VSP High-Lift Modeling

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Outline

- Motivation and Goal
- Modeling High-Lift Components
- Deflecting Flaps and Slats
- Gap, Overlap and Relative Deflection
- Current Shortcomings
- Recommendations

Motivation

- OpenVSP can model high-lift surfaces using simple shearing of the airfoil coordinates. This is an appropriate level of complexity for lower-order aerodynamic analysis methods, such as vortex-lattice.
- For higher-order analysis methods (panel and Euler codes), actual three-dimensional surfaces must be modeled, particularly for slats and slotted flaps.
- No direct method for controlling complex flap and slat motions parametrically or intuitively.

Goal

- Establish a set of best practices for modeling high-lift components in OpenVSP at a level of complexity suitable for higher-order analysis methods.
  - Flaps and slats modeled as separate three-dimensional surfaces
  - Controlling motion using simple parameters in the local frame of reference

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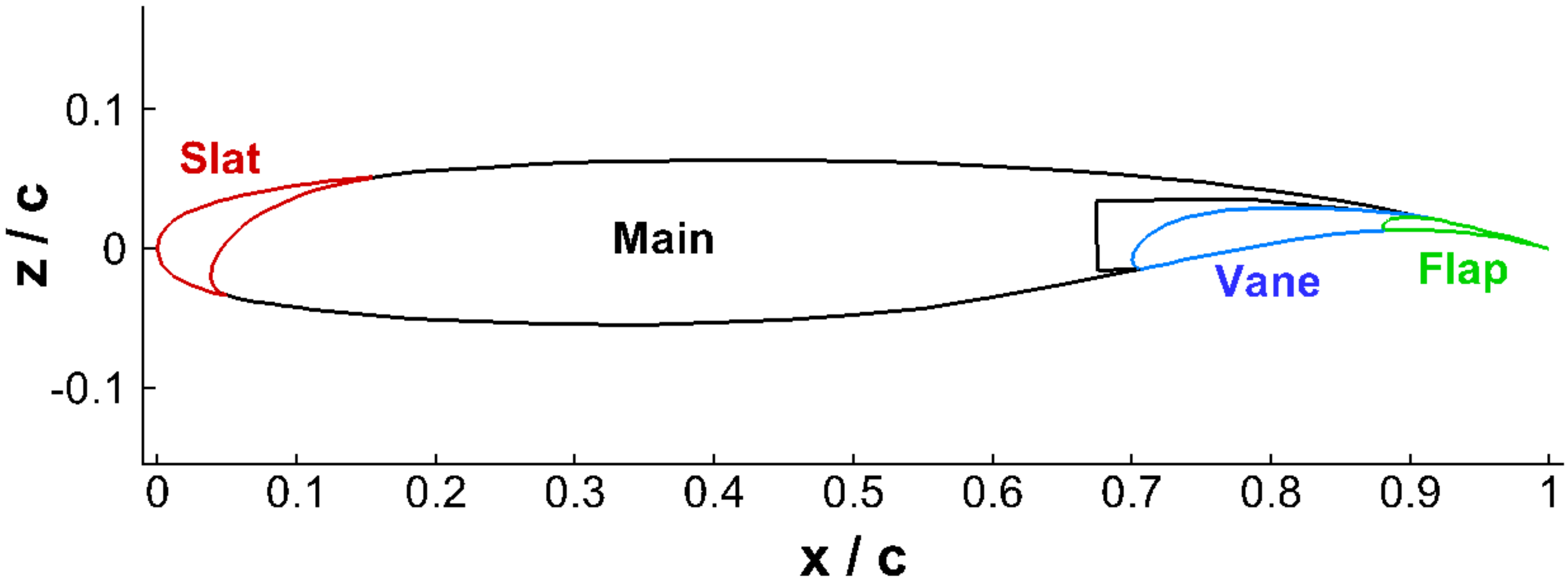
Modeling High-Lift Components

- Components of the high-lift configuration (main wing, slat, vane and flap) modeled as separate wings.
- Planform layout for components identical to the complete wing (same span, tip chord, root chord, sweep, dihedral and twist).
- Component airfoil coordinates use fractional chord but normalized by the chord of the full wing section.
- Transition segments allow for nearly-discontinuous change in cross section.
- Flap and slat surfaces can be assigned to separate sets to visualize and export independently.

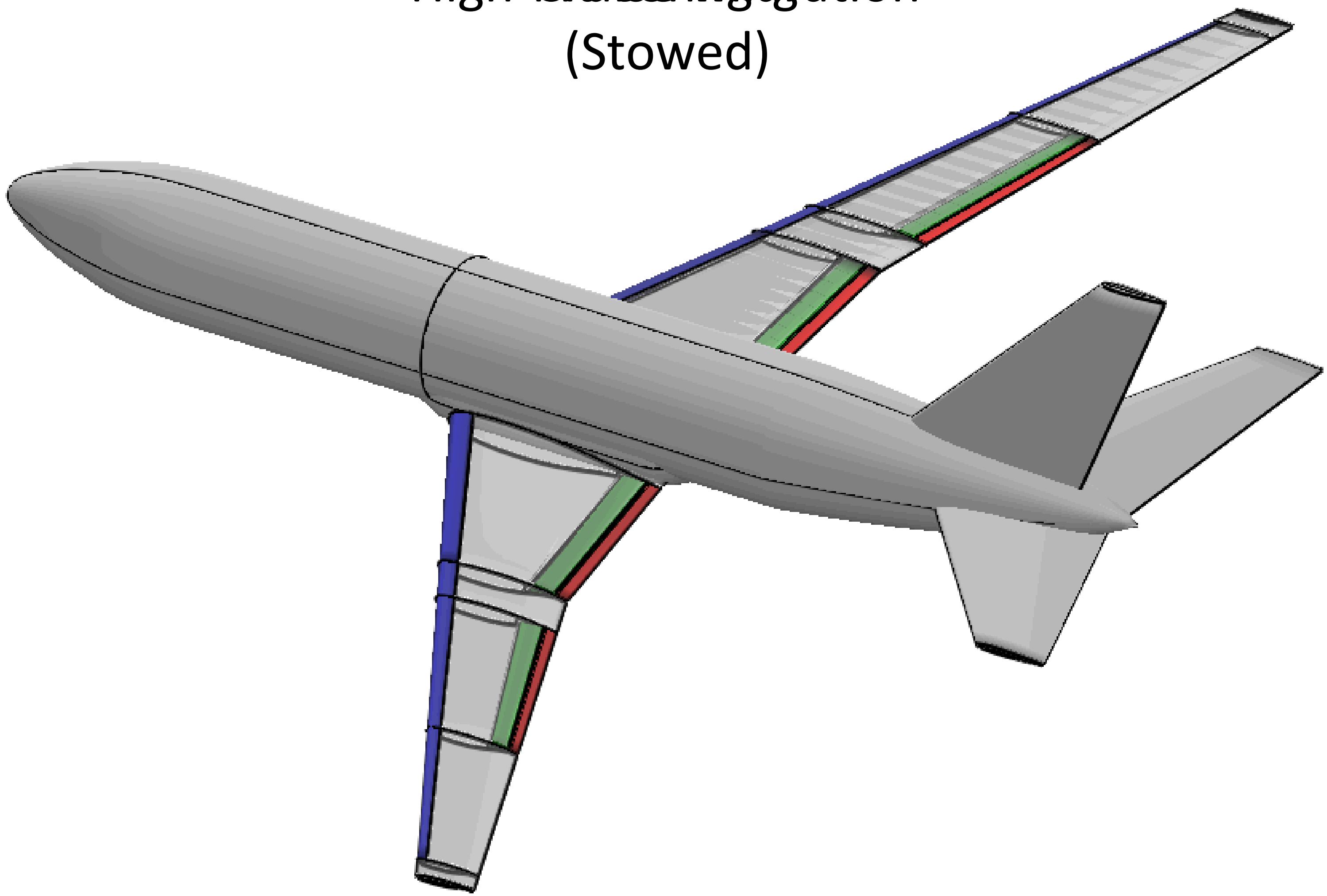
Fractional Airfoil Coordinates



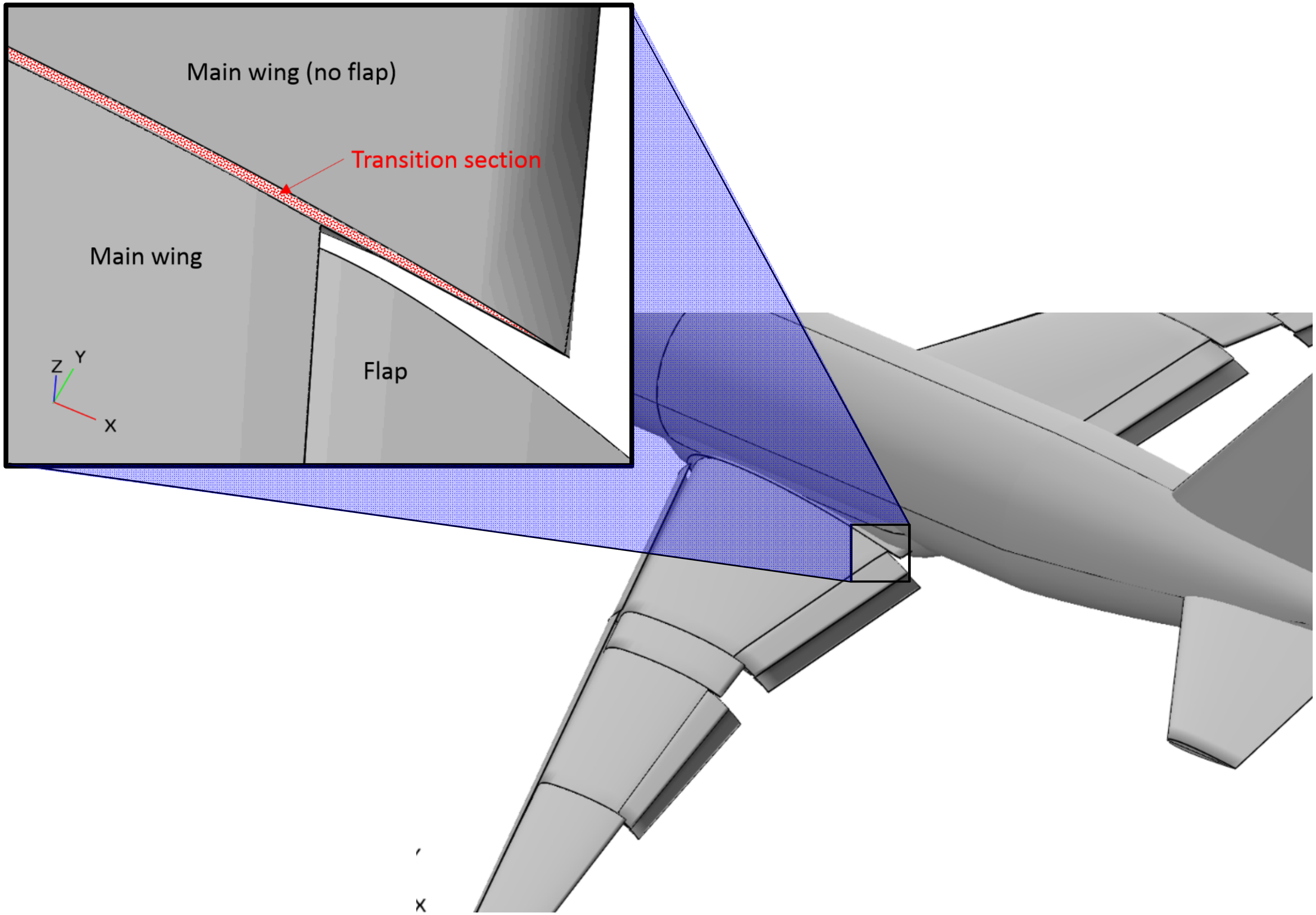
EET AR12 Example

High-lift Configuration

Cruise Wing
(Stowed)



Transition Segments



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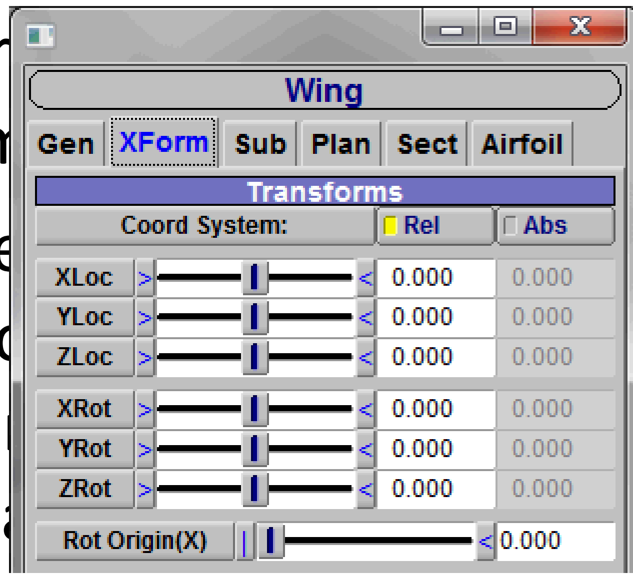
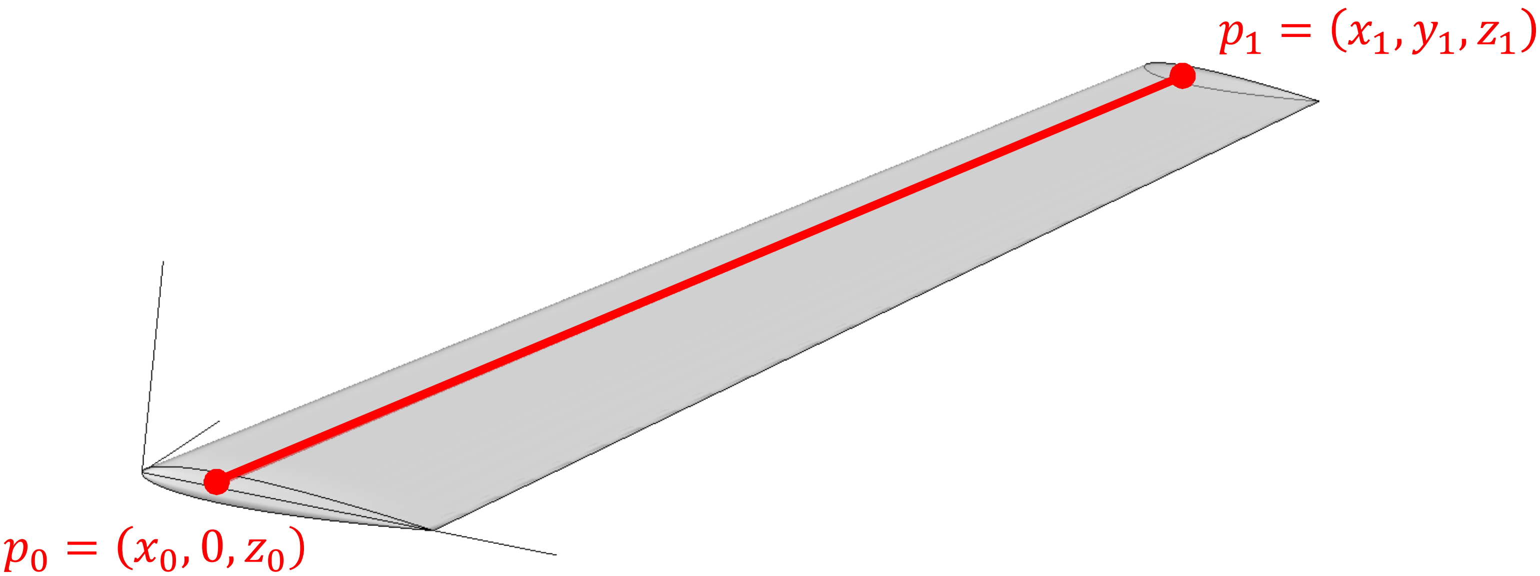
Deflecting Flaps and Slats

- **Problem**: VSP transformations (XForm) are defined relative to the x, y, and z axes – whereas we want to specify flap and slat transformations relative to the hinge axis.
- **Solution**: der the user to directly specify flap m e hinge axis.
- **Approach**: de s for flap transformatic xis, and use Advanced Pa lculate the equivalent tr omponent's XForm parameters.



Definition of Hinge Line

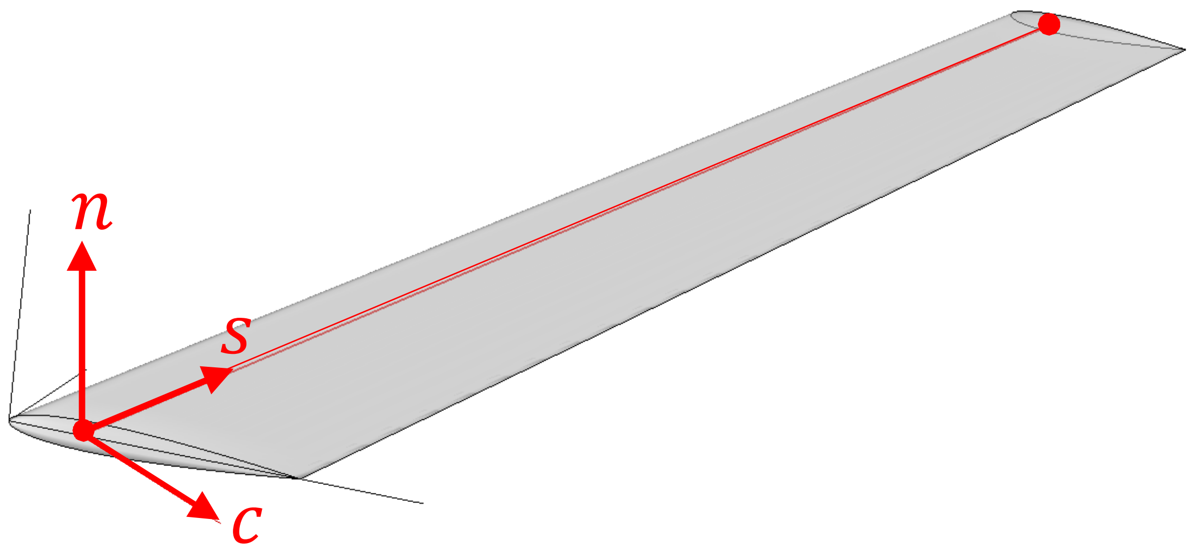


- Flap with semispan, b
- Hinge line between $p_o = (x_0, 0, z_0)$ and $p_1 = (x_1, y_1, z_1)$ where

$$y_1 = \sqrt{b^2 - (z_1 - z_0)^2}$$

- Hinge axis dihedral, $\Gamma = \sin^{-1}\left(\frac{z_1 - z_0}{b}\right)$ and sweep, $\Lambda = \tan^{-1}\left(\frac{x_1 - x_0}{b}\right)$

Hinge Axis Coordinates



- c-axis lies in the plane of the flap, orthogonal to the hinge axis (approx. chordwise).
- s-axis is aligned with hinge axis (approx. spanwise).
- n-axis is orthogonal to c and s (approx. vertical).

Deflection relative to hinge axis

- Inboard end of hinge axis translated by $(\Delta c_0, 0, \Delta n_0)$.
- Outboard translated by $(\Delta c_1, \Delta s_1, \Delta n_1)$, where

$$\Delta s_1 = \sqrt{\left(\frac{b}{\cos\Lambda}\right)^2 - (\Delta c_0 - \Delta c_1)^2 - (\Delta n_0 - \Delta n_1)^2} - \frac{b}{\cos\Lambda}$$

- Component rotated around hinge axis by θ_f.

Translation in xyz Coordinates

- In xyz coordinate system, deflection of inboard end of hinge axis is

$$\Delta p_0 = \begin{pmatrix} \Delta x_0 \\ \Delta y_0 \\ \Delta z_0 \end{pmatrix} = \begin{pmatrix} \Delta c_0 \cos\Lambda \\ -\Delta c_0 \cos\Gamma \sin\Lambda - \Delta n_0 \sin\Gamma \\ -\Delta c_0 \sin\Gamma \sin\Lambda + \Delta n_0 \cos\Gamma \end{pmatrix}$$

- Outboard deflection is

$$\Delta p_1 = \begin{pmatrix} \Delta x_1 \\ \Delta y_1 \\ \Delta z_1 \end{pmatrix} = \begin{pmatrix} \Delta c_1 \cos\Lambda + \Delta s_1 \sin\Lambda \\ -\Delta c_1 \cos\Gamma \sin\Lambda + \Delta s_1 \cos\Gamma \cos\Lambda - \Delta n_1 \sin\Gamma \\ -\Delta c_1 \sin\Gamma \sin\Lambda + \Delta s_1 \sin\Gamma \cos\Lambda + \Delta n_1 \cos\Gamma \end{pmatrix}$$

- New semispan, dihedral, and sweep:

$$b' = \sqrt{(y_1 + \Delta y_1 - y_0 - \Delta y_0)^2 + (z_1 + \Delta z_1 - z_0 - \Delta z_0)^2}$$

$$\Gamma' = \sin^{-1}\left(\frac{z_1+\Delta z_1-z_0-\Delta z_0}{b'}\right),\ \Lambda' = \cos^{-1}\left(\frac{x_1+x_1-x_0-\Delta x_0}{b'}\right)$$

Flap Transformation Steps

1. Translate the flap by $-p_0$ so that the inboard end of the hinge axis coincides with the flap origin.
2. Rotate about the x-axis by the negative of the dihedral angle $(-\Gamma)$ so that the hinge axis lies in the $z = 0$ plane.
3. Rotate about the z-axis by the sweep angle (Λ) so that the hinge axis coincides with the y-axis.
4. Rotate about y-axis by the flap rotation angle (θ_f).
5. Rotate about the z-axis by the negative of the new sweep angle $(-\Lambda')$.
6. Rotate about the x-axis by the new dihedral angle (Γ').
7. Translate by $p_0 + \Delta p_0$ so that the inboard end of the hinge axis coincides with its new location.

Transformation Matrix

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} & X \\ A_{21} & A_{22} & A_{23} & Y \\ A_{31} & A_{32} & A_{33} & Z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where

$$A_{12} = -\sin\Gamma\sin\theta_f\cos\Lambda' - \cos\Gamma\cos\theta_f\sin\Lambda\cos\Lambda' + \cos\Gamma\cos\Lambda\sin\Lambda'$$

$$A_{13} = \cos\Gamma\sin\theta_f\cos\Lambda' - \sin\Gamma\cos\theta_f\sin\Lambda\cos\Lambda' + \sin\Gamma\cos\Lambda\sin\Lambda'$$

$$A_{23} =$$

$$\sin\Gamma\cos\Lambda\cos\Lambda'\cos\Gamma' - \cos\Gamma\left(\sin\theta_f\sin\Lambda'\cos\Gamma' + \cos\theta_f\sin\Gamma'\right)$$
$$- \sin\Gamma\sin\Lambda\left(\sin\theta_f\sin\Gamma' - \cos\theta_f\sin\Lambda'\cos\Gamma'\right)$$

$$\vdots$$

(etc.)

OpenVSP Transformation Steps

1. Rotate around the z-axis by angle γ.
2. Rotate around the y-axis by angle β.
3. Rotate around the x-axis by angle α.
4. Translate along the vector $(\Delta x, \Delta y, \Delta z)$.

$$B = \begin{bmatrix} \cos\beta\cos\gamma & -\cos\beta\sin\gamma & \sin\beta & \Delta x \\ \sin\alpha\sin\beta\cos\gamma + \cos\alpha\sin\gamma & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & -\sin\alpha\cos\beta & \Delta y \\ \sin\alpha\sin\gamma - \cos\alpha\sin\beta\cos\gamma & \sin\alpha\cos\gamma + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta & \Delta z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

If these transformations are equivalent, then $A = B$.

Solve by Inspection

$$A = \begin{bmatrix} A_{11} & \boxed{A_{12}} & \boxed{A_{13}} & \boxed{X} \\ A_{21} & A_{22} & \boxed{A_{23}} & \boxed{Y} \\ A_{31} & A_{32} & A_{33} & \boxed{Z} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$B = \begin{bmatrix} \cos\beta\cos\gamma & \boxed{-\cos\beta\sin\gamma} & \boxed{\sin\beta} & \boxed{\Delta x} \\ \sin\alpha\sin\beta\cos\gamma + \cos\alpha\sin\gamma & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & \boxed{-\sin\alpha\cos\beta} & \boxed{\Delta y} \\ \sin\alpha\sin\gamma - \cos\alpha\sin\beta\cos\gamma & \sin\alpha\cos\gamma + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta & \boxed{\Delta z} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Equivalent Transformations

$$\beta = \sin^{-1} A_{13}$$

$$\alpha = -\sin^{-1} \frac{A_{23}}{\cos\beta}$$

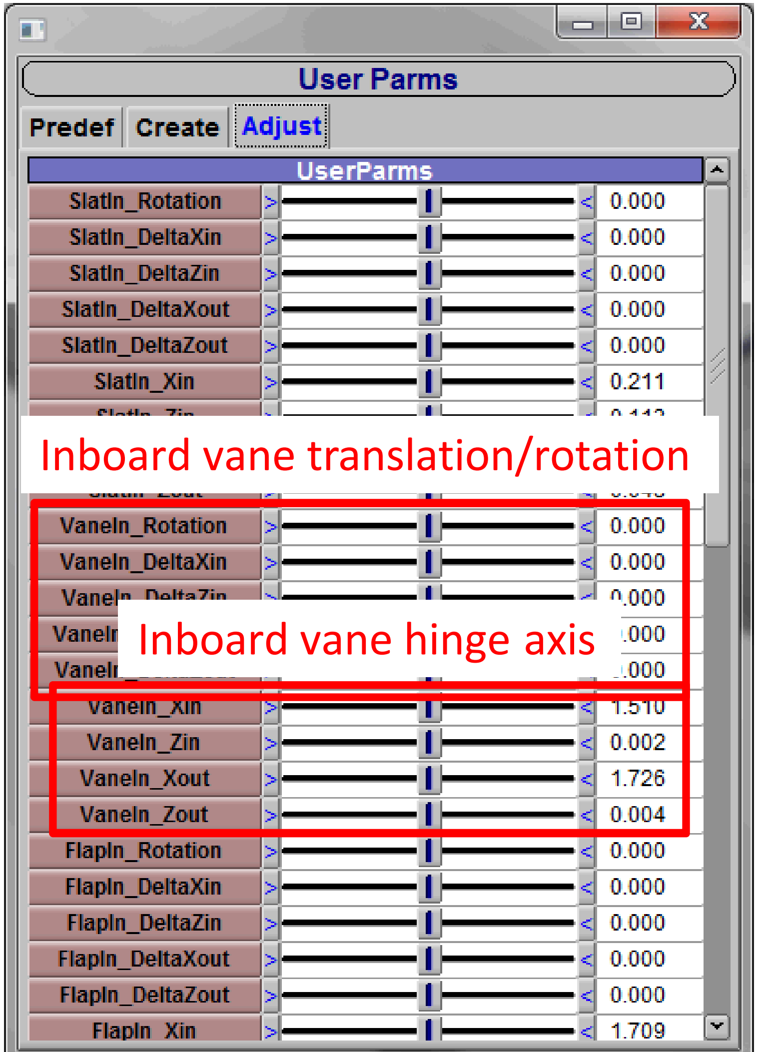
$$\gamma = -\sin^{-1} \frac{A_{12}}{\cos\beta}$$

$$\Delta x = \mathrm{X}$$

$$\Delta y = \mathrm{Y}$$

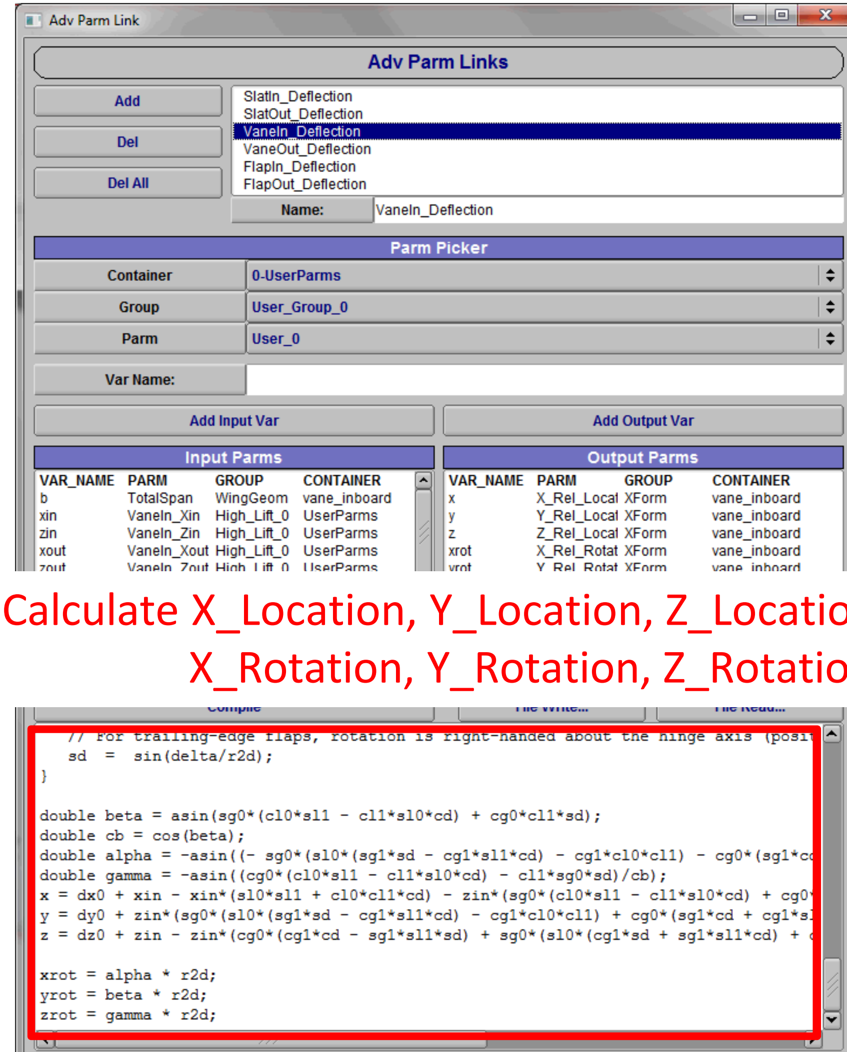
$$\Delta z = \mathrm{Z}$$

Implementation



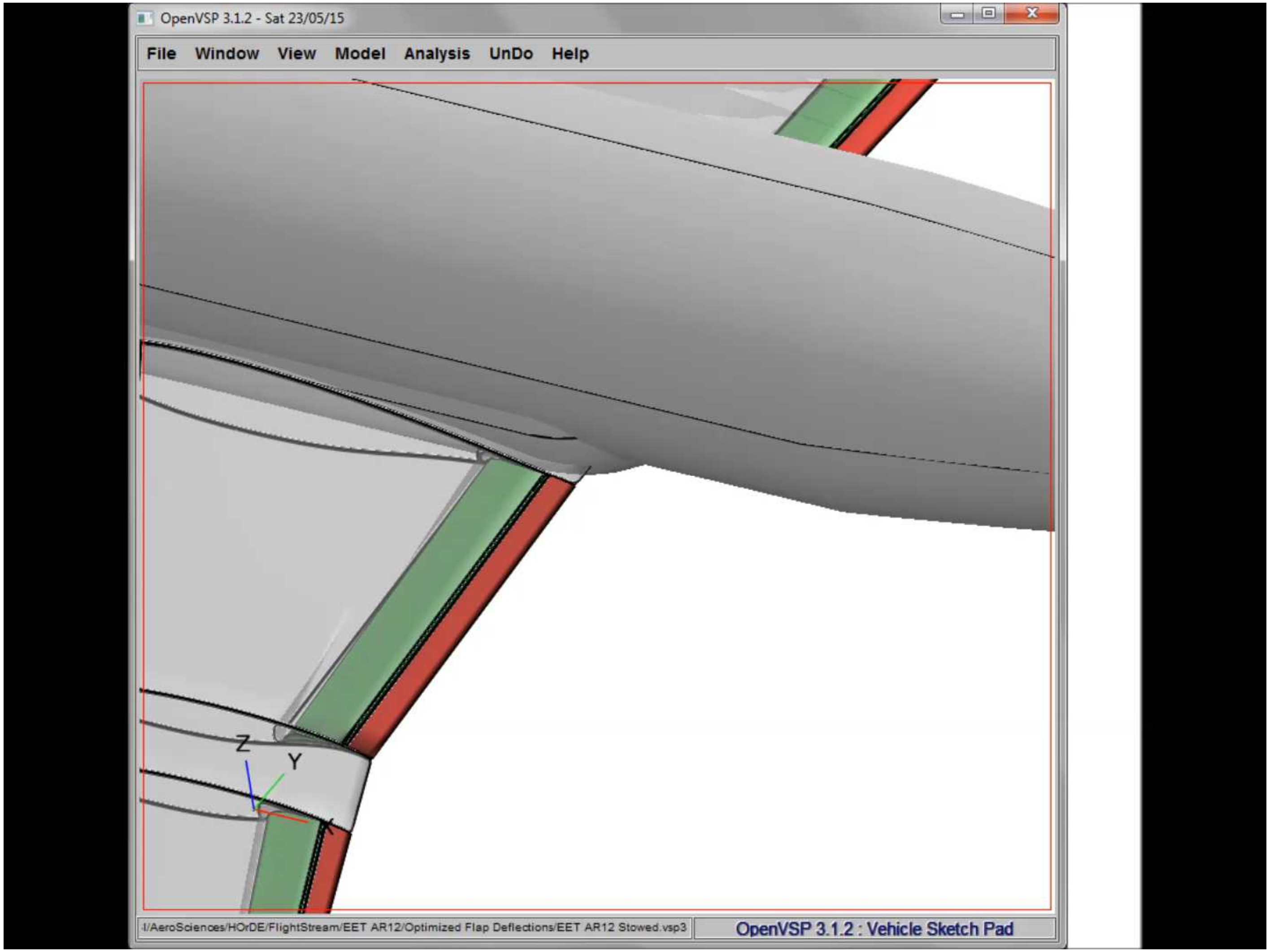
Inboard vane translation/rotation

Inboard vane hinge axis



Calculate X_Location, Y_Location, Z_Location, X_Rotation, Y_Rotation, Z_Rotation

Example


OpenVSP 3.1.2 - Sat 23/05/15
File Window View Model Analysis UnDo Help
Z
Y
/AeroSciences/HOrDE/FlightStream/EET AR12/Optimized Flap Deflections/EET AR12 Stowed.vsp3
OpenVSP 3.1.2 : Vehicle Sketch Pad

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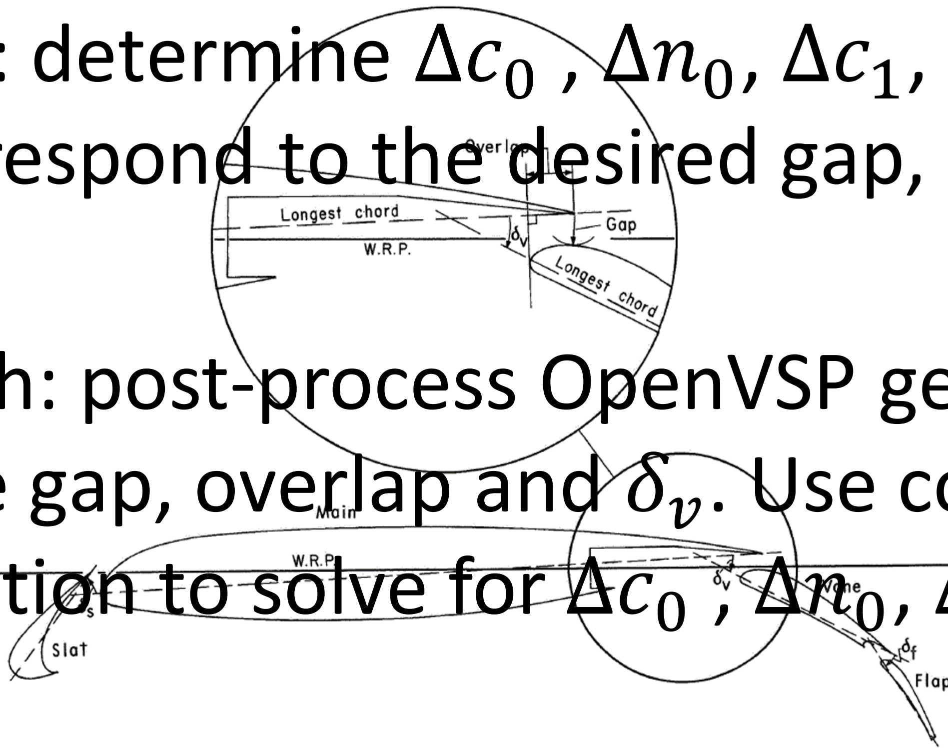
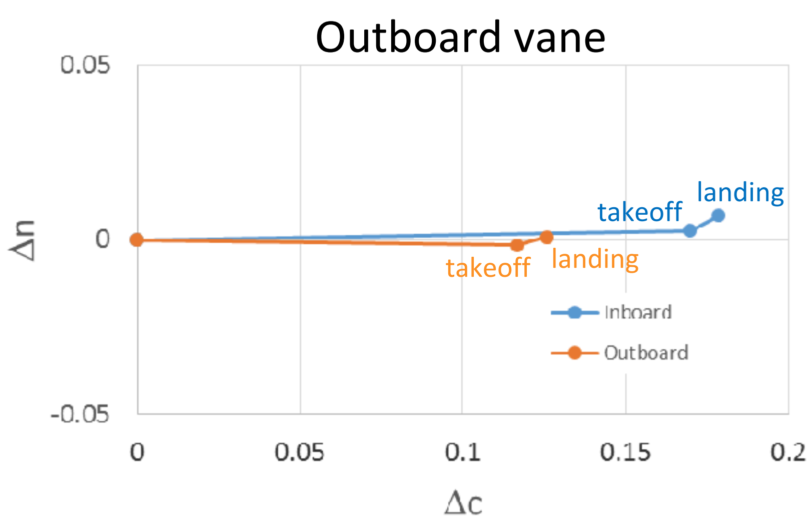
Gap, Overlap, Rel. Deflection

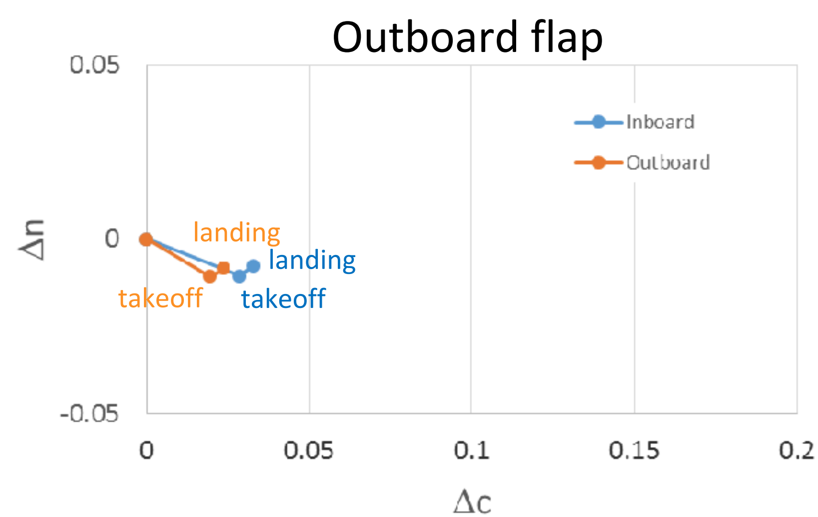
- Problem: flap and slat translation and rotation tends to be specified in terms of Gap, Overlap, and Relative Deflection (δ_v).
- Solution: determine Δc_0 , Δn_0, Δc_1, and Δn_1 that correspond to the desired gap, overlap and δ_v.
- Approach: post-process OpenVSP geometry to calculate gap, overlap and δ_v. Use constrained optimization to solve for Δc_0 , Δn_0, Δc_1, and Δn_1.



EET AR12 Flap Settings

Configuration	Component	Gap/c	Overlap/c	Deflection, deg
Takeoff	Slat	0.02	0.02	50
	Vane	0.015	0.04	15
	Flap	0.01	0.01	15
Landing	Slat	0.02	0.02	50
	Vane	0.02	0.03	30
	Flap	0.01	0.005	30





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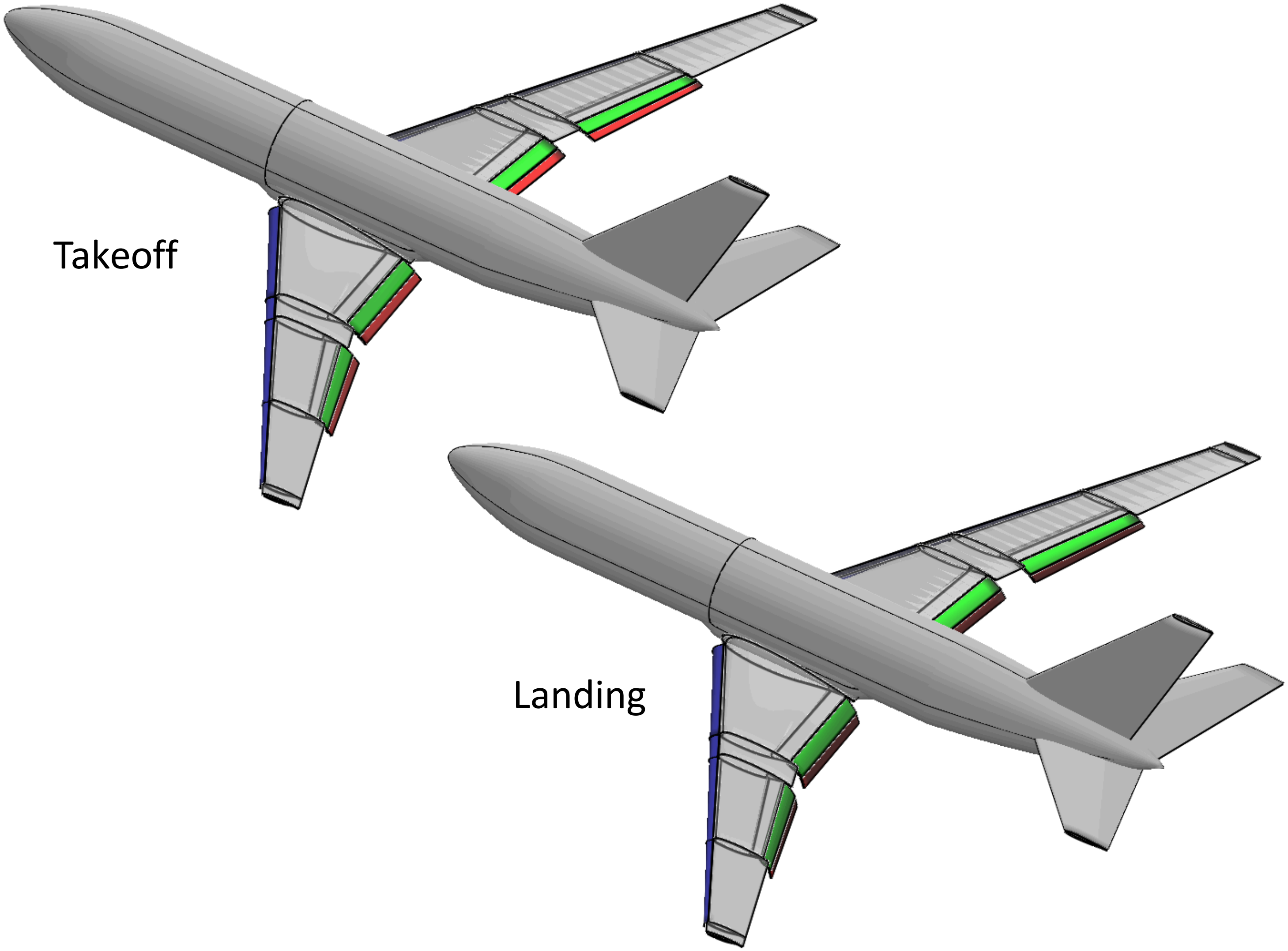

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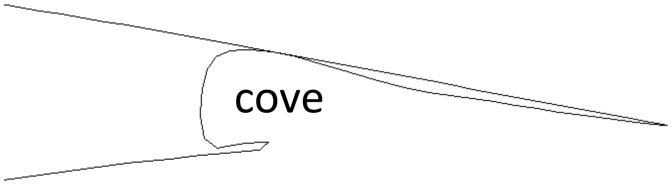
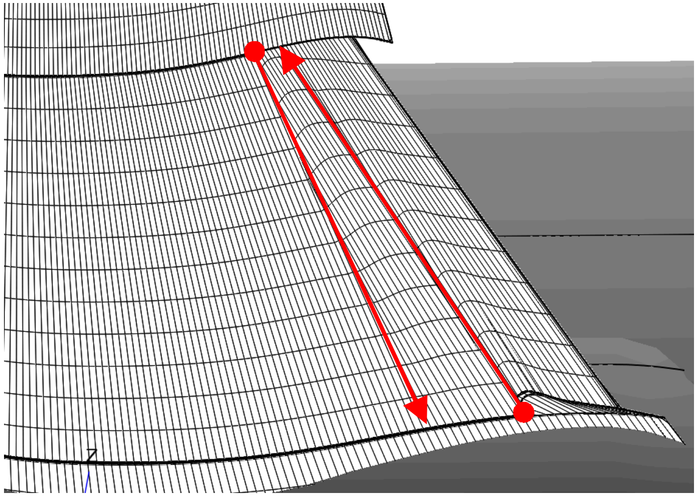
Current Shortcomings

- Discontinuous Airfoils in Cove Region
  - VSP w-lofting (chordwise) is always continuous.
- Spanwise Lofting of Discontinuities
  - When “discontinuities” are at different arc lengths, u-lofting does not connect them to each other.





Recommendations

1. Add rotation about an arbitrary axis.
2. Add a method for introducing discontinuities to airfoils (repeated point?).
3. Automatically connect discontinuities during spanwise lofting (in conjunction with #2) .

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