Aerodynamic Design of a Reusable Booster Stage Flight Experiment

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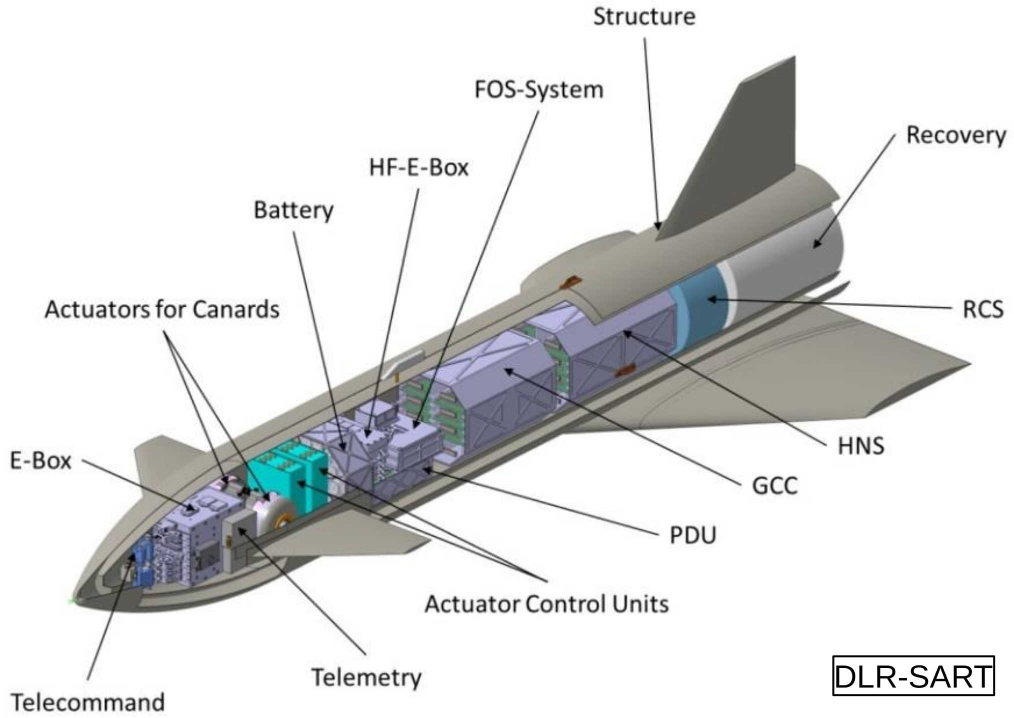
The DLR Projekt ReFEx (Reusable Flight Experiment)

Proof of concept flight experiment of the German Aerospace Center (DLR) for a reusable, horizontally landing booster stage.

- ReFEx dimensions:
  - Length: 2720 mm
  - Wingspan: 1040 mm
  - Diameter: 355 mm
  - Mass: approx. 420 kg
- Ascent to 130 km
- Re-entry at around Mach 5
- Planned: launch in Woomera, Australia, 2022

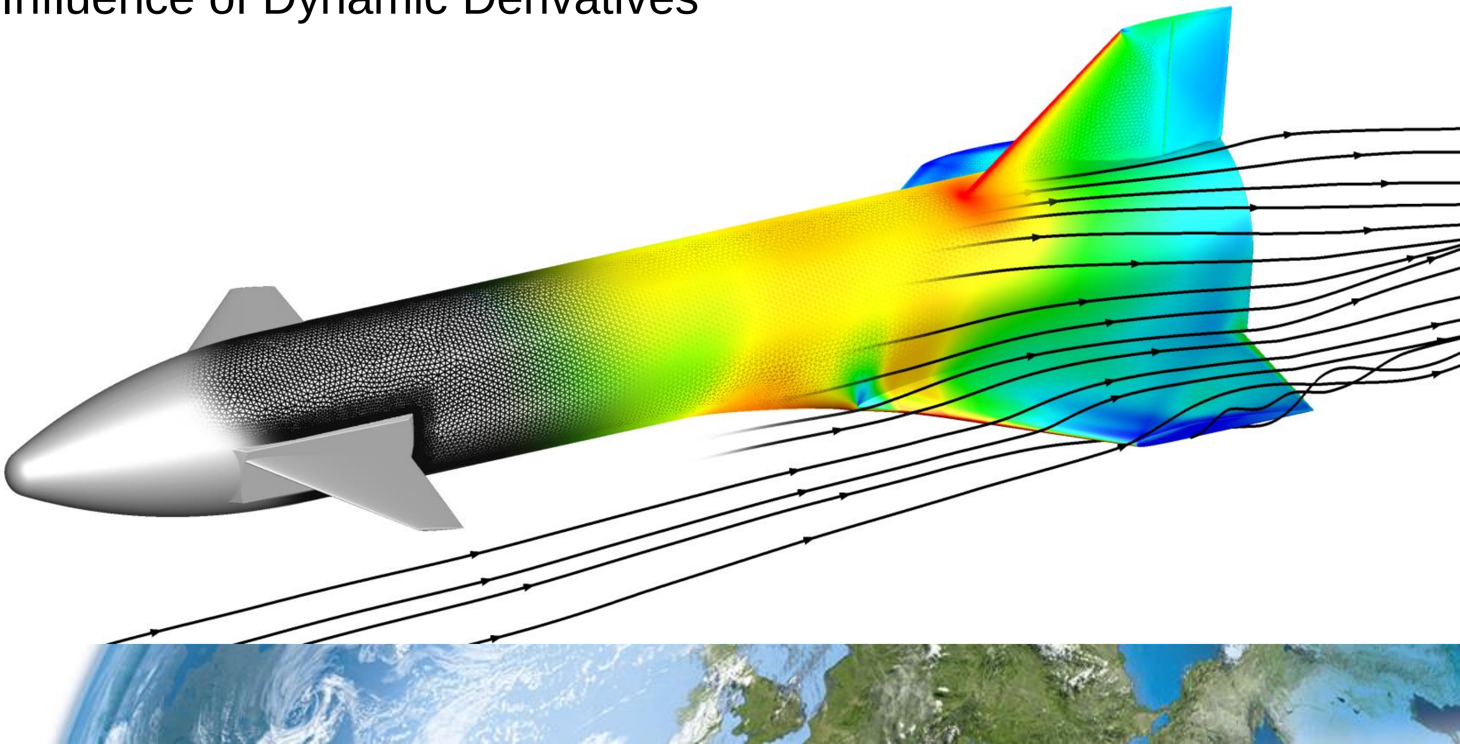


Aerodynamic Design of ReFEx

1. Mission requirements and configuration

2. Stability analysis
   - Static
   - Dynamic – Influence of Dynamic Derivatives

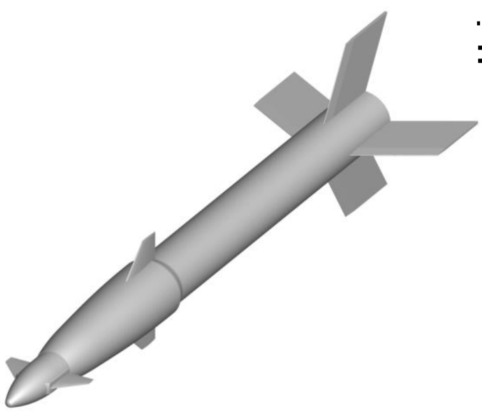
3. Conclusion

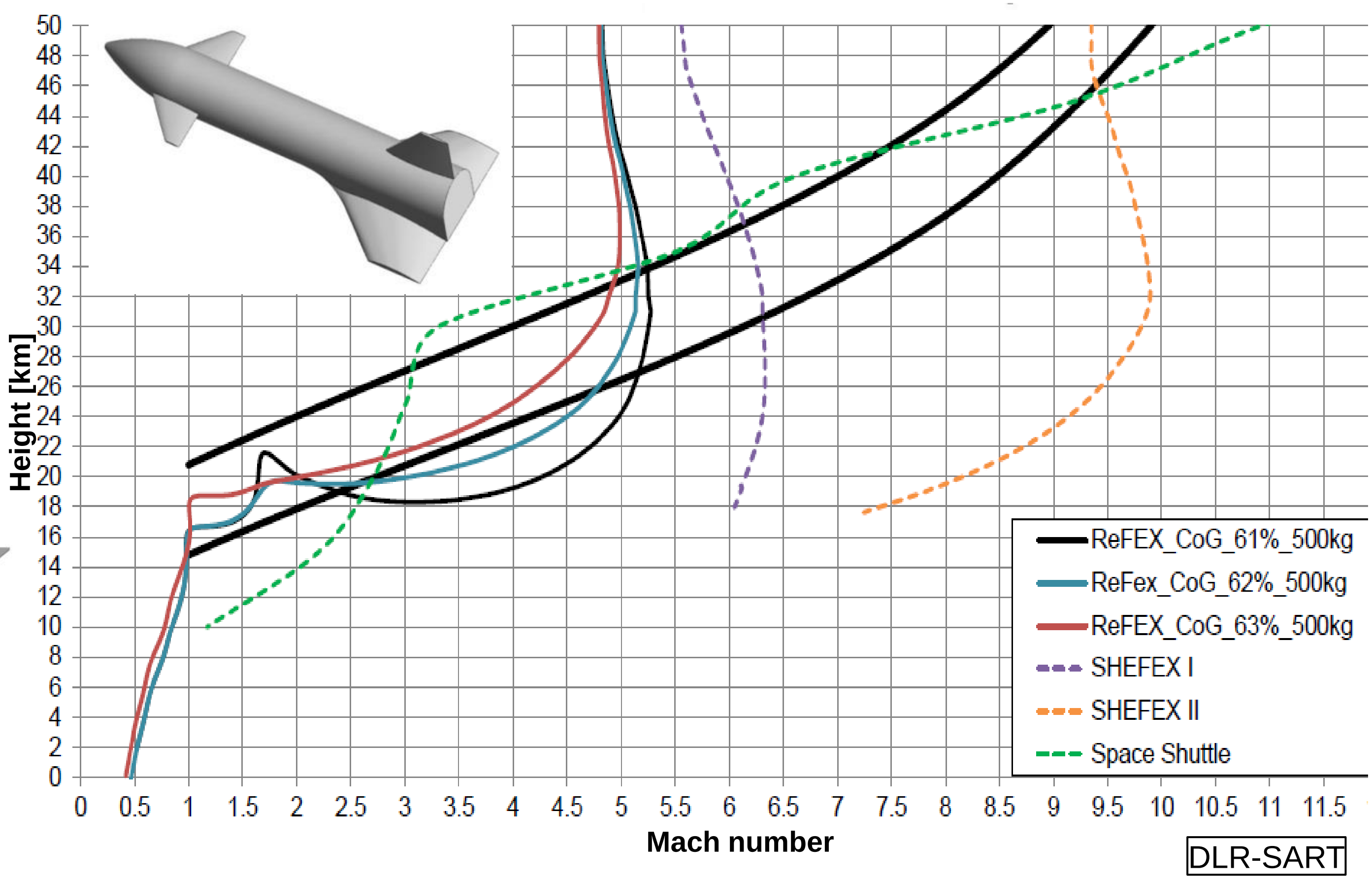


Trajectory – Aerodynamic Design Constrictions

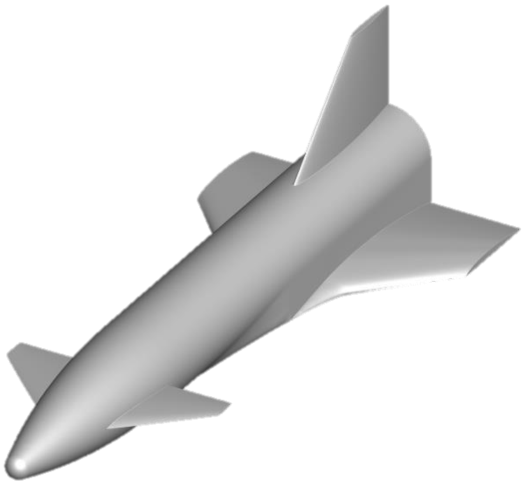
Reentry Goal: Autonomously reach a target destination at a predefined speed.

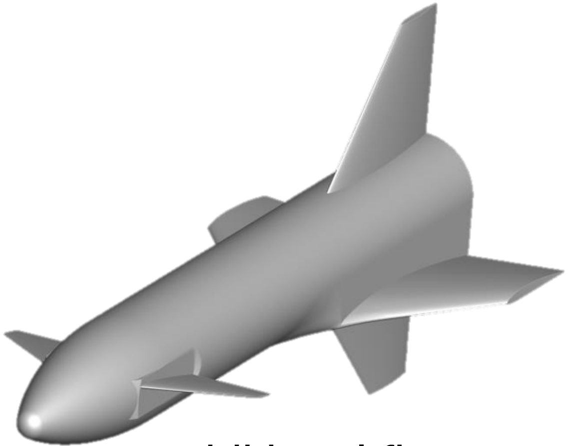
- Controllability
- Loads
- Ascent (VSB30)

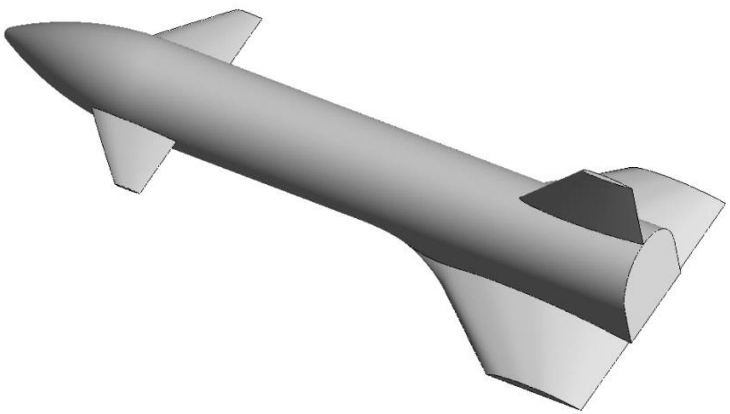


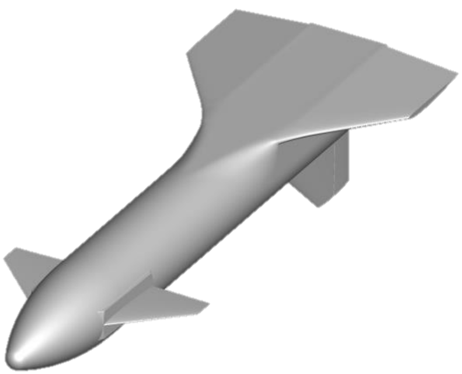


Configuration Development History


Larger fin

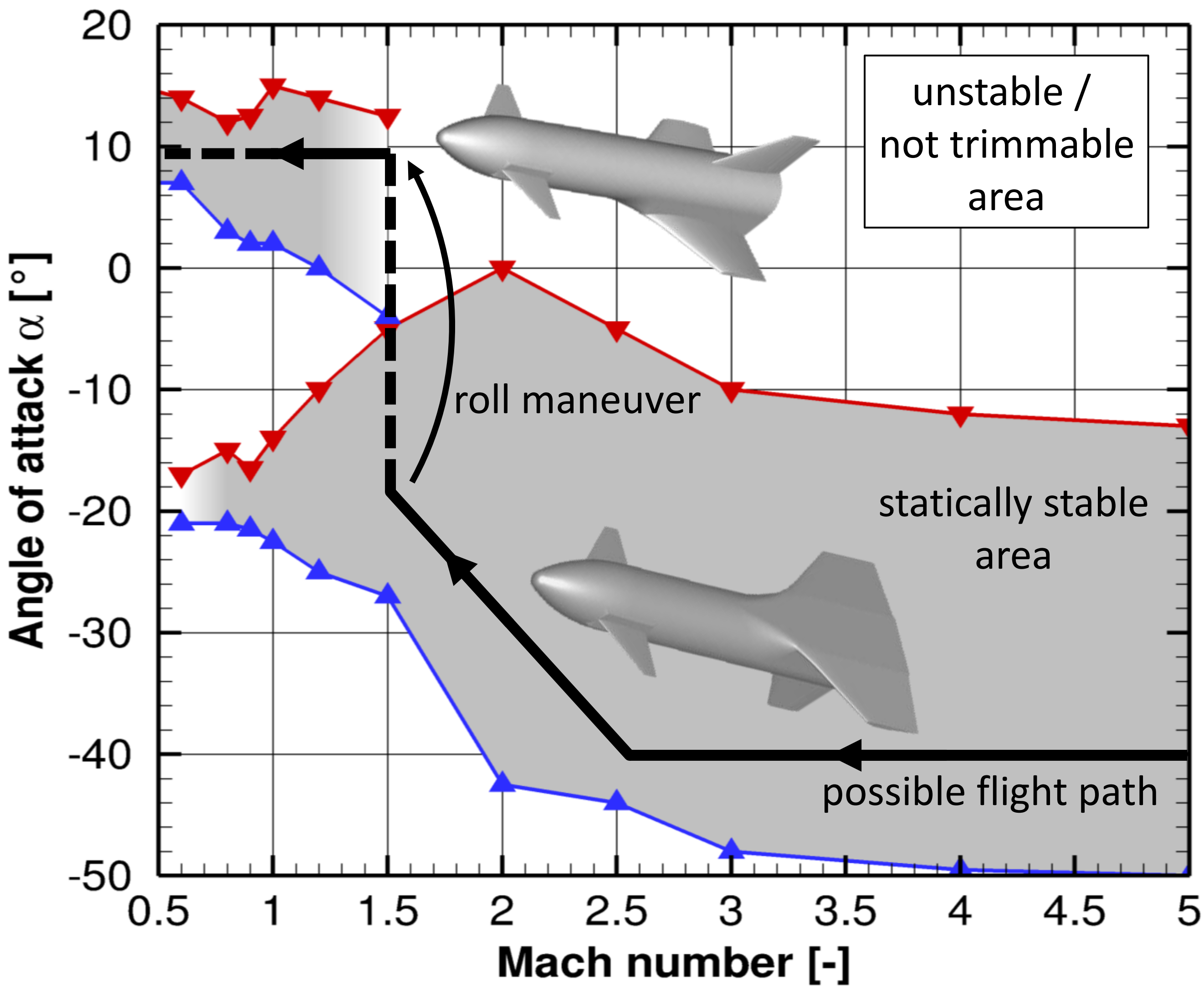

Additional fin


Reference geometry


Upside down deceleration

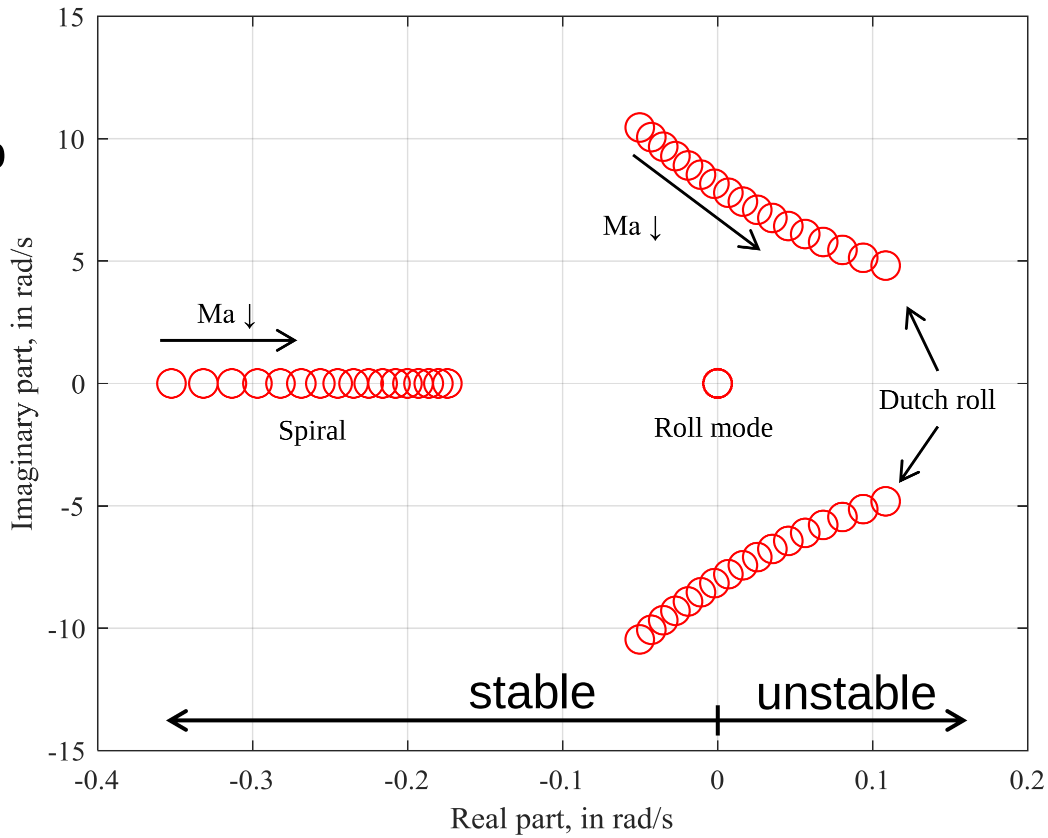

Foldable wings

Flight envelope from aerodynamic dataset (static pitch)



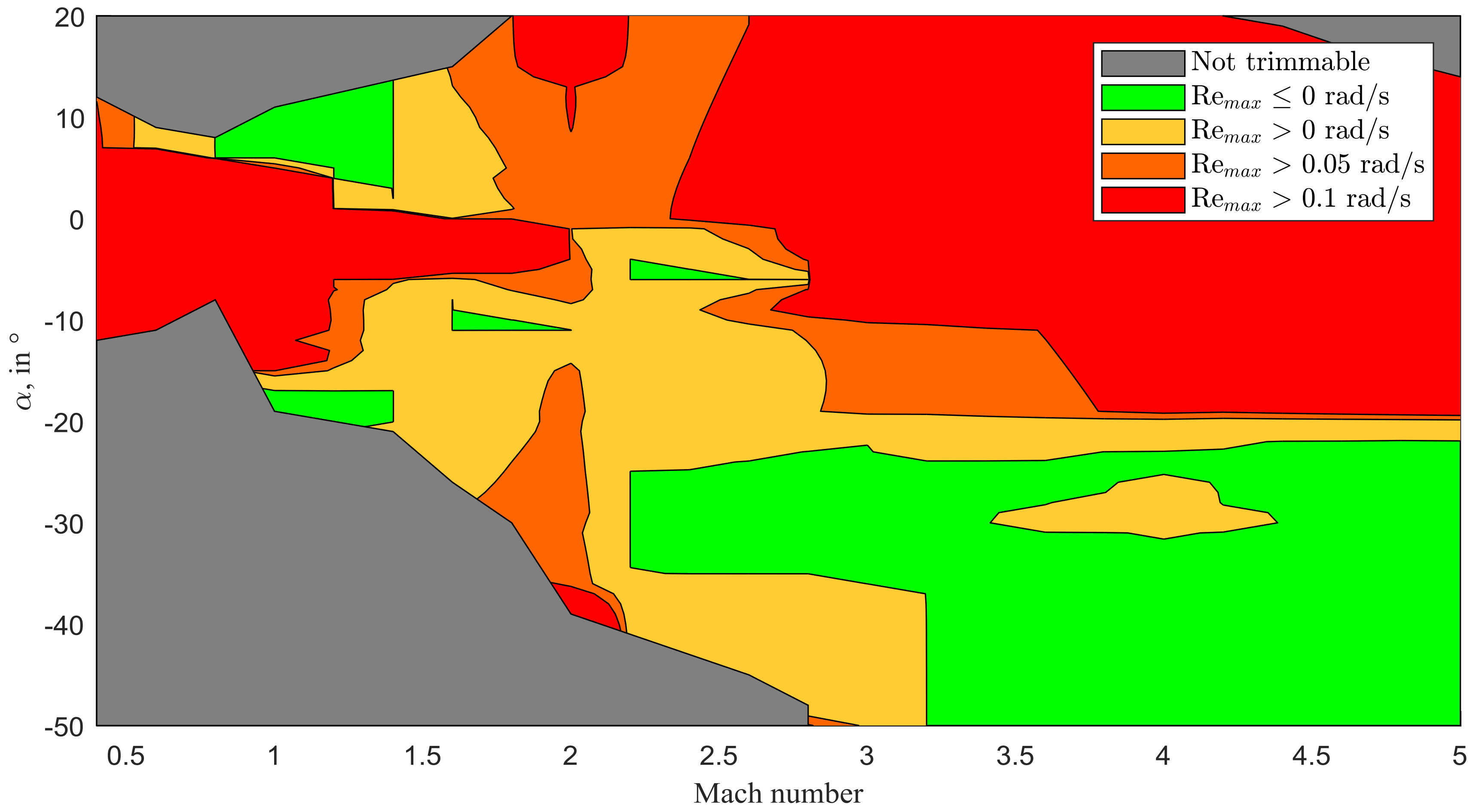
Stability Modelling

- This far, only static pitch stability has been taken into account
- Other forms of movement need to be investigated
- Some types of movement might have destabilizing effects
  - ➢ Eigenvalues of the 6-DoF system matrix are analyzed
  - ➢ Maximum real part represents least stable motion



Lateral motion
Eigenvalues at α = 8°; 0.4 < M < 0.8; ΔM = 0.025

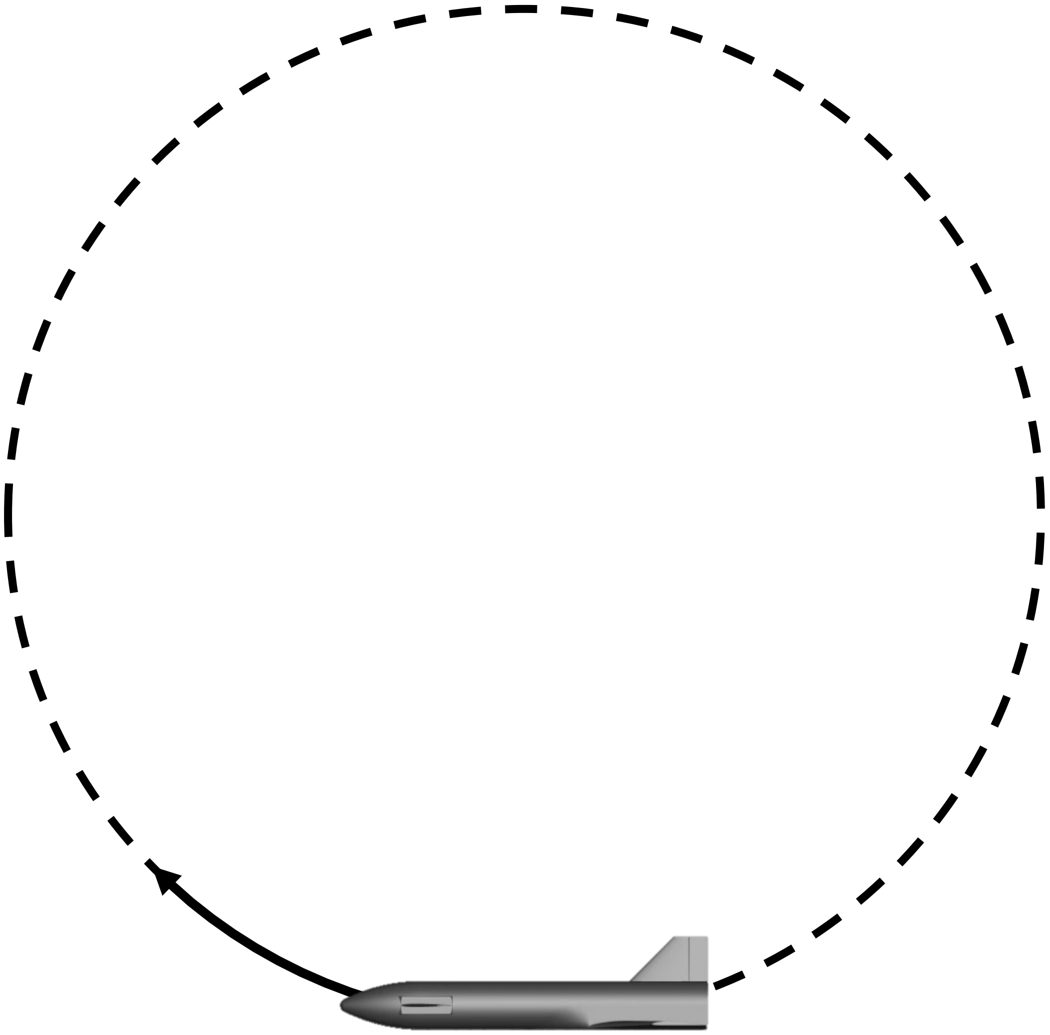
Stability Analysis – Static Aerodynamics



Flight envelope of ReFEx from the stability analysis.

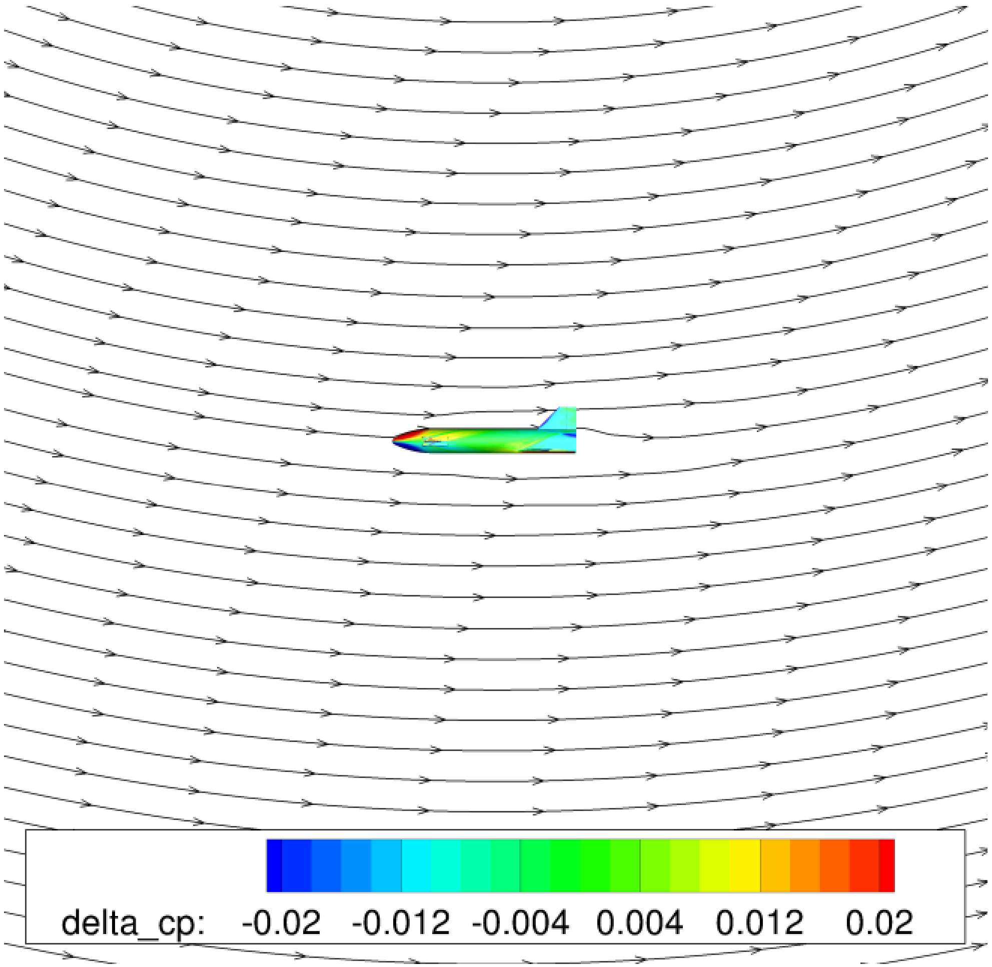
Introduction of Rotation Rate Derivatives

- Improve accuracy of the stability analysis with rotation rate derivatives
- Calculation via static simulations
- Three additional simulation sets (one for each axis)
- The maximum occurring rotational velocity is estimated to be 150 deg/s
- Rotation rates for the data sets need to be determined

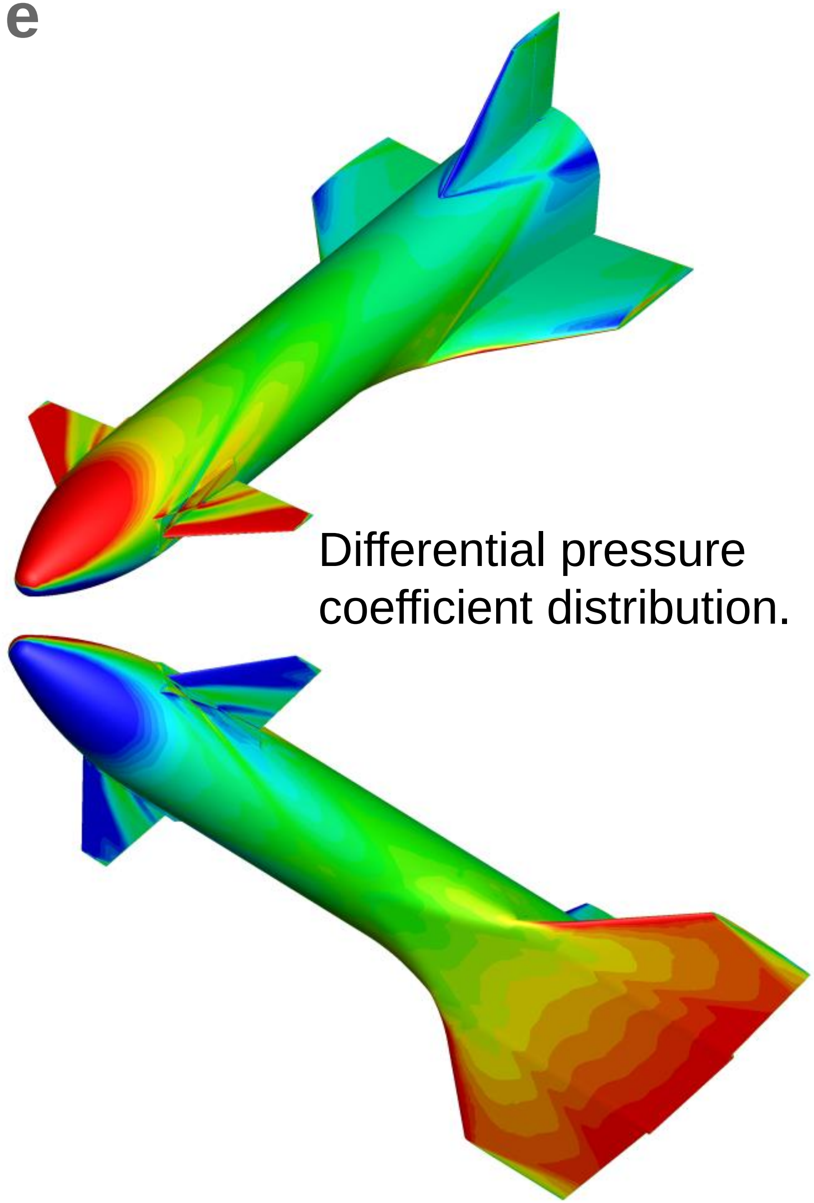


Flight path with constant pitch rate.

Rotation Rate Simulation Example



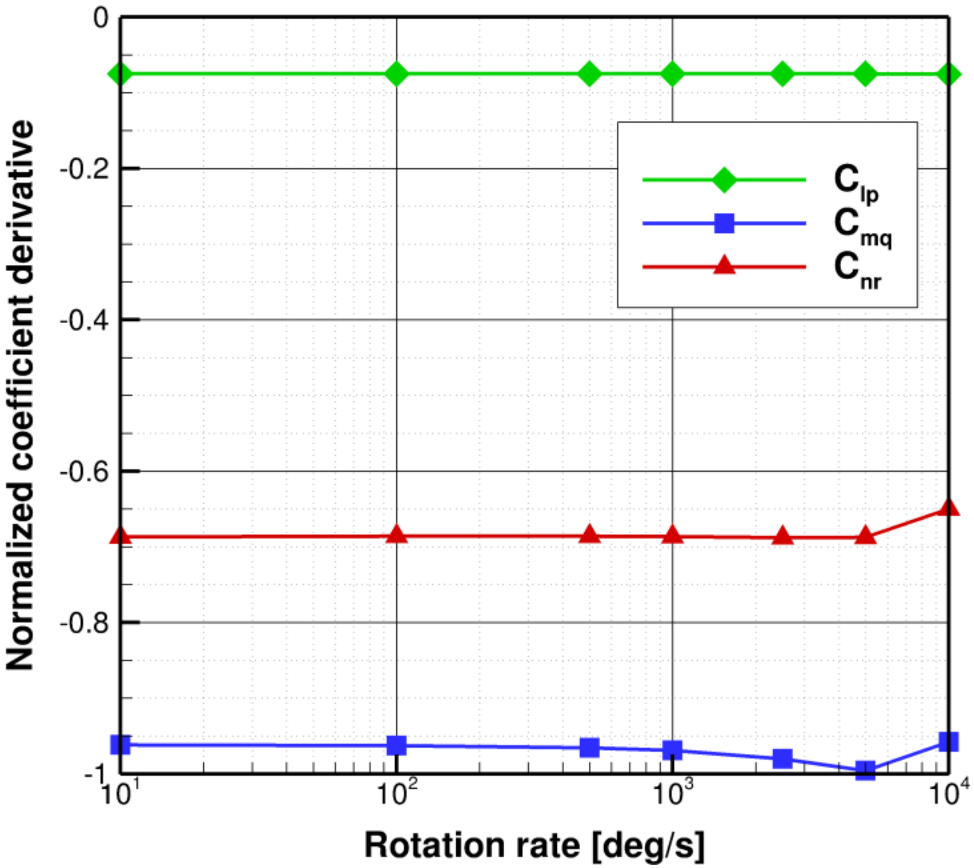
Static simulation with constant pitch rate.



Differential pressure coefficient distribution.

Representative Rotation Rate

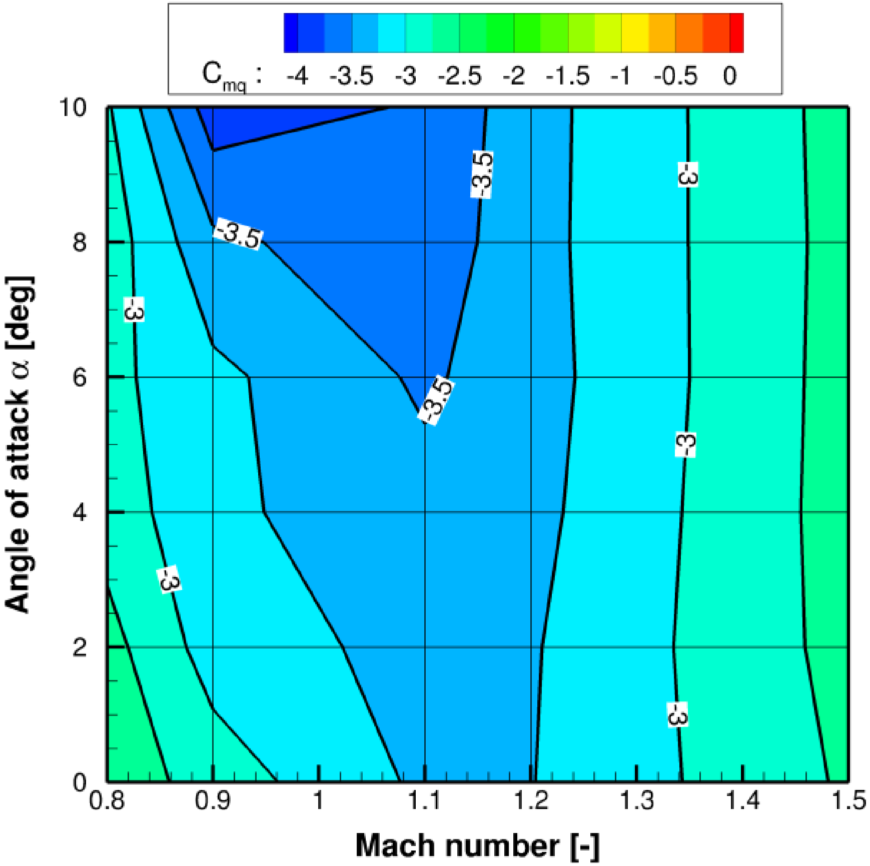
- Mostly linear dependency of the rate on the derivatives
  - Normalization yields mostly independent behavior
- Rate for data set is chosen:
  - Too small: numerical noise is comparably large
  - Too large: nonlinear effects might be a problem
- A rate of 100 deg/s was chosen



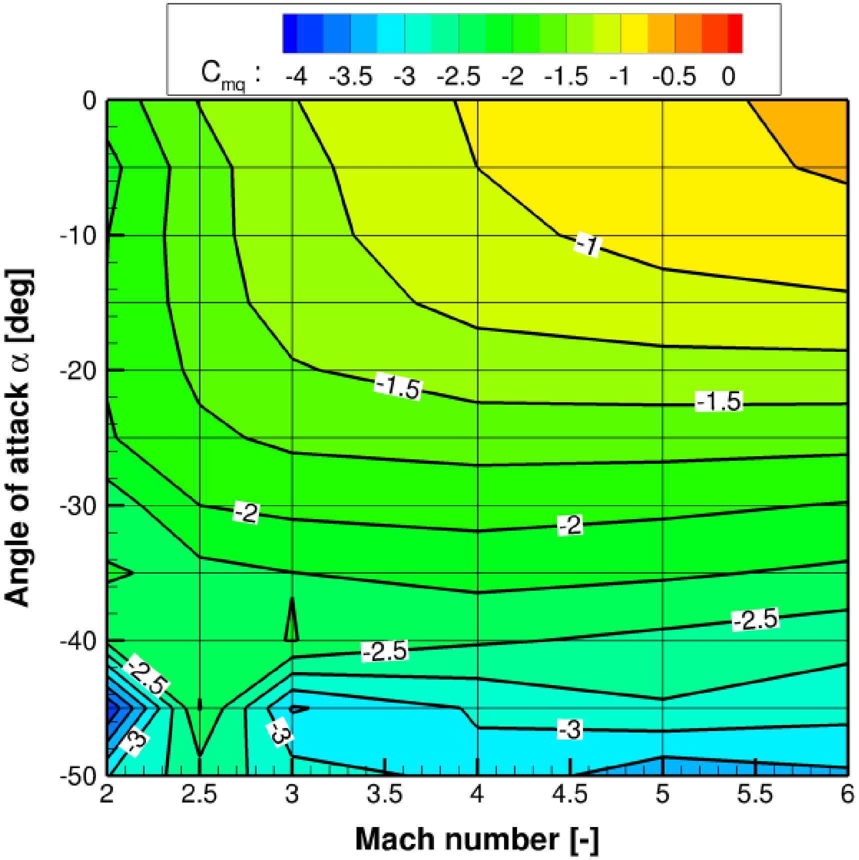
Normalized derivatives for different rotational rates.

Distribution of the Pitch Rate Derivative C_{mq}

Viscous simulation data field.



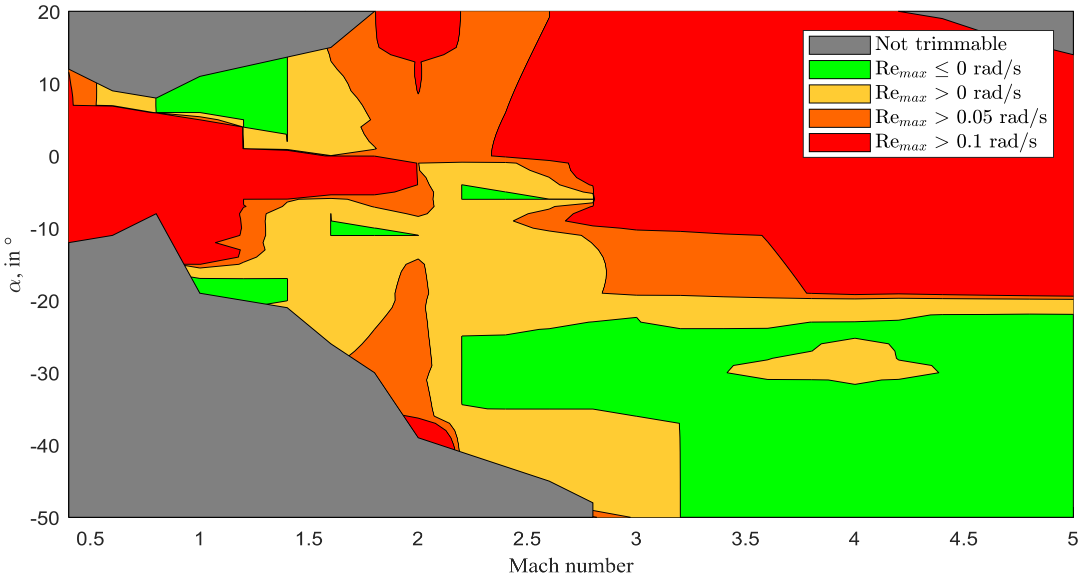
Inviscid simulation data field.



Negative values of C_{mq} represent areas with positive damping.

Influence of Rotation Rate Derivatives

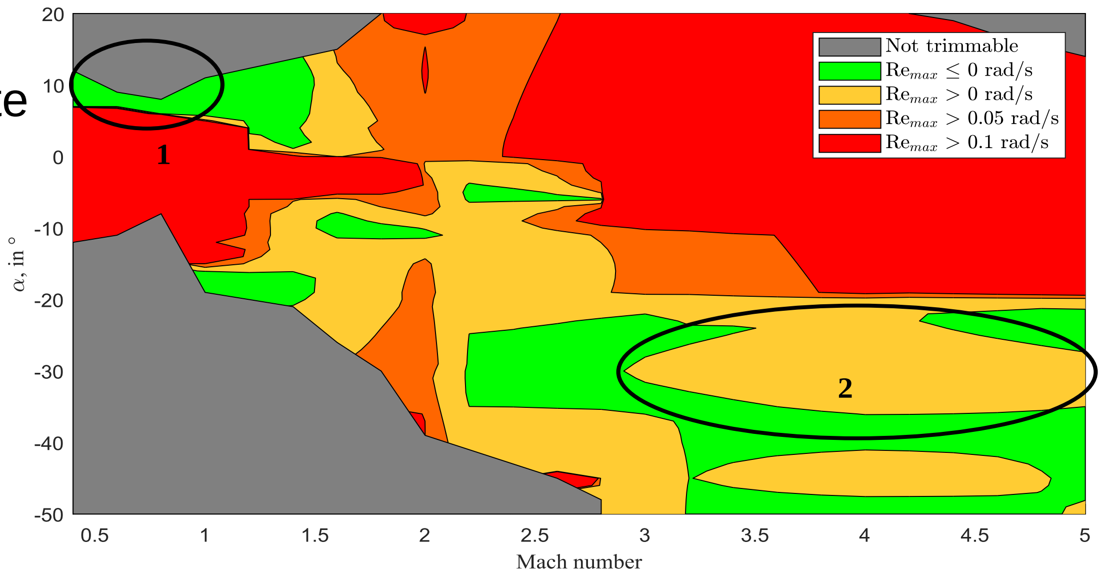
Flight envelope with static stability analysis.



Flight envelope including rotation rate derivatives.

Two regions with changes:

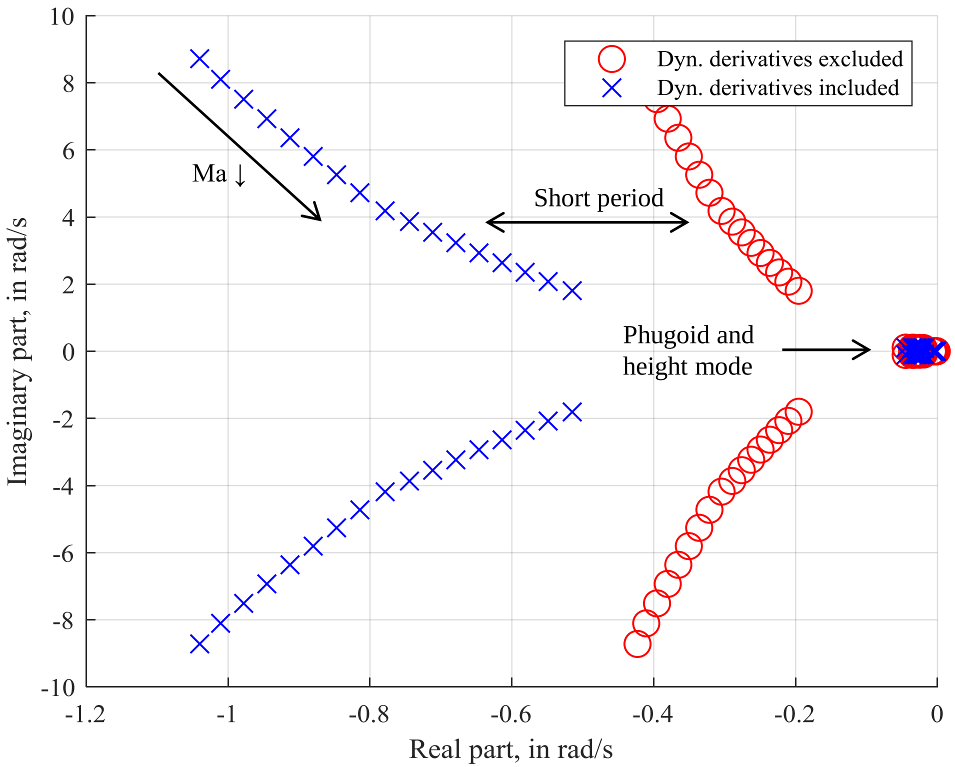
1. End of the trajectory (M < 1)
2. High negative α, high M



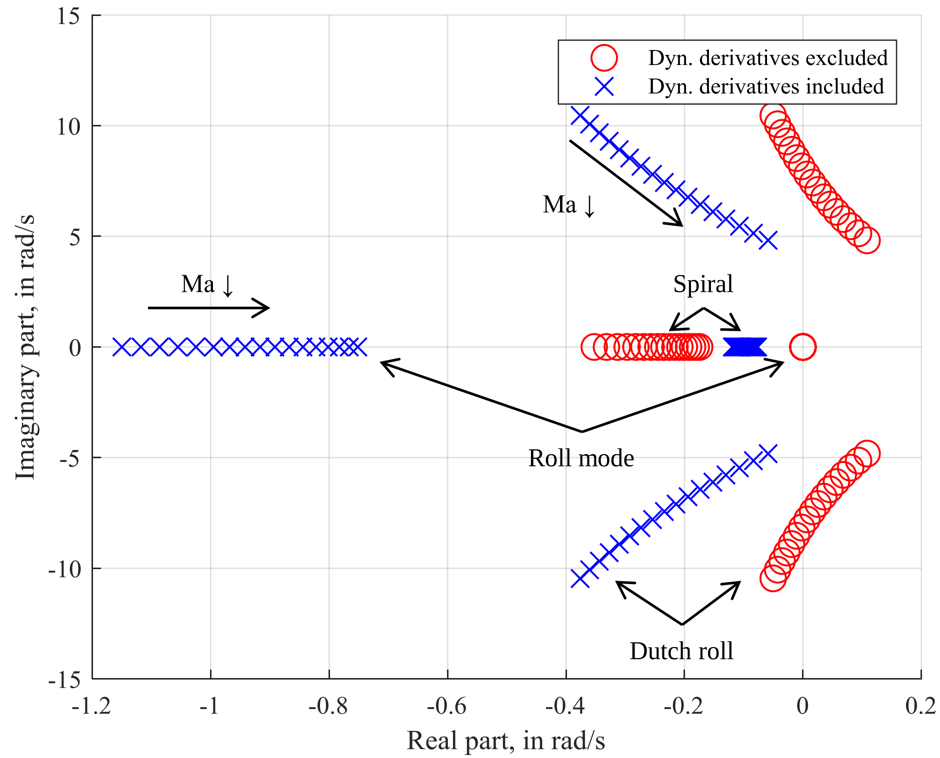
Eigenvalue Analysis – Low Mach numbers

Eigenvalues at α = 8°; 0.4 < M < 0.8; ΔM = 0.025

Longitudinal motion



Lateral motion

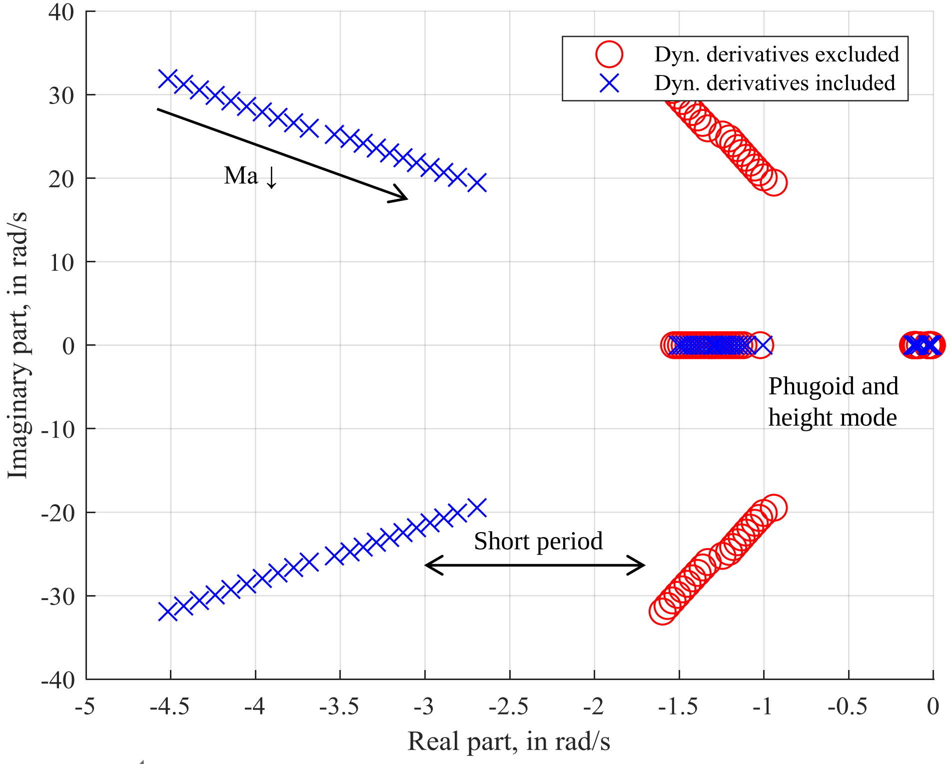


DLR

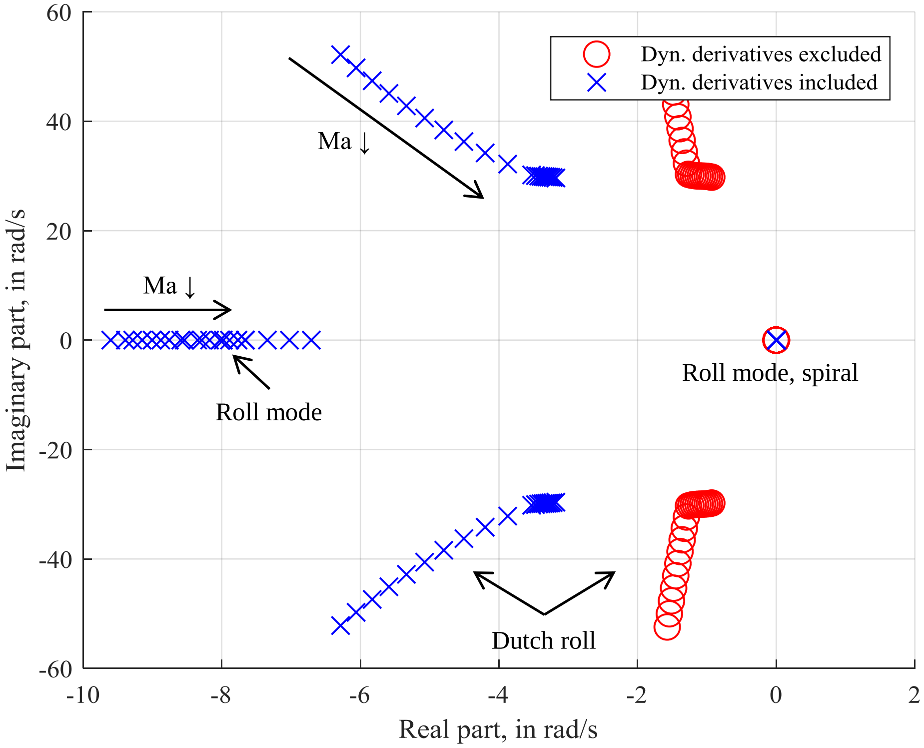
Eigenvalue Analysis – High Mach numbers

Eigenvalues at α = -30°; 3.0 < M < 5.0; ΔM = 0.1

Longitudinal motion



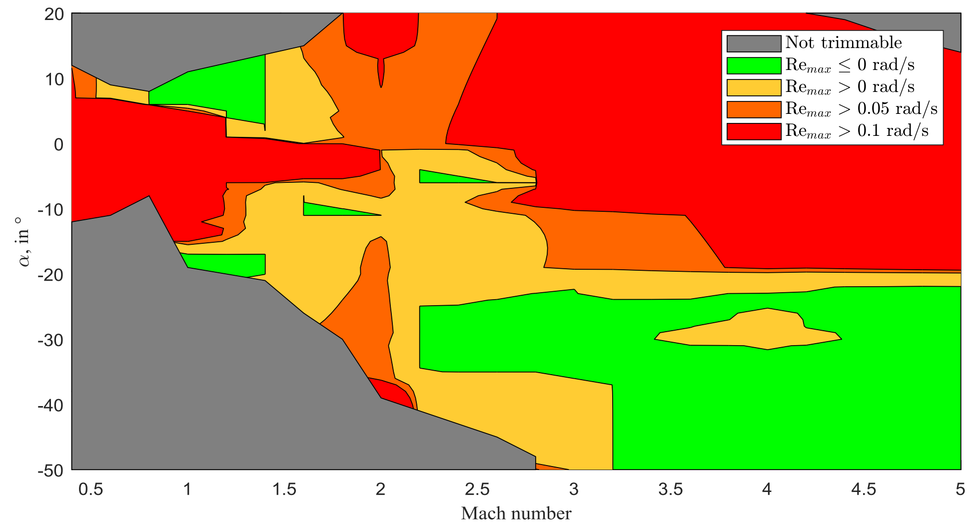
Lateral motion



Conclusion: Influence of Rotation Rate Derivatives

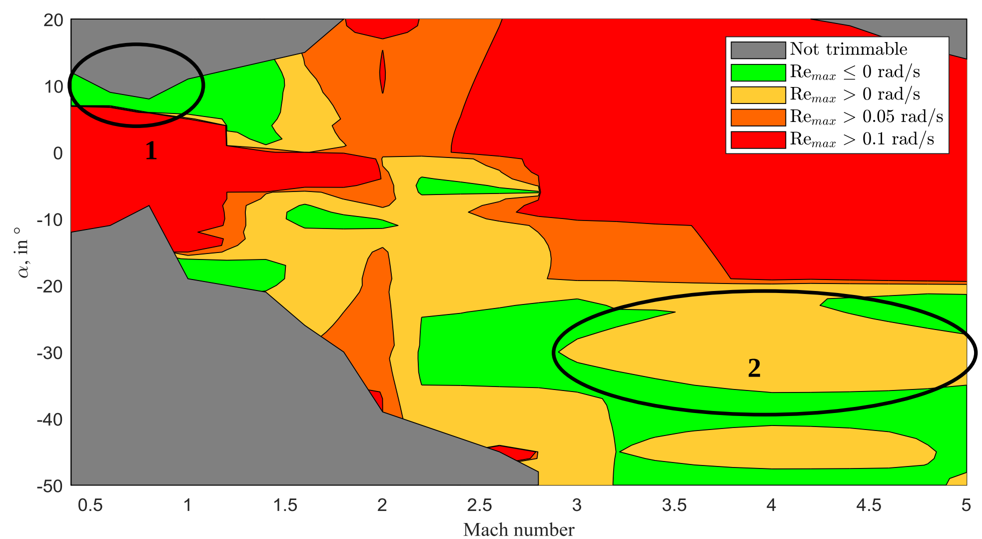
Flight envelope with static stability analysis:

- Smaller envelope than analysis with static dataset only
- Unstable for small Mach numbers



Flight envelope including rotation rate derivatives:

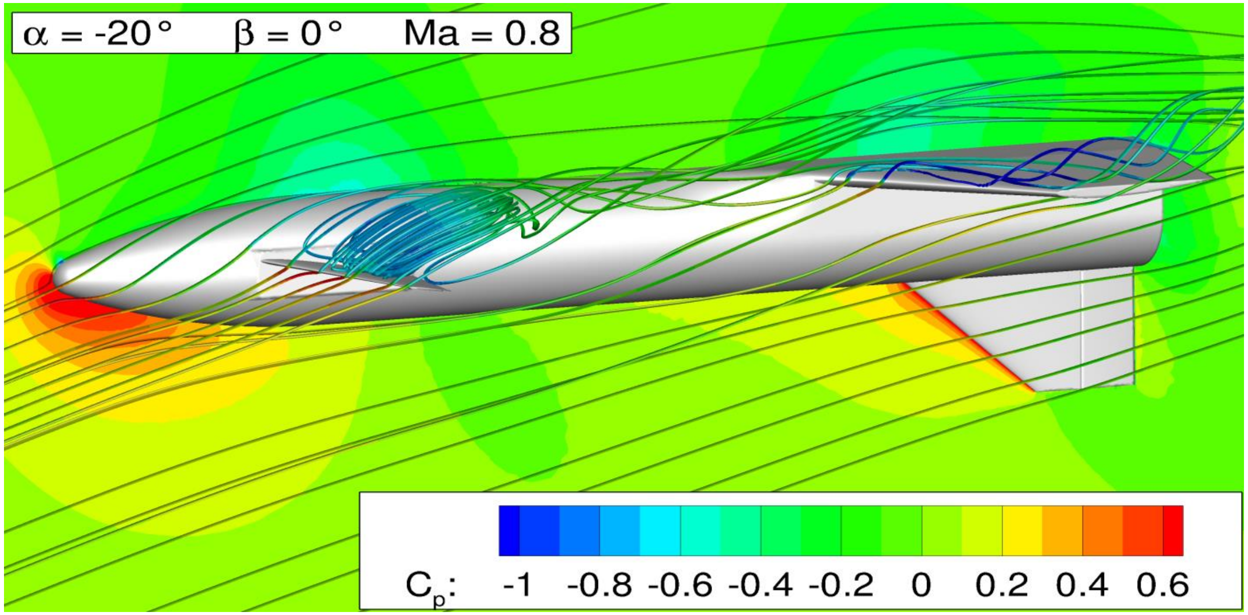
- Only small changes for high Mach numbers (M > 1.5)
- Significant improvement for low velocities (M < 1)



Outlook – Aerodynamic Investigation of ReFEx

- Downstream effects of canards on wings:
  - ➢ Roll reversal
  - ➢ Effects on roll maneuver

- Impact of heat induced bending



Backup

Angular frequency of the movement

$$\omega_i = \|\lambda_i\| = \sqrt{\mathrm{Re}(\lambda_i)^2 + \mathrm{Im}(\lambda_i)^2}$$

Damping ratio of the movement

$$\zeta_i = \frac{-\mathrm{Re}(\lambda_i)}{\omega_i}$$