Combined LIDAR-Based Feedforward and Feedback Gust and Turbulence Load Alleviation

CLEANSKY

SFWA-ITD

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Knowledge for Tomorrow

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Gusts and Turbulence Cause Loads and Passenger Discomfort

Induced additional loads must be taken into account in the design of the structure

- various standardized cases must be demonstrated for certification
- on all these cases the maximum loads on each part of the structure are determined
- additional safety margins are applied
- the structure shall be designed to withstand the maximum loads + safety factors

➔ Reducing the loads acting on the aircraft enables weight savings and thereby more efficient and green aircraft

Additionally when encountering gusts or turbulence

- undesired aircraft motions can be induced by the change in aerodynamic forces and moments (+ coupling with flexibility of the structure)
    - can become a safety threat (e.g. for passengers or cabin crew personnel that would not be seated or with their seat belts unfastened)
    - causes discomfort and passenger anxiety

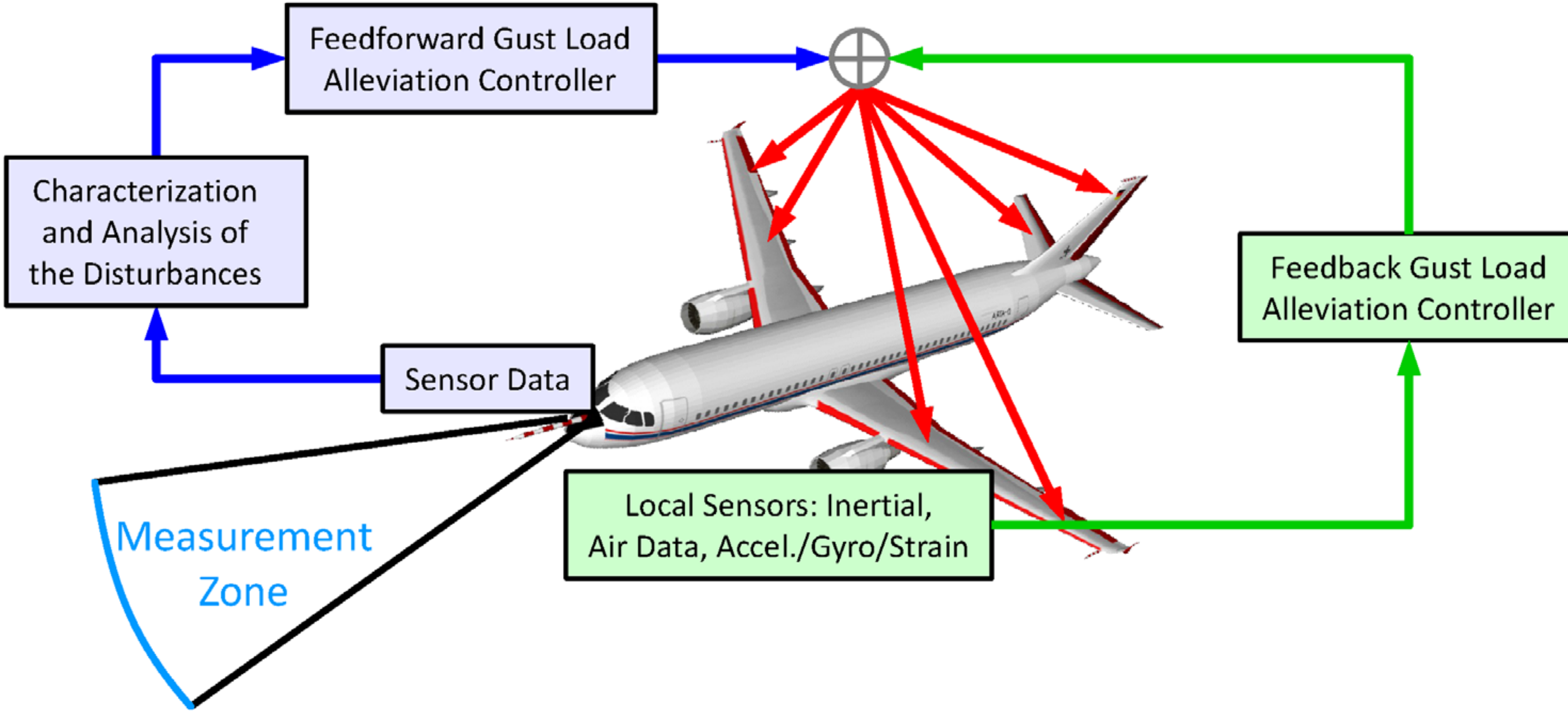
How Can We Reduce the Loads?

- Procedures (e.g. fly at lower speed when in turbulence)

- Passive load alleviation
  → see presentation #122 on Thursday Oct. 13th in Room 202 at 14:30
  "Adaptive Wing: Investigations of Passive Wing Technologies for Loads Reduction in the CleanSky Smart Fixed Wing Aircraft, SFWA Project"

- Active load alleviation
  - Specific control algorithms
  - Additional sensors (accelerometers, gyros, strain-gauges, etc…)
  - Possibly remote wind sensors (e.g. Doppler LIDAR), which permit to anticipate the future disturbances

Active Load Alleviation: Feedback vs. Feedforward?



Active Load Alleviation: Feedback vs. Feedforward?

Feedback load alleviation

- Based on the measurements directly on the aircraft
  - Either of some consequence of the gust/turbulence (e.g. bending motion of the wing)
  - Or the gust itself as the aircraft encounters it (e.g. pressure ports)
- Can allow to add structural damping on the flexible modes
- No anticipation capabilities

Feedforward load alleviation

- Needs remote wind measurements to be effective *(challenge!)*
- Enable the anticipation of near future loads
  → pitching actions can be used!

Note that the load variations that can be reached with pitching actions are roughly one order of magnitude higher than with ailerons and spoilers!

LIDAR-Based Feedforward Load Alleviation Function

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What Are Doppler LIDAR Sensors?

Doppler LIDAR

- Based on the backscattering of light on particle(s)/molecules of the air
- Doppler-shift → relative line-of-sight velocity between the particle(s)/molecules that have scattered the light back and the sensor.

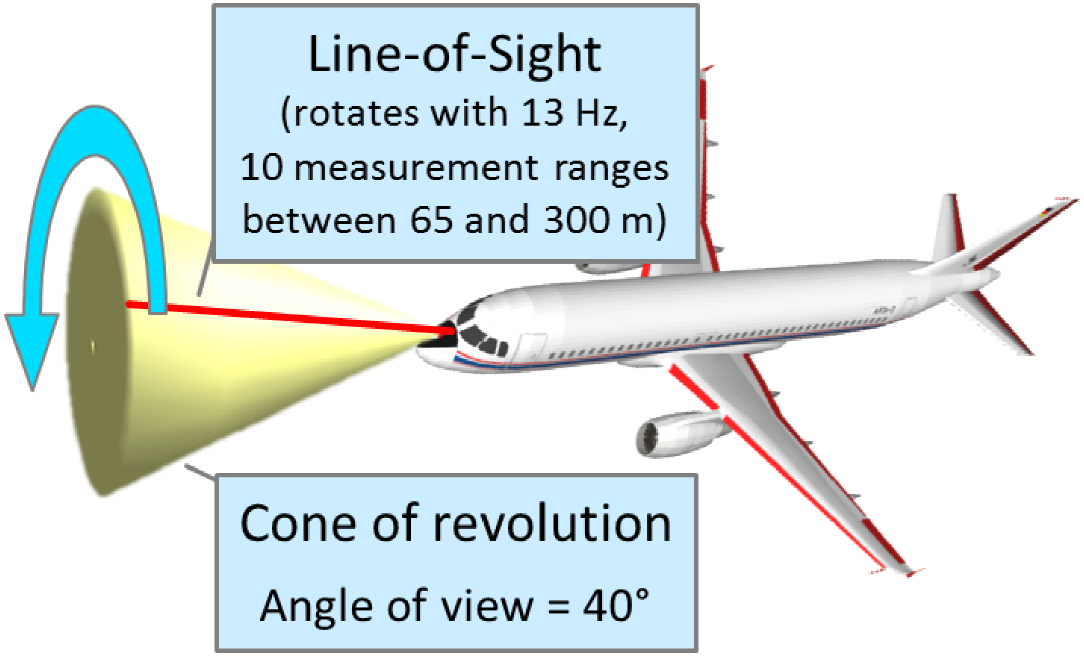
Problem:
→ Relative wind components perpendicular to LoS are lost!
→ And the vertical component at a location ahead of the aircraft is the most interesting wind information for load alleviation

Scanning the Space Ahead of the Aircraft

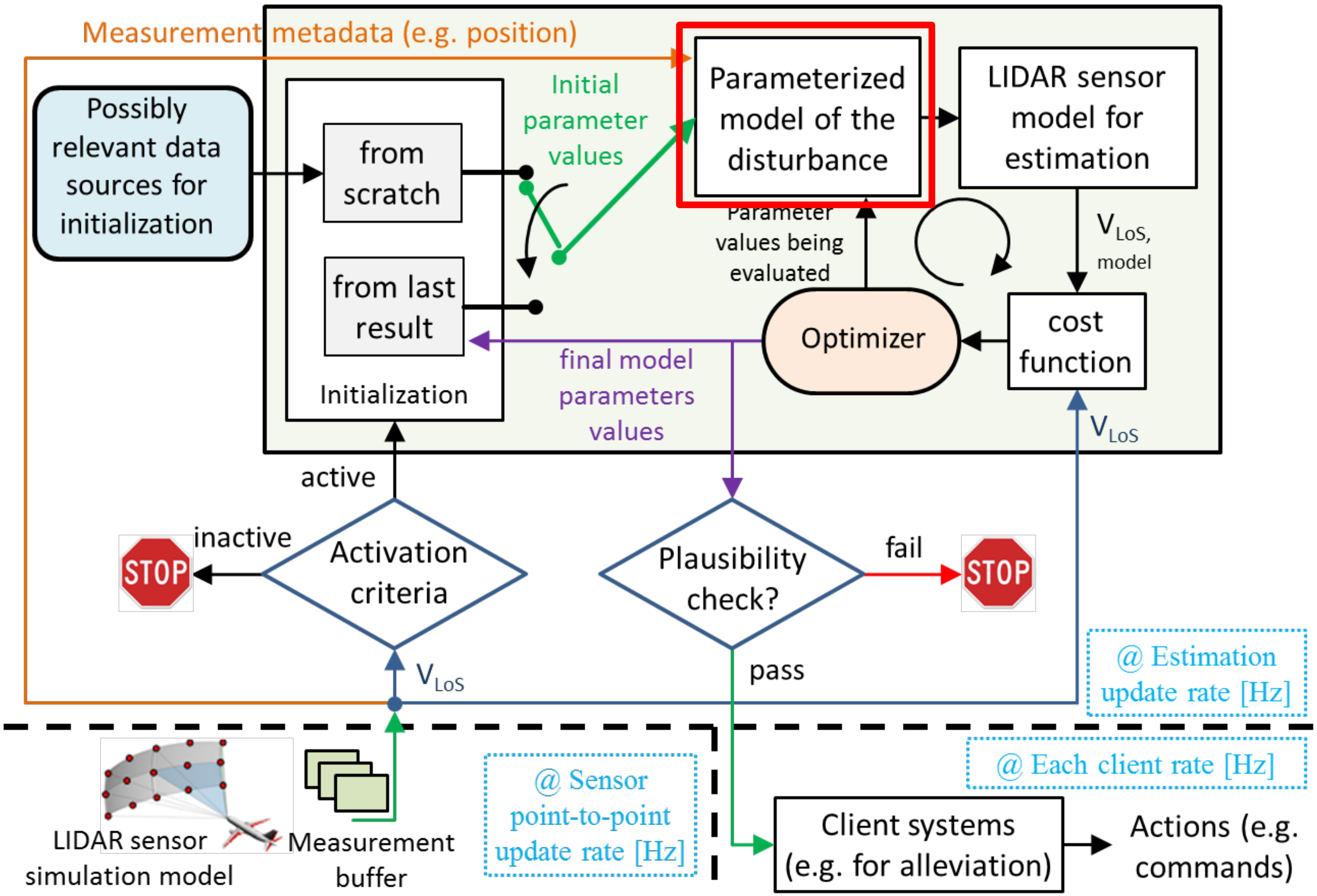
Basic idea:

Perform measurements at different locations ➔ different line-of-sight directions

“Simple” scan geometry based on a cone of revolution

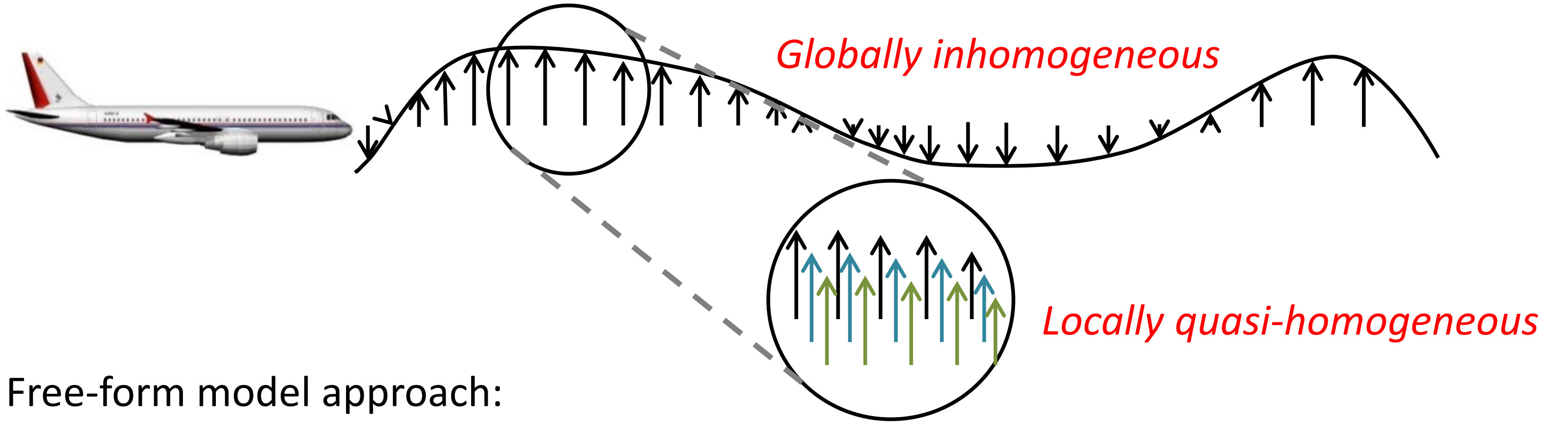


Sketch of the Wind Reconstruction Algorithm

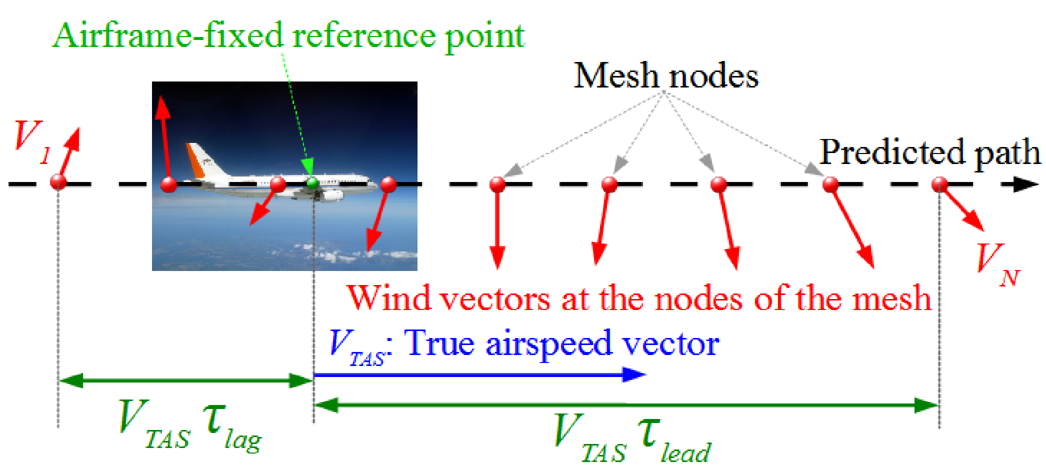


Gusts and Turbulence Reconstruction

- Several measurements are combined to reconstruct the useful wind components
  - Phenomenon is stochastic → no deterministic model can/shall be assumed
  - Reconstruction is made based on a "local quasi-homogeneity assumption"



  - Free-form model approach:



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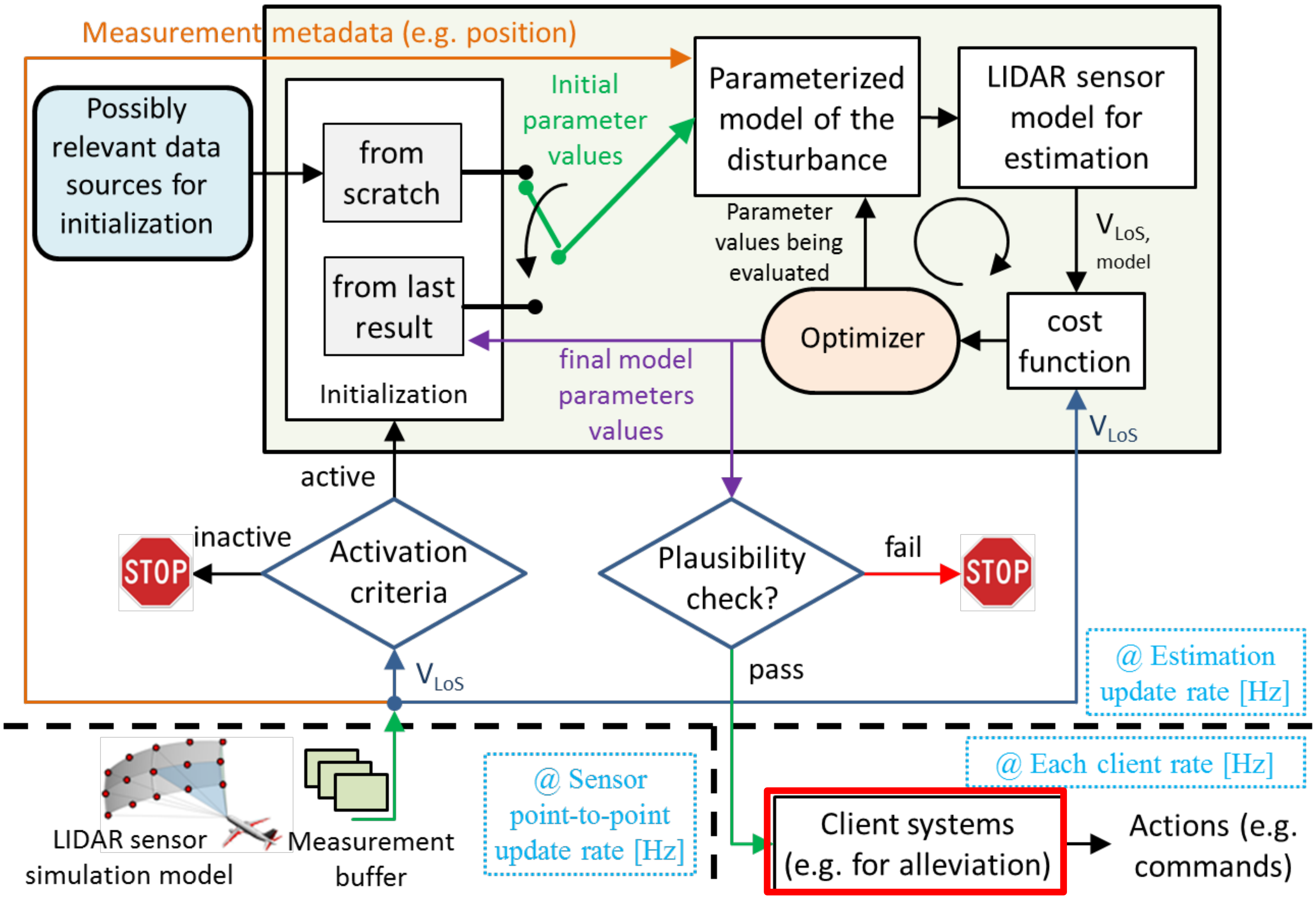

Satisfying Strong Allocation Constraints by Design

Reconstructed wind ahead of the aircraft

↓

Wind profile analysis and decomposition

↓

Controller #1:
- *Low frequencies*
- *Large amplitudes*

→***Pitching actions***

Controller #2:
- *Medium frequencies*
- *Small to medium amplitudes*

→***Symmetrical deflections of ailerons (no spoilers)***

Controller #3:
- *Medium frequencies*
- *Medium to large amplitudes*

→***Symmetrical deflections of ailerons and spoilers***

↓

Gathering and combining commands

↓

Feedforward load alleviation commands

Satisfying Strong Allocation Constraints by Design

Reconstructed wind ahead of the aircraft

The synthesis of each controller only needs to focus on a smaller problem (simple constraints, simple goal, and few tuning parameters).

Advanced tools (e.g. from the linear and robust control theories) can be used for each of these feedforward control design problems.

Controller #1:
- *Low frequencies*
- *Large amplitudes*

→Pitching actions

Controller #2:
- *Medium frequencies*
- *Small to medium amplitudes*

→Symmetrical deflections of ailerons (no spoilers)

Controller #3:
- *Medium frequencies*
- *Medium to large amplitudes*

→Symmetrical deflections of ailerons and spoilers

Gathering and combining commands

Feedforward load alleviation commands

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Feedback
Load Alleviation Function

Design Method for the Feedback Active Load Alleviation

Multi-objective optimization-based design

tool: MOPS (Multi-Objective Parameter Synthesis)

- Free controller structure and evaluation model
  - use (nonlinear) simulation model for design *(complete information)*
  - apply realistic (nonlinear) EFCS *(no approximations)*
  - design (nonlinear) active load alleviation functions *(classical structure, synthesis method (Hinf), …)*

- Direct formulation of design specifications as criteria/constraints
  - loads, comfort & HQ / maneuverability

- Multiple models and cases to cope with robustness
  - parameter variations, scenarios

- Compromise solutions for conflicting requirements
  - Pareto-optimal solutions, what-if scenarios

Application to the XRF1 Configuration

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Application for Benchmark Model (Based on XRF1)

- **Scenarios (56 cases)**
  - 2 (Alt, Mach) combination
    (Ma = 0.86 / Alt = 8279 m, Ma = 0.5 / Alt = 0, Vcas ≈ 175 m/s)
  - 7 load cases (F000, FA2M, FA2T, FA9M, FA9T, FC8T, FT8T)
  - 4 gust lengths = 30, 150, 300, 350 ft

- **Criteria (415 per case)**
  - Loads: RMS/Max/Range-value of Fx, Mx, My from 1-cosine gust time response (for wing and HTP)
  - comfort: Global comfort criterion for seated persons based on ISO standard (1997), frequency-weighted criterion based on IRS a_z-sensor
  - HQ: small influence of the gust load alleviation function on maneuverability

- **Design goal**
  - Alleviate gust loads at wing root
  - Keep within design loads
    (not yet available, keep increase at other positions as small as possible)
  - Improve comfort if possible (not forced)

Mean and Max Loads Along Wingspan - RMS, Range, Max

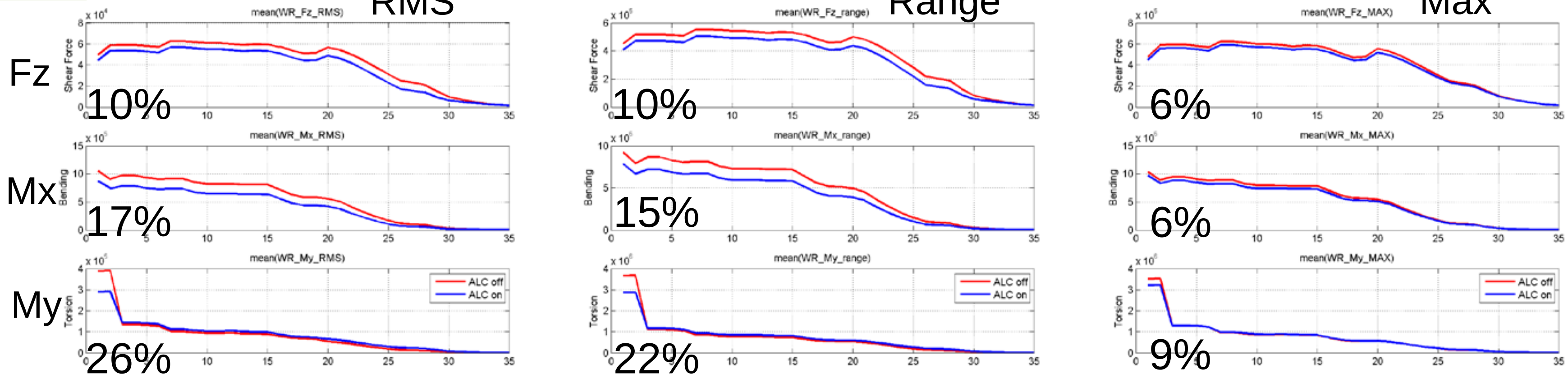
Using only feedback

BLUE = ALC ON **RED = ALC OFF**

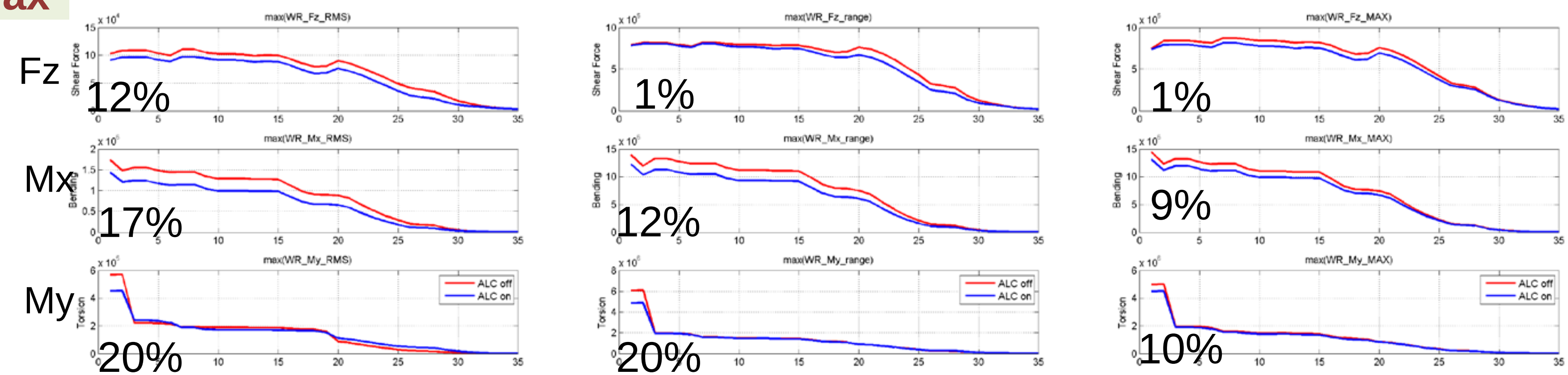
BLUE below RED → improvement

mean

RMS | Range | Max



max



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Loads Along the HTP Span - RMS, Range, Max

Using only feedback

BLUE = ALC ON RED = ALC OFF

BLUE below RED ➔ improvement

mean

RMS Range Max

Fz

Mx

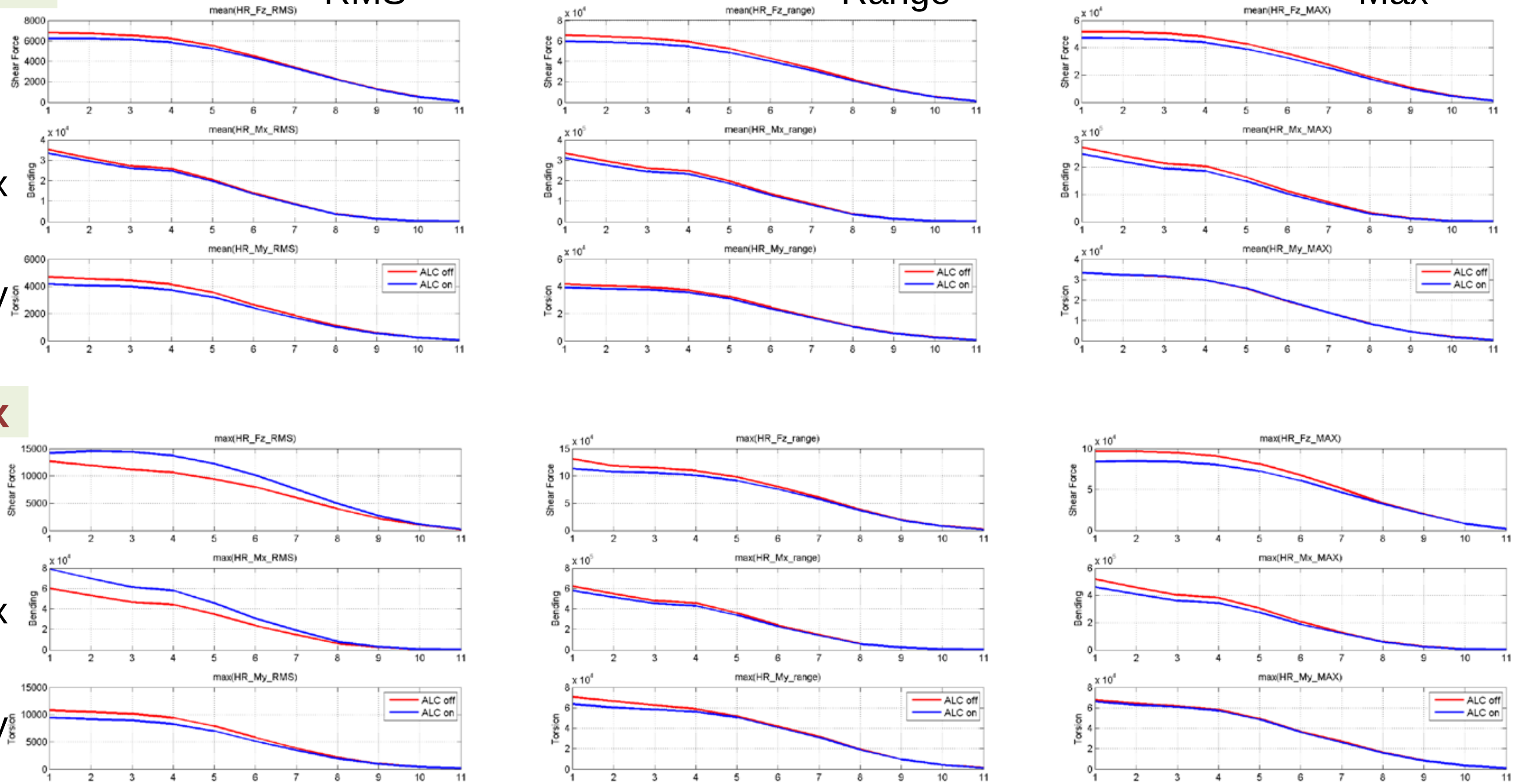
My

max

Fz

Mx

My



max RMS values grow

Max max values not exceeded

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Comfort

Using only feedback

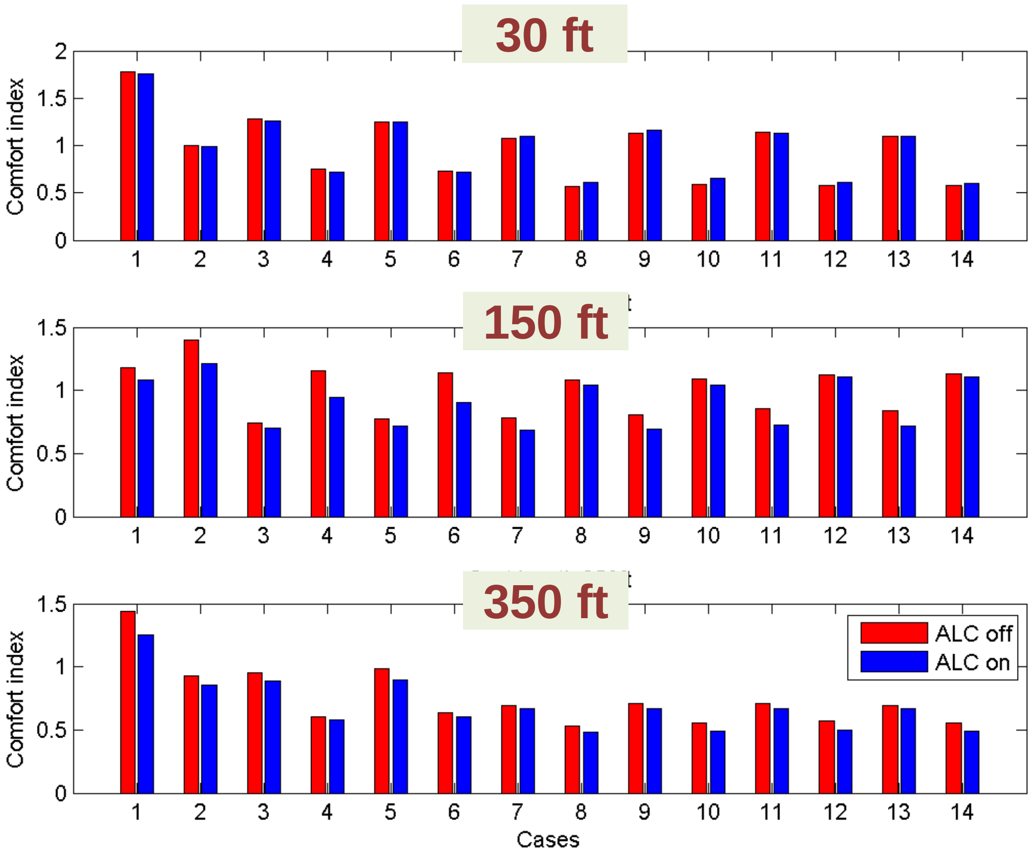
BLUE = ALC ON **RED = ALC OFF**

Comfort index computed according to ISO 2631-1:

- Motion sickness sensitivity
- Seat transfer function

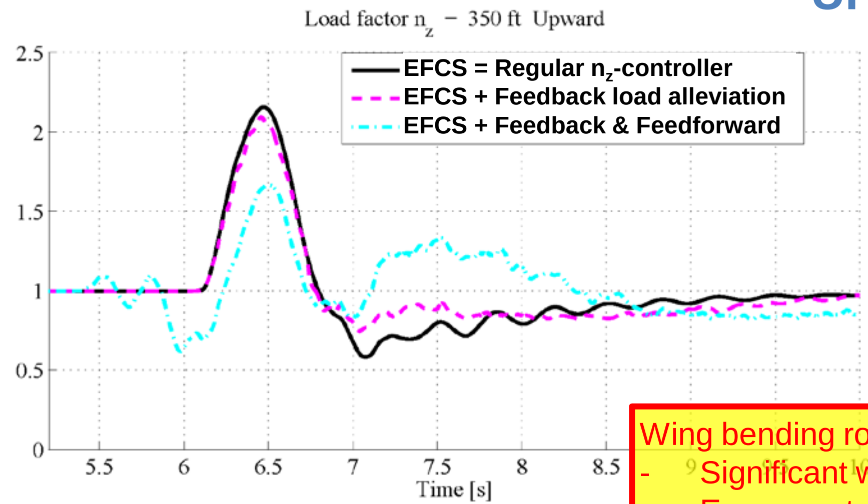
- Longer gusts
  ➔ Comfort improvement

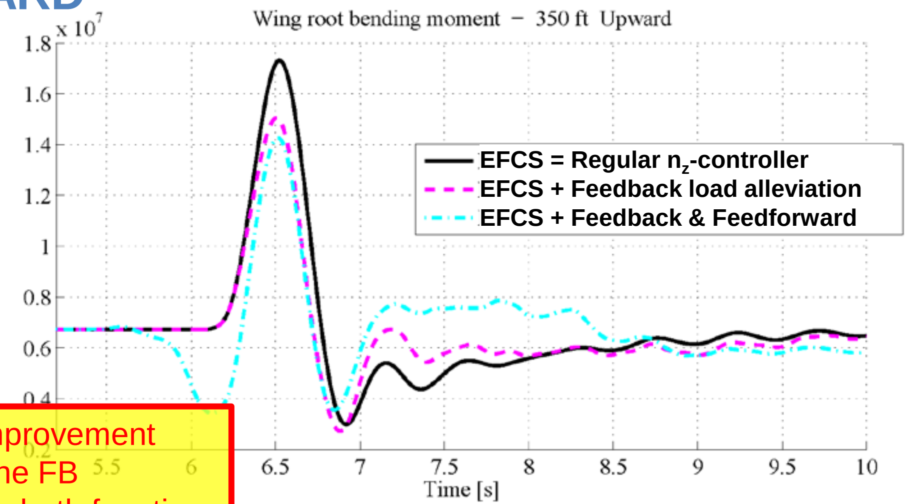
- Short gusts
  ➔ No change



Results – Time Simulation 350 ft Gust

UPWARD



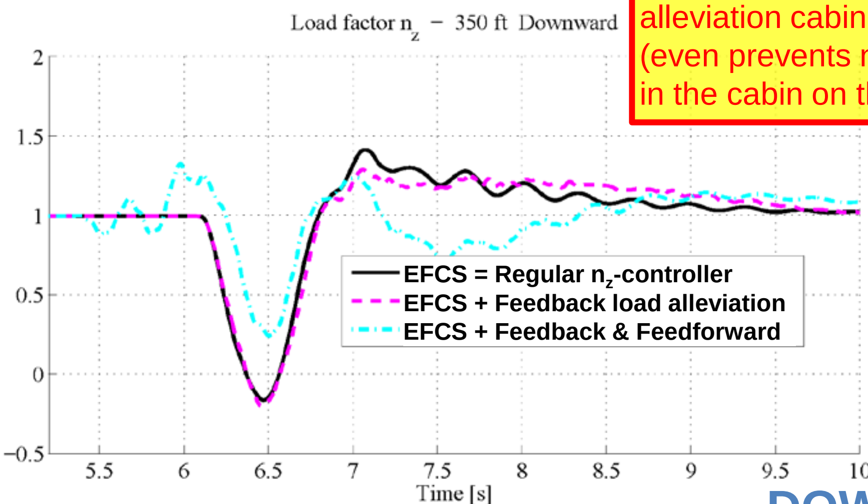


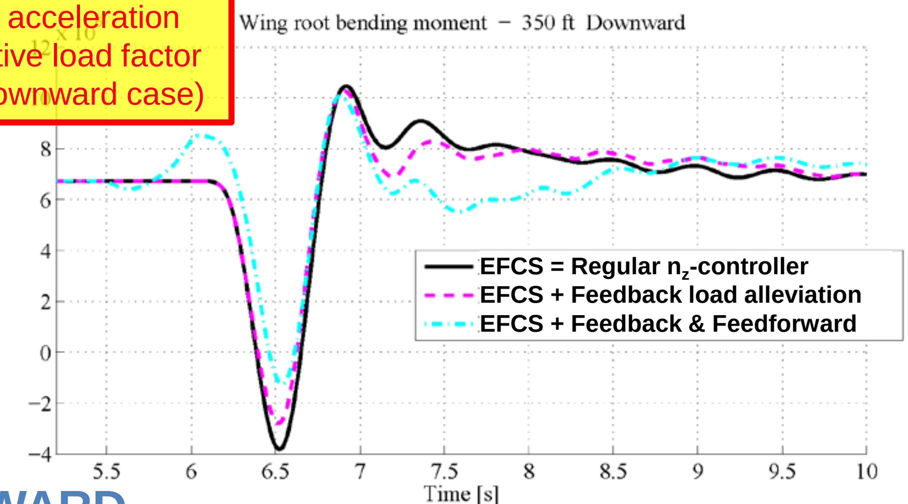
Wing bending root improvement
- Significant with the FB
- Even greater with both functions

FF anticipation permits to strongly alleviation cabin max acceleration (even prevents negative load factor in the cabin on the downward case)

Nz

Wing root bending moment





DOWNWARD

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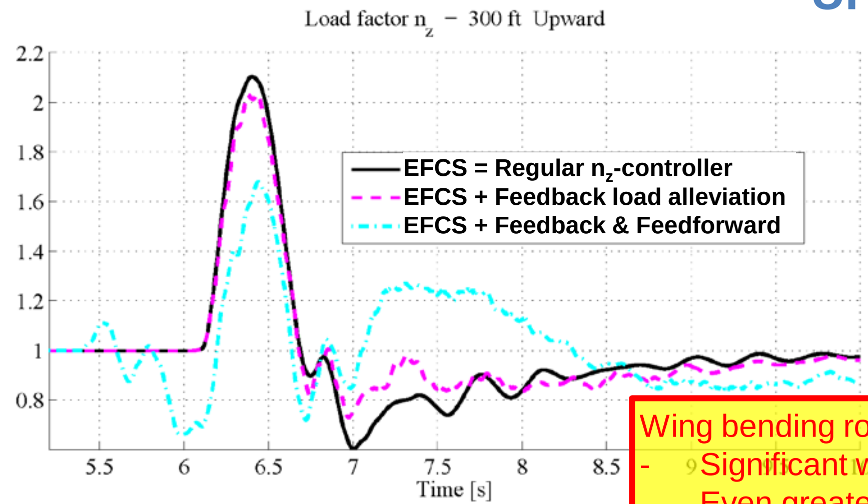
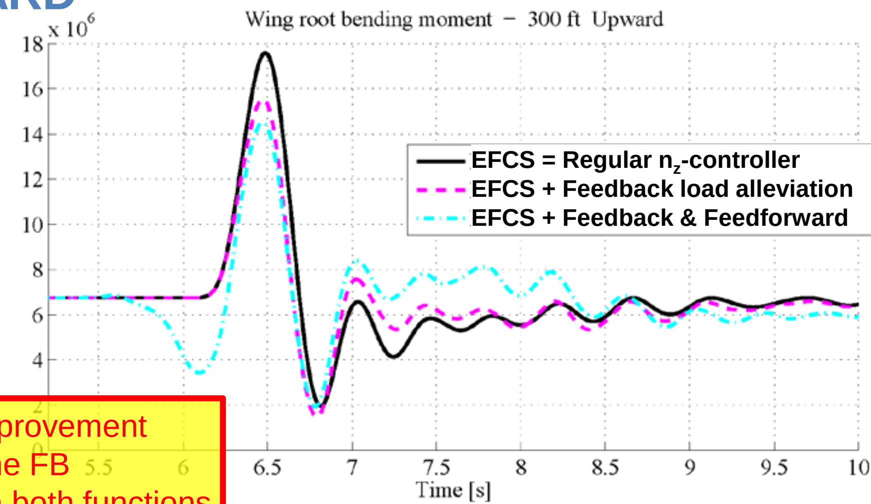
Results – Time Simulation 300 ft Gust

UPWARD





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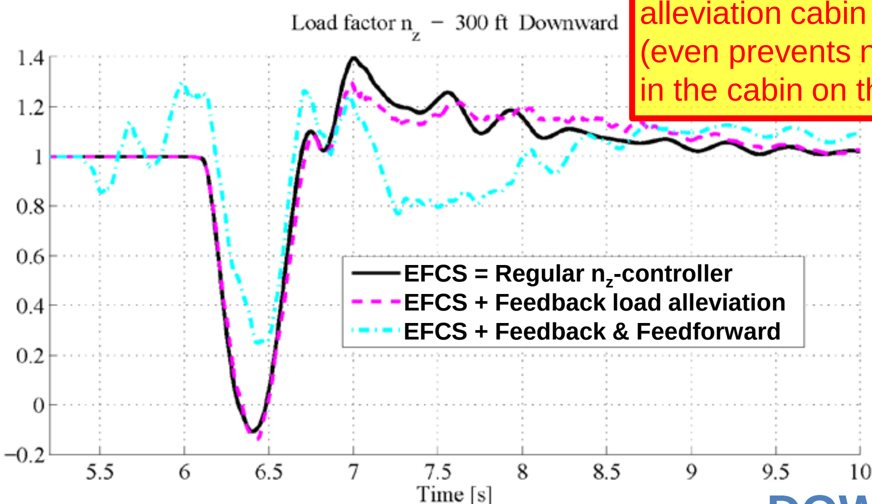
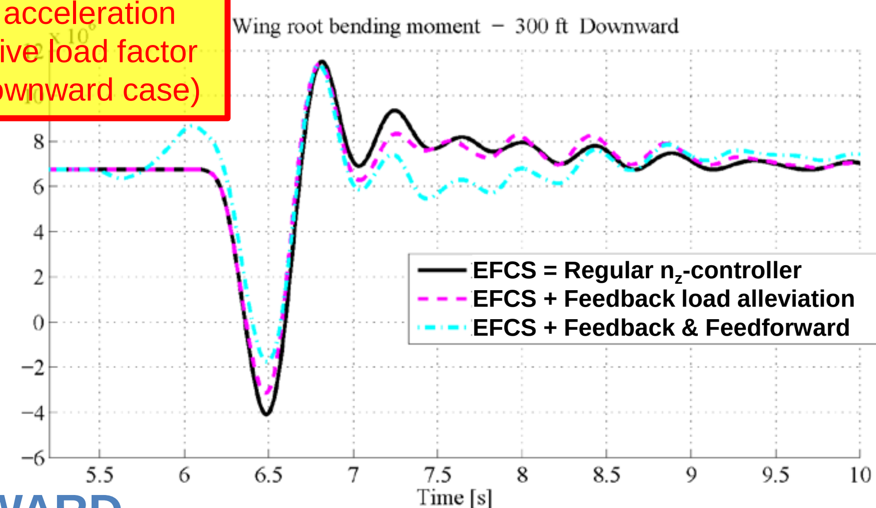
Wing root bending moment





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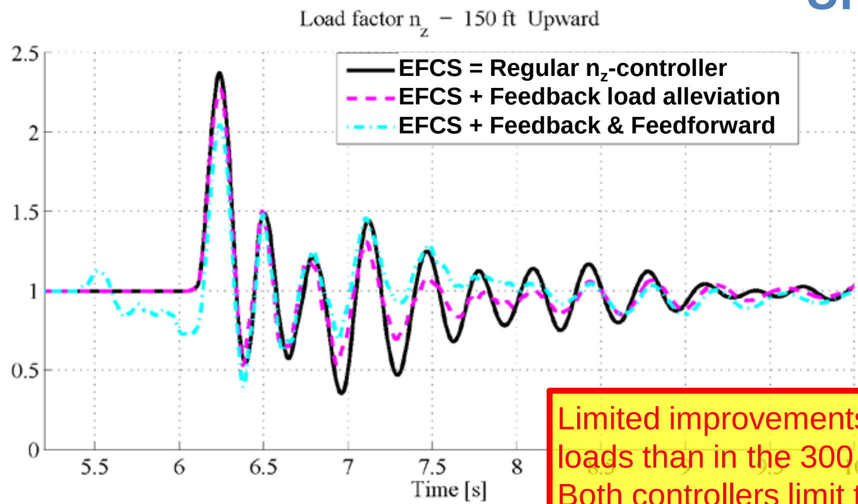
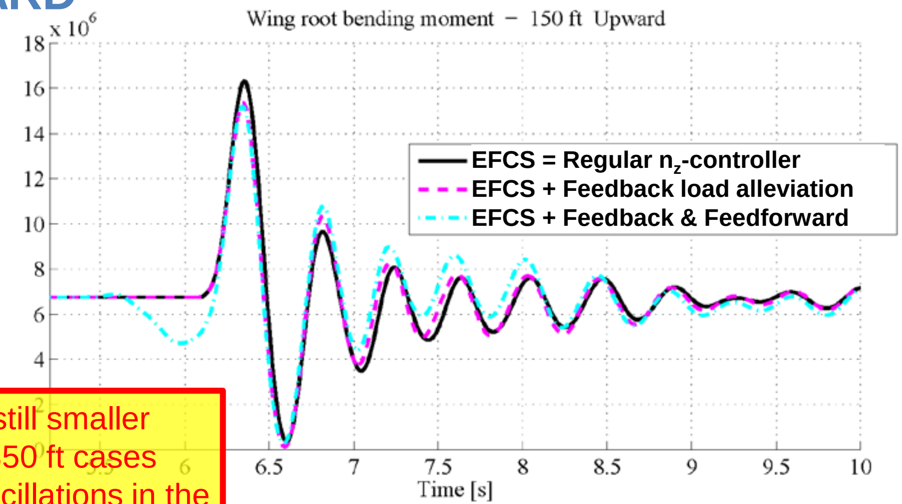
Results – Time Simulation 150 ft Gust

UPWARD

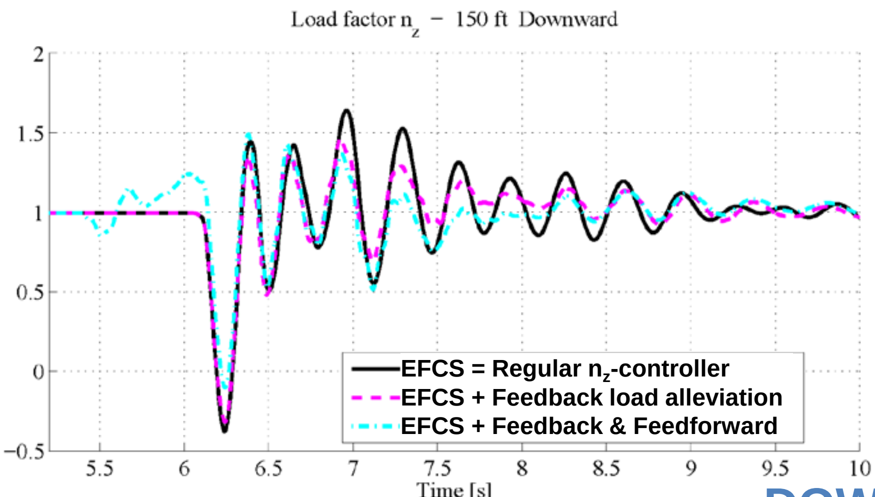


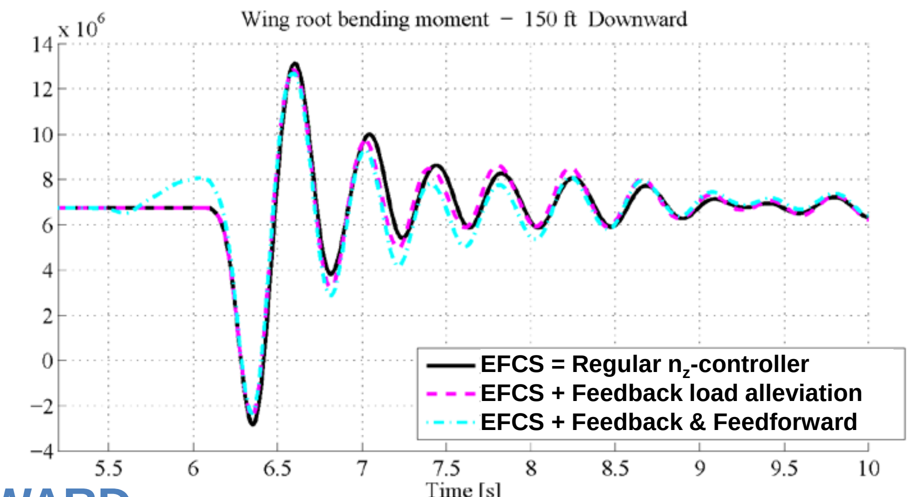


Limited improvements but still smaller loads than in the 300 and 350 ft cases
Both controllers limit the oscillations in the cabin accelerations

Nz

Wing root bending moment





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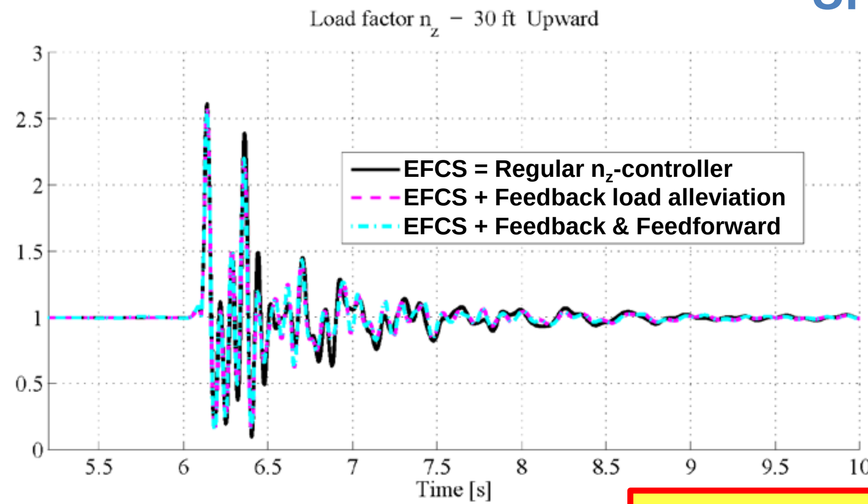
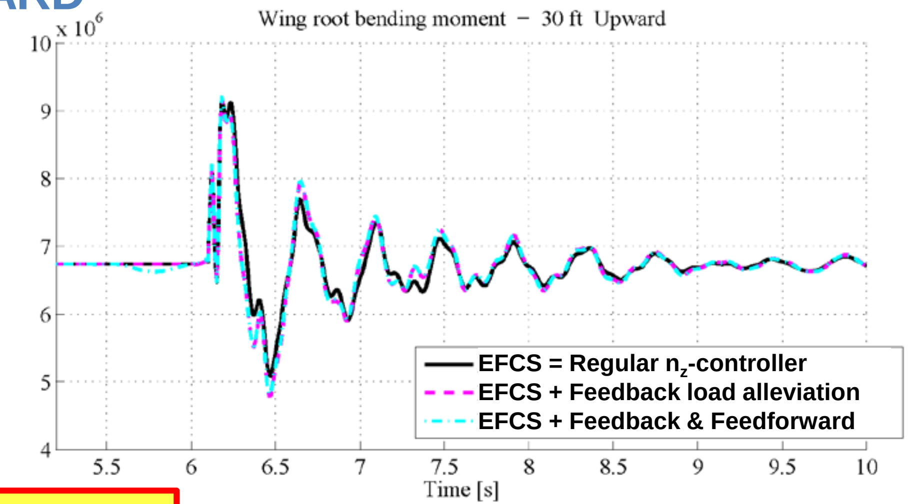
Results – Time Simulation 30 ft Gust

UPWARD

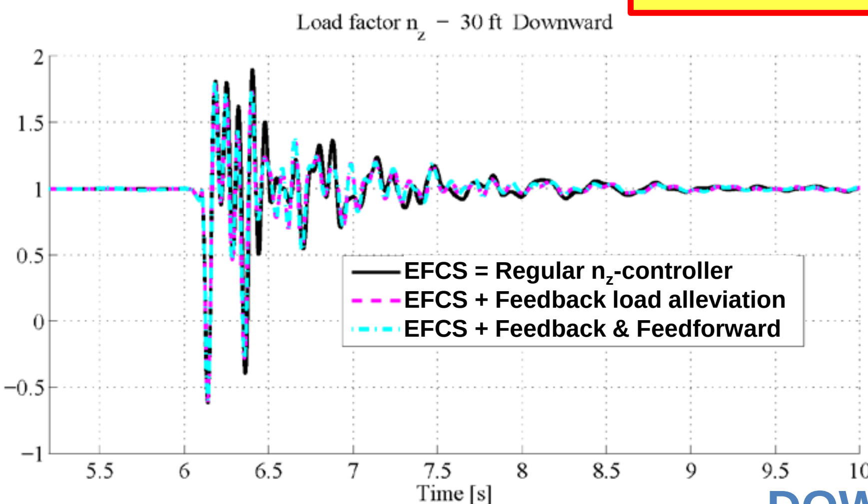


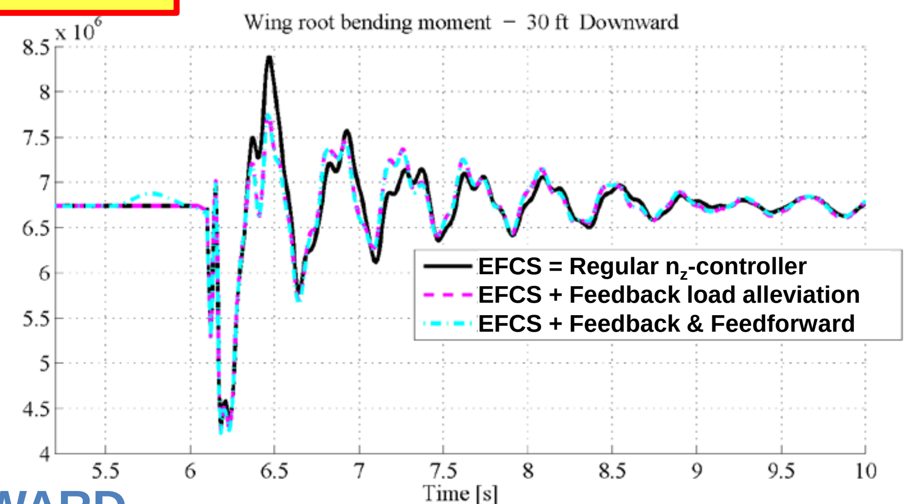


Nz

No improvement but this case is not critical for loads

Wing root bending moment





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Summary and Outlook

- Overview of the work performed by DLR on active gust load alleviation within the **CleanSky Smart Fixed Wing Aircraft** project
  - Feedback load alleviation function
    - Multi-objective approach
    - Capable of working directly with the full nonlinear models
    - Simultaneous consideration of several flight points, mass cases, maneuvers and gust load, etc.
  - LIDAR-based feedforward load alleviation
    - Significantly more advanced exploitation of the measurements than in the AWIATOR program *(sole focus of 1st author's DLRK 15 & CEAS Journal papers)*
    - No demonstration performed in CleanSky(1), … on-going attempt to define a demonstration activity within CleanSky 2 *(interested? → nicolas.fezans@dlr.de)*
    - An original feedforward control structure was designed specifically for this application *(sole focus of 1st author's CEAS EuroGNC 2017 paper)*
- Further publications to come in the near future *(AIAA Aviation 2017?)*
- Further integration work in CleanSky 2 – Airframe-ITD (consideration of business jets in addition to large passenger aircraft)