Aeroelastic-Acoustics Simulation of Flight Systems

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Introductory remarks

- Paper describes a numerical FE based aeroelastic-acoustics analysis methodology
- This is followed by solution details of a 2-D airfoil and results correlation with known theoretical solution
- Also presented the 3-D wing case and related results pertaining to vibration, steady and unsteady flow (CFD), aeroelastic and aeroelastic-acoustic simulations
- Further associated solution results are presented for a numerically simulated unsteady pressure data
- Also SPL results from a SOFIA flight sensor data is presented in some detail
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- Discussions and concluding remarks

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Numerical Formulation

- Structural (FE) free vibration matrix equation solving for ω and φ

$$\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} = \boldsymbol{0} \qquad (1)$$

- The aerodynamic data are next computed by solving the Navier-Stokes (FE) equation

$$\frac{\partial \boldsymbol{v}}{\partial t} + \frac{\partial \boldsymbol{f}_j}{\partial x_j} + \frac{\partial \boldsymbol{g}_j}{\partial x_j} = \boldsymbol{f}_b \quad j = 1,2,3 \qquad (2)$$

in which

$$\boldsymbol{v} = [\rho \quad \rho u_i \quad \rho E]^T \quad i = 1,2,3$$

- Vehicle equation of motion is then cast into the frequency domain

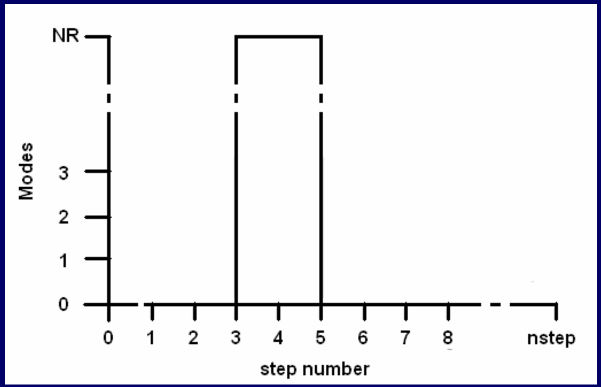
$$\hat{\boldsymbol{M}}\ddot{\boldsymbol{q}} + \hat{\boldsymbol{C}}\dot{\boldsymbol{q}} + \hat{\boldsymbol{K}}\boldsymbol{q} + \boldsymbol{f}_a(t) + \boldsymbol{f}_I(t) = 0 \qquad (3)$$

where

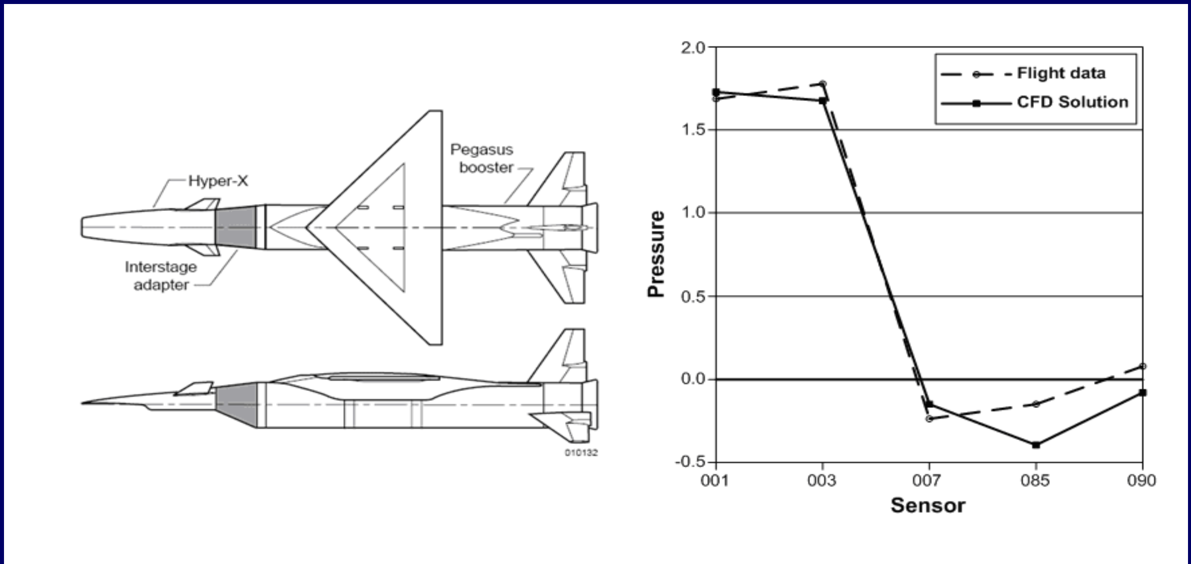
$\hat{\boldsymbol{M}} \left(= \boldsymbol{\Phi}^T \boldsymbol{M} \boldsymbol{\Phi}\right)$ is the generalized mass matrix and similarly $\hat{\boldsymbol{K}}, \hat{\boldsymbol{C}}$; $\boldsymbol{f}_a(t)$ is the aerodynamic load vector; $\boldsymbol{f}_I(t)$ being the generalized impulse force vector

Numerical Formulation (cont'd)

- Generalized impulse force vector $f_I(t)$



- Earlier, the CFD code analysis results were verified with flight test data
  - Hyper-X vehicle and flight data comparison



Numerical Formulation (cont'd)

- Equation (3) may then be cast in a state-space matrix form as

$$\begin{bmatrix} \boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{I} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{q}} \\ \ddot{\boldsymbol{q}} \end{bmatrix} - \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ -\hat{\boldsymbol{M}}^{-1}\hat{\boldsymbol{K}} & -\hat{\boldsymbol{M}}^{-1}\hat{\boldsymbol{C}} \end{bmatrix} \begin{bmatrix} \boldsymbol{q} \\ \dot{\boldsymbol{q}} \end{bmatrix} - \begin{bmatrix} \boldsymbol{0} \\ -\hat{\boldsymbol{M}}^{-1}\boldsymbol{f}_a(t) \end{bmatrix} - \begin{bmatrix} \boldsymbol{0} \\ -\hat{\boldsymbol{M}}^{-1}\boldsymbol{f}_I(t) \end{bmatrix} = \boldsymbol{0} \quad (4)$$

or

$$\dot{\boldsymbol{x}}_s(t) = \boldsymbol{A}_{st}\boldsymbol{x}_s(t) + \boldsymbol{B}_{st}\boldsymbol{f}(t) \quad (5)$$

where

$$\boldsymbol{A}_{st} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ -\hat{\boldsymbol{M}}^{-1}\hat{\boldsymbol{K}} & -\hat{\boldsymbol{M}}^{-1}\hat{\boldsymbol{C}} \end{bmatrix}, \quad \boldsymbol{B}_{st} = \begin{bmatrix} \boldsymbol{0} \\ -\hat{\boldsymbol{M}}^{-1} \end{bmatrix}, \quad \boldsymbol{f}(t) = \boldsymbol{f}_a(t) + \boldsymbol{f}_I(t), \quad \boldsymbol{x}_s = \begin{bmatrix} \boldsymbol{q} \\ \dot{\boldsymbol{q}} \end{bmatrix} \quad (6)$$

and

$$\boldsymbol{y}_s(t) = \boldsymbol{C}_{st}\boldsymbol{x}_s(t) + \boldsymbol{D}_{st}\boldsymbol{f}(t) \quad (7)$$

in which $\boldsymbol{C}_{st} = \boldsymbol{I}$ and $\boldsymbol{D}_{st} = \boldsymbol{0}$

Numerical Formulation (cont'd)

- In the presence of sensors, for the most general aeroservoelastic case these equations are converted into zero order hold (ZOH) discrete time equivalent at the *k-th* step:

$$\boldsymbol{x}_s(k+1) = \boldsymbol{G}_s\,\boldsymbol{x}_s(k) + \boldsymbol{H}_s\,\boldsymbol{f}(k) \quad (8)$$

$$\boldsymbol{y}_s(k+1) = \boldsymbol{C}_s\,\boldsymbol{x}_s(k) + \boldsymbol{D}_s\,\boldsymbol{f}(k) \quad (9)$$

in which

$$\boldsymbol{f}(k) = \boldsymbol{f}_a(k) + \boldsymbol{f}_I(k)$$

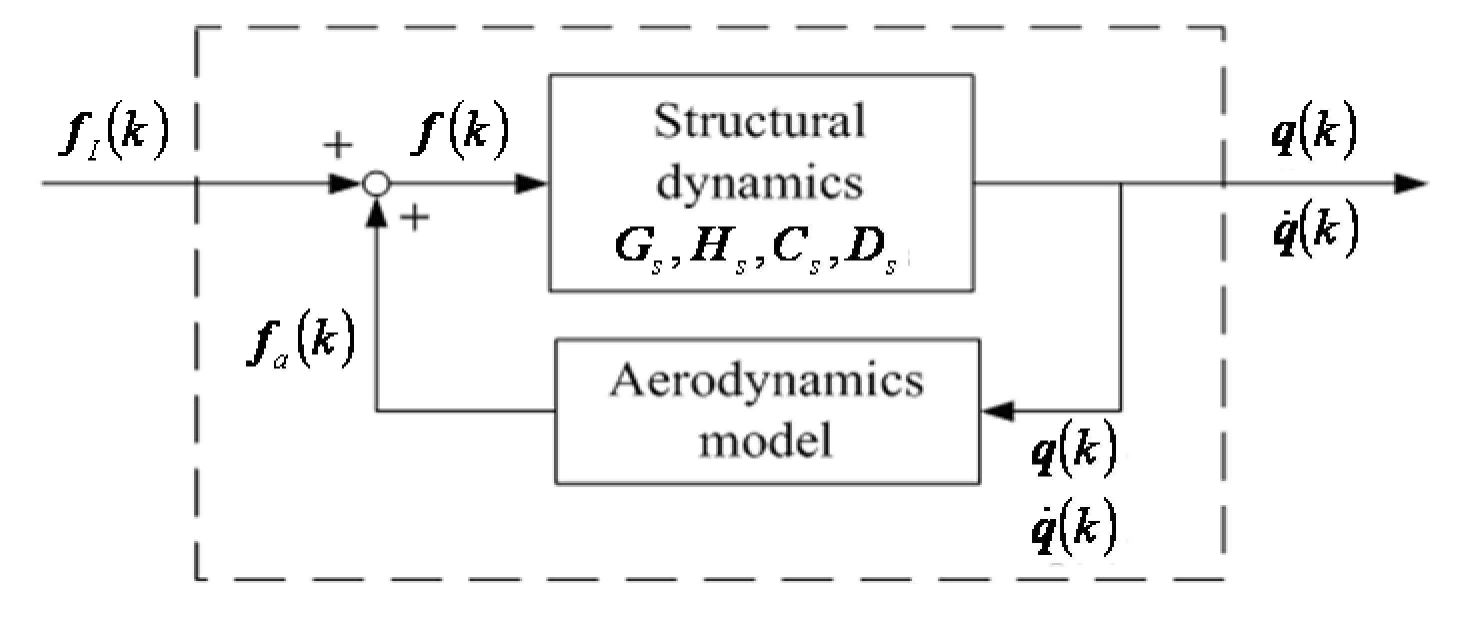
and

$$\boldsymbol{G}_s = e^{\boldsymbol{A}_s \Delta t} \qquad \boldsymbol{H}_s = \left[e^{\boldsymbol{A}_s \Delta t} - \boldsymbol{I}\right]\left[\boldsymbol{A}_s^{-1}\boldsymbol{B}_s\right] \quad (10)$$

where $\boldsymbol{A}_s$ and $\boldsymbol{B}_s$ are $\boldsymbol{A}_{st}$ and $\boldsymbol{B}_{st}$ having been modified to include sensors

Numerical Formulation (cont'd)

- Coupled aeroelastic (AE) model



Numerical Formulation (cont'd)

- Acoustic frequencies are obtained by performing FFT on computed unsteady aerodynamic pressures
- Also the sound pressure level (SPL) for a specified node is computed by first fixing a time band, *t* and then performing the following calculation using *n* number of sampling points

a) compute average pressure

$$P_{\text{avg}} = \left(\sum_{i=1}^{n} P_i \right) \Big/ n \qquad (11)$$

b) compute the root mean square of pressure

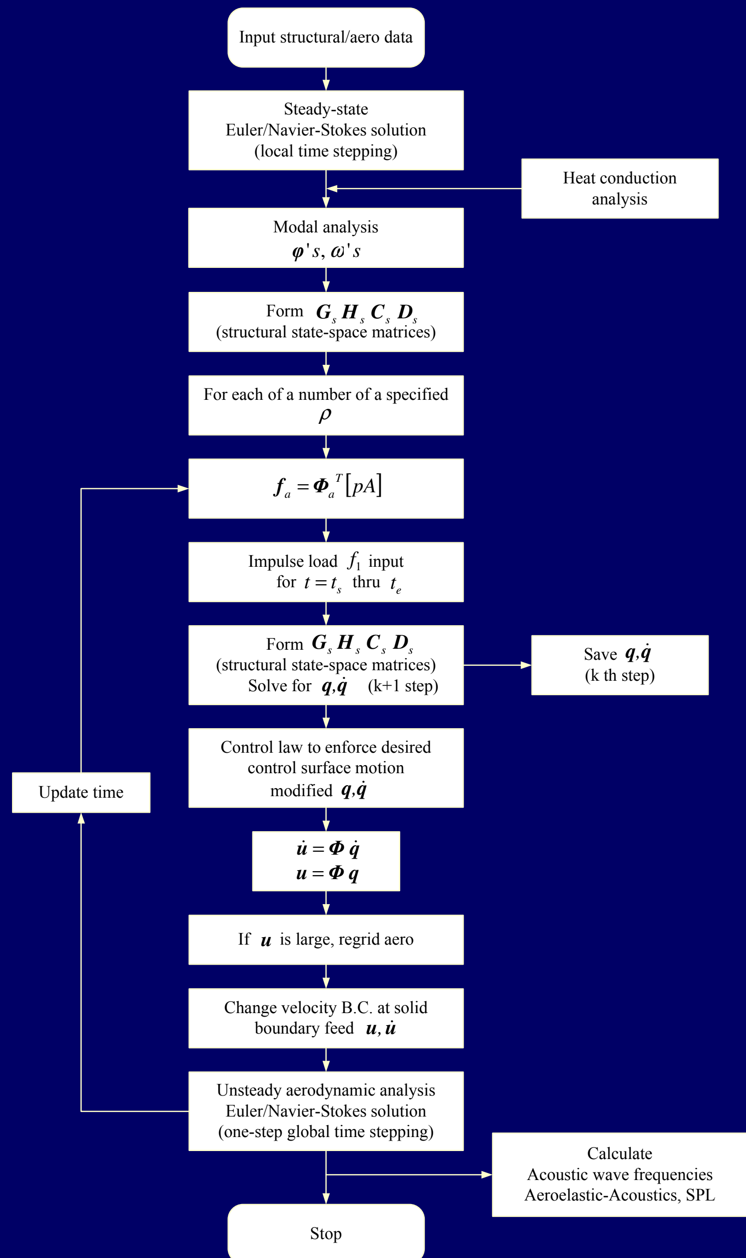
$$P_{rms} = \sqrt{\sum_{i=1}^{n} \left(P_i - P_{avg} \right)^2 \Big/ n} \qquad (12)$$

c) compute the SPL

$$\text{SPL}(dB) = 20 \log_{10} \frac{P_{rms}}{P_{ref}} \qquad (13)$$

where $P_{ref} = 20 \times 10^{-6}\, Pa$ for air

Flowchart of aero-elastic-servo-acoustic analysis



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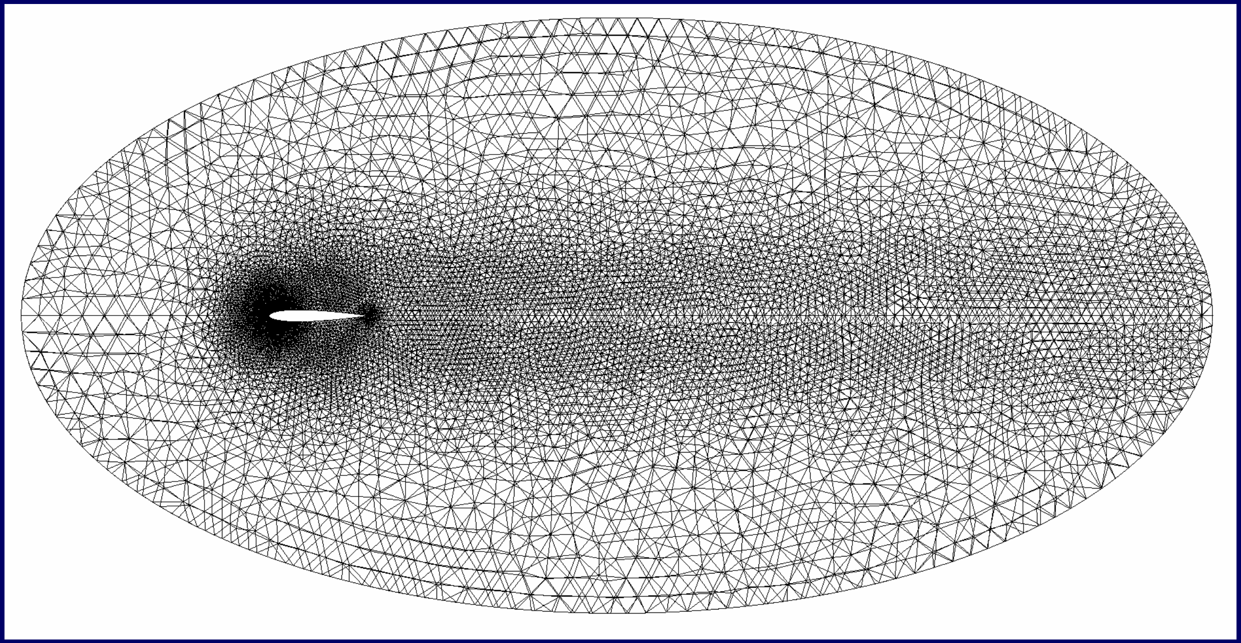
Numerical Example I, 2-D

- 2-D subsonic NACA 0012 Airfoil
  - Flight Condition : Mach Number = 0.3, Angle of Attack = 5-degree

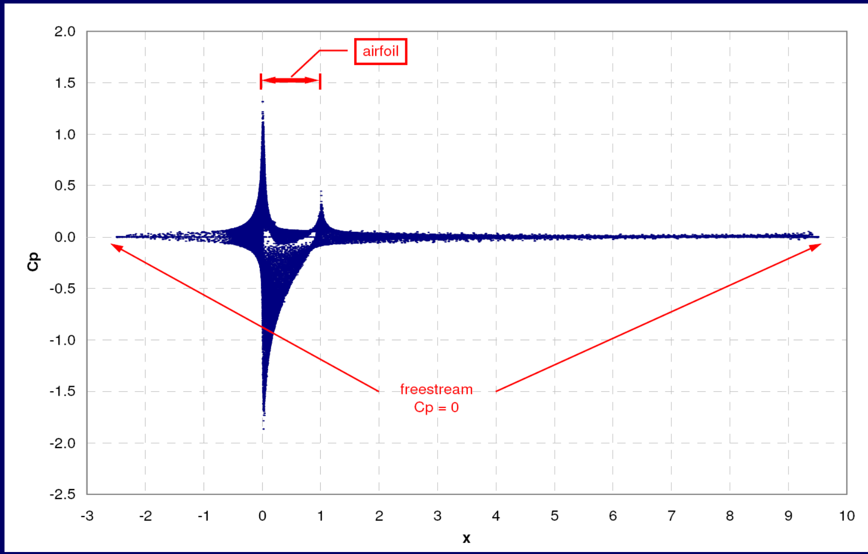
- In an effort to verify the solution accuracy:
  - Steady state : Correlation with (i) Smith-Hess panel method (ii) CFD solver
  - Unsteady analysis solution is compared with Wagner's suddenly accelerated airfoil problem



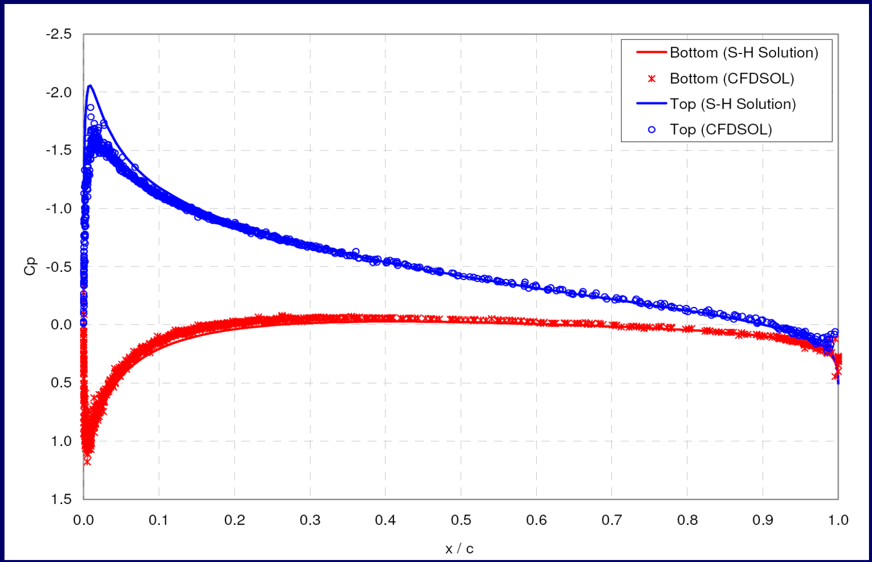
Numerical Example I, 2-D (cont'd)

- Steady state solutions

1. Coefficient of Pressure (Cp) distribution over solution domain

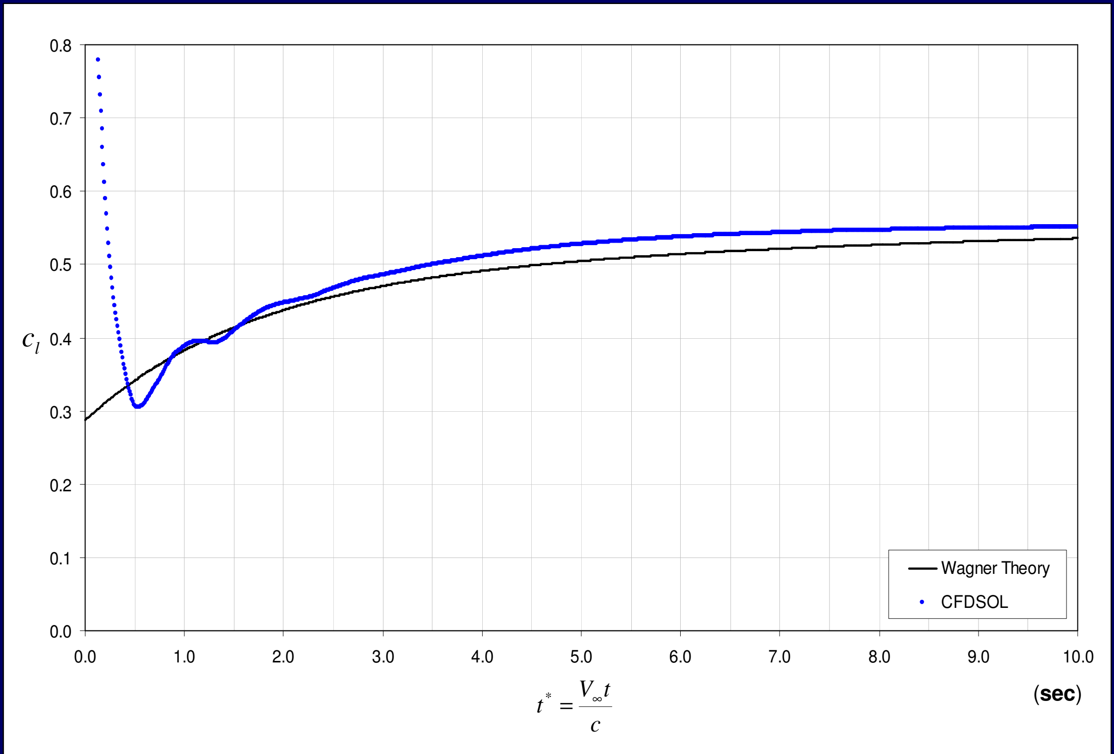


2. Coefficient of Pressure (Cp) distribution comparison on the airfoil



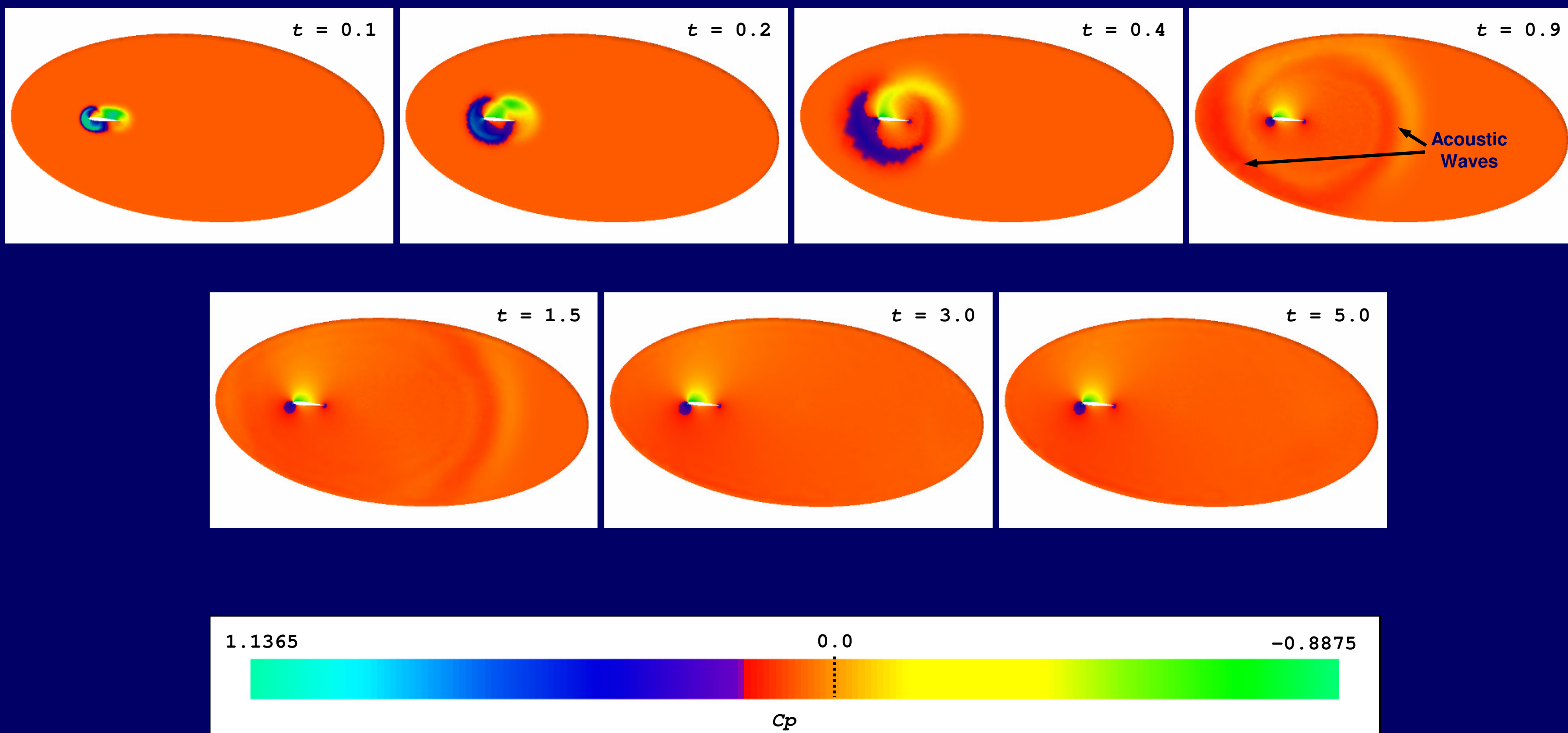
Numerical Example I, 2-D (cont'd)

- Unsteady analysis solution
  - Unsteady Coefficient of Lift (Cl) history comparison



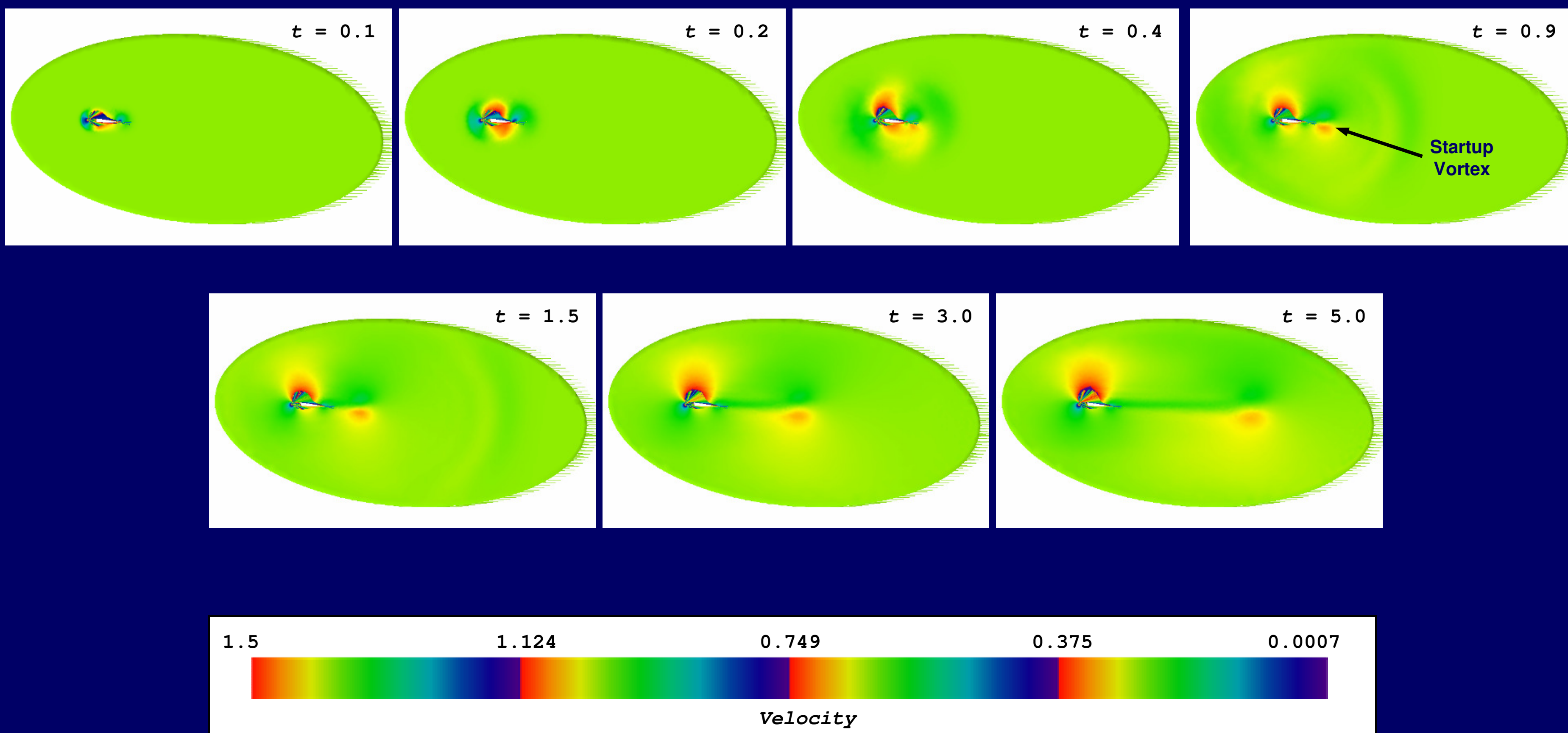
Numerical Example I, 2-D (cont'd)

- Unsteady analysis solutions
  - Coefficient of Pressure (Cp)



Numerical Example I, 2-D (cont'd)

- Unsteady analysis solutions
  - Velocity



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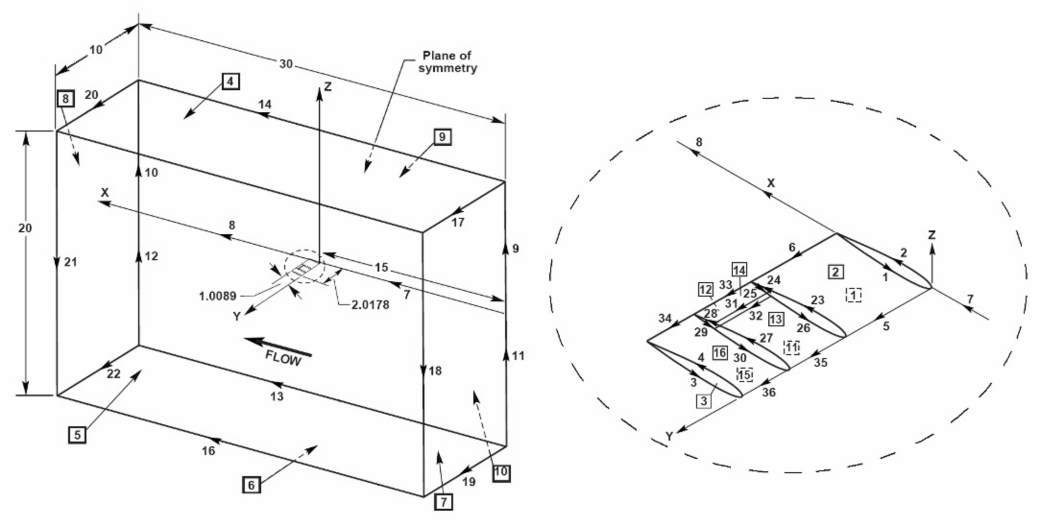
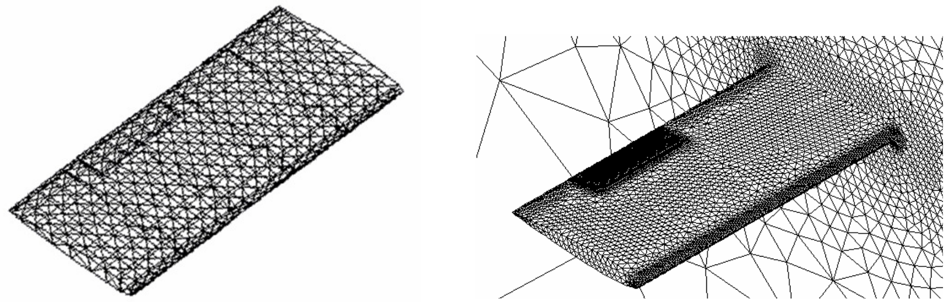
Numerical Example II, 3-D

- 3-D cantilever wing with NACA 0012 airfoil
  - Flight condition : Mach 0.3 and 0.6, Angle of Attack = 0 degree

1. Cantilever wing with aeroelastic solution domain



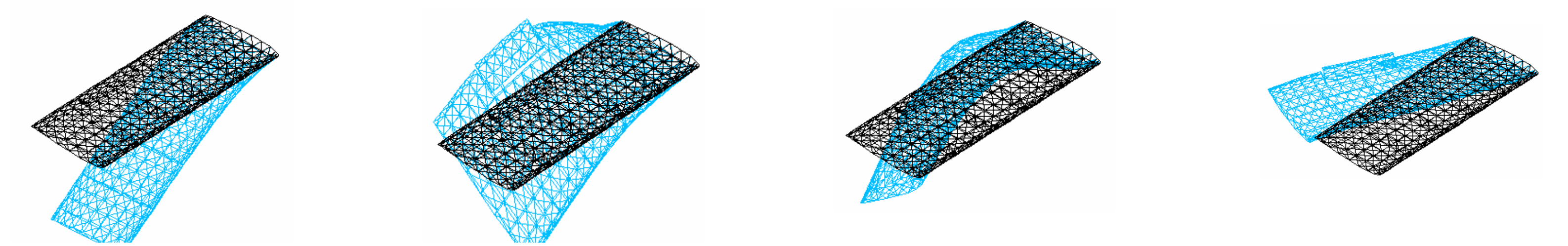
2. Structural (a) and aerodynamic (b) surface grid of wing



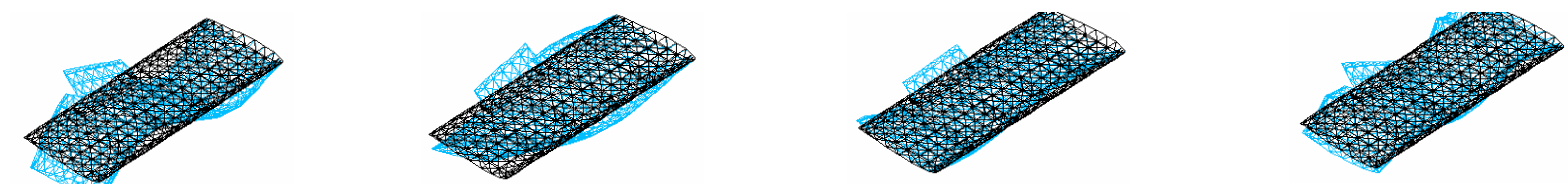
(a) (b)

Numerical Example II, 3-D (cont'd)

- Structural modes of cantilever wing

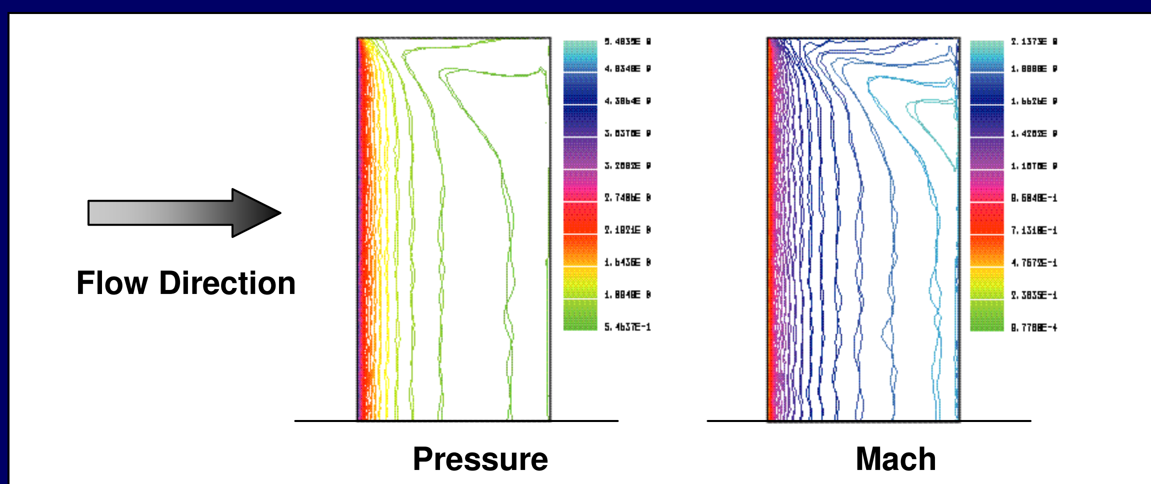


(a) mode 1, 3.521 Hz., 1B | (b) mode 2, 14.819 Hz., 1T | (c) mode 3, 18.819 Hz., 2B | (d) mode 4, 38.026 Hz., in plane



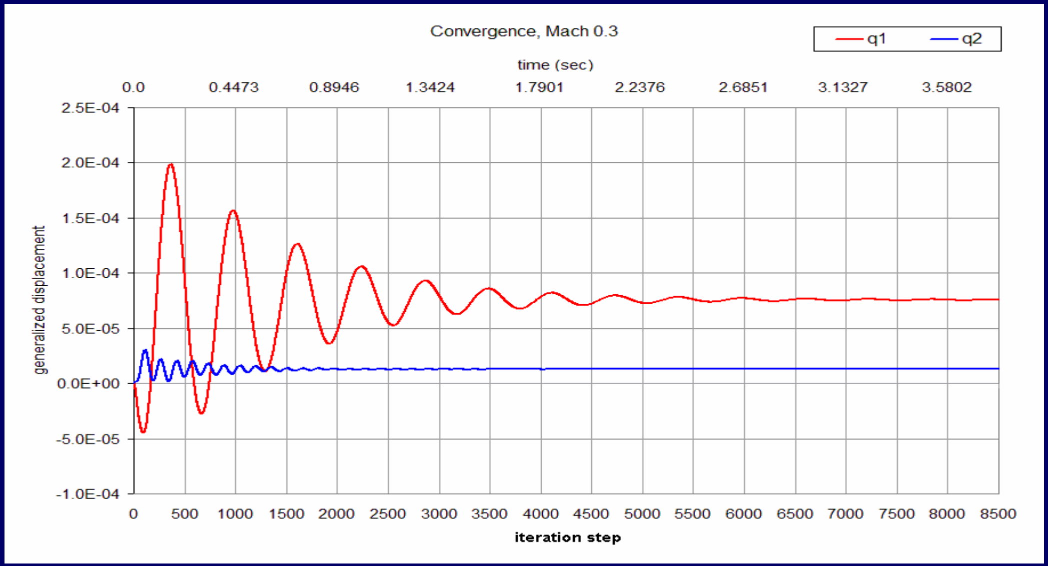
(e) mode 5, 41.408 Hz., 3B | (f) mode 6, 48.636 Hz., 2T | (g) mode 7, 59.797 Hz., 1B control | (h) mode 8, 64.958 Hz., 4B

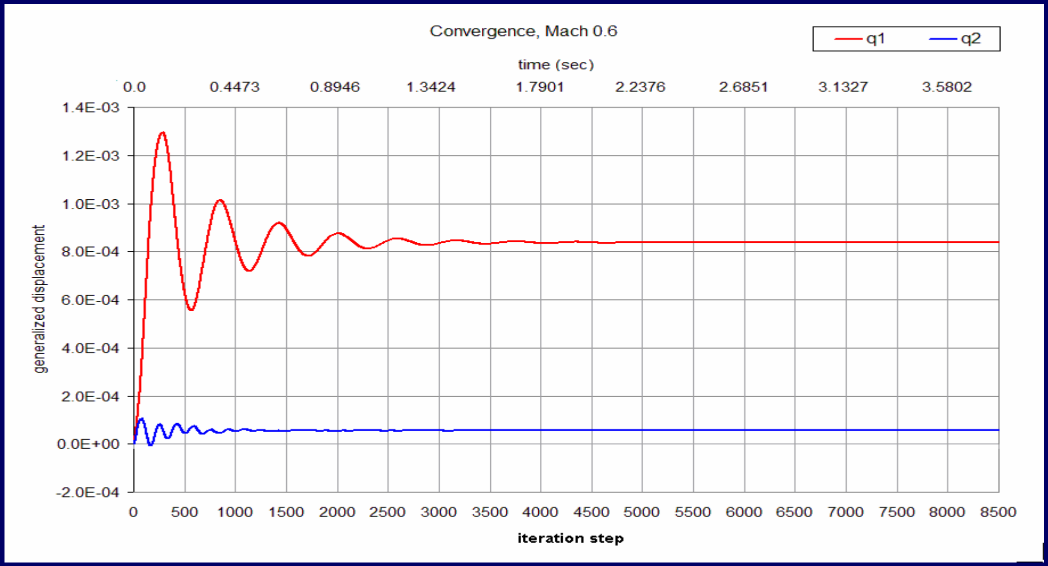
- Aerodynamic steady-state pressure and Mach distribution (M = 2.0)



Numerical Example II, 3-D (cont'd)

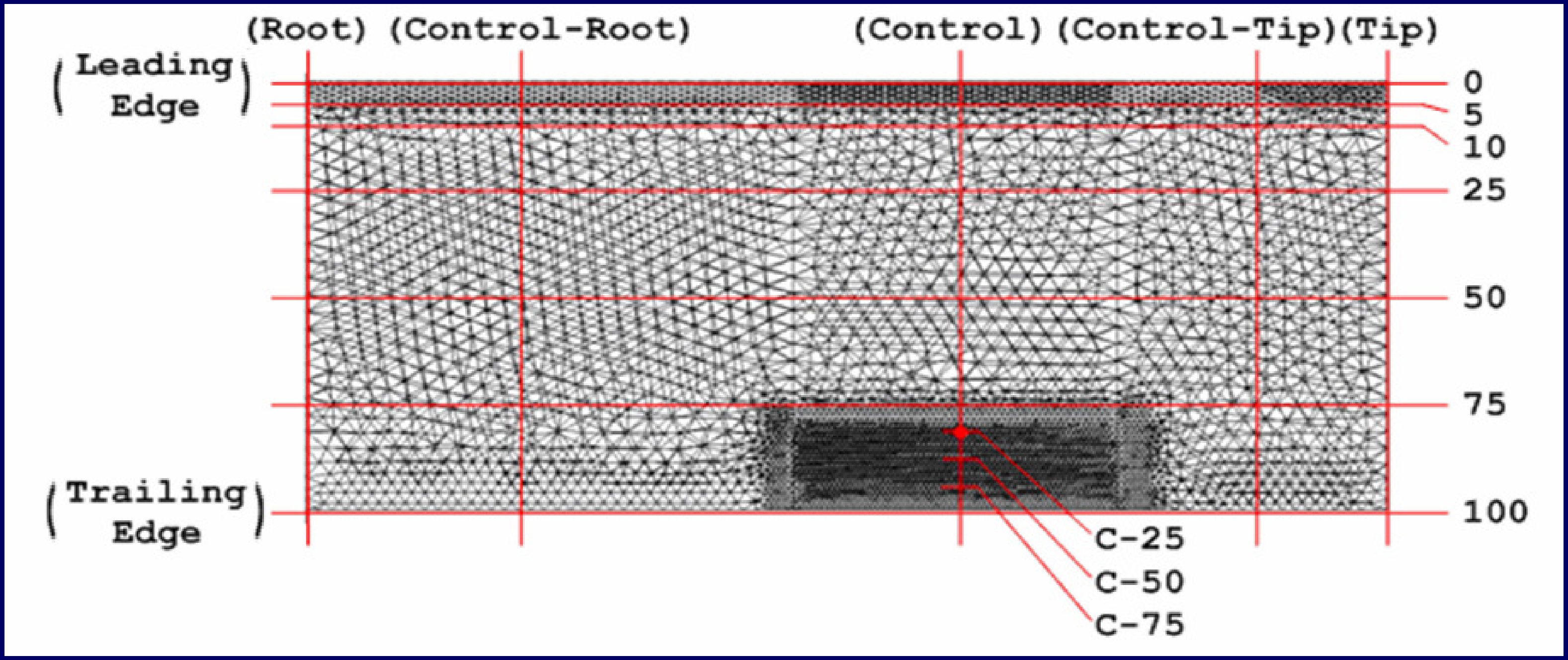
- Typical aeroelastic response plot (generalized displacement)





Numerical Example II, 3-D (cont'd)

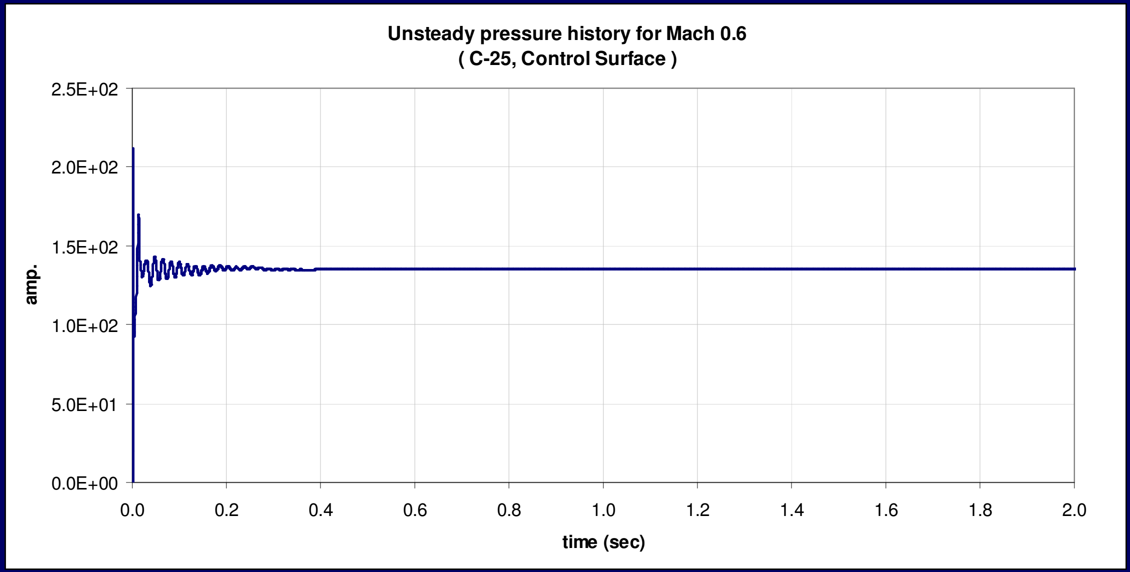
- Layout of the acoustic computation sampling points



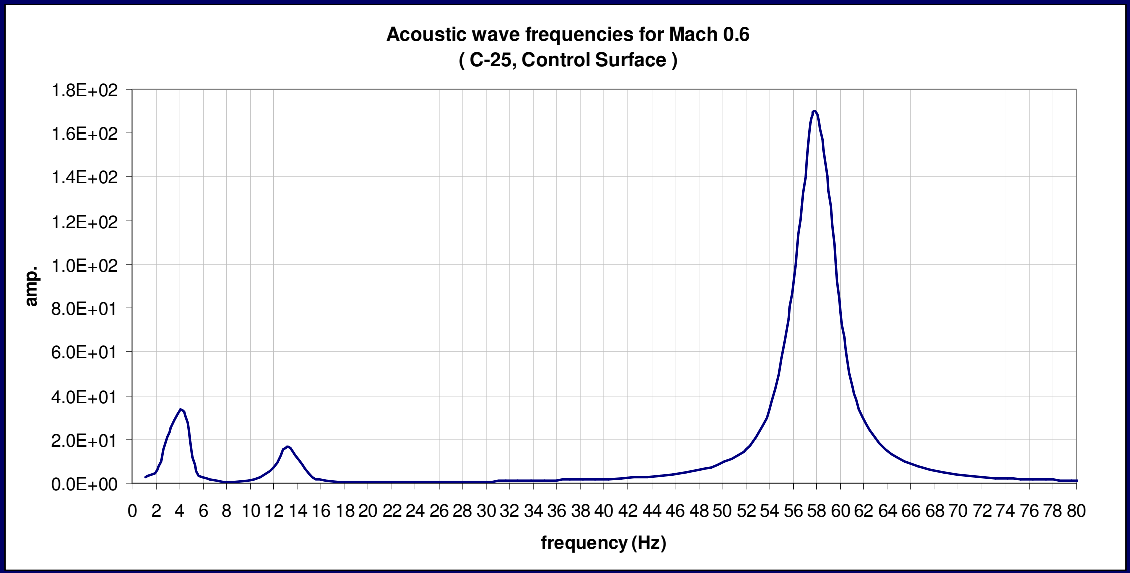
Numerical Example II, 3-D (cont'd)

- Mach 0.6

1. Aeroelastic unsteady pressure response (node, C25)

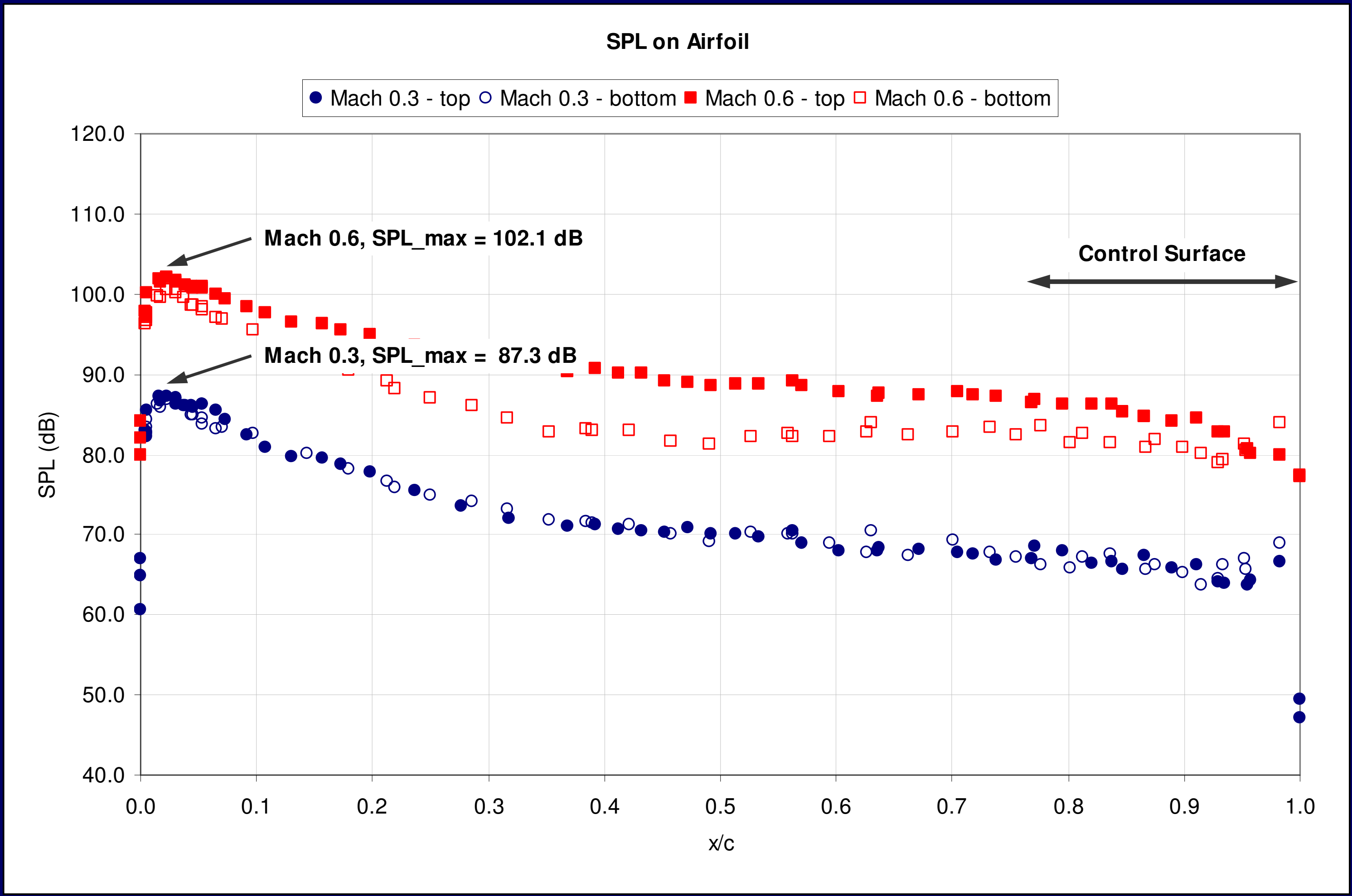


2. Acoustic wave frequencies (node, C25)



Numerical Example II, 3-D (cont'd)

- Sound Pressure Level (SPL) for a line along the cord length (20% from wing tip)



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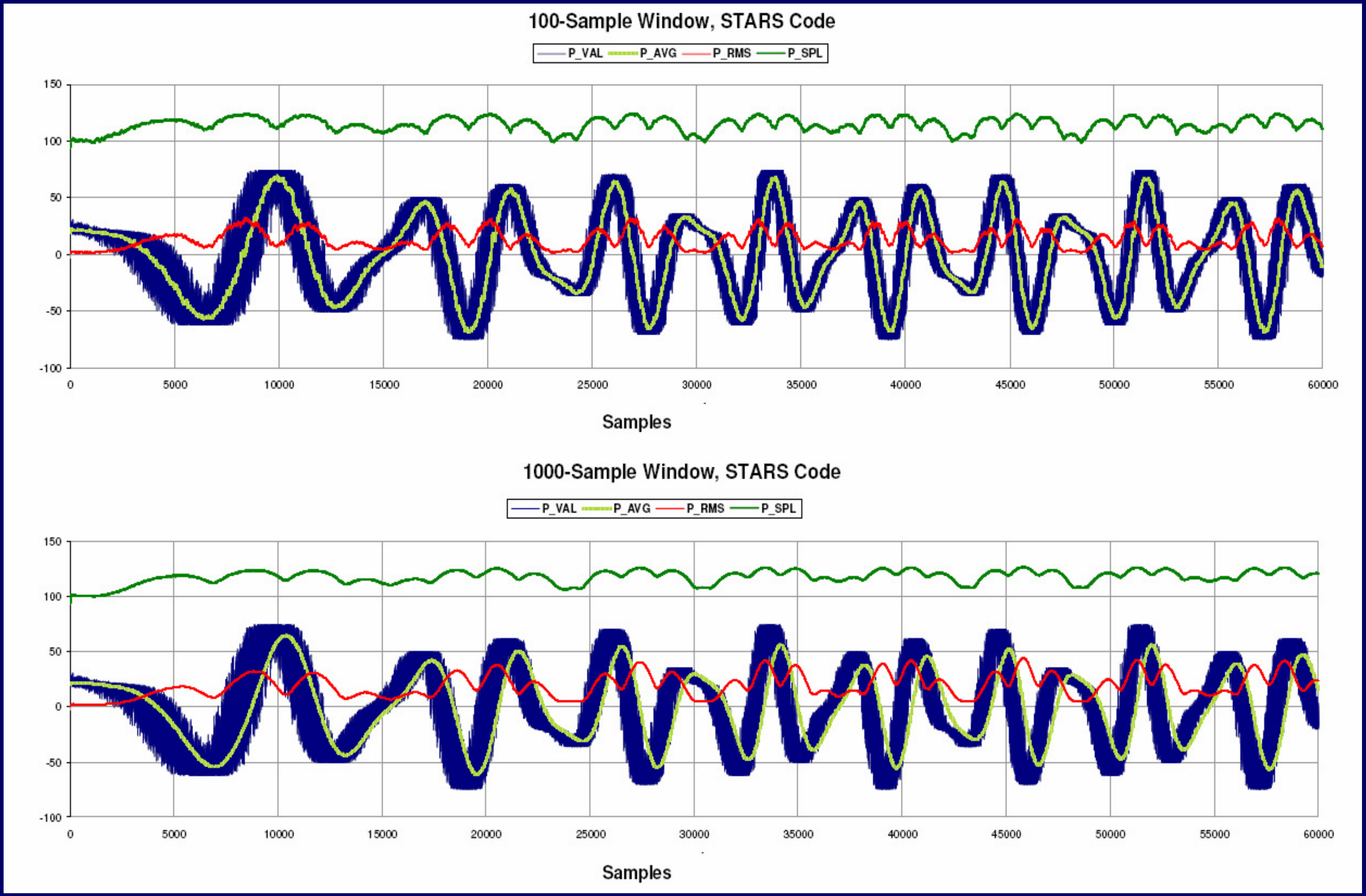
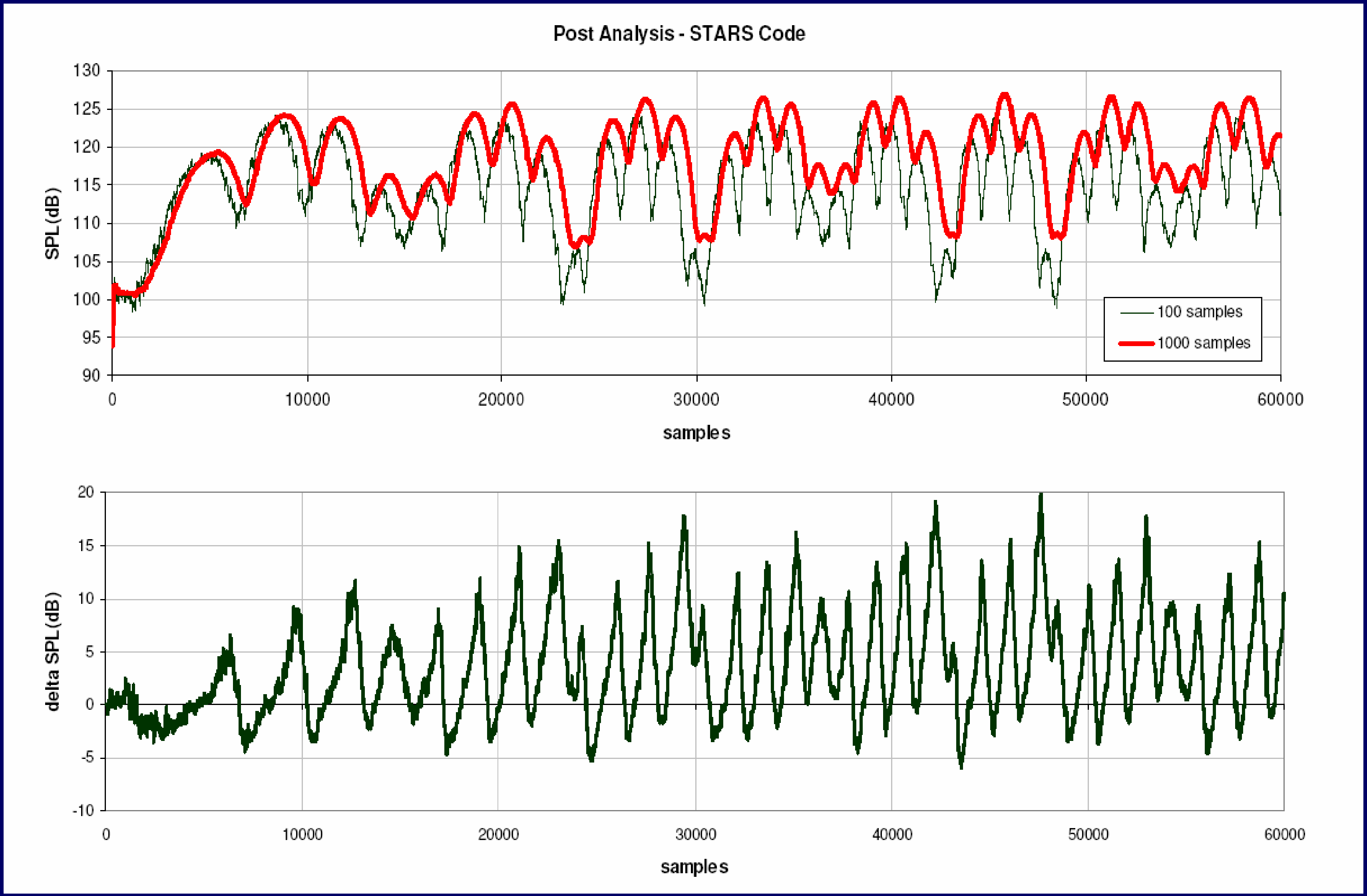
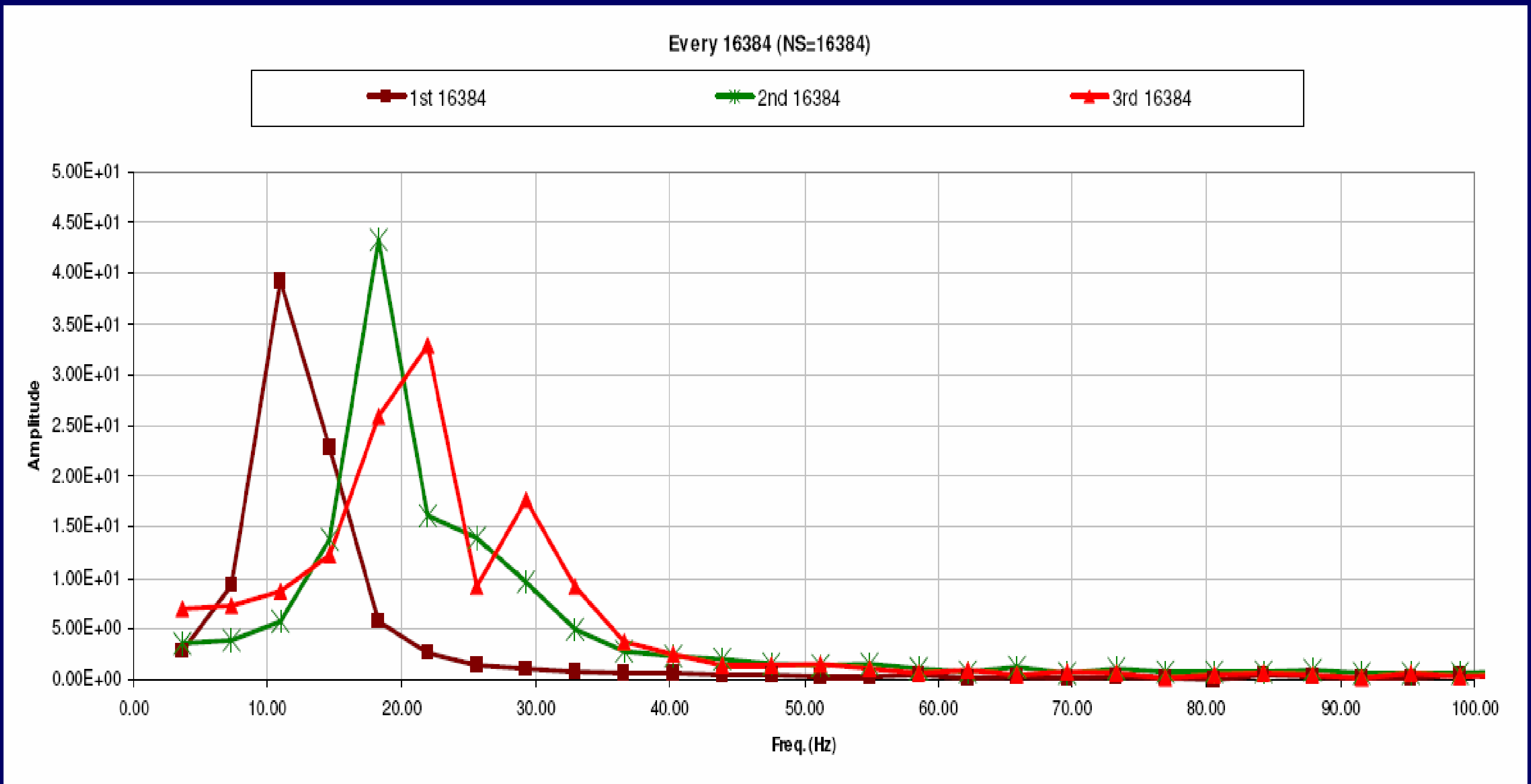


Numerical Example III, simulated data (cont'd)



Numerical Example III, simulated data (cont'd)



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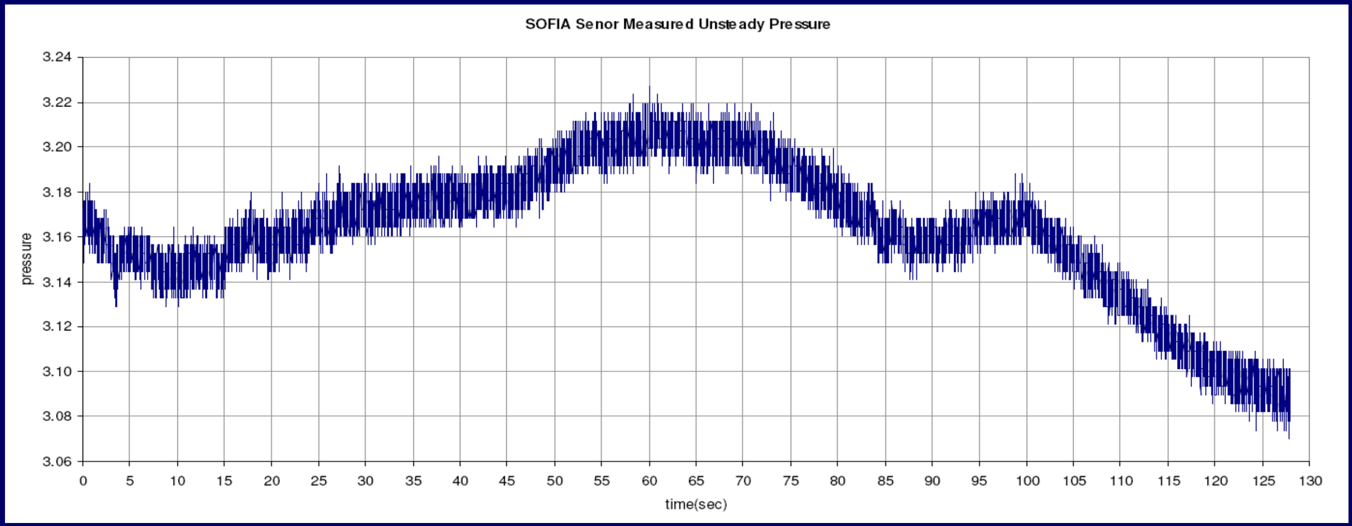
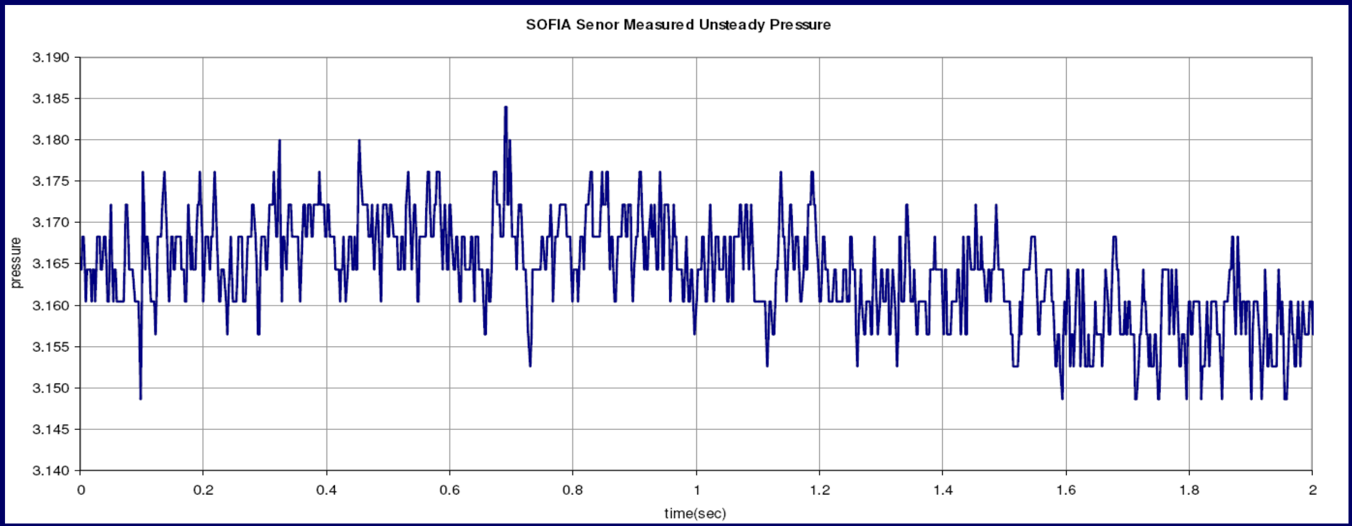
Numerical Example IV, SOFIA measured unsteady pressure data



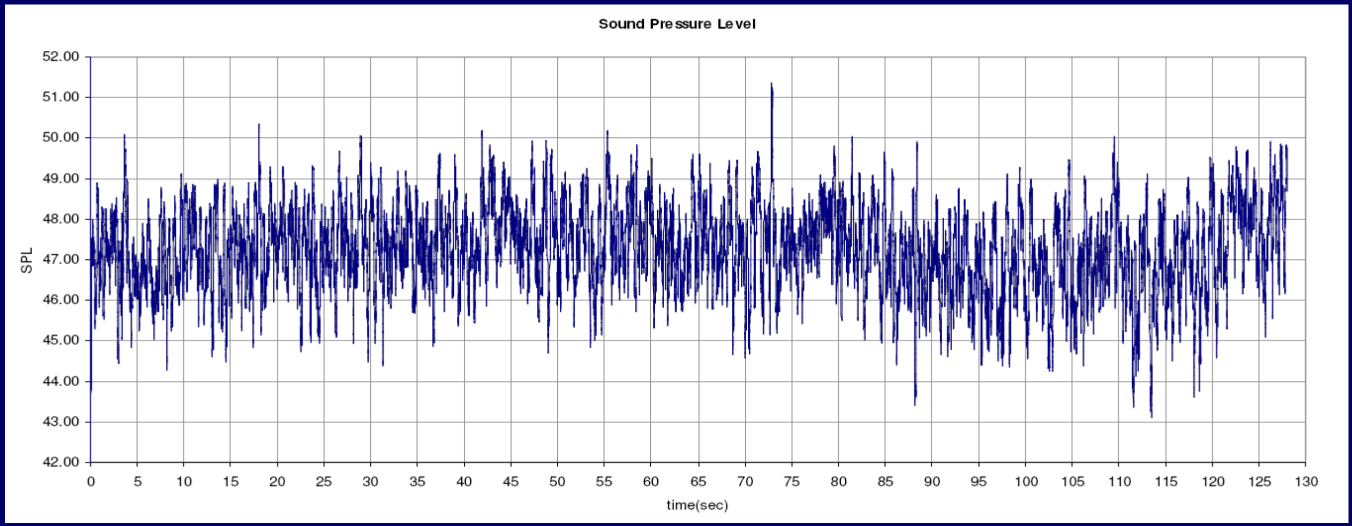
(a) Measured sensor data



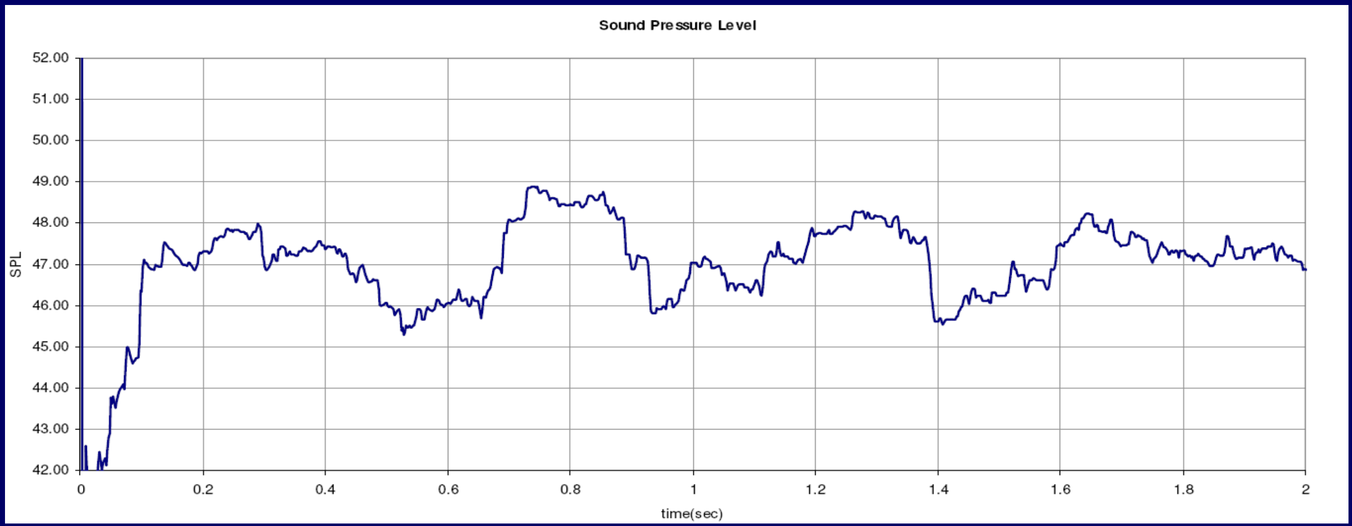
(b) Close up Measured sensor data

SOFIA sensor measured unsteady pressure data

Numerical Example IV, SOFIA measured unsteady pressure data (cont'd)



(a) SPL results data

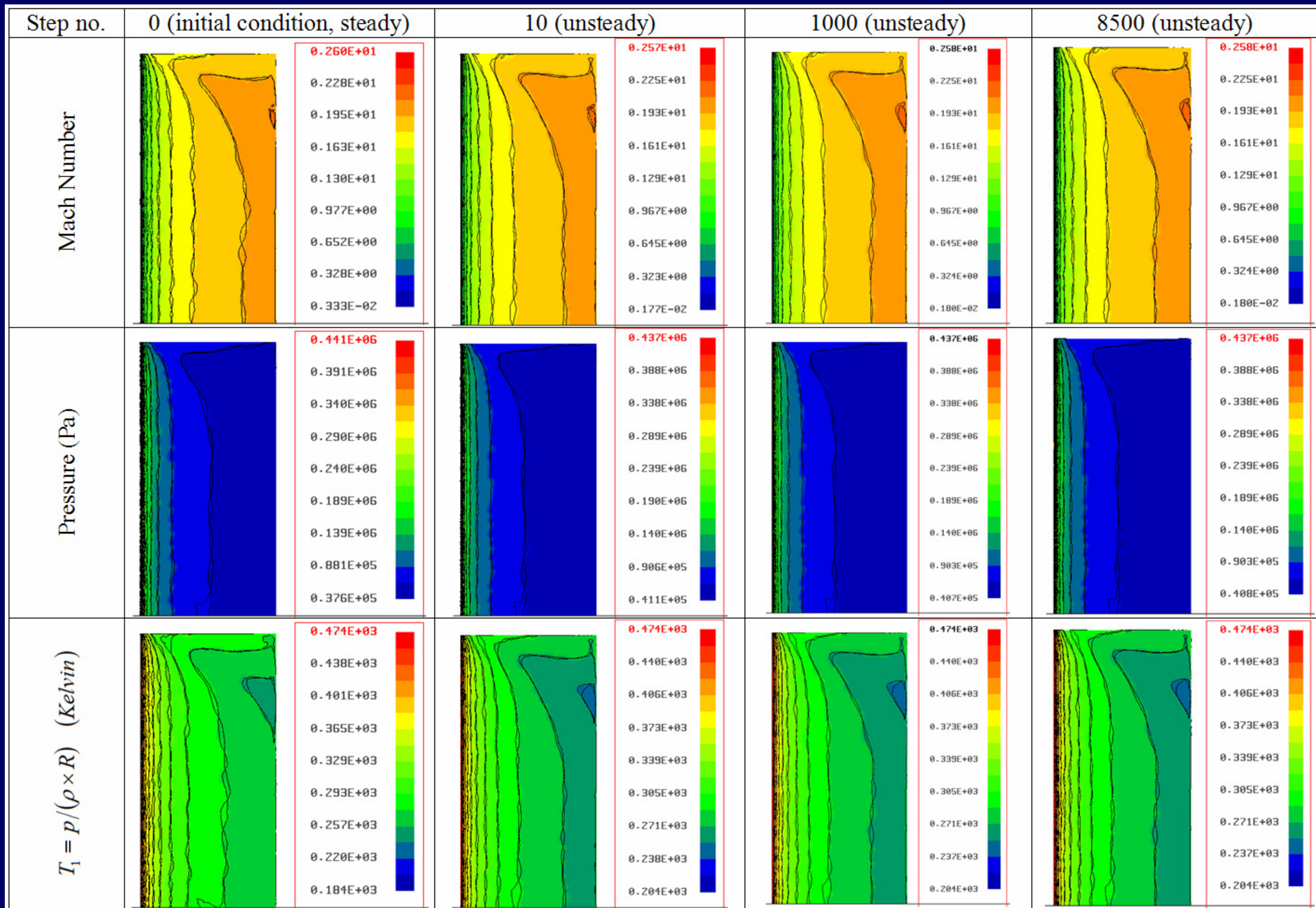


(b) Close up SPL result data

SOFIA calculated SPL results data

Numerical Example II, 3-D (additional)

- Mach 2.0



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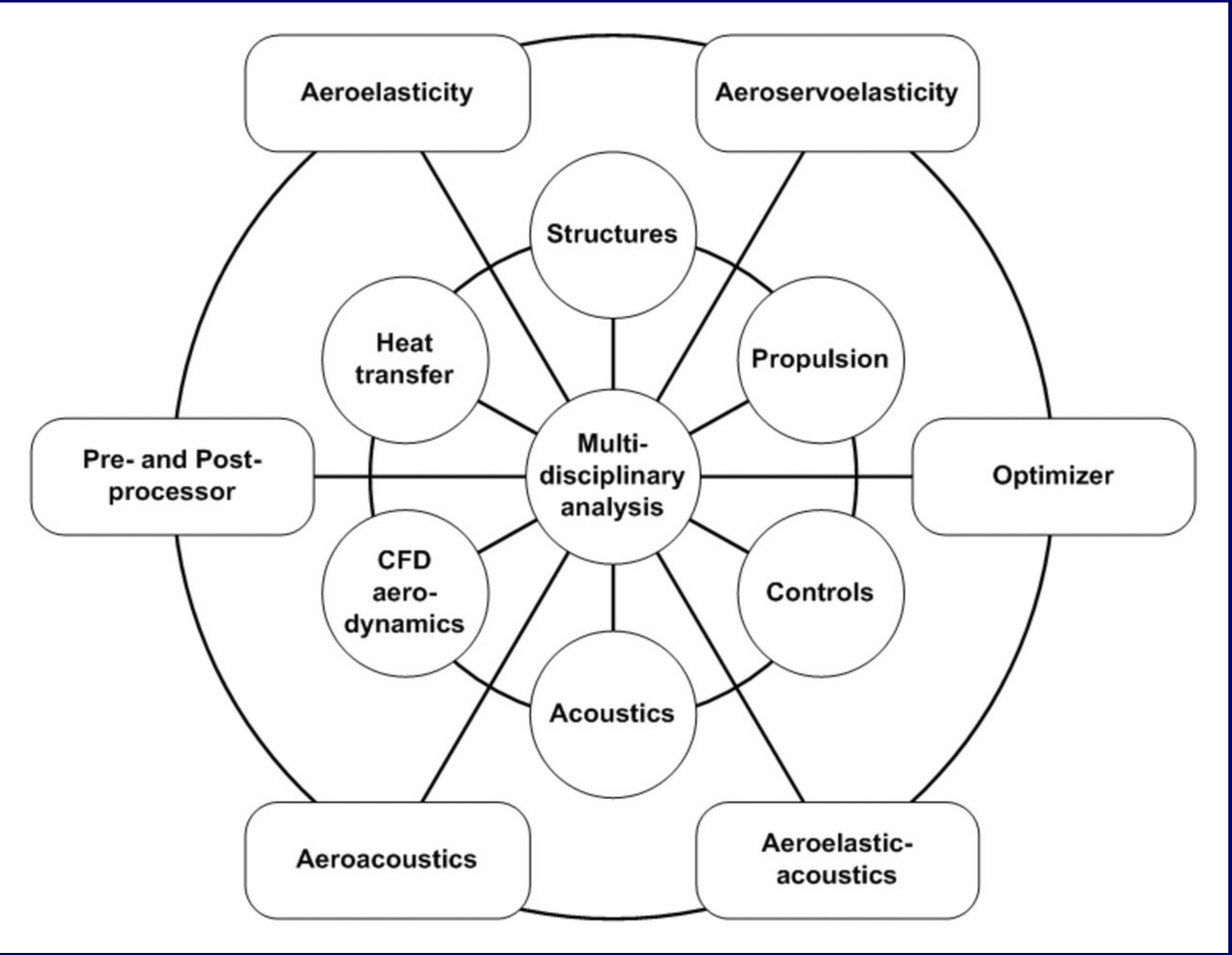
STARS capability



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Concluding Remarks

- An integrated finite element based aeroelastic-acoustics analysis algorithm presented
- Its implementation in a code, suitable for large scale computation, is also presented in some detail
- Numerical verification example problem is demonstrated
- A 3-D wing problem is analyzed in detail, that demonstrate the FE codes capability to solve practical problems routinely
- Also presented a simulated example problem followed by a SOFIA flight measured data solution

Thank you!

QUESTIONS ?