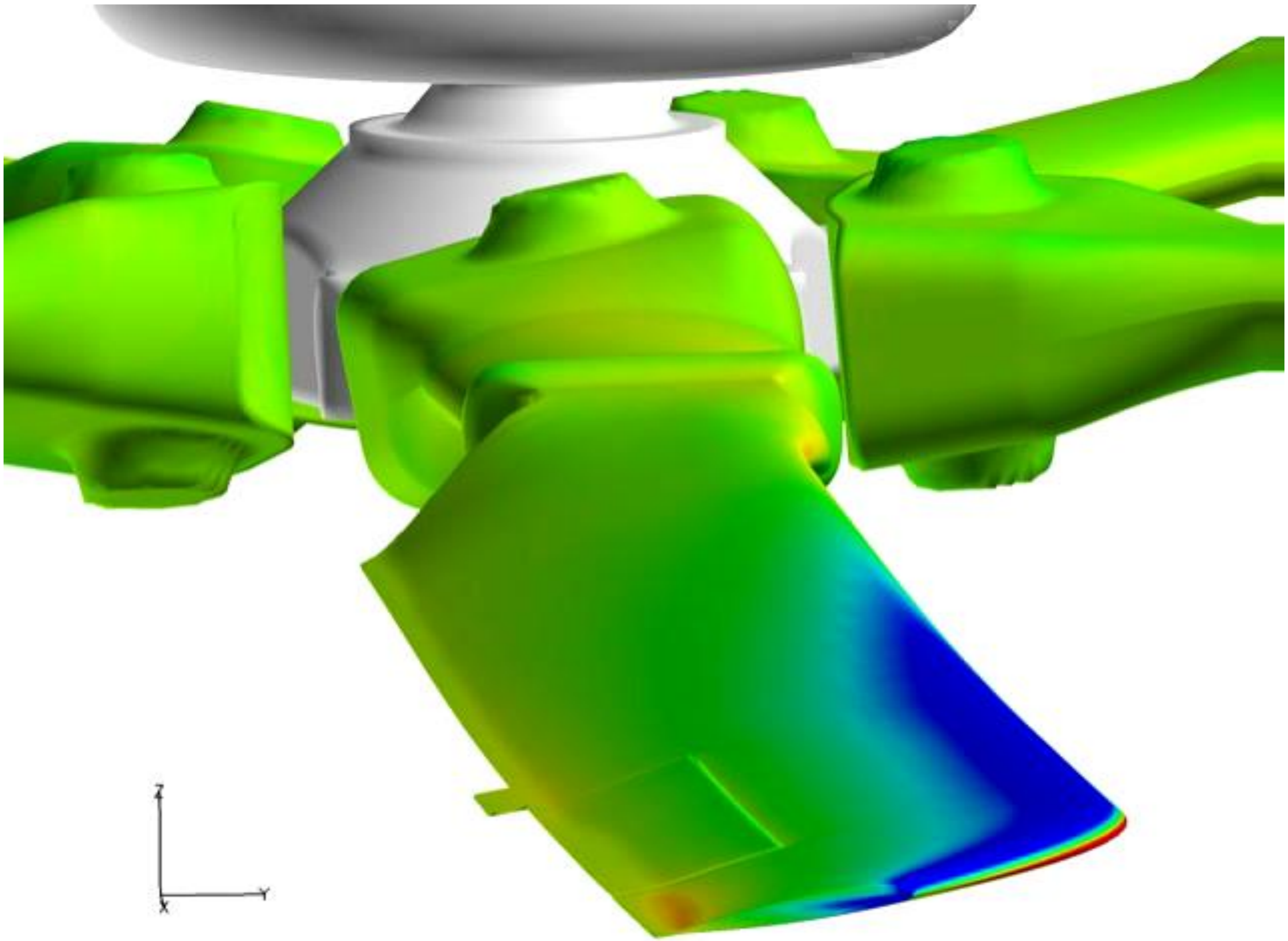
Rotary-Wing Fluid-Structure Interactions



DARPA Active-Flap Rotor System

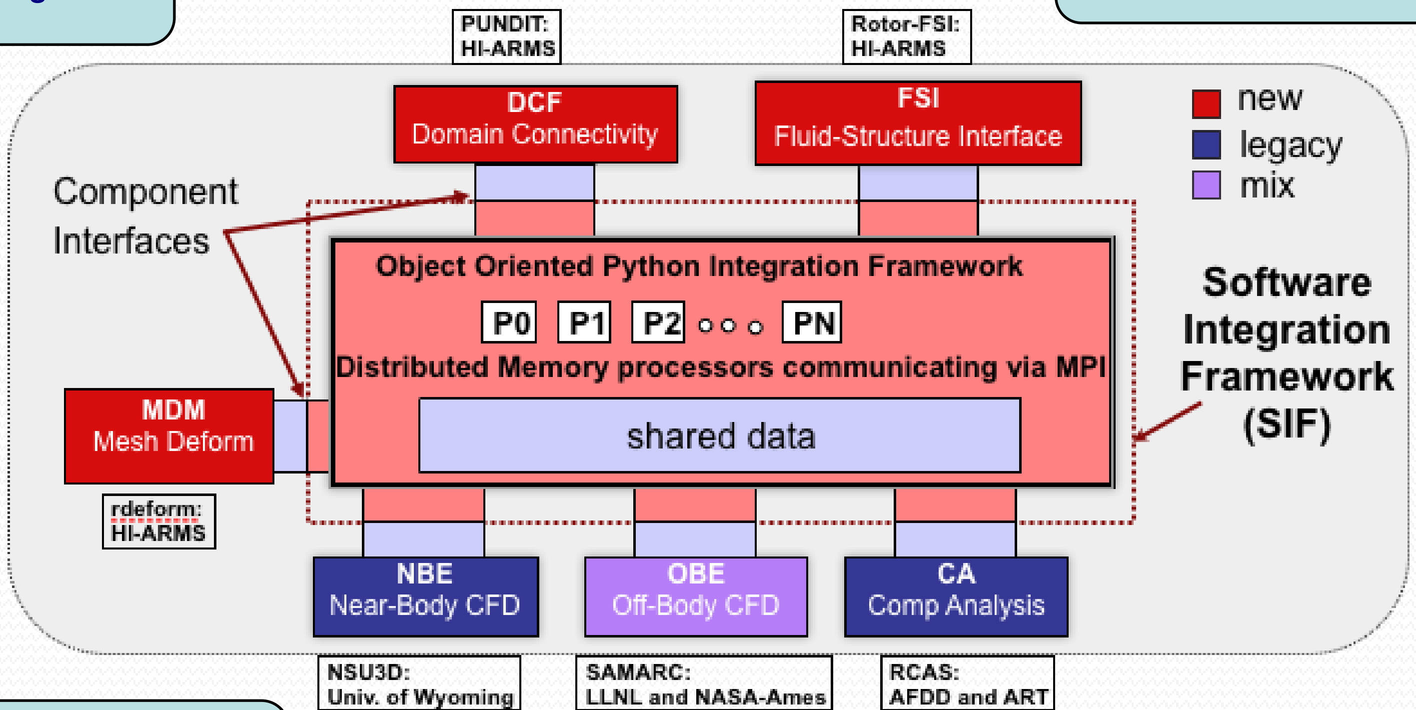
Helios Python Infrastructure

Object Oriented:
Multiple codes

Multiple languages

Light-Weight
Main execution script

Few hundred lines of code



Interfaces
Generalized interfaces

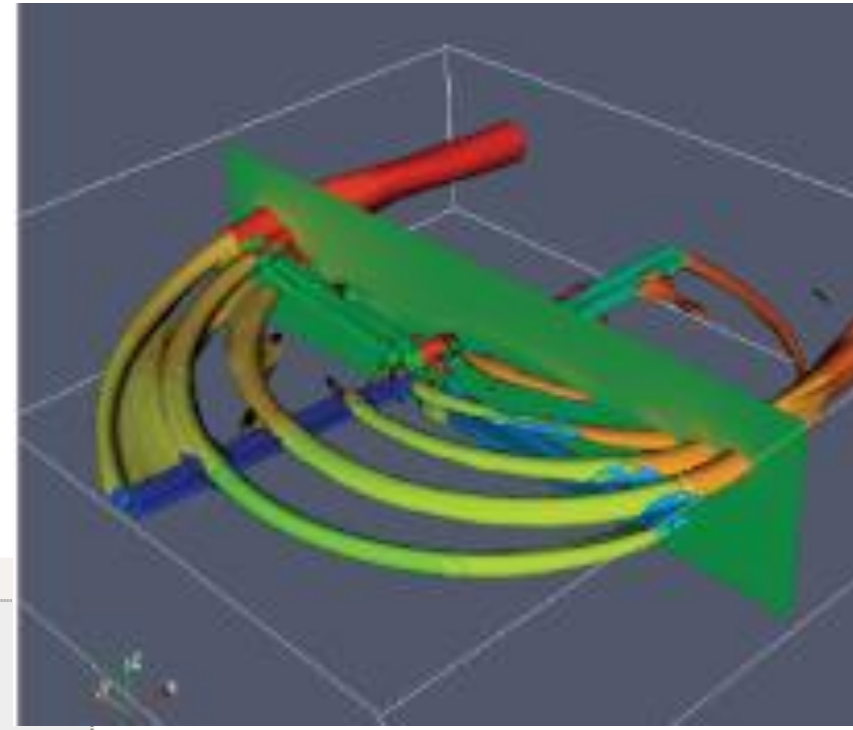
Interoperable and extensible

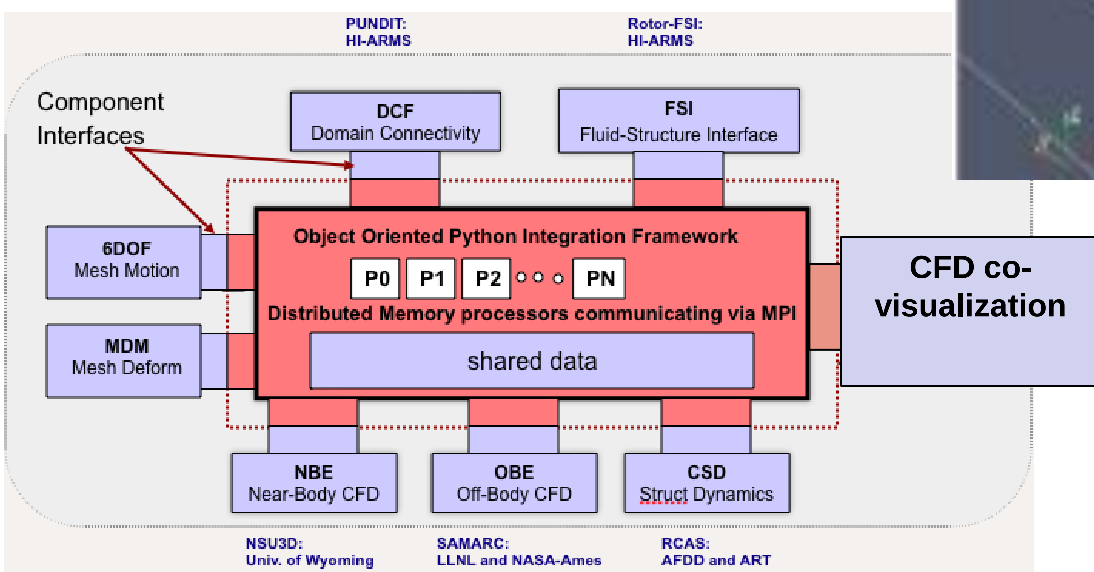
Minimal Overheads
Storage

Efficiency

Army SBIR Projects

- **CFD co-visualization module for Helios**
  - **Develop a plug-in CFD co-visualization module that works with the Helios SIF**
  - **Kitware Phase 2 SBIR ended Fall 2010**
  - **Phase 2 extension recently approved**

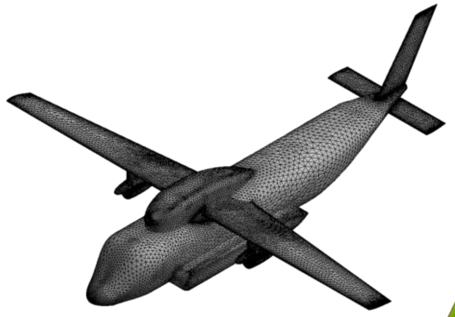


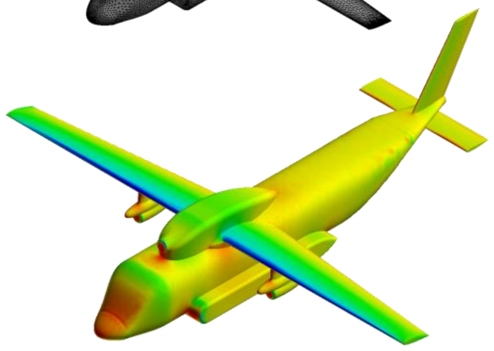


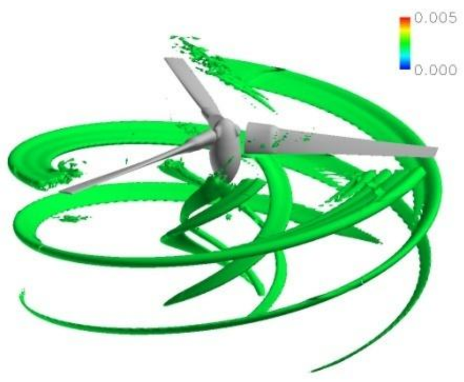
Helios v1 2010 Software Release "Whitney"

STATUS: Beta Release in February 2010

- **Capabilities**
  - Fuselage aerodynamics
  - Fuselage + simplified rotor model
  - Isolated rotor in ideal hover
  - Isolated rotor in forward flight with structural dynamics and trim
  - Eight different use-cases
- **Metrics**
  - Meet or beat existing state-of-the-art
  - Threshold: unstructured codes
  - Goal: structured codes
- **Usability**
  - Grid preprocessing and run-time inputs through GUI
  - Tutorials, training and support infrastructure

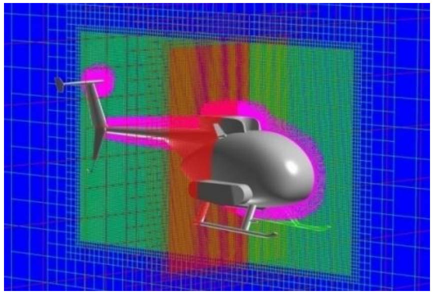


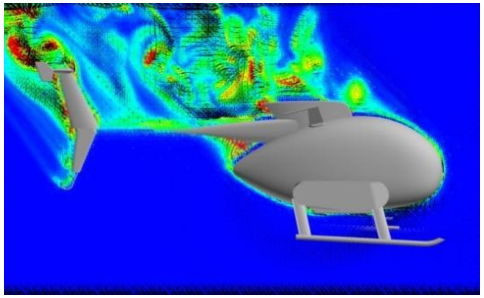


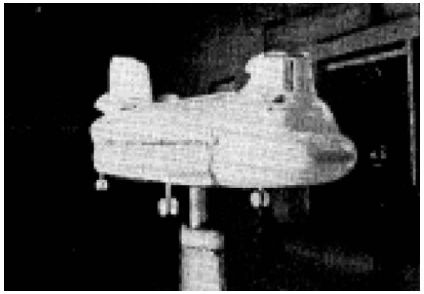


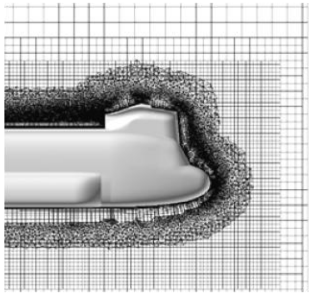
Helios v1 "Whitney" Testing Highlights

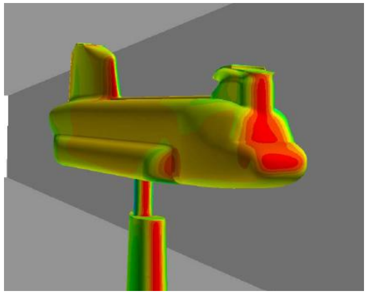
- HI-ARMS and Shadow-Ops testing of basic Helios use cases
- Four industry applications projects funded through NRTC/VLC
  - Bell (John Bridgeman)
    - 409 rotor and hub drag study
  - Boeing Philadelphia (Ted Meadowcroft)
    - CH-47 fuselage drag comparisons to OVERFLOW and BCFD
  - Boeing Mesa (Hormoz Tadghighi)
    - Little Bird fuselage and rotor performance
  - Sikorsky / UTRC (Alan Egolf and Stuart Ochs)
    - X-2 hub drag studies
- Government laboratory projects
  - ARL (Rajneesh Singh)
    - Ducted fan design
  - NAVAIR (Yik Loon Lee)
    - Ship airwake
  - AED (David O'Brien)
    - Robin fuselage









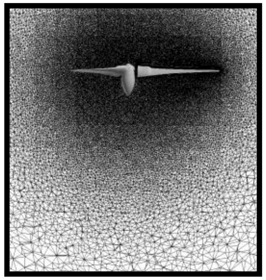


FY011 Software Release
Helios v2.0 “Shasta”

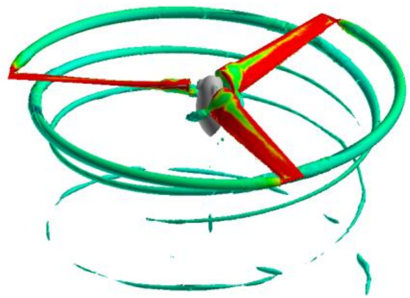
- **Beta release slated for August 2011**
- **New Capabilities**
  - **Rotor-fuselage configuration**
  - **Arbitrary shaft angles**
  - **Multi-bladed rotors**
  - **Adaptive mesh refinement to capture rotor vorticies**
- **New Functionalities**
  - **Automated off-body mesh refinement**
  - **Generalization of interfaces**
- **Helios dedicated test time on Mana at Maui High-Performance Computing Center**
  - **2000 processors from November 1 through January 15**

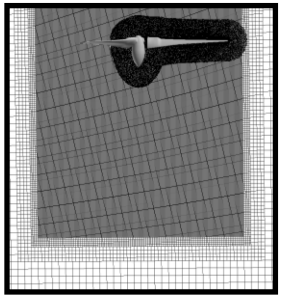
Off-Body Adaptive Mesh Refinement

- High-order block-structured Cartesian Adaptive Mesh Refinement (AMR)
- Offers dramatically-improved resolution of rotor wake features

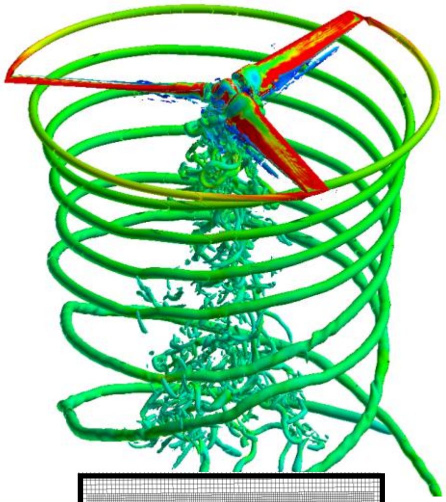


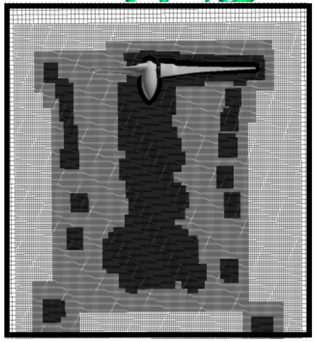
- Fully unstructured





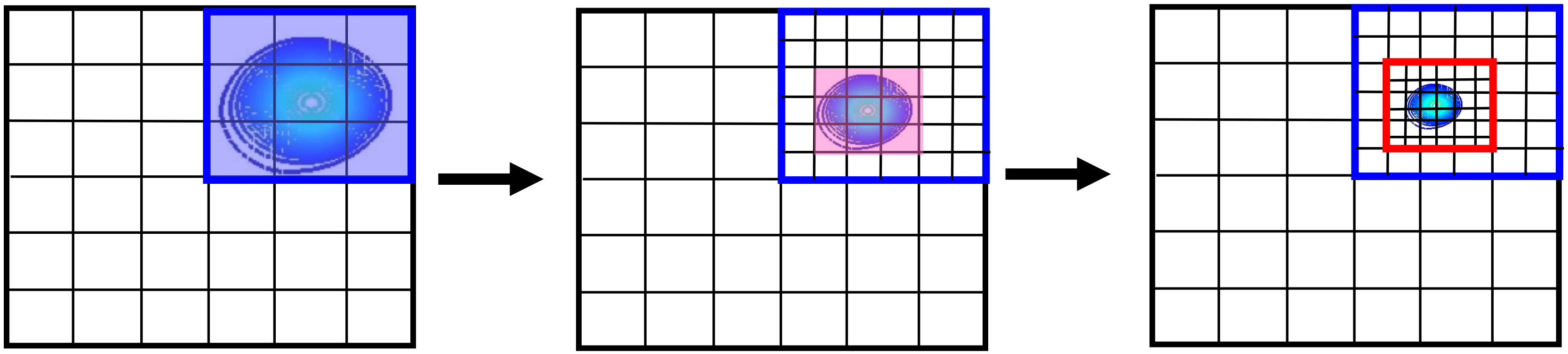
- Unstructured near-body
- Fixed Cartesian high-order off-body





- Unstructured near body
- Adaptive Cartesian high-order off-body

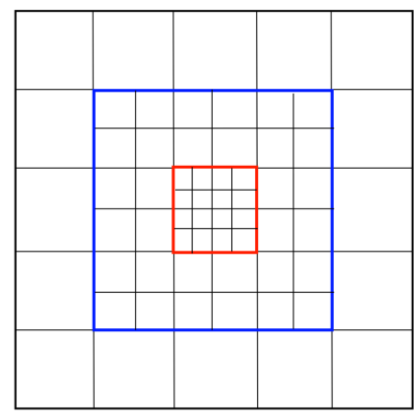
Adaptive Mesh Refinement
(Based on LLNL SAMRAI software)



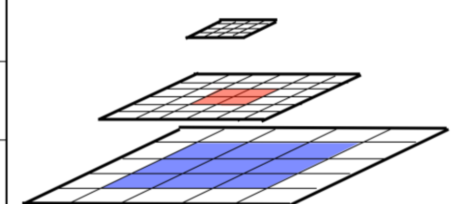
Coarse level　　Intermediate　　Fine

1. “Tag” cells containing high vorticity
2. Cluster tagged cells into blocks
3. Use blocks to create finer level

→ *Repeat*



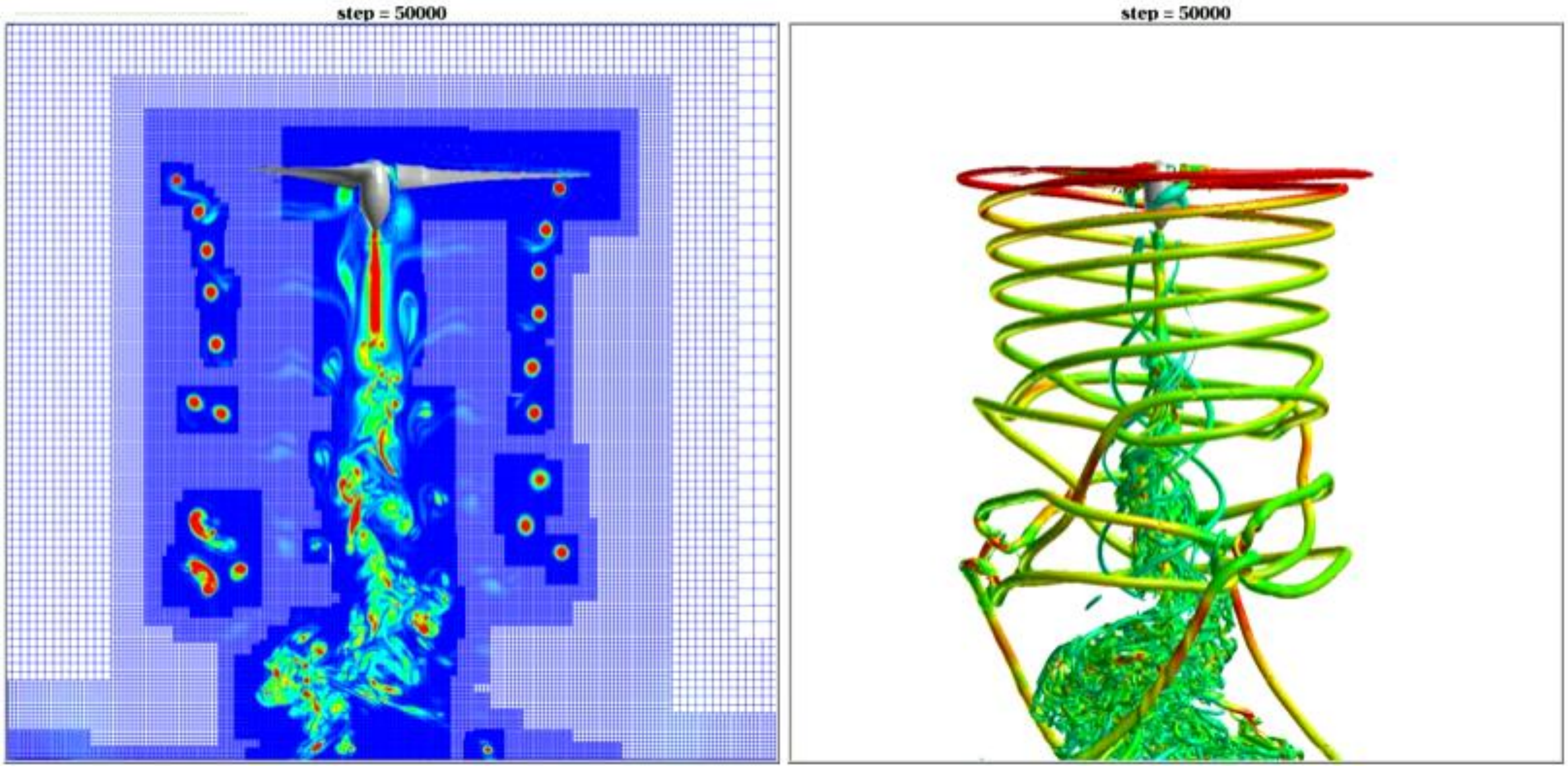
Forms hierarchy of nested levels



- **Efficient computational performance**
  - 3% overhead on 512 processors
  - Tested by LLNL for >15,000 processors

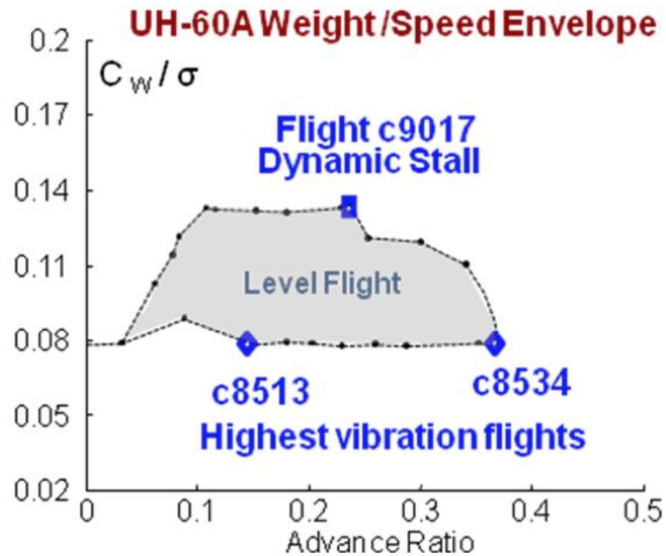
- **Minimal overhead**
- **Parallel mesh generation**
- **Load balance by distributing blocks**

Helios Adaptive Mesh Refinement



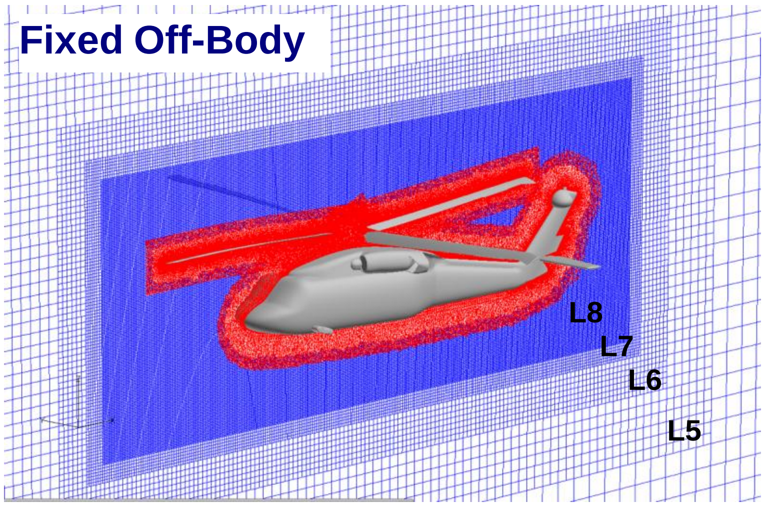
V-22 Rotor in Hover

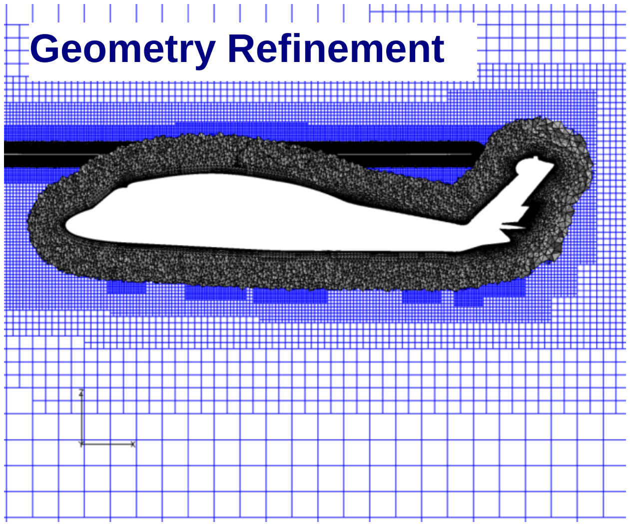
UH-60A Flight Test Correlations



Flight Condition	Advance Ratio	Hover Tip Mach	Angle of Attack	Thrust Coeff
8534	0.388	0.642	-7.31	0.0848
8513	0.153	0.638	+0.75	0.076
9017	0.237	0.666	-0.19	0.1245

UH-60A Off-Body Grids





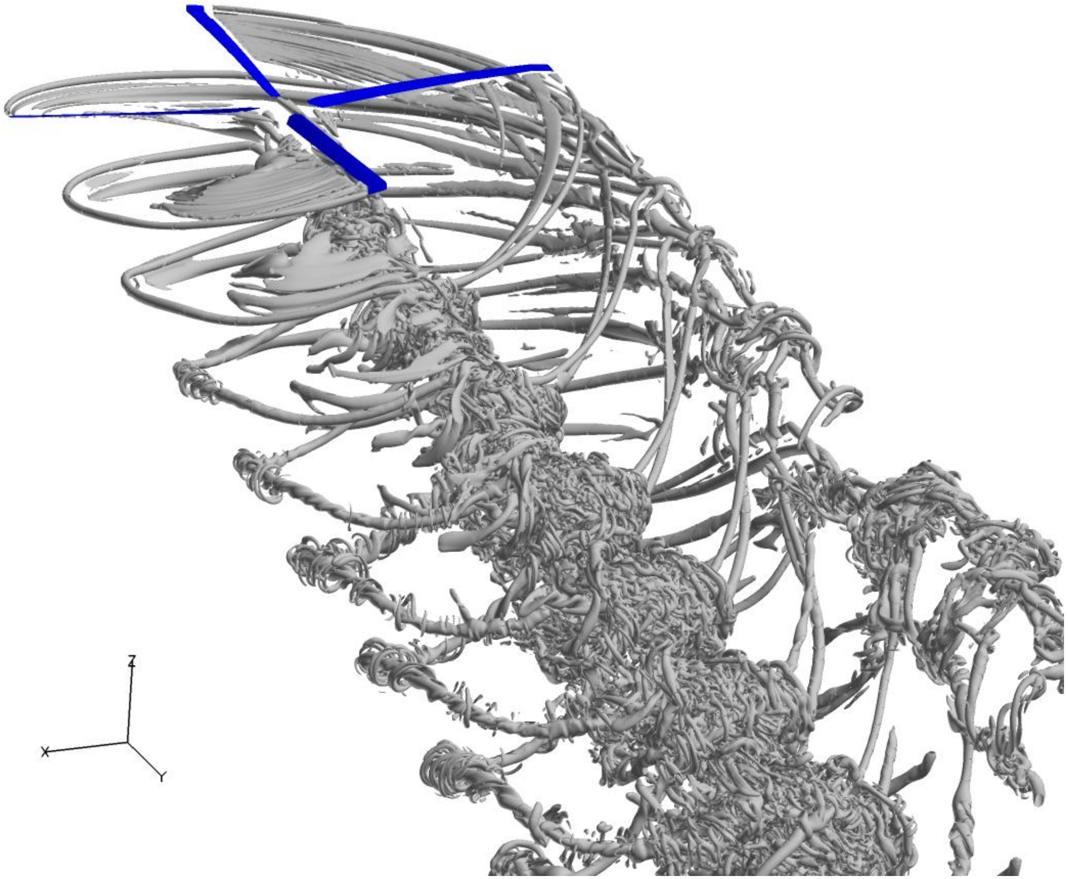
	Refinement Levels	Finest Mesh Spacing	Active Nodes
Coarse L6	6	0.18c	9.1M
Fine L7	7	0.1c	39.1M
Fine L8	8	0.05c	145.7M
Line L8 Adapt	8	0.05c	24.0 - 125 M

UH-60A High-Speed Wake

Fine-Near-Body Adaptive L8

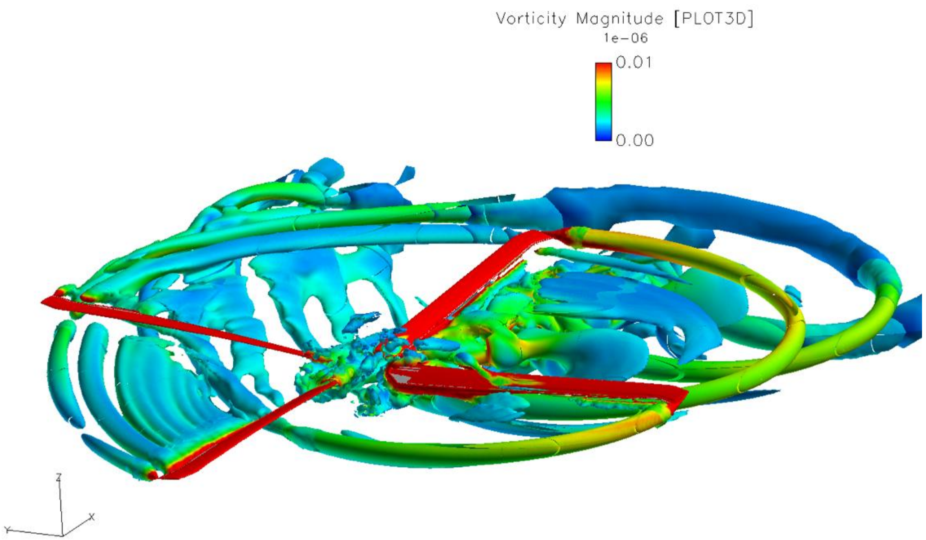
	Coarse	Fine
Near-Body Mesh	4.5M	15.4M
Off-Body Mesh L6	4.3M	
Off-Body Mesh L7		22M
Off-Body Mesh L8		145M
Off-Body Mesh L8a		25M - 125M

6X fewer grid pts



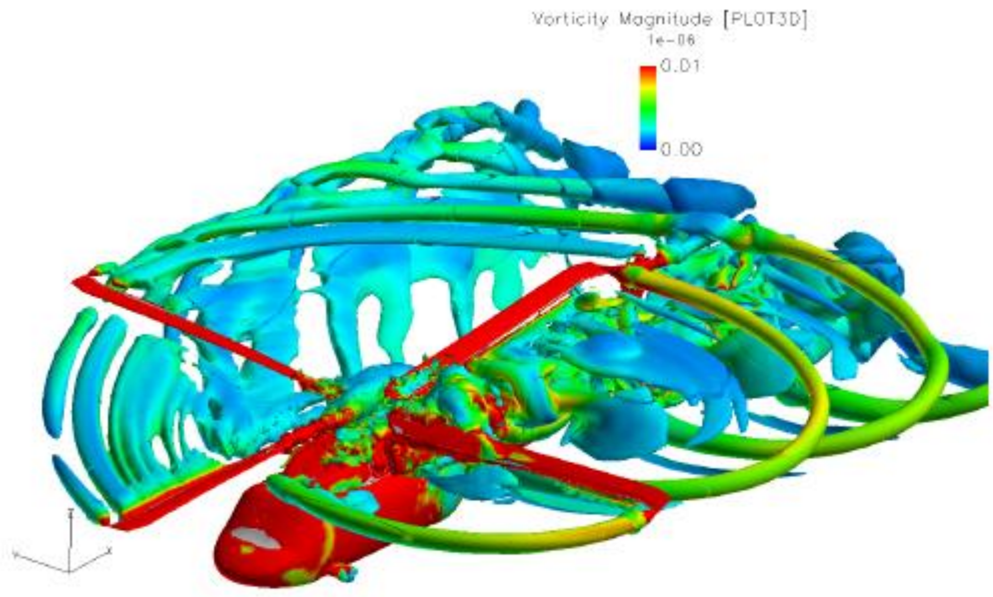
UH-60A Rotor and Fuselage Combination

UH-60A 8534

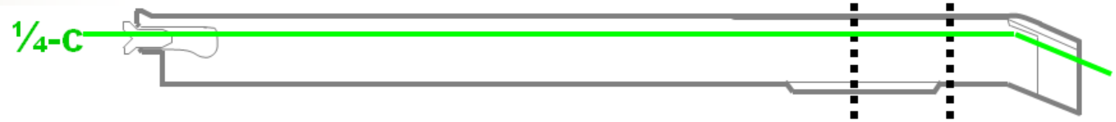


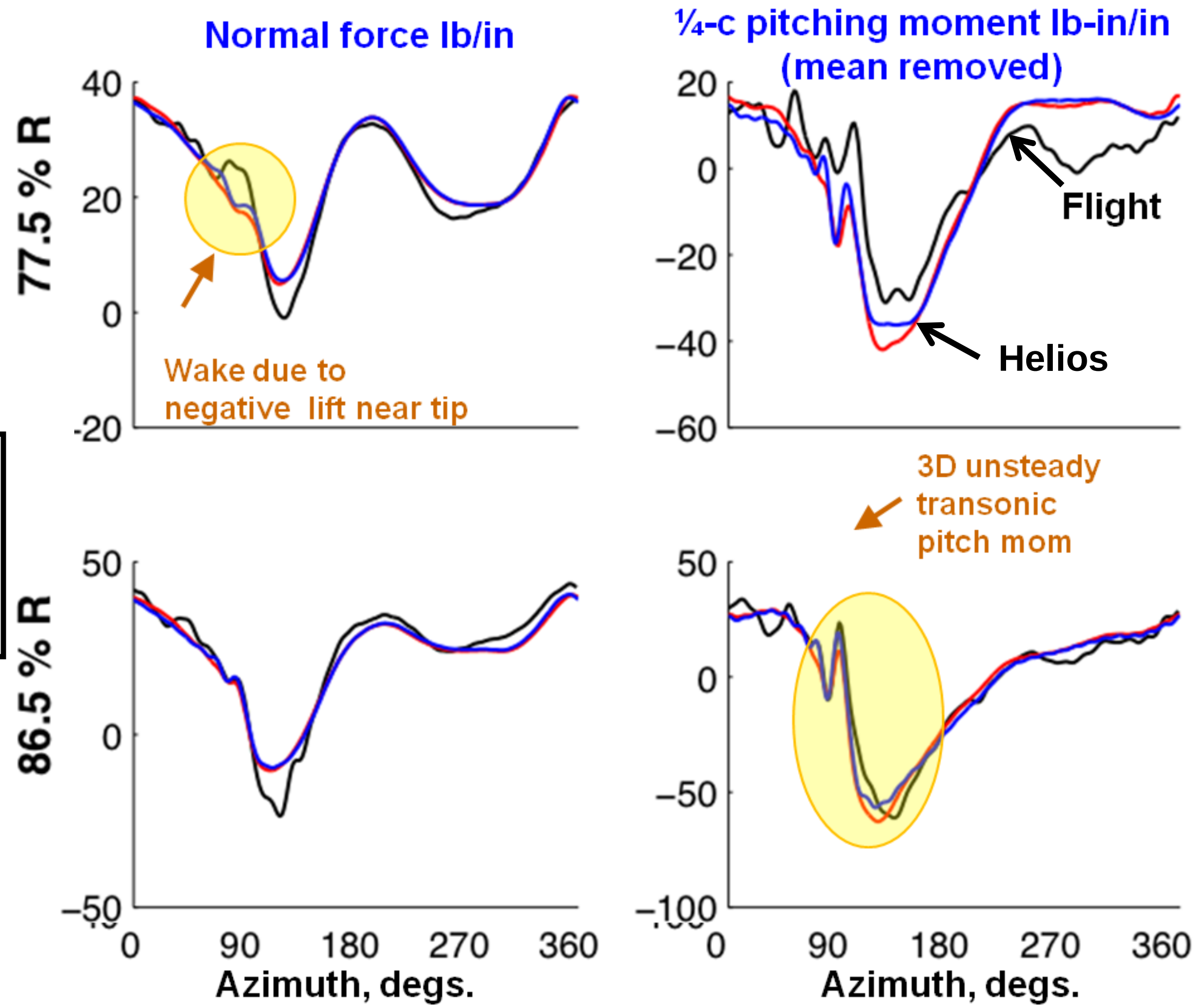
Isolated Rotor

Rotor and Fuselage



UH-60A High-Speed Rotor Airloads

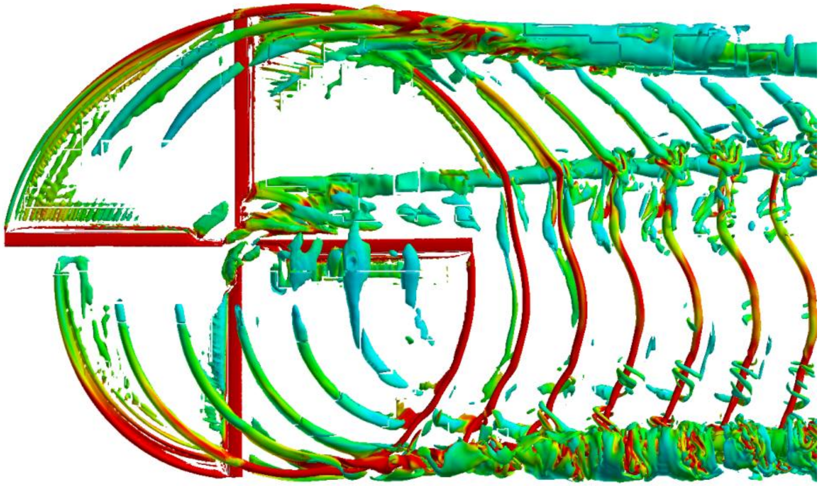


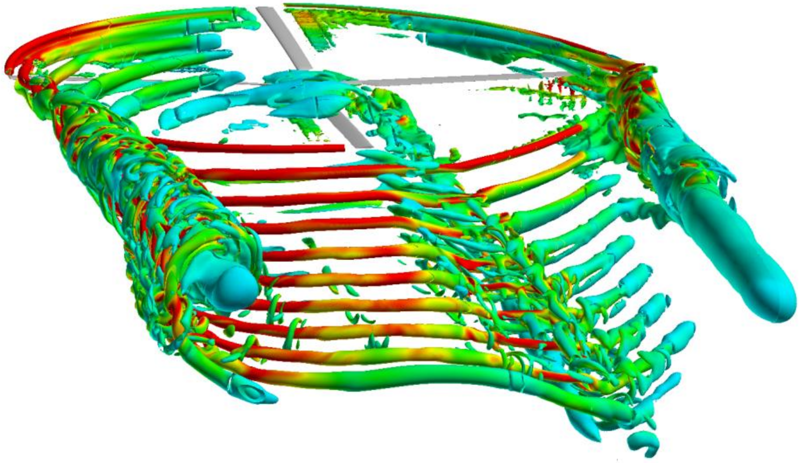


High-speed flight 8534
μ = 0.368
C_T/σ = 0.084
α_S = -7.31°

Similar Results for HART-2 Rotor

- Simulation of 40% Mach-scaled Bo105 model rotor experiments at the DNW wind tunnel
- Low-speed descending flight at $\mu = 0.15$



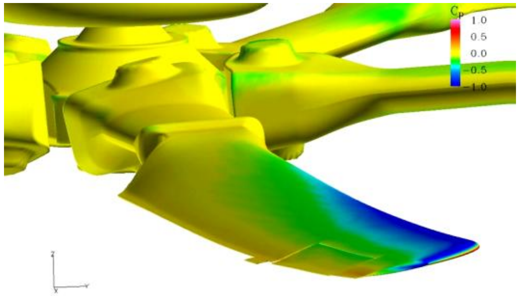


Helios "Rainier" Version 3

Beta release slated for Jan. 2012

Capability Enhancements

- **Full rotorcraft configurations**
  - **Fuselage + multiple rotors, tail rotor, etc.**
- **New turbulence models for off-body meshes**
- **Ability to model maneuvering rotorcraft**
- **Simplified setup and mesh preprocessing input**



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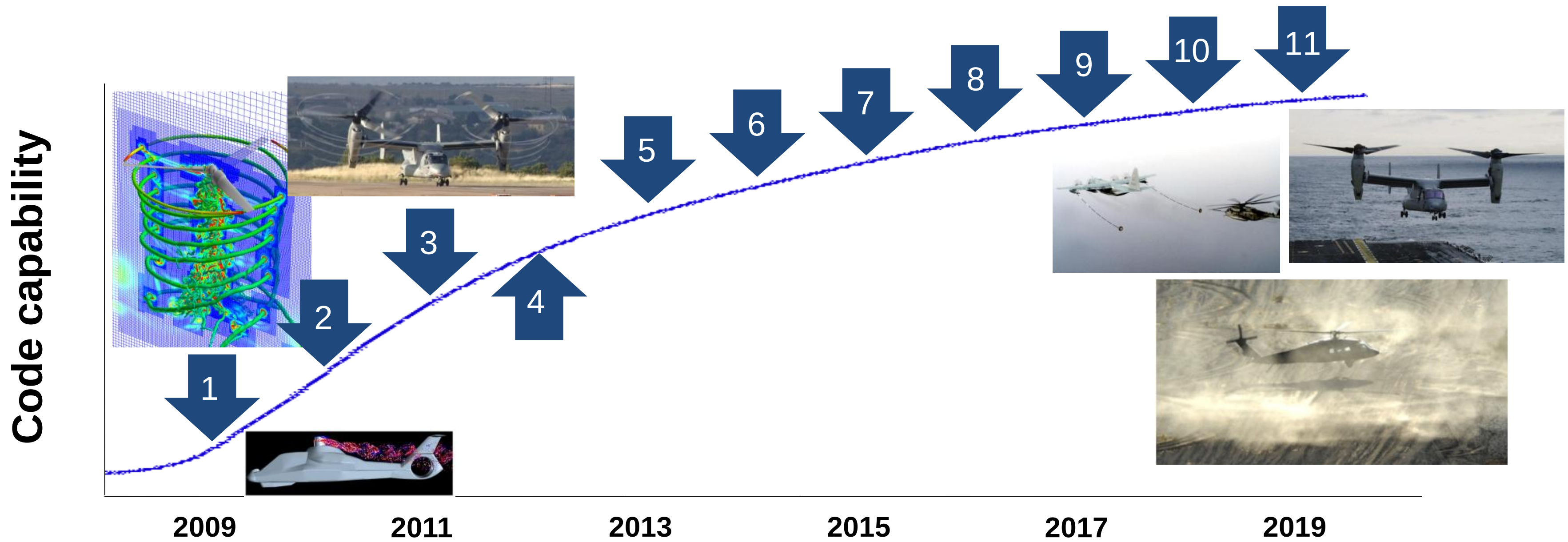
Helios Capability Delivery Schedule



1) Arbitrary complete fuselage (rigid)
- **Engineering model of rotor**
- **Isolated rotors (hover and forward flight)**
- **Aero-elastic blades w/trim**

2) Full rotorcraft configurations (fuselage, rotor, fan)
- **Elastic rotor and fan blades**
- **Automated mesh adaptation for accurate wake capturing**

3) Arbitrary full rotorcraft configurations
- **Multiple rotors/fans**
- **Propulsion effects**
- **Improved fidelity of aerodynamics**
- **Introduction of fuselage structural dynamics**

4) Add capability to accommodate variety of operating conditions (hot, heavy, high altitude)
- High fidelity structural dynamics (rotor and fan blades)

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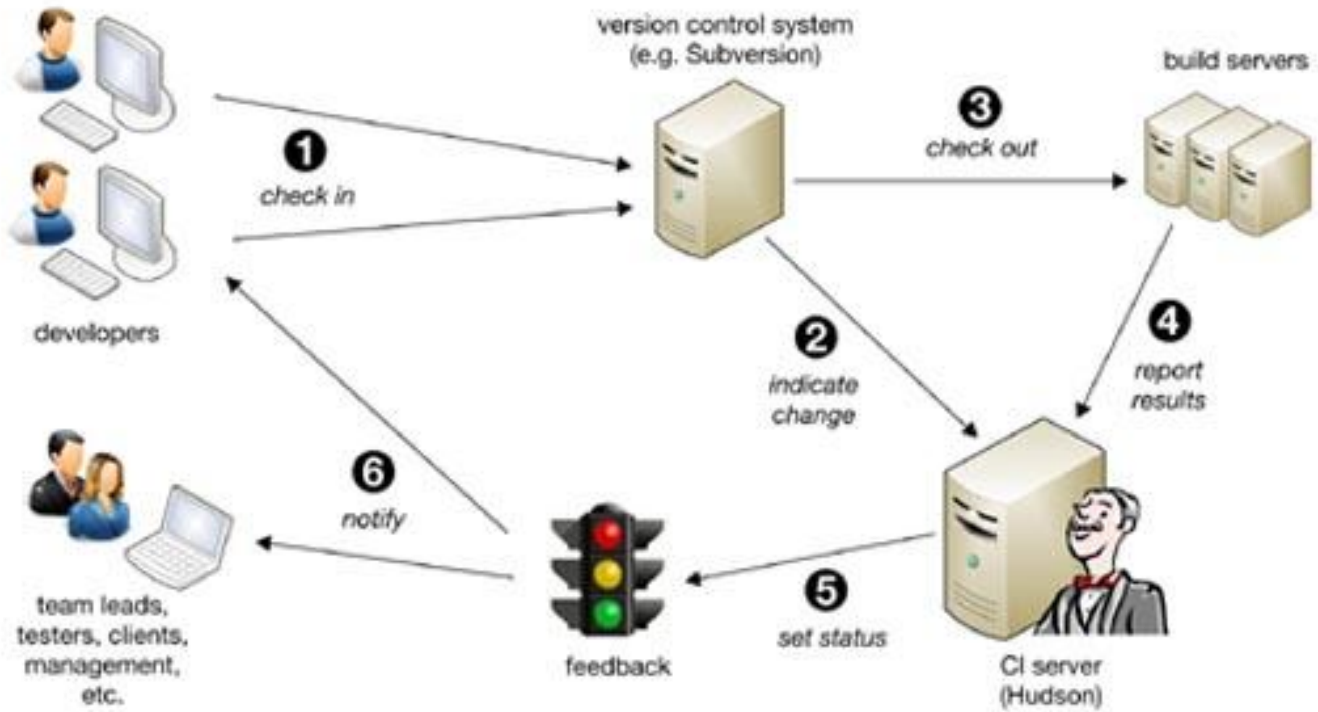
11) Arbitrary full rotorcraft configurations
- High fidelity aerodynamics (hover, fwd-flight, separated flow, etc)
- High fidelity structural dynamics (fuselage and blades)
- Multiple vehicles w/ land and ship takeoff/land sim capability
- Adaptive mesh refinement for evolving near-body dynamics and vortex wake capturing
- Full complement of operational conditions and environments (e.g., hot, heavy, high altitude, dynamic ship deck/sea-states, brownout, icing, etc)

Helios Software Management

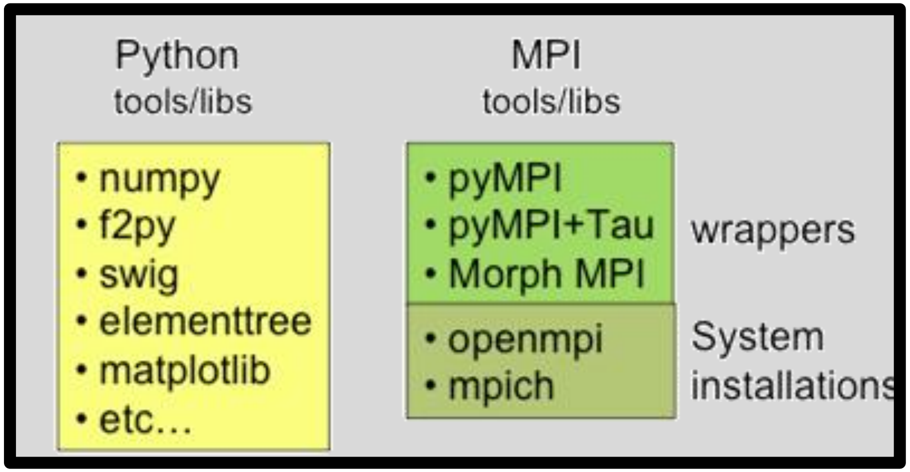


- **Individual SVN repositories for component modules and for integrated Helios build**
- **Use Hudson for continuous integration**
- **Use communications tools supported by CREATE-A/V**
  - JIRA , Wiki, Web based support
  - User manual, Test suites/Tutorials

Helios Build/Runtime Environment

- **Helios requires a variety of freely available build & runtime system libraries**

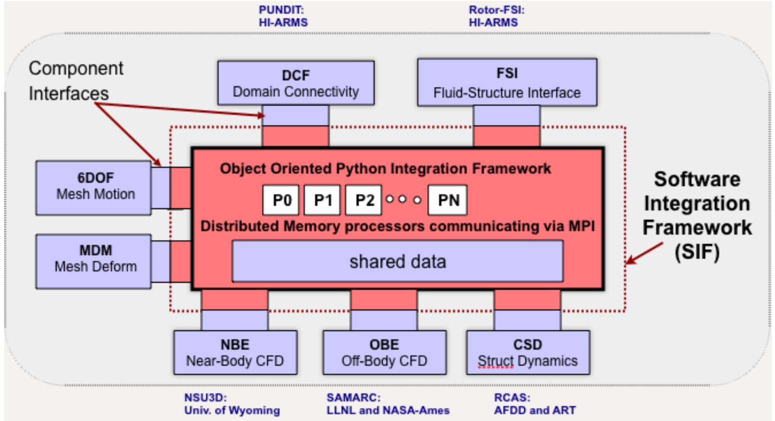
- **Difficult to install this environment consistently across systems**
  - Requires expertise in compilers, linkers, runtime systems, and system administration
  - Very time consuming, even for computer scientists



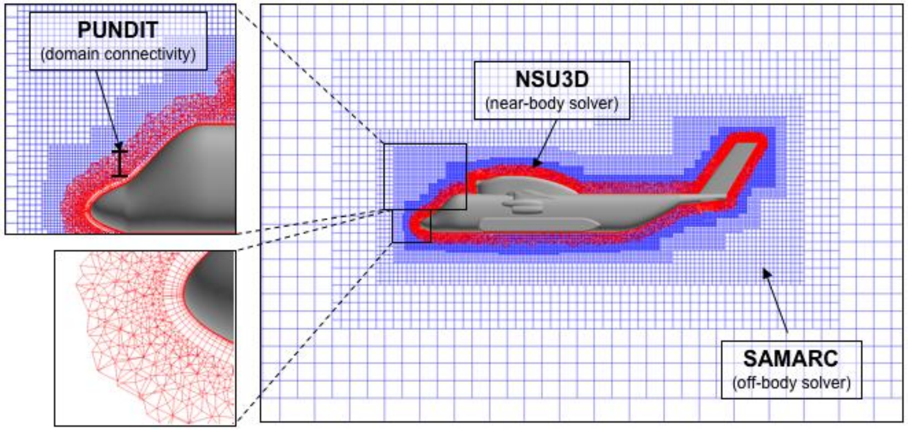
Don't want to force Helios users to shoulder this burden

- **Collaborate on PETT-funded development of a generalized HPC-based Python build & runtime environment**
  - Automated installation of build environment prior to new Helios installations
  - Developed by Sameer Shende from Paratools Inc
  - Now standard on all DSRC's

Helios Future Research Plans



Modular interfaces



Dual mesh paradigm

- **Future Helios research and development will utilize a combination of in-house development, direct funded efforts, leveraged efforts, and collaboration**
  - 3-D structural dynamics for rotor blades
  - New high-accuracy flow solvers for near-body unstructured grids
  - Adjoint-based rotor shape-optimization based on high-fidelity CFD aerodynamics
  - Wind turbine modeling including atmospheric turbulence

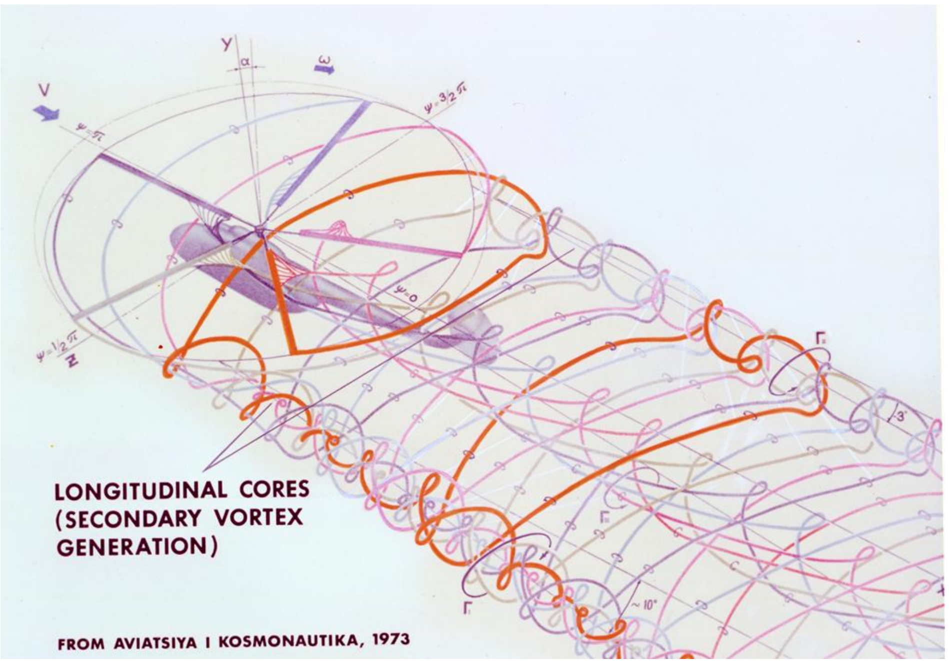
Helios Development Summary

- **CREATE-A/V Helios development has led to dramatic improvements in state of the art for rotary wing aeromechanics**
  - US industry beta testing for Whitney v1 concluded in August 2010
  - New Shasta v2 beta testing is underway
  - Development and alpha testing for Ranier v3

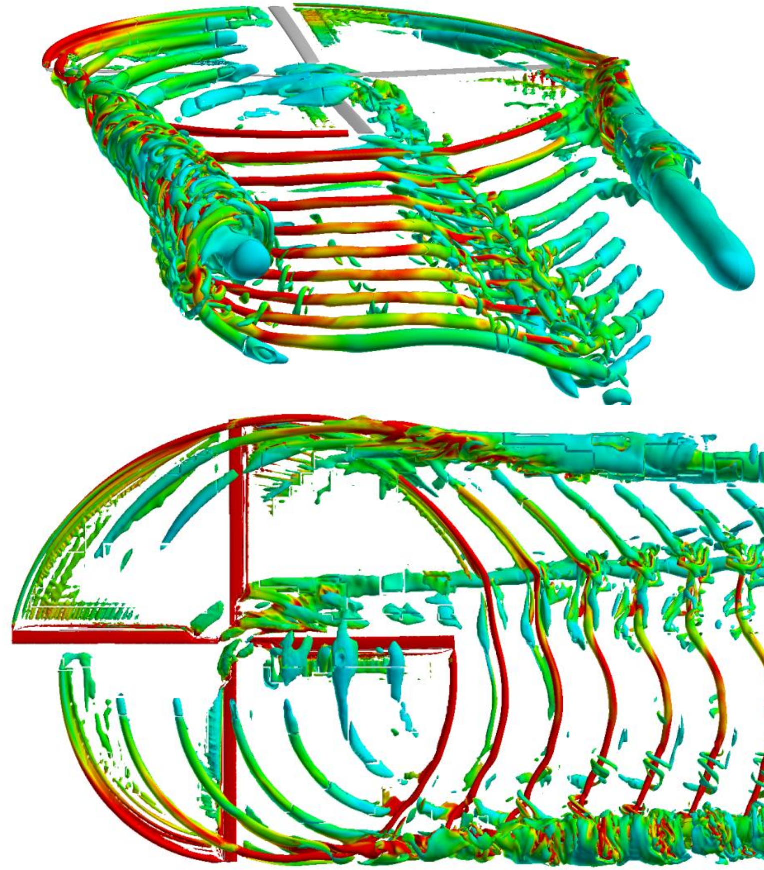
- **Future focus on integration into DoD rotorcraft acquisition programs**
  - Partnerships with US helicopter industry for Helios beta testing
  - Helios development will continue with combined Army and CREATE-A/V funding
  - Modeling and simulation for future DoD vertical lift programs such as Army Joint Multi-Role Rotorcraft

- **Future Helios research and development will utilize a combination of in-house development, direct funded efforts, leveraged efforts, and collaborations**

Questions?



Aviatsiya I Kosmonautika (1973)



Helios (2011)

A Note from our Lawyers

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