Primary control surface design for BWB aircraft

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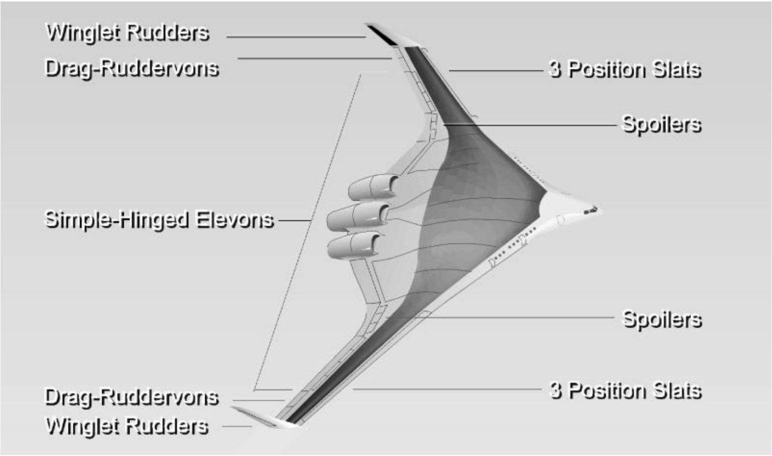
Challenge the future

Challenge

Multiple redundant control surfaces:
- Optimal architecture
- Control surface allocation problem
- Power needed for actuation

Flight regime of interest:
- Low speed (control power)
- Cruise flight (trim drag)



Source: Liebeck, RH. Design of the Blended Wing Body Subsonic Transport, Journal of Aircraft, 41(1)

Source: Cosentino, GB. CFD to Flight: Some Recent Success Stories of X-plane Design to Flight Test at the NASA Dryden Flight Research Center. 2007 ITEA Symposium; 12-15 Nov. 2007; Kaua, HI; United States

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- **Control** surface **allocation problem**
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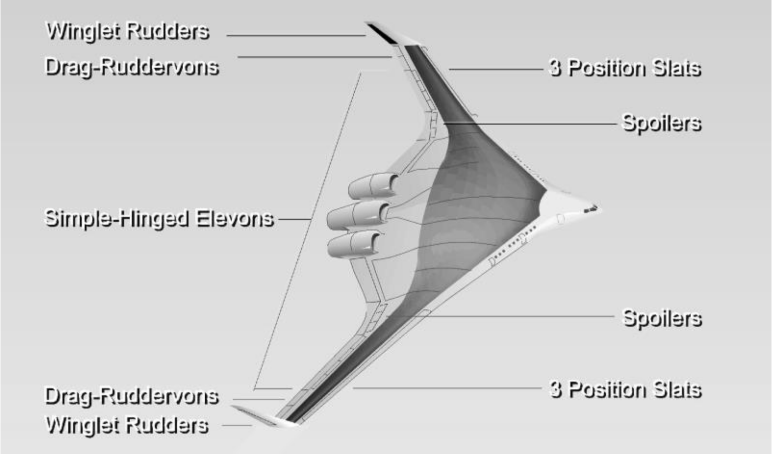

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Control allocation problem definition

$$\boxed{\vec{m} = B\vec{u}}$$

$$\vec{m} = \begin{bmatrix} C_l & C_m & C_n \end{bmatrix}^T, \qquad B = \begin{bmatrix} C_{l_{\delta_1}} & C_{m_{\delta_1}} & C_{n_{\delta_1}} \\ . & . & . \\ . & . & . \\ . & . & . \\ C_{l_{\delta_n}} & C_{m_{\delta_n}} & C_{n_{\delta_n}} \end{bmatrix}, \qquad \vec{u} = \begin{bmatrix} \delta_1 & . & . & . & \delta_n \end{bmatrix}^T$$

- Find the vector ***u*** that provides the desired moment ***m***
- Infinite number of solutions $\Rightarrow$ Select ‘optimal’ solution

Control allocation problem definition

However, what is optimal?

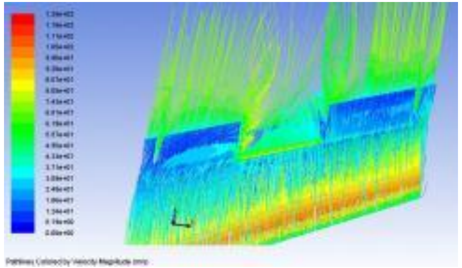
- Minimize control effort
- Minimize drag
- Use most effective control surfaces
- Use algorithm with low computational efficiency (flight control computer)
- Take into account structural loads
- Certification aspects

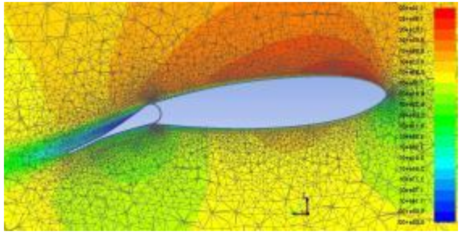
Aims and objectives

Compare performance of typical control allocation algorithms for a BWB test case and determine the impact on the aircraft design

Investigate the effect of typical assumptions w.r.t.:

- Linearity control derivatives
- Control surface interaction effects
- Large deflection angles
- Angle of attack





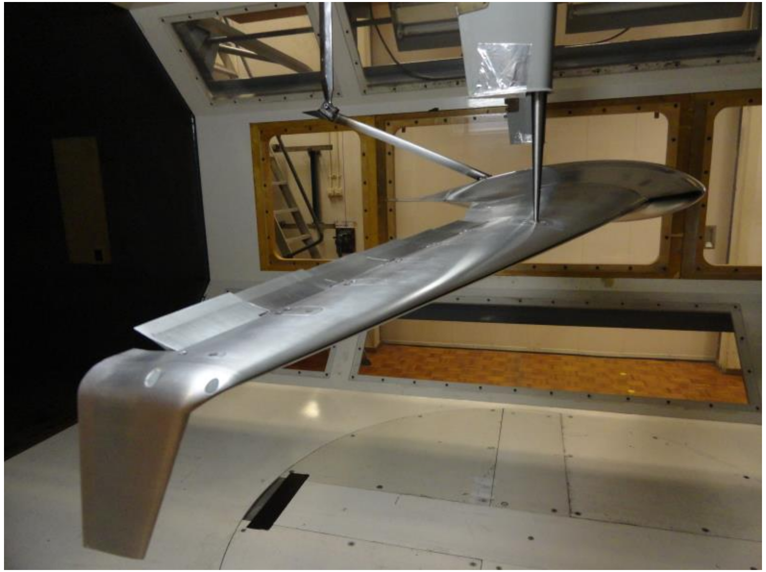
Contents

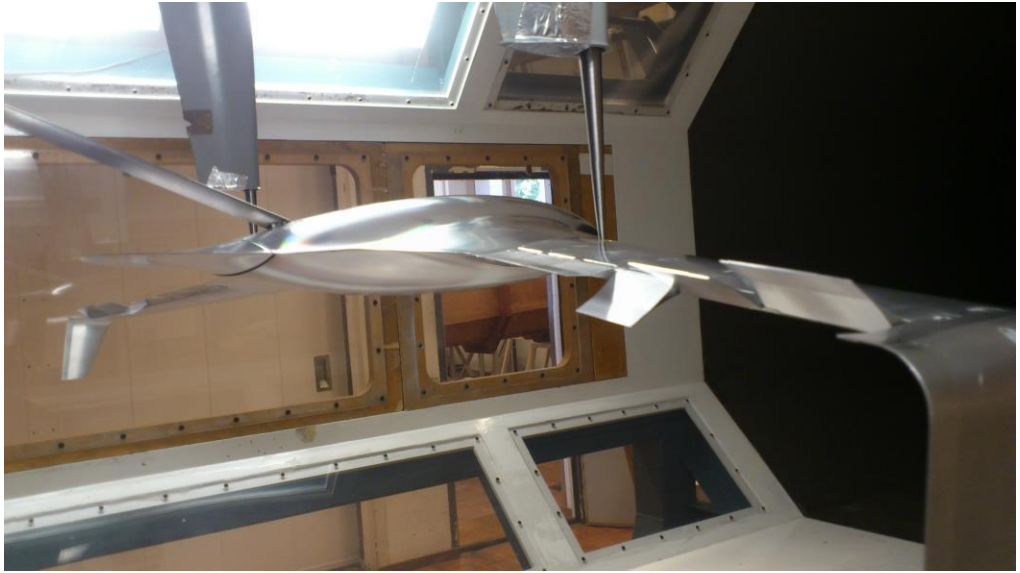
Test case – ZEFT BWB design

- ZEFT: Zero Emission Flying Test Bed
- UAV BWB design by group of 10 students
- 13 primary control surfaces
- Wind tunnel model (span 1.45m)
- Low Turbulence Tunnel (LTT)
  - test section: 1.25m x 1.80m
  - Maximum speed: 120m/s

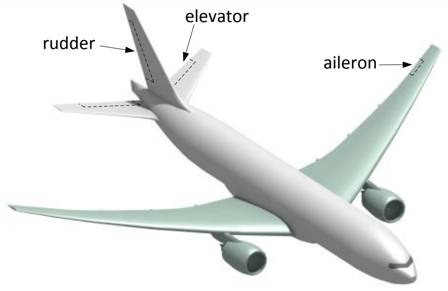
Wind tunnel model – ZEFT BWB – in low turbulence tunnel

Test case – ZEFT BWB design





Test case – CA algorithms



Daisy chain approach

Algorithms:

- Daisy chain (DC)

- Fixed point iteration (FXP)
- Weighted pseudo inverse (WPI)
- L_1 norm linear programming (LP)
- Direct allocation linear programming (DA)

Mathematical problem:

$$\min J = \left\| B\vec{u} - \vec{m}_{desired} \right\| + \varepsilon \left\| \vec{u} - \vec{u}_{preferred} \right\|$$

$$\left\| x_p \right\| = \left(\sum_{i=1}^{n} \left| x_i \right|^p \right)^{1/p}$$

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Method

Wind tunnel test campaign 1
Aerodynamic database

- Lift drag polar (clean - untrimmed)
- Moment coefficient (clean – untrimmed)
- Control derivatives (sensitivity to α, V, $\delta_{1\rightarrow 2}$)

Wind tunnel test campaign 2
Low speed control power

- Comparison of various CA algorithms
- Quantify impact of assumptions (linearity)

Wind tunnel test campaign 3
Trim drag

- Comparison of various CA algorithms
- Quantify Impact of assumptions (linearity)

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- Introduction
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- Method
- **Results**
- Conclusions and recommendations

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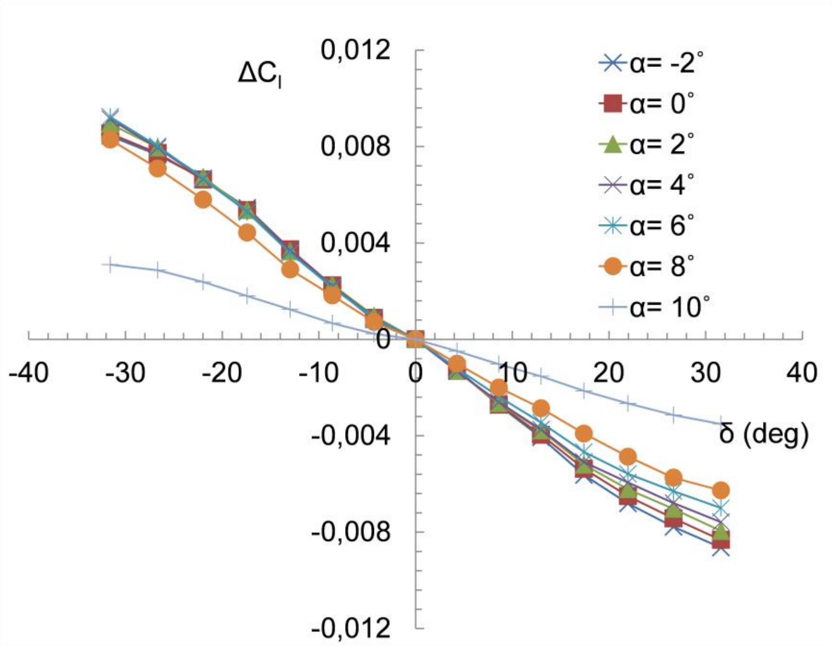
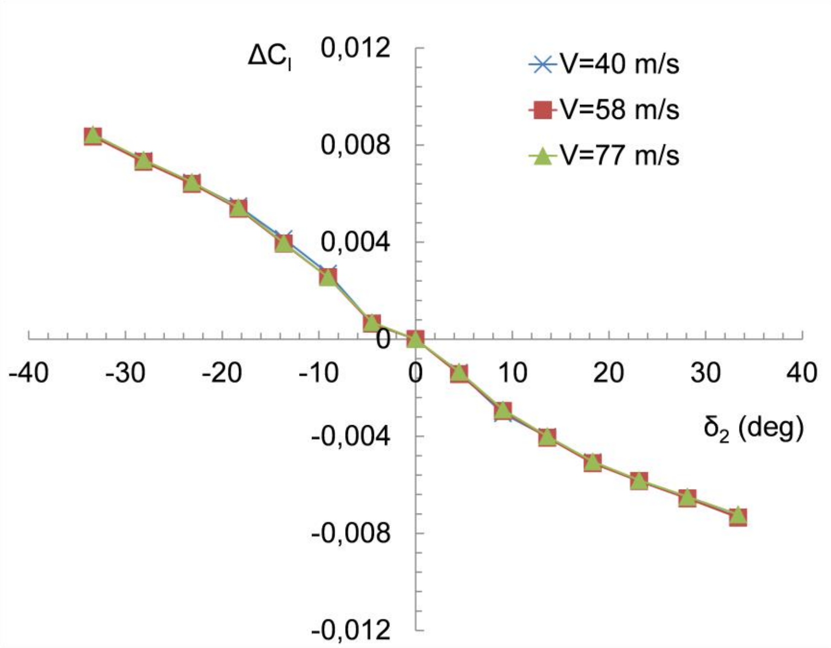
Results wind tunnel – aerodynamic database

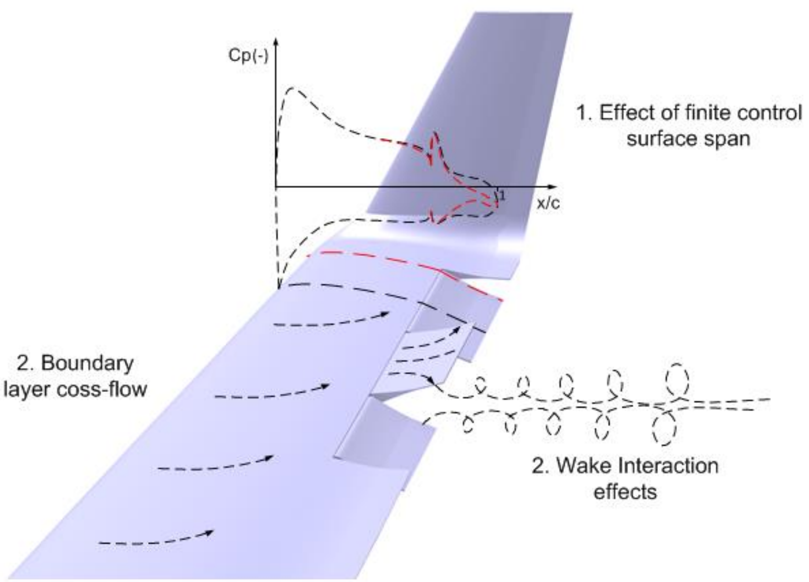


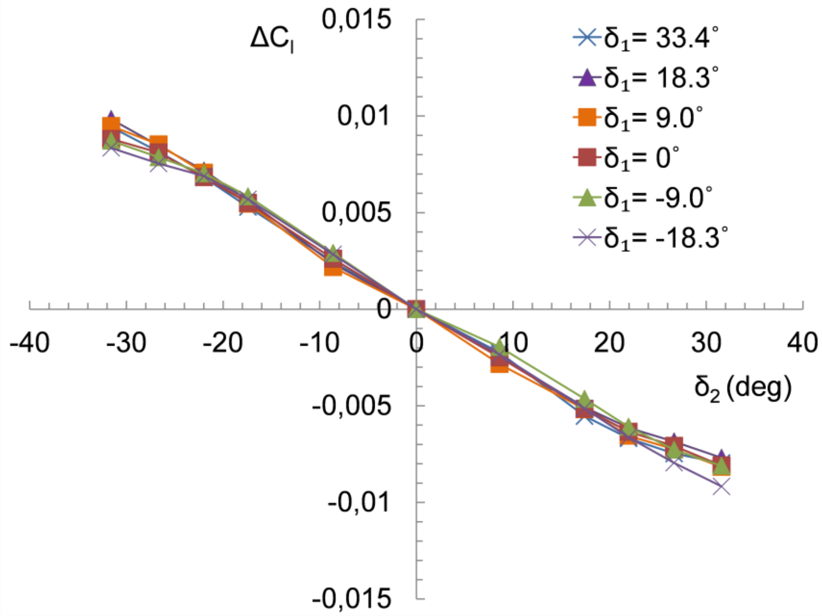
Roll control derivative, as function of α and δ
(control surface 2, V = 80m/s)



Roll control derivative as function of V
(control surface 2, α = 0 deg)

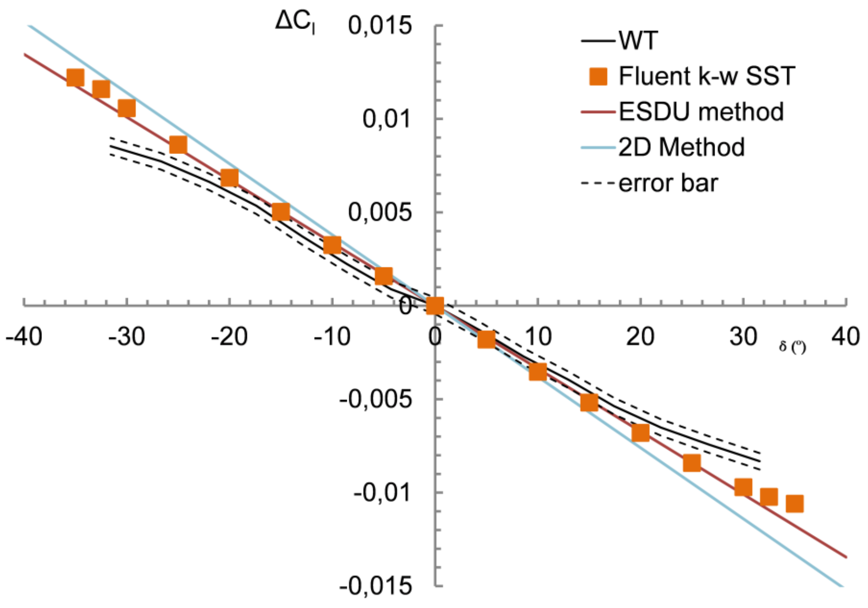
Results wind tunnel – aerodynamic database



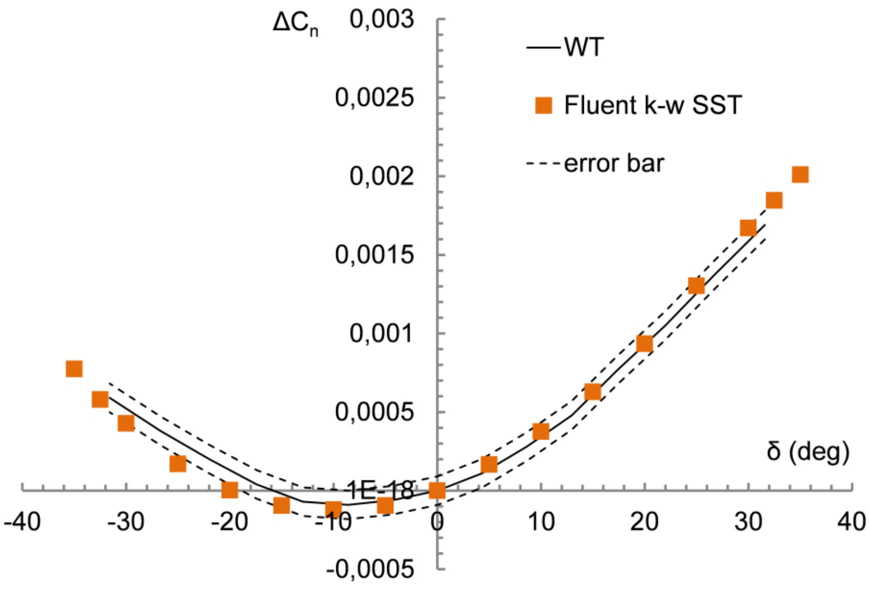


Roll control derivative, interaction effect with control surface 1

Comparison with numerical simulations



Roll control derivative
(V = 80m/s, α = 0deg)



Yaw control derivative
(V = 80m/s, α = 0deg)

Results wind tunnel – aerodynamic database

Database

- Extensive database created
- Control derivative w.r.t. pitch moment and yaw moment also measured
- Clean lift drag polars and moment coefficients included

Preliminary conclusions (for aircraft design purposes)

- Control surface interaction effects on control derivatives can be neglected
- Angle of attack and control deflection has a significant effect on control derivatives
- At large deflection angles control effectiveness is reduced significantly
- Airspeed effects on derivatives can be neglected

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↓

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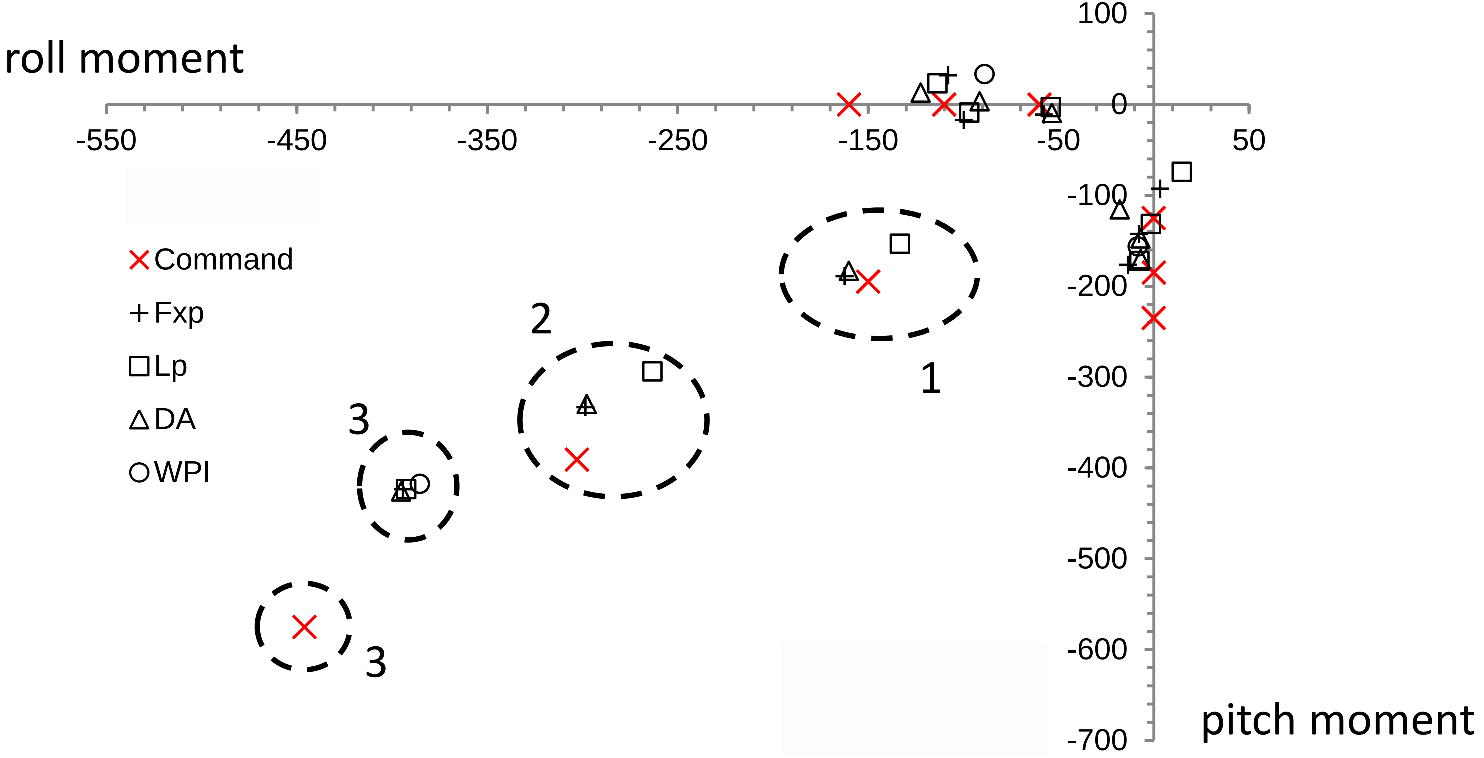
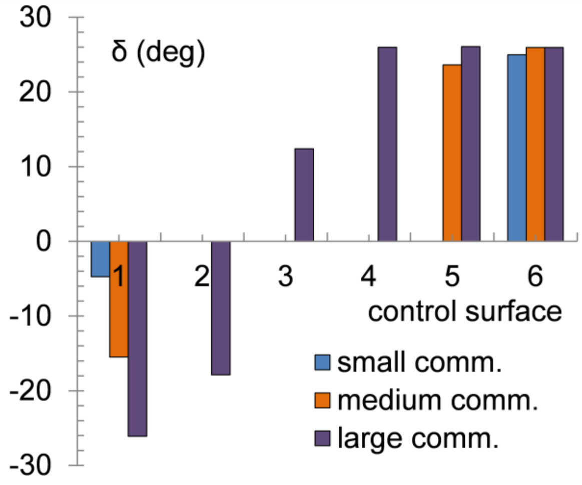
Results wind tunnel – control power

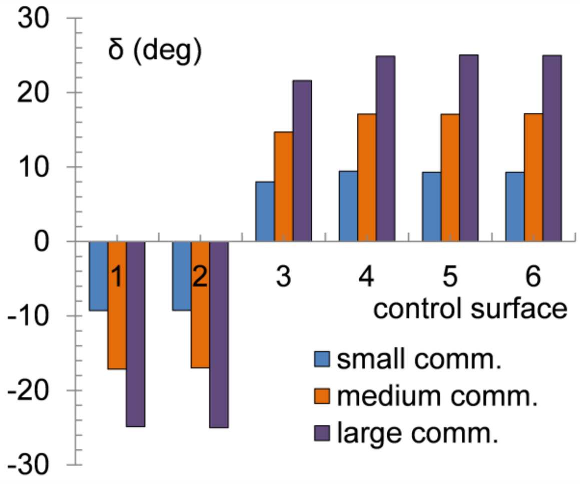


Results wind tunnel – control power

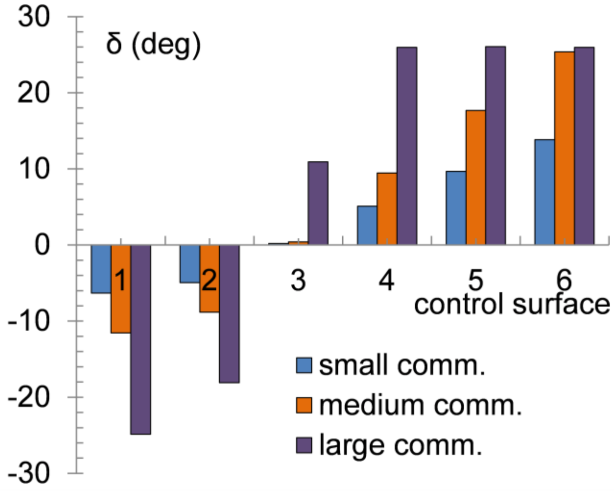
Pure roll command - Different solutions are found by the control allocation algorithms:



LP-1 method



LP-DA method



FXP method

Results wind tunnel – control power

Command $[C_l \; C_m]$ $(\cdot 10^4)$	Performance of CA algorithms (%)			
	LP-1	WPI	FXP	LP-DA
$[-60 \; 0]$	89.1	81.1	81.1	81.2
$[-110 \; 0]$	85.6	81.9	81.9	82.9
$[-160 \; 0]$	67.5	50.9	61.8	75.1
$[0 \; -125]$	57.5	73.9	73.9	83.8
$[0 \; -185]$	71.0	76.6	76.6	79.3
$[0 \; -235]$	73.0	66.3	74.4	72.2
$[-150 \; -195]$	81.7	94.4	94.4	93.6
$[-303 \; -391]$	78.8	88.3	88.3	87.5
$[-446 \; -575]$	77.9	76.8	78.0	78.4
Average	**75.8**	**76.7**	**78.9**	**81.6**

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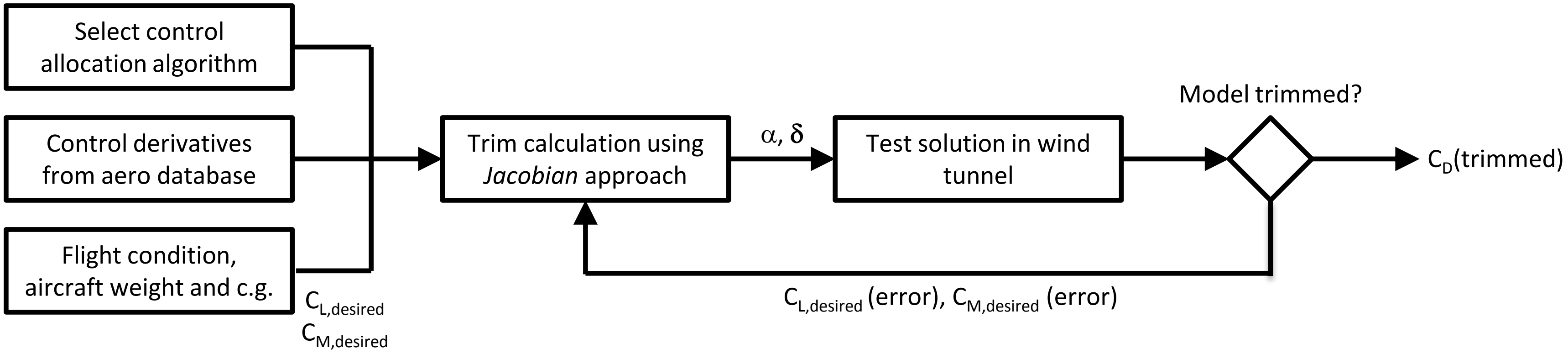
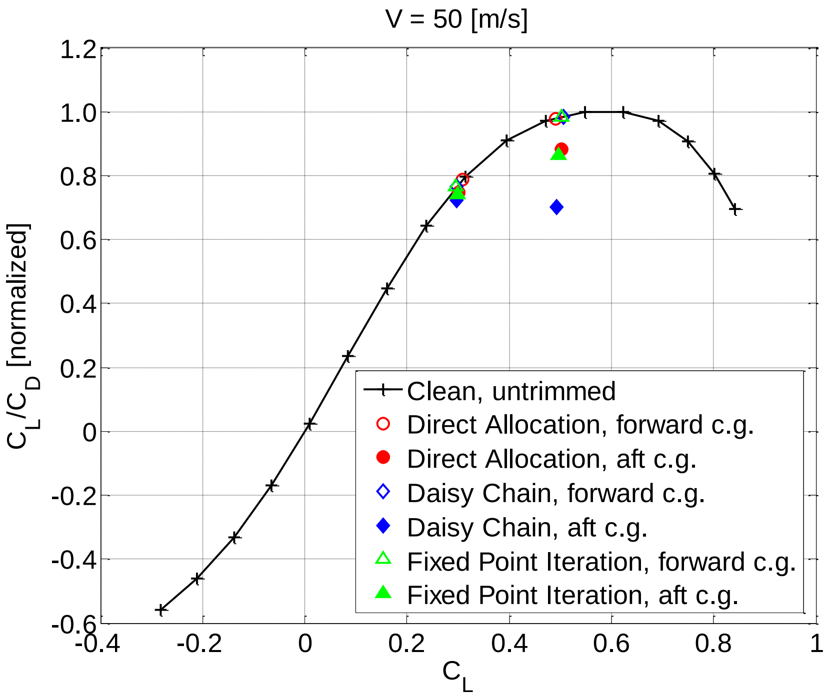
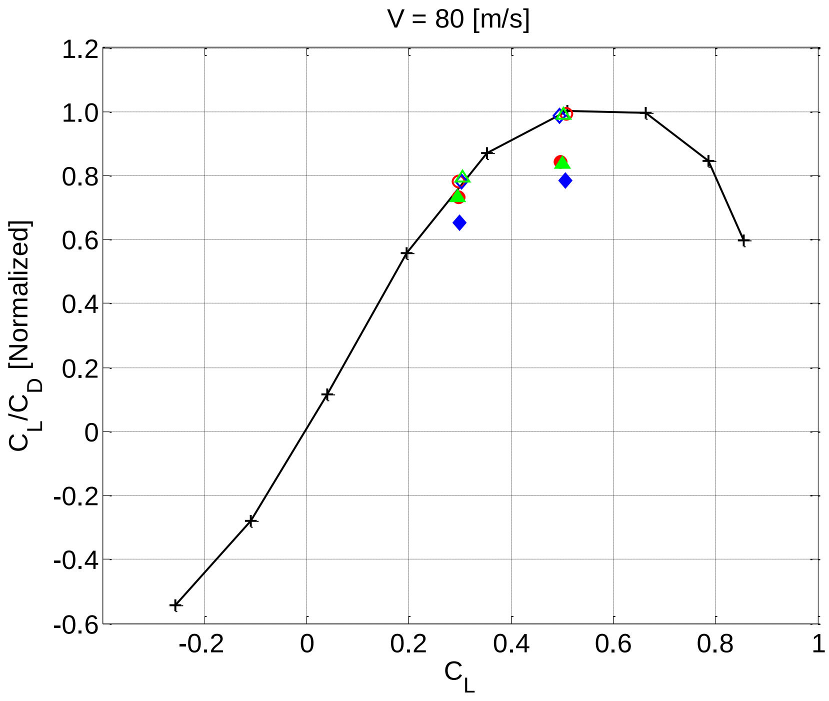


Results wind tunnel – trim drag





Contents

Conclusions and recommendations

Design guidelines for BWB control surfaces:

- The type of control allocation algorithm used has a large impact on trim drag
- The traditional control allocation method used in conventional aircraft designs (daisy chain) should not be used
- The use of linear control derivatives can result in large errors with respect to predicted trim drag and control power
- Use of relatively high fidelity aerodynamic analysis is recommended
- Control allocation schemes must be included in the early design phases
- Design for optimal C_L / C_D and zero C_M for range of cruise conditions
- Alternative trim methods should be considered (e.g. cg shift by fuel trim)

Conclusions and recommendations

- Use design guidelines to set up MDO framework for BWB subsonic passenger transport including control surface architecture and sizing and power needed for actuation
- It is recommended to compute the optimal control allocation for the trim condition offline (using nonlinear techniques) and to store the result as the preferred control vector u_p (slide 10). A simple control allocation technique which can relatively easily be certified, can be used for the control power problem.

Thank you for your attention!

Questions?

More information can be found in the following articles:

Waters, S. M., Voskuijl, M., Veldhuis, L.L.M., Geuskens, F. "Control allocation performance for blended wing body aircraft and its impact on control surface design," *Aerospace Science and Technology*, Vol. 29, No. 1, pp. 18-27, August 2013

Huijts, C., Voskuijl, M., "The impact of control allocation on trim drag of blended wing body aircraft," *Aerospace Science and Technology*, 2014. (*submitted for publication – under review*)