A CFD-based local sensitivity study of the aerodynamic performance of strut-braced wing aircraft

M. Fossati, B. Jones, P. Nagy, E. Minisci, G. Arnoult, M. Meheut

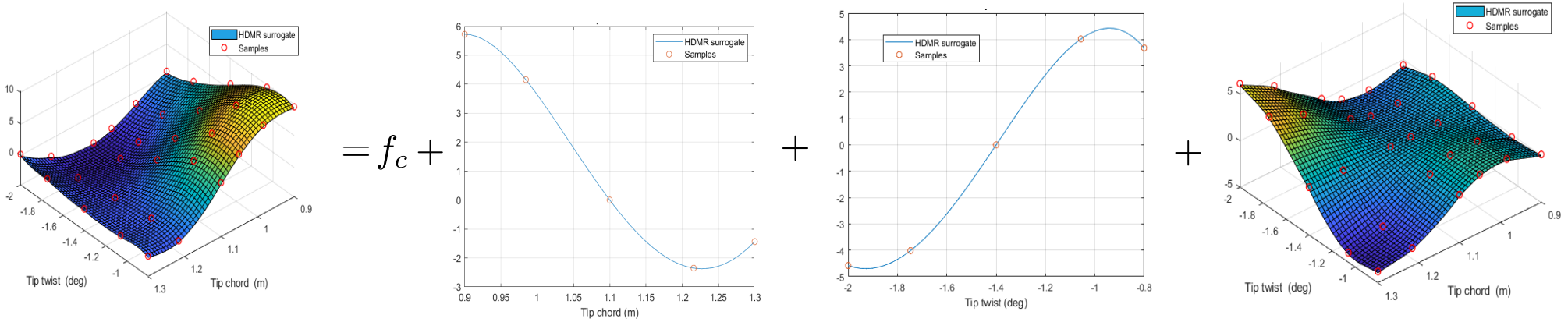
Outline

- Adaptive-cut HDMR
- DoE and problem definition
- High-fidelity local sensitivity analysis:
  - Drag decomposition and analysis
  - Lift decomposition and analysis
  - Constant lift analysis (N=1)
- Final remarks

High-fidelity sensitivity analysis: A-cut-HDMR

- The cost function is decomposed into individual n-factor contributions and their interactions
- The decomposition is used to analyse the influence of the parameters on the cost function and facilitate the interpretation of the physics

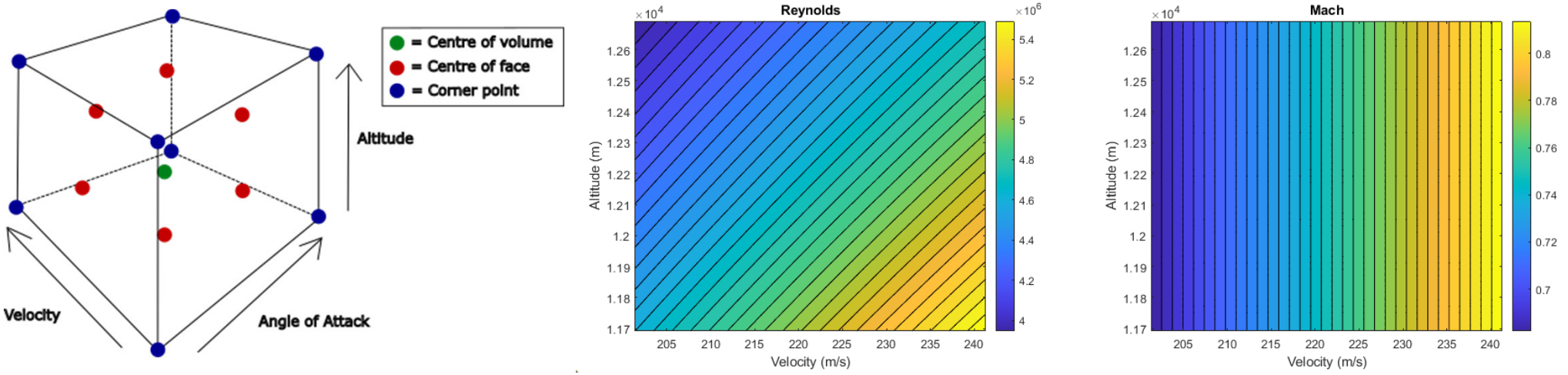
$$f(\mathbf{U}) = f_c + \sum_{i=1}^{N_u} F_i(U_i) + \sum_{i<j<=N_u} F_{i,j}(U_i, U_j) + \ldots + F_{1,2,\ldots,N_u}(U_1, U_2, \ldots, U_{N_u})$$



Example of a 2-factor decomposition

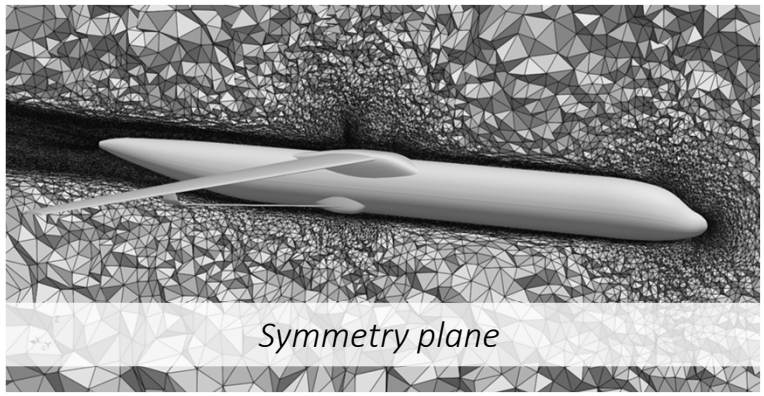
High-fidelity sensitivity analysis: DoE

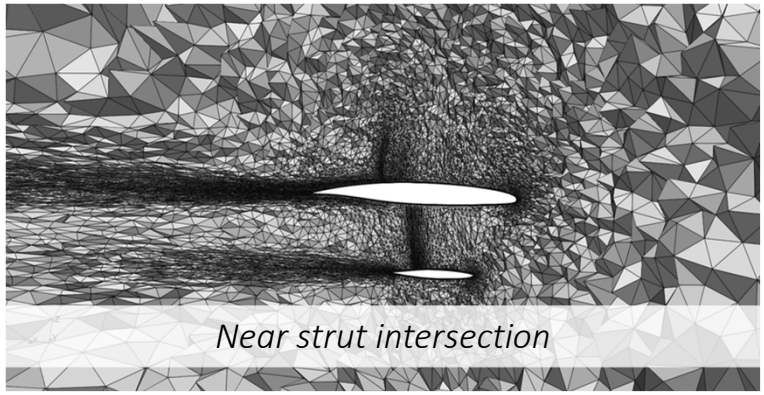
	Altitude [m]	Velocity [m/s]	Angle of Attack [deg]
Cruise	12,192	221.3	1.53
Range	± 500	± 5	± 0.5



Initial DoE (left), variations of Reynolds (centre) and Mach number (right) over the parameter space

Solution at cruise conditions



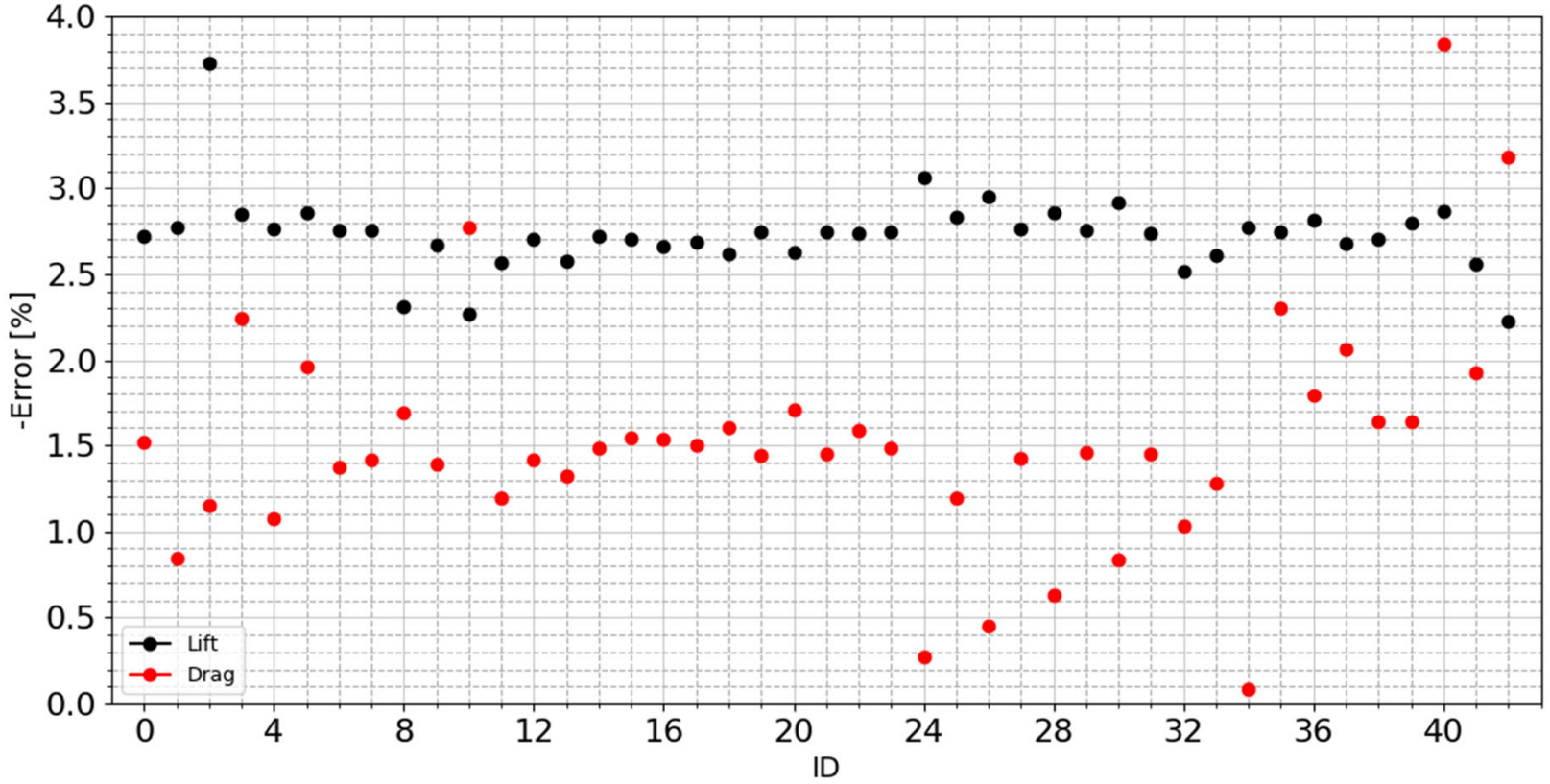


Altitude [m]	Velocity [m/s]	Angle of Attack [deg]	C_L	C_D
12,192	221.3	1.53	0.638	239*

*drag count

Reduced Order Modelling approach: Proper Orthogonal Decomposition

- ROM is built using snapshot-based POD, from 43 snapshots
- Validation through leave-one-out error analysis on Lift and Drag

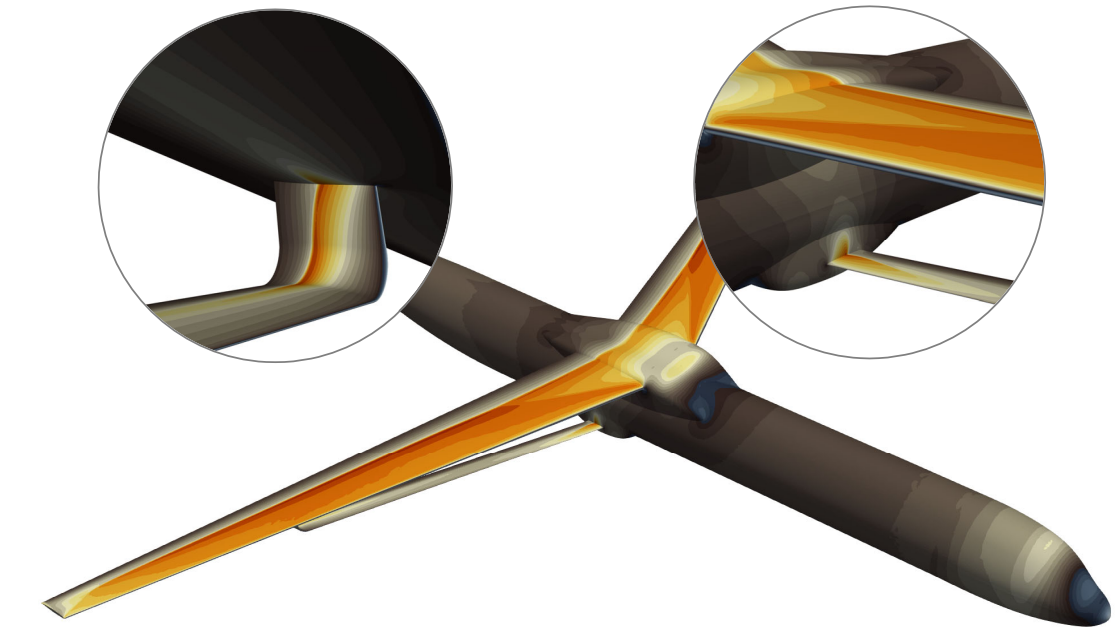


Outcome of the sensitivity for Drag

Drag at cruise: 14.137 kN

	Min ΔD	Max ΔD	Drag Range	Combined
v	-7.51%	16.42%	23.92%	23.92%
α	-7.87%	10.74%	18.62%	18.62%
h	-7.11%	7.66%	14.77%	14.77%
v - α	-5.21%	8.32%	13.53%	49.76%
h - v	-1.38%	1.52%	2.90%	39.64%
h - α	-0.89%	0.98%	1.87%	33.74%
h - v - α	-0.71%	0.76%	1.47%	66.68%
All	-20.28%	46.40%	-	66.68%

v [m/s]	α [deg]	h [km]	Ma
226.3	2.0347	12.192	0.7669



CFD at 2-factor Max Drag conditions (i.e. highest v and highest α) contours of Pressure Coefficient

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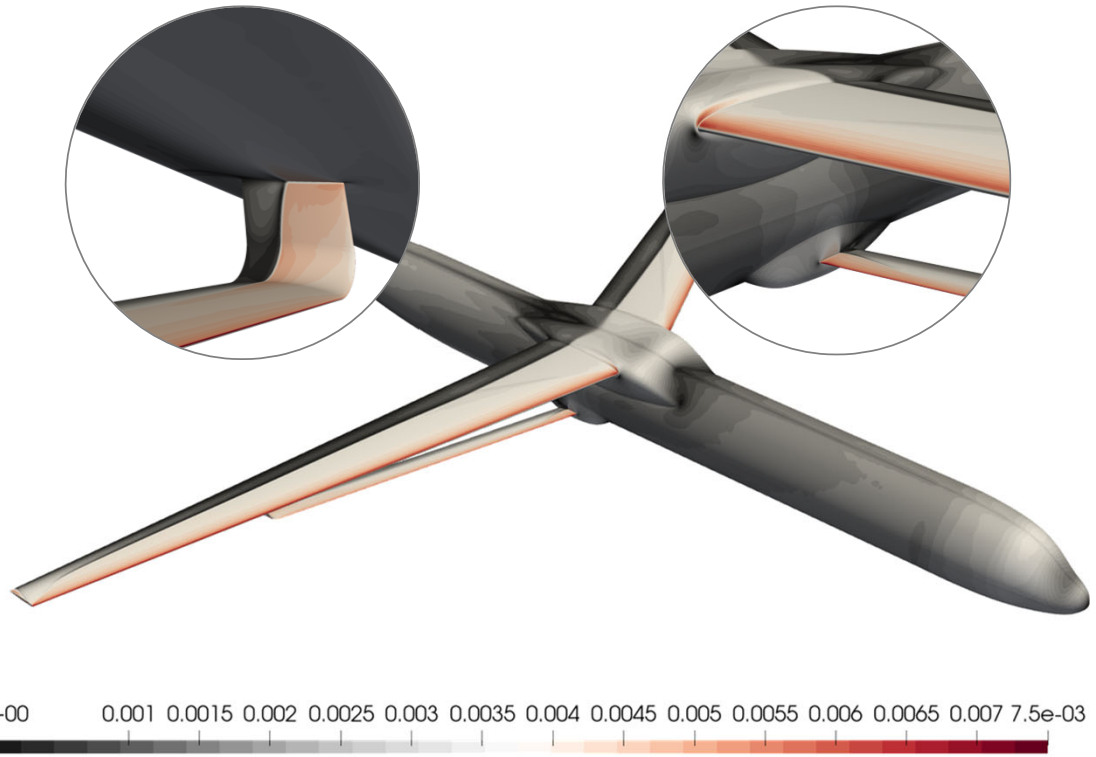

v [m/s]	α [deg]	h [km]	Ma
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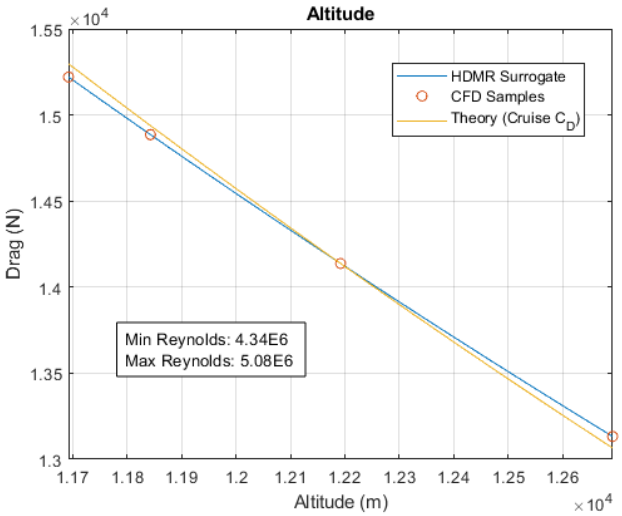
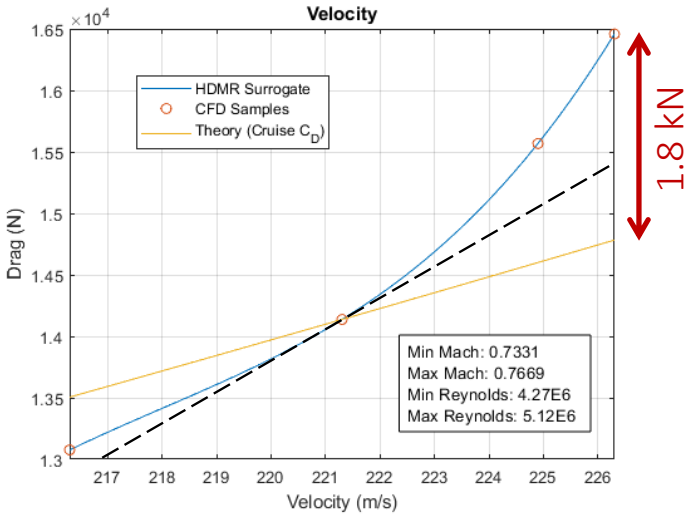
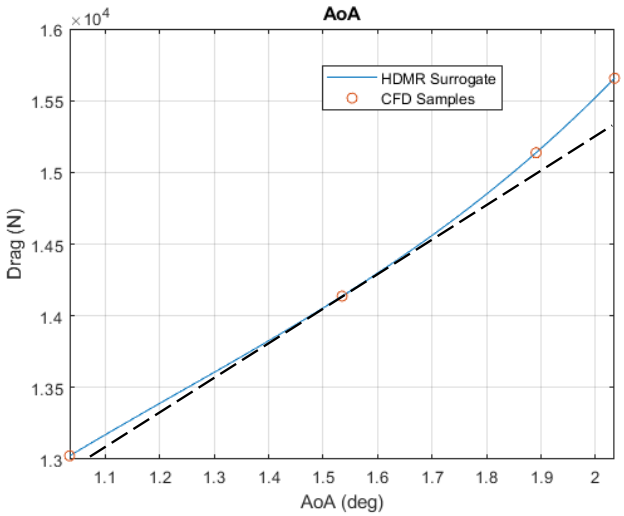
CFD at two-factor Max Drag conditions (i.e. highest v and highest α) contours of Skin friction Coefficient

Drag decomposition 1-factor



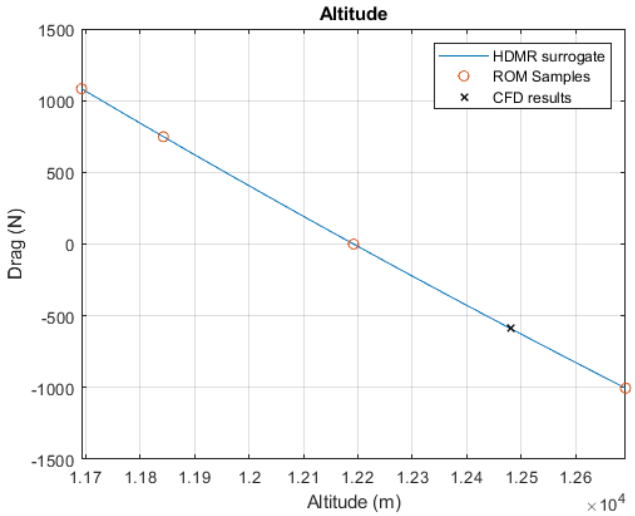


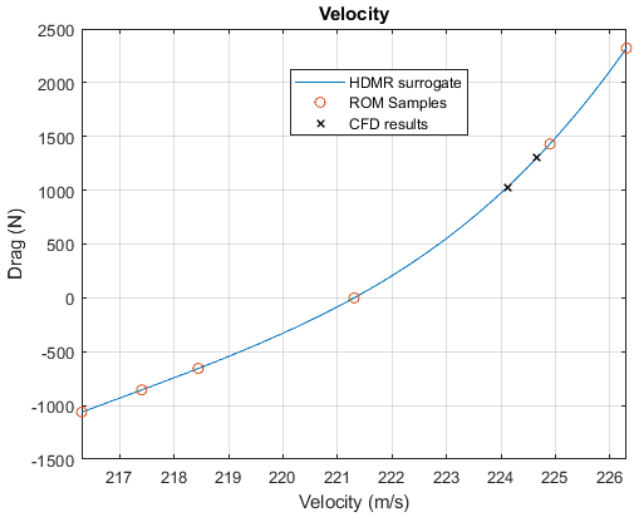


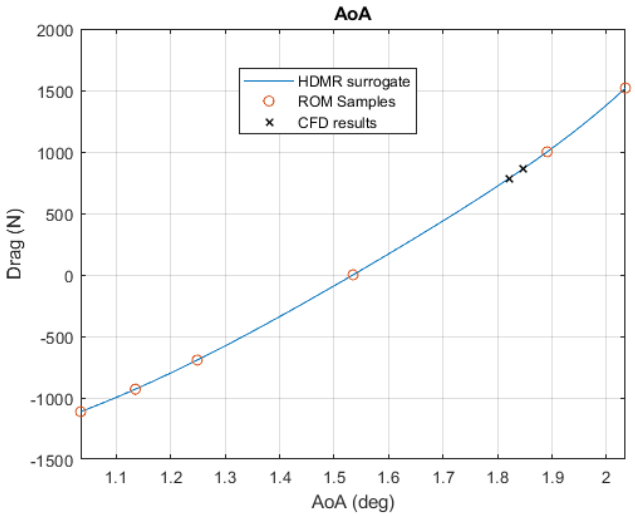
Drag @ cruise: 14.137 kN

	Min ΔD	Max ΔD	Range	*Combined*	Gradient @ cruise point
v	-7.51%	16.42%	23.92%	*23.92%*	1.97% / m/s
α□	-7.87%	10.74%	18.62%	*18.62%*	18.28% / deg
h	-7.11%	7.66%	14.77%	*14.77%*	-0.015% / m

Drag decomposition 1-factor via ROM







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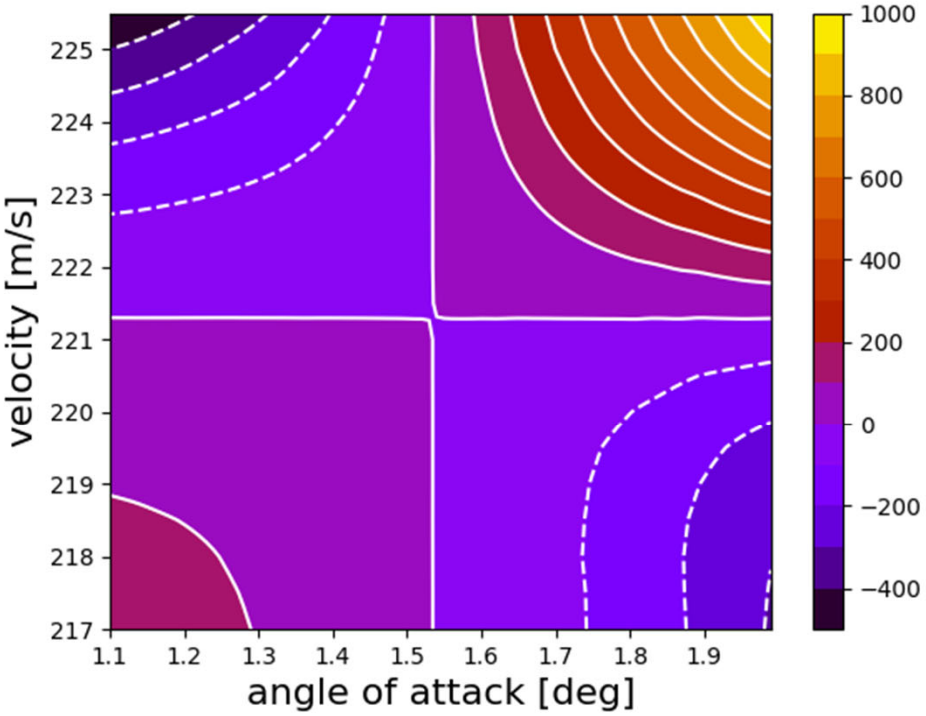
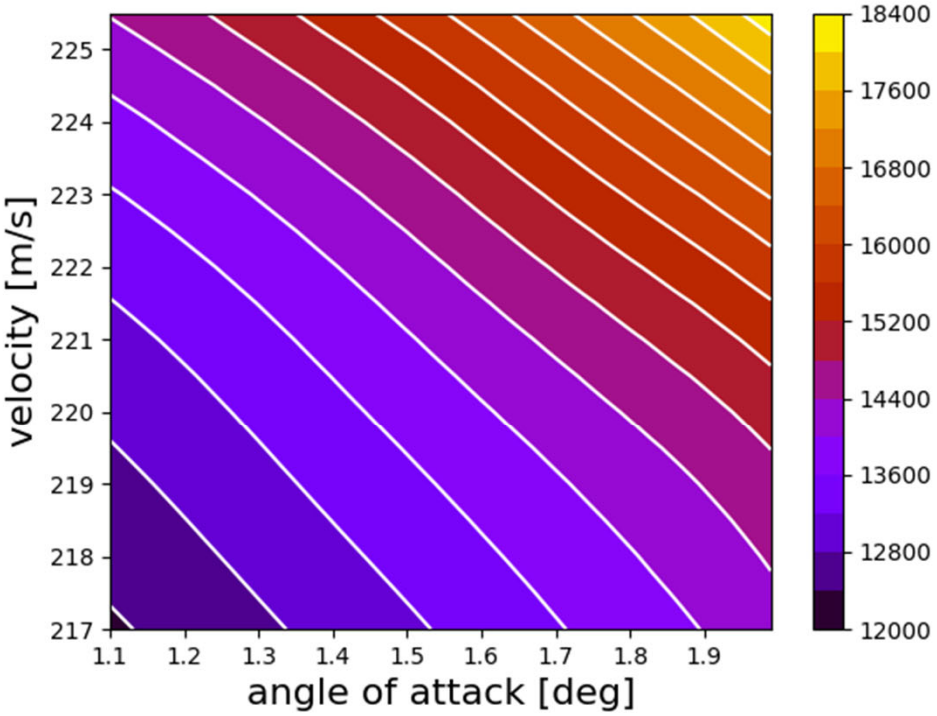
Drag decomposition 2-factors





Incremental response:

$$F_{v,\alpha}(v,\alpha)$$

Cumulative response:

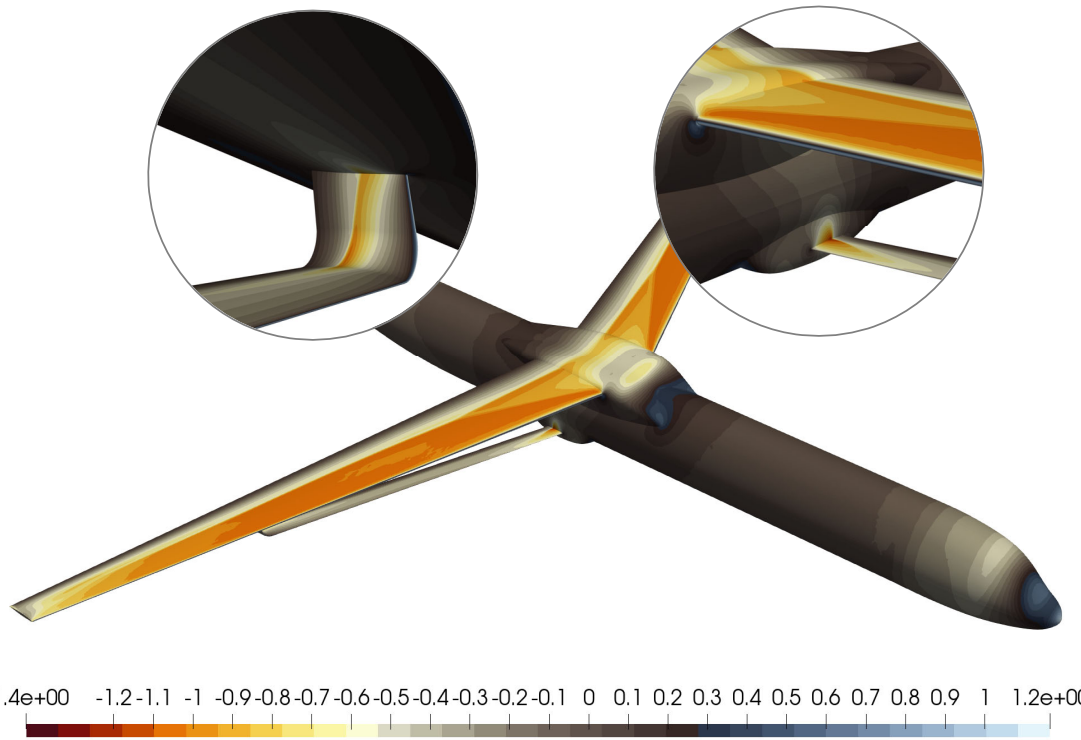
$$D_{\text{2-factor}}(v,\alpha) = f_c + F_v(v) + F_\alpha(\alpha) + F_{v,\alpha}(v,\alpha)$$

Outcome of the sensitivity for Lift

Central value: 377.142 kN

	Min ΔL	Max ΔL	Lift Range	Combined
a	-12.87%	13.17%	26.04%	26.04%
h	-7.86%	8.53%	16.39%	16.39%
v	-7.86%	8.01%	15.87%	15.87%
h - α	-1.09%	1.12%	2.21%	42.54%
v - α	-1.38%	1.18%	2.57%	40.10%
h - v	-0.69%	0.70%	1.40%	32.33%
h - v - α	-0.13%	0.11%	0.24%	56.71%
All	-25.86%	30.85%	-	56.71%

v [m/s]	α [deg]	h [km]	Ma
221.3	2.0347	11.692	0.75



CFD at two-factor Max Lift conditions (i.e. lowest h and highest α) contours of Pressure Coefficient

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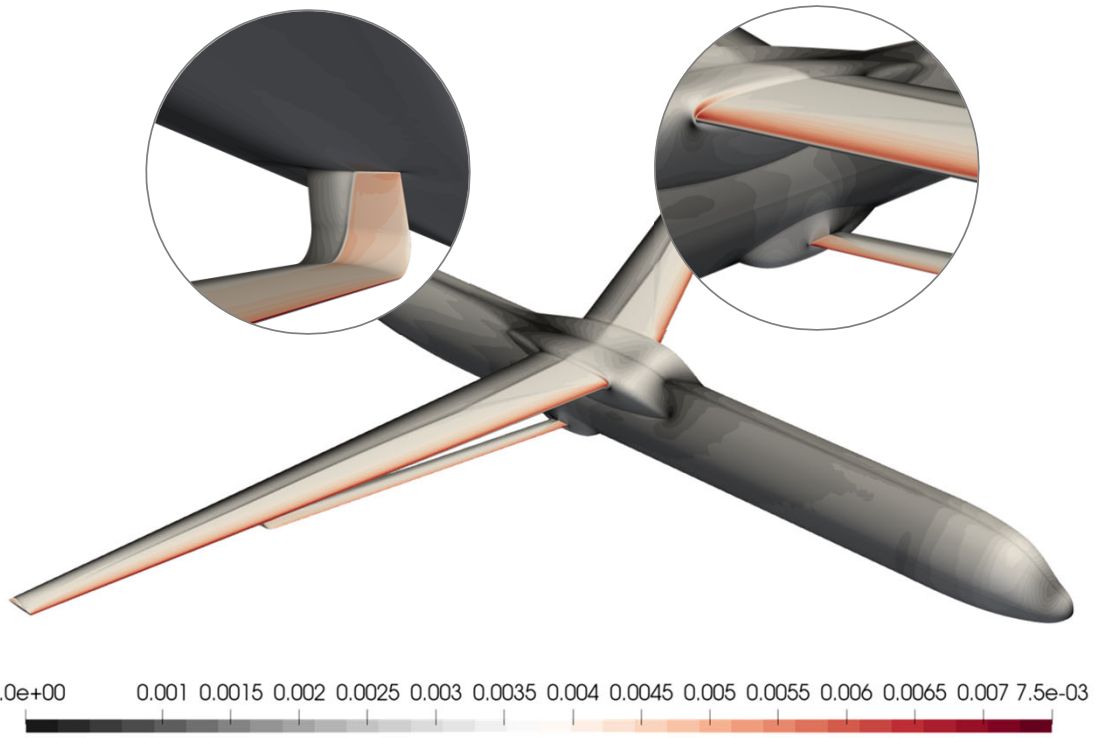
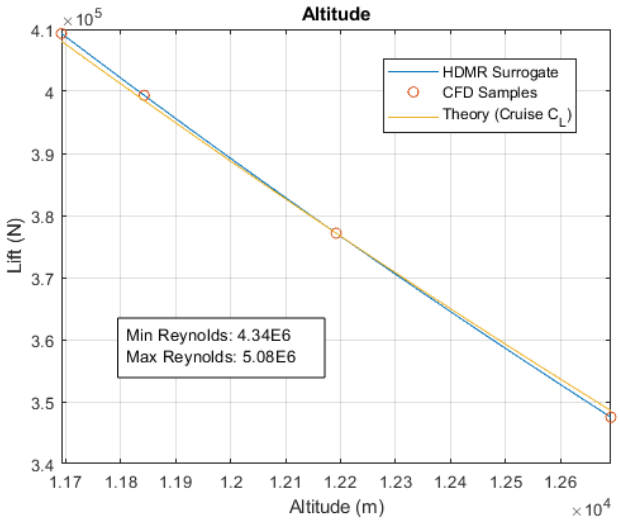
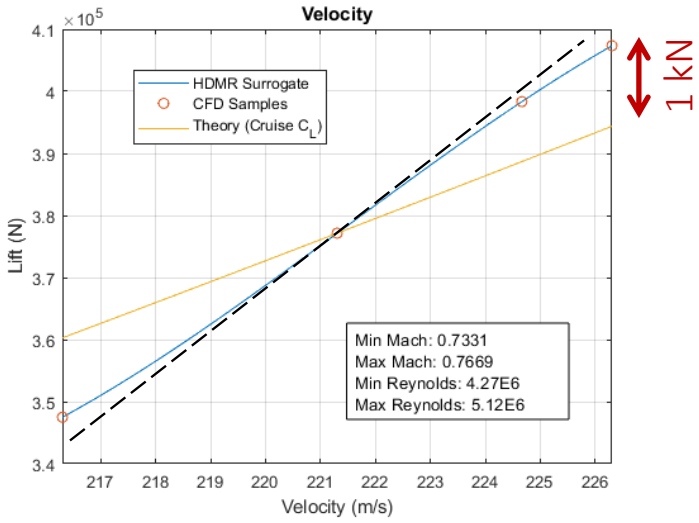
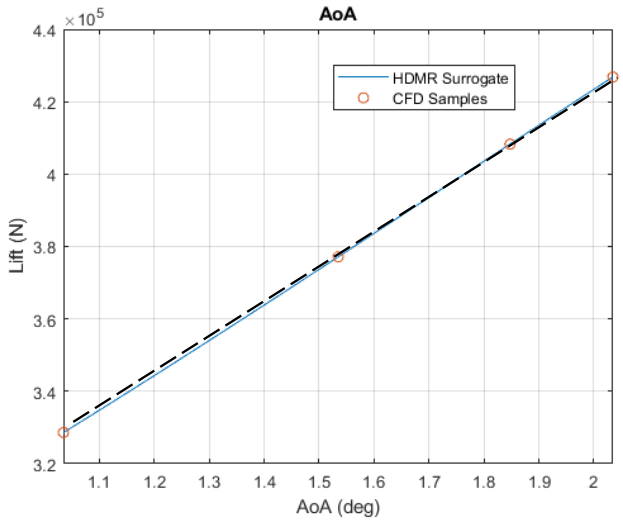


CFD at two-factor Max Lift conditions (i.e. lowest h and highest α) contours of Skin friction Coefficient

Lift decomposition 1-factor



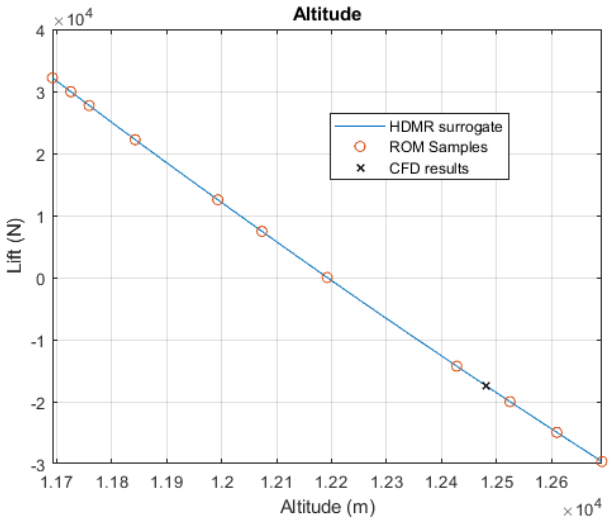


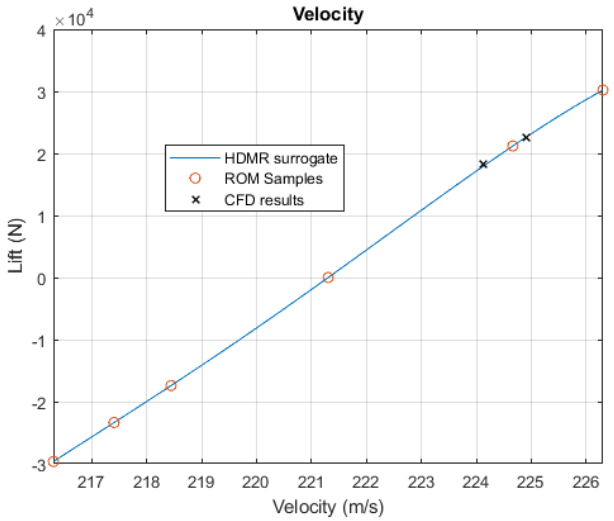


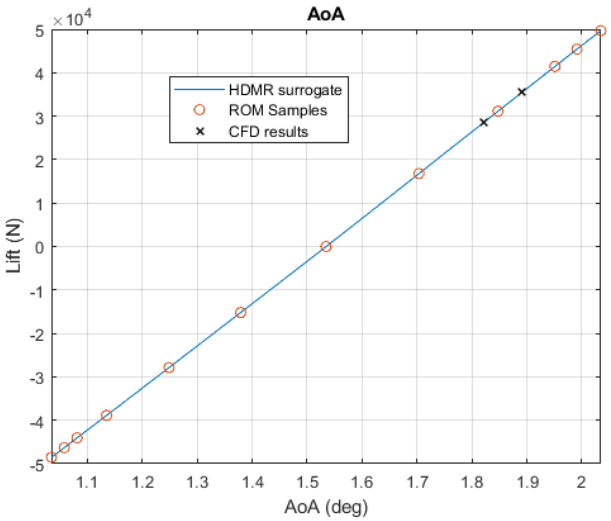
Lift @ cruise: 377.142 kN

	Min ΔD	Max ΔD	Range	*Combined*	Gradient @ cruise point
α	-12.87%	13.17%	26.04%	*26.04%*	26.13% / deg
ℏ	-7.86%	8.53%	16.39%	*16.39%*	-0.016% / m
v	-7.86%	8.01%	15.87%	*15.87%*	1.68% / m/s

Lift decomposition 1-factor via ROM







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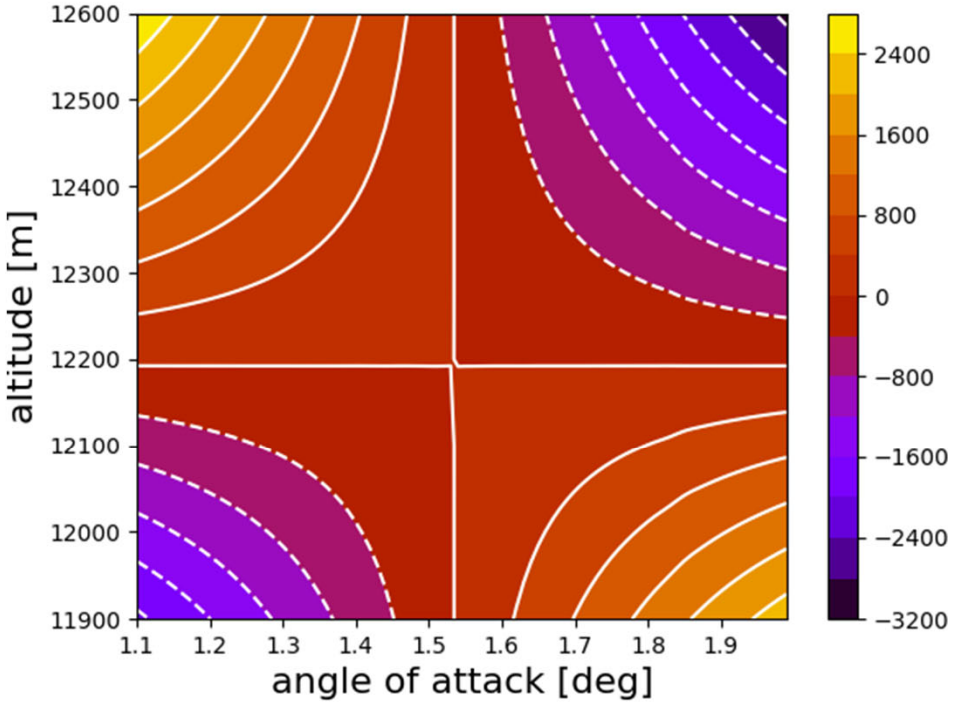
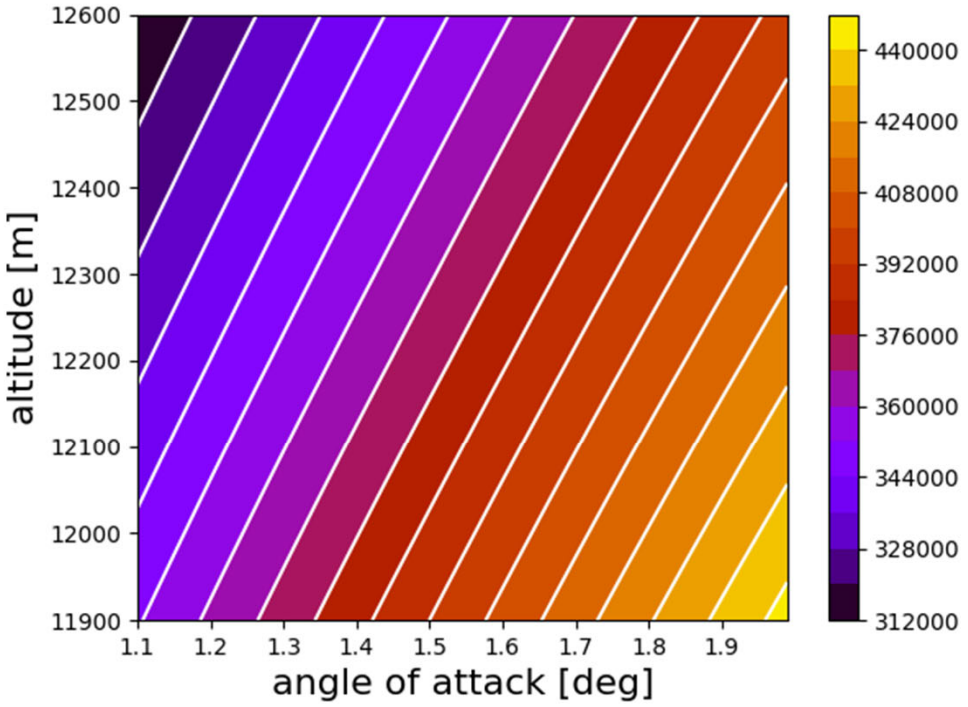
Lift decomposition 2-factor





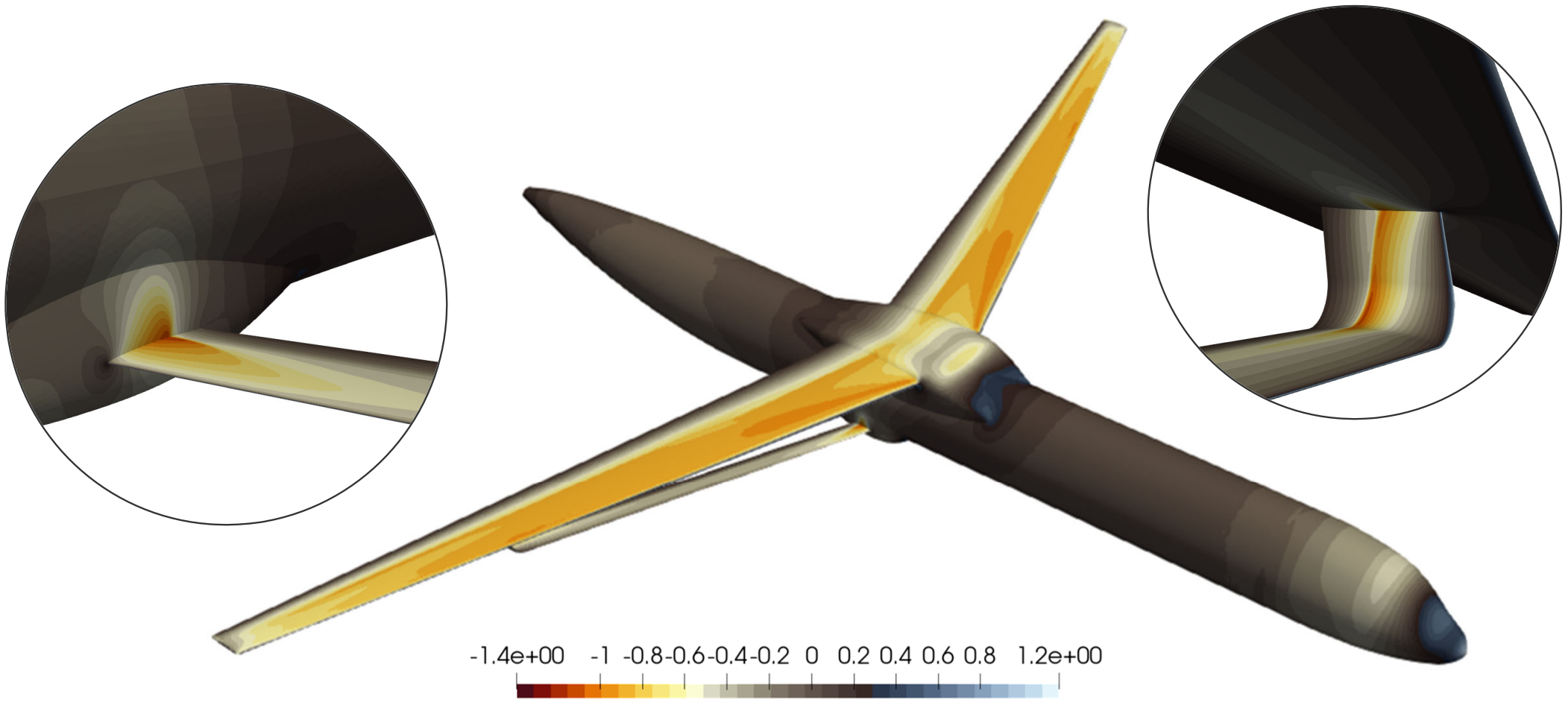
Incremental response:

$$F_{\alpha,h}(\alpha, h)$$

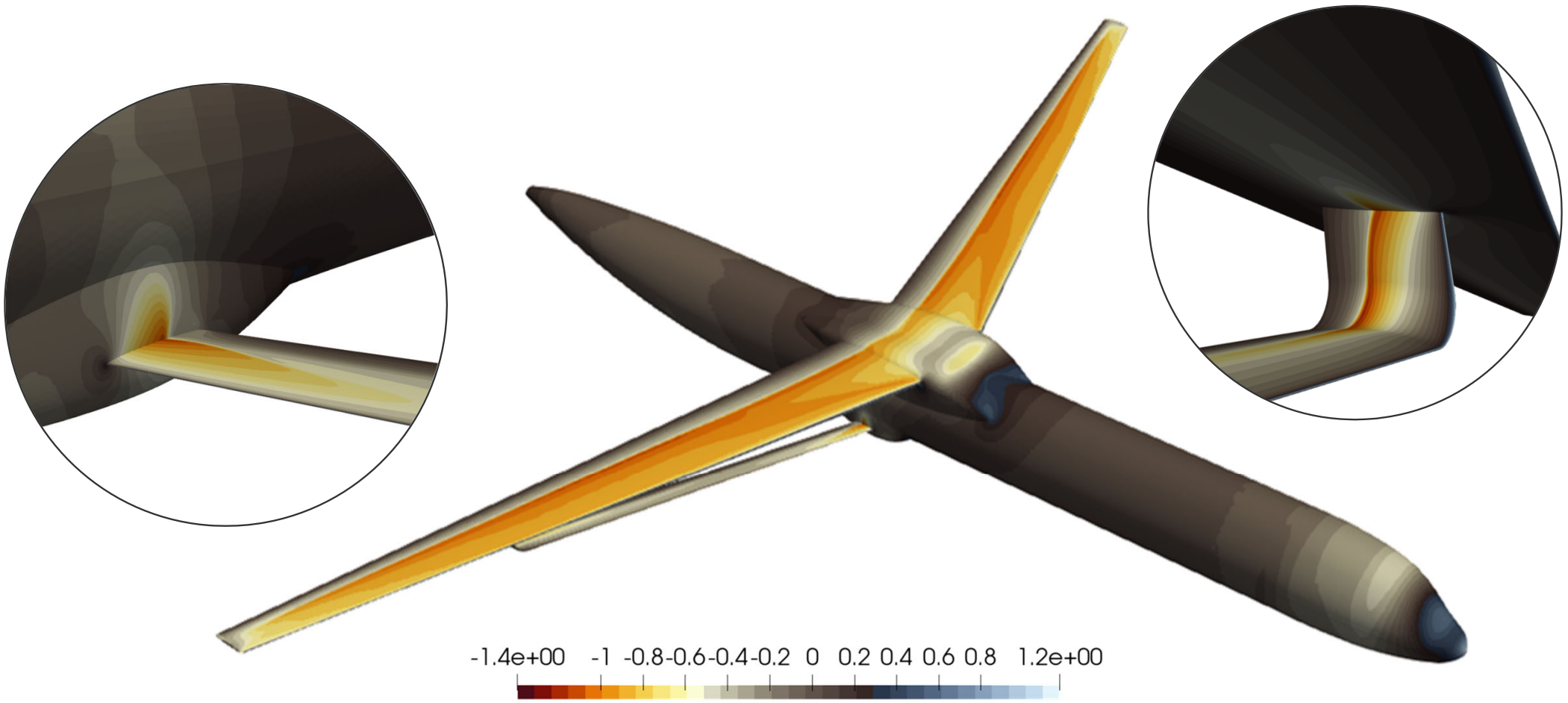
Cumulative response:

$$L_{\text{2-factor}}(\alpha, h) = f_c + F_\alpha(\alpha) + F_h(h) + F_{\alpha,h}(\alpha, h)$$

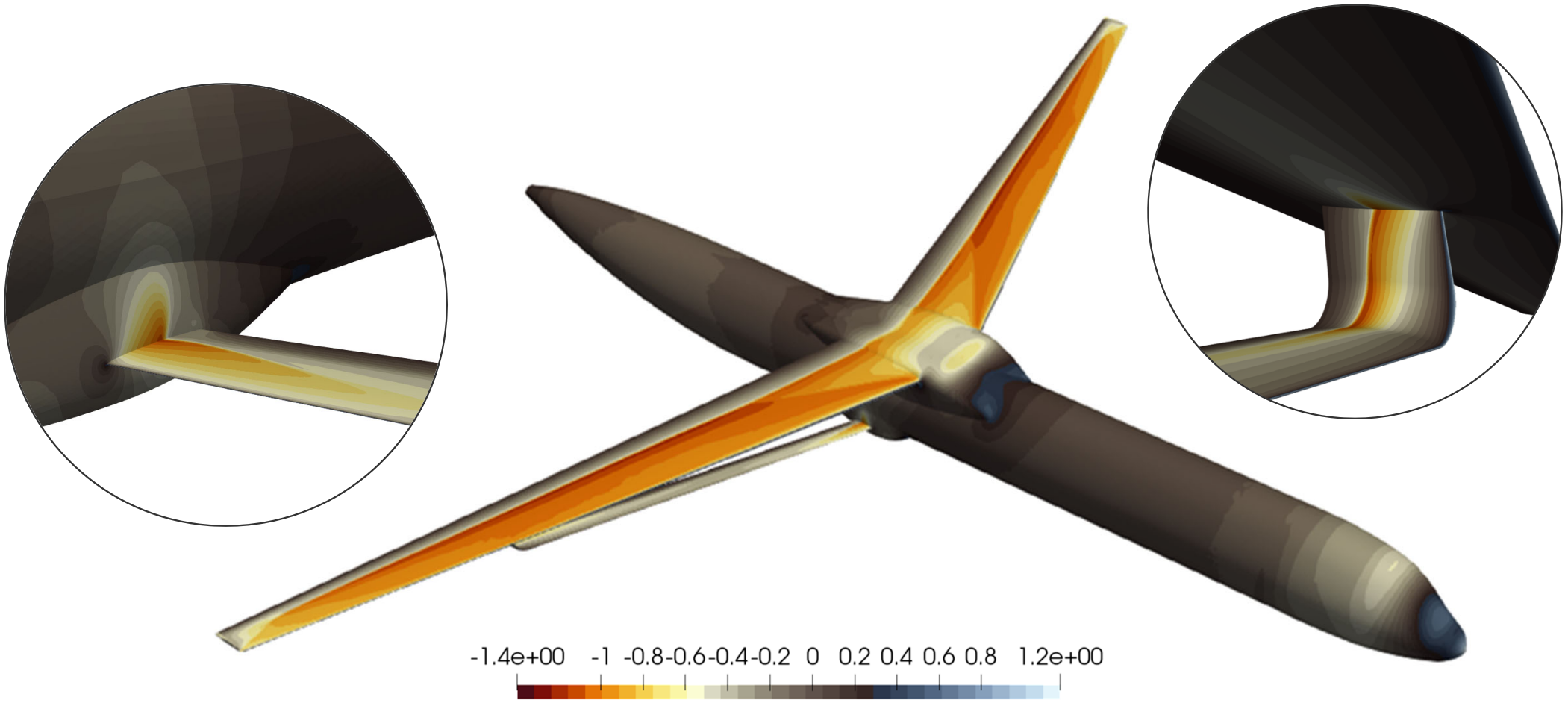
Cruise conditions



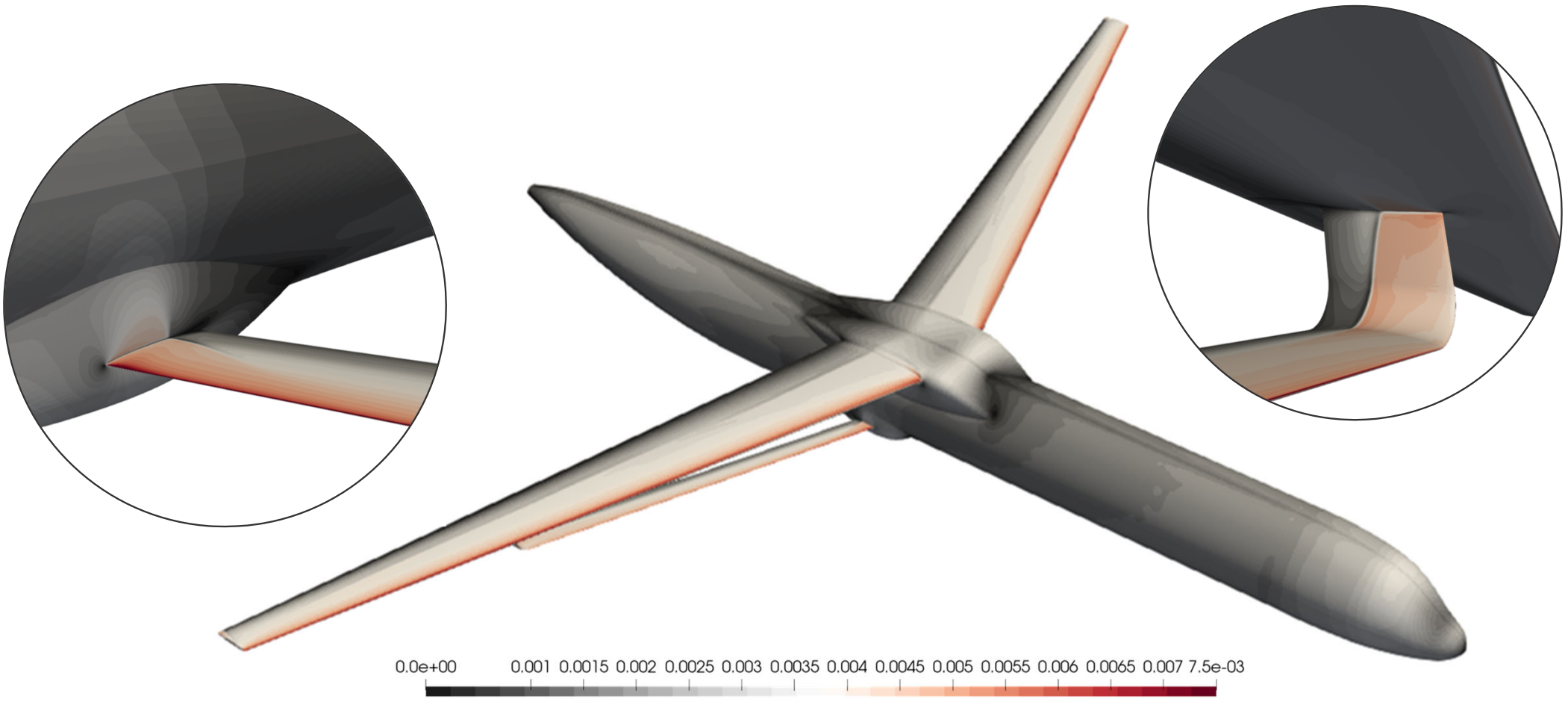
Max velocity (other params constant at cruise)



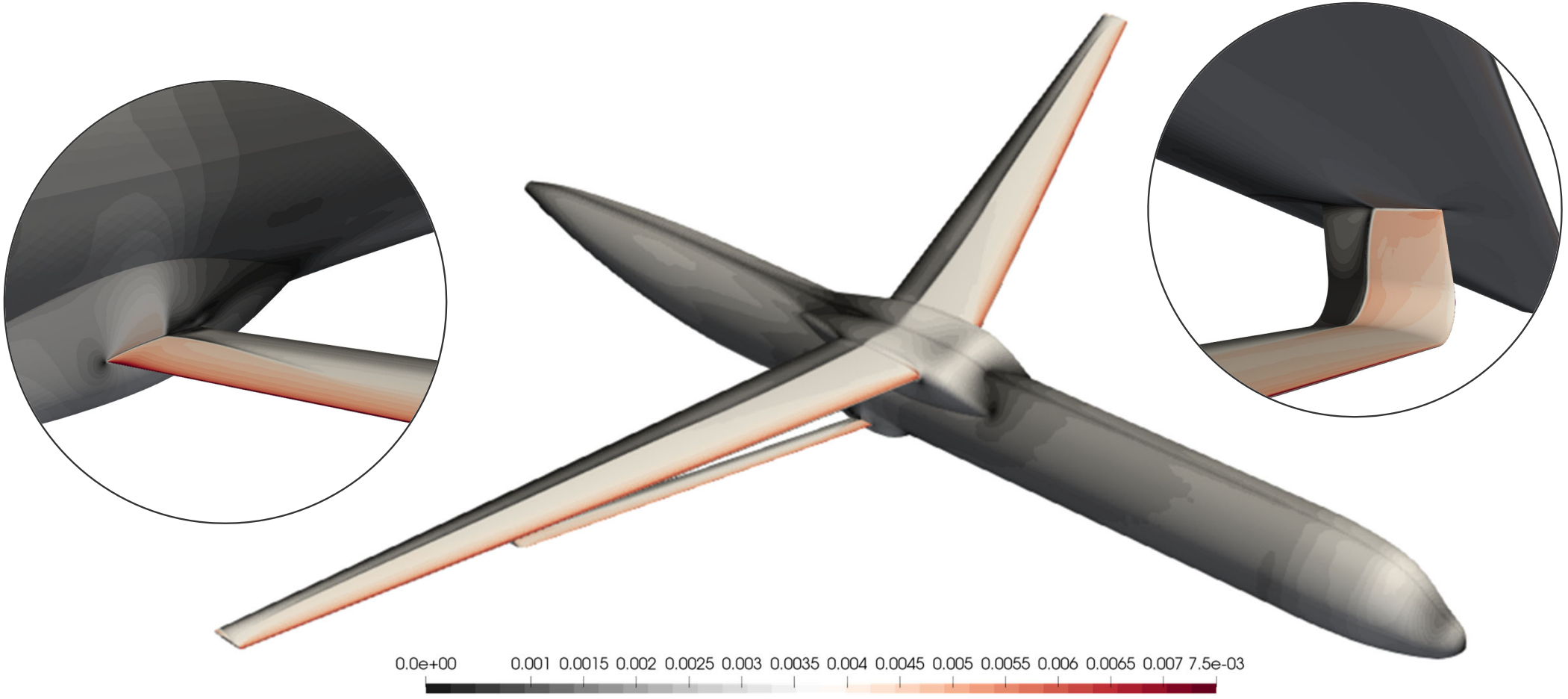
Max velocity - max α (other params constant at cruise)



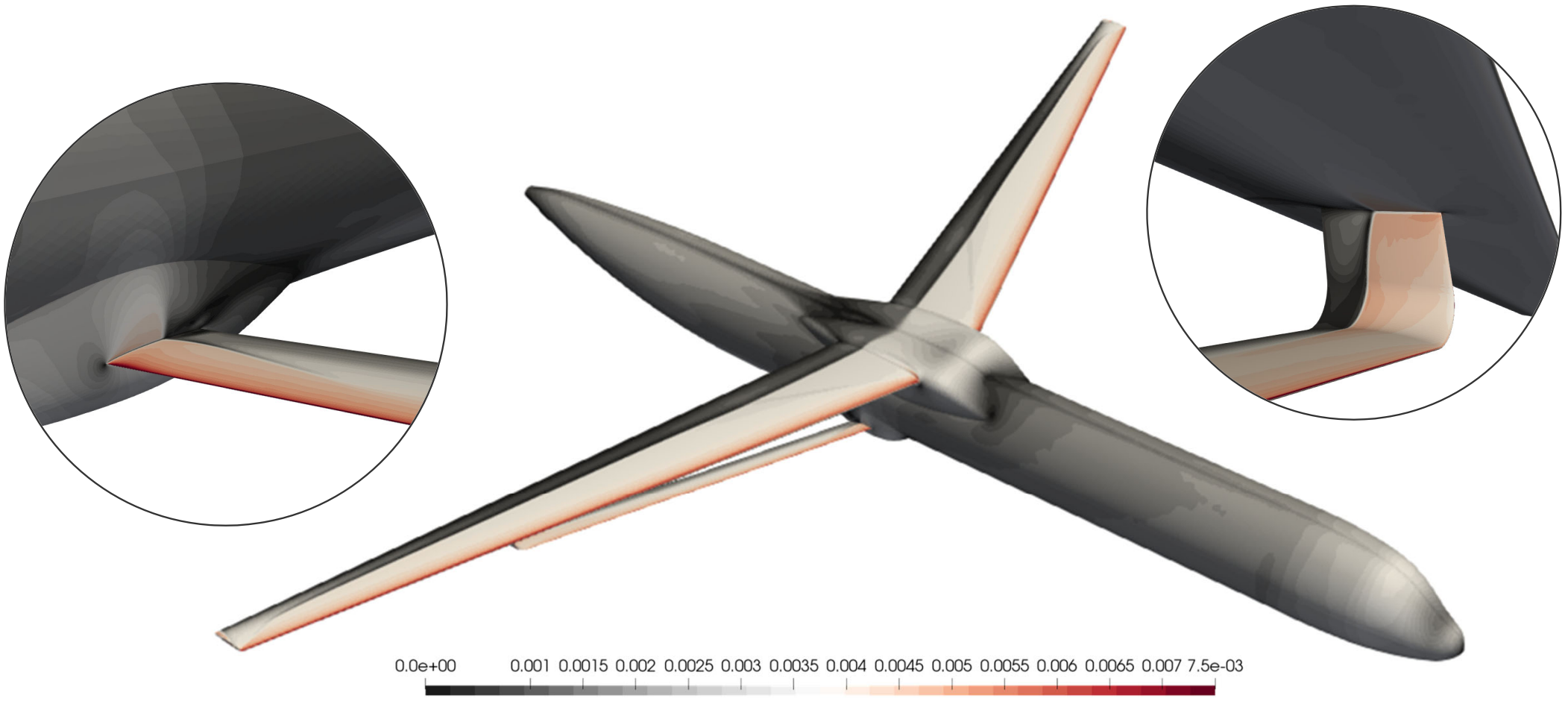
Cruise conditions



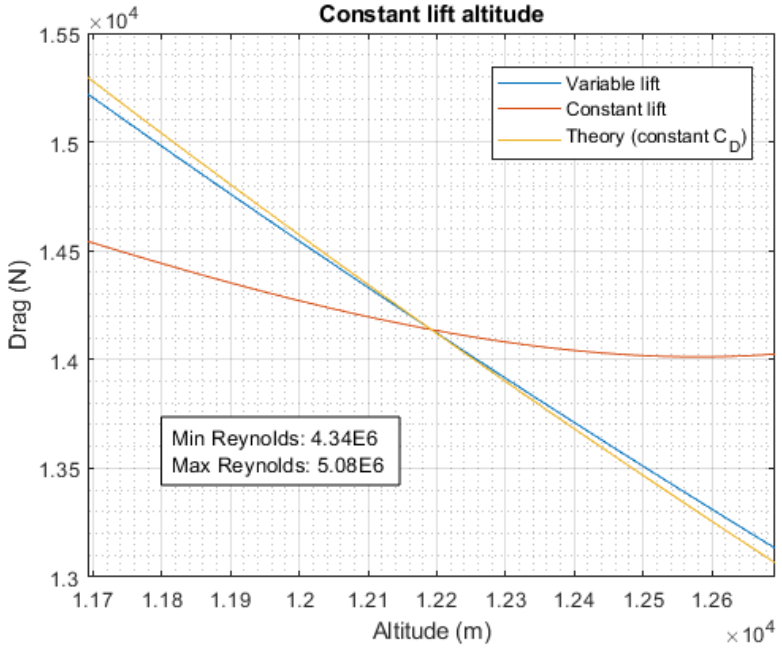
Max velocity (other params constant at cruise)

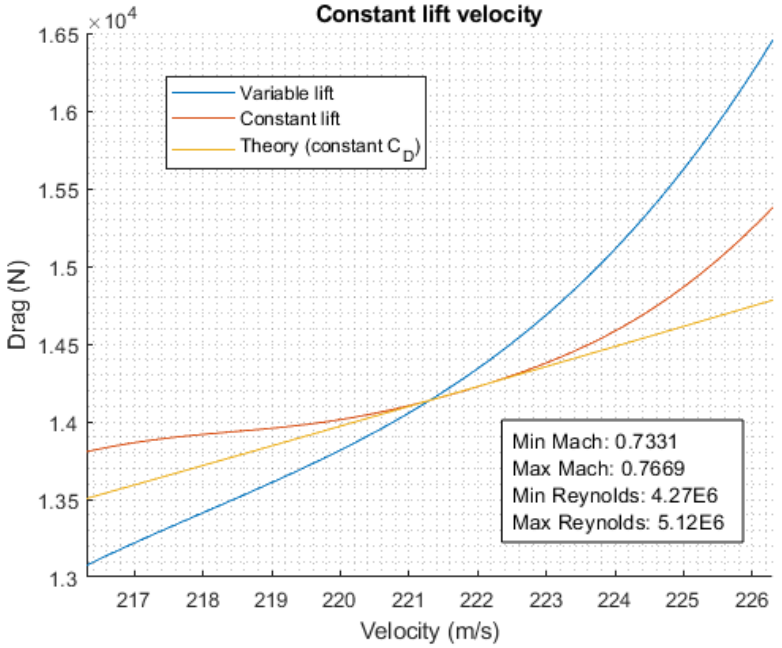


Max velocity - max α (other params constant at cruise)



Constant lift analysis (N=1)



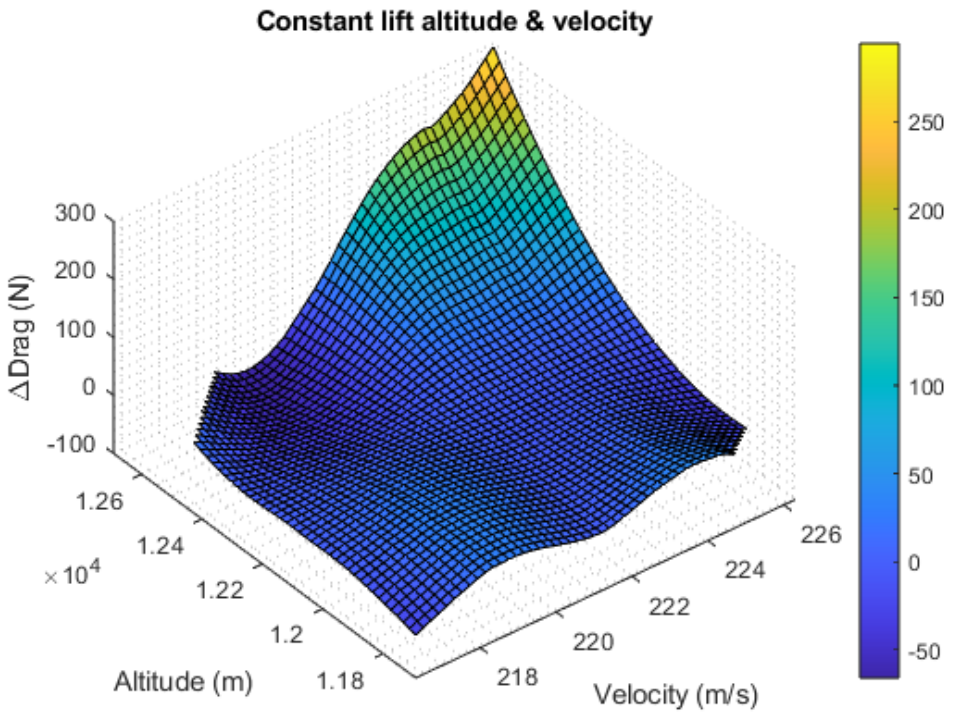


	Min ΔD	Max ΔD	Drag Range
v	-2.29%	7.82%	10.11%
h	-1.31%	2.04%	3.35%
v - h	-0.47%	2.08%	2.55%

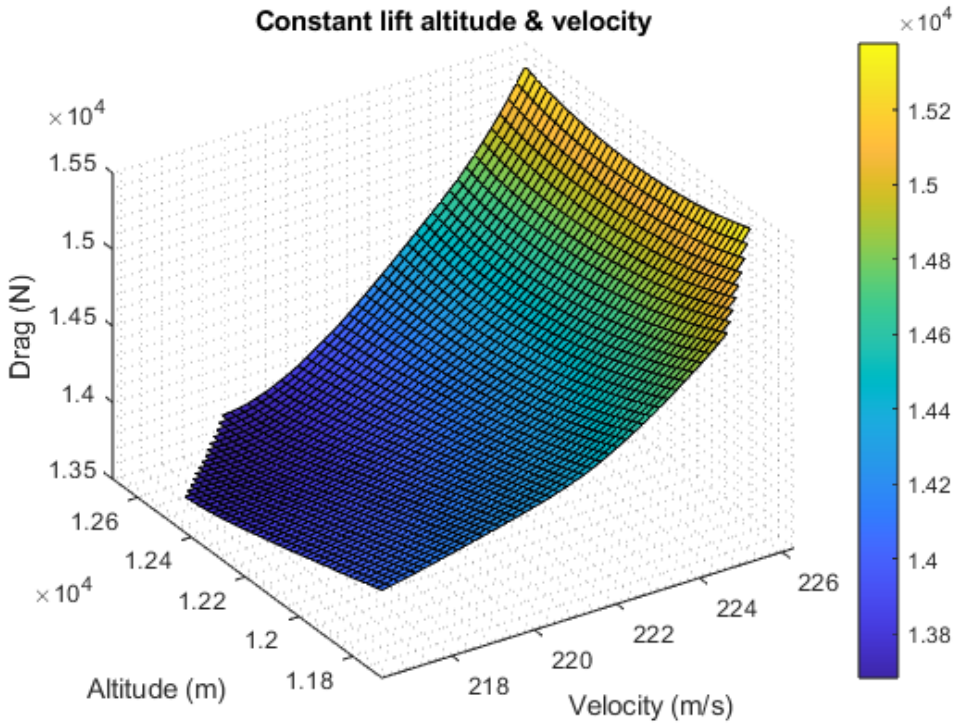
Drag @ cruise: 14.137 kN

All	-3.21%	8.59%	11.80%

Constant lift analysis (N=1)



Incremental response

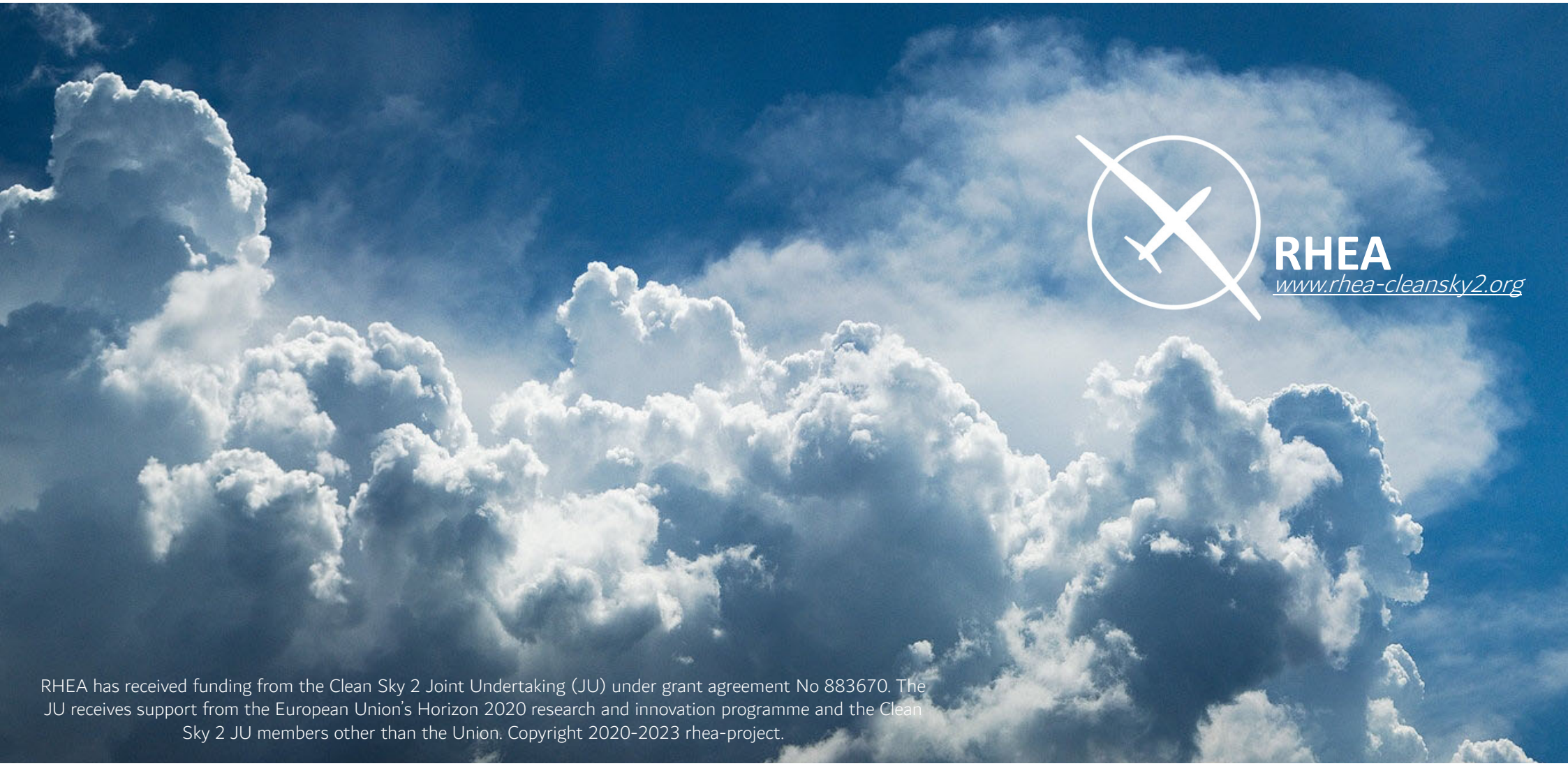


Cumulative response

Final remarks & Acknowledgment

- For the given range of parameters the central design will experience substantial changes in lift and drag
- Velocity and Angle of Attack are the most relevant parameters
- Angle of Attack is the most relevant for small deviations from cruise conditions
- Indications that the wave drag on the strut is a dominant factor
- Comparison with a cantilever wing configuration of the same design is underway

This work has been part of a collaborative effort between RHEA and UHARWARD consortia. A special acknowledgment goes to POLIMI and ONERA for the exchange of data and the analysis



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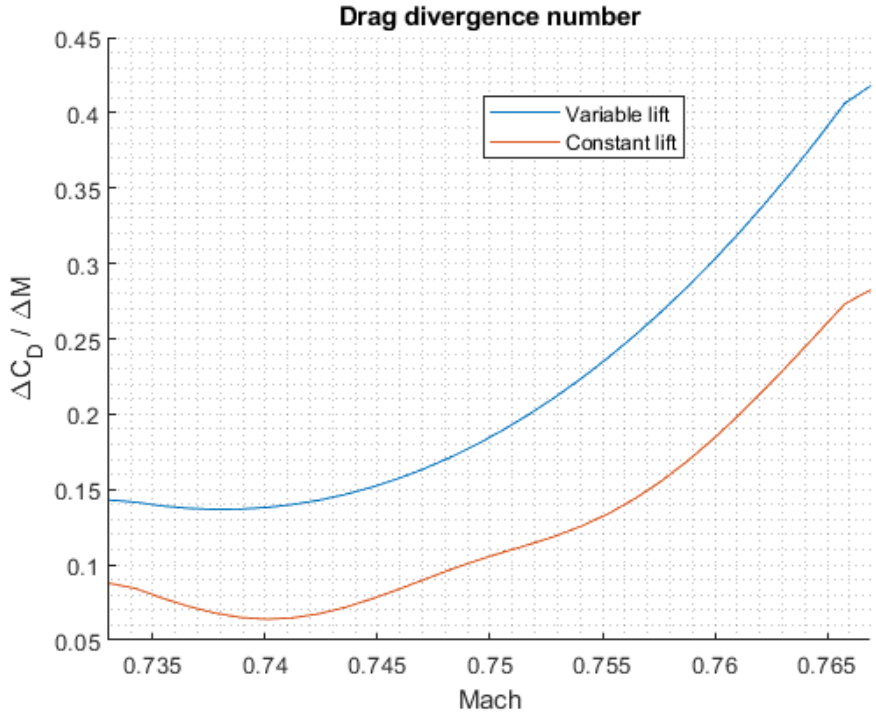
Clean Sky 2 Imperial College London DNW German-Dutch Wind Tunnels SAINT EXUPÉRY University of Southampton

Drag Divergence