A New Vertical Tail Design Procedure for General Aviation and Turboprop Aircraft

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http://dx.doi.org/10.5281/zenodo.546414

11th EWADE, Linkoping (Sweden), September 17-18 2013
Research motivation

• Tail plane design needs an accurate determination of stability derivatives
• Semi-empirical methods are based on obsolete geometries (NACA ‘30s to ‘50s)
• Discrepancies between methods USAF DATCOM and ESDU
• Develop a new reliable procedure for turboprop and commuter airplanes
USAF DATCOM and ESDU procedures for the evaluation of directional static stability derivatives are mainly based on these geometries!

Geometry for the investigation on wing position in fuselage

Geometry for the investigation on tail-body interaction

Actual geometries ATR-42

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USAF DATCOM approach

\[ C_{L_{\alpha}} = \frac{2\pi A}{2 + \left[ \frac{B^2 A^2}{\kappa^2} \left( 1 + \frac{\tan^2 \Lambda_{c/2}}{B^2} \right) + 4 \right]^{1/2}} \]

VT effective aspect ratio, sweep angle, Mach number

\[ A_{V_{\text{eff}}} = \frac{A_{V(f)}}{A_V} \left[ 1 + k_{Vh} \left( \frac{A_{V(hf)}}{A_{V(f)}} - 1 \right) \right] \]

\[ C_{Y_{\beta}} = -k_V C_{L_{\alpha}} V \left( 1 + \frac{d\sigma}{d\beta} \right) \eta_V \frac{S_V}{S} \]

\[ \left( 1 + \frac{d\sigma}{d\beta} \right) \eta_V = \text{Sidewash (Wing effect)} \]

\[ = 0.724 + 3.06 \frac{S_V/S}{1 + \cos \Lambda_{c/4}} + 0.4 \frac{z_W}{z_f} + 0.009 \]

TProp values (ATR-72):
\[ S_V/S = 0.25, \quad A = 12 \]
High wing = 1.04
Low wing = 1.44

Body effect

H-tail effect
Star-CCM+

CAD import → Mesh generation

Post-process → Analysis

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Computing Grid

- University’s cluster grid
- Up to 128 CPUs for a single run
- Advice: 1 CPU every 250000 cells
- CPU time (no mesh generation):
  - minutes for partial configurations
  - hours for complete airplane
NACA Test cases

Convergence

- Check of convergence
  1. Residuals
  2. Aerodynamic coefficients
  3. Wall $y^+$

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Test cases – NACA 540

Longitudinal test case
\[ A = 6 \quad Re = 3\times10^6 \]
no. of cells \( \approx 1\times10^6 \)
Test cases – NACA 730

Directional test case
\[ \alpha = 0^\circ \quad \beta = 5^\circ \quad Re = 609\,000 \]
no. of cells \( \approx 5\,000\,000 \)
Test cases – NACA 1049

Directional test case
$\alpha = 0^\circ$  $\beta = -10^\circ$ to $10^\circ$
$Re = 710\,000$
no. of cells $\approx 4\,000\,000$
Development of a new approach

Based on the aerodynamic interference effects highlighted by semi-empirical methodologies, for a typical configuration, the same effects have been investigated through a parametric CFD analysis.

Analysis of:
• Isolated vertical tail (effect of the VT aspect ratio and sweep angle)
• VT-body interference (effect of VT/body relative size)
• Wing sidewash effects (difference between high and low wing position)
• Horizontal tail effects (tailplane position, i.e. body-mounted vs. T-tail, and size)
• Separate effects estimation for control derivative
Many configurations have been investigated with a modular model, to provide a new approach to preliminary tailplane design.

**Table 8**

<table>
<thead>
<tr>
<th></th>
<th>$l_f/d_f$</th>
<th>$l_h/l_f$</th>
<th>$l_c/l_f$</th>
<th>$x_{MLE}/l_f$</th>
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</thead>
<tbody>
<tr>
<td>ATR-72</td>
<td>10.3</td>
<td>1.3</td>
<td>3.2</td>
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</tr>
<tr>
<td>NGTP-5</td>
<td>9</td>
<td>1.3</td>
<td>3.3</td>
<td>0.47</td>
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<tr>
<td>CFD model</td>
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<td>1.3</td>
<td>3.3</td>
<td>0.45</td>
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</table>

**Table 9**

<table>
<thead>
<tr>
<th></th>
<th>$A_v$</th>
<th>$\lambda_v$</th>
<th>$\Delta_{VLE}$</th>
<th>$\Delta_{VT}$</th>
<th>$S_v/S$</th>
<th>$x_{MLE}/l_f$</th>
<th>$V_v$</th>
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</thead>
<tbody>
<tr>
<td>ATR-72</td>
<td>1.56</td>
<td>0.61</td>
<td>32°</td>
<td>17°</td>
<td>0.20</td>
<td>0.83</td>
<td>0.098</td>
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<tr>
<td>NGTP-5</td>
<td>1.43</td>
<td>0.63</td>
<td>25°</td>
<td>15°</td>
<td>0.24</td>
<td>0.85</td>
<td>0.110</td>
</tr>
<tr>
<td>CFD model</td>
<td>Variable</td>
<td>Variable</td>
<td>30°</td>
<td>15°</td>
<td>Variable</td>
<td>Variable</td>
<td>Variable</td>
</tr>
</tbody>
</table>

**Table 10**

<table>
<thead>
<tr>
<th></th>
<th>$A_h$</th>
<th>$\lambda_h$</th>
<th>$\Delta_{MLE}$</th>
<th>$\Delta_{TLE}$</th>
<th>$S_h/S$</th>
<th>$x_{MLE}/l_f$</th>
<th>$V_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATR-72</td>
<td>4.1</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.18</td>
<td>n.a.</td>
<td>0.19</td>
</tr>
<tr>
<td>NGTP-5</td>
<td>4.1</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.25</td>
<td>n.a.</td>
<td>0.19</td>
</tr>
<tr>
<td>CFD model</td>
<td>4.1</td>
<td>0</td>
<td>0°</td>
<td>0°</td>
<td>Variable</td>
<td>Variable</td>
<td>Variable</td>
</tr>
</tbody>
</table>
Vertical tail planform effects on lift curve slope

Typical values

$A_v = 1.5$

$\Lambda_v = 30^\circ$

d$CL \alpha /dA_v \approx 1$

$$C_{L,\alpha} = \frac{2\pi A}{2 + \left( \frac{B^2 A^2}{\kappa^2} \left( 1 + \frac{\tan^2 \Lambda_v / 2}{B^2} \right) + 4 \right)^{1/2}}$$
The effect of the fuselage is measured by the ratio between the vertical tail sideforce coefficients of the body-vertical configurations and those of the same vertical tail planforms previously analysed.

\[
\frac{X_{ac,mac}}{b_v}
\]
Fuselage effect $K_F$

![Diagram showing typical values and best fit line for $K_F$ versus $b_v / 2r$.](image)

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USAF DATCOM
Configurations involved in the wing-body-tail investigation

Straight wings of different aspect ratio (6 to 16) in three fuselage positions (high, mid and low) have been considered. Two vertical tailplane aspect ratio (1 and 2) are considered.

\[ \frac{z_w}{r_f} > 0 \]

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Wing effect $K_w$

**Primary effect (wing position)**
Influence on angle of sideslip and dynamic pressure at VT root

**Secondary effect (wing AR)**

$K_w$ against $A$ for different wing positions:
- Low wing $A_r = 1$
- Low wing $A_r = 2$
- Mid wing $A_r = 1$
- Mid wing $A_r = 2$
- High wing $A_r = 1$
- High wing $A_r = 2$

$K_w$ against $z_w/r_t$ for different aspect ratios ($A$):
- $A = 6$
- $A = 8$
- $A = 10$
- $A = 12$
- $A = 14$
- $A = 16$

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Wing-body sidewash

\[ A = 10 \]
\[ A_v = 1 \]
\[ \beta = 5^\circ \]

Cross-wind direction →

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Horizontal tailplane effect

1 straight horizontal tail
6 spanwise positions
3 chordwise positions
3 vertical tail’s aspect ratios

Wing position (high/low) is not important (verified)
Horizontal tailplane effect $K_H$

$$K_H = 1 + K_{Hs} (K_{Hp} - 1)$$

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T-tail configuration

<table>
<thead>
<tr>
<th>$A_v$</th>
<th>$C_{Yv}(BVH)$</th>
<th>$C_{Yv}(BV)$</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.0253</td>
<td>0.0194</td>
<td>1.30</td>
</tr>
<tr>
<td>1.5</td>
<td>0.0394</td>
<td>0.0322</td>
<td>1.22</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0521</td>
<td>0.0451</td>
<td>1.15</td>
</tr>
</tbody>
</table>

In this approach the increase of VT effectiveness for T-tail configuration is much lower than USAF DATCOM prediction.

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Directional control derivative

\[ C_{Y_v} = C_{Y_{\beta,v}} \beta + C_{Y_{\delta r}} \delta_r \]

\[ C_{\eta_{\delta r}} = -C_{Y_{\delta r}} \left( l_v \cos \alpha + z_v \sin \alpha \right) / b \]

\[ C_{Y_{\beta}} = -k_v C_{L_{\alpha,v}} \left( 1 + \frac{d\sigma}{d\beta} \right) \eta_v \frac{S_v}{S} \]

\[ C_{Y_{\delta r}} = C_{L_{\alpha,v}} \left( A_{\text{eff}} \right) \tau K_{\eta} \frac{S_v}{S} \]

Our approach:

\[ C_{Y_{\beta,v}} = f(K_F, K_W, K_H) \]

\[ C_{Y_{\delta r}} = f(K_{\delta r}) \]

USAF DATCOM

The aerodynamic interference effects due to fuselage and horizontal tail are considered to be the same for both derivatives (stability and control).

\[ \delta_r = 10^\circ \]
Investigation on rudder deflection’s effects

<table>
<thead>
<tr>
<th>( A_r )</th>
<th>( b/2r )</th>
<th>( C_{Y_V}(V) )</th>
<th>( C_{Y_V}(BV) )</th>
<th>( BV/V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.06</td>
<td>0.0303</td>
<td>0.0348</td>
<td>1.15</td>
</tr>
<tr>
<td>1.5</td>
<td>3.01</td>
<td>0.0505</td>
<td>0.0563</td>
<td>1.12</td>
</tr>
<tr>
<td>2.0</td>
<td>3.89</td>
<td>0.0682</td>
<td>0.0751</td>
<td>1.10</td>
</tr>
</tbody>
</table>

\( \beta = 0^\circ \)
\( \delta r = 10^\circ \)
Vertical Tail Stability and Control

Evaluation of the vertical tail contribution to aircraft directional stability and control. Developed with more than 200 CFD simulations. Valid in subsonic incompressible flow at low angles of incidence and sideslip.

\[ C_{Yv} = C_{Y_{\beta v}} \beta + C_{Y_{\delta r}} \delta_r \]

where

- \( C_{Y_{\beta v}} \) directional stability derivative,
- \( \beta \) sideslip angle,
- \( C_{Y_{\delta r}} \) directional control derivative,
- \( \delta_r \) rudder’s deflection angle.
Directional stability

The interference effects previously evaluated are now combined.

\[ C_{Y\beta_v} = K_F K_W K_H C_{L\alpha_v} \frac{S_v}{S} \]

where

- \( K_F \) fuselage effect,
- \( K_W \) wing effect,
- \( K_H = 1 + K_{Hs} (K_{Hp} - 1) \) horizontal tailplane effect,
- \( K_{Hp} \) horizontal tailplane position effect,
- \( K_{Hs} \) horizontal tailplane size effect,
- \( C_{L\alpha_v} = f(A_v, \Lambda_v, M) \) Helmbold-Diederich formula.
The new approach for directional control derivative

\[ C_{Y_{\delta r}} = K_{\delta r} C_{L_{\alpha v}} \alpha \delta \frac{S_v}{S} \]

3D rudder effectiveness (estimated on the isolated vertical tail)

\[ K_{\delta r} = \left[ 1 + \frac{K_F - 1}{2.2} \right] \cdot \begin{cases} 1.07, & \text{if horizontal tail is body-mounted,} \\ 1.33 - 0.9A_v, & \text{for T-tail configurations.} \end{cases} \]

Body effect is the reduced to the half of that one previously investigated in sideslip
Example of application

Tecnam P2012

$\triangle$ from CFD

<table>
<thead>
<tr>
<th>Method</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>New meth</td>
<td>5.0 %</td>
</tr>
<tr>
<td>USAF</td>
<td>34.0 %</td>
</tr>
<tr>
<td>ESDU</td>
<td>8.8 %</td>
</tr>
</tbody>
</table>

$C_L_{\alpha v}$: 2.160 rad$^{-1}$
$K_F$: 1.260
$K_W$: 0.953
$K_{Hp}$: 1.139
$K_{Hs}$: 1.022
$K_H$: 1.142
$K_F K_W K_H$: 1.371
$C_Y_{\beta v}$: 0.358 rad$^{-1}$
$C_Y_{\beta v}$ USAF: 0.249 rad$^{-1}$
$C_Y_{\beta v}$ ESDU: 0.410 rad$^{-1}$
$C_Y_{\beta v}$ CFD: 0.377 rad$^{-1}$
Conclusion

A new procedure to evaluate the aerodynamic interference of airplane’s components on the vertical tailplane has been proposed. It has been developed by solving Navier-Stokes equations in a fully turbulent subsonic flow regime on more than 200 regional turboprop aircraft configurations, with the aim to bring CFD into aircraft preliminary design.

Features of the new procedure:
• Based on actual turboprop aircraft geometries
• Low data scatter among configurations
• Simplicity of the approach

Drawbacks:
• Extendable to commuters or jet airplanes?
• No engine, dihedral, wing sweep, flaps or propeller effects considered
• To do: wind tunnel tests

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