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CFD for Applications to Aircraft Aeroelasticity

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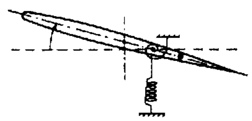
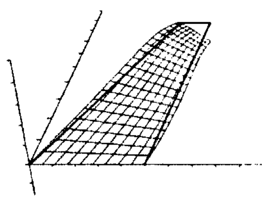
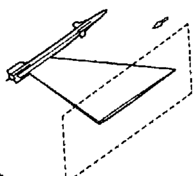
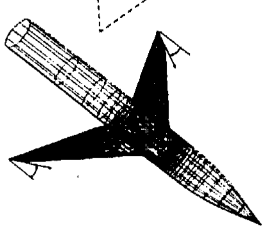
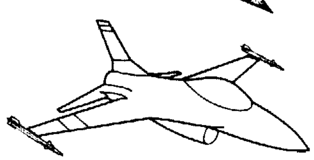
Abstract

Strong interactions of structures and fluids are common in many engineering environments. Such interactions can give rise to physically important phenomena such as those occurring for aircraft due to aeroelasticity. Aeroelasticity can significantly influence the safe performance of aircraft. At present exact methods are available for making aeroelastic computations when flows are in either the linear subsonic or supersonic range. However, for complex flows containing shock waves, vortices and flow separations, computational methods are still under development. Several phenomena that can be dangerous and limit the performance of an aircraft occur due to the interaction of these complex flows with flexible aircraft components such as wings. For example, aircraft with highly swept wings experience vortex induced aeroelastic oscillations. Correct understanding of these complex aeroelastic phenomena requires direct coupling of fluids and structural equations. This paper provides a summary of the development of such coupled methods and its applications to aeroelasticity since about 1978 to present. A part of the paper discusses the successful use of the transonic small perturbation theory(TSP) coupled with structures. This served as a major stepping stone for the current stage of aeroelasticity using CFD. The need for the use of more exact Euler/Navier-Stokes(ENS) equations for aeroelastic problems is explained. The current development of unsteady aerodynamic and aeroelastic procedures based on the ENS equations are discussed. The paper illustrates aeroelastic results computed using both TSP and ENS equations.

HISTORY OF CFD APPLICATIONS TO AEROELASTICITY

BASED ON UNSTEADY TIME ACCURATE METHODS

	TSP	FP	EULER	NAVIER STOKES
	1978	?	1986	1988
	1982	1984	1988	?
	1986	?	?	?
	1988	?	?	?
	?	?	?	?

MAJOR ISSUES FOR ADVANCED CFD METHODS

- Computational speed
  - Aeroelastic computations require two orders more computational time than steady computations
- Time accuracy
  - An essential requirement for accurate aeroelastic computations
- Grid and its unsteady movement
  - Time accuracy between zones
- Validity of turbulence models for unsteady and separated flows
- Robustness of solution methods
  - Other issues like artificial viscosity, upwinding, etc.

APPROACH FOR COMPUTER SIMULATION

- GOVERNING EQUATIONS
  - Aerodynamics : 3-D Euler/Navier-Stokes equations (ENS) and transonic small perturbation equation (TSP)
  - Aeroelastic : Modal equations of motion

- ALGORITHM
  - Aerodynamics : time accurate finite difference methods based on alternate direction implicit schemes
  - Aeroelastic : Simultaneous time integration method

- Note
  - ENS computations are made using aeroelastic adaptive dynamic grids
  - For TSP computations, aerodynamic and structural properties of the fuselage tip stores, and control surfaces are modeled

COUPLED AEROELASTIC EQUATIONS OF MOTION

- Deformed shape is a sum of modal coordinates
- Equations are solved by simultaneous integration technique
- Equations of Motion

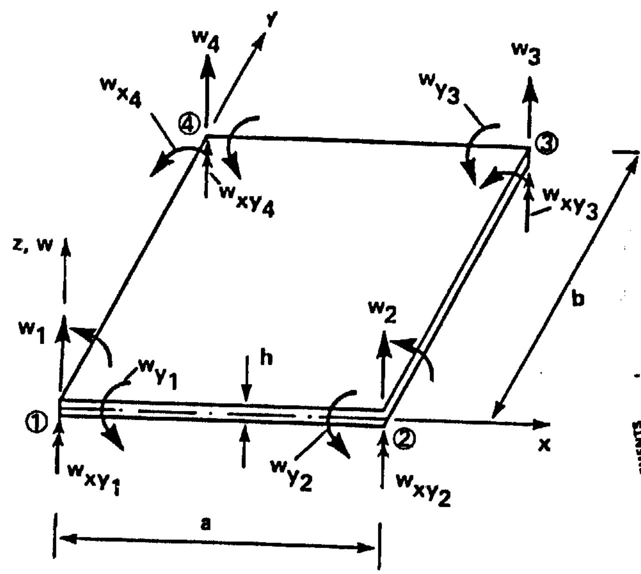
  - Assuming displacement vector $\{d\} = [\phi]\{q\}$ where $[\phi]$ is the modal matrix and $\{q\}$ is the generalized displacement vector, the aeroelastic equation of motion is

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

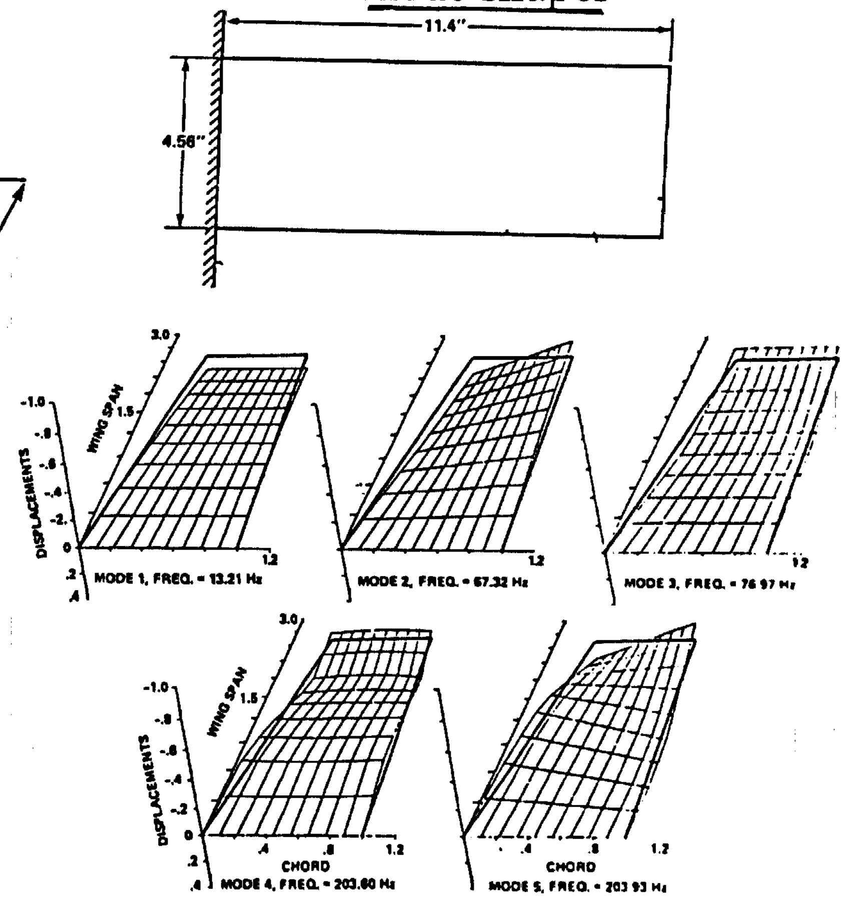
[M], [G], and [K] mass, damping and stiffness matrices
$\{F\} = (\frac{1}{2})\rho U_{\infty}^{2}[\phi]^{T}[A]\{\Delta C_p\}$ is the aerodynamic force vector
$[A]$ is the diagonal area matrix of the aerodynamic control points.

MODES OF A RECTANGULAR WING

16 d.o.f finite element



mode shapes



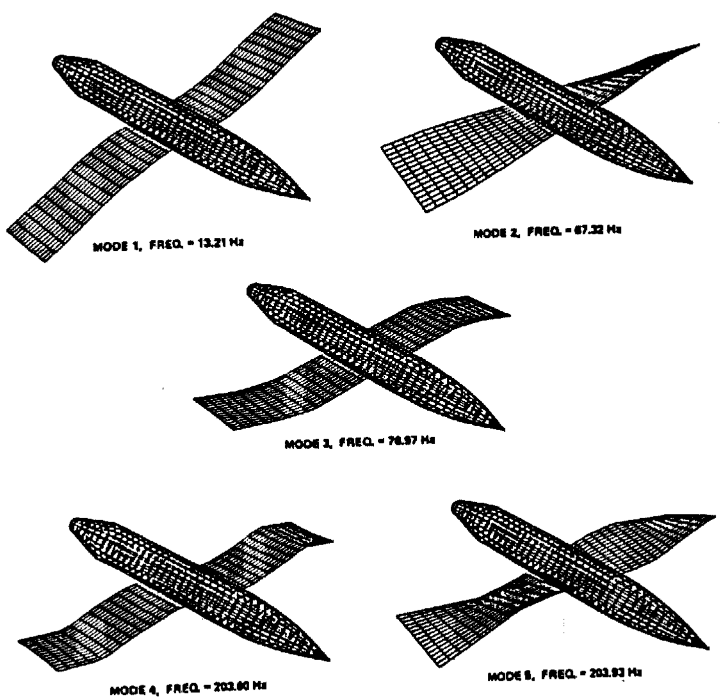
SOME APPLICATIONS OF TSP THEORY

- Transonic flutter boundaries of transport and fighter wings
- Aeroelasticity of a variable sweep wing (B-1 wing)
- Aeroelasticity of wings with tip stores
- Aeroelasticity of wings with active control surfaces
- Aeroelasticity of full span wing-body configurations (Symmetric and Asymmetric modes)

TYPICAL RESULTS FROM TSP CODE ATRAN3S

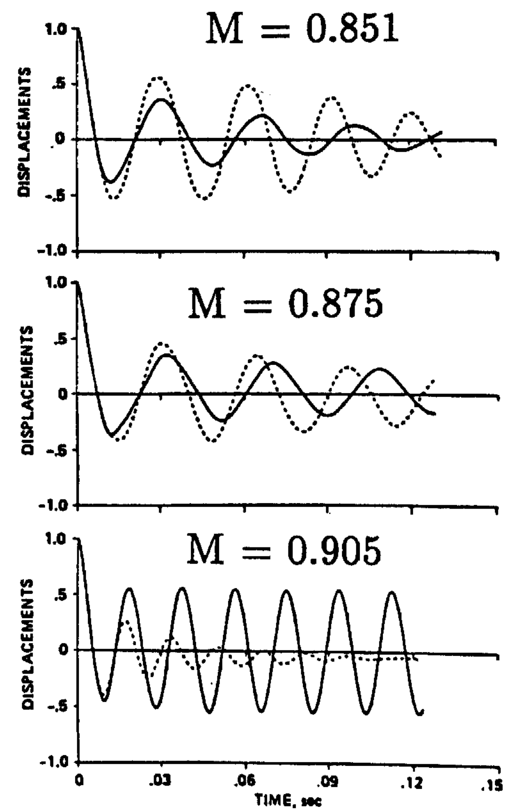
Full-Span Wing-Body Aeroelasticity

ANTISYMMETRIC MODES



RESPONSES

Symmetric ---Antisymmetric



DEVELOPMENT OF ENSAERO

- PURPOSE
  - To develop an aeroelastic code to solve Euler/Navier Stokes equations coupled with structural equations of motion for full aircraft
- CHARACTERISTICS
  - Solves either Euler or Navier Stokes equations
  - Models structure by either modal or finite element equations
  - Includes aeroelastic configuration adaptive grid scheme
  - Modular to adopt different finite difference schemes
  - Transportable to different computer configurations
- ENSAERO-version 2.0
  - Solves Euler/Navier Stokes equations with modal structural equations of motion for wings

CONFIGURATION ADAPTIVE DYNAMIC GRID

- Grids are generated by an algebraic method
- Grids conform to the wing surface defined by displacements $\{d\}$
- Grids are generated every time-step of integration
- Time metrics are computed every time step

$$\xi_t = -x_\tau \xi_x - y_\tau \xi_y - z_\tau \xi_z$$
$$\eta_t = -x_\tau \eta_x - y_\tau \eta_y - z_\tau \eta_z$$
$$\zeta_t = -x_\tau \zeta_x - y_\tau \zeta_y - z_\tau \zeta_z$$

$$J^{-1} = x_\xi y_\eta z_\zeta + x_\zeta y_\xi z_\eta + x_\eta y_\zeta z_\xi - x_\xi y_\zeta z_\eta - x_\eta y_\xi z_\zeta - x_\zeta y_\eta z_\xi$$

- Note - Present technique can be used for both structured and unstructured grids

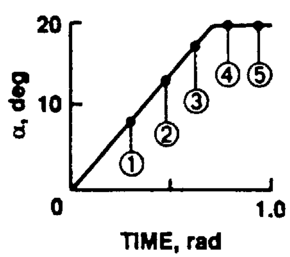
VORTEX DOMINATED UNSTEADY PRESSURES

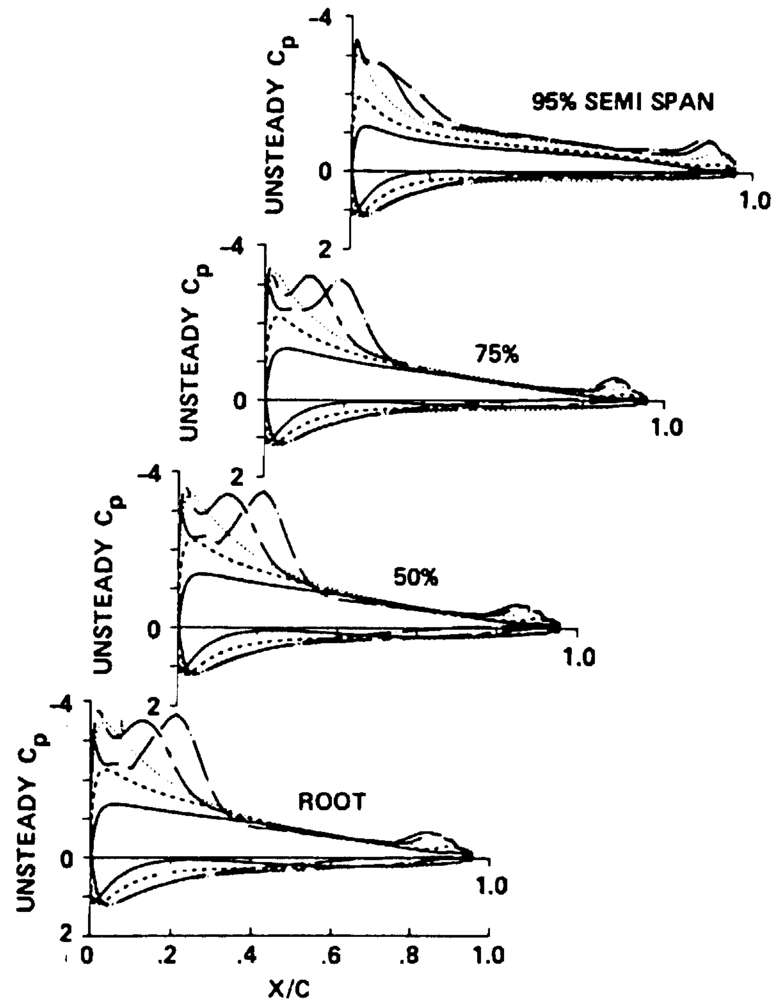
Navier-Stokes Computations

Rectangular Wing in ramp motion , AR = 4.0, NACA0015

GRID 151x20x40
$M_\infty = 0.50$, A = 0.30,
$R_e = 60000.0$

	$\tau(\alpha)$
——— (solid)	0.31,(8.8°)
– – – (dashed)	0.47,(13.5°)
······ (dotted)	0.63,(18.1°)
—— – —— (long dash)	0.79,(20.0°)
—·— (dash-dot)	0.94,(20.0°)



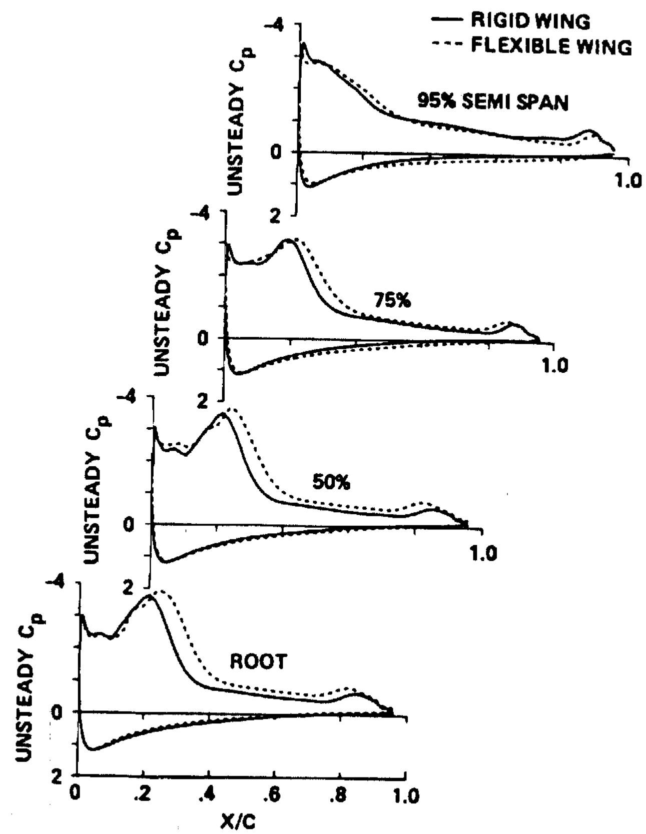


COMPARISON OF UNSTEADY PRESSURES BETWEEN RIGID AND FLEXIBLE WINGS
(Navier-Stokes Computations)

Rectangular Wing in ramp motion , AR = 4.0, NACA0015

GRID 151x20x40
$M_\infty = 0.50$, A = 0.30,
$R_e = 60000.0$
$\alpha = 20^o$, $\tau = 0.94$

——— Rigid Wing
– – – Flexible Wing



CONCLUDING REMARKS

- During last decade TSP applications have progressed from airfoils to almost full aircraft
  - Computational speed has increased by a factor of about 100
  - Robust codes such as ATRAN3S are now available
  - Applied for advanced applications such as active controls
- Euler/Navier Stokes (ENS) equations are currently being used for aeroelastic problems of wings

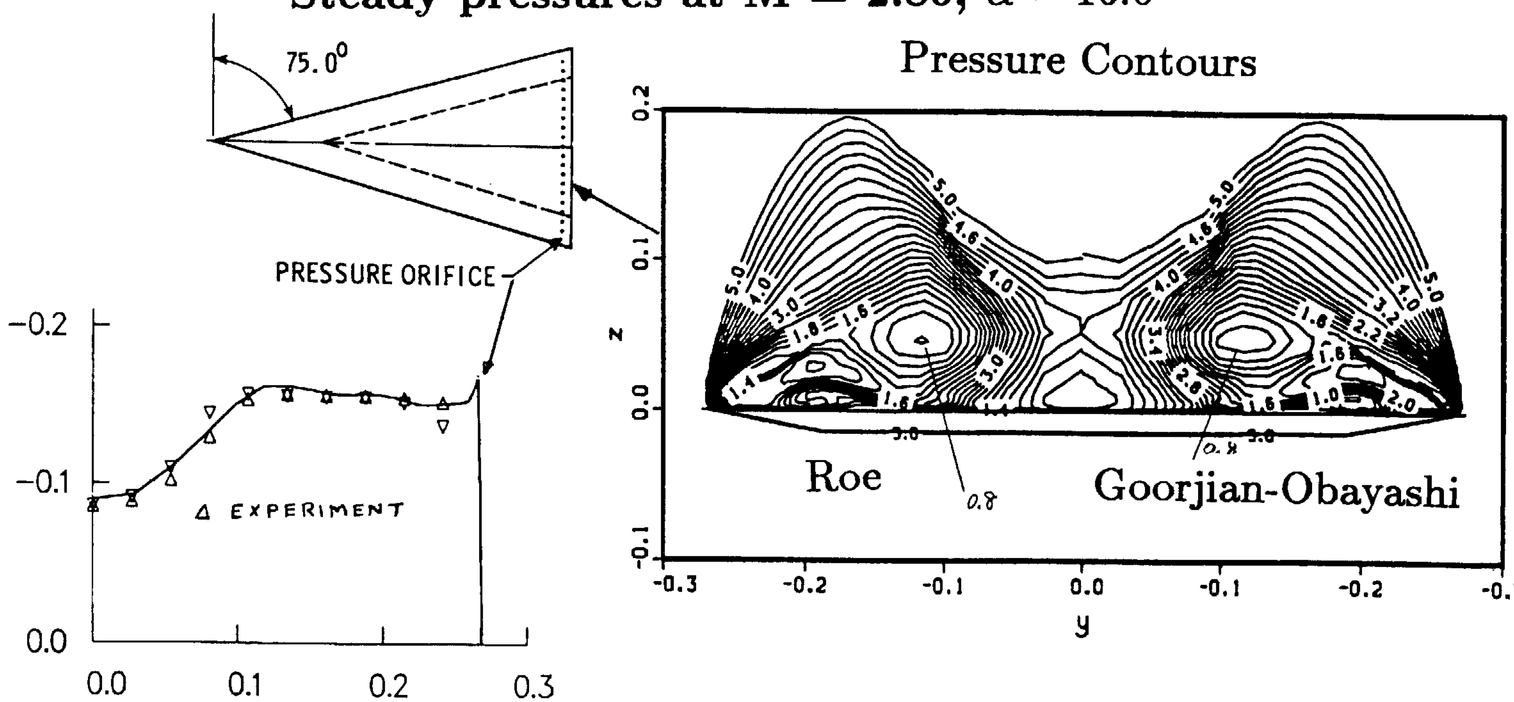
FUTURE DIRECTIONS

- Improve time accurate Euler/Navier Stokes(ENS) algorithms
- Extend unsteady ENS algorithms for full aircraft configurations
- Couple advanced CFD methods with advanced CSM methods
- Conduct research in unsteady aerodynamics and aeroelasticity of full aircraft at high angles of attack
- Maintain TSP codes for immediate industrial use

FUTURE DIRECTIONS (continued)
Algorithm Development

- Typical results from a new upwind scheme that will be implemented in ENSAERO

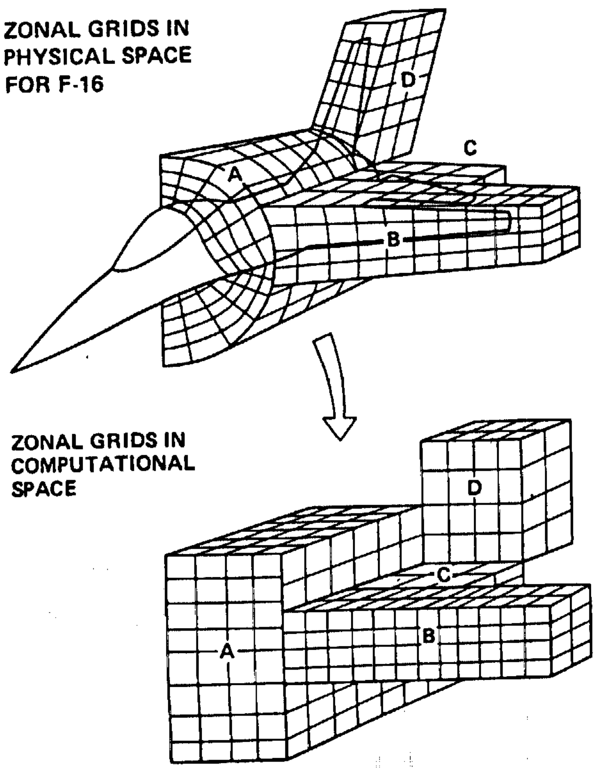
Vortical flow on a 75^o delta wing
Steady pressures at M = 2.80, $\alpha = 16.0^o$



FUTURE DIRECTIONS (continued)

- Typical steady results from Transonic Navier Stokes (TNS) code
- Unsteady algorithm will be implemented in full aircraft TNS code

ZONAL GRIDS IN PHYSICAL SPACE FOR F-16



ZONAL GRIDS IN COMPUTATIONAL SPACE

MACH CONTOURS

$M = 0.9$, $\alpha = 1.69°$, $Re = 4.5 \times 10^6$