Shape Sensing for Wings with Spars and Ribs using Simulated Strain

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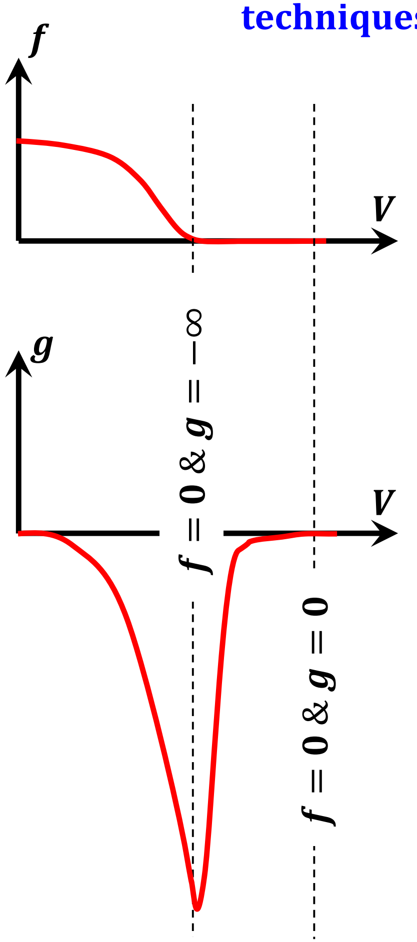
Active Shape Control

- NASA Helios fuel cell aircraft (2004)
  - Had an over-damped response to external loads before mishap
    - Recommendation 11: develop a method to **measure wing dihedral in real-time** with a visual display available to the test crew.
    - Recommendation 12: **develop manual and/or automatic techniques to control wing dihedral in flight.**



- NASA Low Boom Flight Demonstration aircraft (2021)
  - Minimize trim shape error: use "Jig shape optimization"
    - The major issue with this jig shape optimization is that the updated jig shape is optimum **only at the design flight condition**.
    - To overcome this limitation, **an active trim shape control technique can be used to minimize error between the target and the actual trim shapes during flight.**

Aircraft Shape Sensing from Strain Data

- **Tessler and Spangler: 2003**
  - Inverse finite element method
    - Create simplified **3D structural** model
    - Need a finite element model
    - Use numerical optimization technique to minimize strain error at strain gage locations
    - **Off-line method**
  - Tessler, A., and Spangler, J., "A Variational Principle for Reconstruction of Elastic Deformations in Shear Deformable Plates and Shells," NASA Langley Research Center TM-212445, Hampton, Virginia, 2003.
- **Ko: 2007**
  - Use closed-form equation for deformation computation
    - Deformation along a line is available during flight; **On-line method**
    - Don't need a finite element model
    - **Pitch slope is not available**.
  - Ko, W. L., Richards, W. L., and Tran, V. T., "Displacement Theories for In-Flight Deformed Shape Predictions of Aerospace Structures," NASA TP-2007-214612, 2007.
- **Pak: 2016**
  - Use two-step approach; **On-line method**; **Based on 3D structure**
    - Step 1: deformation along a line (don't need a finite element model)
    - Step 2: expand deformation along the sensor lines to a 3D structure (Need a finite element model)
  - Deformation sensing
    - Pak, C.-g., "Wing Shape Sensing from Measured Strain," *AIAA Journal*, Vol. 54, No. 3, 2016, pp. 1068–1077.
  - Velocity, Acceleration, and Load sensing
    - Pak, C.-g., "Unsteady Aerodynamic Force Sensing from Strain Data," *Journal of Aircraft*, Vol. 54, No. 4, 2017, pp. 1476–1485.

Definition of Curvature κ

- Upper strain due to pure bending
  - $\epsilon_u - x = \epsilon_u - \frac{\epsilon_u+\epsilon_l}{2} = \frac{\epsilon_u-\epsilon_l}{2}$
  - $\kappa = -\frac{(\epsilon_u-\epsilon_l)/2}{h/2} = -\frac{\epsilon_u-\epsilon_l}{h}$
- Lower strain due to pure bending
  - $\epsilon_l - x = \epsilon_l - \frac{\epsilon_u+\epsilon_l}{2} = -\frac{\epsilon_u-\epsilon_l}{2}$

$$\epsilon_u - x = -(\epsilon_l - x)$$

$$\epsilon_u - x = x - \epsilon_l$$

$$2x = \epsilon_u + \epsilon_l$$

$x = \frac{\epsilon_u+\epsilon_l}{2}$: Strain due to in-plane loading

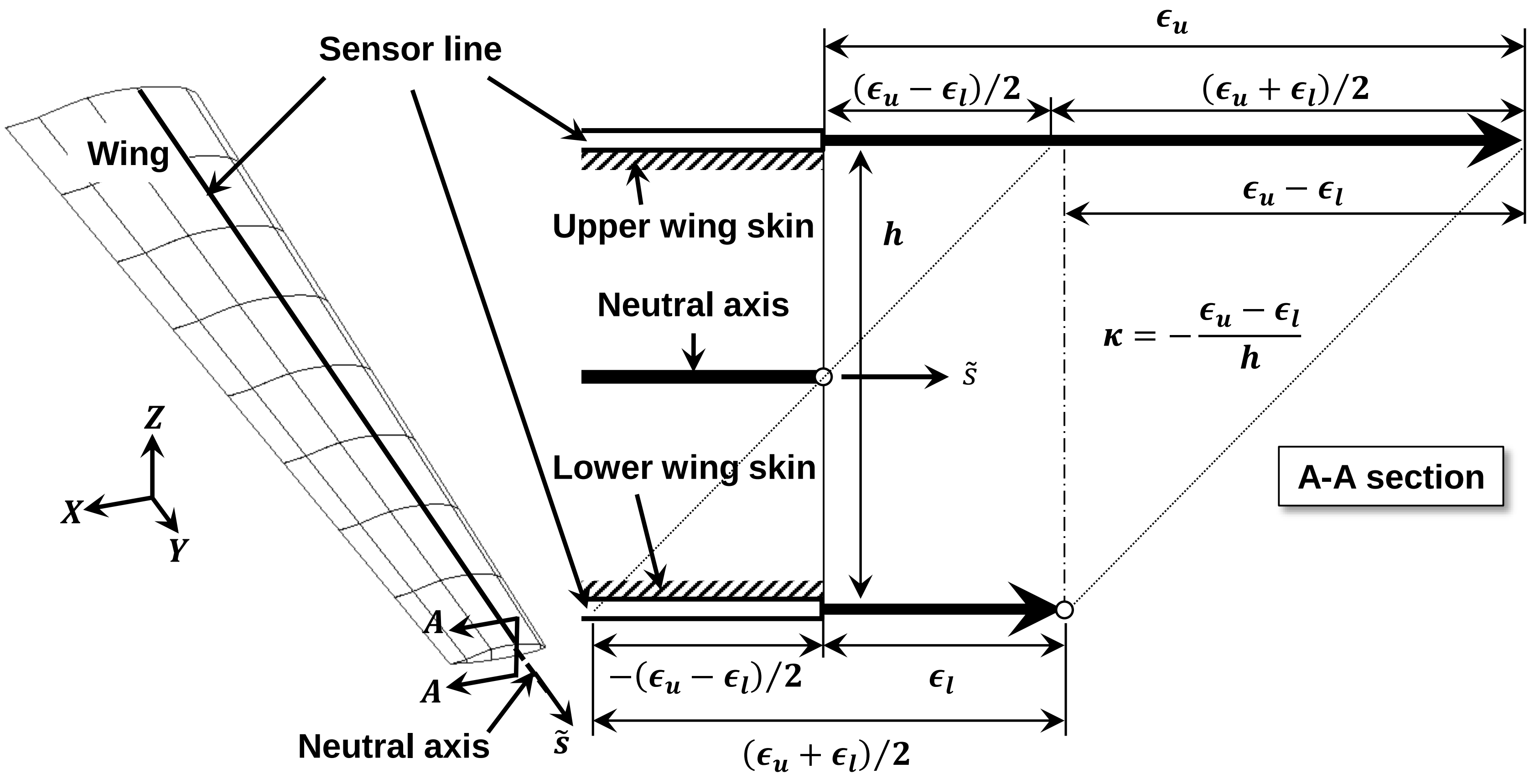
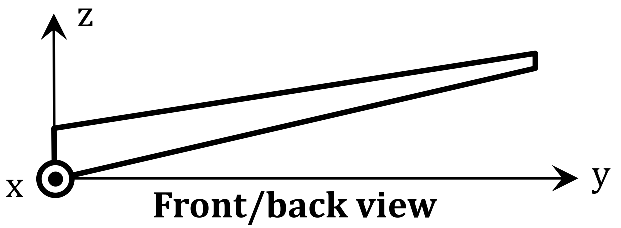


Fig. 1

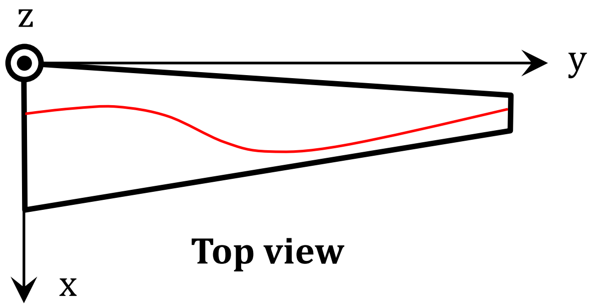
Definition of coordinate systems for deformation computations

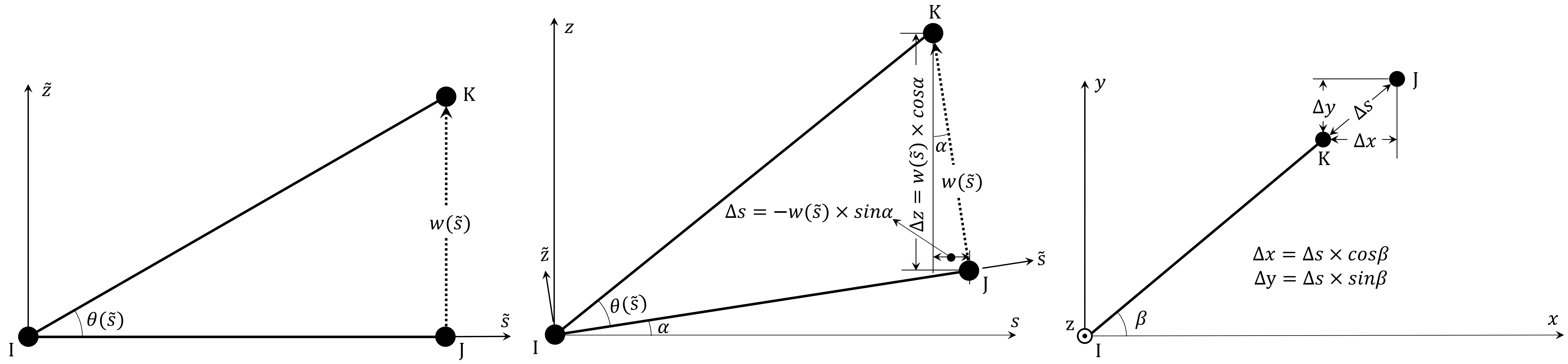
- Each fiber element
- Axial strain
- Rotation θ($\tilde{s}$) and translation w($\tilde{s}$) in “Fiber coordinate”
  - Use linear assumption
  - θ($\tilde{s}$) : integrate curvature with respect to $\tilde{s}$
  - w($\tilde{s}$): integrate θ($\tilde{s}$) with respect to $\tilde{s}$

- Effect of dihedral/anhedral and/or taper, α



- Curved fiber element, β





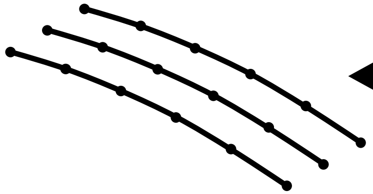
(a) Fiber coordinate ($\tilde{s}$,$\tilde{z}$) **(b) Local coordinate (s,z)** **(c) Global coordinate (x, y, z)**

Fig. 2

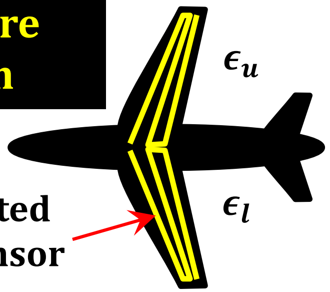
Mathematical Background of the Two-step Theory

Compute curvature along sensor lines

$$\kappa(s) \equiv -\frac{(\epsilon_u - \epsilon_l)/2}{h/2} = -\frac{\epsilon_u(s) - \epsilon_l(s)}{h(s)}$$



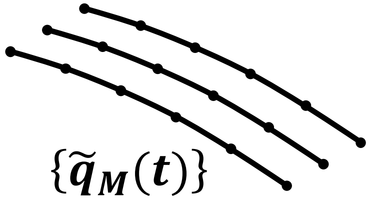
Measure strain



Step 1: Compute wing deflection along sensor lines

Curvature → Rotation → Translation

$$\frac{d^2w(s)}{ds^2} = \kappa(s) \qquad \frac{dw(s)}{ds} \qquad w(s)$$

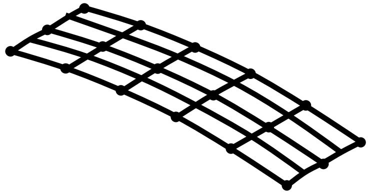


$\{\tilde{q}_M(t)\}$

Model independent

Step 2: Expand wing deflection

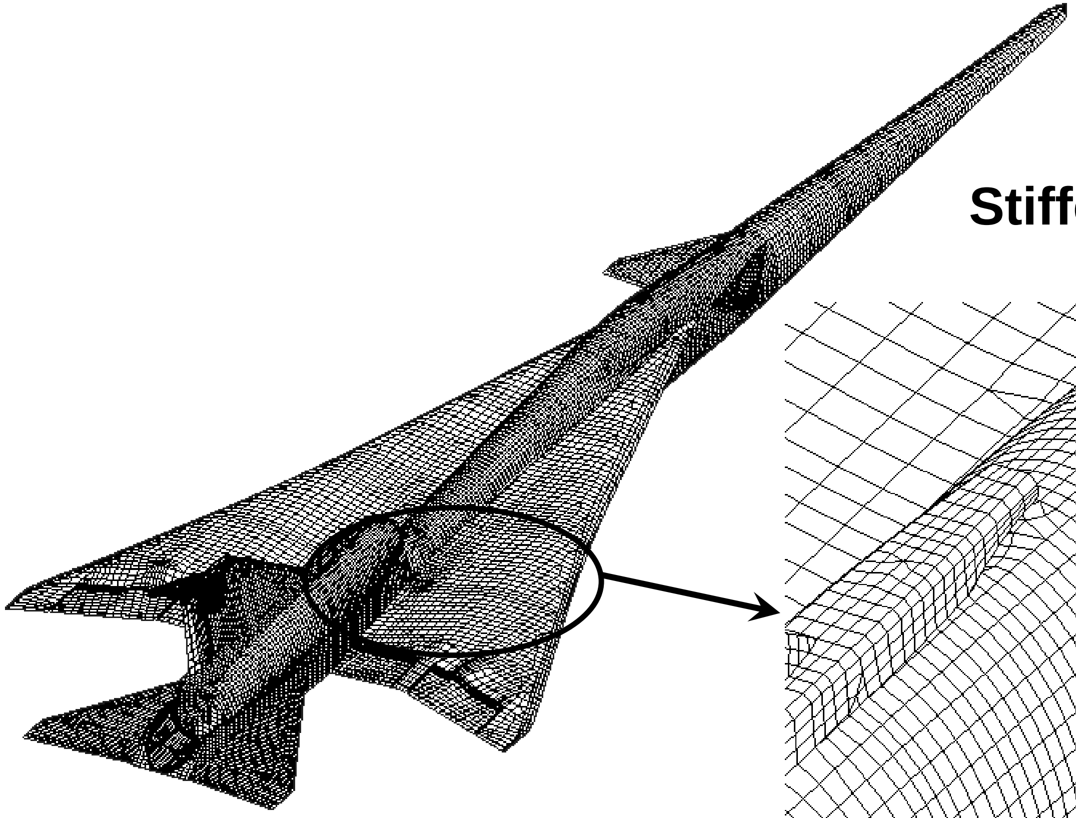
$$\begin{Bmatrix} q_M(t) \\ q_S(t) \end{Bmatrix} = [T]\{\tilde{q}_M(t)\}$$

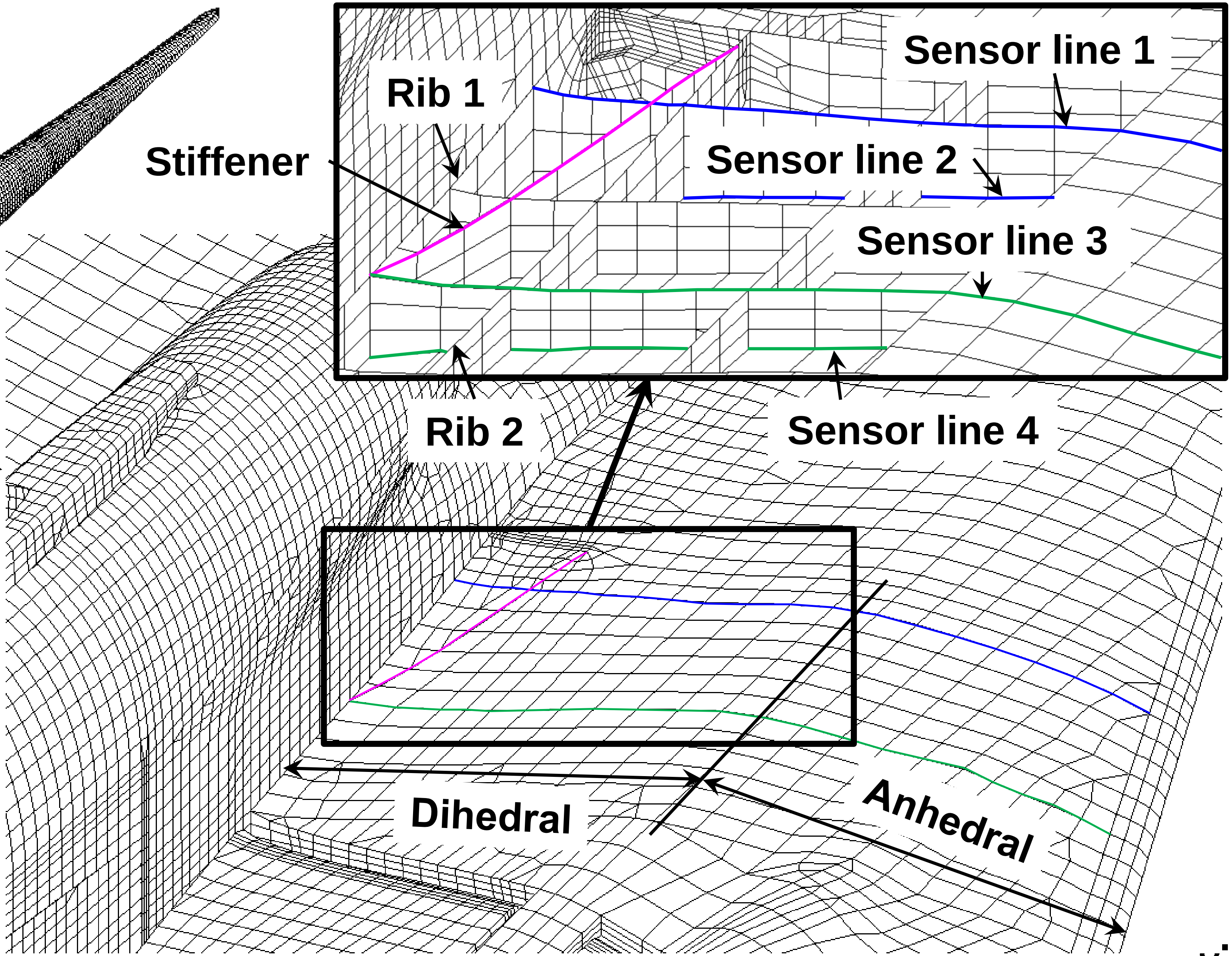


Model dependent

Low-Boom Flight Demonstration aircraft

C607 Wing


C607 Model


Stiffener
Rib 1
Sensor line 1
Sensor line 2
Sensor line 3
Rib 2
Sensor line 4
Dihedral
Anhedral

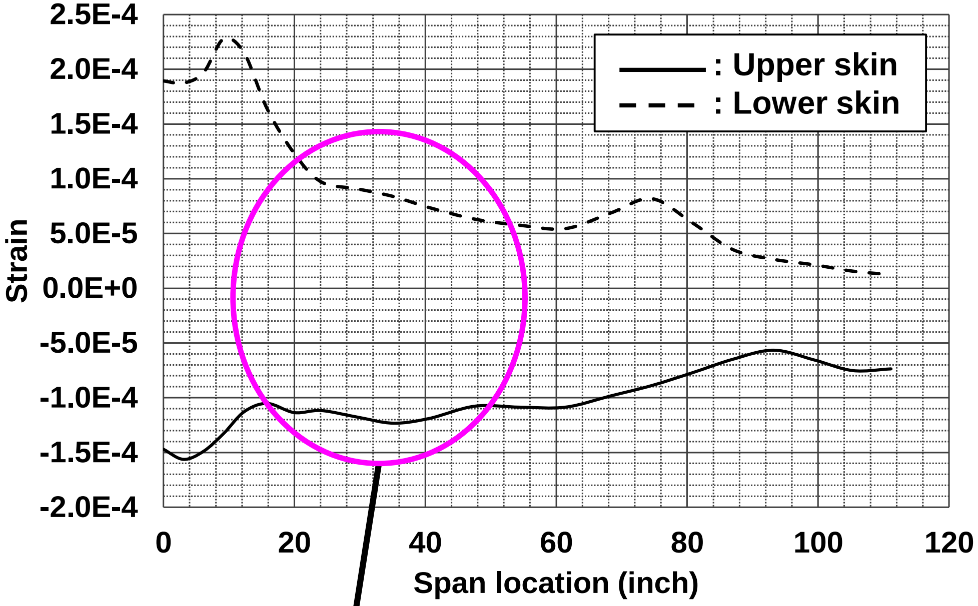
Strain, curvature, & deformation

- ❑ Trim load under Mach 1.42 flight condition.
- ❑ Differences at wing tip
  - ❖ Slope: **-11.2%**
  - ❖ Deflection: **-19.8%**
- ❑ Issue
  - ❖ Curvature definition
    - ➢ Looks **fine**

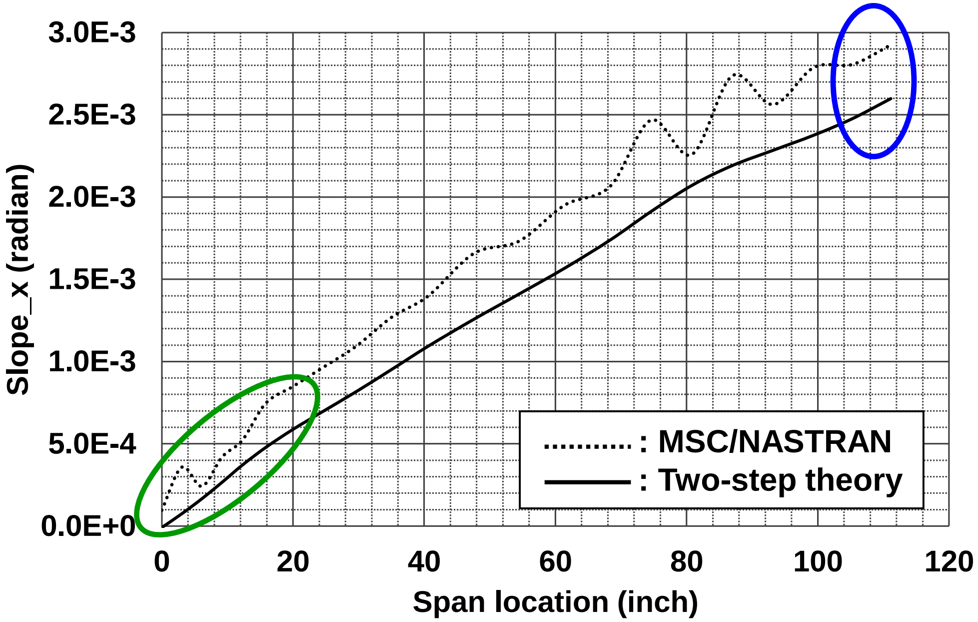
$$\boldsymbol{\kappa} = -\frac{\epsilon_u - \epsilon_l}{h}$$

  - ❖ FE structural model
    - ➢ NASTRAN **slope??** near wing root

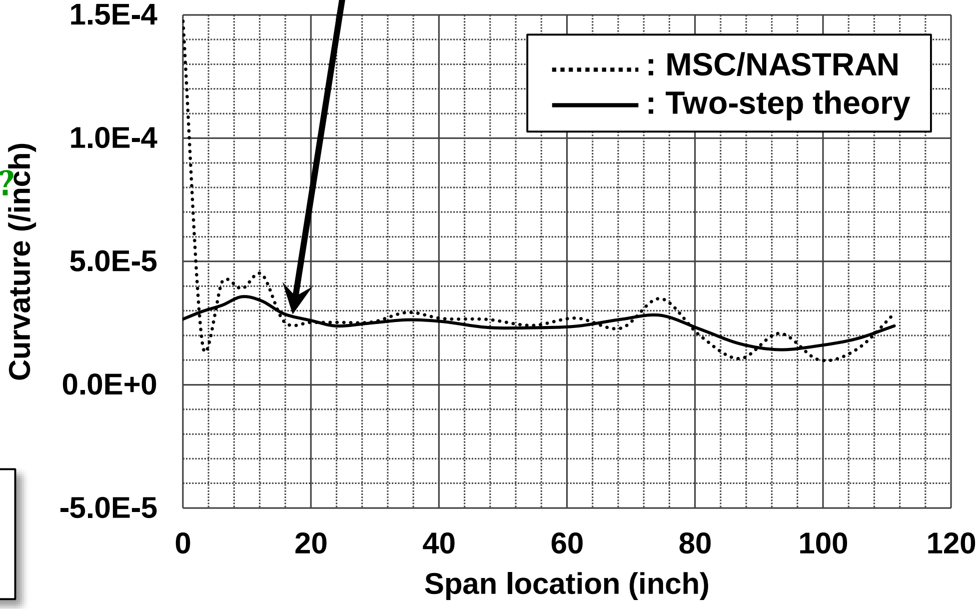
LBFD aircraft using sensor lines 1 & 2 data



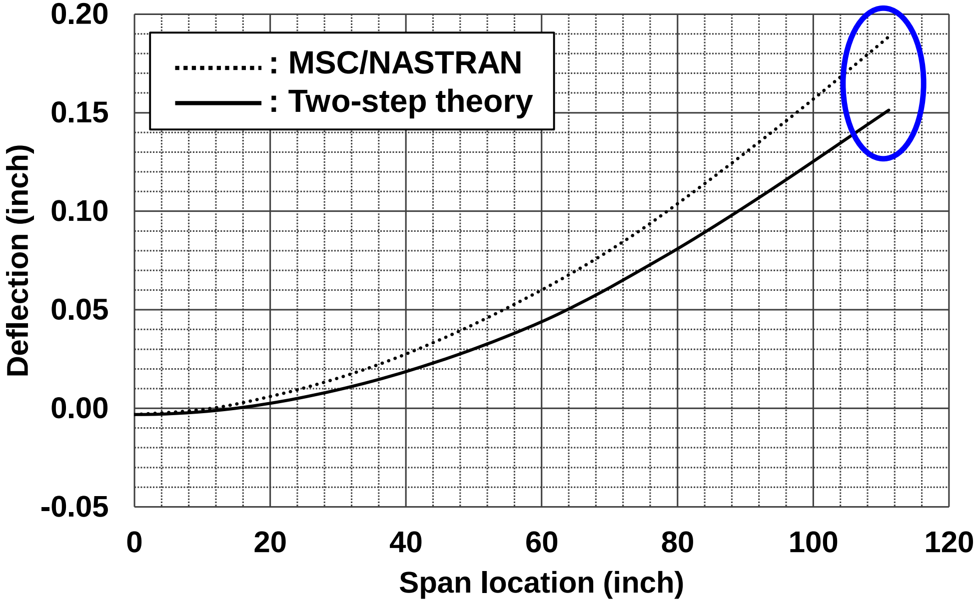
(a) Strain on the upper and lower skin



(c) Slope in roll direction



(b) Curvature

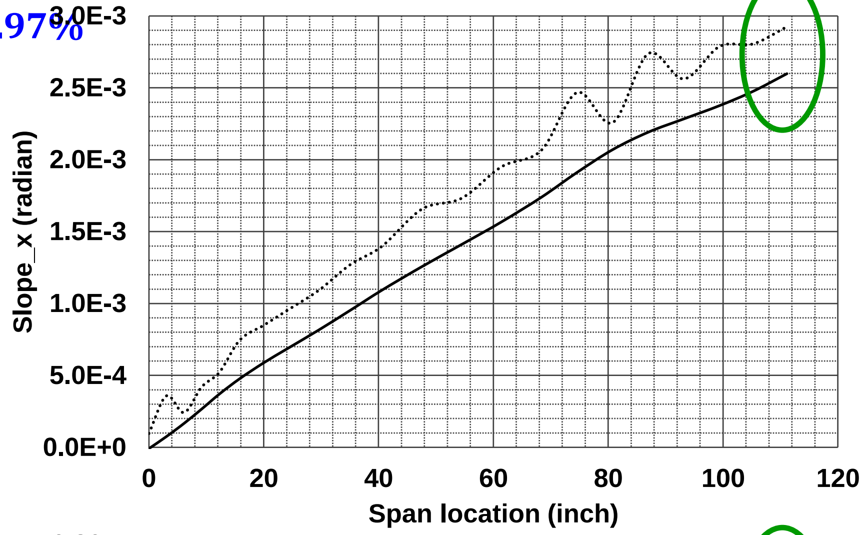


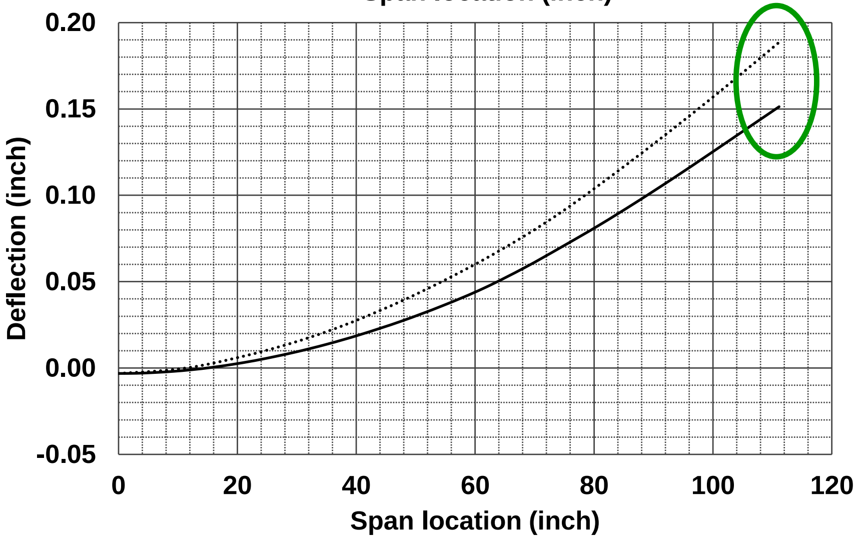
(d) Deflection

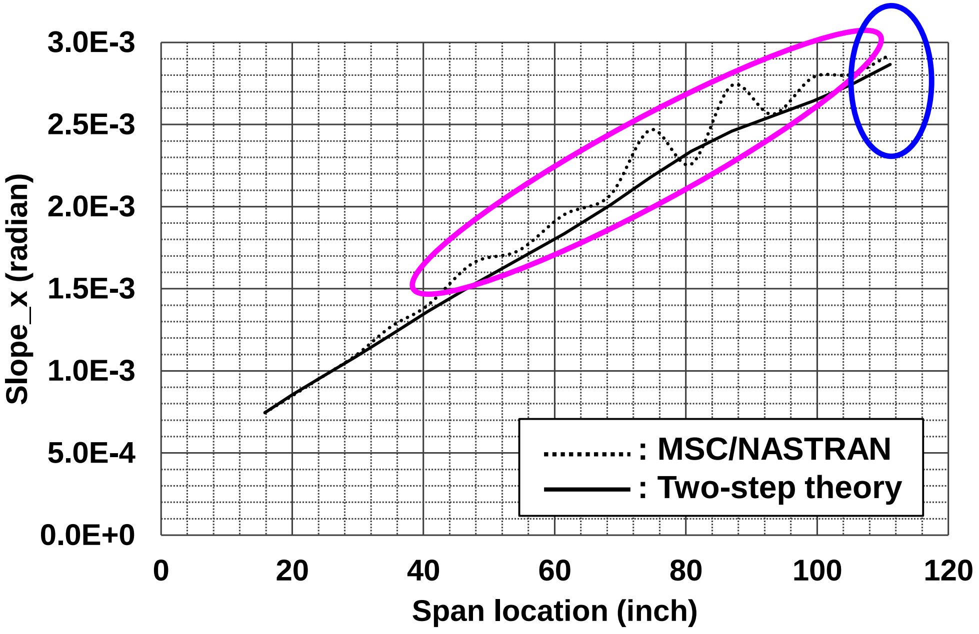
Fig. 4

Deformation of LBFD aircraft integrated from 18 inch using sensor lines 1 & 2 data

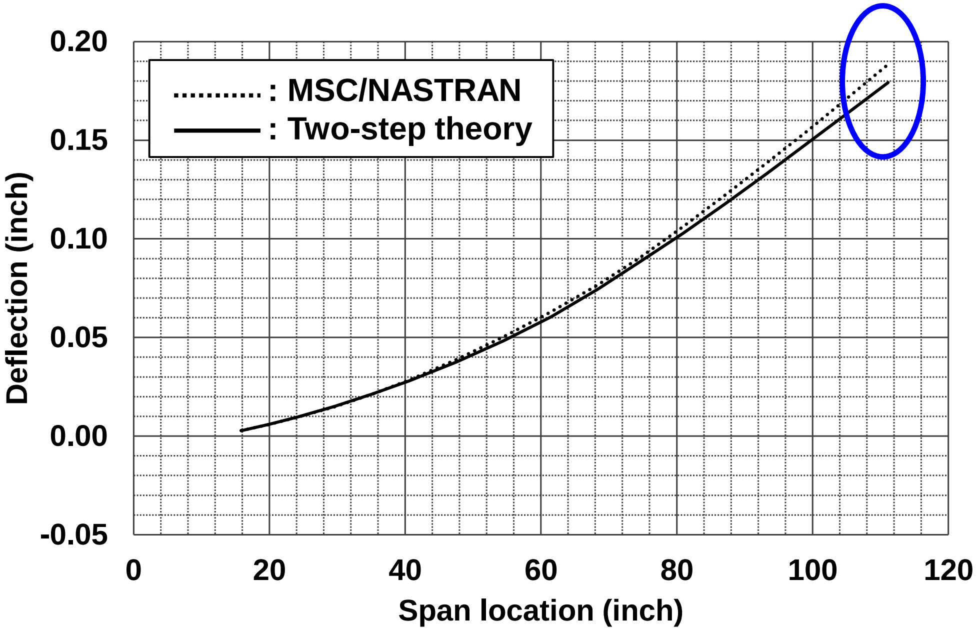
- Don’t include wing root to 18 inch
- Differences at wing tip
  - Slope: -11.2% ---> -2.02%
  - Deflection: -19.8% ---> -4.97%
- Issue
  - Curvature definition
  - FE structural model
    - NASTRAN slope







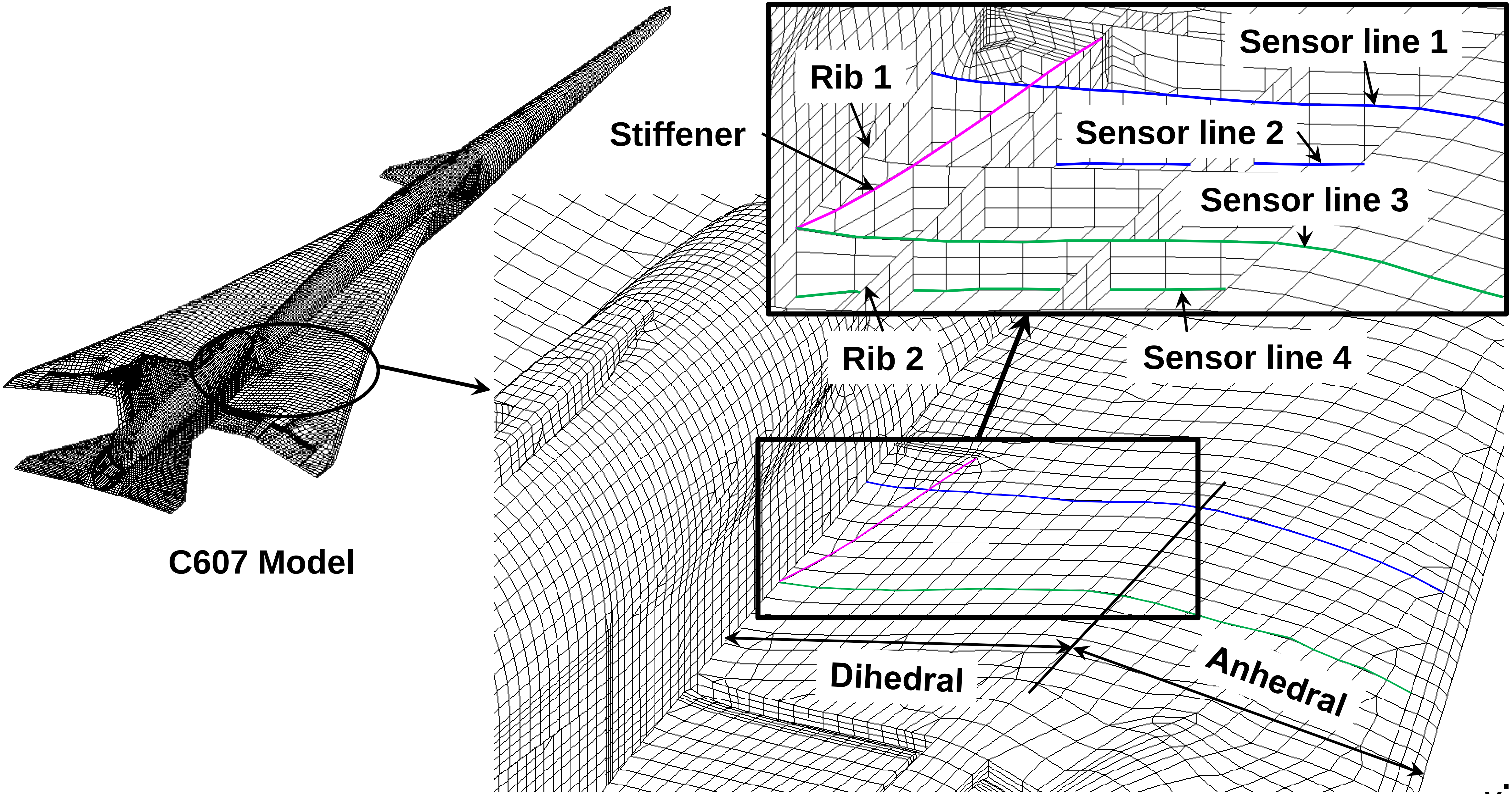
(a) Slope in roll direction



(b) Deflection

Fig. 5

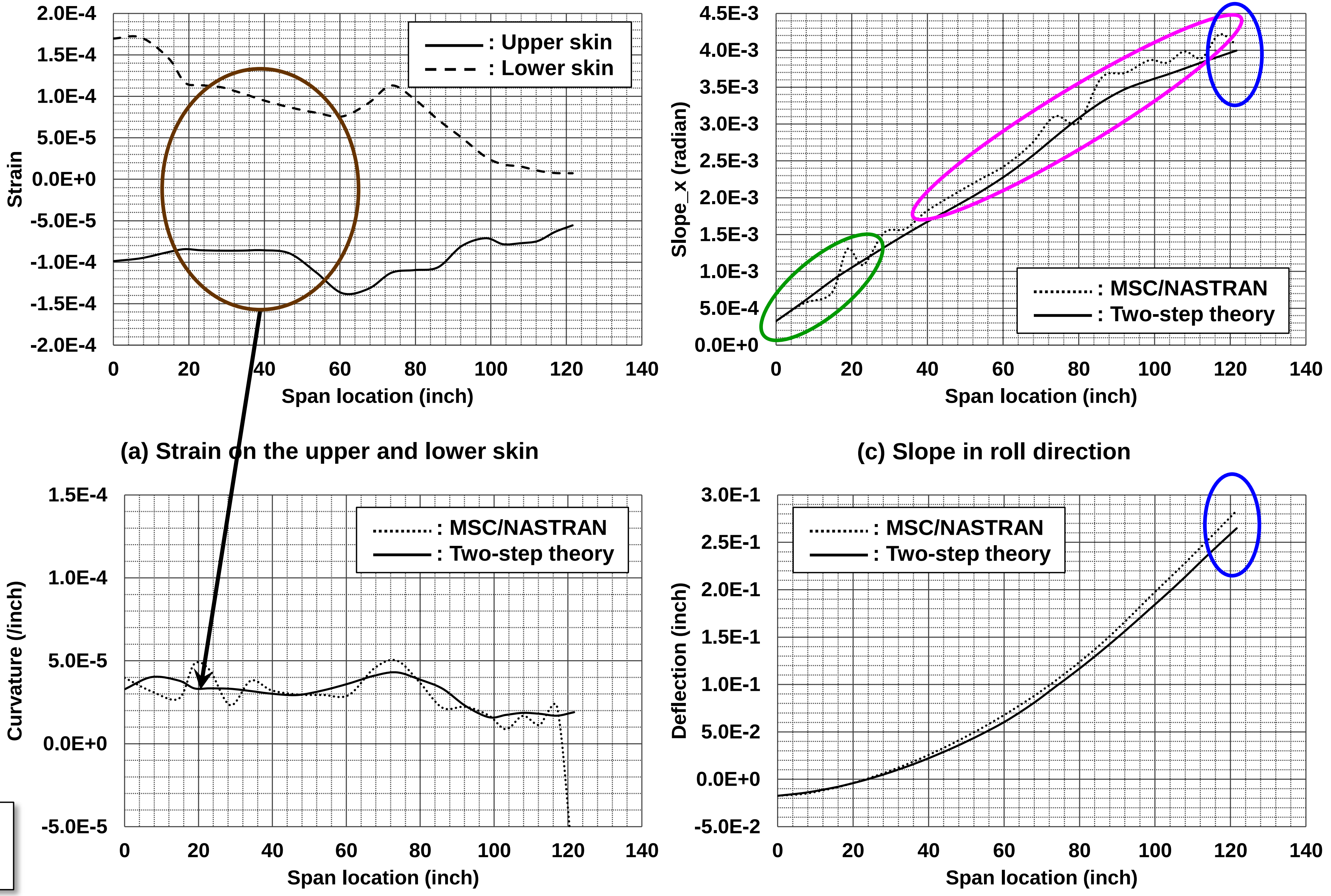
C607 Wing


C607 Model
Stiffener
Rib 1
Sensor line 1
Sensor line 2
Sensor line 3
Rib 2
Sensor line 4
Dihedral
Anhedral

Strain, curvature, & deformation

- ❑ NASTRAN slope near wing root area becomes better
  - ❖ Stiffening structure effect??
- ❑ Differences at wing tip
  - ❖ Slope: **-1.91%**
  - ❖ Deflection: **-6.63%**
- ❑ Issue
  - ❖ Curvature definition
    - ➢ Looks **fine**
  - ❖ FE structural model
    - ➢ NASTRAN **slope**

LBFD aircraft using sensor lines 3 & 4 data



(a) Strain on the upper and lower skin

(c) Slope in roll direction

(b) Curvature

(d) Deflection

Fig. 6

Tapered Wing

Tapered wing with coarse and fine meshes

- ❑ Aluminum
- ❑ Eight ribs
  - ❖ Every 50 inch
- ❑ Four spars
  - ❖ 4, 22, 40 58 inches from LE of wing root section
- ❑ Root chord: 70 inch
- ❑ Tip chord: 35 inch
- ❑ Half span length = 400 inch
- ❑ Results are based on sensor lines 1 and 2
- ❑ External load: 1 G loading

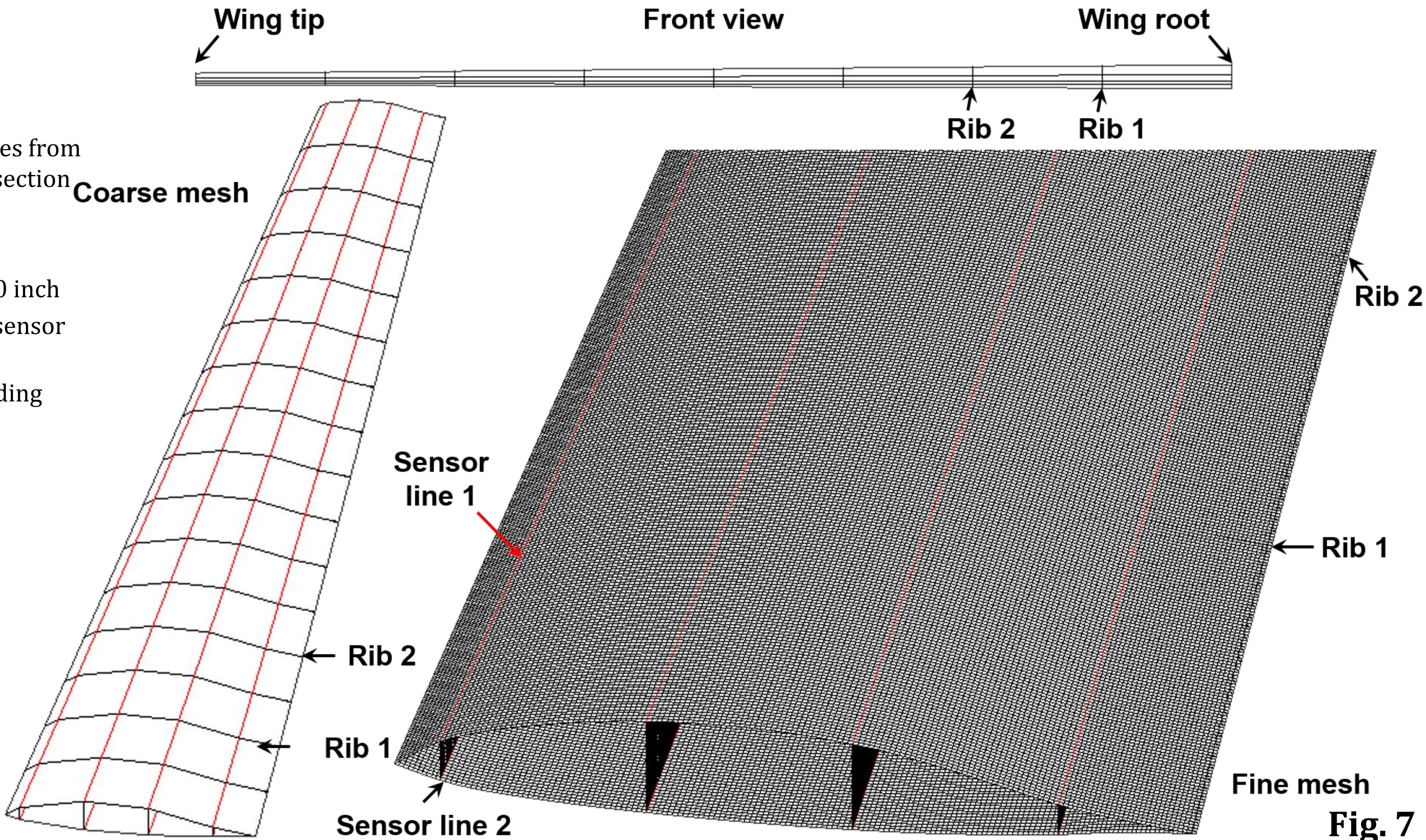
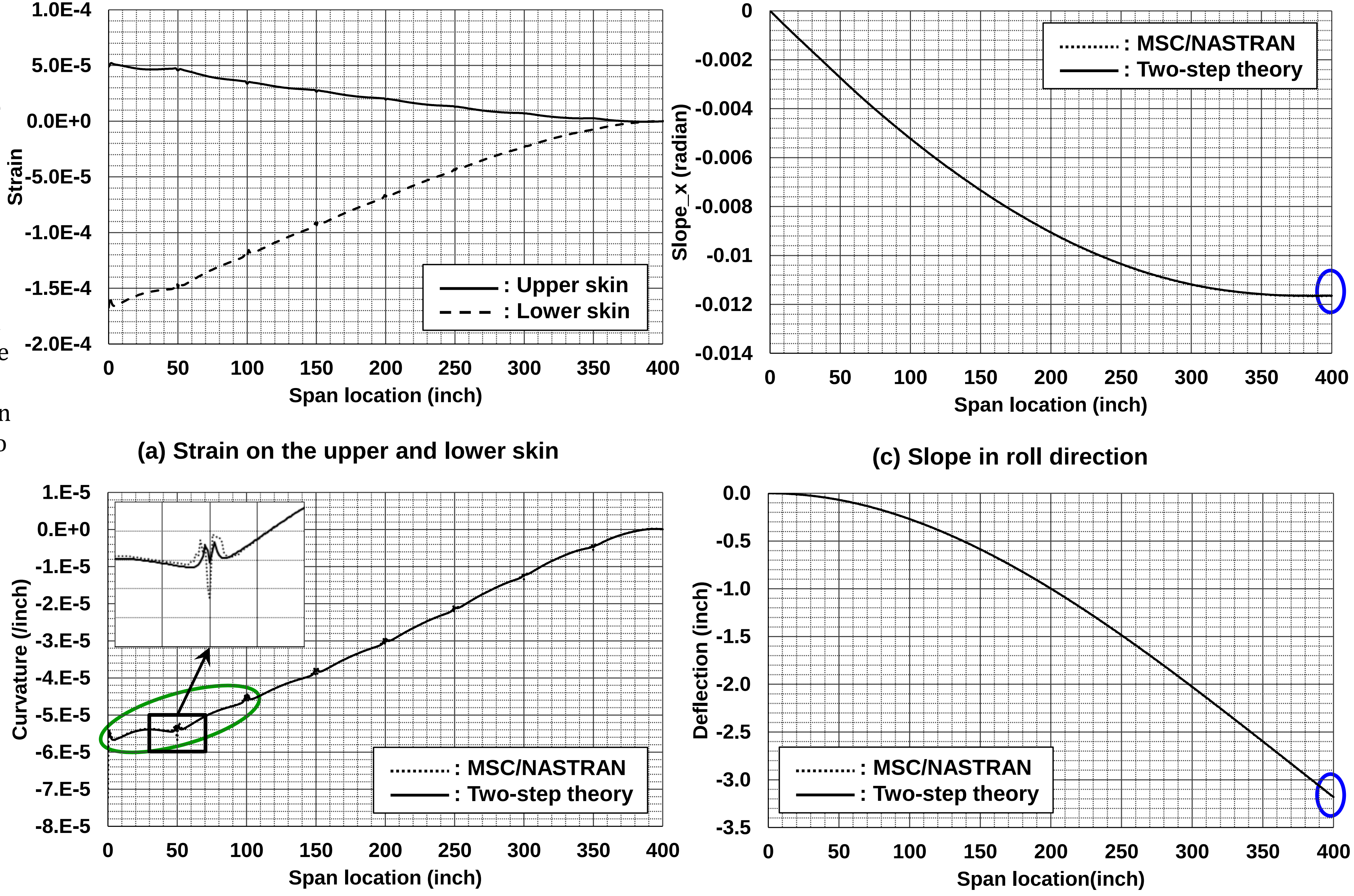


Fig. 7

Strain, curvature, & deformation

- ❑ Differences at wing tip
  - ❖ Slope: **-0.019%**
  - ❖ Deflection: **-0.046%**
- ❑ Curvatures computed from the two-step theory and the MSC/NASTRAN code are excellent matching between root chord and the first two rib.
- ❑ A fine FE mesh gives excellent results

Tapered wing with fine mesh



(a) Strain on the upper and lower skin

(c) Slope in roll direction

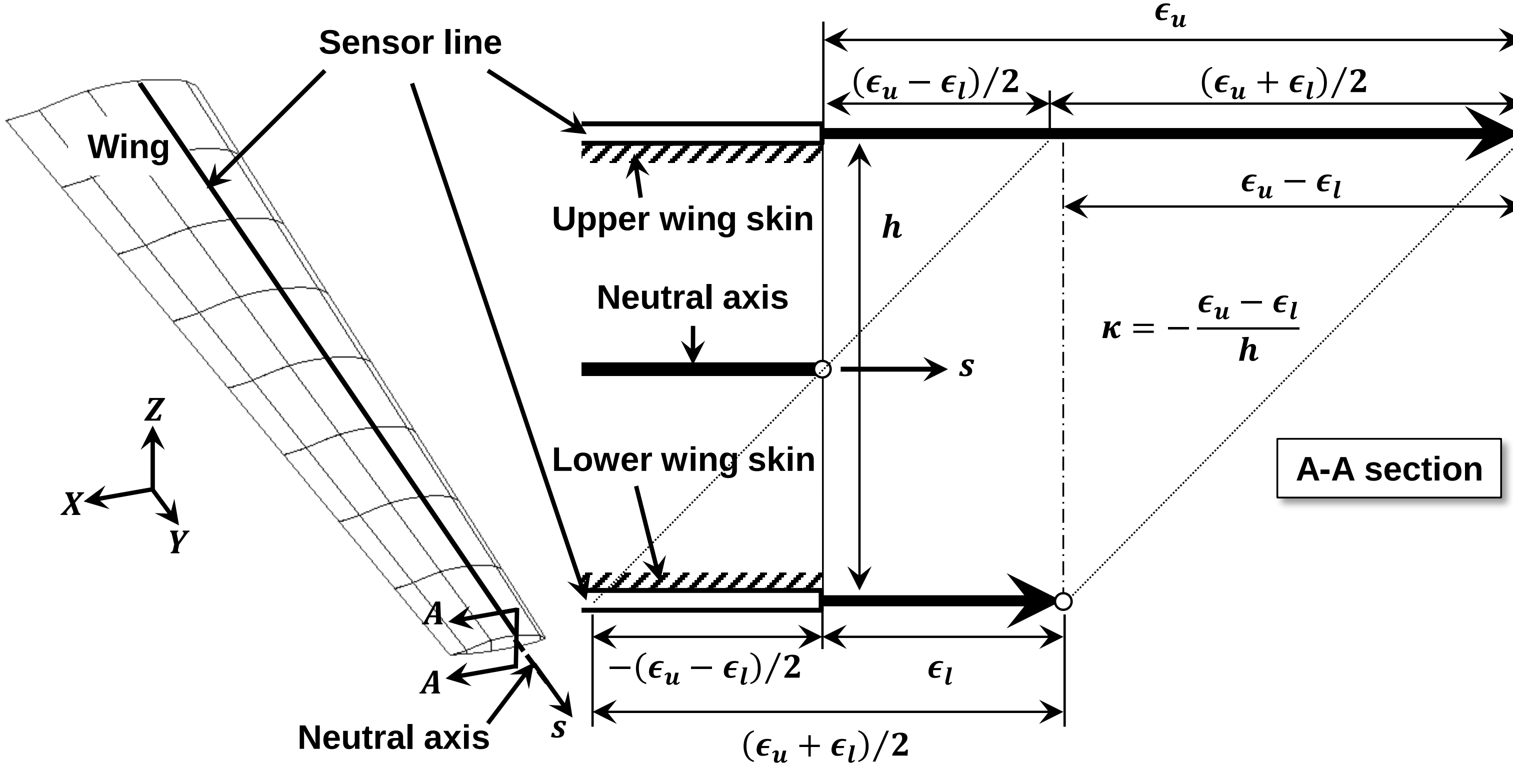
(b) Curvature

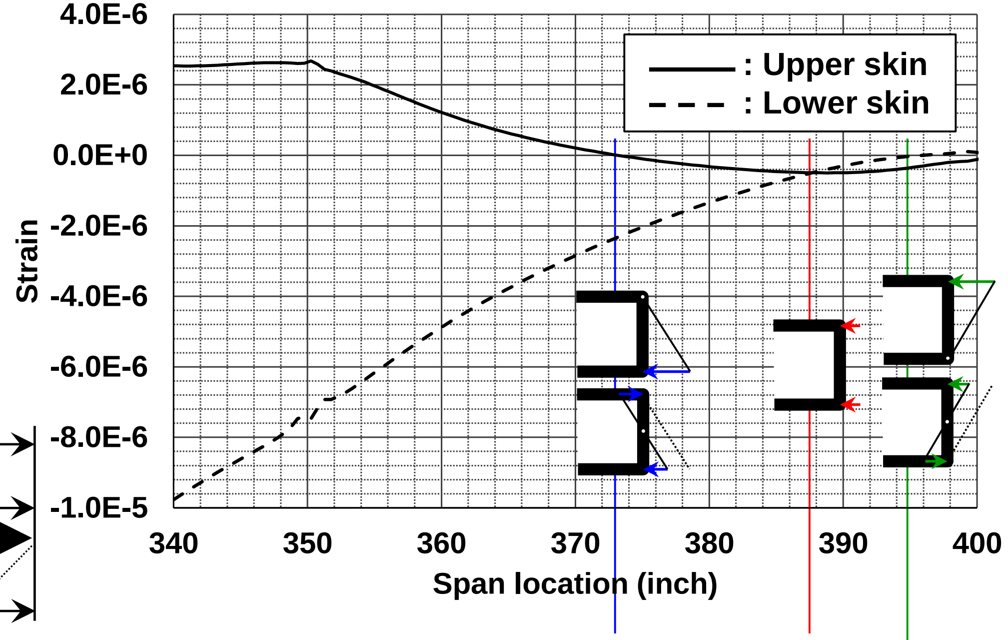
(d) Deflection

Fig. 8

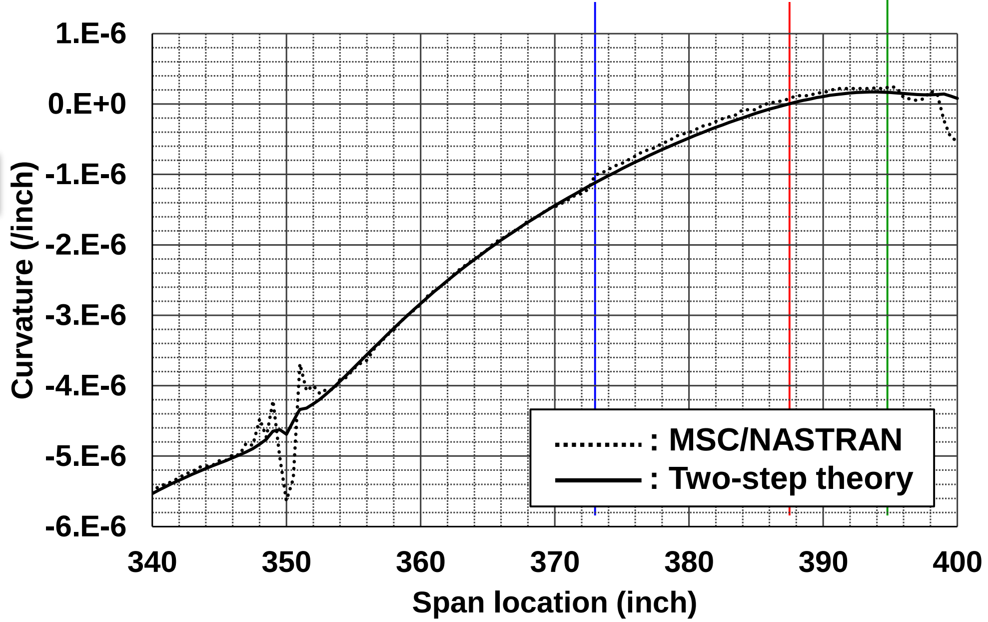
Tapered wing strain and curvature along reference line (zoom in)

- The upper and lower strains between span stations of 372.5 inch and 395.5 inch are both compressions.
  - Curvature definition, $\kappa = -\dfrac{\epsilon_u - \epsilon_l}{h}$, is **accurate**.





(a) Strain on the upper and lower skin

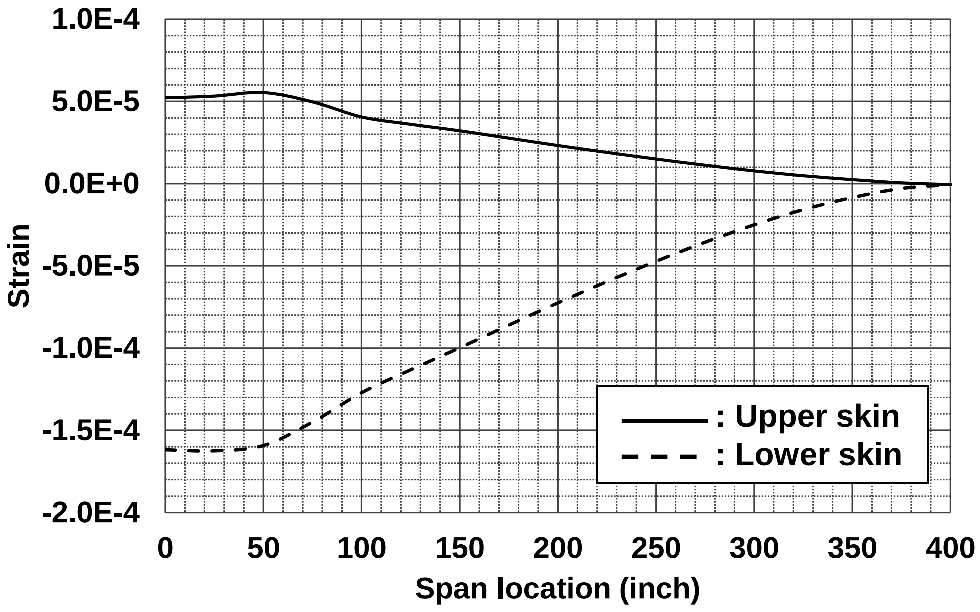


(b) Curvature

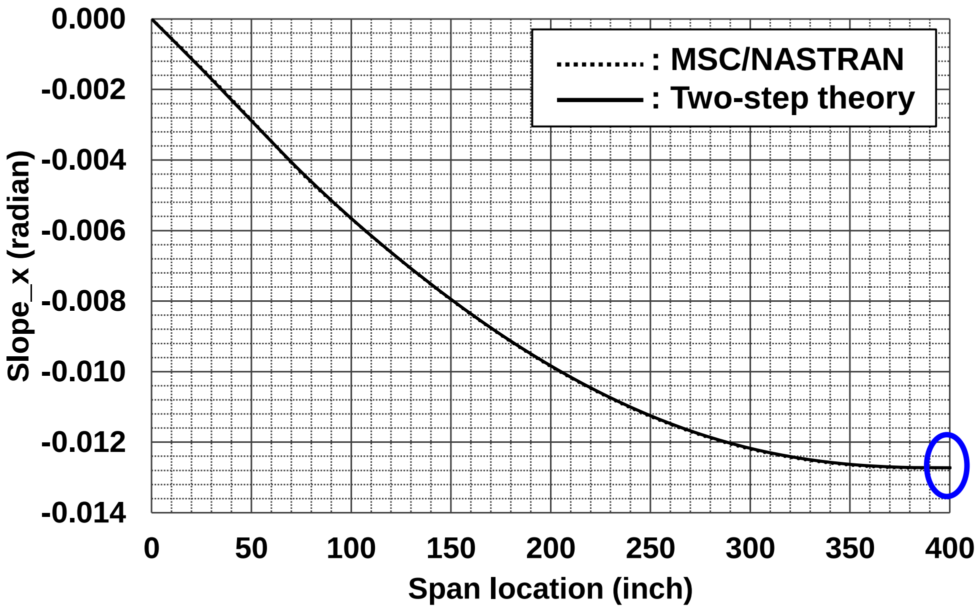
Strain, curvature, & deformation

- ❑ Differences at wing tip
  - ❖ Slope: **-0.036%**
  - ❖ Deflection: **-0.066%**
- ❑ Curvatures obtained from the two-step theory and the MSC/NASTRAN code are good matching between root chord and the first two rib.
  - ❖ Rib effect??
- ❑ A coarse FE mesh also gives excellent results. (Why??)

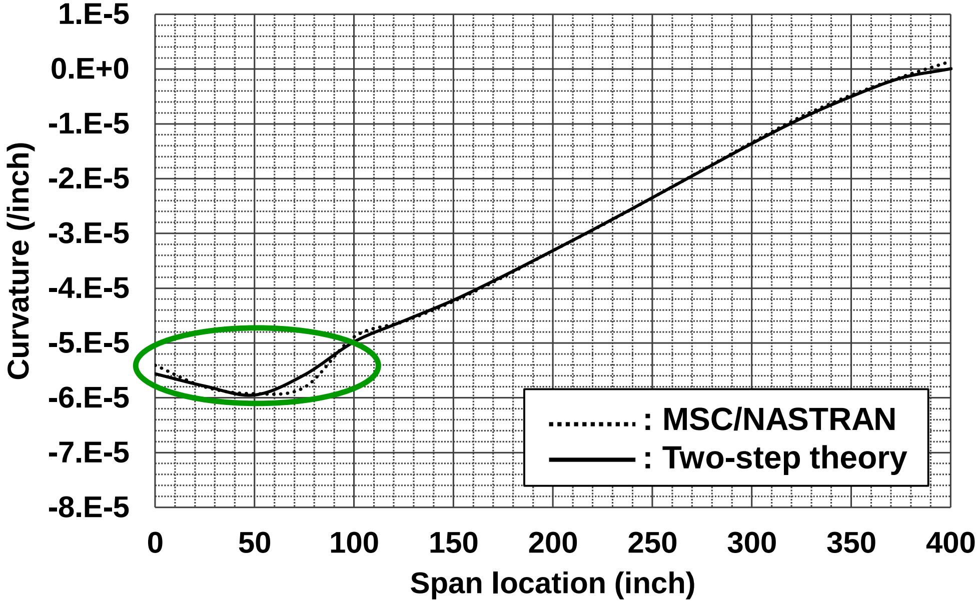
Tapered wing with coarse mesh



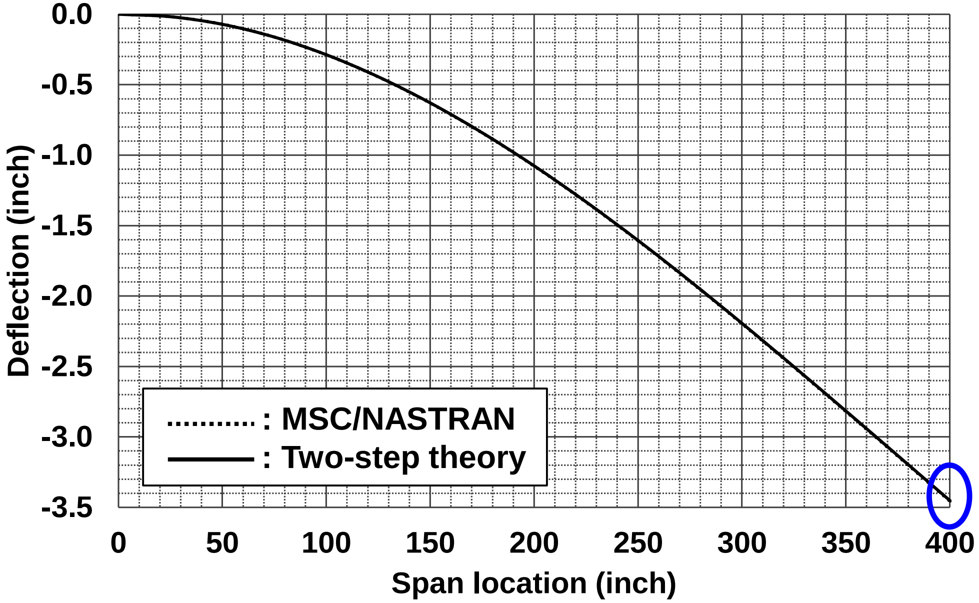
(a) Strain on the upper and lower skin



(c) Slope in roll direction



(b) Curvature



(d) Deflection

Fig. 9

Tapered Wing with Dihedral/Anhedral

Dihedral/anhedral wing with coarse and fine meshes

- ❑ Same material and properties with the tapered wing
- ❑ **Wing has "Dihedral" & "Anhedral" effects.**
  - ❖ The LBFD aircraft wing also has dihedral and anhedral effects.

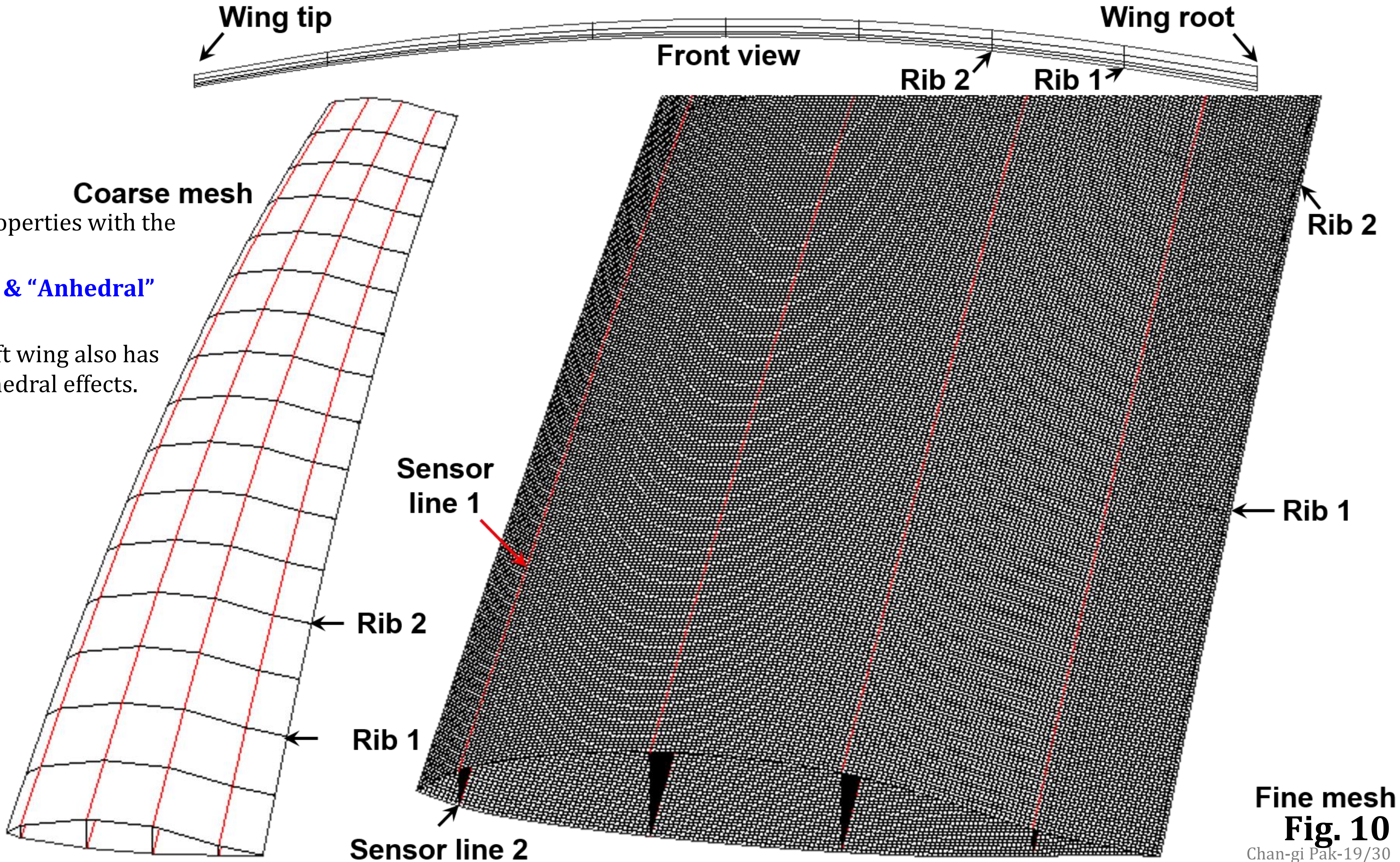
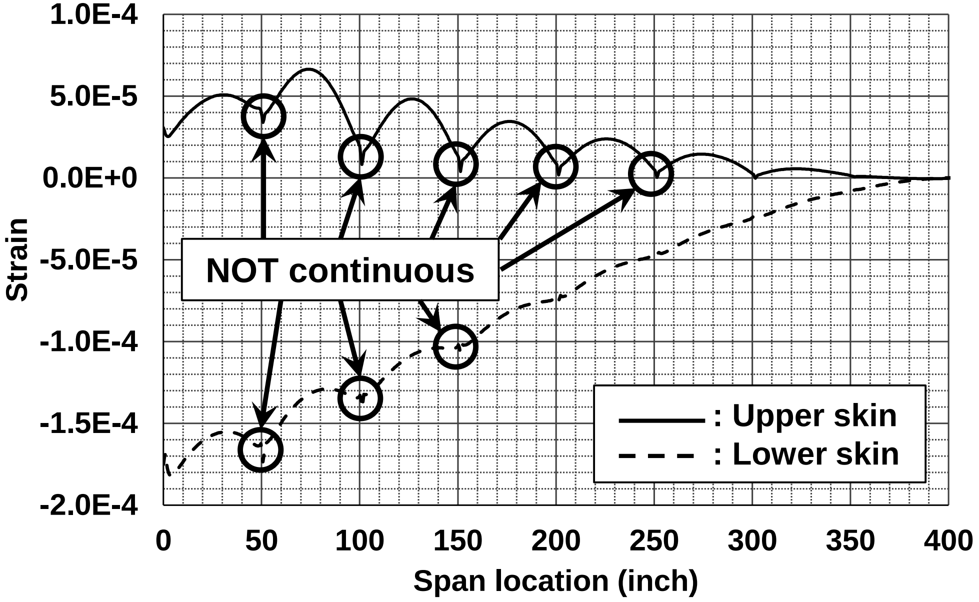


Fig. 10

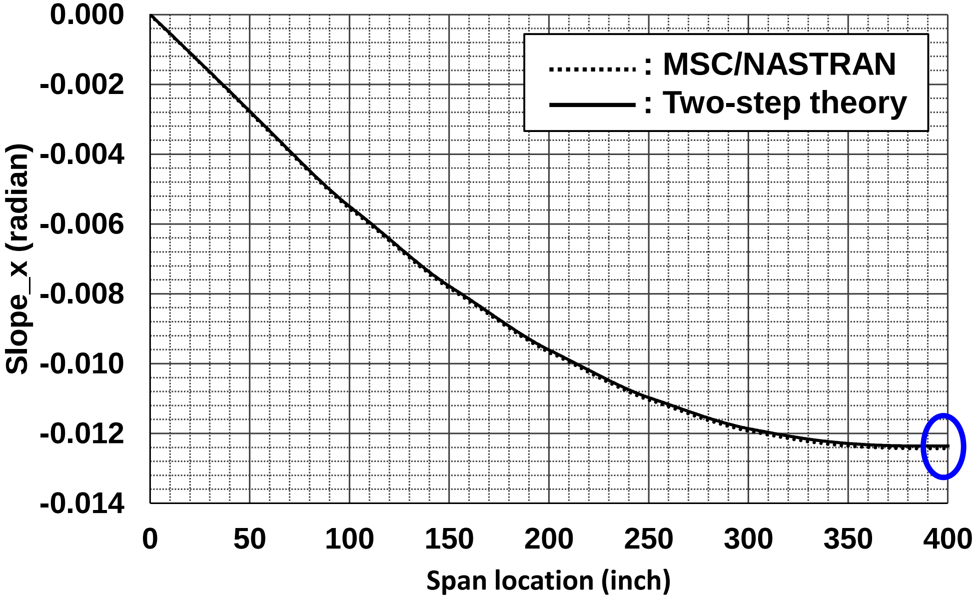
Strain, curvature, & deformation

- ❑ Differences at wing tip
  - ❖ Slope: **-0.603%**
  - ❖ Deflection: **-0.779%**
- ❑ Bigger difference than tapered wing case.
  - ❖ Strains near the rib location are not continuous.
  - ❖ Needs more fine mesh near rib location
- ❑ Curvatures from two-step theory and MSC/NASTRAN are excellent matching between root chord and the first two rib.
- ❑ A fine FE mesh gives good results

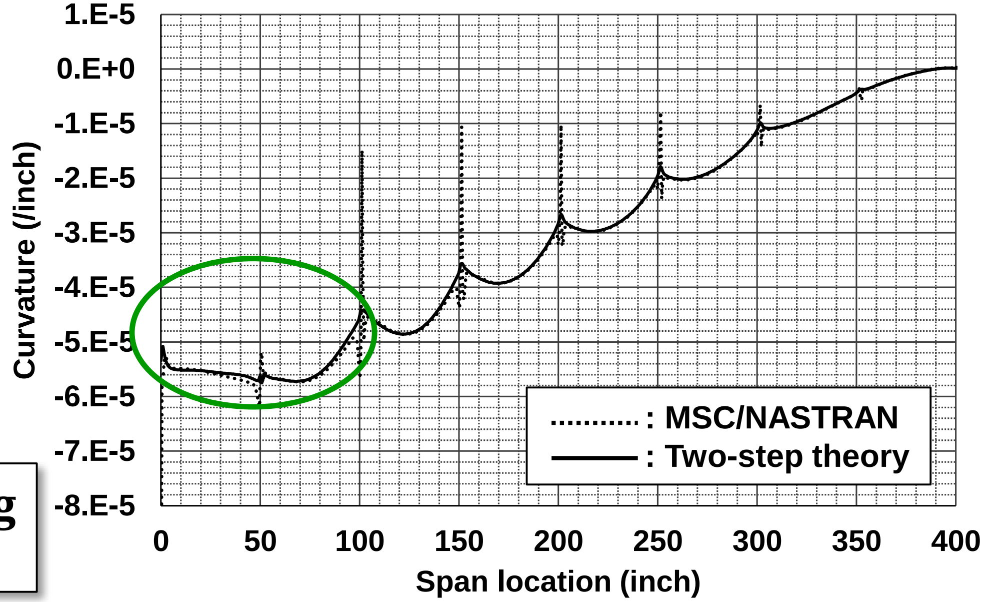
Dihedral/anhedral wing with fine mesh



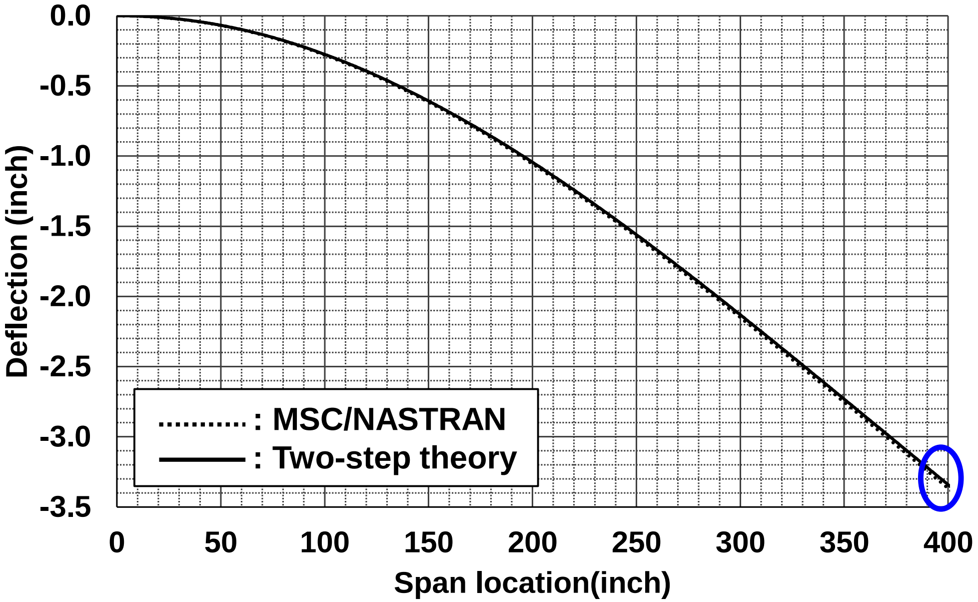
(a) Strain on the upper and lower skin



(c) Slope in roll direction



(b) Curvature



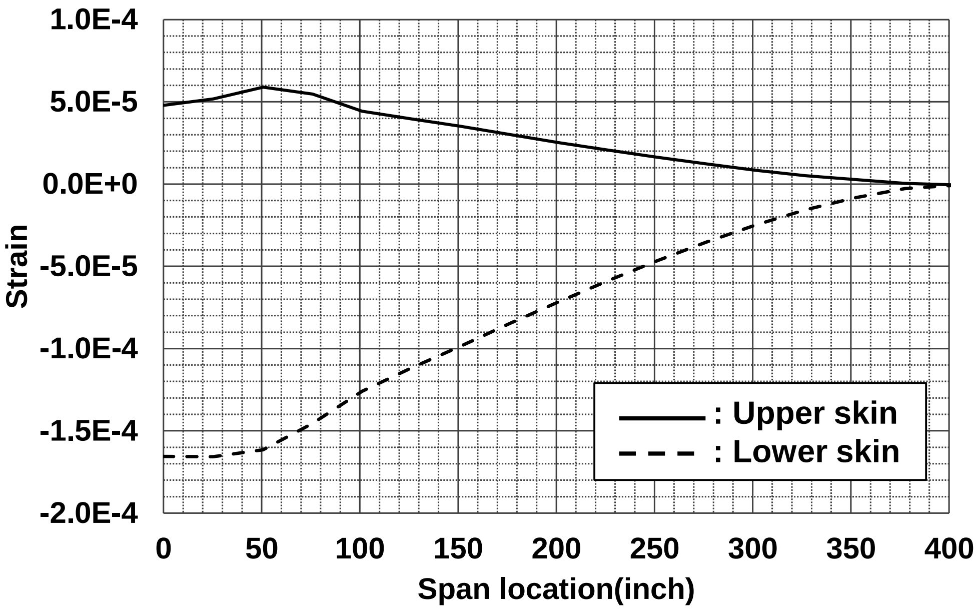
(d) Deflection

Fig. 11

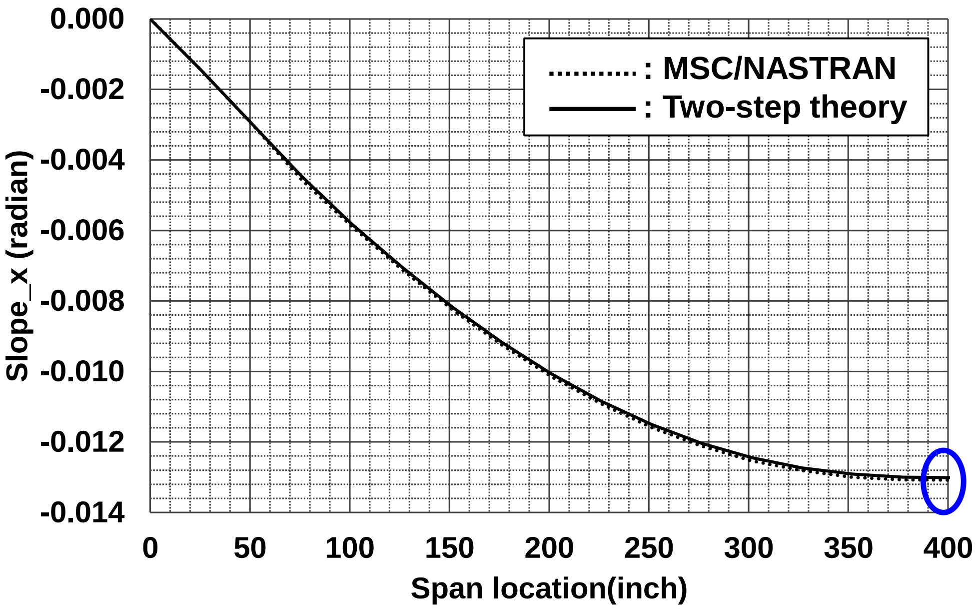
Strain, curvature, & deformation

- ❑ Differences at wing tip
  - ❖ Slope: **-0.548%**
  - ❖ Deflection: **-0.794%**
- ❑ Deflection difference is bigger than fine mesh.
- ❑ Curvatures from two-step theory and MSC/NASTRAN are good matching between root chord and the first two rib.
  - ❖ Rib effect??
- ❑ A coarse FE mesh also gives good results. (Why??)

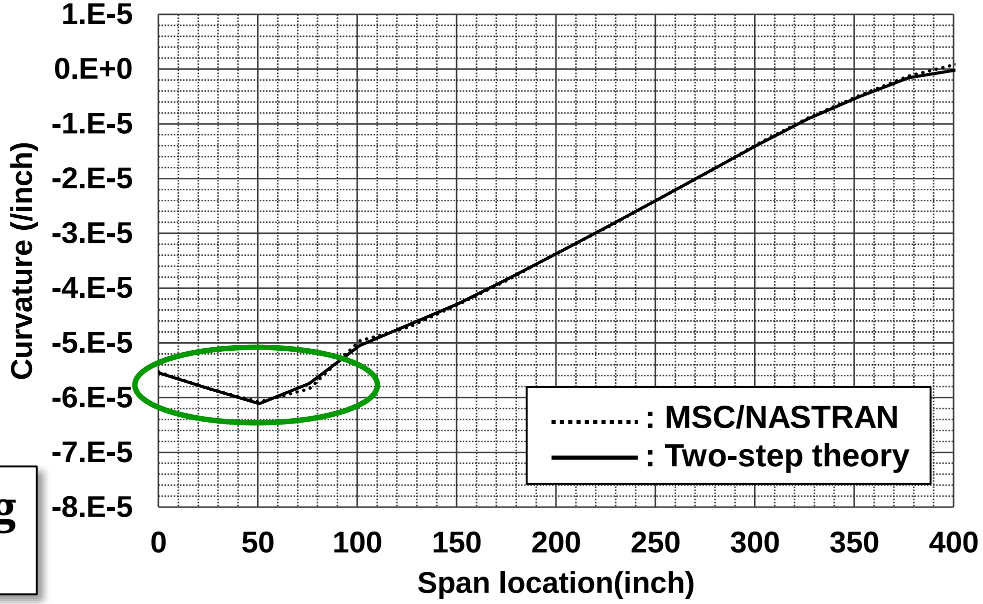
Dihedral/anhedral wing with coarse mesh



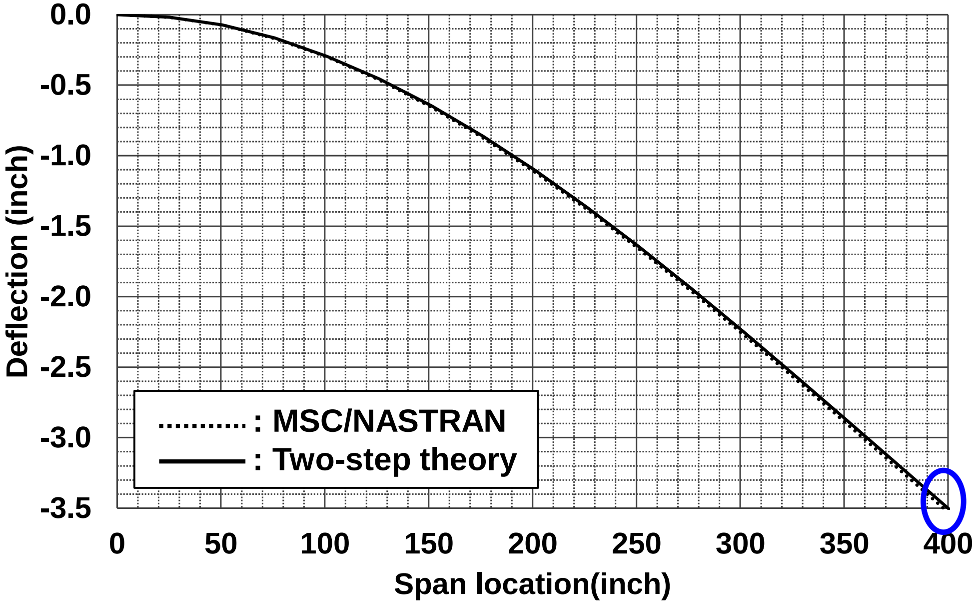
(a) Strain on the upper and lower skin



(c) Slope in roll direction



(b) Curvature

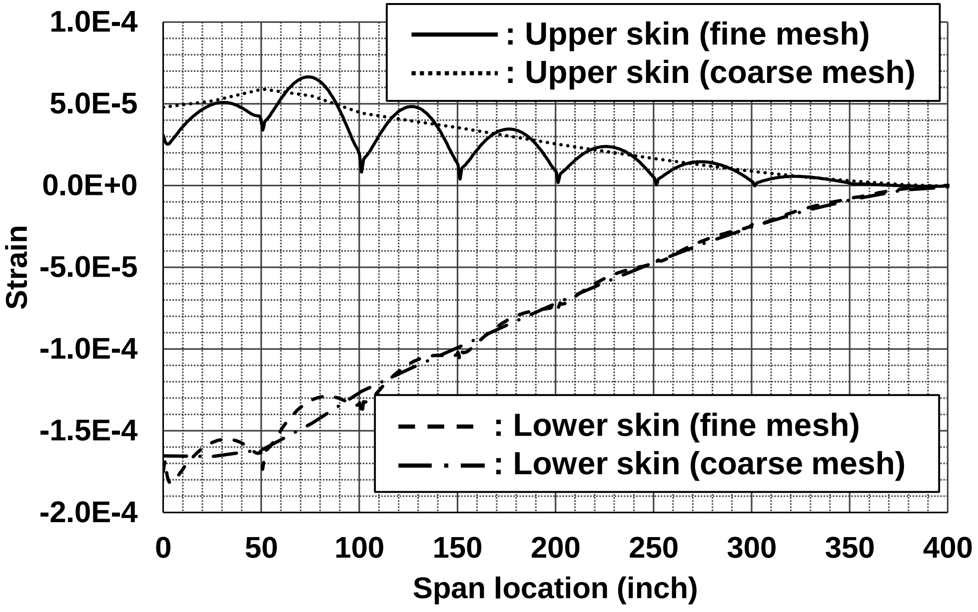


(d) Deflection

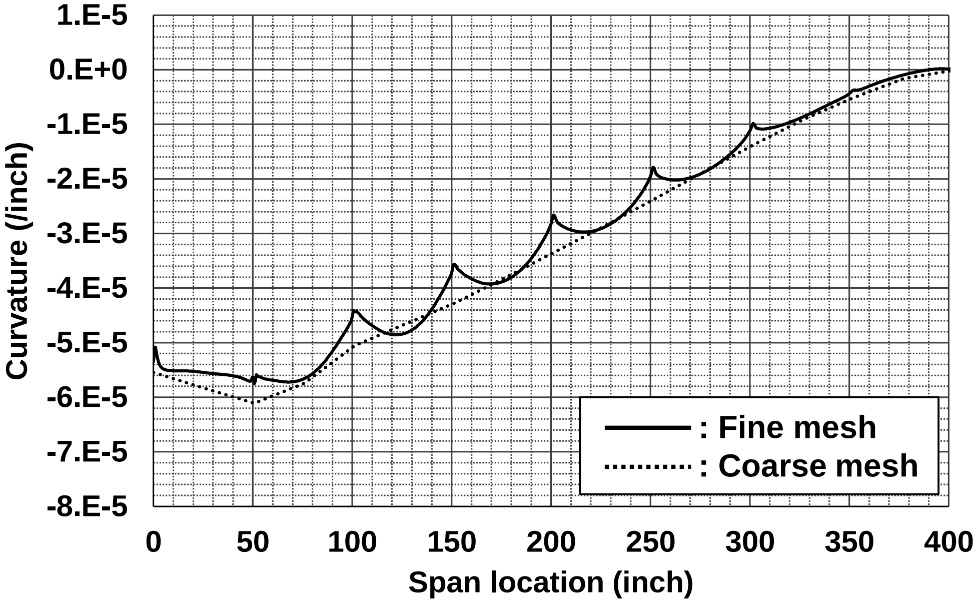
Fig. 12

Comparison of strain and curvature results using coarse and fine meshes

- Strain values from the coarse mesh are close to the average values of the strain values obtained from the fine mesh.
- Therefore, curvature values computed from the coarse and fine meshes have similar behavior.
- However, the fine mesh is needed to have accurate curvature distribution.
- In general, deformation results obtained from the coarse mesh are good. (why??)



(a) Strain on the upper and lower skin



(b) Curvature from two-step theory

Tapered Wing with Dihedral/Anhedral and Wing Root Stiffnener

Stiffened dihedral/anhedral wing with coarse, intermediate, and fine meshes

- ❑ Same material and properties with dihedral/anhedral wing
- ❑ **Investigate stiffener effect**
  - ❖ LBFD also has a stiffening structure near FOSS 1 & 2 root.

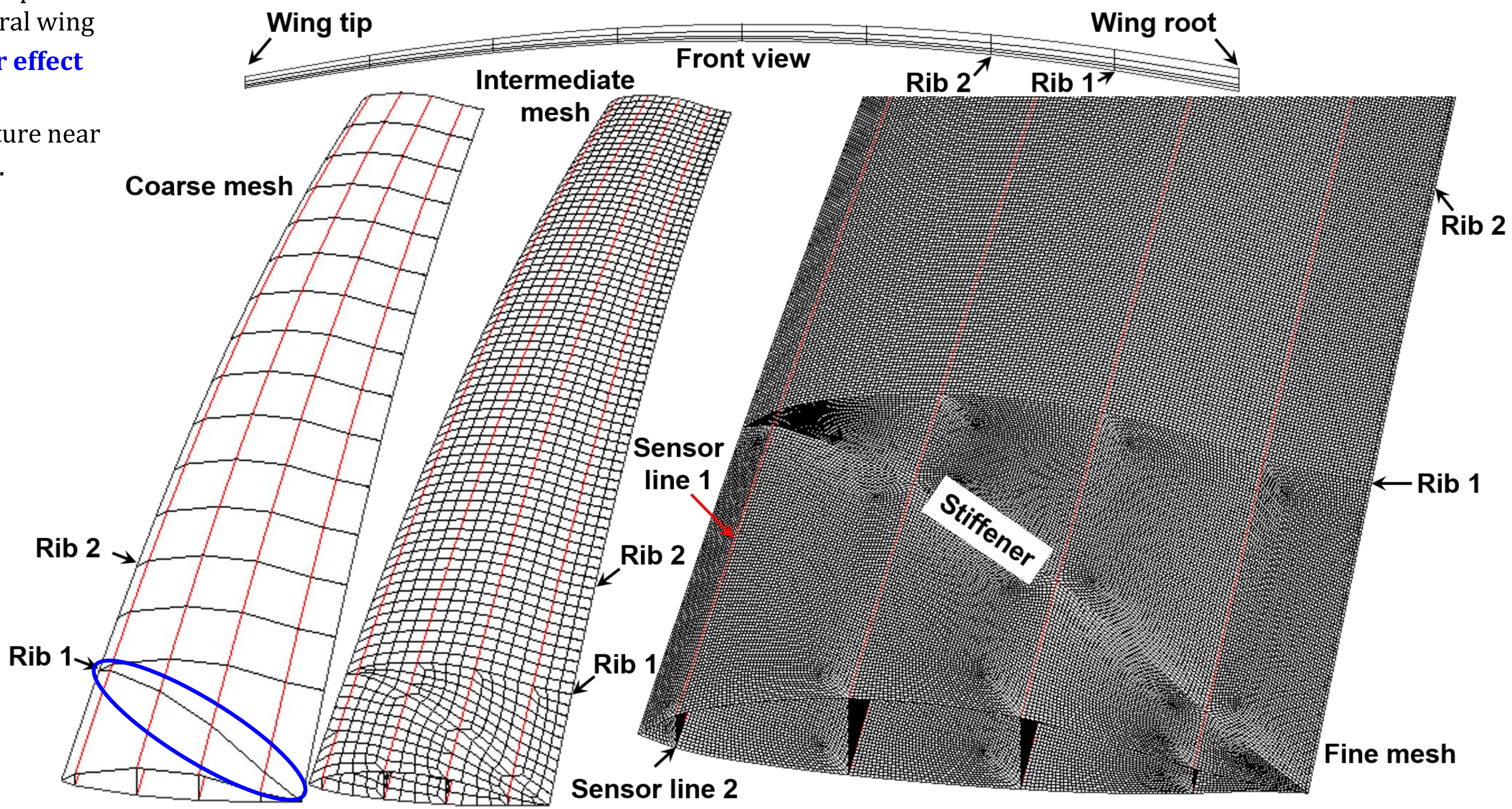
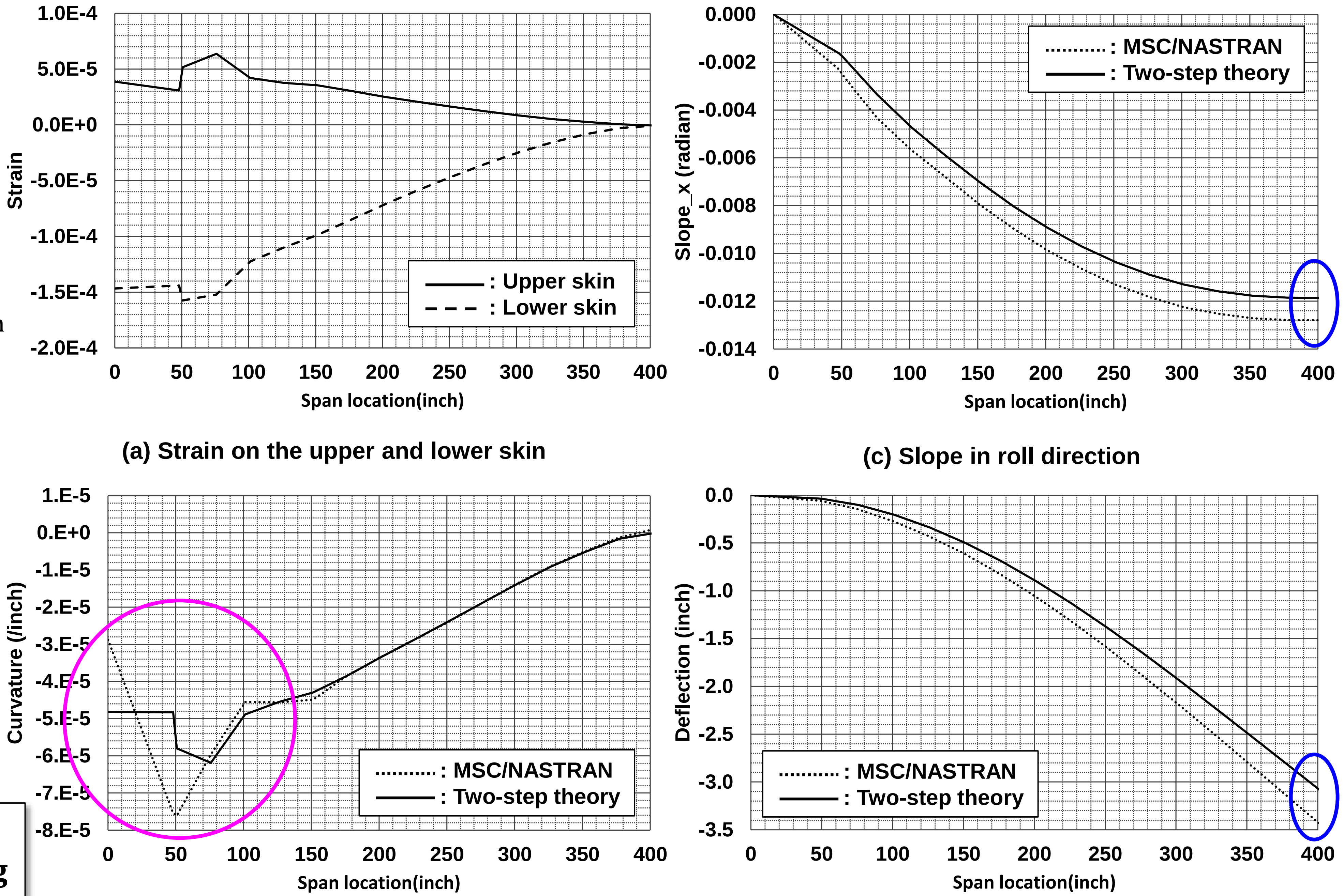


Fig. 13

Strain, curvature, & deformation

- ❑ Differences at wing tip
  - ❖ Slope: **-7.27%**
  - ❖ Deflection: **-10.2%**
- ❑ Similar prediction error with LBFD case is obtained.
  - ❖ Mainly cause by curvature error near wing root area
- ❑ Curvatures from two-step theory and MSC/NASTRAN are not matching between root chord and the first two rib.
  - ❖ Rib effect??

Stiffened dihedral/anhedral wing with coarse mesh



(a) Strain on the upper and lower skin

(c) Slope in roll direction

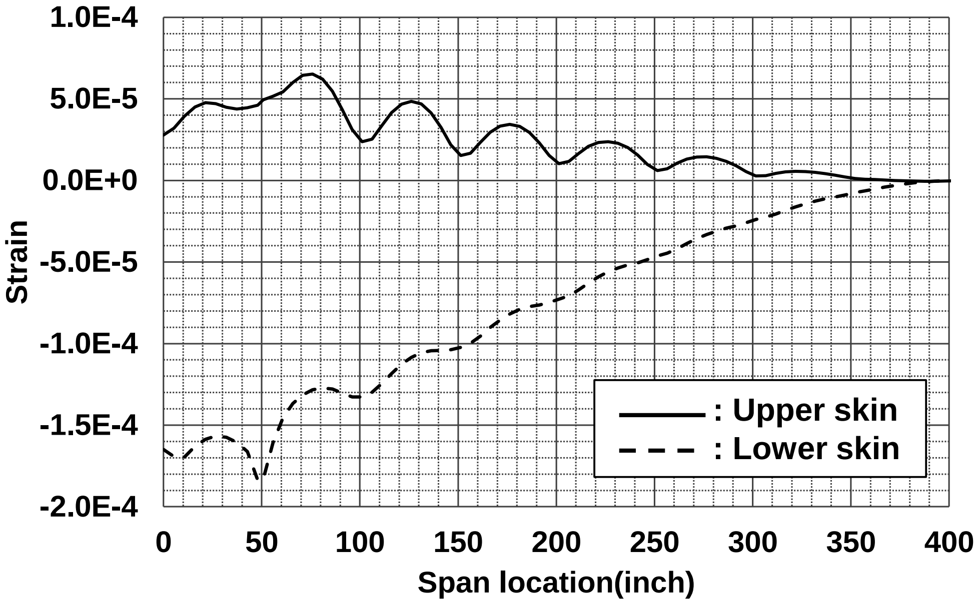
(b) Curvature

(d) Deflection

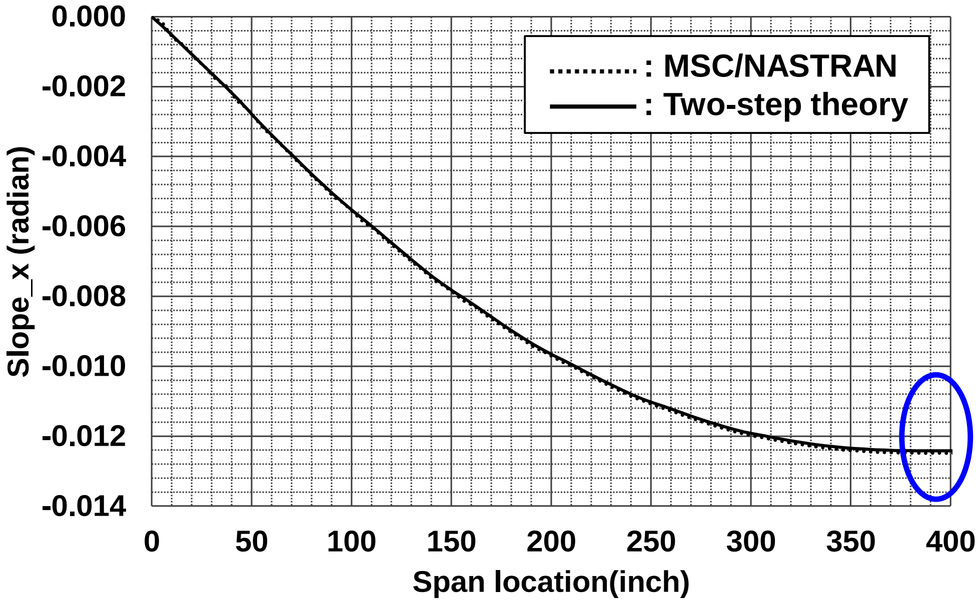
Fig. 14

Strain, curvature, & deformation

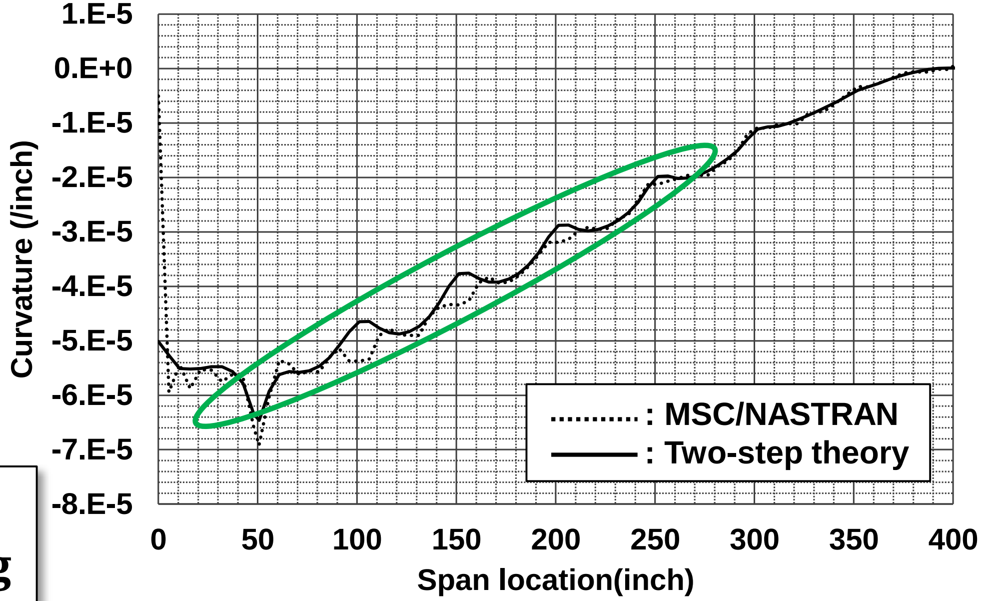
- ❑ Differences at wing tip
  - ❖ Slope: **-0.535%**
  - ❖ Deflection: **-0.694%**
- ❑ A medium FE mesh gives good results.
- ❑ Curvature values computed from the medium mesh is **similar** to the NASTRAN results.
  - ❖ Rib effects exist



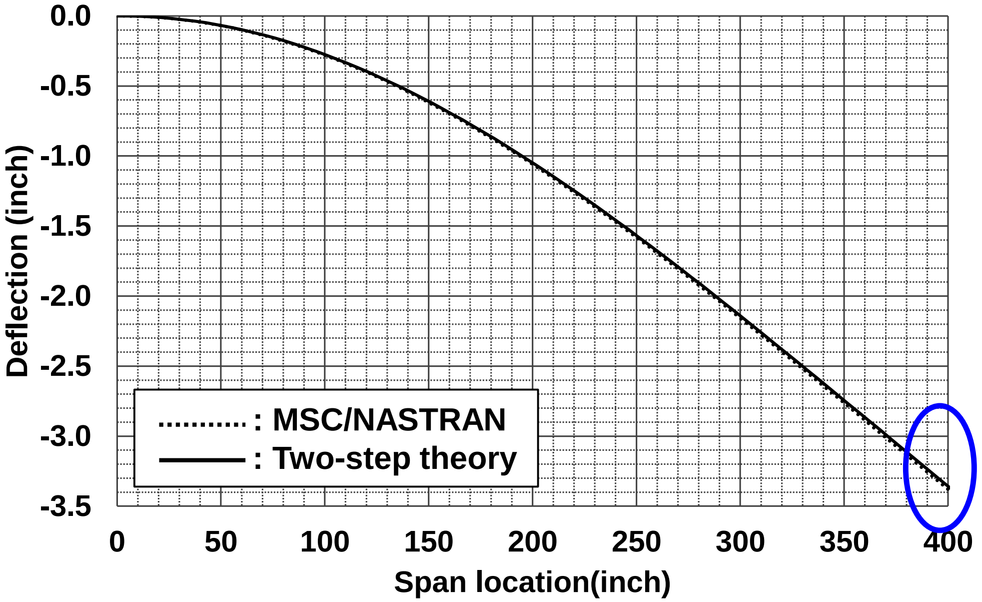
(a) Strain on the upper and lower skin



(c) Slope in roll direction



(b) Curvature



(d) Deflection

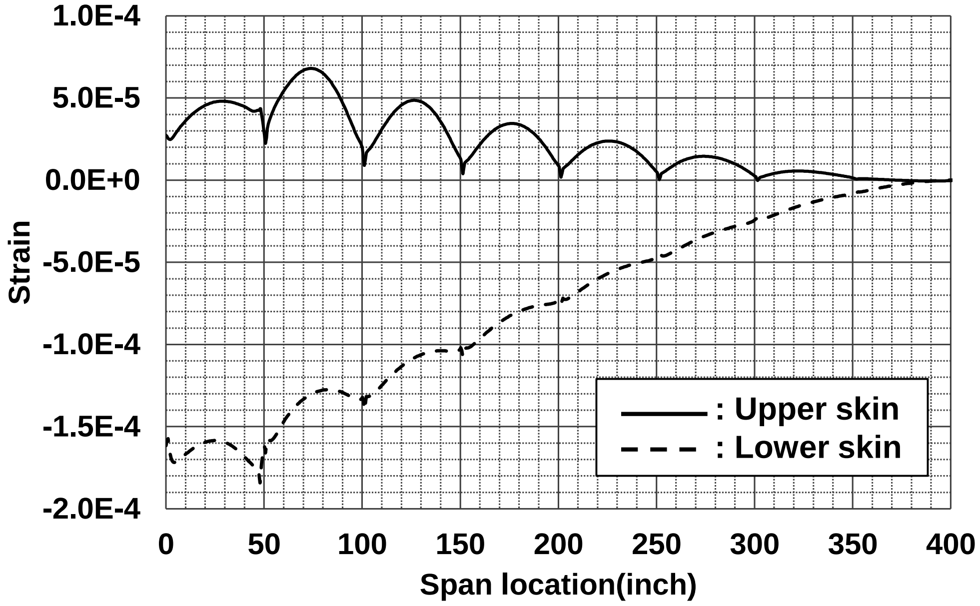
Stiffened dihedral/anhedral wing with intermediate mesh

Fig. 15

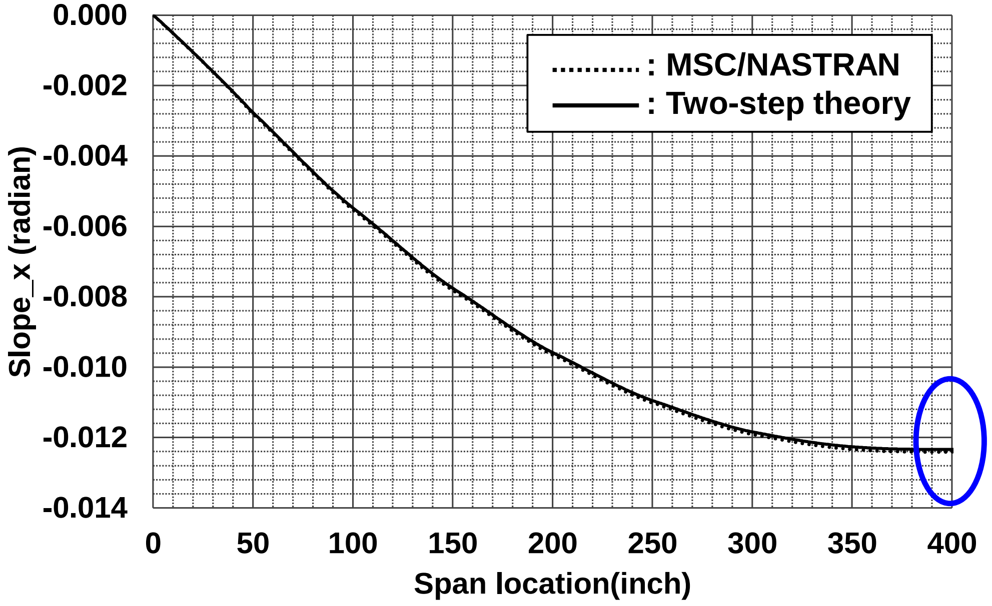
Strain, curvature, & deformation

- ❑ Differences at wing tip
  - ❖ Slope: **-0.564%**
  - ❖ Deflection: **-0.796%**
- ❑ A fine FE mesh gives good results.
- ❑ Curvatures from two-step theory and MSC/NASTRAN are excellent matching between root chord and the first two rib.
- ❑ The fine mesh is needed to have **accurate** curvature distribution
  - ❖ **Numerical derivatives** are used for the computation of curvatures from MSC/NASTRAN

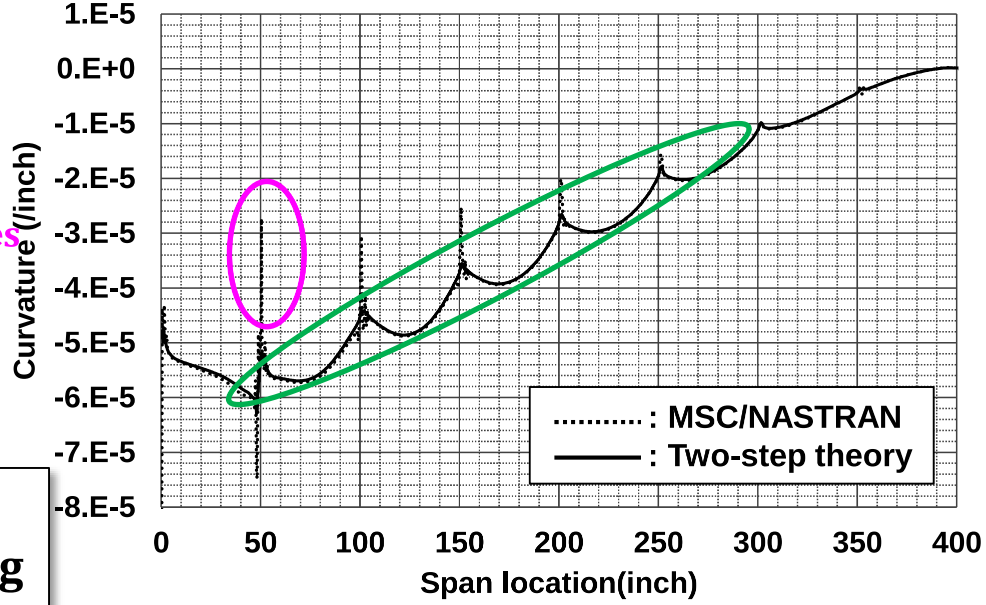
Stiffened dihedral/anhedral wing with fine mesh



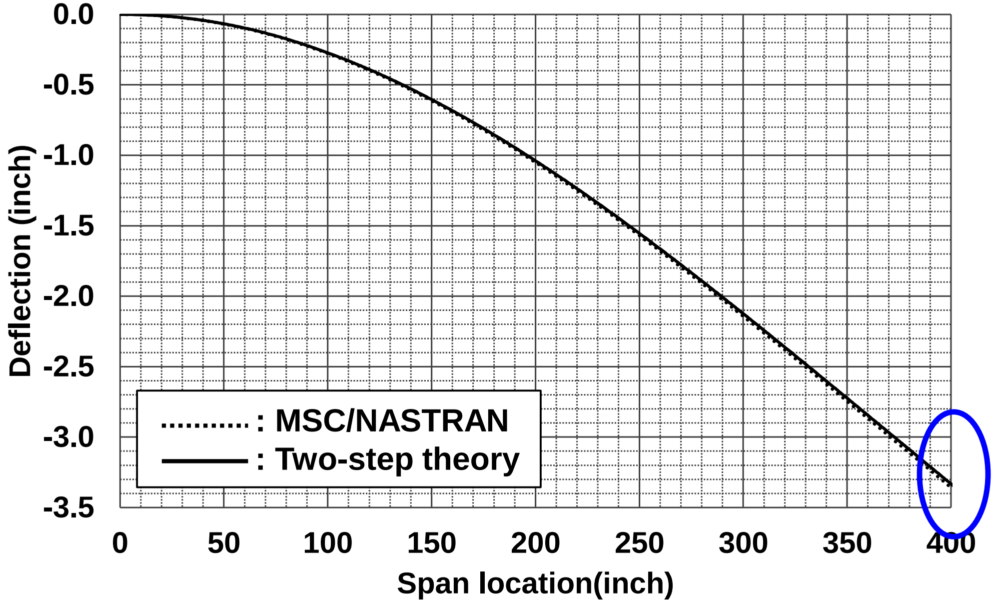
(a) Strain on the upper and lower skin



(c) Slope in roll direction



(b) Curvature



(d) Deflection

Fig. 16

Chord-wise deformation of Stiffened dihedral/anhedral wing

- Step 2 is the FE model dependent procedure.
- Expand measured master DOF to master and slave DOF

$$\{q(t)\} = \begin{Bmatrix} q_M(t) \\ q_S(t) \end{Bmatrix} = \begin{bmatrix} \Phi_M(\Phi_M^T\Phi_M)^{-1}\Phi_M^T \\ \Phi_S(\Phi_M^T\Phi_M)^{-1}\Phi_M^T \end{bmatrix} \{\tilde{q}_M(t)\}$$

Values are based on the fine mesh.

  - DOF of $\{\tilde{q}_M(t)\}$ = coarse mesh (51); intermediate mesh (972); & fine mesh (2403)
- The first six flexible mode shapes are selected as the basis functions.
- Eigen-matrices, Φ_M & Φ_S, are computed based on the FE model with coarse or intermediate meshes. (computer speed and memory issue with fine mesh)
  - DOF of coarse mesh = 1,356 $\Phi_M(51 \times 6)$; $\Phi_M^T\Phi_M(6 \times 6)$; & $\Phi_S(1305 \times 6)$
  - DOF of intermediate mesh = 21,192 $\Phi_M(972 \times 6)$; $\Phi_M^T\Phi_M(6 \times 6)$; & $\Phi_S(20220 \times 6)$
  - DOF of fine mesh =2,240,442 $\Phi_M(2403 \times 6)$; $\Phi_M^T\Phi_M(6 \times 6)$; & $\Phi_S(2238039 \times 6)$

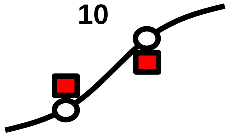
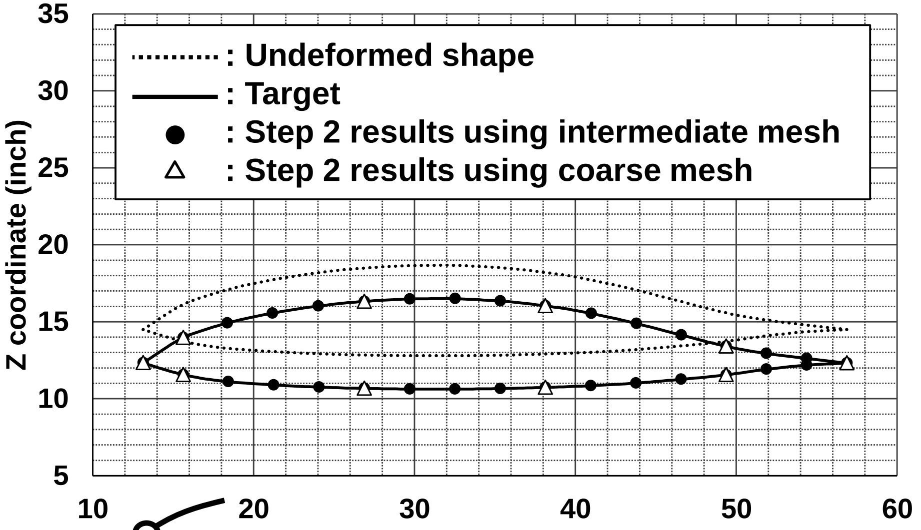


Table 3. Deformation of stiffened dihedral/anhedral wing at wing-tip section

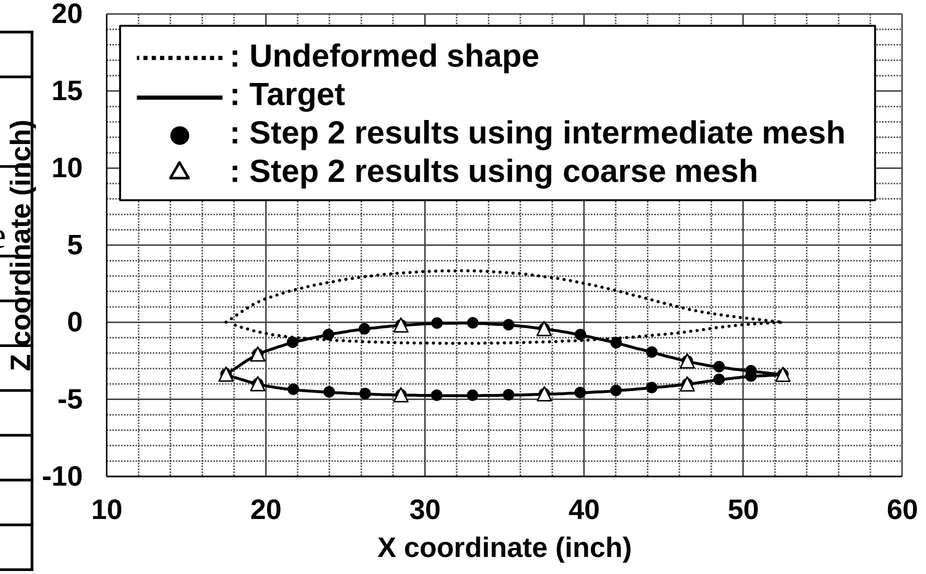
Deformation	Target	Step 1 (fine mesh)		Step 2 (coarse mesh)		Step 2 (intermediate mesh)	
		Value	% difference	Value	% difference	Value	% difference
X	-0.06057			-0.05113	-15.6	-0.05571	-8.02
Y	-0.1740	-0.1821	4.66	-0.1725	-0.86	-0.1738	-0.11
Z	-3.392	-3.365	-0.80	-3.367	-0.74	-3.368	-0.71
Roll	-0.01241	-0.01234	-0.56	-0.01234	-0.56	-0.01237	-0.32
Pitch	3.205E-4			2.924E-4	-8.77	3.019E-4	-5.80
Yaw	1.981E-4			1.601E-4	-19.2	1.820E-4	-8.13

Results are based on strains along the sensor lines 1 and 2.

Least squares surface fitting technique (SEREP)



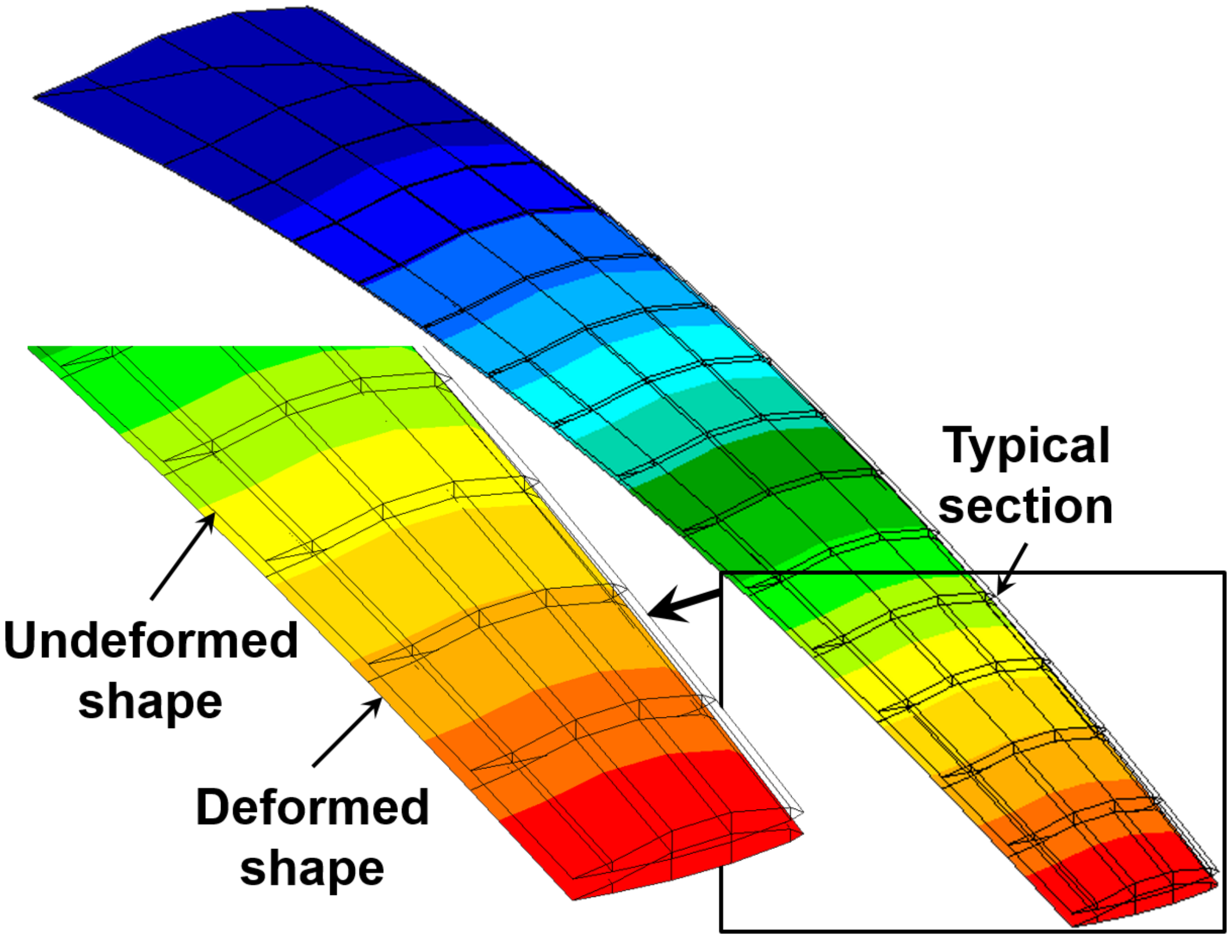
(a) At typical section



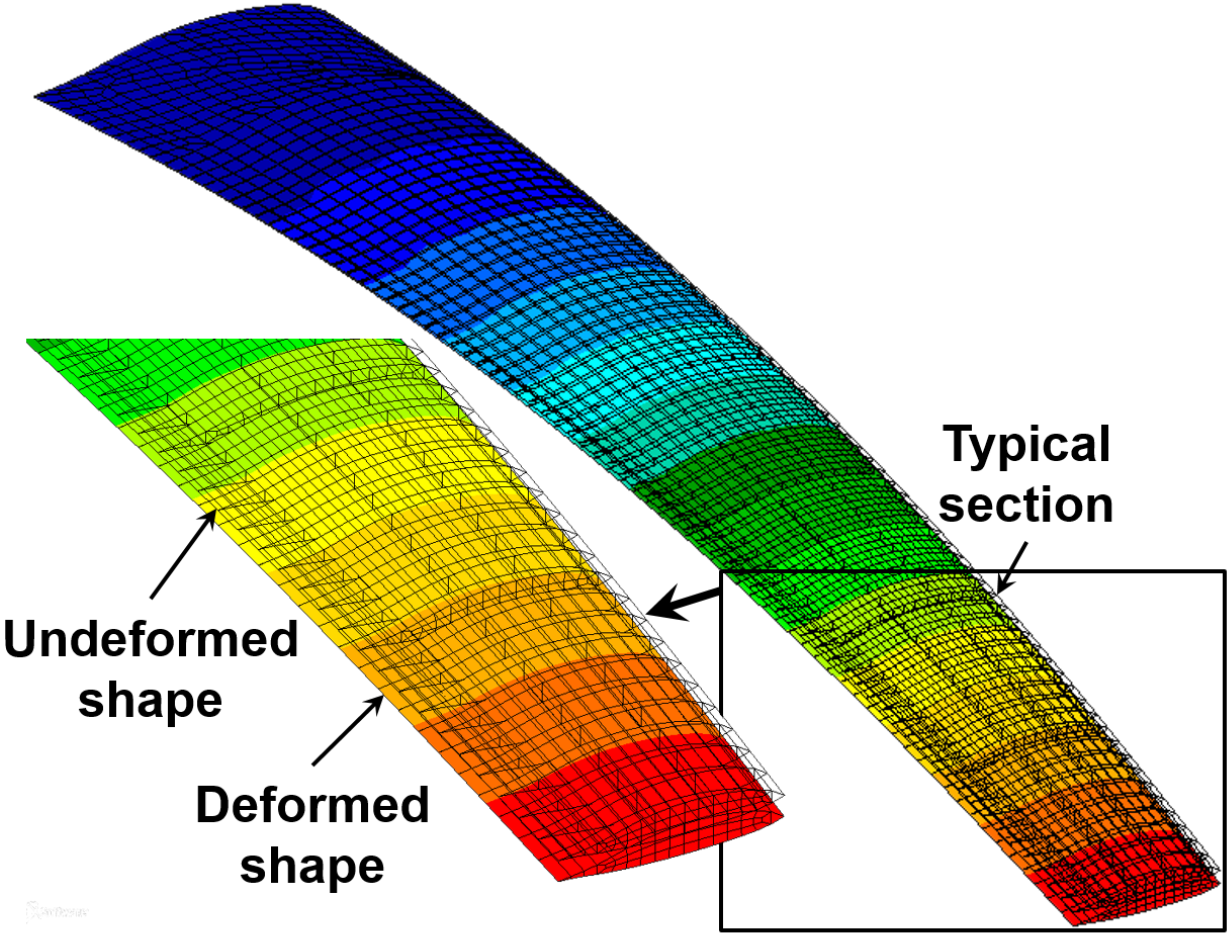
(b) At wing-tip section

Fig. 17

Deformed shape of stiffened dihedral/anhedral wing after step 2



(a) Use coarse mesh for step 2



(b) Use intermediate mesh for step 2

Fig. 18

Conclusion

- A finite element structural model with **a fine mesh is desired** to have **accurate curvature distributions** during a pre-test analysis for the wing shape sensing of a wing with ribs and spars.

- In case of a finite element (FE) model with **a regular rib configuration**, such as the tapered wing and the dihedral/anhedral wing in this study, even the FE models with **coarse mesh give acceptable** strain data and slope and deflection information.
  - However, there's no guarantee that the strain data obtained from the coarse mesh is acceptable.
  - A FE model with a fine mesh may be needed to have accurate curvature distribution.
  - A FE model with **a fine mesh is needed for the pre-test analysis of the LBFD aircraft**.

- It is proved that **the two-step theory** used in this study **works excellent** for the wing shape sensing of the tapered wing, the dihedral/anhedral wing, and the stiffened dihedral/anhedral wing.
  - The curvature equation based on the decomposition of the in-plane strain and pure bending strain was successfully applied to the wing with spars and ribs.

Questions?