LIDAR-BASED GUST LOAD ALLEVIATION – RESULTS OBTAINED ON A GENERIC LONG RANGE AIRCRAFT CONFIGURATION

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Motivation for Active Gust Load Alleviation

Aeroplanes in operational service are **exposed to variety of loads** during flight

Landing shock | maneuvering loads | **external disturbances** (turbulence and **gusts**)

Structural load hierarchies are often dominated by gusts

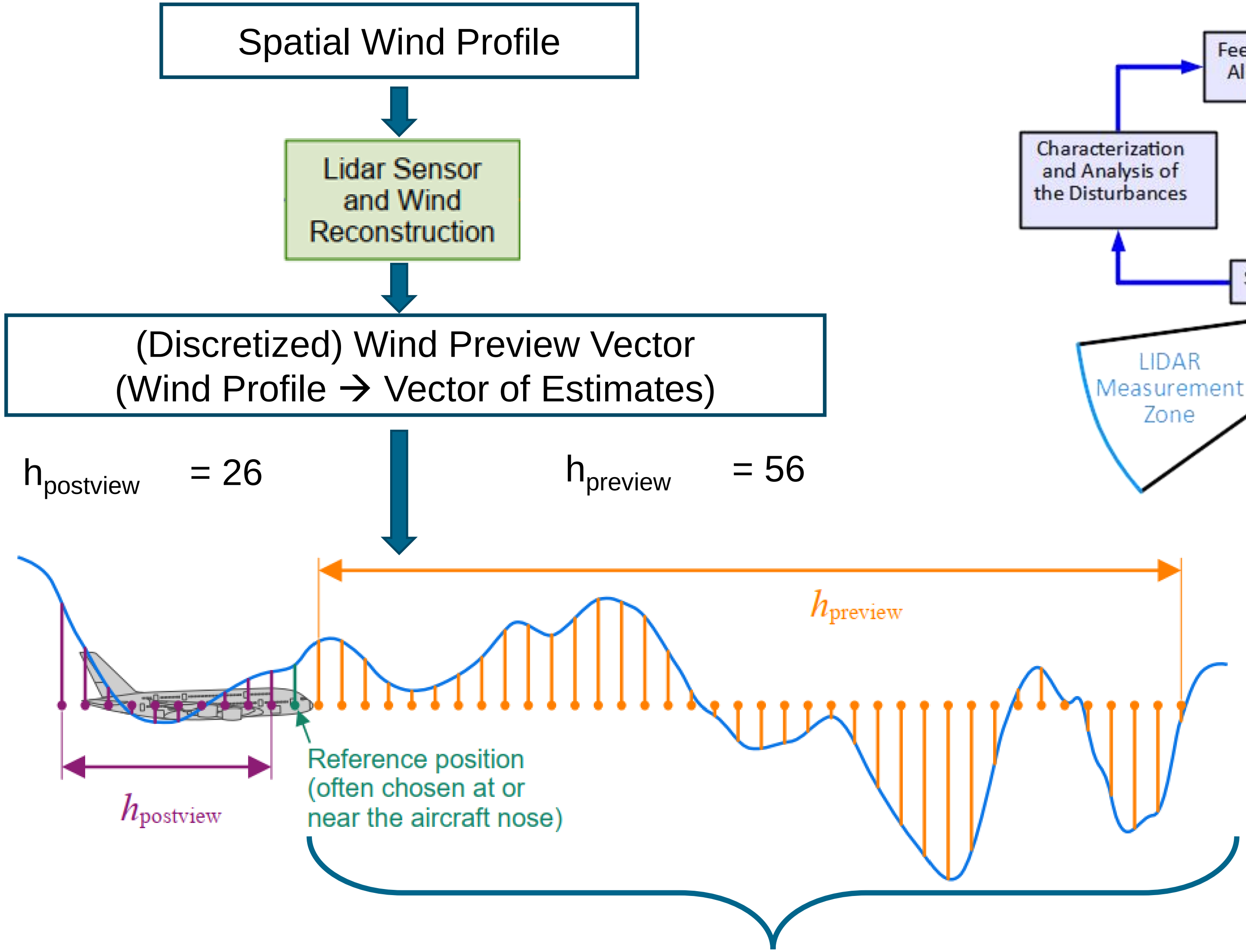
Significant portions of the **primary wing structure** are often **sized by gust load cases**

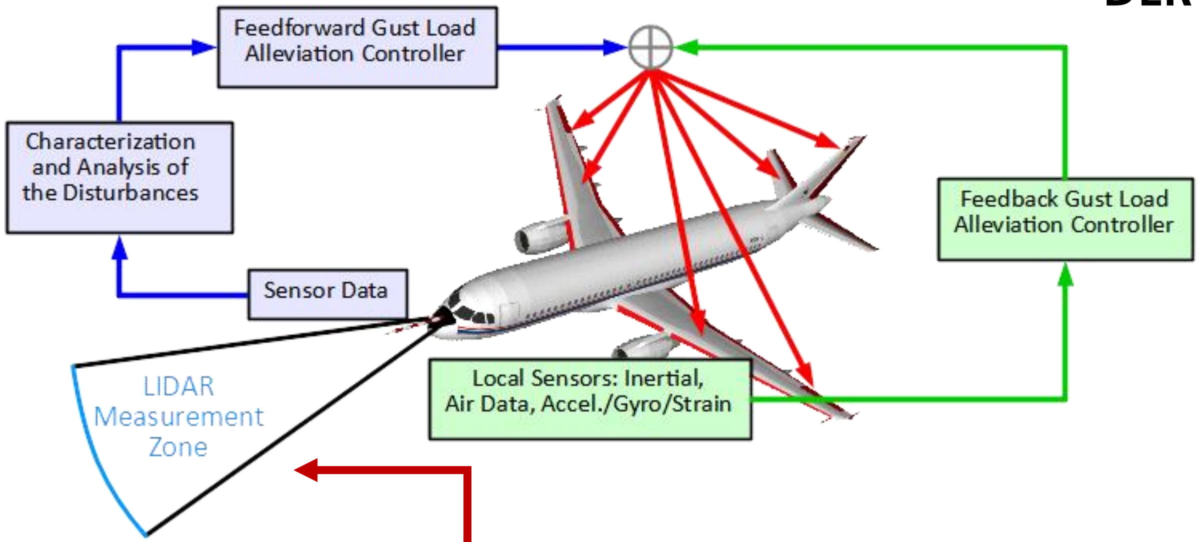
Active **Gust Load Alleviation** (GLA)

Providing opportunity to **redistribute** and **modify wing lift** distribution

Lower structural loads and mass reduction

Lidar-Based Load Alleviation Technology





- Optical sensing of wind field via lidar sensor
- Spatial measurement range (gross) of about 180.0 m

Equivalent to a spatial measurement range (net) of about 148 m (0.56 s / 56 wind preview channels @ V_{TAS} = 264.26 m/s / 100 Hz)

Lidar-Based Load Alleviation Technology

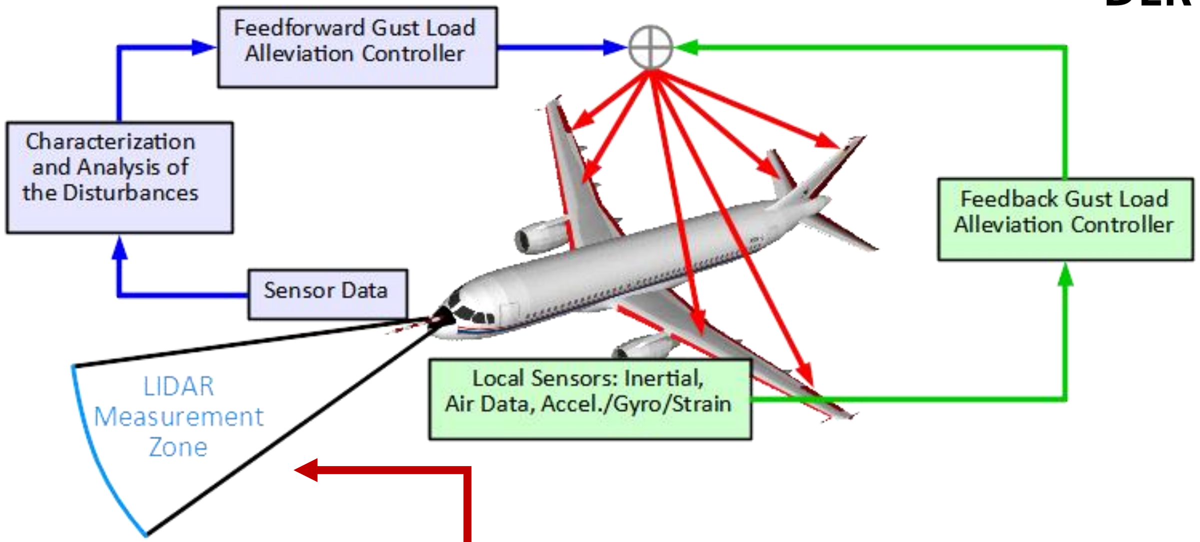
Vertical wind speed measurements are processed by a wind field estimation algorithm

Information of upcoming wind field is provided in advance

System can act **prior** to gust encounter, influencing aircraft motion via intelligent control surface commands

Pitch aircraft up/down

Changing Angle-of-Attack in advance is extremely **effective** and **efficient** for **modulating** the aerodynamic forces

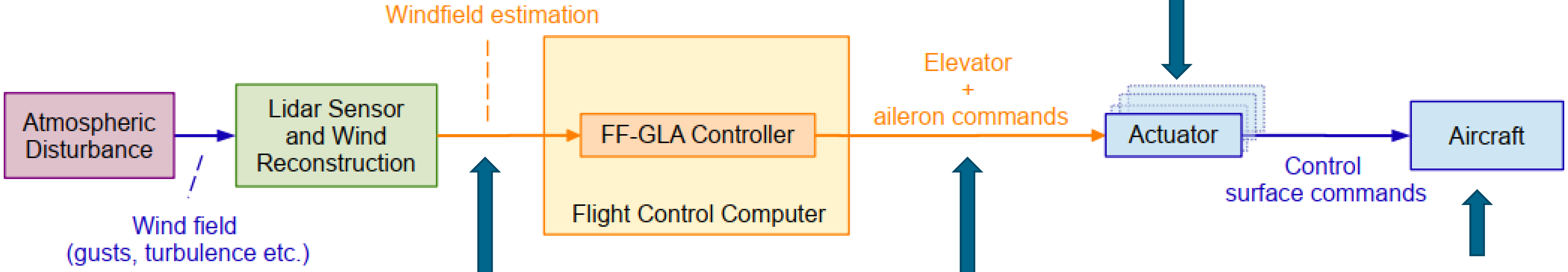


- Optical sensing of wind field via lidar sensor
- Spatial measurement range (gross) of about 180.0 m

Feedforward Preview-GLA Control „Loop“

Nonlinear Limits

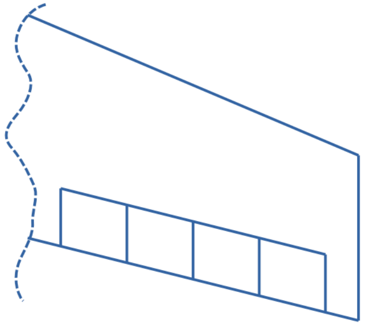
	Position	Rate
Elevators	± 25°	± 50°/s
Ailerons	± 25°	± 50°/s



Generic Long Range Aircraft Model

Wind Preview Vector
83 Wind Measurement Channels

5 independent and **symmetric** (identical signal for left and right wing) **actuator commands [1 x Elevator, 4 x Aileron Pairs]**



Generic Long Range Aircraft – Aeroelastic Modelling Approach

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- Used **aircraft models** based on “mean axes” formulation:
  - Non-linear Newton-Euler equations of motion for the “rigid-body” part
  - Linear modal representation of the structural dynamics
  - Aerodynamic loads are derived by the **Doublet Lattice Method** (DLM) and transformed into State Space formulation by a **Rational Functional Approximation** (RFA)
  - Cut loads are recovered by the **Force Summation Method** (FSM)

- **Nonlinear aircraft modelling structure** consists of
  - over **2800 states**
  - **100 disturbance inputs** (for vertical wind and turbulence),
  - **22 control surface inputs** (8 ailerons, 2 elevators, 12 spoilers),
  - over **2500 cut load outputs**,
  - over **4800 velocities and acceleration outputs**.

Individual
mass distribution

modelling approach

Individual
nonlinear aeroelastic model

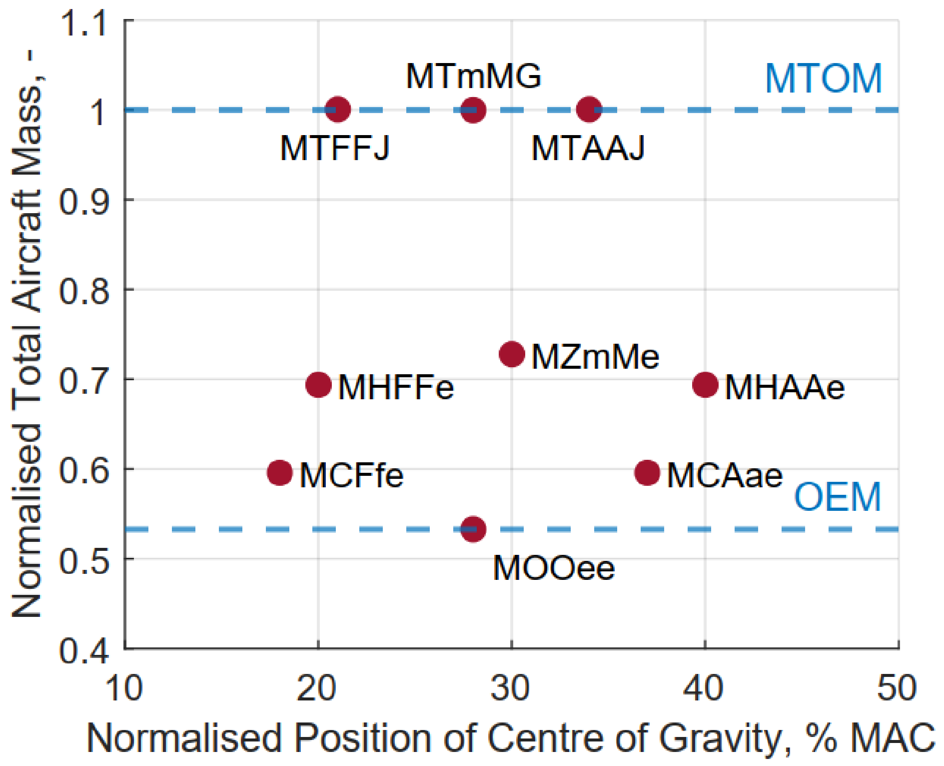
trimming and **linearisation** at specific conditions

Multiple **linear time invariant aeroelastic models** per mass case

Generic Long Range Aircraft – Considered Mass Cases and Trim Conditions

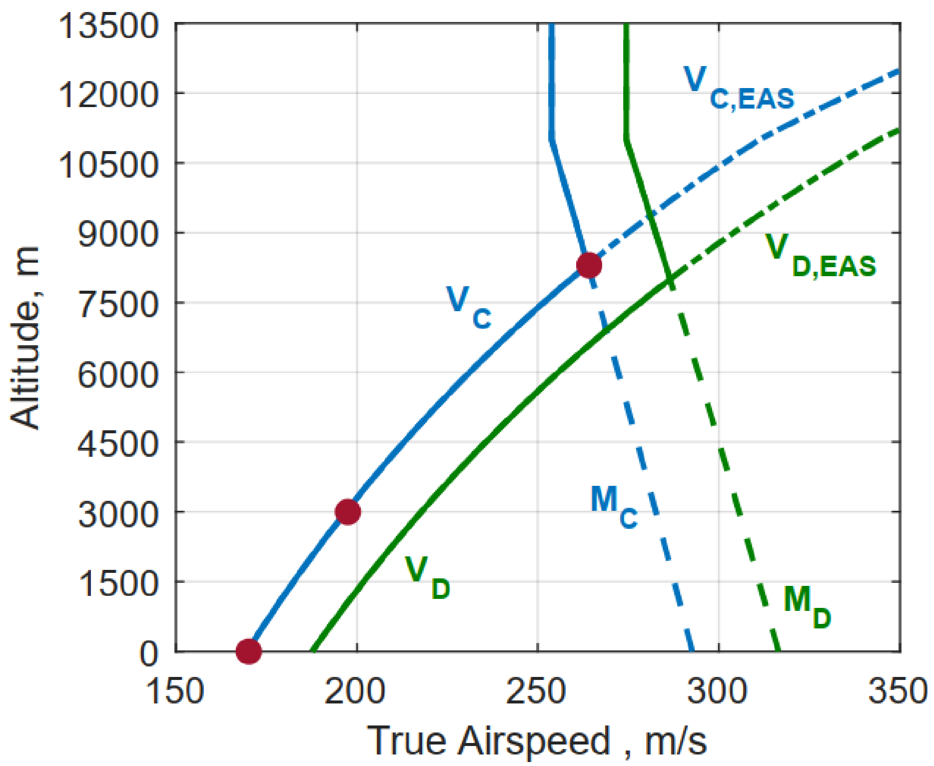
9 mass distributions

Δ 46.76 %



Δ 22 % MAC

3 flight points



Δ 8300 m (27231 ft.)

Δ 94 m/s (183 kts)

- **54** linear models were considered for GLA controller development
  - **9** (mass distributions) x **3** (flight points) x **2** (wing configurations: clean wing + airbrake out)

Controller Tuning (Synthesis)

DLR-FT-GLRA-GLA-FF-v1

Reducing the **bending moment at the wing root** was the **top priority**!

Open loop preliminary analysis: identification of worst gust load cases

(Composed by only 4 different aeroelastic models (out of 54 LTI-models))

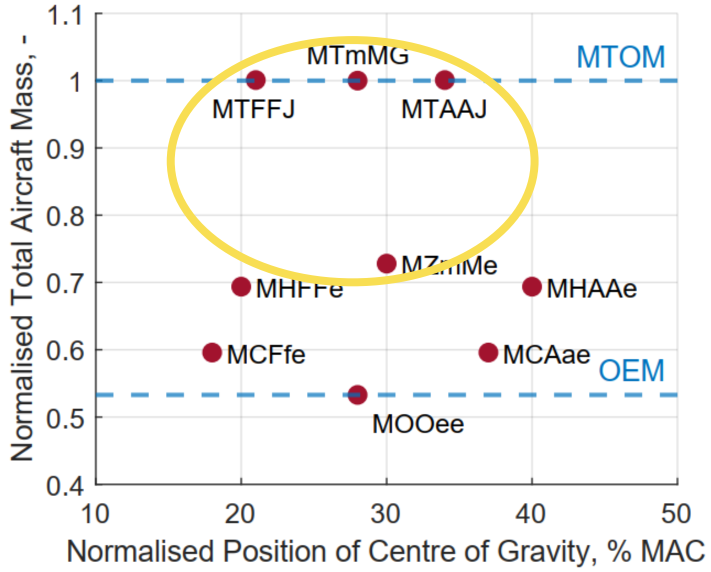
Controller tuning based on these 4 specific aeroelastic design models

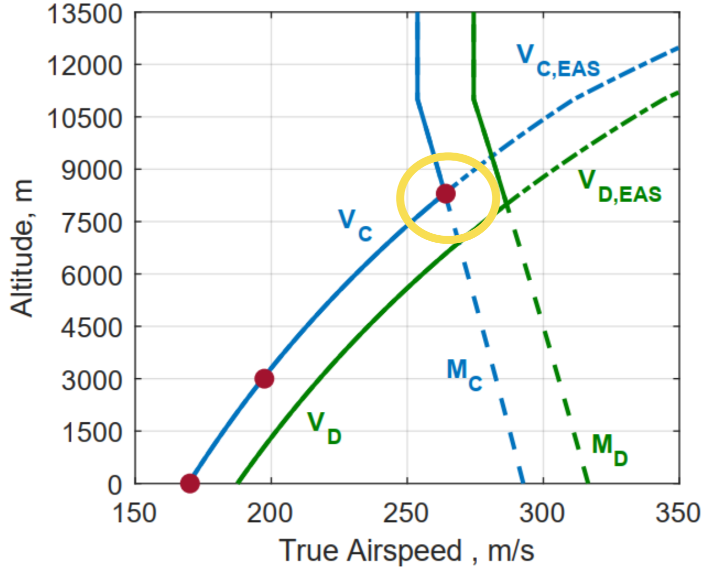
Control function is **optimised** directly **in discrete time**

(via modern **robust control** methods (**H-infinity**))

Tuning based on **multiple different optimisation criteria**

(Multi-Model-Multi-Channel-Synthesis)

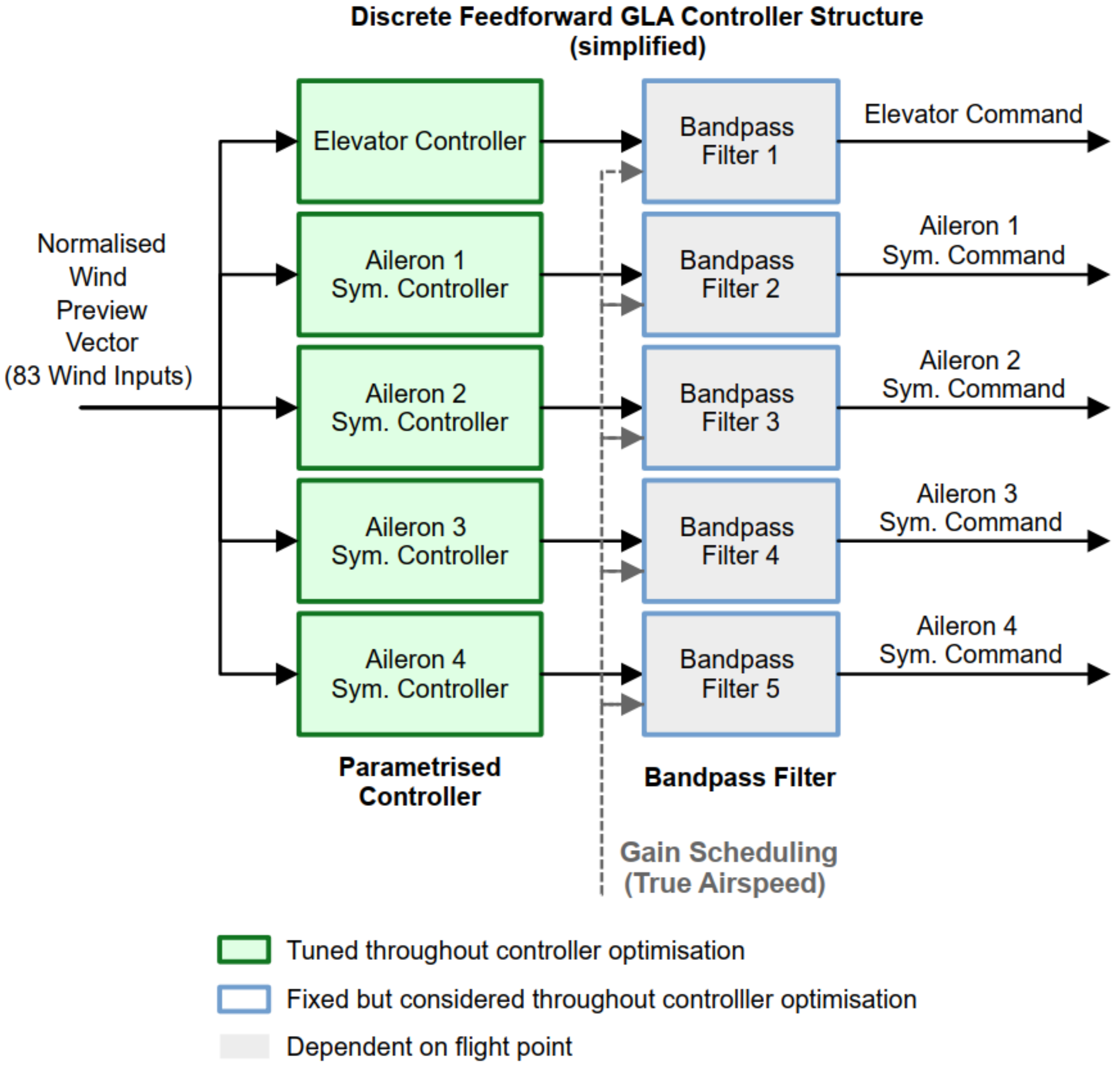




Controller Structure

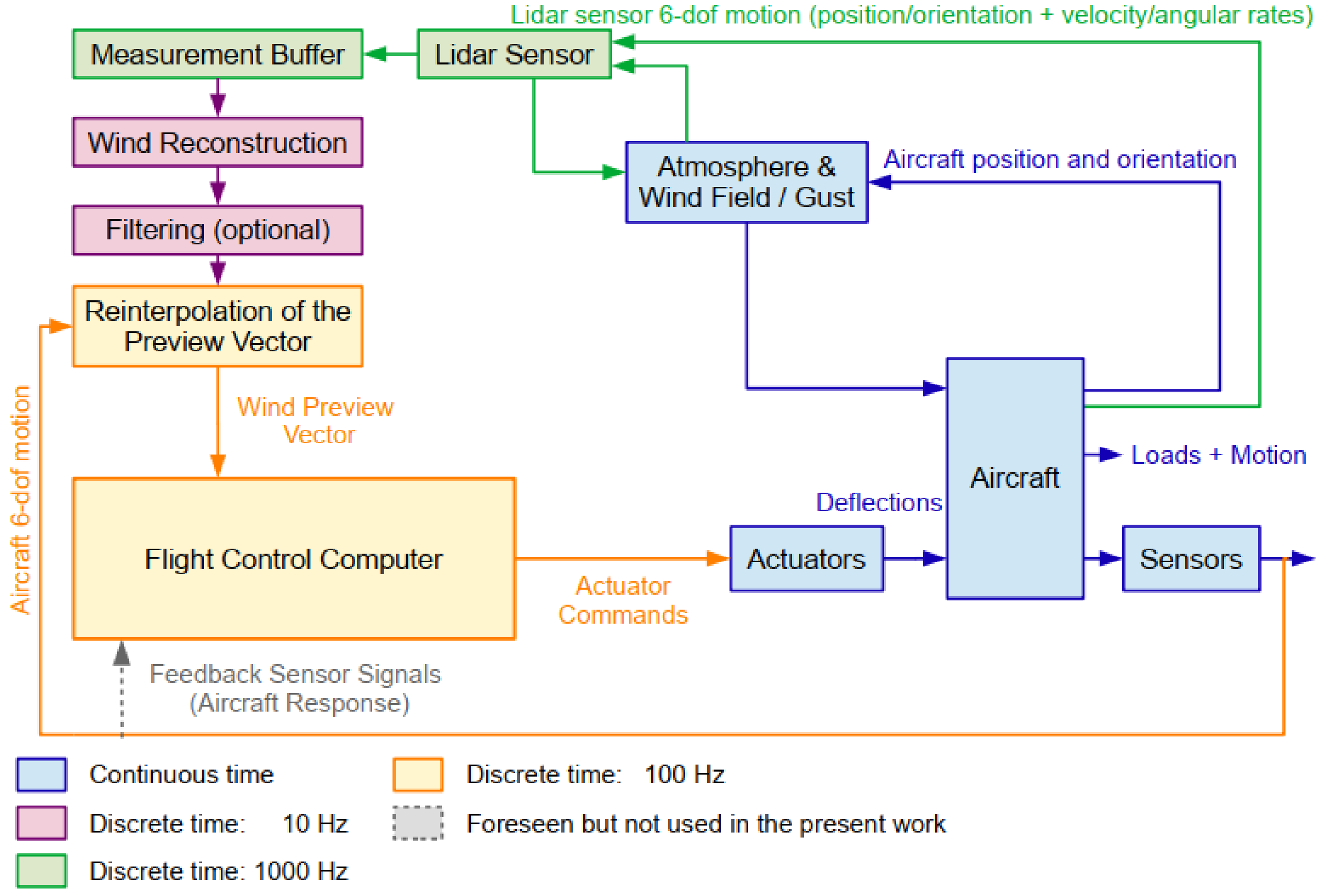
DLR-FT-GLRA-GLA-FF-v1

- Implemented in discrete time (100 Hz)
- **Controller structure consists of** only **15 States** → easily implementable controller
- **Requires only wind information**
- **Gain-scheduled** with **true airspeed**
- **No gain scheduling based on mass, centre of gravity, or mass distribution**



Multi-Rate and Hybrid-Simulation Environment

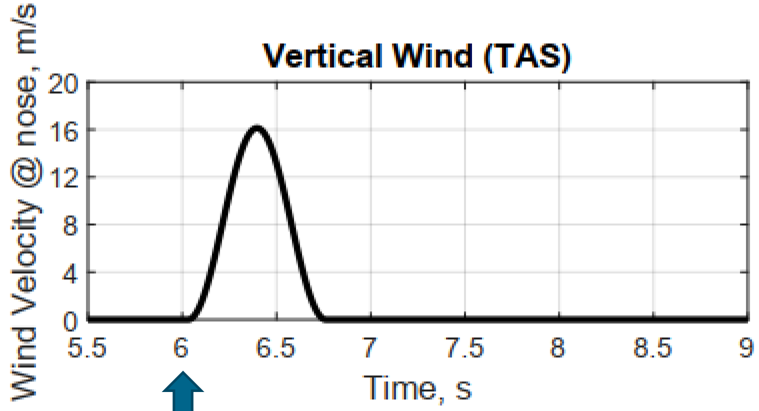
- **Simulation environment** to perform time simulations and to evaluate GLA controller:
  - includes a **detailed lidar sensor model** including an advanced wind reconstruction algorithm,
  - consideration of **arbitrary controller configurations** like the feedforward preview control loop,
  - **complex aeroservoelastic aircraft models.**



Used for all results that are shown hereafter.

Controller Evaluation

A/C Behaviour in Time Domain – Aircraft Excitation (Example)



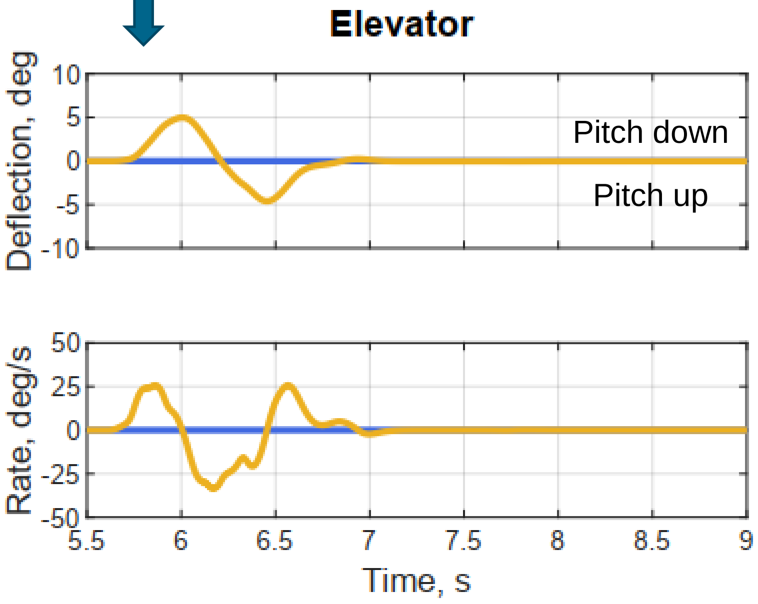
Elevator deflects prior to gust impact

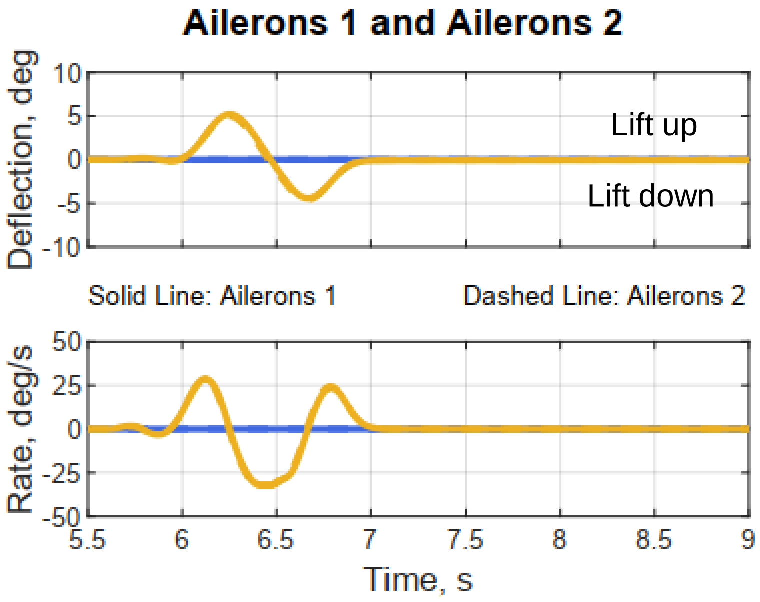
Critical gust load case for wing root bending moment

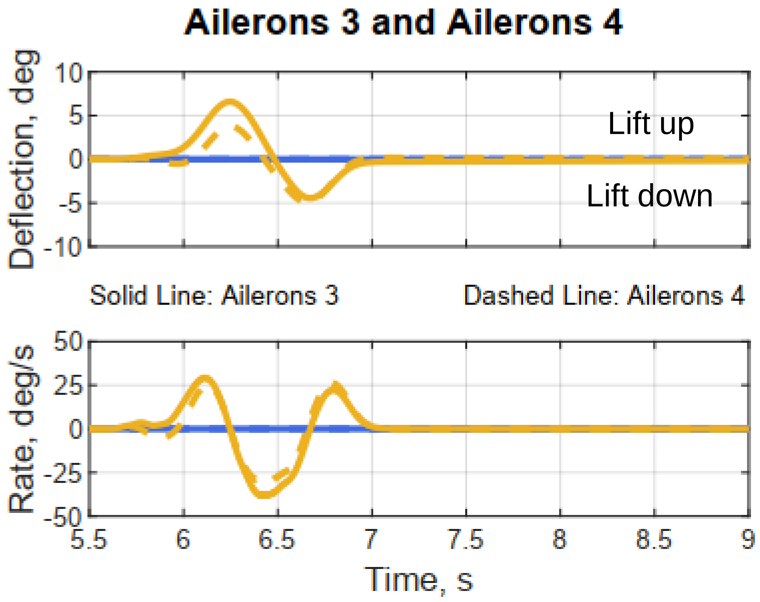
Open Loop

Preview Controller

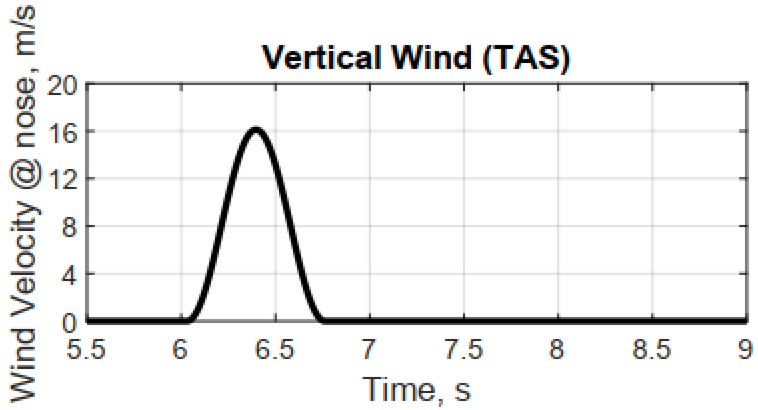
Aircraft Model:	**GLRA**
Mass Distribution:	**MTmMG**
Altitude:	**8300 m**
True Airspeed:	**264.2596 m/s**
Design Speed:	**VC**
Wing Configuration:	**clean**
Gust Length:	**96.6842 m**
Gust Direction:	**upwards**







Controller Evaluation
A/C Behaviour in Time Domain – Aircraft Reaction (Example)



Critical gust load case for wing root bending moment

Open Loop | Preview Controller

Aircraft Model:	GLRA
Mass Distribution:	MTmMG
Altitude:	8300 m
True Airspeed:	264.2596 m/s
Design Speed:	VC
Wing Configuration:	clean
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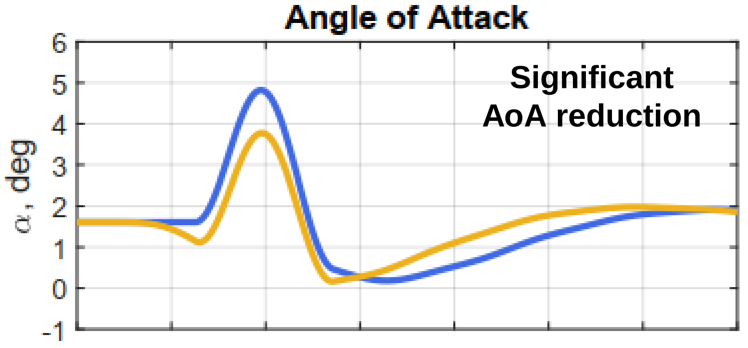
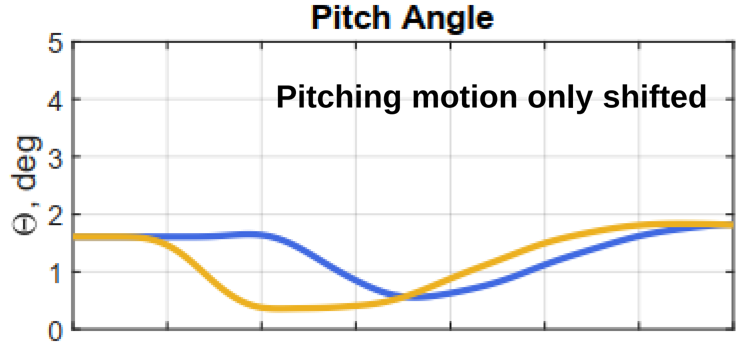
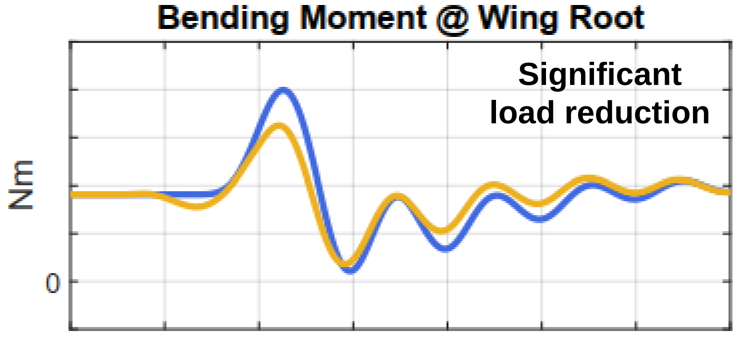
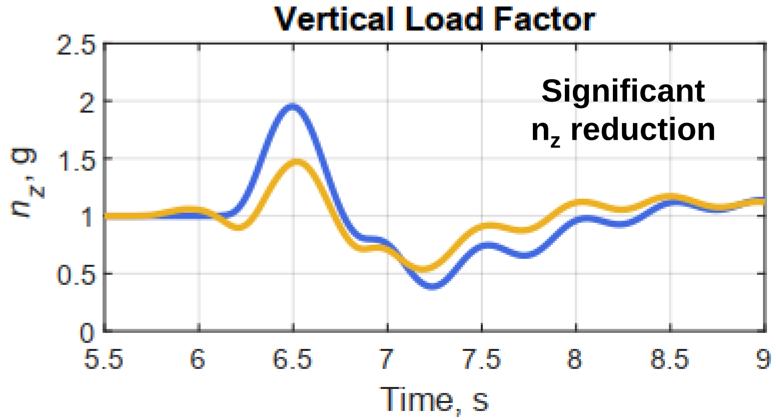
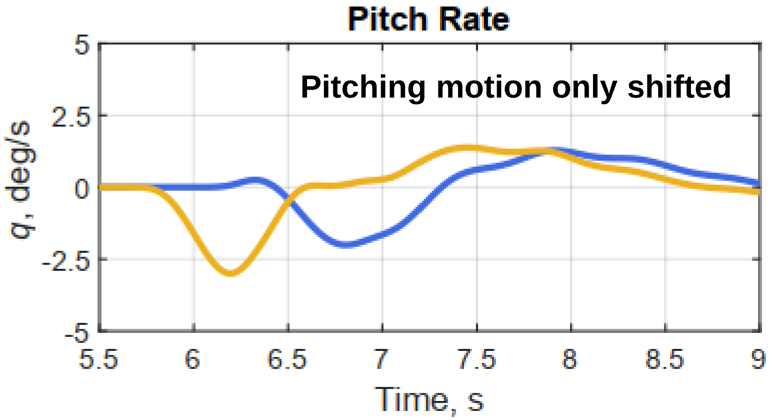
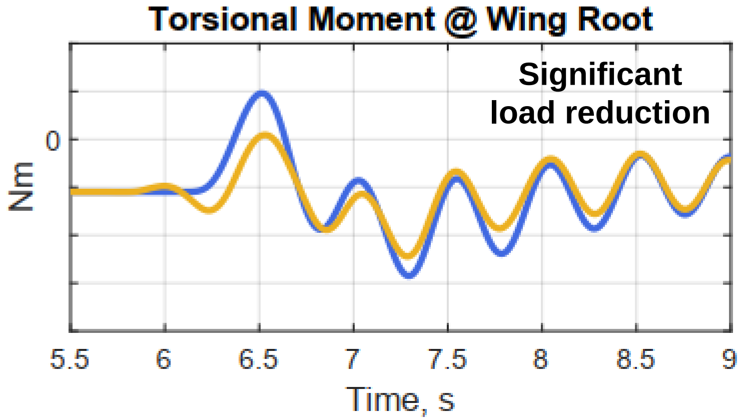












Controller Evaluation: Gust Load Cases

Gust Load Cases (CS 25.341a)

Gust Lengths		Gust Directions
9.00 m	**29.53 ft.**	upwards / downwards
14.16 m	46.45 ft.	
19.32 m	63.37 ft.	
24.47 m	80.29 ft.	
29.63 m	97.22 ft.	
34.79 m	114.14 ft.	
39.95 m	131.06 ft.	
45.11 m	147.98 ft.	
50.26 m	164.91 ft.	
55.42 m	181.83 ft.	
60.58 m	198.75 ft.	
65.74 m	215.67 ft.	
70.89 m	232.59 ft.	
76.05 m	249.52 ft.	
81.21 m	266.44 ft.	
86.37 m	283.36 ft.	
91.53 m	300.28 ft.	
96.68 m	317.21 ft.	
101.84 m	334.13 ft.	
107.00 m	**351.05 ft.**	

20 gust lengths x **2** gust directions

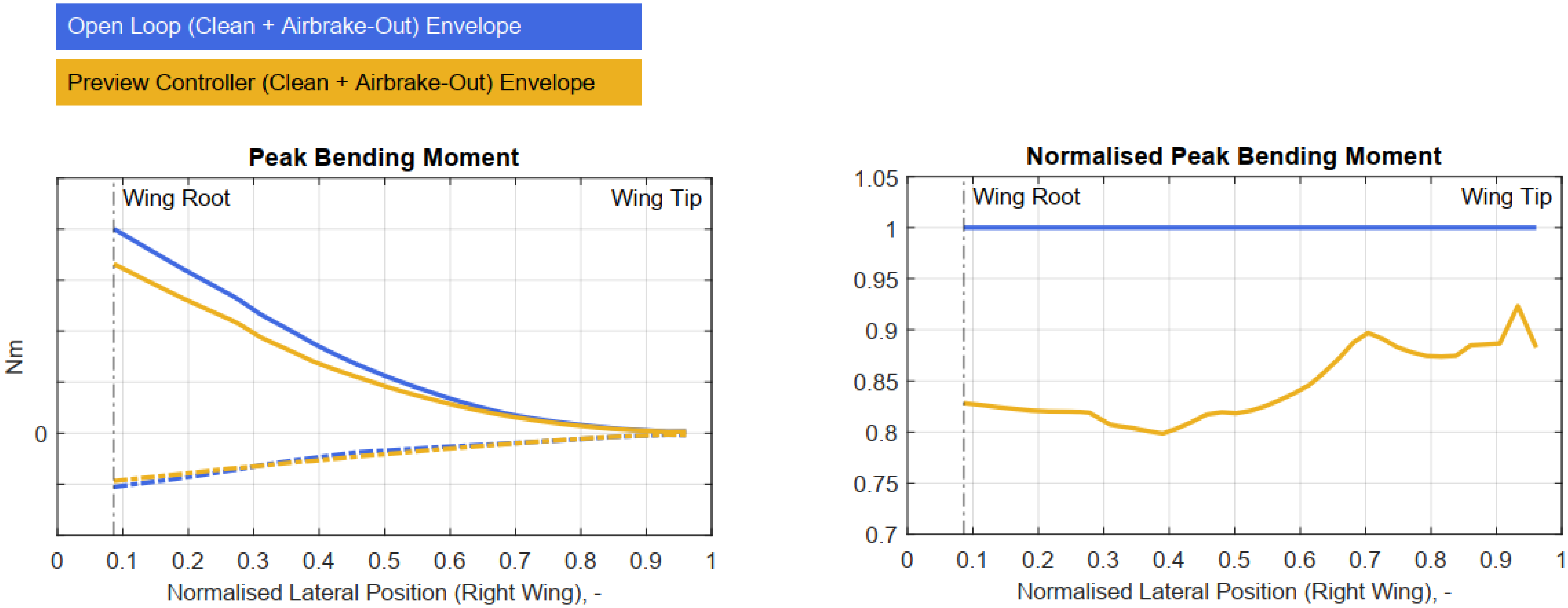
Load cases per controller configuration

54 aircraft models x **40** gust load cases

2160 gust load cases for each configuration

- Open Loop (Clean + Airbrake-Out) Envelope
- Preview Controller (Clean + Airbrake-Out) Envelope

Load Alleviation Results – Wing Bending Moment

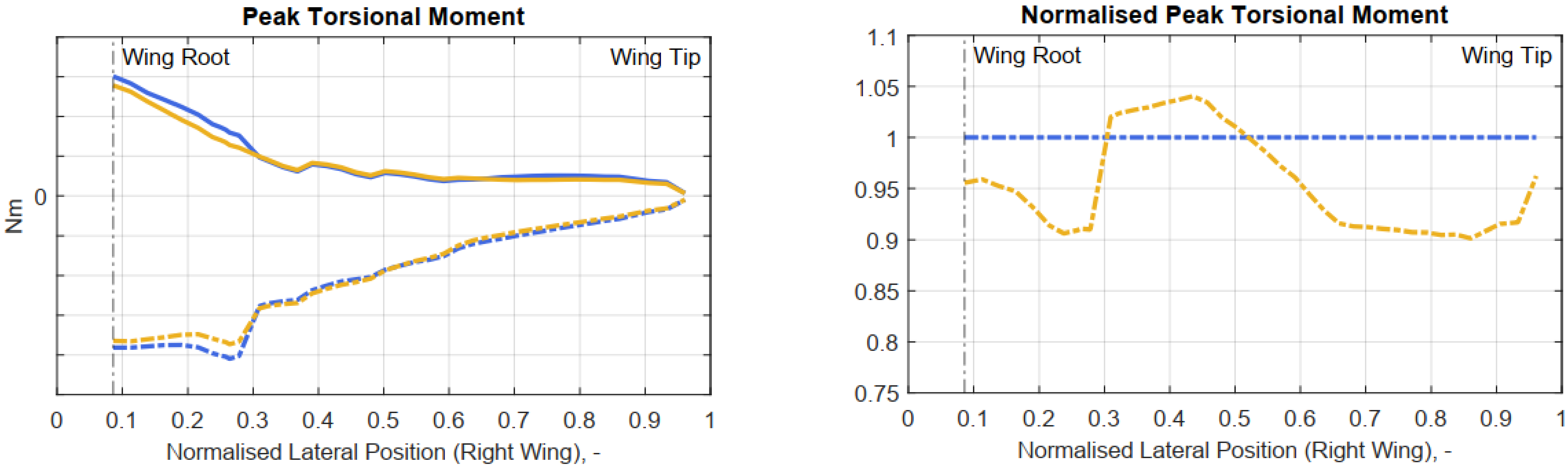


- Achieved performance of the feedforward preview controller
  - **17% bending moment reduction at wing root**,
  - **maximum bending moment reduction** of about **20%**,
  - improved bending moment envelope distribution over the entire wing.

Load Alleviation Results – Wing Torsional Moment

Open Loop (Clean + Airbrake-Out) Envelope

Preview Controller (Clean + Airbrake-Out) Envelope



- Achieved performance of the feedforward preview controller:
  - reduced torsional moment between the wing root and the engine pylon,
  - reduced torsional moment between the mid-wing and the wing tip,
  - increased torsional moment between the engine pylon and mid-wing.

Summary and Conclusions

- **Complete load alleviation system was designed and evaluated**
  - using a multi-rate and hybrid simulation environment including
    - a **realistic lidar sensor system** / post-processing algorithms
    - a **complex aeroservoelastic model**
    - a discrete preview controller running at 100 Hz
  - **Assessment of HTP loads and differentiated analysis of wing loads for clean-wing and airbrake-out cases are shown in the paper**

- Feedforward preview controller achieves a **significant reduction** of the peak **bending moment**
  - about **17-18 %** around the **wing root**,
  - **up to around 20 %** close to 1/3 of the wing span,
  - about 10-12 % near the wing tip
- Feedforward preview controller **balances** need for strong **load reduction** vs. **gentle control commands**
- Feedforward preview controller yields slight torsional load increase in the middle of the wing
  - Should not be a problem, potential mass reduction caused by bending moment reduction predominates potential mass increase caused by additional torsional moment

Thank you very much for your attention! Questions?

Impressum

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