Advances in Computational Aeroelasticity Using Supercomputers

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Global Summit of Overseas and Resident Indian Scientists and Academicians
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Background

- Structural deformations impact vehicle performance
  - High speed civil transports
  - Launch vehicles
  - Rotorcraft
  - Flexible thermal protection system
- Strong fluid/structure interactions occur due to
  - Flow separations, moving shock waves
  - Large structural displacements
  - Aeroelastic instabilities such as flutter
- Current analysis tools for design compute aeroelasticity within linear aerodynamic limitations (NASTRAN)
  - Euler/Navier-Stokes (ENS) based methods are needed
- Many current procedures use ENS as corrections to linear aerodynamic
  - Not adequate when flow non-linearities occur
  - Cannot account for non-linear phase angles
  - Not adequate for transient cases
  - Not suitable for active-controls
- Of recent more tendency towards using Reduced Order Method
  - Limited to Euler equations
  - Not robust for Navier-Stokes equations (Stanford)
  - Not shown better than uncoupled modal approach (ENSAERO)

Key References

“Aeroelastic Time Response Analysis of Thin Airfoils by Transonic Code LTRAN2,” Computers and Fluids, (1981)

“Efficient Algorithm for Unsteady Transonic Aerodynamics of Low-Aspect-Ratio Wings,” J. of Aircraft, (1985),

“An Integrated Approach for Active Coupling of Structures and Fluids,” AIAA J., (1989)

“Unsteady Aerodynamic and Aeroelastic Calculations for Wings Using Euler Equations,” AIAA J., (1990),

“Vortical Flow Computations on a Flexible Blended Wing-Body Configuration,” AIAA Jl., (1992)

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“Direct Coupling of the Euler Flow Equations with Plate Finite Element Structures," AIAA J., (1995).)

“Navier-Stokes Computations for Oscillating Control Surfaces,” J of Aircraft, (1994),

“Convergence Acceleration of a Navier-Stokes Solver for Efficient Static Aeroelastic Computations,” AIAA J., (1995)

”CFD/CSD Interaction Methodology for Aircraft Wings", AIAA J (1998)

“Aerodynamic Influence Coefficient Computations Using ENS Equations on Parallel Computers,” AIAA J., (1999)

“Development and Applications of a Large-Scale Fluids/ Structures Simulation Process on Clusters,” C & Fluids (2007)

“Time-Accurate Aeroelastic Computations of a Full Helicopter Model RANS” J. of Aerospace Innovations, (2013).

“Dual Level Parallel Computations for Database to Design Aerospace Vehicles,” NASA TM-2013-216602, (2013).

“Dynamic Stability Analysis of Hypersonic Transport during Reentry,” AIAA J (2017)

“Time Accurate Coupling of 3-DOF Parachute System using Navier-Stokes Equations,” J Spacecraft and Rockets, (2016)

“N–S Equations-Based Aeroelasticity of Supersonic Transport Including Short-Period Oscillations, “ AIAA J, (2018)

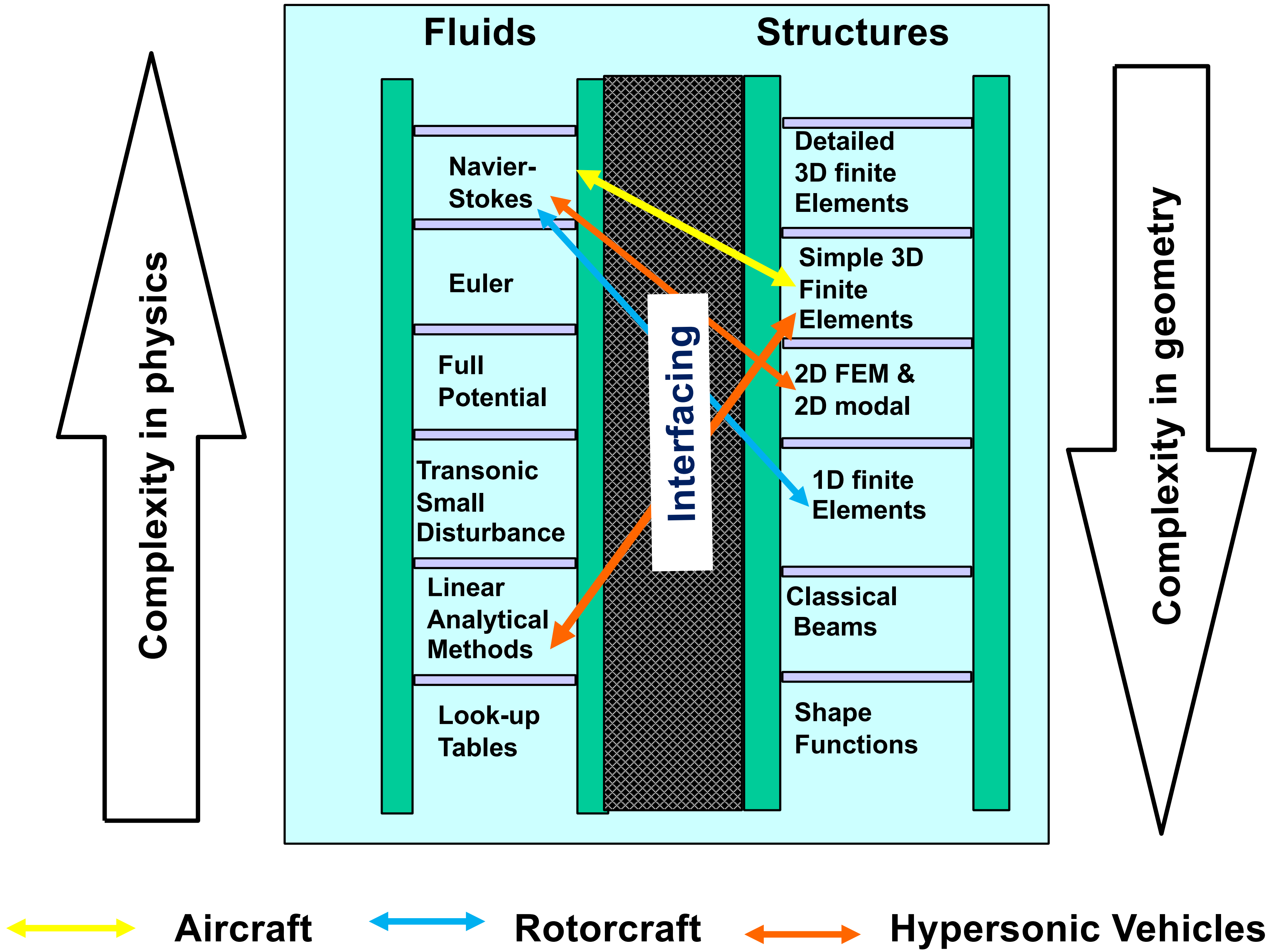
“Takeoff Simulation of Lift + Cruise Air Taxi by Using Navier-Stokes Equations,” AIAA J, Feb 2020

Objective

- To present a summary of frequency and time domain procedures for aeroelasticity by using non-linear flow equations

  - Transonic small perturbation theory
  - Euler/Navier-Stokes Equations
  - Suitable for frameworks
  - Focus on efforts at Ames Research Center since 1975
  - 100 person-year effort!

Levels of Fidelity



Solver Approaches

- Transonic Small Perturbation Equations
  - Limited to transonic flows
  - Robust since no grid movements
  - Super fast and still good for conceptual design

- Euler/Navier-Stokes equations
  - Reynolds averaged Navier-Stokes (RANS) equations
  - Baldwin-Lomax & Spalart-Allmaras turbulence models
  - Diagonal form of Beam-Warming central difference solver
  - Stream-wise upwind algorithm of Obayashi and Goorjian
  - Structured grids, patched & overset
  - Implemented in NASA codes HIMAP, OVERFLOW
  - Grids are validated for space and temporal accuracies

- Lagrange's structural equations
  - Finite element and modal form

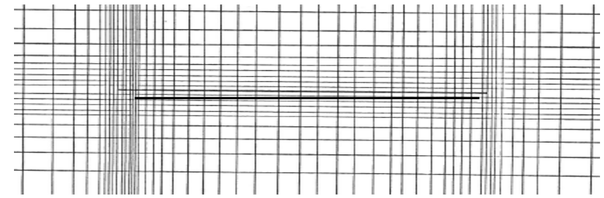
- Trajectory Equations

  3 DOF - Parachutes

  Phugoid Motion – Supersonic Transport

  Take off Simulation of eVTOL

CFD Grid Topologies



- Transonic Small Perturbation (TSP)
  - Cartesian grids
  - Grid motions are simulated with velocity perturbations
  - Immersed boundary conditions

- Euler/Navier-Stokes-Structured Grids
  - Patched Zonal Grids with implicit interzone interfaces
  - Overset grids with explicit overlapping zonal grids

IMB for TSP

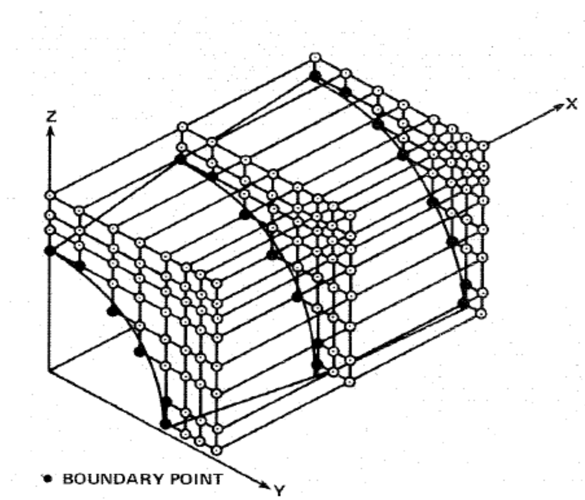
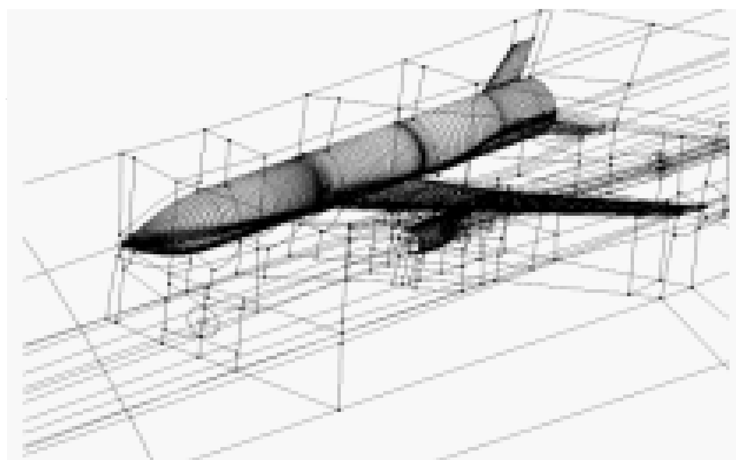
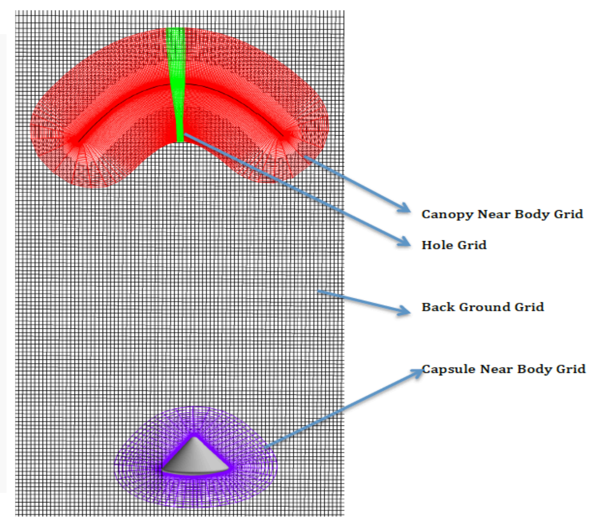


Fig. 2 Body boundary points.

Patched Zonal Grids



Overlapping zonal grids



Coupled Aeroelastic Equations of Motion

- **Lagrangian equations of motion**

$$[m]\{\ddot{d}\}+[g]\{\dot{d}\}+[k]\{d\}=\{f\}$$

Where [m], [g], and [k] are mass, damping, and stiffness matrices
{d} and {f} are the nodal displacements and aerodynamic force

- **[m], [g] and [k] are computed using FEM**
- **{f} is computed solving ENS equations**
- **Solved using direct time integration**

Modal Equations of Motion

From Rayleigh-Ritz analysis, the displacement vector {d} can be expressed as:

$$\{d\} = [\psi]\{q\}$$

where $[\psi]$ is the modal matrix and {q} is the generalized displacement vector. The final modal form of Lagrange's equations of motion is:

$$[M]\{\ddot{q}\} + [G]\{\dot{q}\} + [K]\{q\} = \{F\}$$

where [M], [G], and [K] are modal mass, damping, and stiffness matrices respectively. {F} is the generalized aerodynamics force vector defined as

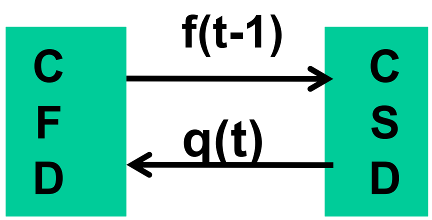
$$\frac{1}{2}\rho U^2[\psi]^T[A]\{C_P\}$$

where Cp is the pressure coefficient [A] is the diagonal area matrix of the aerodynamic control points, ρ the free-stream density, and U is velocity.

Coupled Procedures Using CFD/CSD

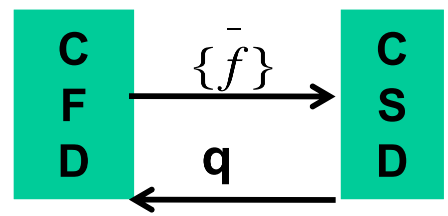
- Can be grouped into two categories based on type of fluid/structure coupling

TA-time Accurate



Every step

HB-Hybrid Methods



Ad-hoc

- In both methods CFD is computed time accurately
- In TA, airload {f(t-1)} is from previous CFD time step for explicit time integration with CSD. Same time is used both for CFD and CSD

$$[m]\{\ddot{q}\}+[c]\{\ddot{q}\}+[k]\{q\}=\{f_{CFD}\}$$

- In HB, $\{\bar{f}\}$ is modified using non-CFD (look –up tables!)

$$[m]\{\ddot{q}\}+[C]\{\dot{q}\}+[k]\{q\}=\{\bar{f}\}=g(\{q\})+\{\Delta f_{CFD}\}$$

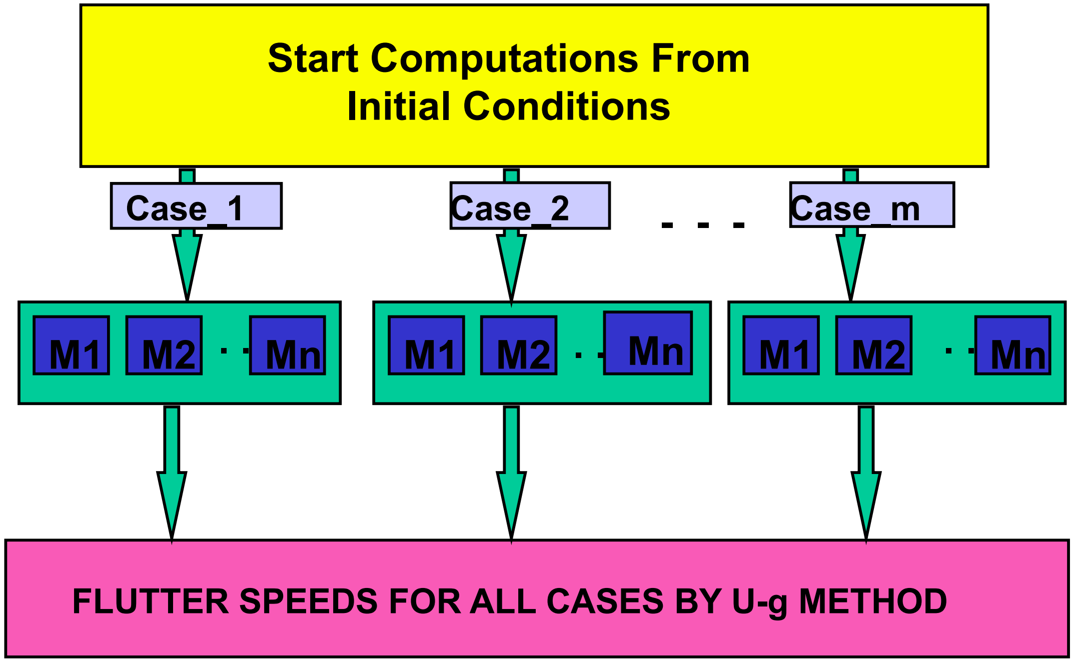
- G is based on linear theory, look-up tables etc.
- CFD and CSD is not in the same time frame

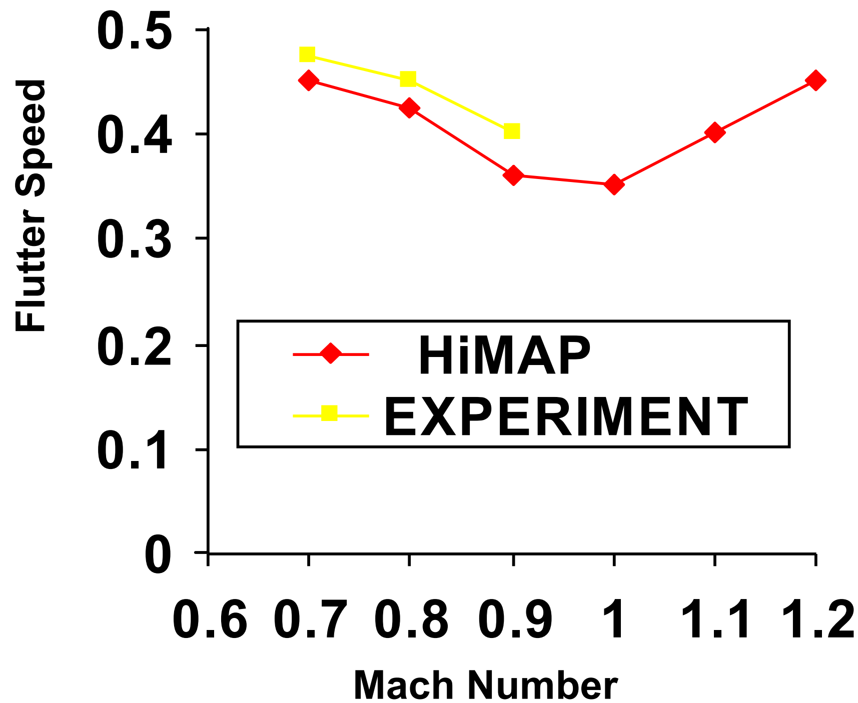
Uncoupled Aeroelastic Procedure

(AKA Reduced Order Structures Model, ROSM)

- **Onset of instability starts as a small perturbation phenomena**
- **Unsteady aerodynamic forces for all frequencies are computed using fast indicial response approach**
- **Primary stability depends on rigid body pitch and plunge motions**
- **Fast generation of indicial responses is accomplished using dual-level parallel computations**
- **Stability analysis is performed in <u>frequency domain</u> using pre-computed unsteady aerodynamic data. (uncoupled analysis)**

Example for Uncoupled Computations





Mn N Modes = Number Of Modes X Number Of Frequencies Selected

Case_m Each Case May Have Different Flow Conditions

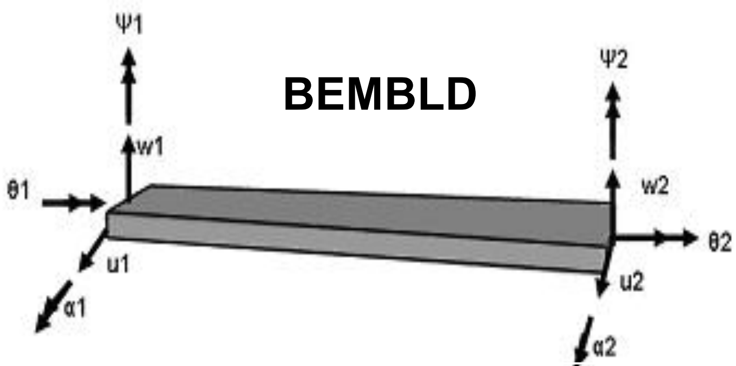
Note : 100 Gflop Performance On 1024 Nodes On O2000
Suitable Low- Fidelity Computations To Fill Design Space

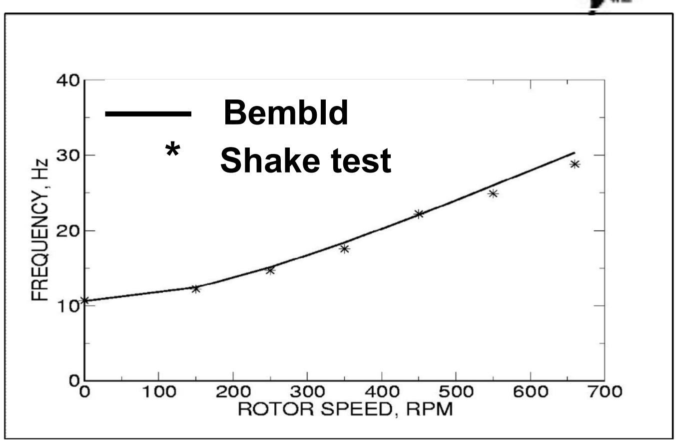
Typical Finite Elements Used

In-house NASA 1D, 2D and 3D CSD models

- BEMBLD : 10-dof rotating beam element
- SPARH: shear panel for spars and ribs
- PLTSHL: 18-dof skin/plate/shell fem
- TET3D: 12-dof tetrahedron solid element (future)
- NASTRAN

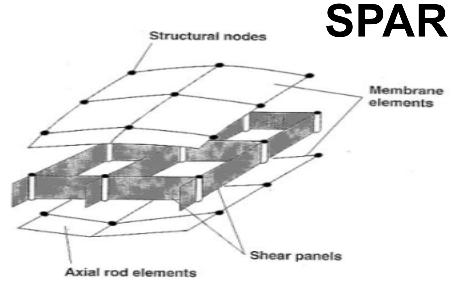
BEMBLD



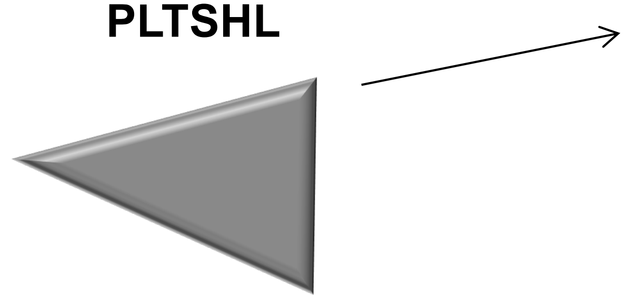


First flapping frequency

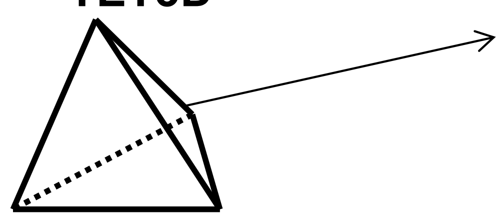
SPARH



PLTSHL



TET3D



Newmark's Time Integration

- **Assuming linear acceleration:**

$$\{\ddot{q}\}_{t+\Delta t} = [D](\{F\}_{t+\Delta t} - [G]\{v\} - [K]\{w\})$$

$$\{\dot{q}\}_{t+\Delta t} = \{\dot{q}\}_t + \left(\frac{\Delta t}{2}\right)\{\ddot{q}\}_t + \left(\frac{\Delta t}{2}\right)\{\ddot{q}\}_{t+\Delta t}$$

$$\{q\}_{t+\Delta t} = \{q\}_t + (\Delta t)\{\dot{q}\}_t + \left(\frac{\Delta t^2}{3}\right)\{\ddot{q}\}_t + \left(\frac{\Delta t^2}{6}\right)\{\ddot{q}\}_{t+\Delta t}$$

where

$$[D] = \left([M] + \left(\frac{\Delta t}{2}\right)[G] + \left(\frac{\Delta t^2}{6}\right)[K]\right)^{-1}$$

$$v = \{\dot{q}\}_t + \left(\frac{\Delta t}{2}\right)\{\ddot{q}\}_t$$

$$w = \{q\}_t + (\Delta t)\{\dot{q}\}_t + \left(\frac{\Delta t^2}{3}\right)\{\ddot{q}\}_t$$

- **Above can be made implicit, assuming constant acceleration.**

FSI Implicit (staggered) algorithm

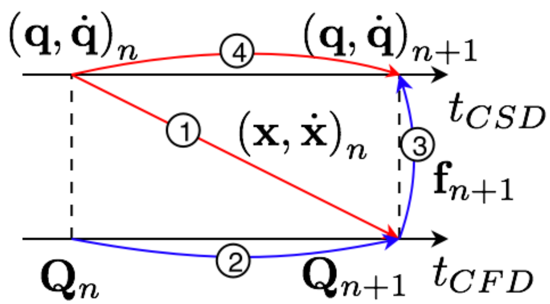
- **Algorithm**

  a) Compute deformations using loads at t

  b) Using a) advance CFD from time *t* to *t* + Δ*t*

  c) Compute deformations using loads at *t* + Δ*t*

  d) Repeat a) b) c) until converge (use Newton method)



- **Increases book-keeping and adds significant computational expense**

- **No impact on CFD and CSD (linear and geometrically non-linear) computations**
  - **In-house research**
  - **NASA sponsored research grants (UMD, Stanford)**

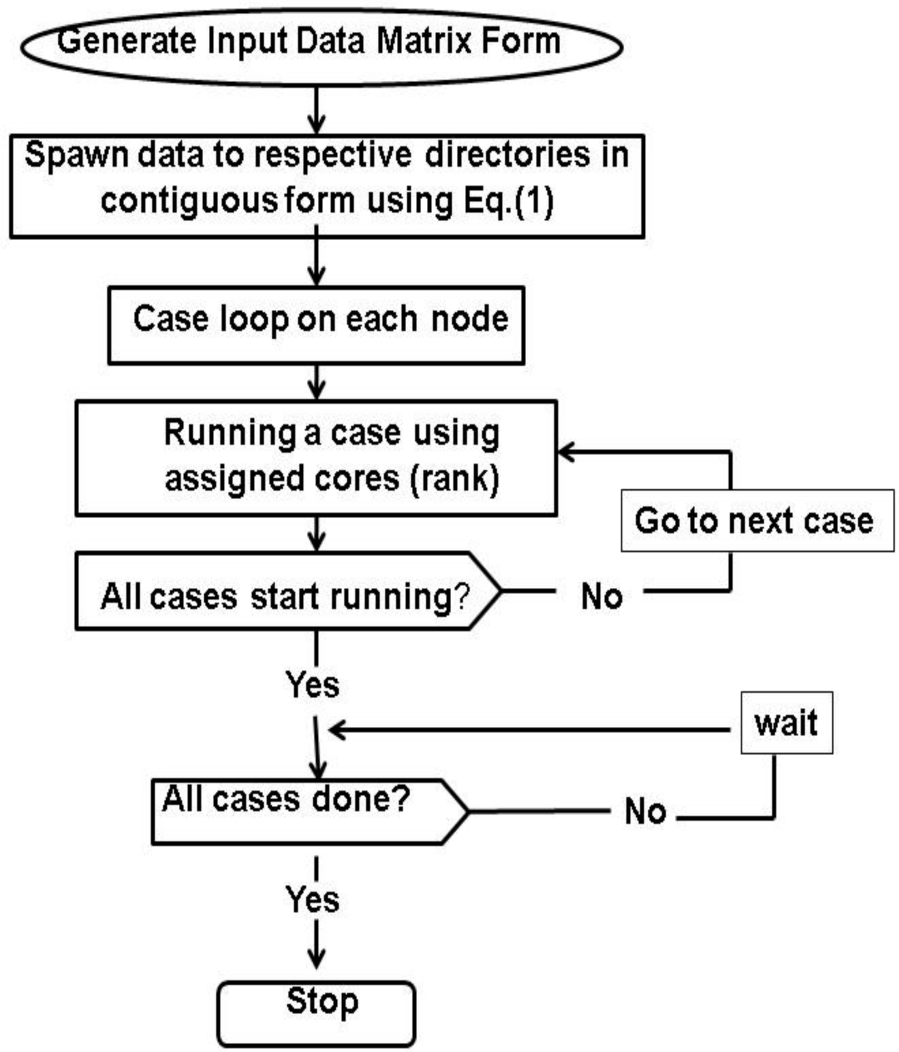
Some Related Developments

(in-house and/or sponsored)

- Sheared grids for swept tapered wings (TSP)
- Characteristics BCs for supersonic flows (TSP & ENS)
- Stream-wise upwind algorithm for ENS solvers
- Pipe-line Gauss-Seidel algorithm for parallel CFD
- Parallel direct & sub-structure solver for CSD (NASTRAN)
- MPIRUN, for parallel fluid/structure/control simulation
- Parallel version of SA turbulence model
- Virtual surface method for FSI
- Virtual surface method for sliding CFD grid zones (controls)
- Area co-ordinate method for FSI(wing-box)
- Tcl/Tk, C++ for CFD/CSD communications (GUI)
- Staggered FSI (rotorcraft)

Dual-Level Parallel Computing

- **Efficient single job environment for multiple cases, each running on multiple cores:**
  - **Reduces system start/end overhead**
  - **Makes sure that cores do not overlap**
  - **All cases are completed at the same time enabling designer to plan his work accordingly rather than "baby-sitting" the multiple jobs**



- **Facilitates fast generation of indicial response data for use in stability analysis**

Guruswamy, G.P., "Dual Level Parallel Computations for Large Scale High-Fidelity Database to Design Aerospace Vehicles," *NASA/TM-2013-216602*, Sept. 2013.

Three Level Parallel Computing

Description of High Fidelity Multidisciplinary Analysis Process (HiMAP)

A 3-level parallel, meta modular, multidisciplinary analysis software that runs on single-image shared/ distributed memory supercomputers using MPIAPI middleware

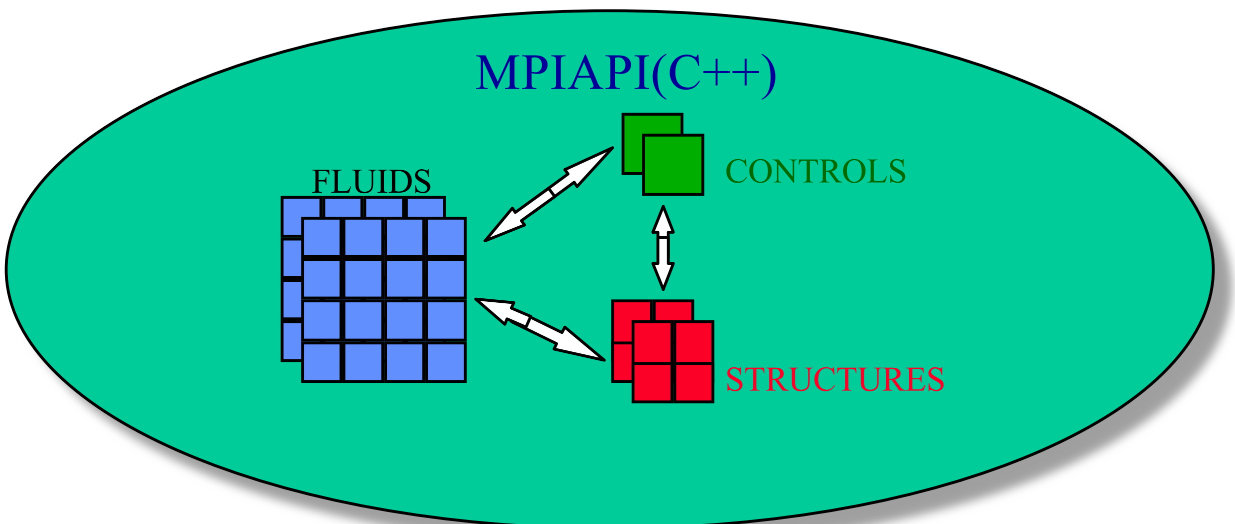
Accomplishments

Can handle disciplines based on time accurately coupled high fidelity methods

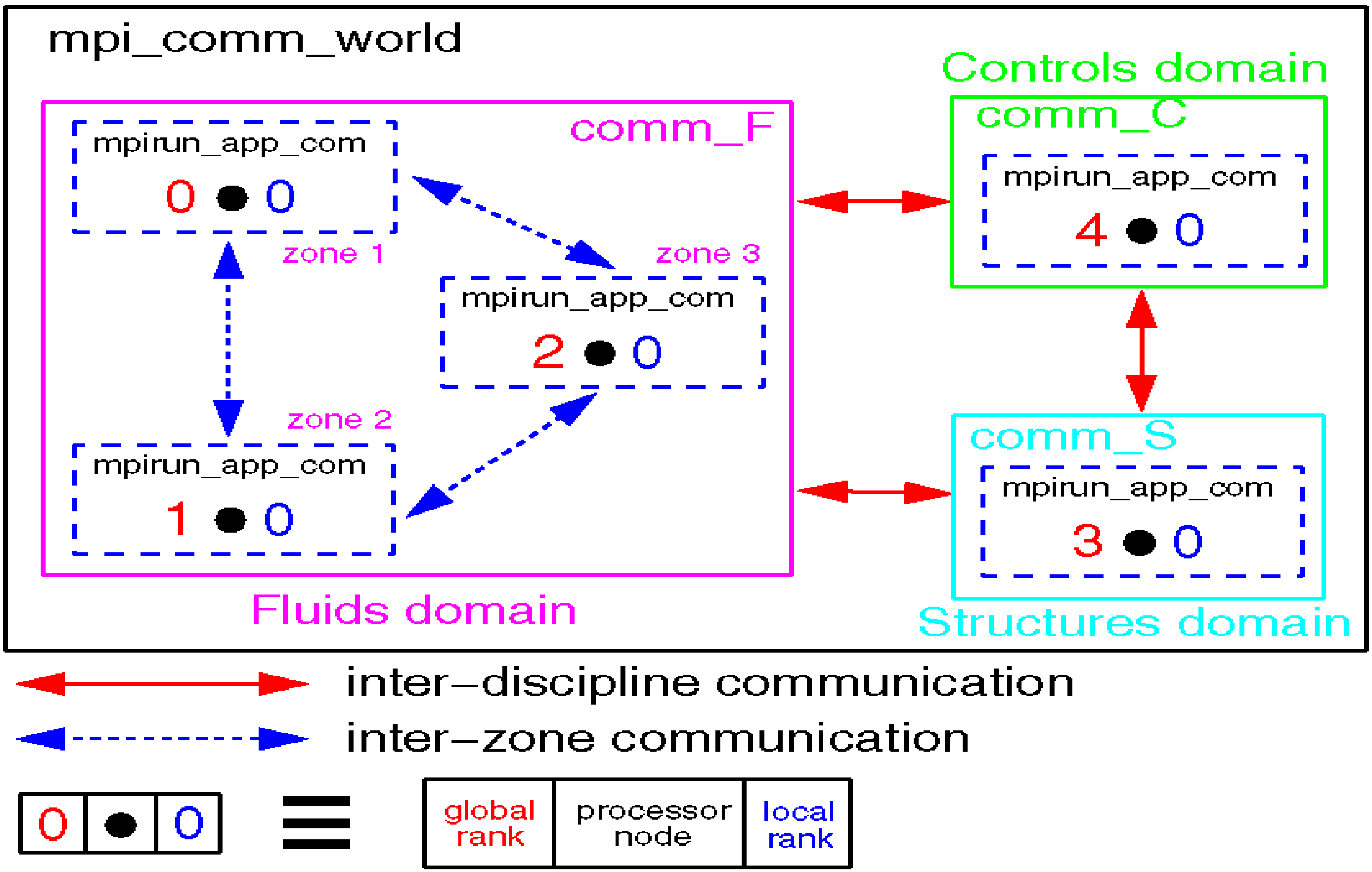
- **Structured/unstructured grid-based Euler/Navier-Stokes solvers (ARC3D, GO3D,USM3D) with parallel multi-block moving grid**
- **Modal and parallel finite element structures (NASTRAN)**
- **Time domain controls**
- **Winner of NASA Sofware Release award**

Applications

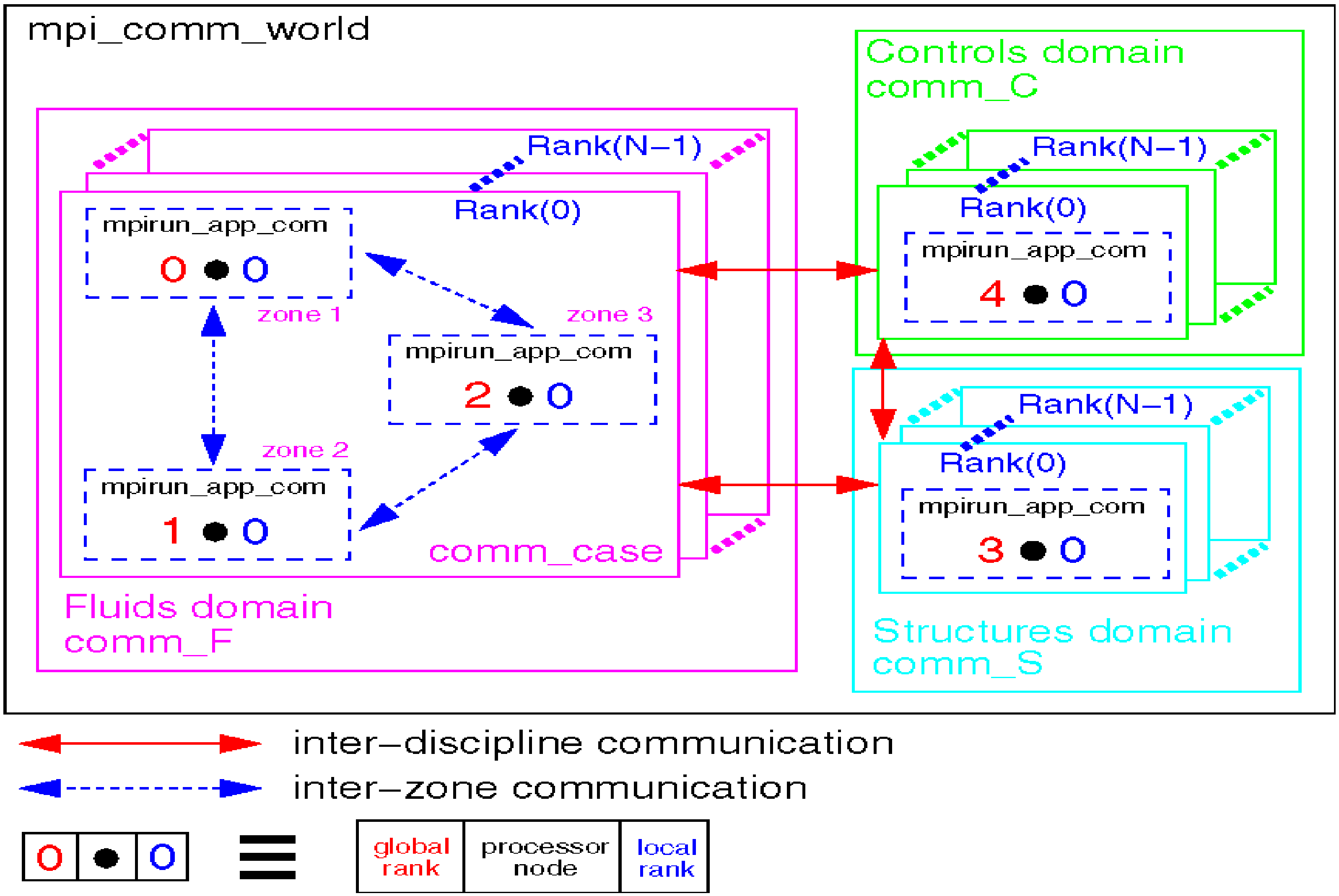
Demonstrated for full F-18, L1011, 777, HSCT, X-31 and UCAV configurations



Multizonal/Multidiscipline Parallel Communication In HiMAP



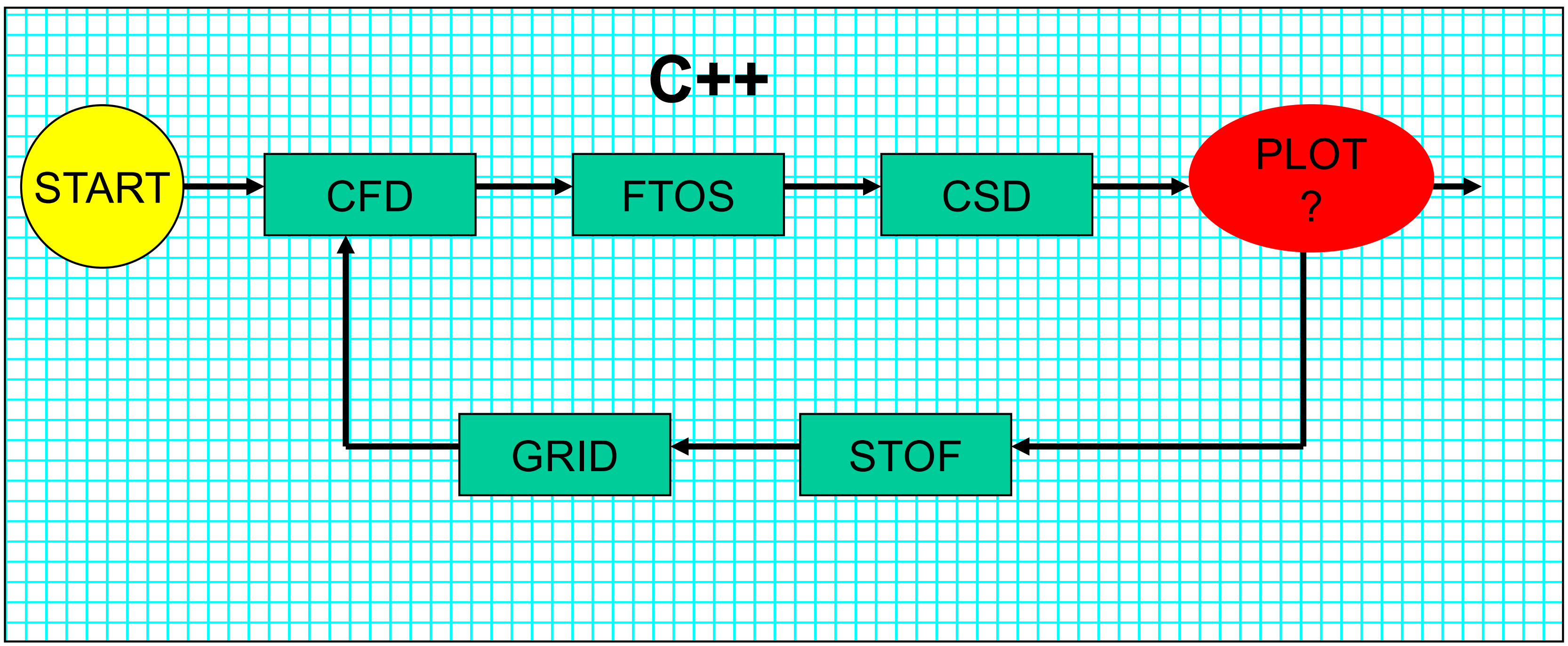
3-level Parallel Communication In HiMAP for MIMD Architectures



Effort towards Framework

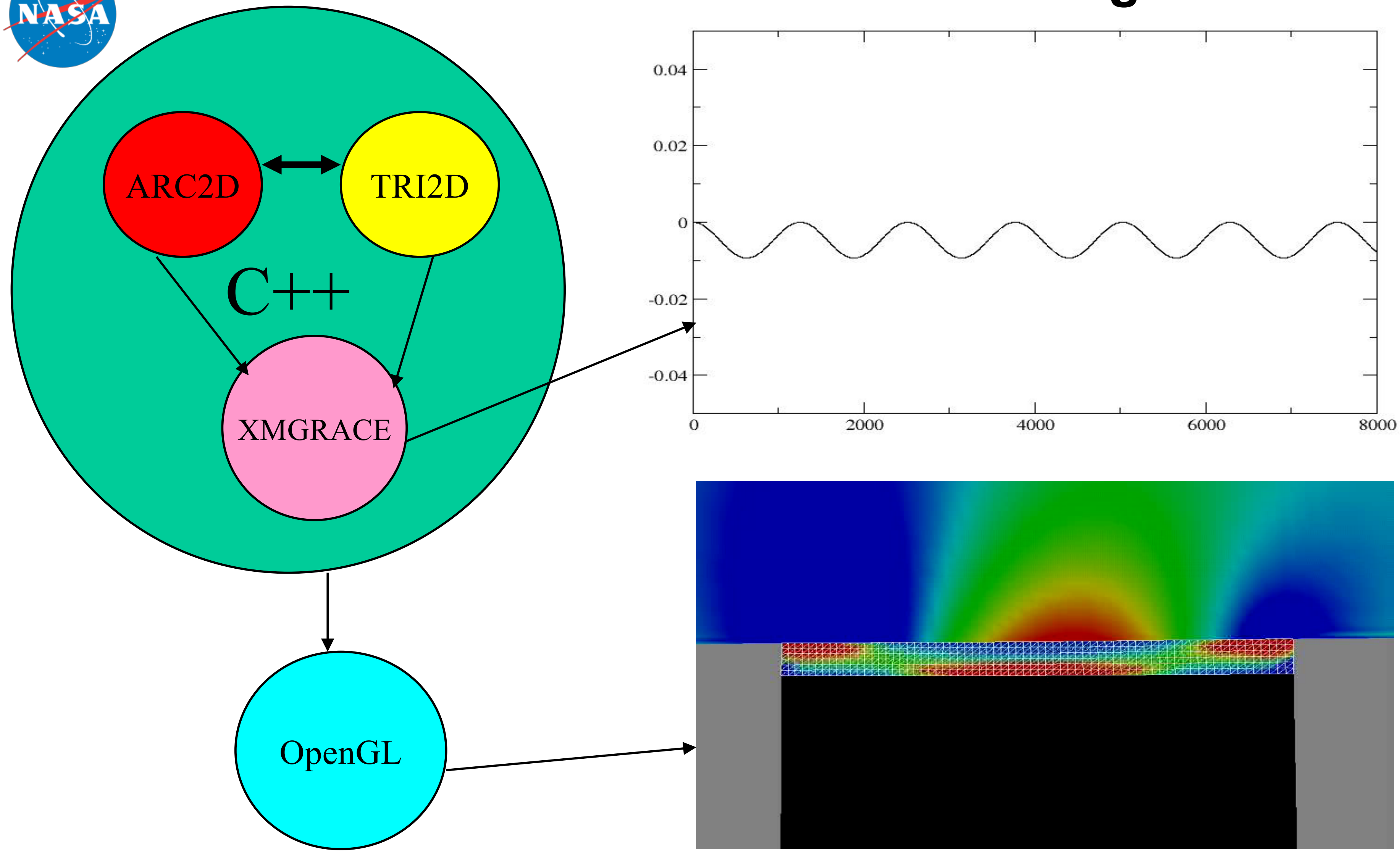
RUNEXE - C++ Based Super Modular Process

- All modules are treated separately as objects and executed using C++ system commands
- Communication among modules is accomplished using I/O, MPI and/or TCL/TK
- On-the-fly based graphics, xmgrace, opengl
- Manages data for visualization (field view)



CURRENT FORTRAN 95 HAS SOME SIMILAR CAPABILITIES

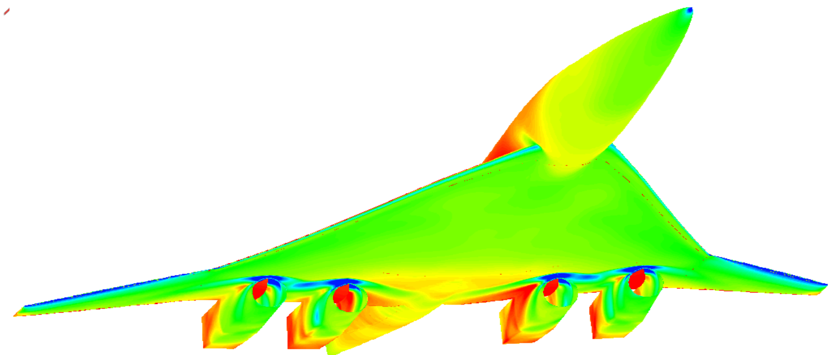
Illustration of RUNEXE Process using SCIRUN

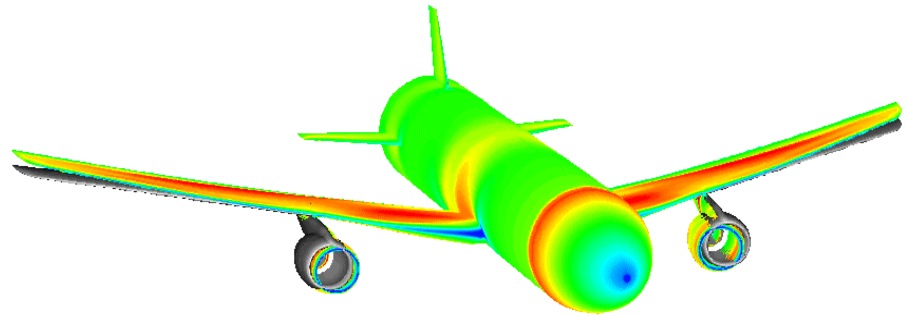


Guruswamy, G. P. and Cheung, C., 2D "Static FSI Analysis Using TCL/Tk Based PSE," International Conf on Parallel and Distributed Computing," Las Vegas, NV, June 2003

SCIRun - Scientific Computing and Imaging Institute - University of Utah
www.sci.utah.edu/cibc-software/scirun.html

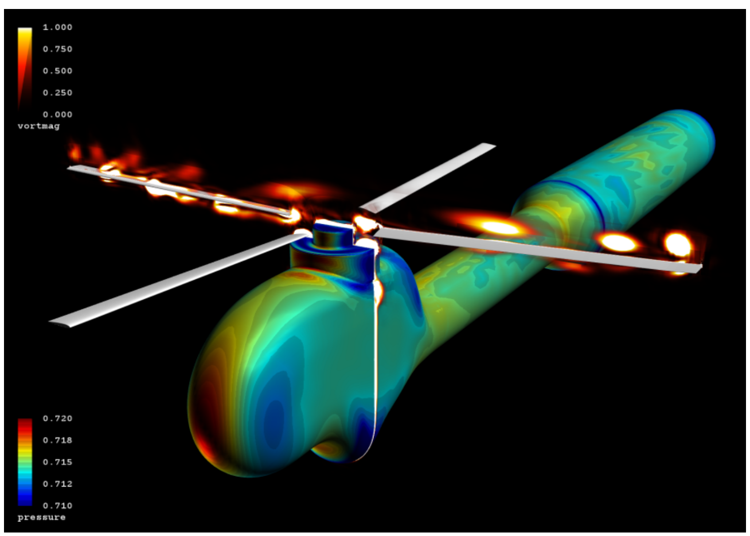
HiMAP and OVERFLOW _Aero Applications

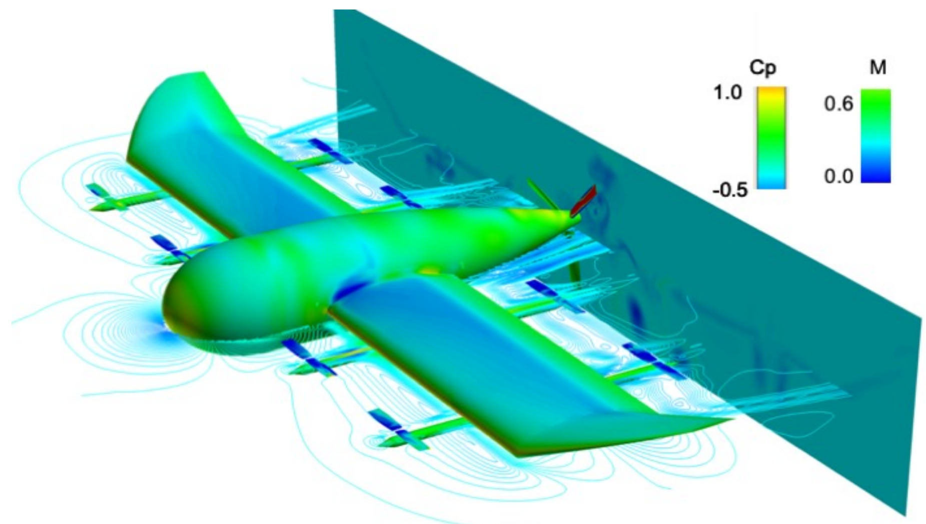




L1011, 10m Pts
Modalstructures

Hsct -12 M Grid Points
Elfini Fem



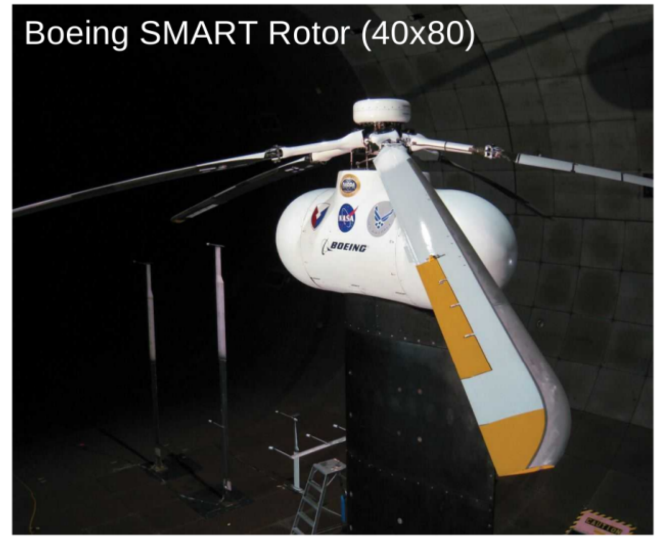


HART II Helicopter (27M Points)

Generic eVTOL (20M points)

CFD based Modeling of Moving Control Surfaces for Active Controls

- Active controls are in use for modern aerospace vehicles
  - suppress vibrations
  - improve maneuverability
  - prevent flutter
  - decrease acoustic noise



- Flow, structures and controls coupling is strong
  - pronounced in transonic regime

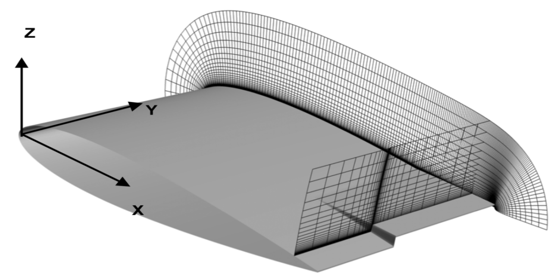
- Current fast flow solver procedures use linear theory (LT)

- Higher order methods such as based on the Navier-Stokes (NS) equations are needed for improved accuracy

- Efficient use of massively parallel computers is needed for large scale NS based computations

Moving Control Surfaces for Active Controls

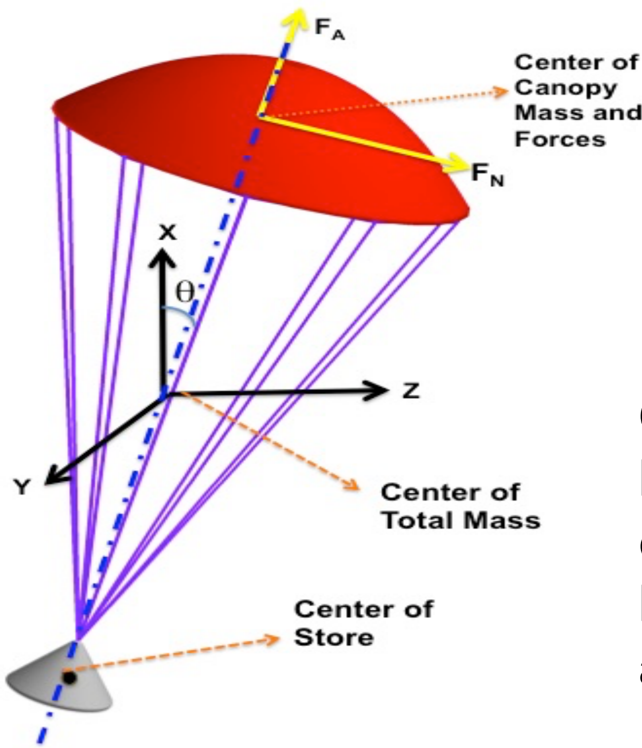
- **TSP equations**
  - control surface deflections are modelled using transpiration BCs
  - demonstrated for wing-body-tip store configuration
  - demonstrated for active control
  - Guruswamy, G. P., "Integrated Approach for Active Coupling of Structures and Fluids", AIAA Jl., Vol. 27, No. 6, June 89
  - Guruswamy, G. P. and Tu, E. L., " Transonic Aeroelasticity Wings with Active Control Surfaces," AIAA-87-0709, April 87



- **ENS Equations**
  - Parallel sheared grid module
  - Sliding zonal grid
  - Applied to active controls
  - Byun C. and Guruswamy, G. P., "Aeroelastic Computations on WB Control Configurations, ", Jl. of Aircraft, Vol. 35, No 2 April 1998
  - Obayashi ,"Virtual zone Navier-Stokes computations for oscillating control surfaces," AIAA 1993-336
  - Yeh, D, "Aeroelastic analysis of a hinged-flap and control effectiveness using the Navier-Stokes equations, " AIAA 1995-2263
  - Guruswamy, G. P, "Modeling of Oscillating Control Surfaces Using Overset-Grid-Based Navier–Stokes Equations Solver, " ASME *J. Dyn. Sys., Meas., Control* (Jan 10, 2017)

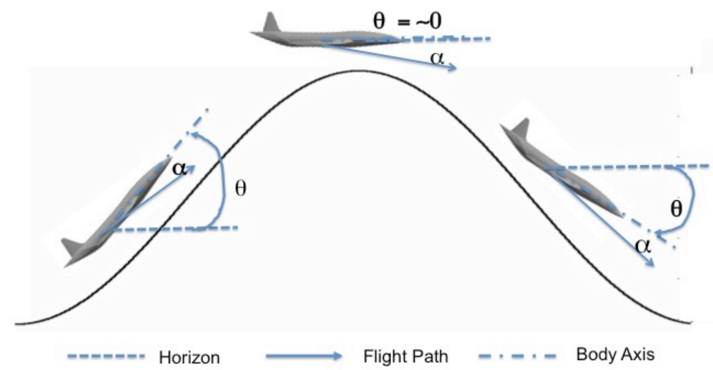
Coupling of NS and Trajectory Equations of Motion

Descending Parachute



Stability is critical after deployment particularly In supersonic regime

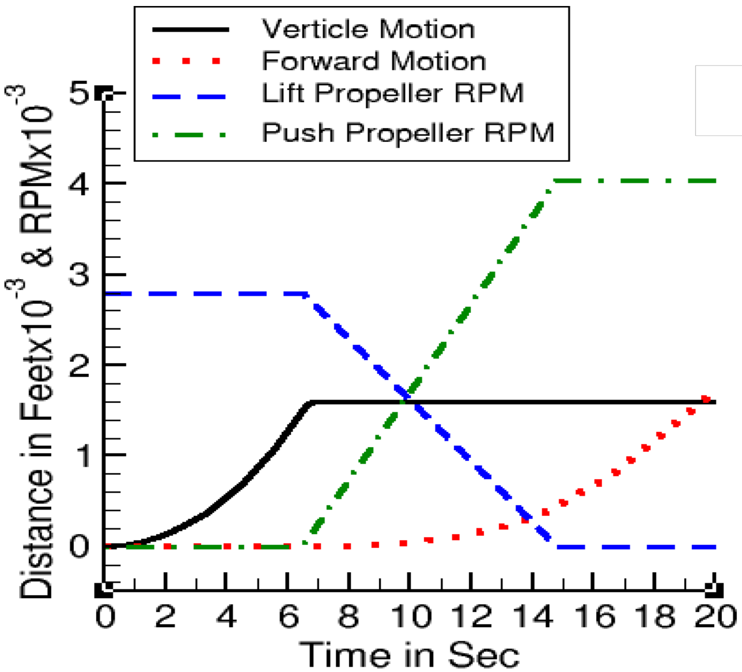
Phugoid Motion Simulation



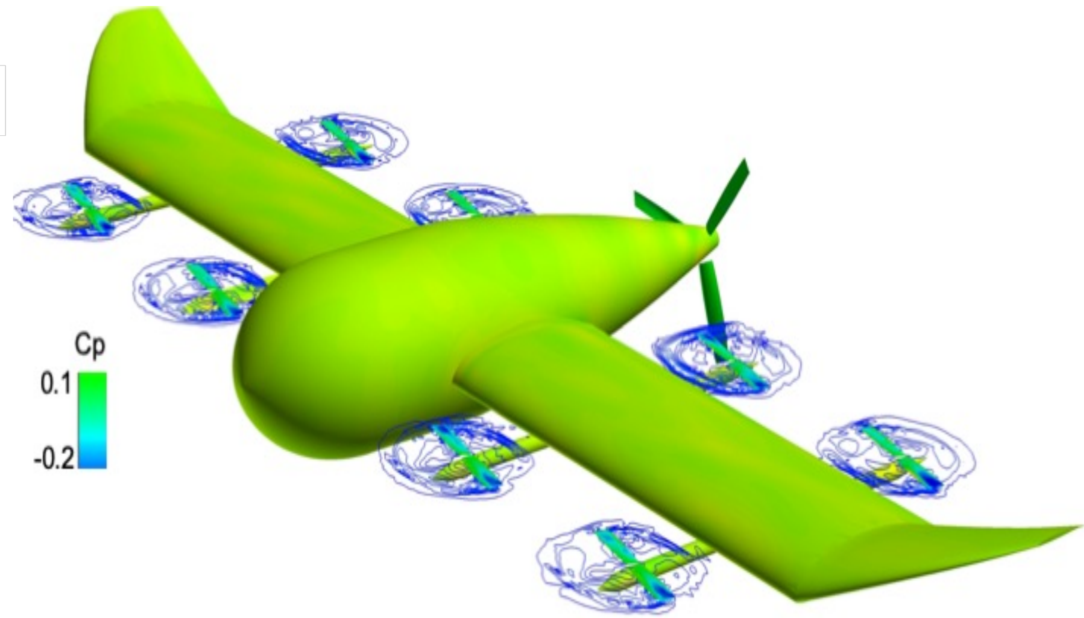
Oscillation in the altitude due to the exchange between potential energy and kinetic energy is called the phugoid oscillation. Beginning at the bottom of the cycle, pitch angle (θ) increases as the aircraft gains altitude and loses forward speed (V). During phugoid motion, the angle of attack (α) remains constant so that a drop in forward speed decreases lift and flattens pitch attitude.

Guruswamy, G.P., "Phugoid Motion Simulation of a Supersonic Transport Using Navier-Stokes Equations," AIAA J, Vol 56, No 6, June 2018. Guruswamy, G.P., "Time-Accurate Coupling of Three-Degree-of-Freedom Parachute System with Navier–Stokes Equations," J of Spacecraft and Rockets, Vol. 54, No. 6, November–December 2017.

Take-off Trajectory of eVTOL



Trajectory response for vertical and forward motion.



Snap shot of surface Cp and field Mach number distributions during vertical take-off.

Guruswamy, "Takeoff Simulation of Lift+Cruise Air Taxi by Using Navier–Stokes Equations," AIAA Journal, February 2020.

Where CFD/CSD made a Difference

- Transonic flutter-dip of transport aircraft
- Lateral vortex motion coupled with bending motion of blended wing body configuration (B-1, HSCT, BWB)
- Control-reversal due to moving shock-waves
- Jump in phase angles near shock-wave
- Leading edge vortex induced vertical tail oscillations (F18)
- Nacelle oscillations of aircraft in transonic regime (L1011)
- Blade vortex interactions of rotorcraft

Onset of Dutch Roll oscillations

What is Happening Elsewhere

- Rigorous Math models are being developed for FSI
  - Not yet proven better than engineering approaches

- Reduced order models for flows
  - Still as good as modal approach for Euler
  - Not robust for use with Navier-Stokes equations compared to modal approach (reduced structures model)

- Using unstructured CFD
  - Computationally slow
  - Still has issues in viscous zones dominated by turbulence

- Lattice Boltzmann equations embedded in NS
  - Bookkeeping can be nightmare!
  -

- MDAO frameworks
  - too many but still lack robust high fidelity MDA tools
  - OpenMDAO supported by NASA has potential

- Aeroelastic prediction workshop
  - good international effort
  - yet to catch-up with NASA ARC progress (say WBN L1011)

Validation Efforts Since 1978

- CFD- based frequency domain uncoupled methods

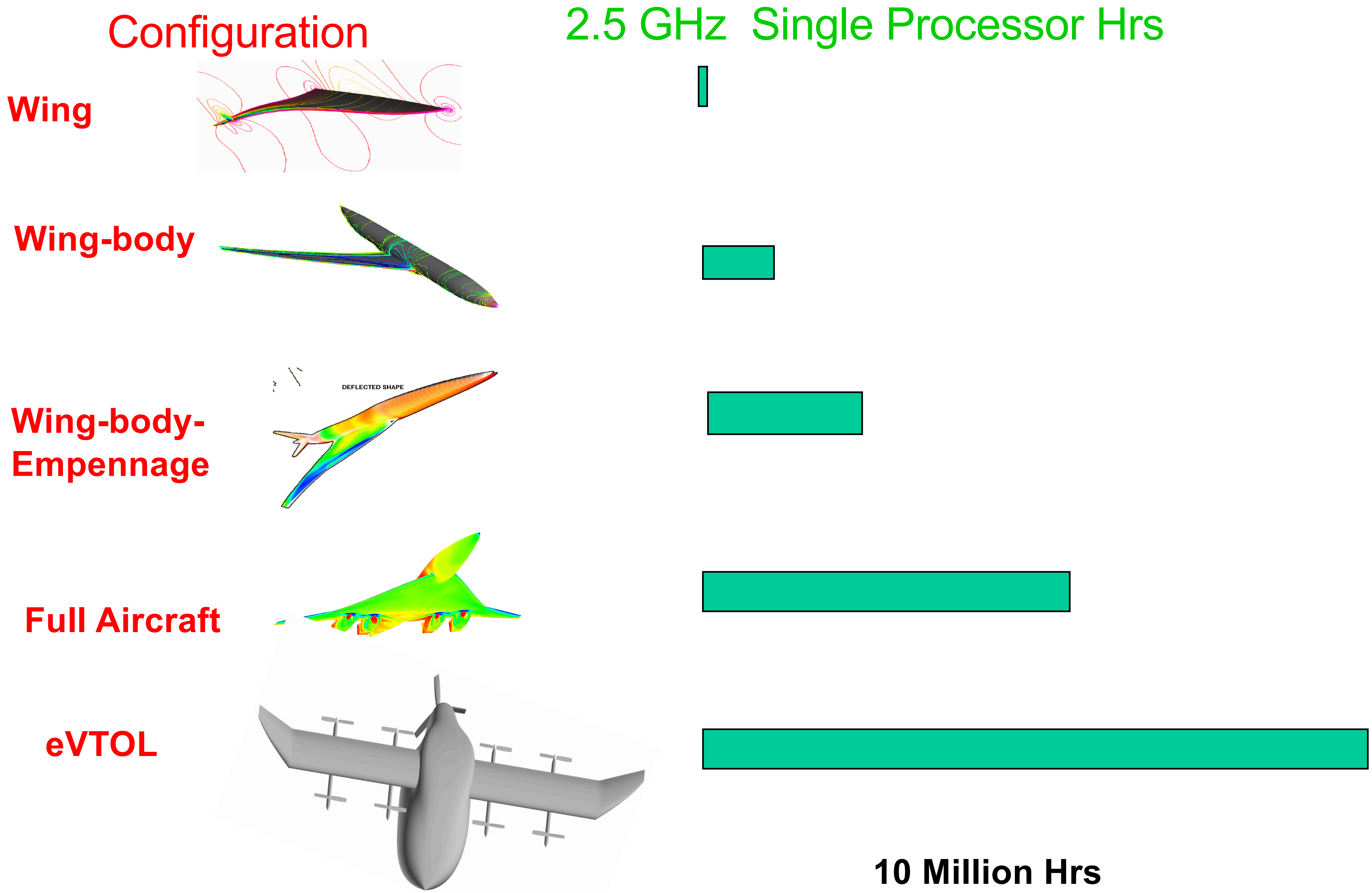
- Classical methods such as Theodorsen's theory

- Linear aerodynamics theories
  - Kernel function method
  - Doublet-Lattice method (NASTRAN)

- Wind tunnel
  - NASA TND344: unsteady aero, rectangular wing
  - NASA TMX79: flutter of rectangular wing
  - NASA ARW: aeroelasticity of wing body
  - B-1 aircraft: vortex induced oscillations
  - F-18 aircraft: vertical tail buffet
  - HART II rotorcraft: blade vortex interaction
  - F5-wing: oscillating control surfaces
  - AFW: aeroelastic flexible wing, active controls
  - L1011: Nacelle oscillations
  - NASA/RAE/NLR – Moving control surfaces

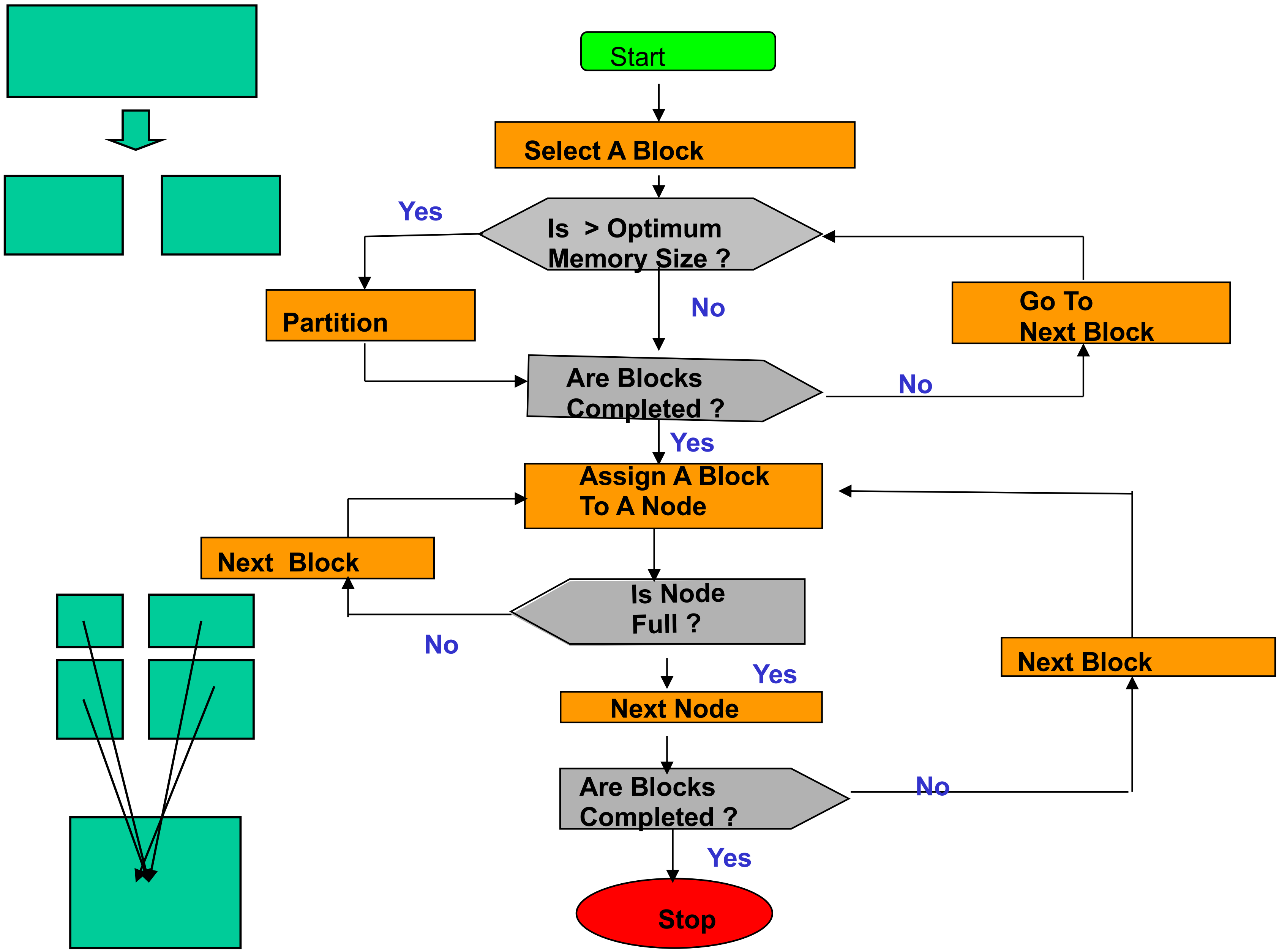
- Flight tests
  - B-1 aircraft
  - F-18A -aircraft
  - UH-60A rotorcraft

CPU Hours to Compute Flutter Boundary for Cruise



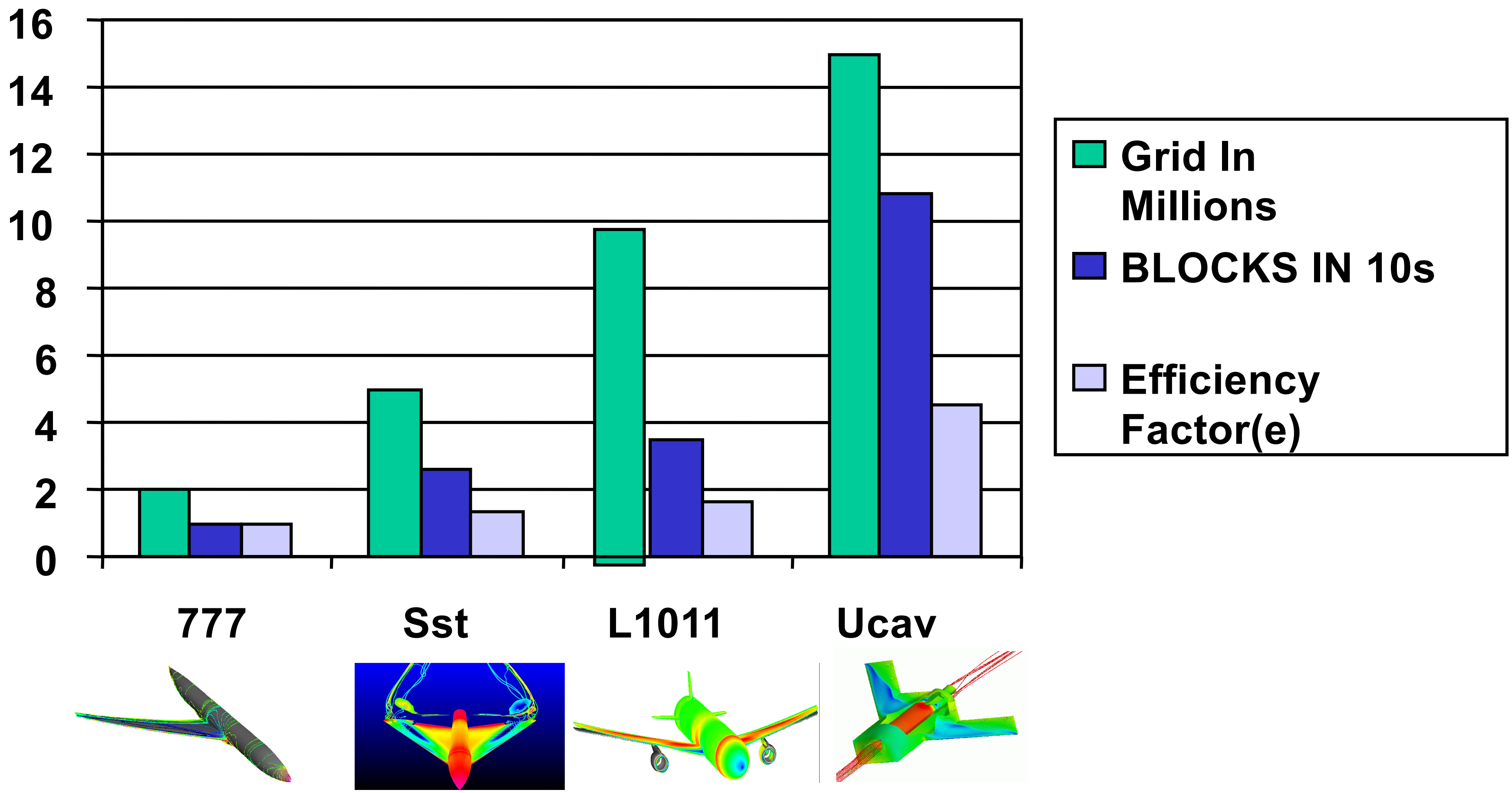
- **Using Parallel Computers at NAS and RUNDUA Protocol Flutter Boundary of eVTOL (20 M Grid Points) can be Computed In 72 Hrs of Wall Clock Time Using 200 Processors**

Load Balancing Scheme In HiMAP



Ferhat H., Jespersen, D., Guruswamy, G.P., Rizk, Y., and Byun, C. "A Multi-level Parallelization Concept for High-Fidelity Multi-Block Solvers", Super Computing 97, San Jose, Nov 1997

Summary of Results from Load Balancing Scheme



- **Efficiency Factor 'e' is Defined as**

  $$e = ZO/ZN$$

  where ZO is number zones before load balancing and ZN is the number of regrouped zones after load balancing.

Guruswamy, G. P "Development and Applications of a Large-Scale Fluids/ Structures Simulation Process on Clusters," Computers & Fluids (2007)

Conclusions

- A summary of about 40-years, 100-person-year effort on development and applications of accurate coupled and uncoupled aeroelastic procedures using non-linear aerodynamics is presented.
- Case-by-case validations with either experiment or linear theory are shown to establish aeroelastic computations
- From this research it is observed that
  - Transonic small perturbation theory still useful for conceptual design
  - Euler/Navier Stokes equations and time accurate couplings are required to predict phase angles
  - Modal approach is adequate for responses
  - Staggered time integration is not necessary
  - Modal method is better suited for NS than Reduced order modelling
- Given present computational resources, there is no need to hybridize CFD with linear/empirical aerodynamics
  - Introduces significant errors when inertial loads are present, which is common for flexible configurations
  - Not capable of predicting transient physics associated with coupling of non-linear flows with structures
- Classical Indicial method is robust and more efficient than reduced order method for RANS

Future Efforts

- **Coupled Procedures need Higher Fidelity CSD**
  - **Higher than 1D FEM and FSI for Rotorcraft**
  - **Composites for all Aerospace Vehicles**
  - **Visco-elastic for Spacecrafts**
  - **3d Modal for Rotorcraft**

- **Faster and More Accurate CFD**
  - **Further improve body fitted structured grid topology**
  - **Better Turbulence Models**
  - **Robust Moving Grids**
  - **Larger Time Steps with no CPU Time Penalty**

- **CFD/CSD Method Time Accurately Integrated with Stability and Maneuver Dynamics Equations Is Needed for Full Simulation including Avionics**
  - Appa, K., Argyris J.H and Guruswamy G. P., "Aircraft Dynamics and Load Computations Using CFD Methods," AIAA 96-1342.

- **Framework Suitable for Time Integration Approaches for CFD/CSD**
  - **Need collaborative efforts with Computer Scientist (e.g SCIRUN of U of Utah)**