Interactive Wave Drag
in OpenVSP
(eta ~6mos)

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Roadmap

• **Background**: Wave Drag and OpenVSP
  – Problem & Solution

• **Wave Drag Evaluation and Analysis**
  – Leveraging the wave drag integral

• **Incorporating Wave Drag Evaluation in OpenVSP**
  – Building the wave drag tool

• **Tool Implementation**
  – Demonstrating use of the Wave Drag Tool

• **Analytical Comparisons**
  – Verifying proper application of wave drag evaluation

• **Tool Demonstration**

• **Conclusion**
Wave Drag Background

- Drag experienced during transonic/supersonic flight due to presence of shock waves
- Contributed to the false notion that manned supersonic flight would be impossible → “sound barrier”
- Wave drag problematic for design of jet-powered military aircraft
- Rocket-powered Bell X-1 crossed sound barrier in 1947
  - Shaped like a bullet
Wave Drag Background

• Area-ruling technique independently discovered by Richard Whitcomb of NACA in 1952
  – Manage cross-sectional area distribution to reduce wave drag
• “Whitcomb area rule” salvaged Convair F-102 program
Existing Tools

- **“Harris Wave Drag” code**
  - Roy Harris, NASA LaRC
  - Used by NASA, Boeing
  - Fortran code publically available
    - Requires column input of geometry data
    - Inaccuracies from lack of component intersection capability
    - Mandatory X-Z plane symmetry

- **“AWAVE”**
  - L. A. McCullers, NASA LaRC
  - Streamlined the Harris code
  - Not publically available
Wave Drag Theory

**Momentum analysis:** Aircraft in control surface

\[
D = -\rho_\infty U_\infty^2 \iint_{\text{Surf}_2} \phi_x \phi_r \, d\text{Surf}_2 + \frac{1}{2} \rho_\infty U_\infty^2 \iint_{\text{Surf}_3} \left( \phi_y^2 + \phi_z^2 \right) \, d\text{Surf}_3
\]

**Wave drag integral:**

\[
I = -\frac{1}{2\pi} \int_0^1 \int_0^1 S''(x)S''(y) \log|x-y| \, dx \, dy
\]

\[
D = \frac{1}{2\pi} \int_0^{2\pi} D(\theta) \, d\theta
\]

**Far field perspective:**
Mach cone from control surface is planar at aircraft.
Cross-Sectional Area Calculation

Slice aircraft with Mach cutting planes rotated about aircraft axis

Calculate resulting area projections onto Y-Z plane

Need the 2\textsuperscript{nd} derivative for the wave drag integral
Eminton-Lord Wave Drag Evaluation

• Evaluate wave drag integral with Fourier series
  – Elegant estimate of of $2^{nd}$ derivative of area
  – Uses additional terms to find minimum wave drag shape for the given data

• The standard method for wave drag estimation
  – Used by Harris Wave Drag code and AWAVE
  – C code reimplementation of Eminton-Lord provided by Dr. Sriram Rallabhandi for use in this work
Maximum Wave Drag Contribution

• Automatically finds maximum wave drag location along aircraft axis
  – Maximum drag per cutting plane rotation
  – Maximum drag overall
• GUI buttons “snap” area plot and cutting plane visualizer to max drag location
• Provides design intuition for wave drag mitigation
Maximum Drag Contribution

- Location of maximum drag contribution

\[ I = -\frac{1}{2\pi} \int_0^1 \int_0^1 S''(x)S''(y) \log |x - y| \, dx \, dy \]

Reaches max magnitude as \(|x-y| \to 0\)

\(|x-y| \to 0 \text{ as } x \to y\)

Thus, to pursue max magnitude, let \(x=y\)

Note: \(\ln(0)\) singularity handled by Eminton-Lord
Maximum Drag Contribution

• Location of maximum drag contribution

\[ I = -\frac{1}{2\pi} \int_0^1 \int_0^1 S''(x)S''(y) \log|x-y| \, dx \, dy \]

If \( x=y \), then \( S''(x)S''(y) = [S''(x)]^2 \)

Max magnitude occurs at \( \max |S''(x)| \)

Max \( |S''(x)| \) produces largest drag contribution
Modeling Engine Flow-Through

• Two options to account for flow-through components:

  Make component hollow:
  – Not always practical for the user

  Use subsurface on a solid:
  – Subsurface area must be subtracted
Modeling Engine Flow-Through

Inlet/exit noticeable in steps

Air not impeded by flow-through

Inlet/exit projected area included
Modeling Engine Flow-Through

- Inlet/exit projected area included
- Curve starts/ends at non-zero
- $S(x)$ shifted by a constant

- Inlet projected area subtracted
- Curve starts at zero, may end at non-zero
- $S(x)$ shifted by a constant

- Linear combo of inlet/exit area subtracted
- Curve starts/end at zero
- $S(x)$ shifted by 1st order function of $x$
Modeling Flow-Through

- Wave drag depends on 2\textsuperscript{nd} derivative of $S(x)$
- Terms added in Approaches A, B, and C differentiate to zero in $S''''(x)$
- Identical $S''$ values $\rightarrow$ Identical wave drag results
- Approach C chosen so $S(x)$ curve starts/ends at zero
Cutting Plane Procedure

- Start/end cutting planes determined automatically
- Ensures full capture of the aircraft
**Cutting Plane Procedure**

- Set of planes constructed for each theta
  - Rotated to theta, rotated to Mach angle, and translated along x-axis
- Planes intersected with aircraft
- Projected intersection areas are calculated
Subsurface Modeling of Flow-Through
Handling Flow-Through

Select all flow face subsurfaces in Wave Drag GUI

Normal vectors determine inlet or exit

Flow face extended
Handling Flow-Through
Eminton Lord Solution

Eminton-Lord solution used to plot smooth area distribution curve

Connected linearly

Eminton Lord series

Also used to find location of max wave drag contribution

\[ S'''(x) = \sum_{r=1}^{\infty} a_r r \cos(r\theta) \frac{1}{\sqrt{- (x-1)x}} \]
Verification Tests

**Sears-Haack Body**

- Known analytical wave drag solution
- Flow-through version created
  - Different radius, same area
  - Same analytical drag solution
- Conducted sweeps over r/L and number of cutting planes
- Permitted verification of proper application of wave drag theory
Verification Tests

- Convergence study on Sears-Haack \( r/L = 0.04 \) vs. number of cutting plane slices
  - <1% error after 6 slices, <0.1% error after 12 slices
  - Flow-through version within 0.016% error for equivalent \( r/L = 0.04 \)
Verification Tests

Eminton Body

- Known analytical wave drag solution
- Similar area to a fuselage with swept wings
- Conducted convergence study vs. number of cutting plane slices
  - Error <1% after 34 slices
Demo
Accessing the Wave Drag Tool

Accessible from the “Analysis” menu

Plot area starts out empty until data exists
“Run” Tab

- Select number of slices
- Select number of rotations
- Choose XZ symmetry option
  - Will run same number of rotations, but on 0-180° and update drag result accordingly
- Select component set
- Set Mach number and $S_{ref}$
- Choose output file (optional)
Running Tool

- Fighter model example
- Results appear upon clicking “START” button
“Plot” Tab

Manage from “Plot” tab

Control which theta rotation is visible

All remaining visual tools

Discrete data points in black, Fourier approximation in blue
“Plot” Tab

• Using global max drag button, reference bar and plane visualizer relocate accordingly
“Flow Faces” Tab

- List auto-populates with existing subsurfaces
- Check the boxes next to subsurfaces intended to be flow faces
- Tool will determine inlet/exit status
“Flow Faces” Tab

- Fighter model example run with flow faces activated
Body of Revolution Visualizing

- Access drop-down menu from “Plot” tab
- Equivalent body of revolution using length, radius, and volume of existing model

Sears-Haack Body
von Karman Ogive
Lighthill’s Body
Mach Cutting Plane Visualizer

- A translucent plane on the main screen
- Represents current theta and Mach angle
- Location controlled by Slice Axis Reference slider
- Turn on/off with visualizer toggle button
- Provides visual correlation of model and area distribution
Questions?