Higher Fidelity Transonic Aerodynamic Modeling in Preliminary Aircraft Design

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Aerodynamics & aeroelastic tailoring

Objective
Aerodynamic loads
• Given wing shape

Early preliminary design stage
Fast computations
• Linear solvers

Challenges
Flow nonlinearities
• Shock and boundary layer

Develop a fast non-linear solver
Overview

**Benchmark**

- Evaluate existing models & methods to efficiently solve transonic flows

**Development**

- Develop a fast aerodynamic solver for transonic loads computation based on the most efficient flow model
Outline

Benchmark
• Levels of fidelity & methods
• Embraer Benchmark Wing 2
• Results
• Analysis

Development
• Methodology
• Panel & field modules
• Challenges
• Transonic computation

Conclusion
• Summary
Overview

**Evaluate** existing models & methods to efficiently solve transonic flows

**Develop** a fast aerodynamic solver for transonic loads computation based on the most efficient flow model
Levels of fidelity

Linear Potential Equation
- Subsonic
- Supersonic
- Attached
- Linear

Full Potential Equation
- Subsonic
- Supersonic
- Weak transonic
- Attached

Euler equations
- Subsonic
- Supersonic
- Transonic
- Attached

RANS equations
- Subsonic
- Supersonic
- Transonic
- Mildly separated

Non-linearity

Non-isentropicity

Viscosity
Numerical discretization

Models

Linear
- Linear Potential Equation (LPE)

Nonlinear
- Full Potential Equation (FPE)
- Euler equations
- RANS equations

Methods

- Boundary Element Method (BEM)
  - Field Panel Method (FPM)
  - Field Method (FM)
Methods

**Boundary Element Method**
- Only boundary is discretized
- Linear equations only

**Field Method**
- Whole field is discretized
- Linear and nonlinear equations

Adapted from *Workshop on Aerodynamics* – G. Dimitriadis
## Evaluated models & methods

<table>
<thead>
<tr>
<th>Models</th>
<th>Software</th>
<th>Methods</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Potential Equation</td>
<td><em>Panair</em></td>
<td>Panel (doublet/source)</td>
<td>Red</td>
</tr>
<tr>
<td>Full Potential Equation</td>
<td><em>Tranair++</em></td>
<td>Finite element</td>
<td>Orange</td>
</tr>
<tr>
<td>Full Potential Equation + Boundary Layer Equations</td>
<td><em>Tranair++</em></td>
<td>Finite element</td>
<td>Green</td>
</tr>
<tr>
<td>Euler equations</td>
<td><em>SU²</em></td>
<td>Finite volume</td>
<td>Blue</td>
</tr>
<tr>
<td>RANS equations</td>
<td><em>SU²</em></td>
<td>Finite volume</td>
<td>Violet</td>
</tr>
</tbody>
</table>
# Embraer Benchmark Wing 2

<table>
<thead>
<tr>
<th></th>
<th>$M$</th>
<th>$C_L$</th>
<th>$FL$</th>
<th>$Re$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise</td>
<td>0.78</td>
<td>0.47</td>
<td>350</td>
<td>$\sim 20 \times 10^6$</td>
</tr>
</tbody>
</table>
Pressure contours

Full potential

Full potential + BLE

Linear potential

Euler

RANS

\[ C_p \]

-1.5

0

0.5
Pressure distributions

\[ \frac{y}{b} = 0.406 \] (\( \bar{c} \))

<table>
<thead>
<tr>
<th>Model</th>
<th>~CPU time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear potential</td>
<td>1 × 10 [s]</td>
</tr>
<tr>
<td>Full potential</td>
<td>1 × 600 [s]</td>
</tr>
<tr>
<td>Euler</td>
<td>6 × 3 [h]</td>
</tr>
<tr>
<td>Full potential + BLE</td>
<td>1 × 900 [s]</td>
</tr>
<tr>
<td>RANS</td>
<td>32 × 24 [h]</td>
</tr>
</tbody>
</table>

\[ C_p \] vs \[ x/c_{local} \]
Lift distributions

\[ FPE \quad \alpha = -1.8^\circ \]

\[ FPE + BLE \quad \alpha = -0.7^\circ \]

\[ LPE \quad \alpha = -1.6^\circ \]

\[ RANS \quad \alpha = -0.3^\circ \]

\[ Euler \quad \alpha = -1.7^\circ \]
Moment distributions

\[ X_{ref} = X_{ac} \]

\[
\begin{align*}
\text{viscous} & : \quad \alpha = -0.3^\circ \\
\text{FPE + BLE} & : \quad \alpha = -0.7^\circ \\
\text{FPE} & : \quad \alpha = -1.8^\circ \\
\text{Euler} & : \quad \alpha = -1.7^\circ \\
\text{LPE} & : \quad \alpha = -1.6^\circ \\
\text{inviscid} & : \quad \alpha = -1.7^\circ
\end{align*}
\]
Near-field drag breakdown

\[ C_D = 0.15 \]

\[ \alpha = -1.6^\circ \]
\[ \alpha = -1.8^\circ \]
\[ \alpha = -0.7^\circ \]
\[ \alpha = -1.7^\circ \]
\[ \alpha = -0.3^\circ \]

FPA: Flat Plate Analogy
Analysis

**Physics**

- **Shocks** completely change the physics and **must** be taken into account.
- The **boundary layer** significantly impacts **shock location** and **strength** and should be modeled.
- The **friction drag** can be accurately computed by the **FPA**.

**Modeling**

- The **Linear Potential** Equation is **not accurate** enough for transonic flows while **Euler** and **RANS** equations are too **costly**.
- The **Full Potential** Equation gives **meaningful results** for **little runtime**, especially when corrected by the **Boundary Layer** Equations.
- The **Full Potential Equation** alone can be used for **routine computations** and supplemented by a **boundary layer** model to **adjust** the **solution**.
Overview

**Evaluate** existing models & methods to efficiently solve transonic flows

**Develop** a fast aerodynamic solver for transonic loads computation based on the most efficient flow model
Potential equation

Linear Potential Equation

Flow
- Linear
- Subsonic or supersonic
- NOT transonic

Solver – Boundary Element Method

Wing panel

Wake panel

Singularities

Full Potential Equation

Flow
- Nonlinear
- Subsonic, weak transonic or supersonic

Solvers
- Finite Element/Volume Method
- Field Panel Method

\[ \sigma = 0 \quad \Delta \phi = \sigma \quad \sigma = -\frac{\nabla \rho}{\rho} \cdot \nabla \phi \]
Field Panel Method

Boundary Element Method
• $\Delta \phi = 0$
• On the wing surface

Field Method
• $\sigma = -\frac{\nabla \rho}{\rho} \cdot \nabla \phi$
• In the field

Advantages
• Cartesian grid
• Aerodynamic Influence Coefficients

Disadvantages
• Memory requirement
• Not well documented
Incompressible prediction (PM)

1. \( \tau = -u_{n,\infty} - u_{n,\sigma} \)
2. \( \mu = A^{-1}B\tau \)
3. \( u_i = f(\tau, \mu) \)
4. \( c_p = g(u_i) \)


Onera M6 (\( \bar{c} \))

\[ M = 0, \quad \alpha = 3^\circ \]
Compressible correction (FM)

Method implemented following Gebahrt et al., *An Implicit-Explicit Dirichlet-Based Field Panel Method for Transonic Aircraft Design* (2001)

\[ \phi = A_f \mu + B_f \tau + C_f \sigma \]
\[ \rho = h(\partial_i \phi) \]
\[ \sigma = -\frac{\partial_i \phi \partial_i \rho}{\rho} \]
\[ u_{n,\sigma} = C_b \sigma \]

NACA 0012 (\(\bar{c}\))

\(M = 0.7, \quad \alpha = 0^\circ\)

Tranair
My code
Transonic computation - pressure

Onera M6 (\( \bar{c} \))

\[ M = 0.84, \quad \alpha = 3^\circ \]

Panair
Tranair
Gebhardt
My code
Transonic computation – lift & moment

Onera M6

\[ M = 0.84, \quad \alpha = 3^\circ \]
Summary

Benchmark

- Comparison of different levels of fidelity
- FPE + BLE achieves best efficiency

Development

- Development of the FPM
- Incompressible and subcritical flow results are very good
- Transonic results are not yet satisfactory