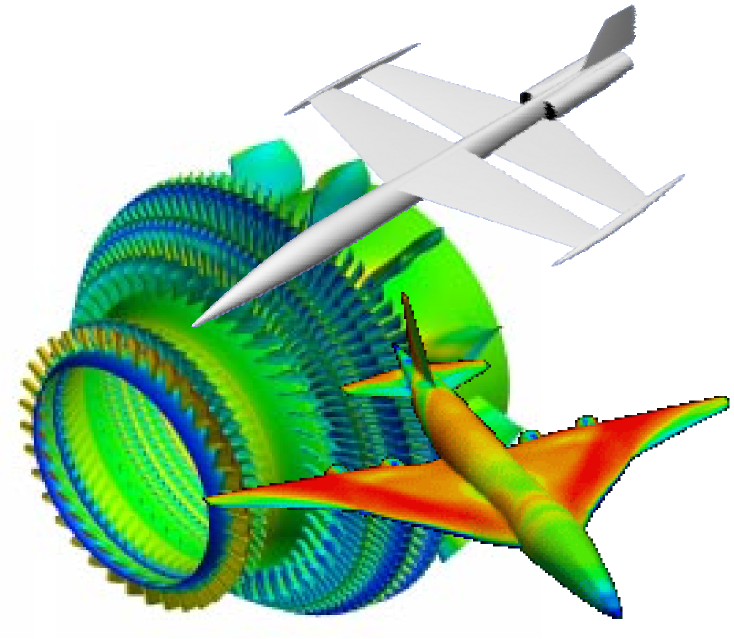
Computational Fluid-Structure Interaction



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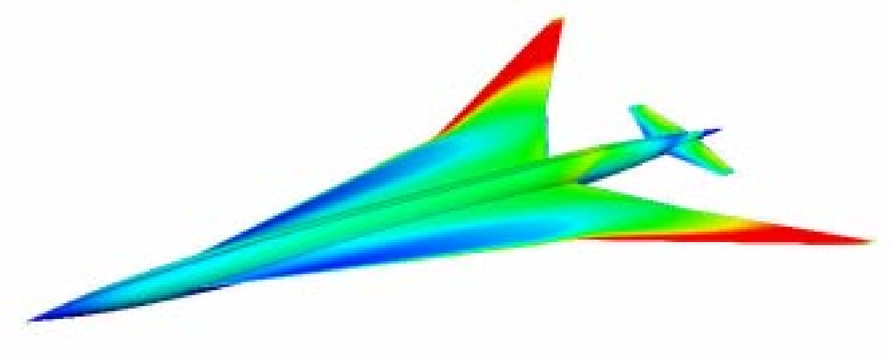
Importance of Aeroelasticity

- Coupling between aerodynamics and structures is most fundamental in aerospace system development
- It is difficult to account for and typically causes either catastrophic failure or costly fixes and redesigns
- Aeroelasticity also plays a key role in the design of flight control systems (aeroservoelasticity)
- Designers need methods to foresee all of these potential problems to work around them or to use them to his/her advantage

Aeroelastic Problems

- *High-Altitude-Long-Endurance (HALE) vehicles*

- *Quiet Supersonic Platform (QSP) business jets*
- *Supersonic transports*

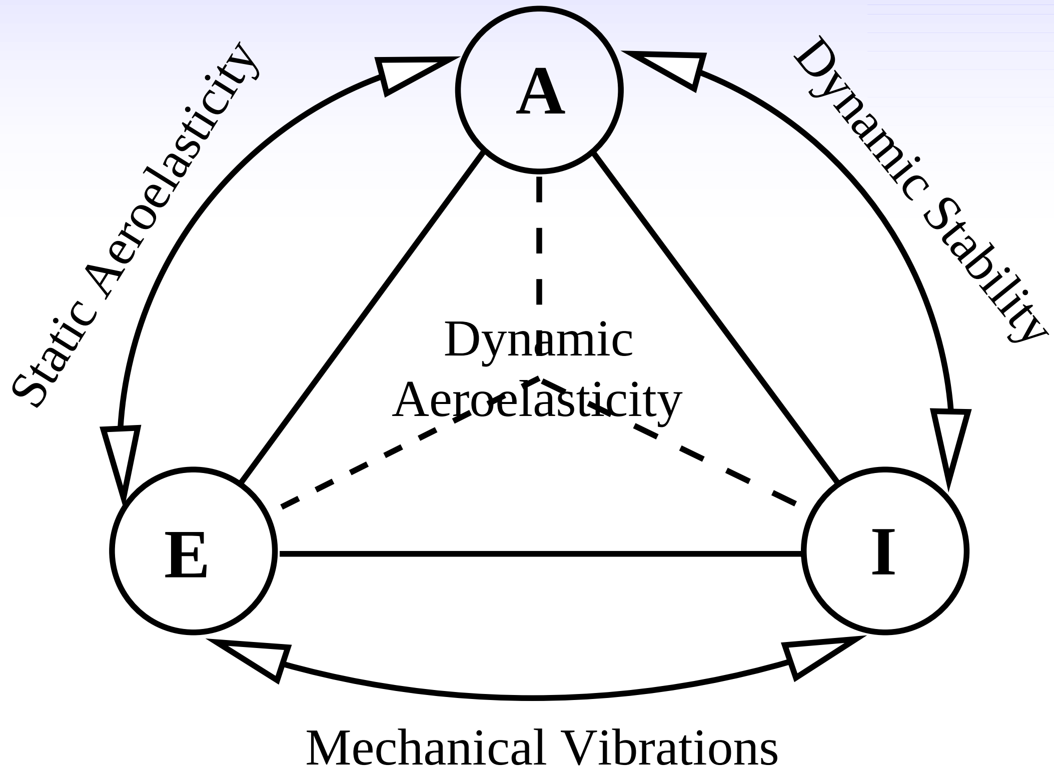


Joined-Wing Aircraft

- Good for electronic surveillance
- Potential stealth characteristics
- Possibility of significant weight reduction
- Severe non-linear buckling problems

NASA : Box Wing Airliner (325 Passenger)

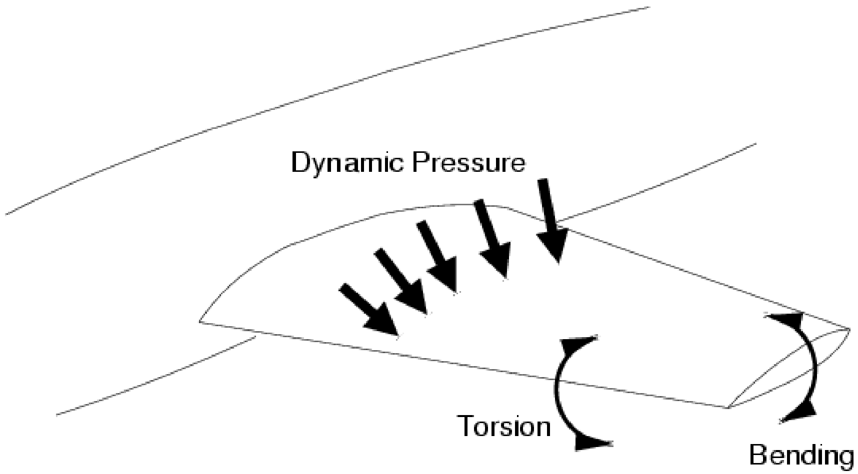
Aeroelastic Triangle



A: Aerodynamic Forces
E: Elastic Forces
I: Inertial Forces

Main Features of Flutter in External Flow

Isolated Wing in External Flow

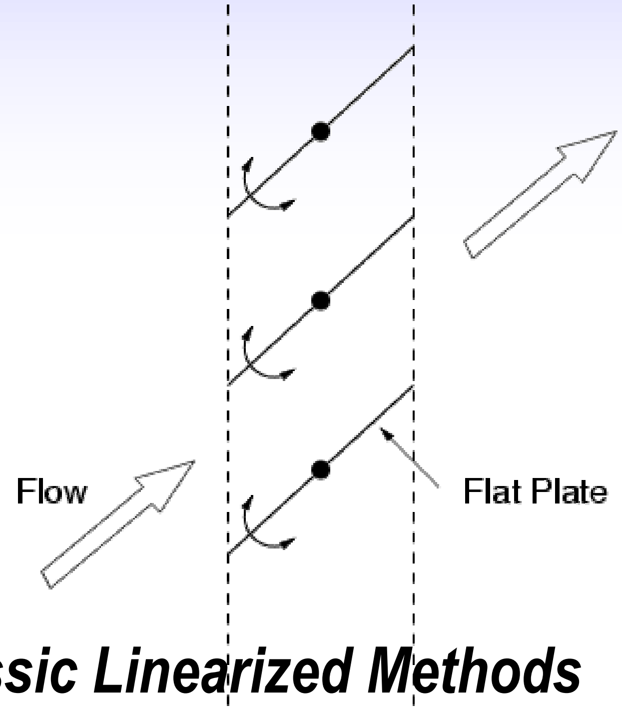


- High mass ratio between the structure and the fluid
- Highly turbulent flow

Governing Equations of the Flow

- The governing equations are either
  - Euler equations for an inviscid fluid
  - Reynolds-Averaged Navier-Stokes equations (with suitable turbulence models)
- Everything is applicable to other flow models
- Governing equations are solved numerically using the most efficient computational techniques and parallel computing

Linearized Methods



$$W = W_{steady} + \Delta W e^{i\omega t}$$

or

$$W = \sum_{n} W_n e^{i\omega_n t}$$

- **Classic Linearized Methods**
  - *Two dimensional*
  - *Inviscid*
  - *Small disturbance assumption*
  - *No camber, no loadings*
  - *Prescribed structural motion*
- **Time-Linearized Methods**
  - *Potential flow, Euler, NS*
  - *Small disturbance assumption*
  - *Fourier series assumption*
  - *Prescribed motion*
  - *Work per cycle analysis*

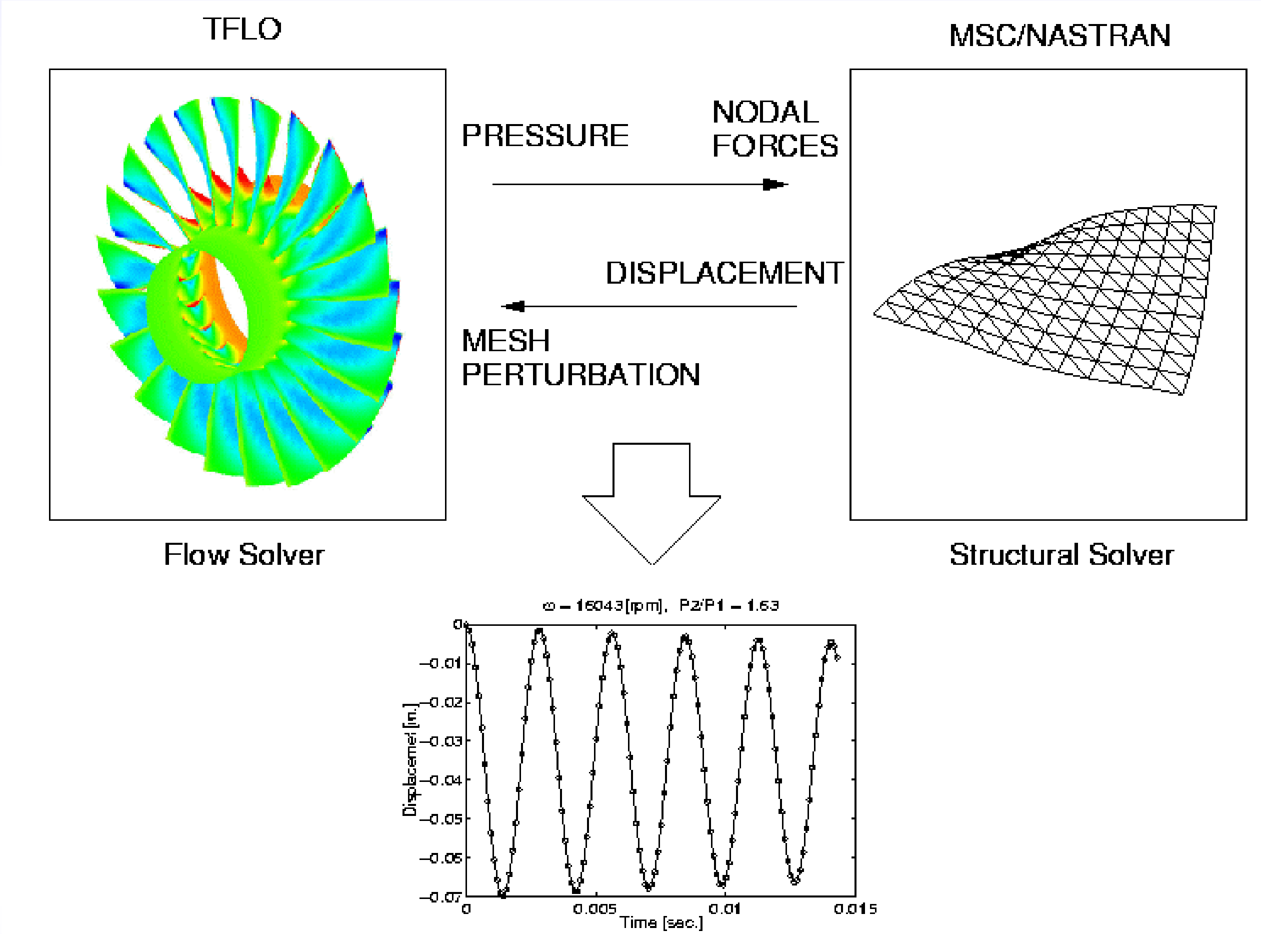
Governing Equations of the Structure

- Mostly linear structural models. Non-linear models are currently being studied.
- The governing equations can be put in the form

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

- [M], [C], and [K] are the mass, damping, and stiffness matrices, usually obtained using a finite element discretization
- In most problems of interest to aerospace applications, the non-linearities result from the flow and not the structure. However, this is not always true.

Fluid/Structure Coupling



Aeroelastic Response of the Blade

Coupling Between Fluid-Structure

- The fluid dynamics provides a distributed pressure load and shear stress on the surface of the CFD mesh that is transferred to the structure as a series of point loads

- The structure provides displacements that need to be transferred to the surface of the CFD mesh. These displacements modify the boundary conditions on the fluid solution

- Procedure is repeated as a function of time

Conservation of Loads and Energy

- **Conservation of Load**
  - The nodal forces must yield the same net forces as the pressure loads do

$$\sum_m f^{(m)} = \int_{\delta\Omega} p\,dS, \quad f^{(m)}\text{: nodal force, } p\text{: pressure, } S\text{: surface area}$$

- **Conservation of Energy**
  - The virtual work done by the nodal forces must be equal to that by the pressure loads

$$\sum_m f^{(m)}\,\partial q = \int_{\delta\Omega} p\,\partial x\,dS, \quad q\text{: nodal displacement, } x\text{: surface coordinate}$$

- **Consistent and Conservative Linear Transfer Function**
  - Based on the area coordinate of the closest element from each CFD mesh point

$$dx = \left[N(x)\right]q, \;\; f = pS\left[N(x)\right], \;\; \left\|\left[N(x)\right]\right\| = 1$$

$$\left[N(x)\right]\text{: interpolation function}$$

Synchronization and Coupled Simulation

- Fluid solutions are typically second or third order accurate in time
- Structural solution is typically second order accurate in time
- Is coupled solution of the same order of accuracy?

- One must devise coupled integration schemes that result in preserved order of accuracy of the coupled simulation.

Algorithms for Fluid-Structure Coupling

- **As we saw earlier, it is necessary to have a procedure that transfers loads from CFD to the structure and, at the same time, can transfer the structural displacements from the structural mesh to the CFD mesh**
- **Many alternatives exist and their suitability can be debated for static aeroelastic flows**
- **However, for unsteady aeroelasticity, and for systems with very low damping ratios, the choice of transfer procedure is critical to achieve high accuracy**
  - If the load transfer is not energy conserving, a system that is in a flutter state may appear to be stable with catastrophic design consequences

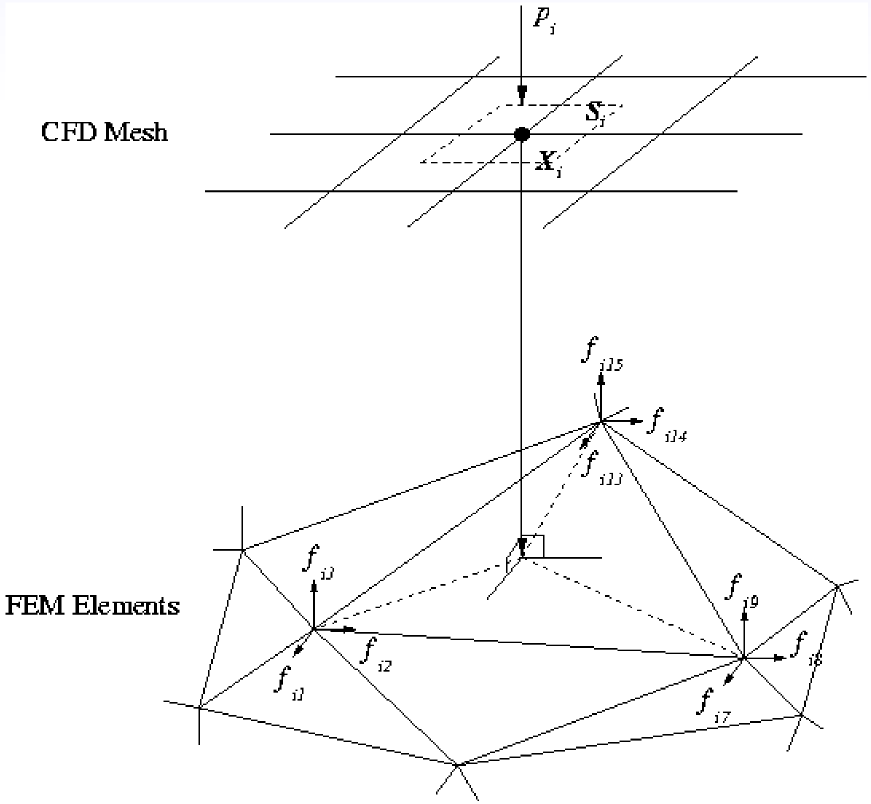
Algorithms for Fluid-Structure Coupling

- There are an infinite number of structural load vectors that produce the same resultant forces and moments (conservation of load)
- There is, however, only one such load vector which in addition conserves energy (if both the structural and CFD meshes undergo corresponding virtual displacements)
- In order to construct this load vector, knowledge of both the finite element discretization basis functions and an association procedure between points in the CFD and structural meshes is necessary

Algorithm for Fluid-Structure Coupling

- For every CFD point, find the nearest point on the surface of the structural mesh (not necessarily a node on the structural mesh)
- At this associated point, evaluate the basis functions for the structural element in question and store the values in a linear transfer function
- Calculate distances between corresponding points in both meshes
- Add effect of small rotations to compute the influence of all CFD surface pressures on all structural node load vectors

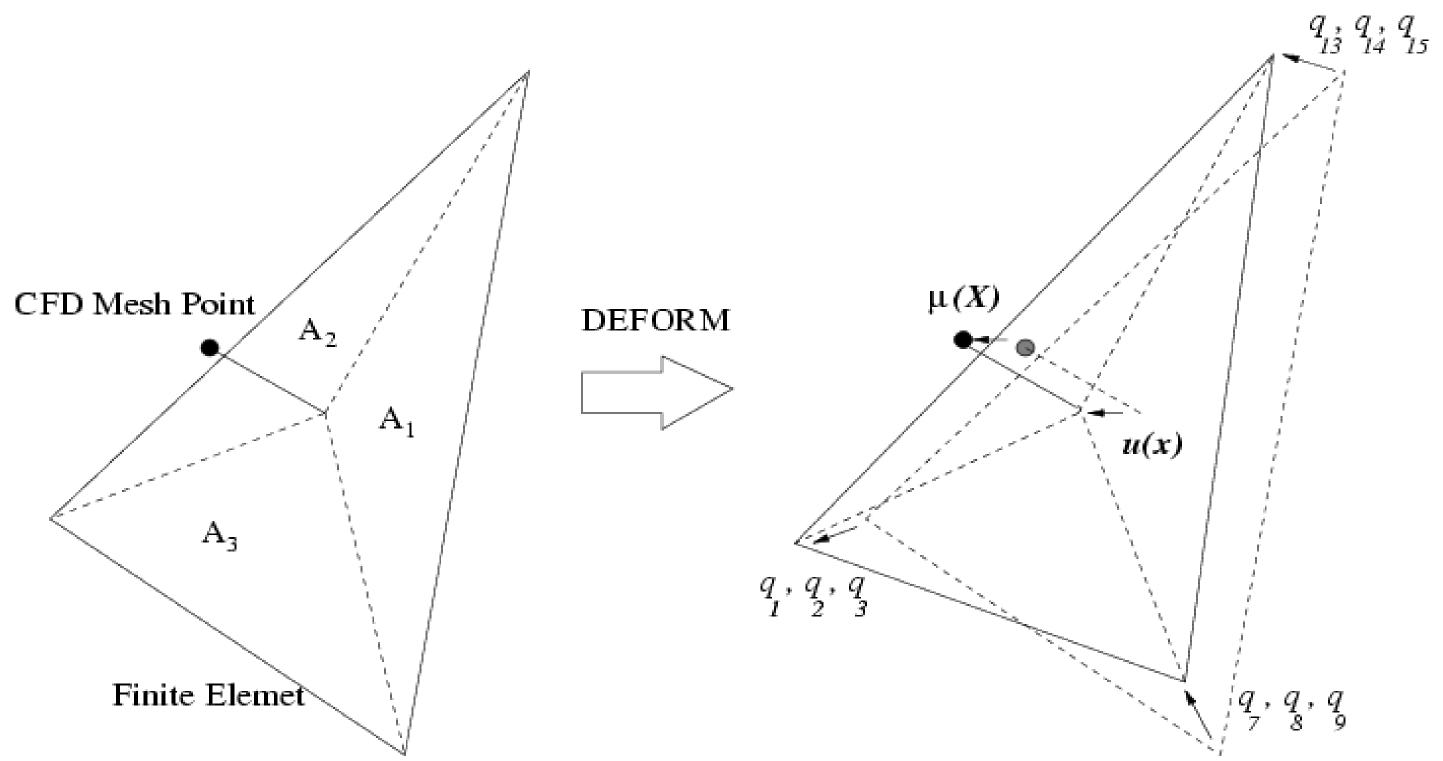
Load Transfer System



Integrate pressure over the area surrounding the CFD mesh point

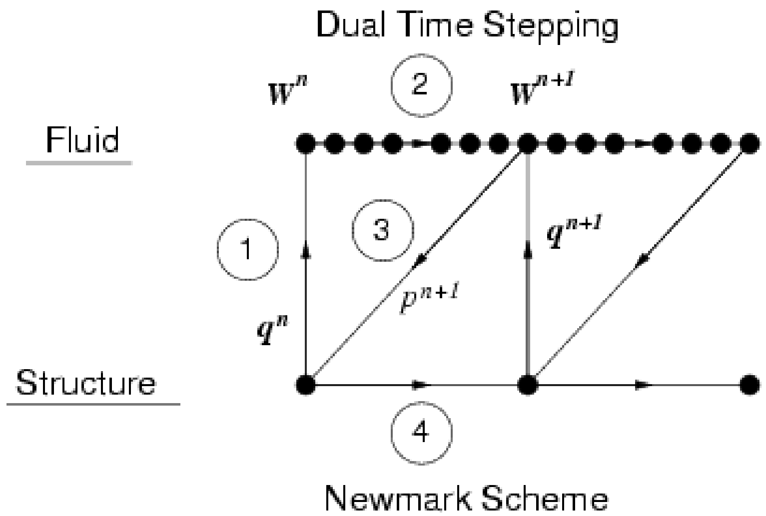
Distribute the force according to the area coordinate of a triangle

Deformation Tracking System



Every CFD point is associated with the nodal displacements of the closest element
Small rotations are included
For large rotations a more complicated non-linear transfer method is necessary and results cannot be pre-computed

Synchronization



- Perturb CFD mesh according to structural displacements
- Advance fluid system using dual time stepping
- Transfer pressure to nodal forces
- Advance structural system using Newmark trapezoidal rule

Summary and Conclusions

- Aeroelastic problems of relevance to the aerospace industry have been presented
- Individual equations of motion (fluid+structure) must be advanced forward in time with appropriate information exchange so that accuracy in time is preserved
- Algorithms for all of these procedures must be devised so that computations can be carried out in a reasonable amount of time

Wing Flutter vs. Flapping Flight*

- ✈A new paradigm for understanding wing flutter and flapping flight
- ✈The paradigm integrates aeroelastic interactions with applied and induced propulsive effects
- ✈The framework is based on the conservation of energy

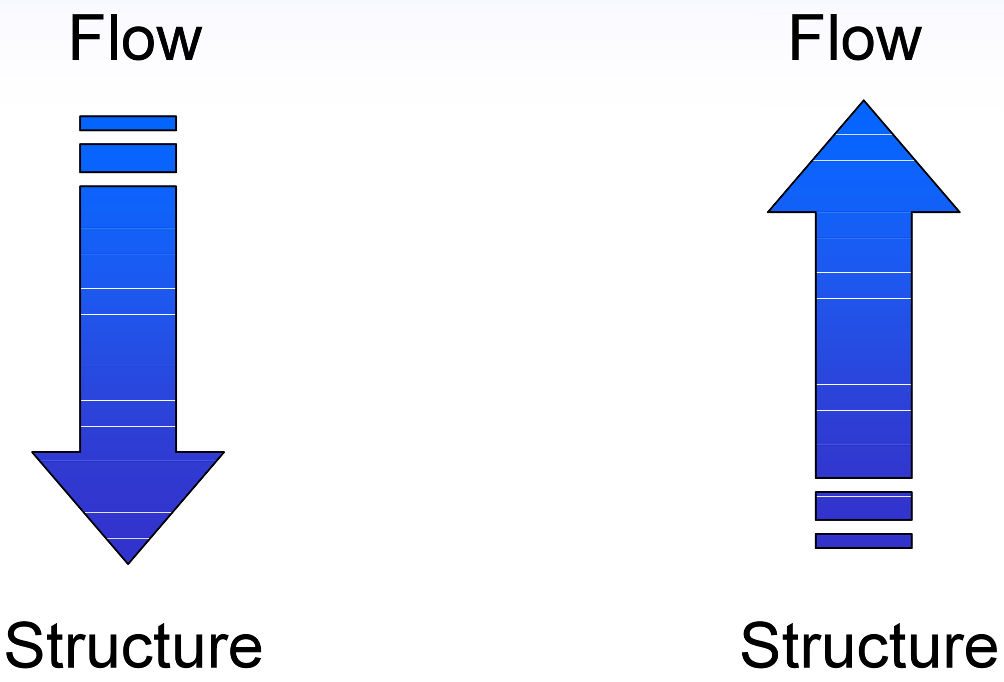
* Patil, M.J, “From fluttering wings to flapping flight: the energy connection” AIAA-2001-1460, 2001.

Garrick, I. E., “Propulsion of a flapping and oscillating airfoil”, NACA TR 567, 1936.

Theodorsen, T., “General theory of aerodynamic instability and the mechanism of flutter”, NACA TR 496, 1935.

Prevalent View

Energy Transfer in Aeroelasticity

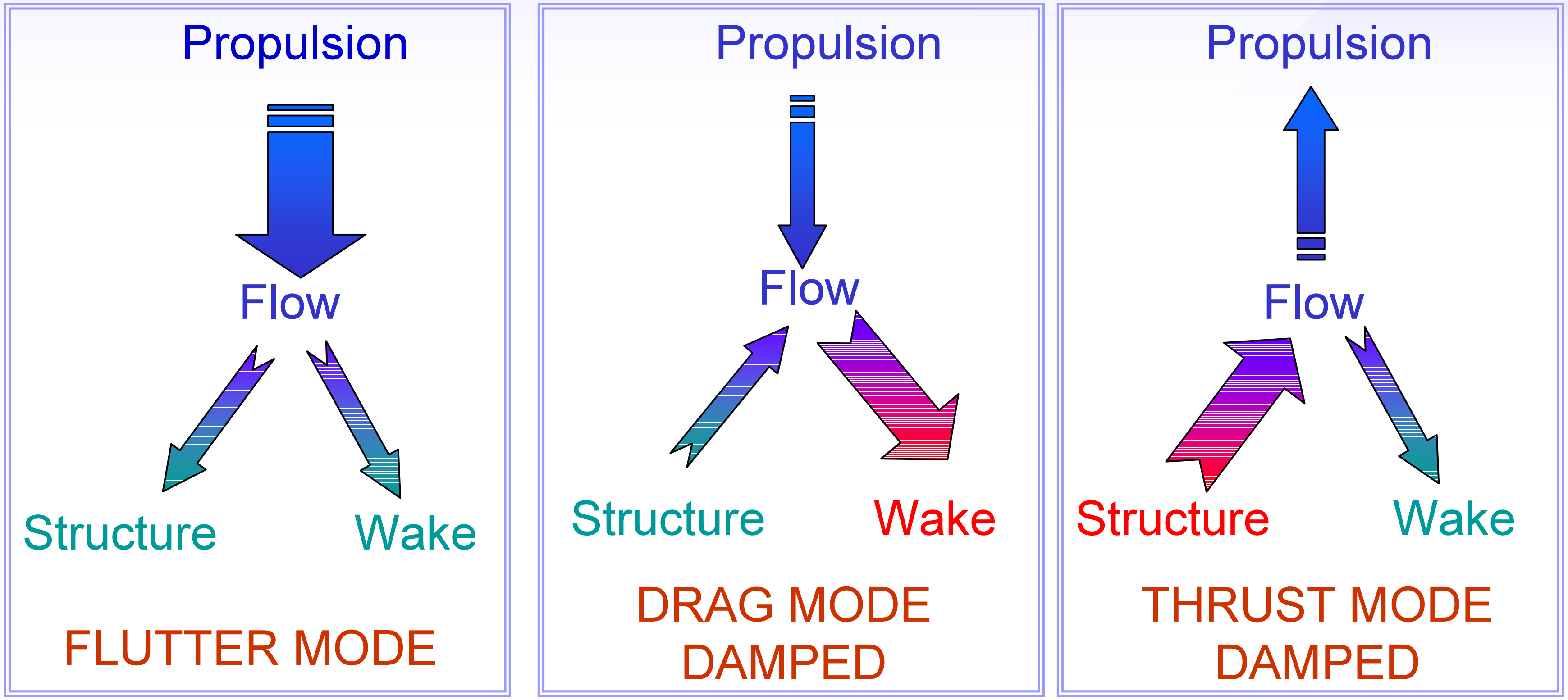


FLUTTER MODE

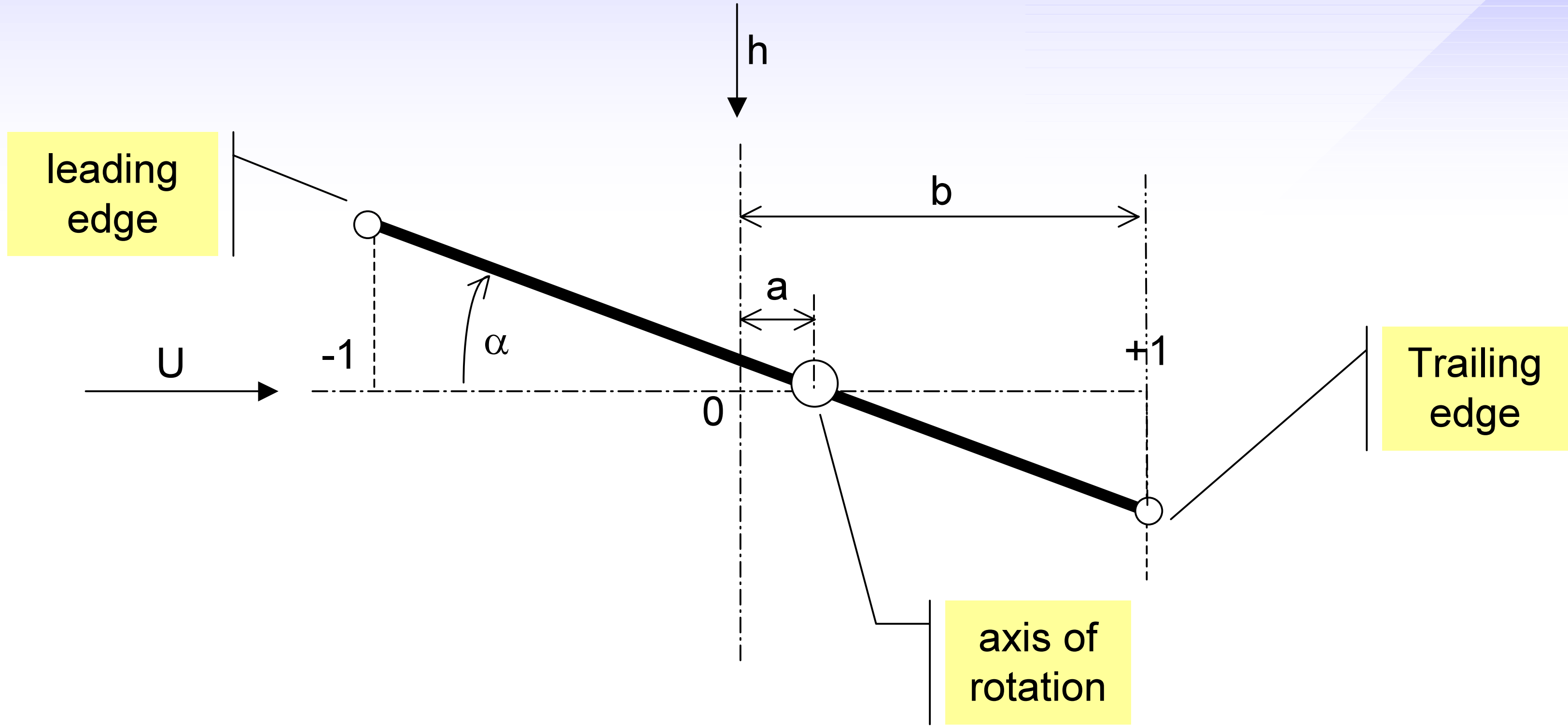
DAMPED MODE

Proposed Perspective

Energy Transfer in Aeroelasticity and Flapping Flight



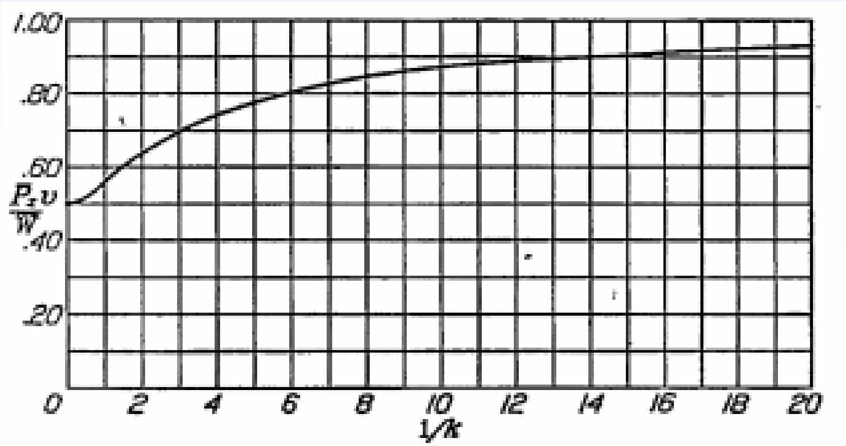
Airfoil Pitch and Plunge

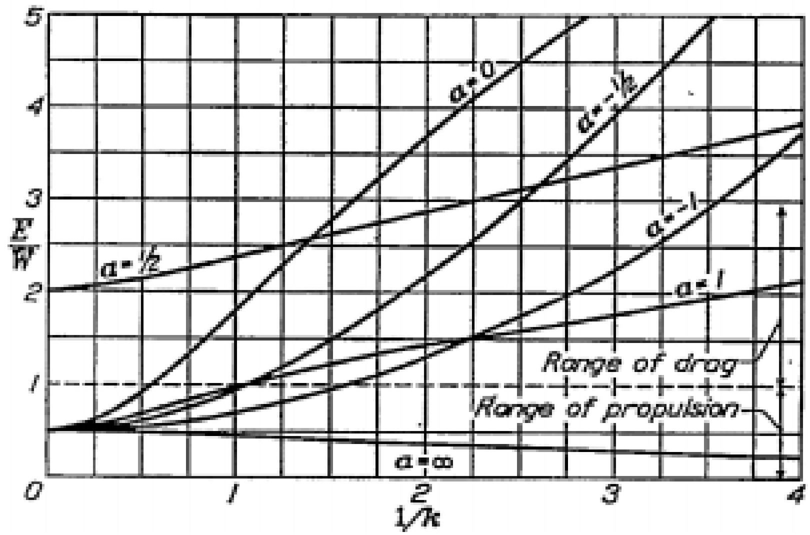


$$h = \overline{h}_0 \, b \, e^{i\omega t}$$

$$\alpha = \alpha_0 \, e^{i\omega t}$$

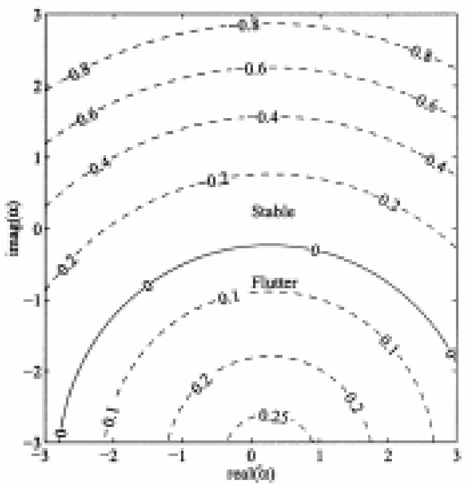
Pure flapping/pitching motions



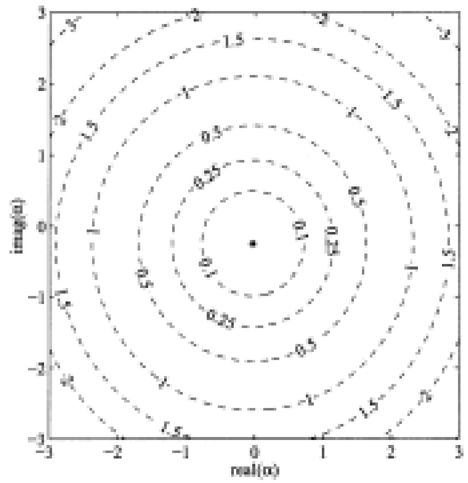


$$\eta = \frac{\overline{P}_x U}{W} = \frac{\text{energy of propulsion}}{\text{total energy}}$$

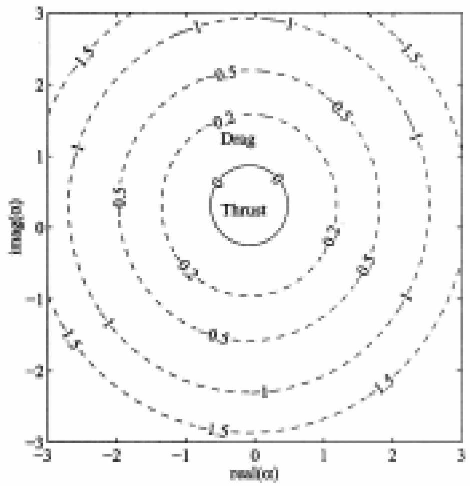
Energy Contours



structural energy



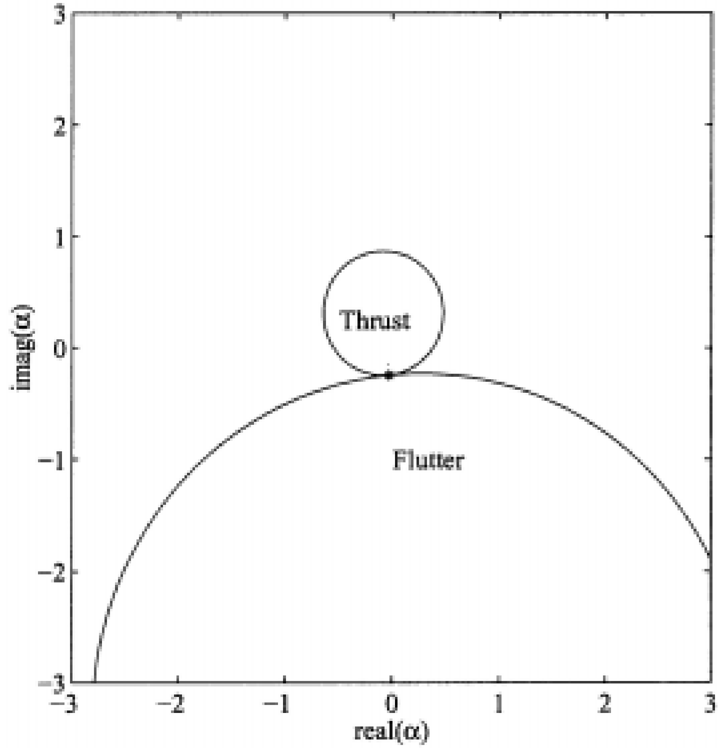
Kinetic energy



propulsive work

k = 0.25

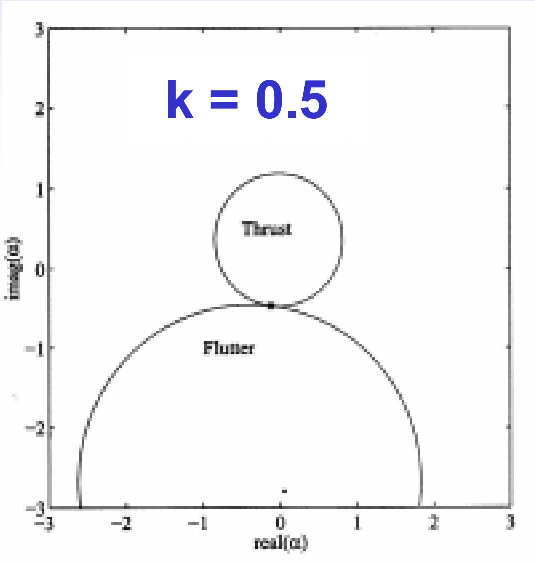
Flutter Boundary



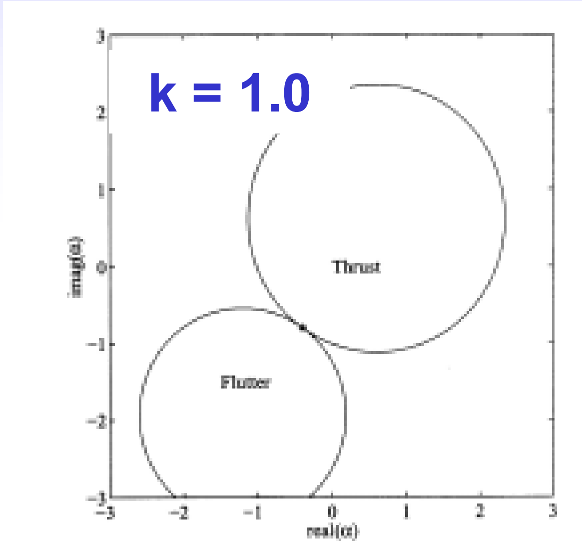
boundary of flutter/thrust

k = 0.25

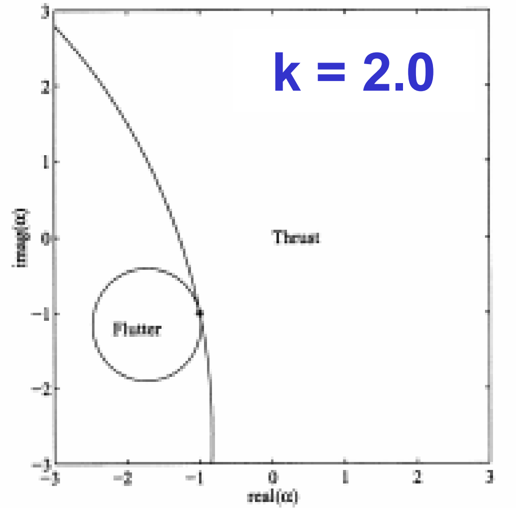
Flutter/thrust boundary



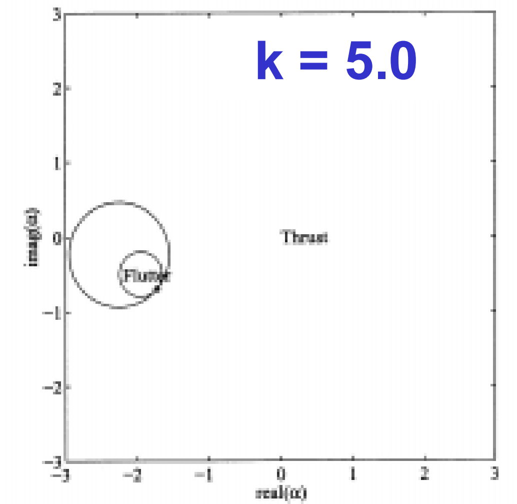
a) $k = 0.5$



b) $k = 1.0$

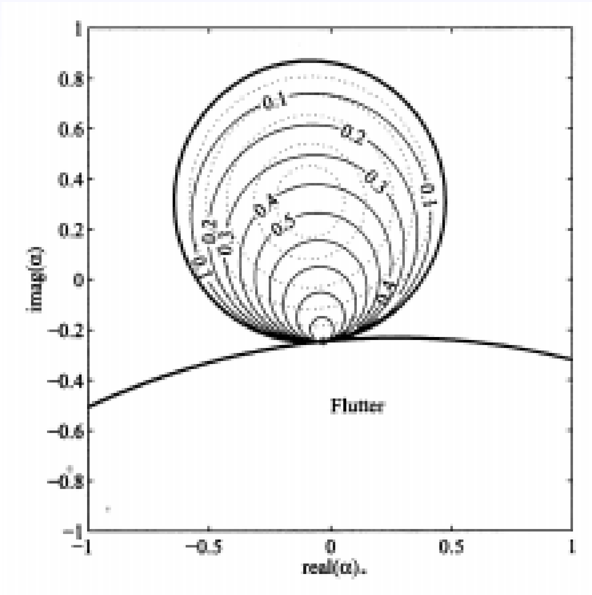


c) $k = 2.0$

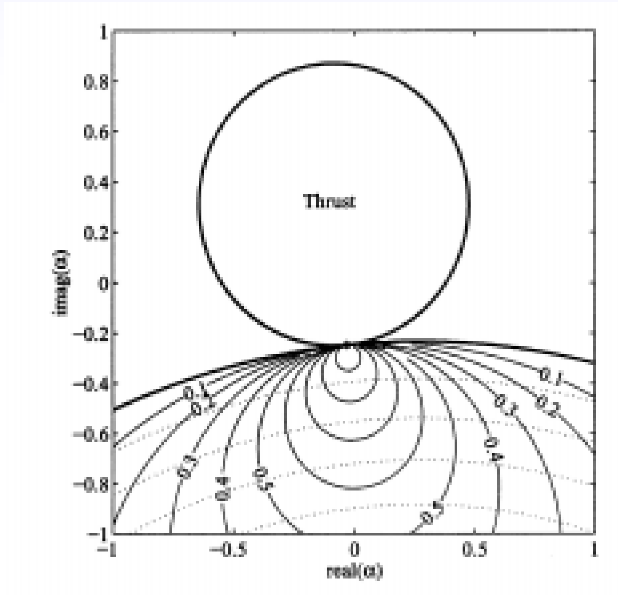


d) $k = 5.0$

Efficiency



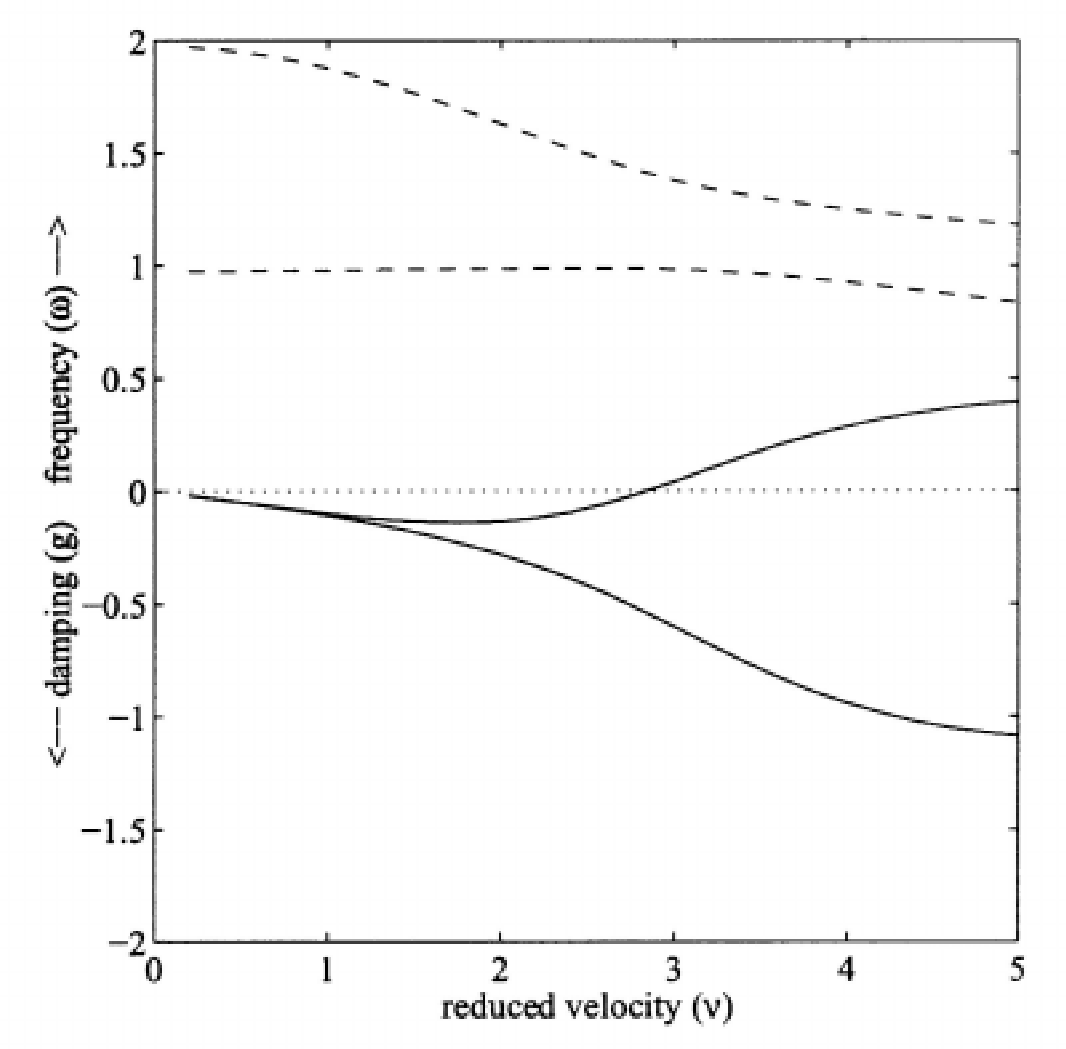
propulsion



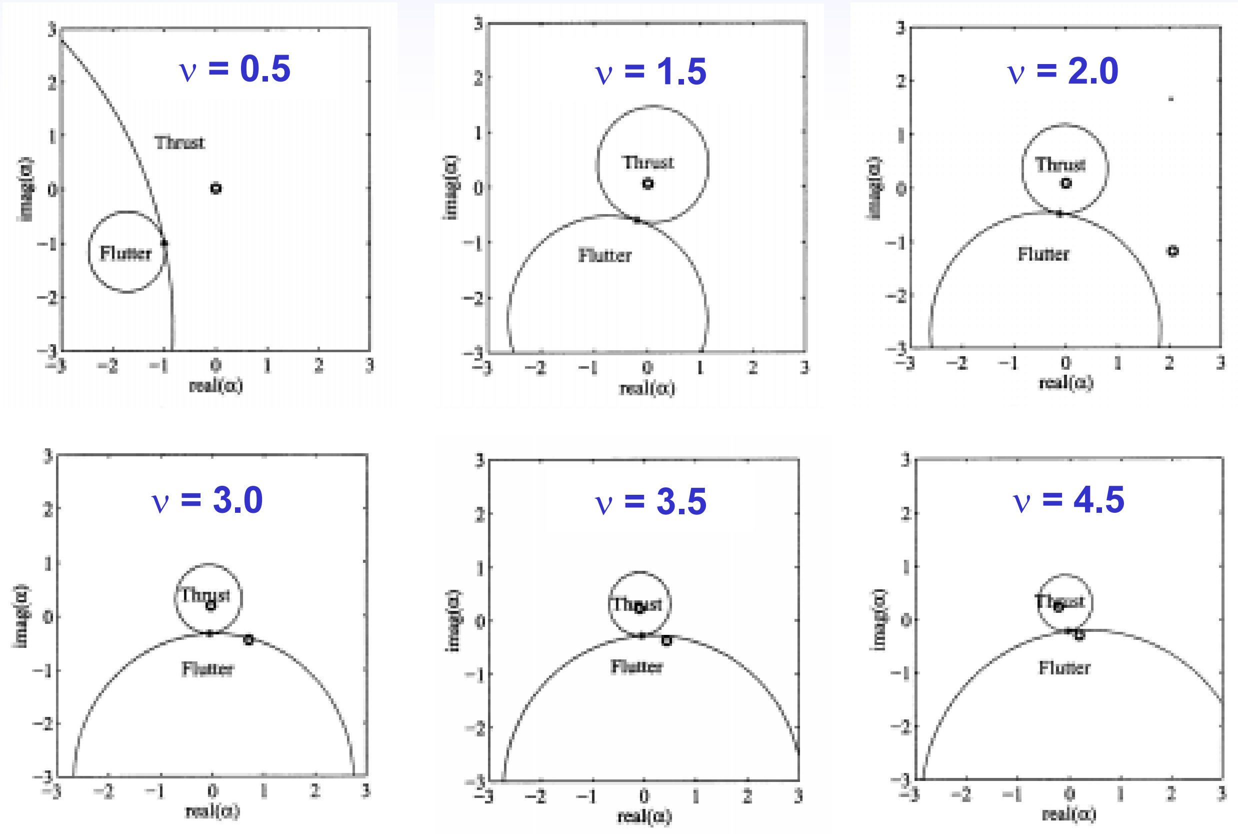
flutter

k = 0.25

Flutter analysis



Mode vs. Reduced velocity



Dynamic Similitude

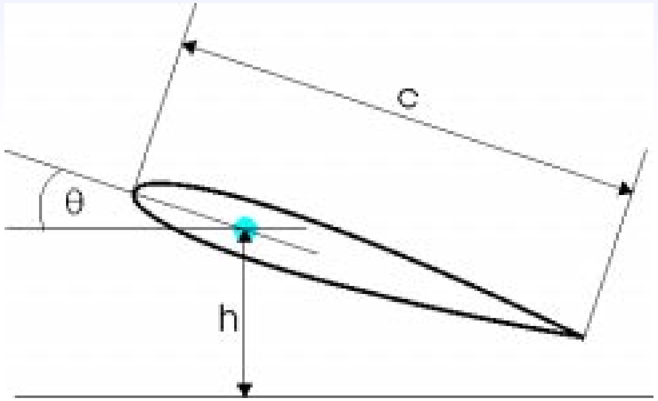
- ✈Cayley (1876) inferred that trout have the ideal, minimum-resistance, body shape for an airplane.

- ✈Why a trout and not a bird?

- ✈Rules of dynamic similitude! They show that a small fish in water behaves more like a large machine in the air than a small bird in the air does.

Hydrofoil

Hydrofoil Motion



- The hydrofoil was forced to pitch (θ) and heave (h) according to the following equations:

$$h = h_0 \sin\left[2\pi f\left(t - t_0\right) - \Psi\right]$$
$$\theta = \theta_0 \sin\left[2\pi f\left(t - t_0\right)\right]$$

- Where:
  - h_0 is the maximum heaving amplitude.
  - θ_0 is the maximum pitching angle.
  - f is the frequency of oscillation.
  - ψ is the phase angle.

Hydrofoil
Parameters

- The performance of the hydrofoil is measured using several key parameters.

$$C_T = \frac{T}{\frac{1}{2}\rho U^2 cb} \longrightarrow$$ **Thrust coefficient**

$$C_L = \frac{L}{\frac{1}{2}\rho U^2 cb} \longrightarrow$$ **Lift coefficient**

$$C_P = \frac{P}{\frac{1}{2}\rho U^3 cb} \longrightarrow$$ **Power coefficient**

$$P(t) = -L(t)\frac{dh}{dt} - M(t)\frac{d\theta}{dt} \longrightarrow$$ **Power, where M is the moment at the axis of rotation (quarter chord).**

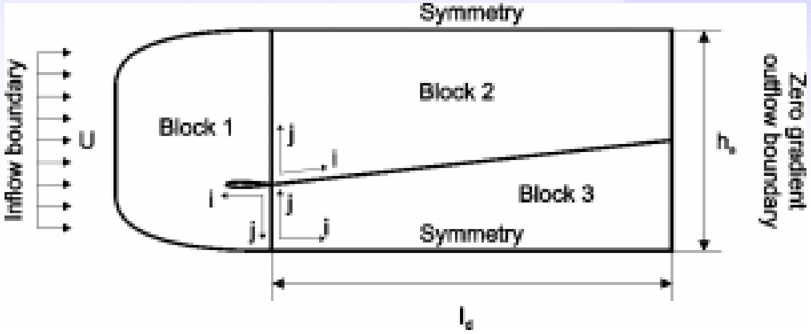
$$\eta = \frac{U\langle T\rangle}{\langle P\rangle} \longrightarrow$$ **Efficiency where <T> and <P> are the average thrust and power respectively.**

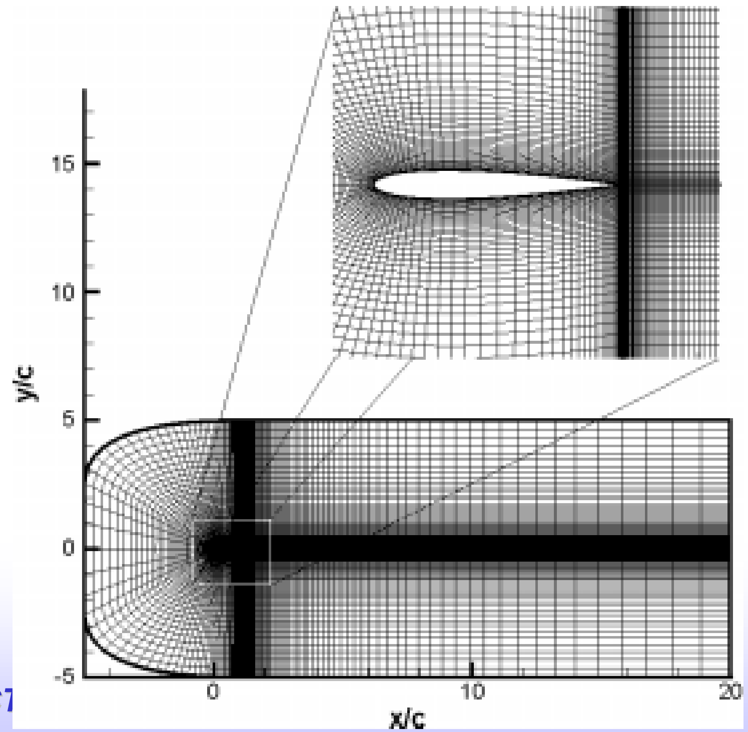
Hydrofoil
Domain

•The domain is broken up into 3 blocks. One C-type grid around the hydrofoil and 2 blocks downstream.

•A grid refinement study was undertaken. The final mesh is made up of 25,260 grid points.

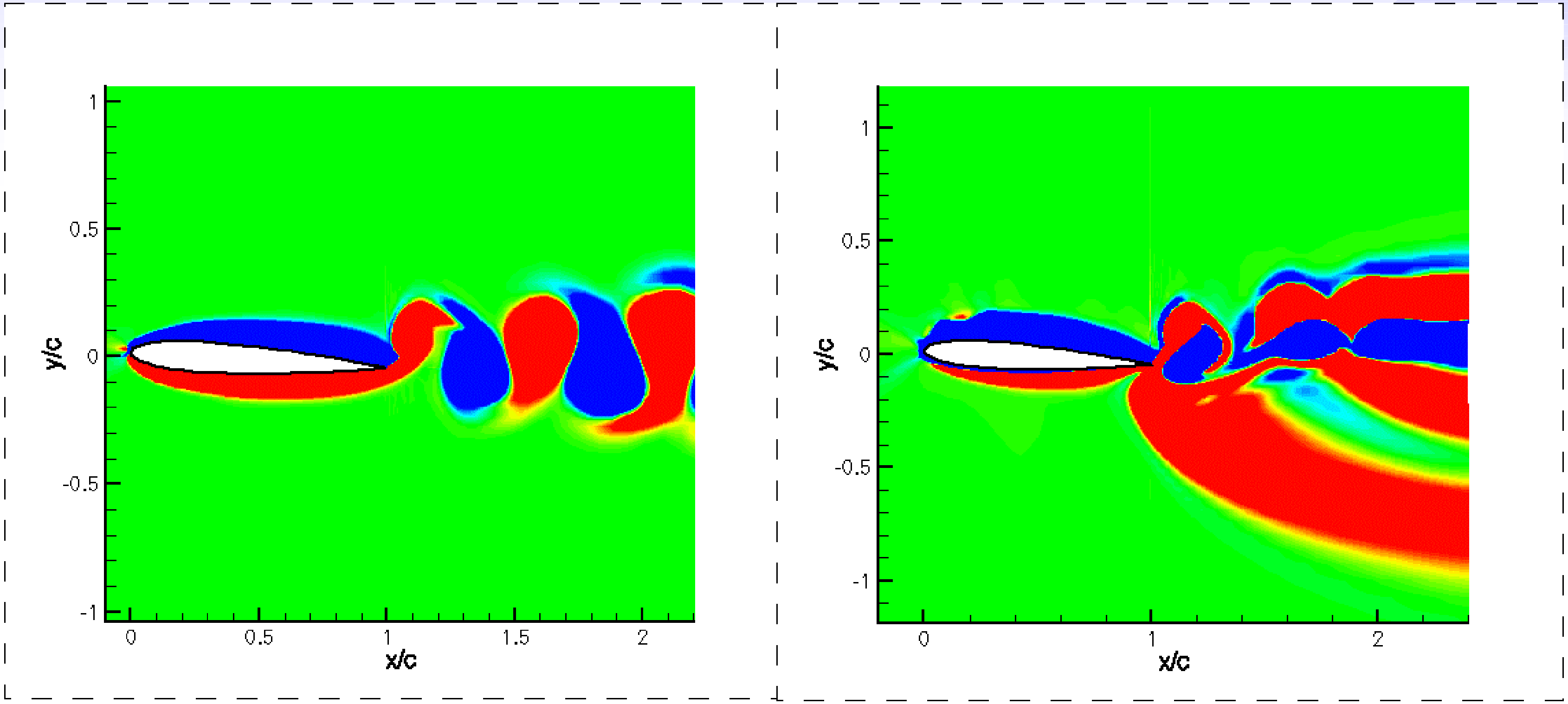
•The Reynolds number was set to 1100. This allowed for the exclusion of turbulence models and kept the number of grid points manageable.





Pitching Motion

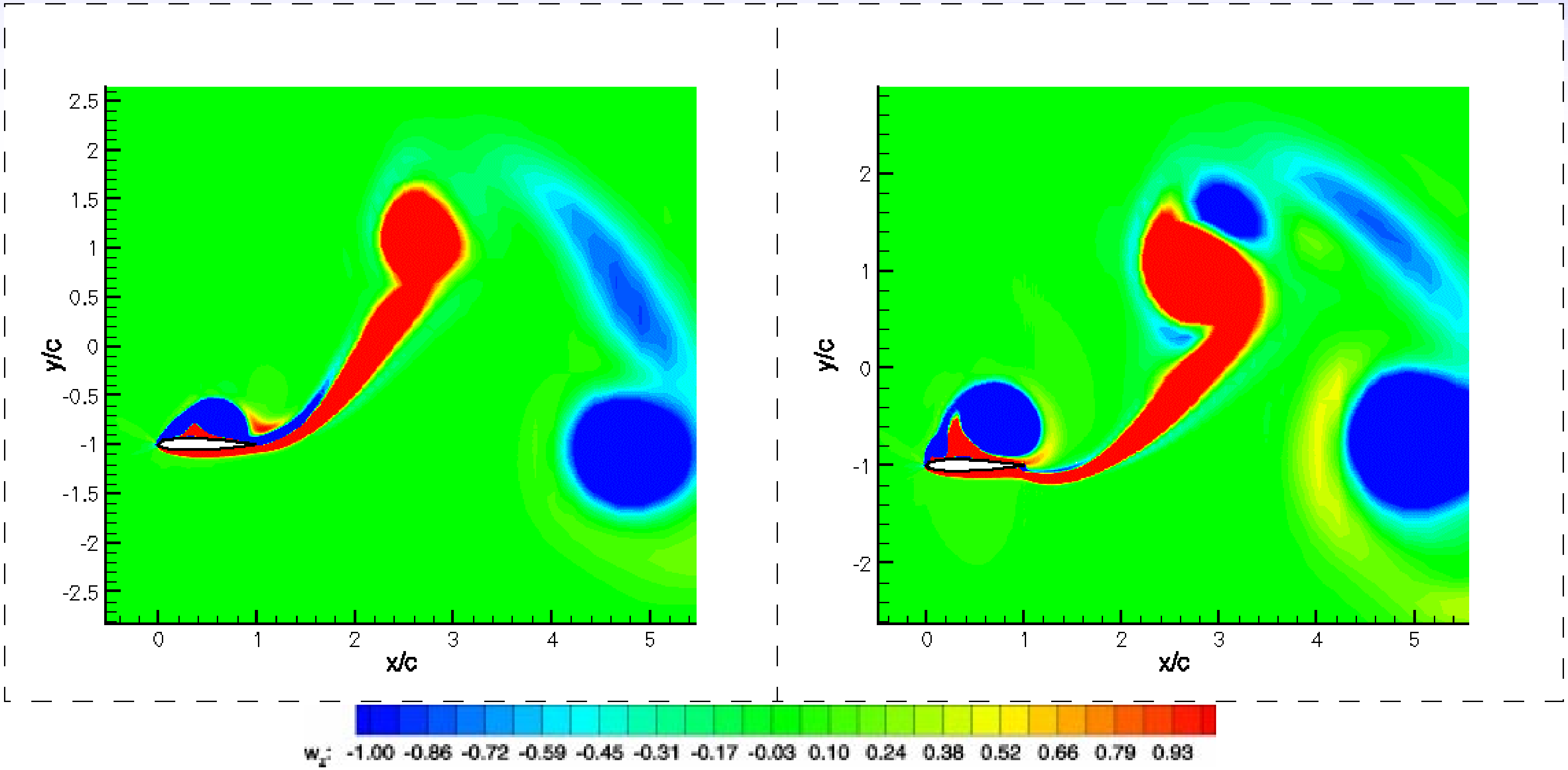
Flow field visualization



k=8, θ_0=5° **k=20, θ_0=5°**

Pitching and Heaving Motion:

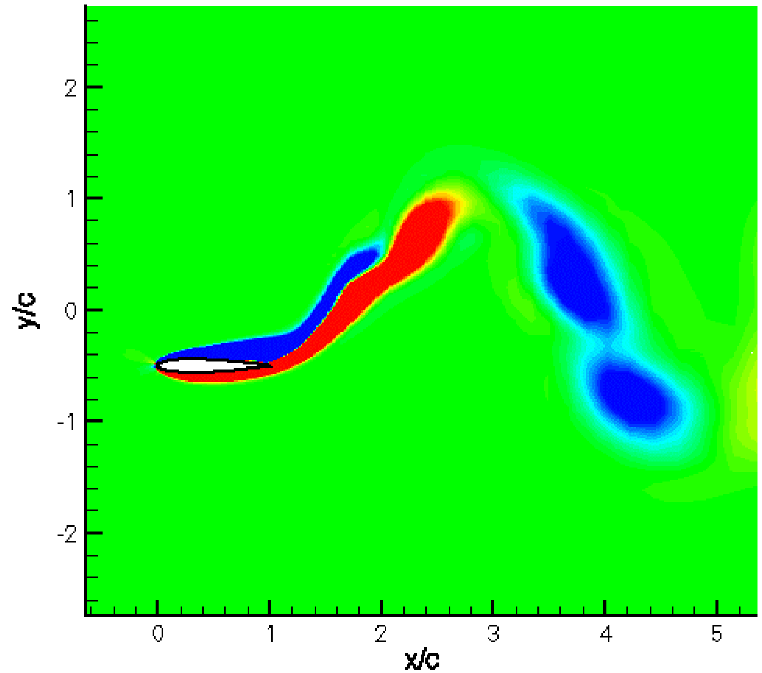
Effect of maximum pitching angle

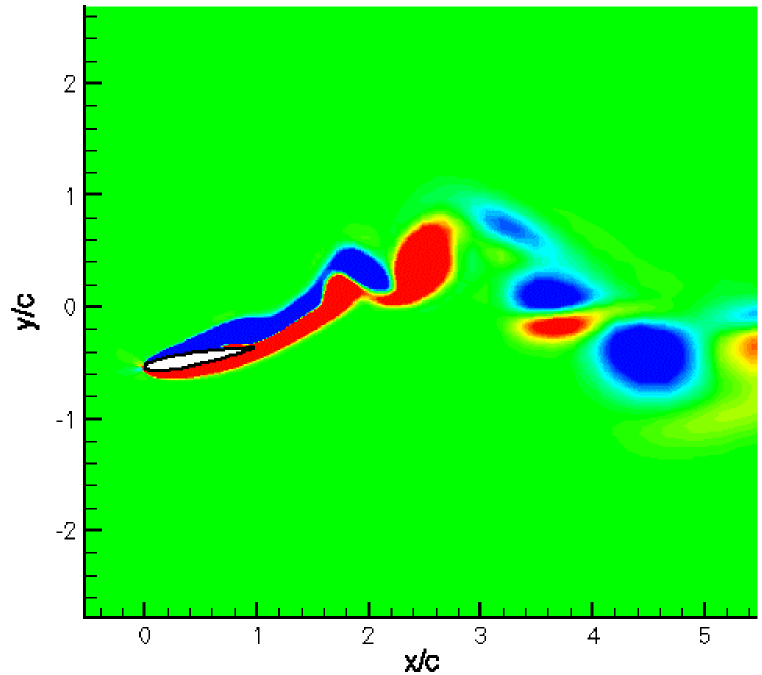


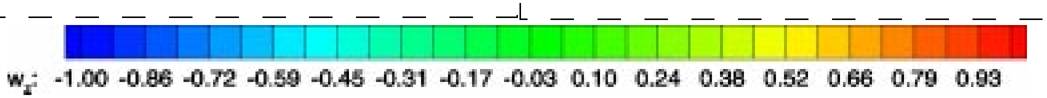
$\theta_0 = 30°$ $\theta_0 = 5°$

Pitching and Heaving Motion

Effect of phase angle



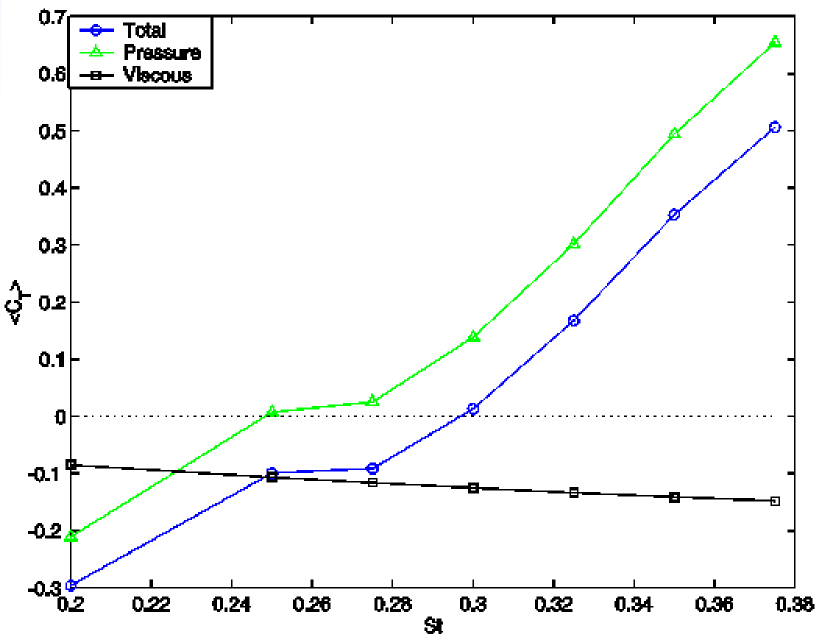




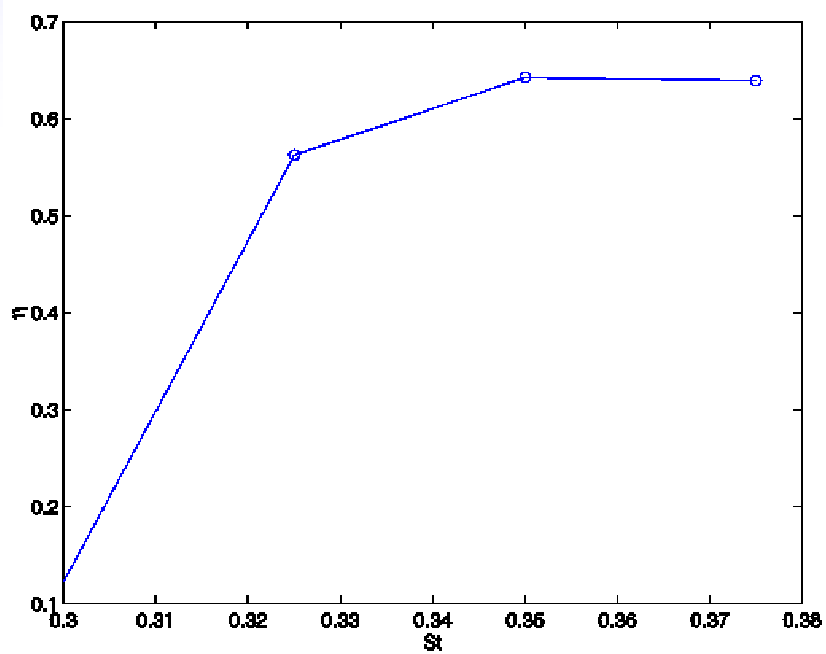
$\Psi = 90°$ $\Psi = 70°$

Pitching and Heaving Motion

Effect of Strouhal number



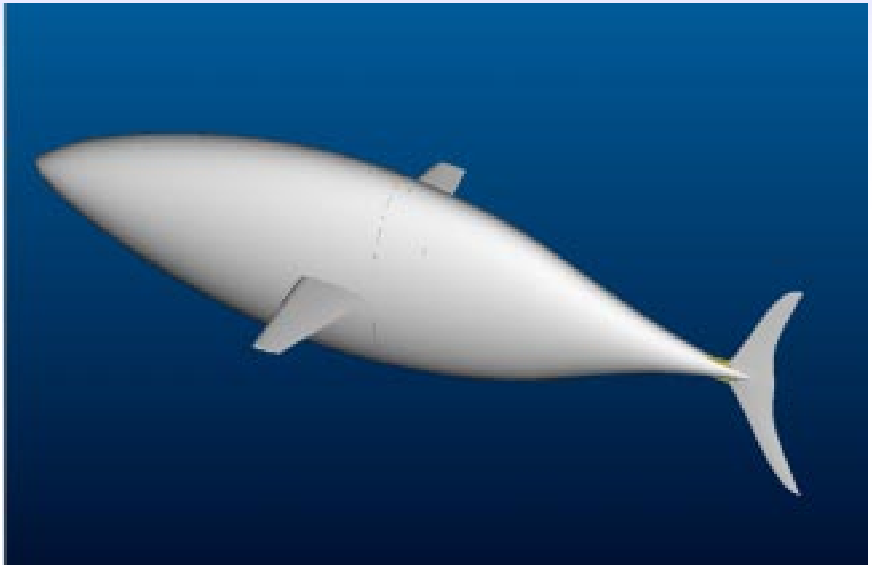
Thrust



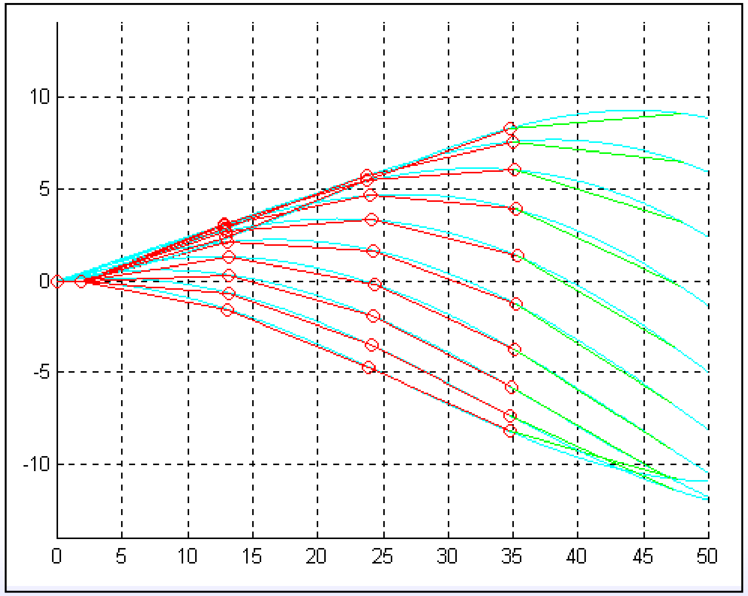
Efficiency

Autonomous Undersea Vehicle

SMA fish layout



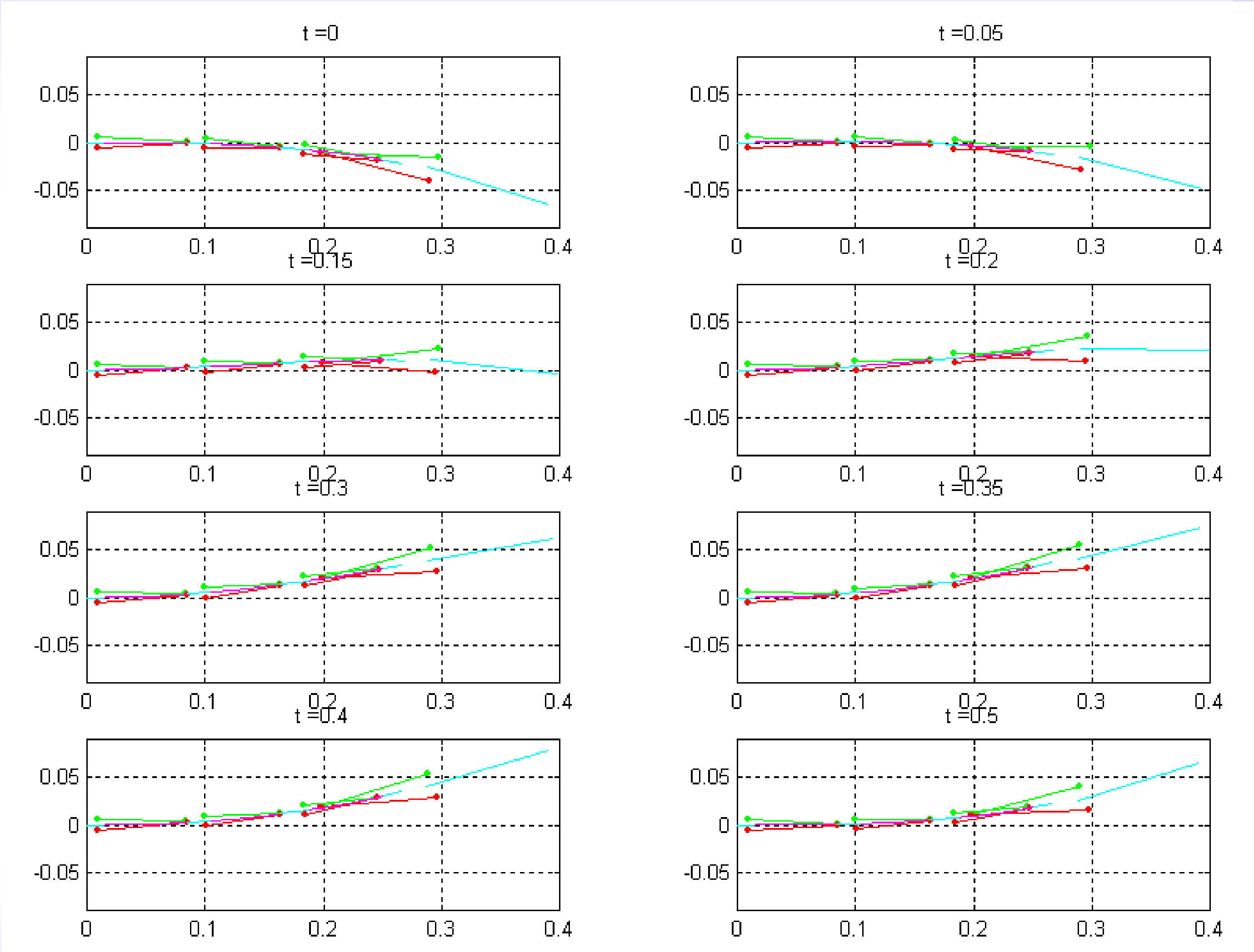
Bluefin Tuna AUV



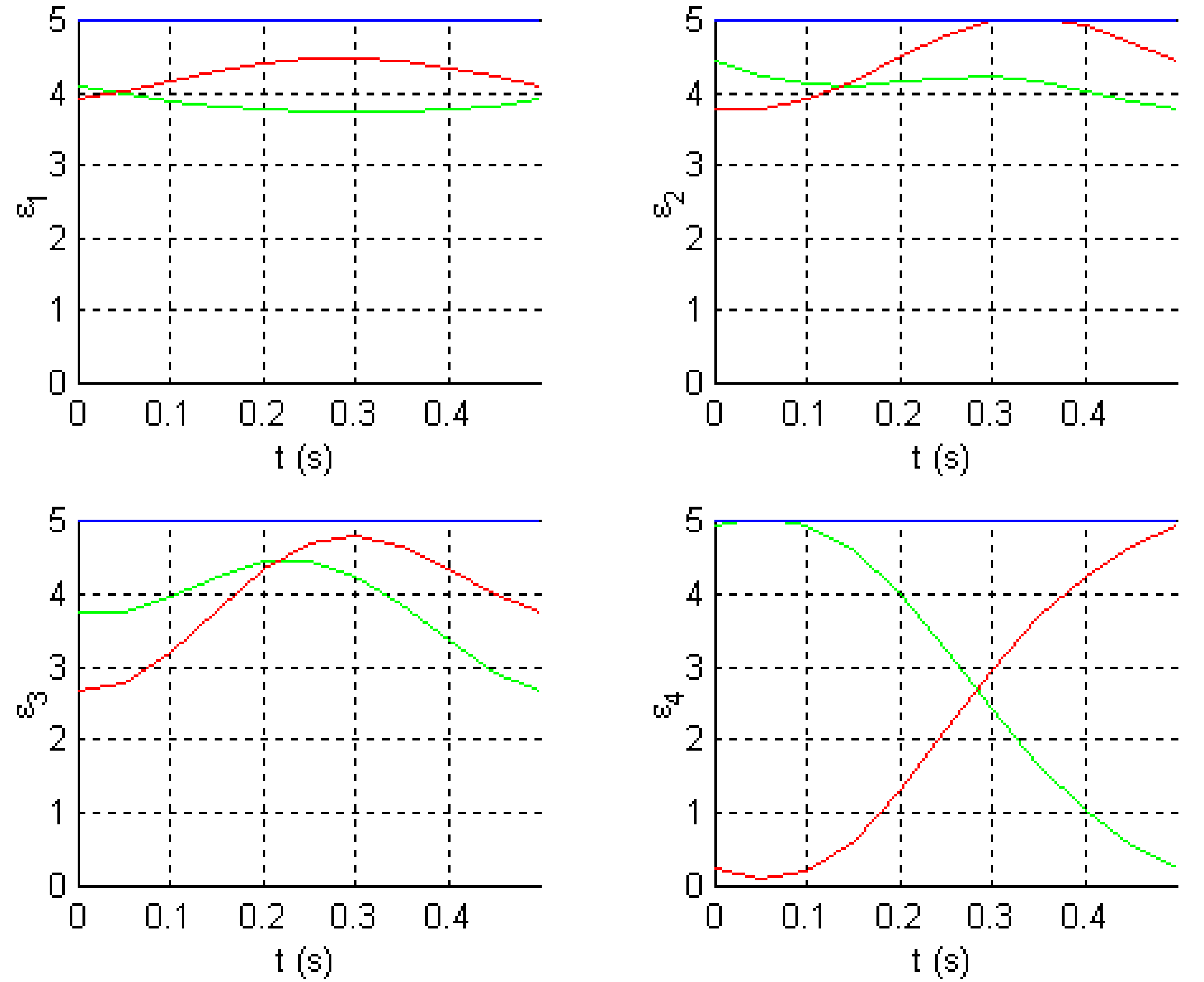
Linkage motion

Caudal Fin

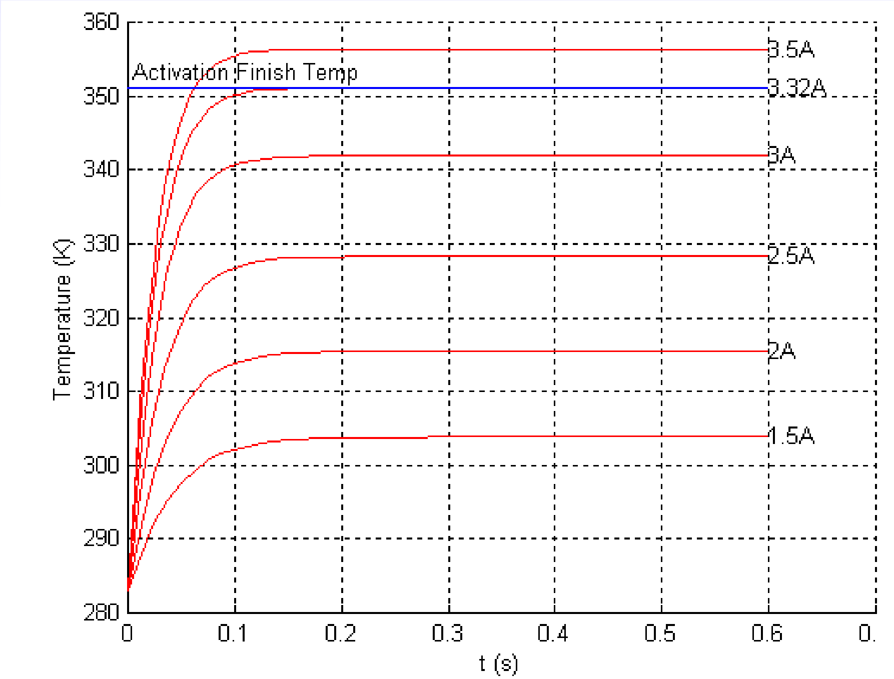
SMA actuation sequence

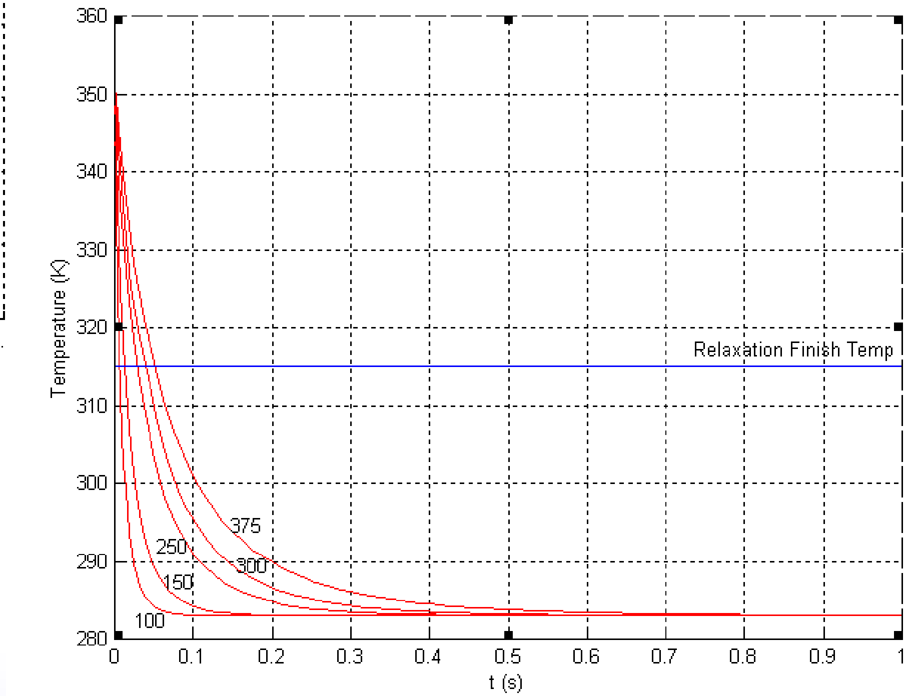


SMA wire strain time histories

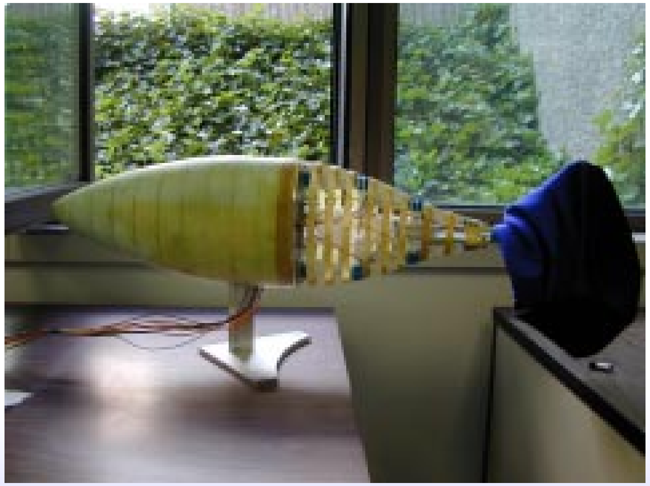


SMA wire heating and cooling





Prototype



Future Work

- Smart Structures, Hydrodynamics and Propulsion
- Mechatronics, sensors, actuators and electronics interface
- Navigation, communication, automation and control
- Systems Engineering and Integration

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