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

Nicolas Fezans, Hans-Dieter Joos

DLR (German Aerospace Center)

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Gusts and Turbulence Cause Loads and Passenger Discomfort

- **Additional loads must be taken into account in the design of the structure**
  - ➔ Reducing the loads acting on the aircraft enables weight savings and thereby also more efficient aircraft
- **Additionally cause undesired aircraft motions through the change in aerodynamic forces and moments** (+ coupling with the structure)
  - ➔ can become a safety threat (e.g. for passengers or cabin crew personnel who are not seated or with their seat belts unfastened)
  - ➔ causes discomfort and passenger anxiety
- **Three main options:**
  1. Procedure (e.g. fly slower when in turbulence)
  2. Passive load alleviation
  3. **Active load alleviation**

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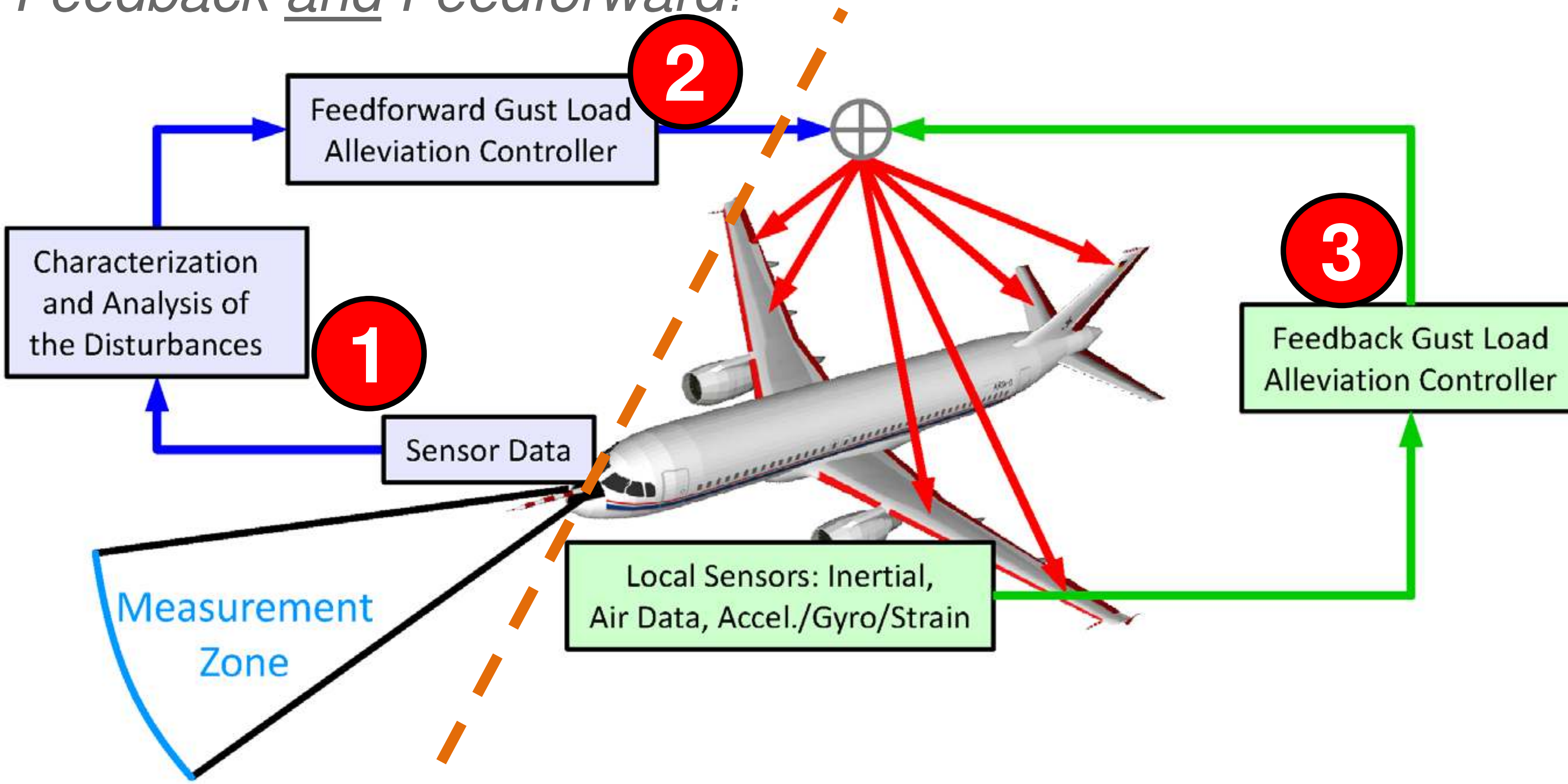
Active Load Alleviation: Feedback vs. Feedforward?

→ Feedback and Feedforward!



Anticipation is possible with LIDAR-based feedforward

4 Results

Feedback controller can act on the flexible modes (e.g. to damp them)

LIDAR

What are Doppler LIDAR sensors?

How can they help to detect gust and turbulence ahead of the aircraft?

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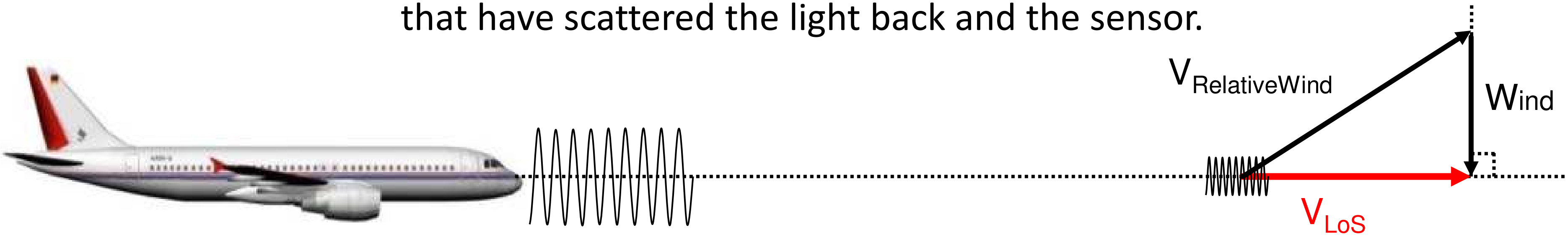
What Are Doppler LIDAR Sensors?

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.



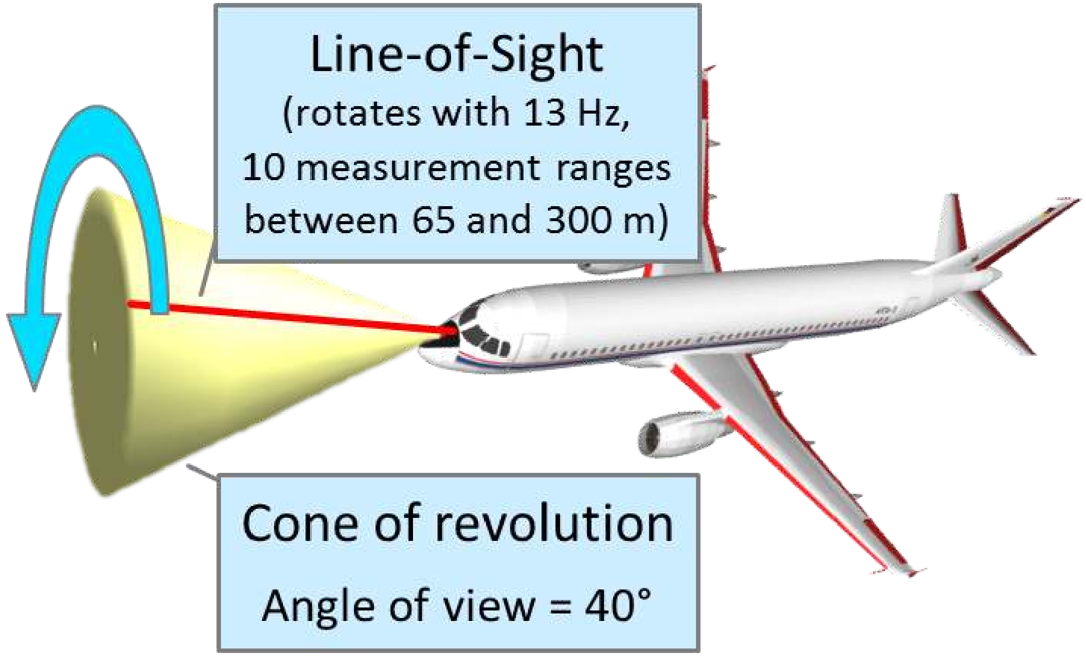
Problem:
→ Relative wind components perpendicular to LoS are lost!
→ And the vertical component at a location ahead of the aircraft is the most interesting wind information for load alleviation

Scanning the Space Ahead of the Aircraft

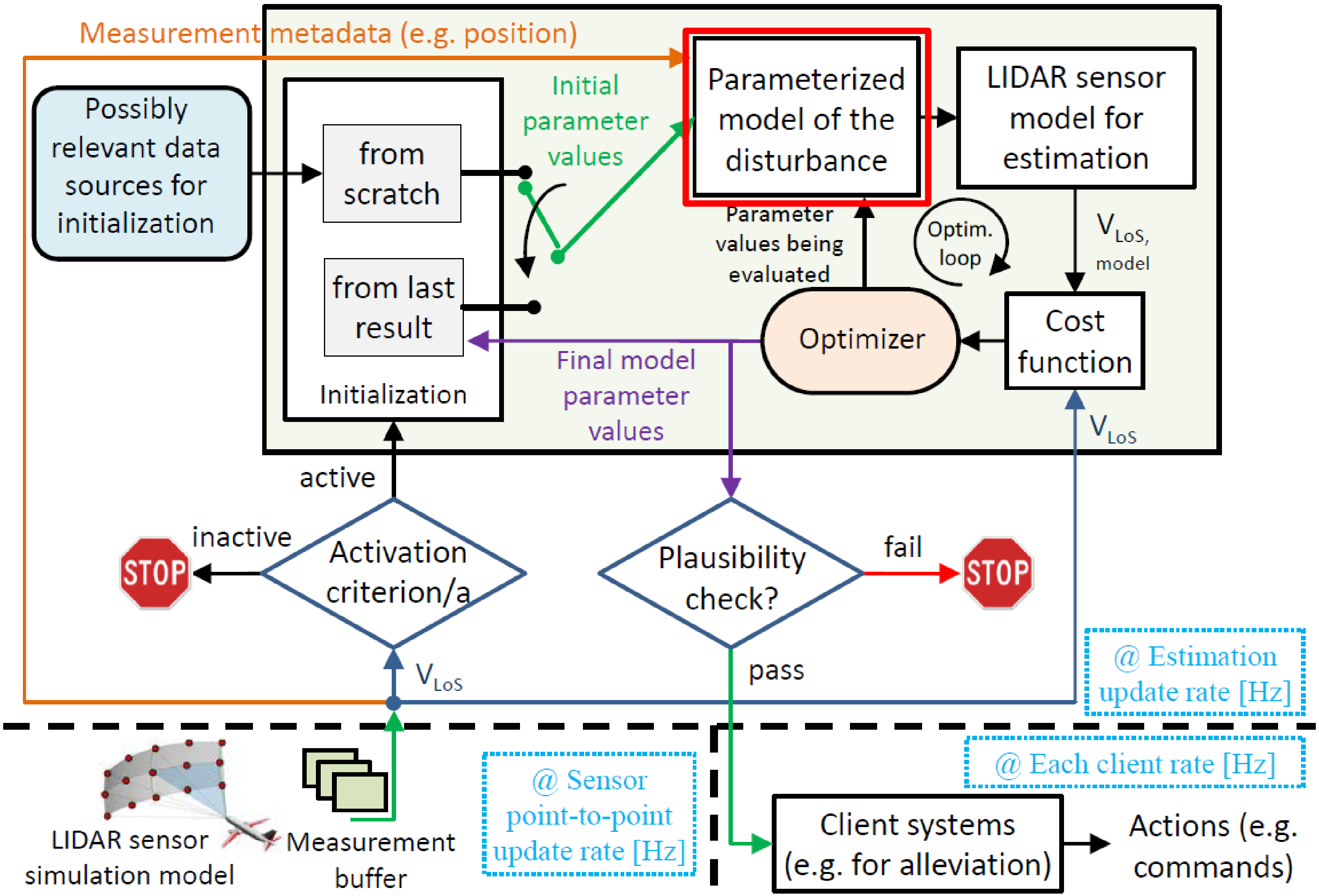
Basic idea:

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

“Simple” scan geometry based on a cone of revolution

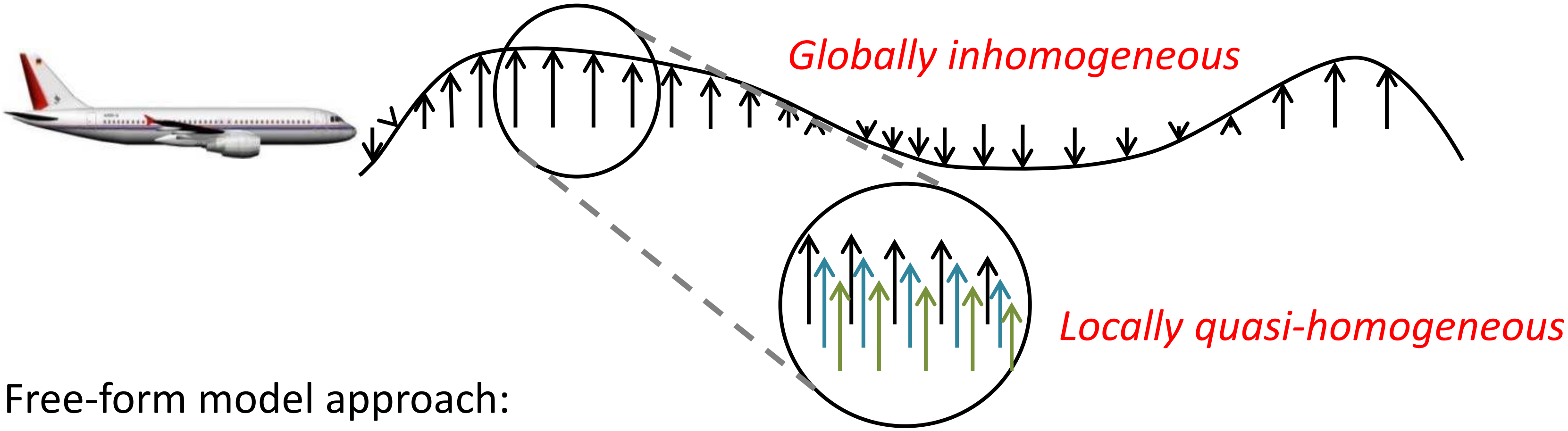


Sketch of the Wind Reconstruction Algorithm

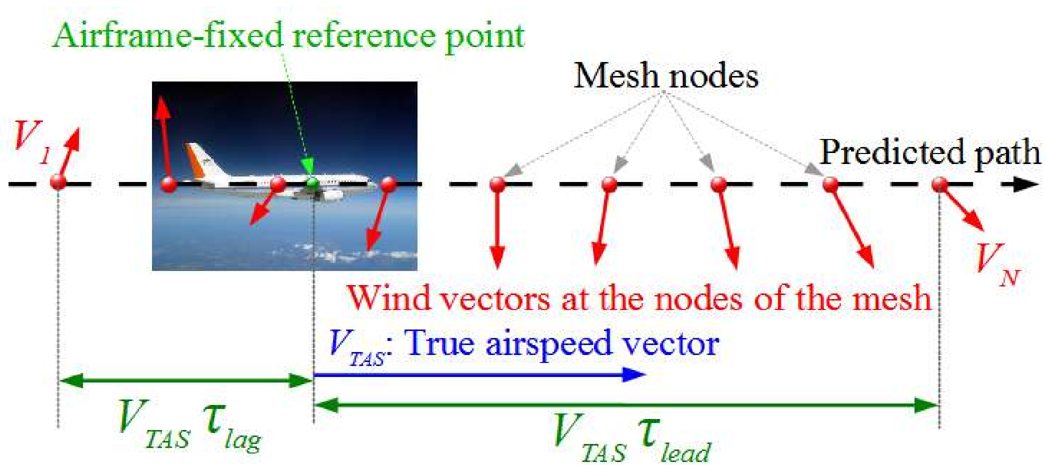


Gusts and Turbulence Reconstruction

- 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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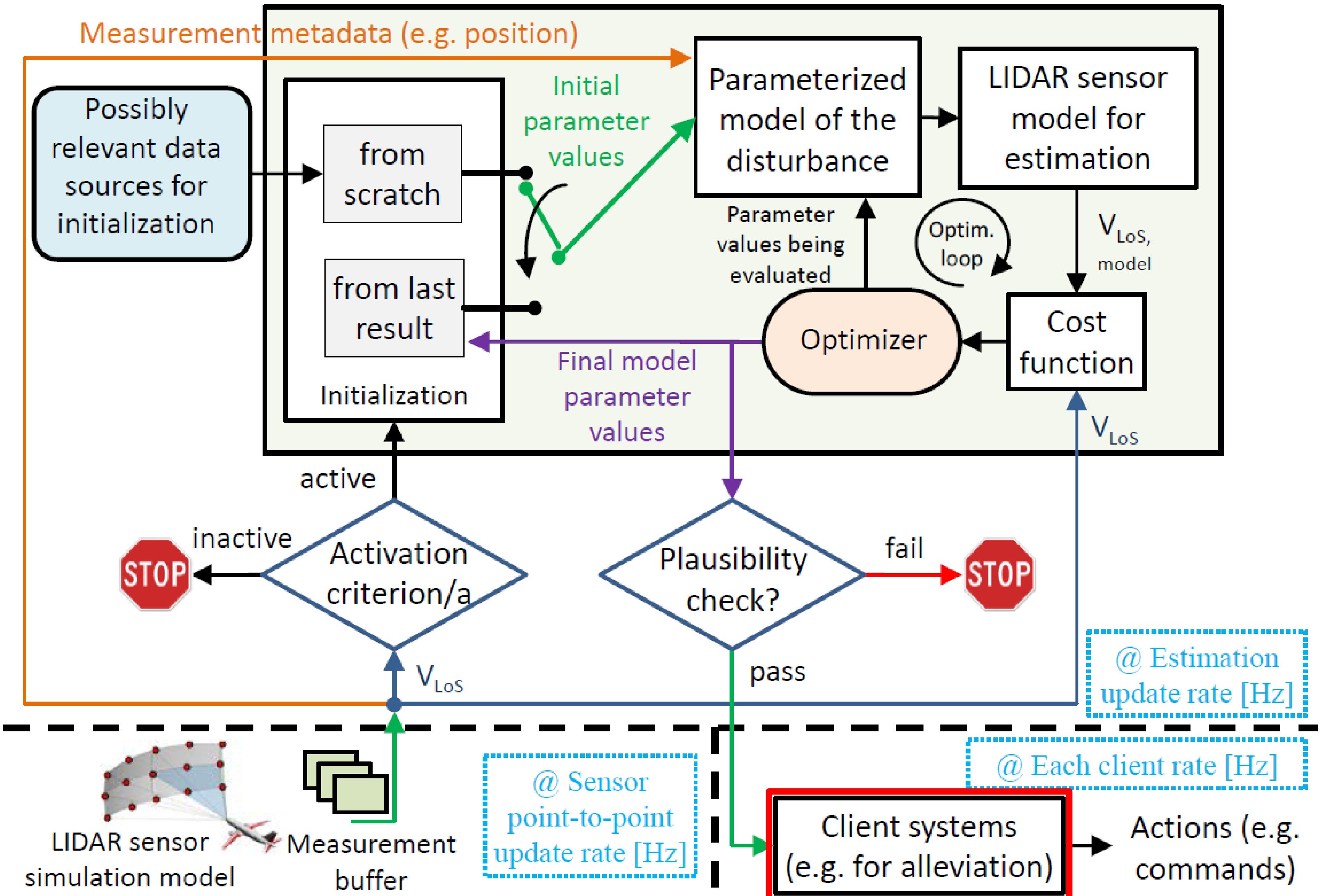

LIDAR-Based Feedforward Load Alleviation Function

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Satisfying Strong Allocation Constraints by Design

Reconstructed wind profile 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

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Satisfying Strong Allocation Constraints by Design

Reconstructed wind profile 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***

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.

Feedforward load alleviation commands

Feedback
Load Alleviation Function

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Design Method for the Feedback Active Load Alleviation

Multi-objective optimization-based design

DLR in-house 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

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 Fz, 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

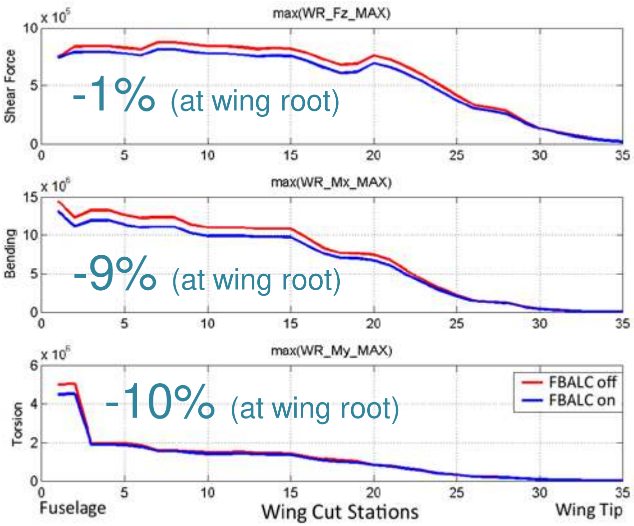
- **Design goal**
  - Alleviate gust loads at wing root
  - Keep within design loads
    (not yet available, keep increase at other positions as small as possible)
  - Improve comfort if possible (not forced)

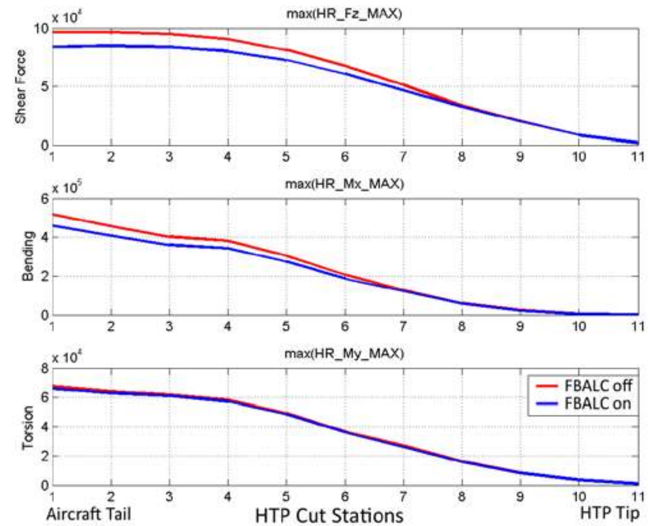
Mean and Max Loads Along Wingspan and HTP span

WING **HTP**

max_{cases} (peak loads)

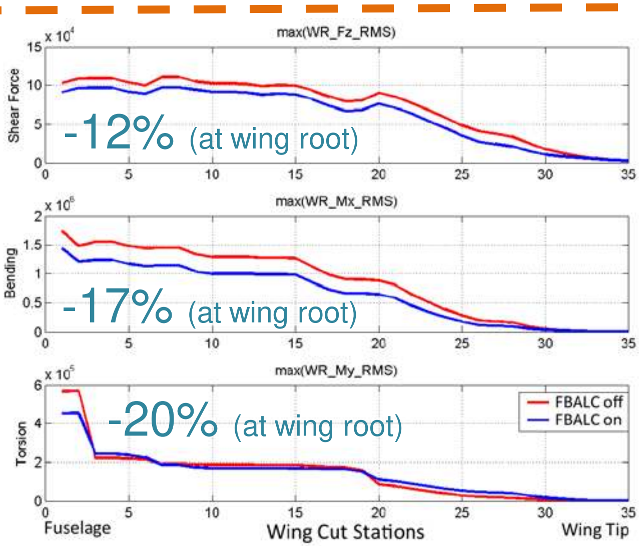
Fz
Mx
My

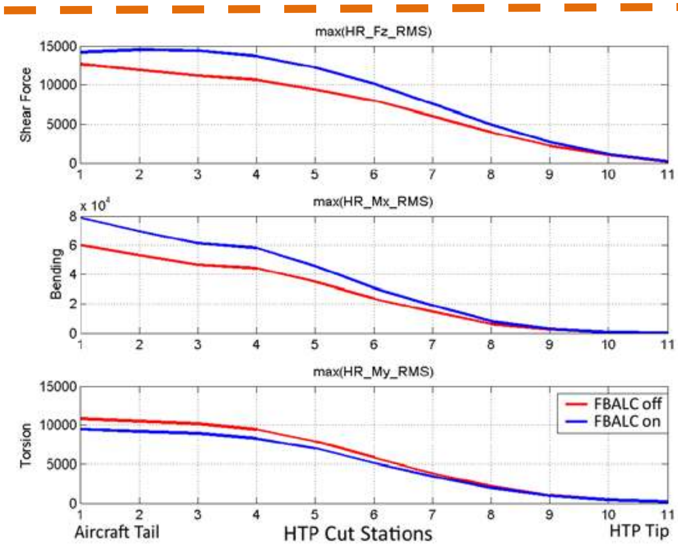




max_{cases} (RMS loads)

Fz
Mx
My





Using only feedback alleviation

BLUE = ALC ON
RED = ALC OFF

BLUE below RED
➔ improvement

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Comfort

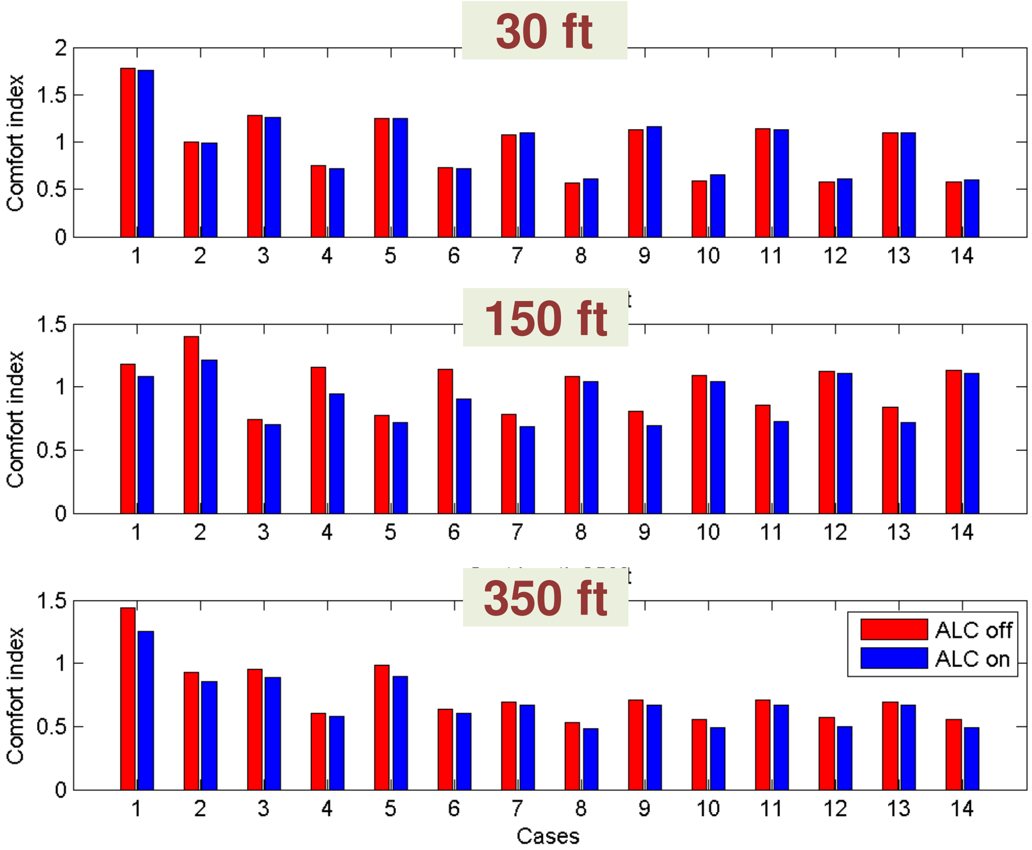
Using only feedback alleviation

Comfort index computed according to ISO 2631-1:
- Motion sickness sensitivity
- Seat transfer function

- Longer gusts
  ➔ Comfort improvement

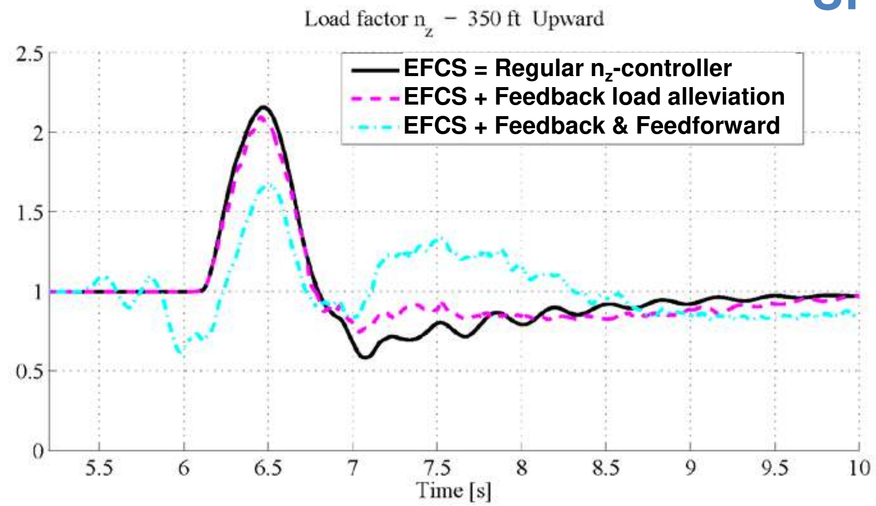
- Short gusts
  ➔ No real change

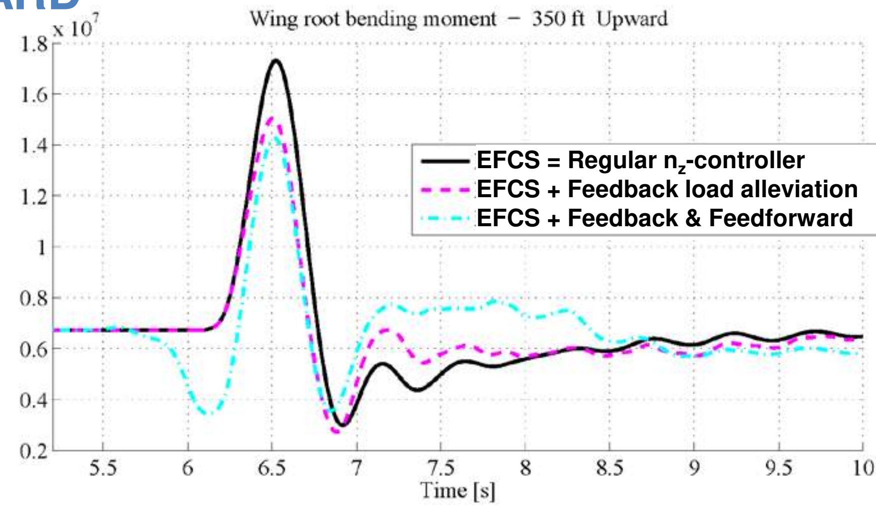
BLUE = ALC ON **RED = ALC OFF**



Results – Time Simulation 350 ft Gust

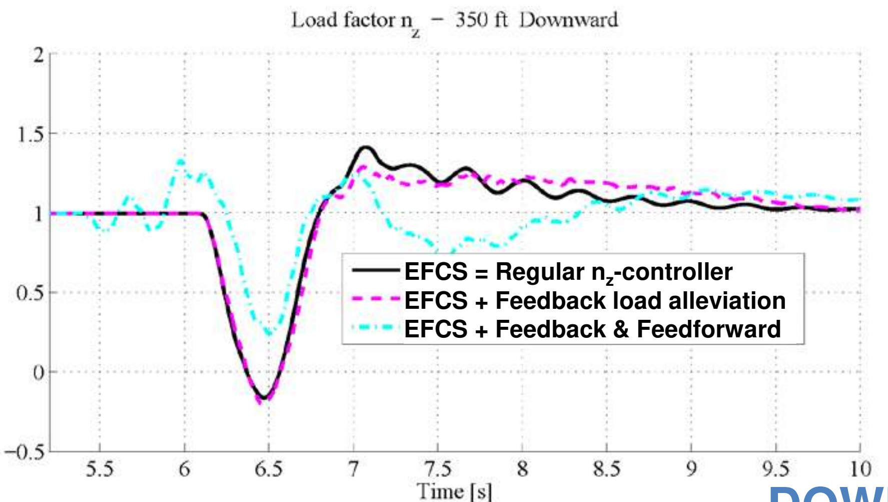
UPWARD

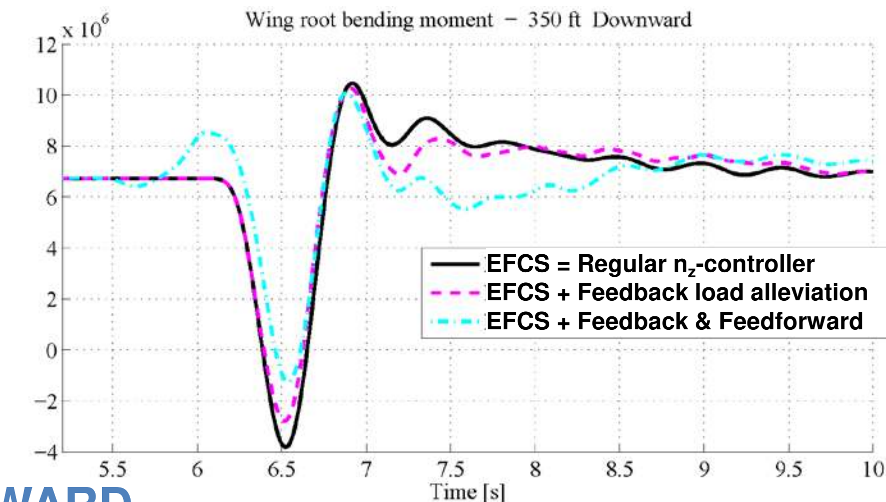




Nz

Wing root bending moment





DOWNWARD

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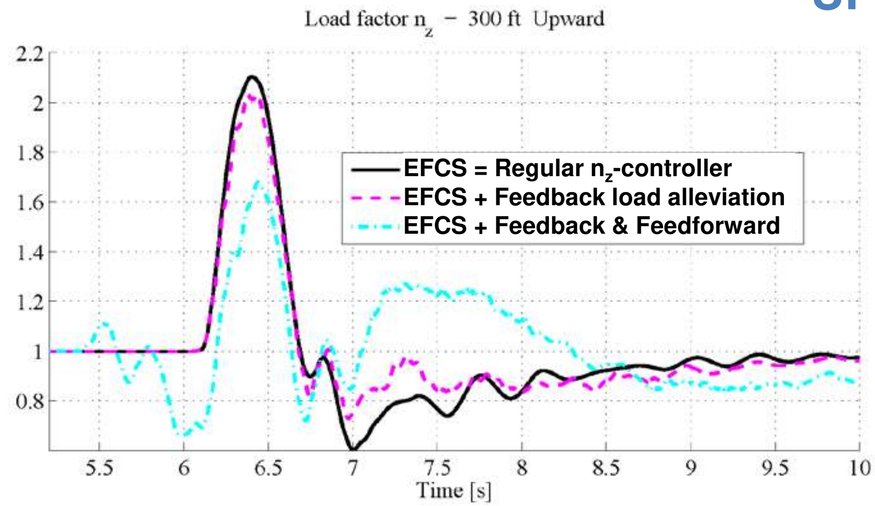
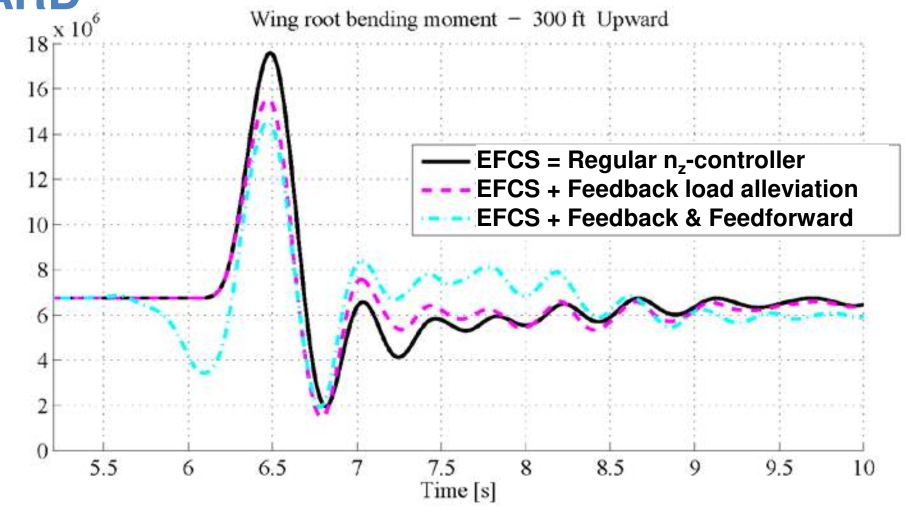
Results – Time Simulation 300 ft Gust

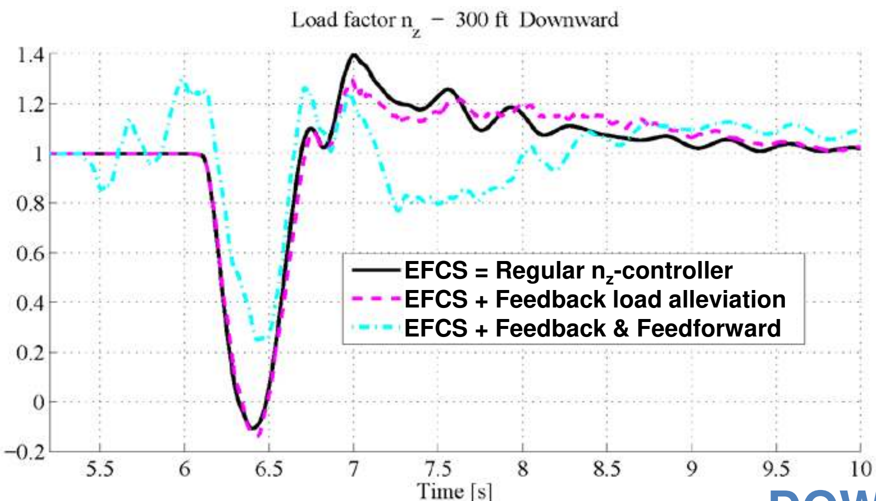
UPWARD

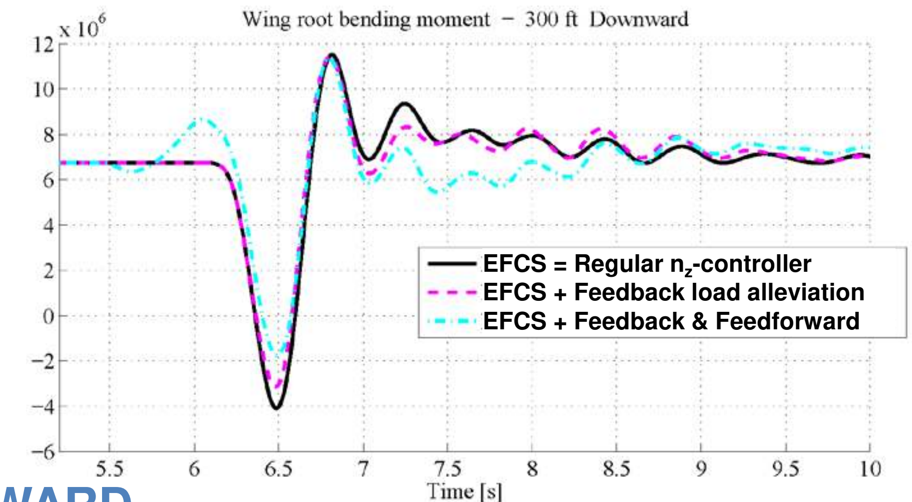




Nz

Wing root bending moment

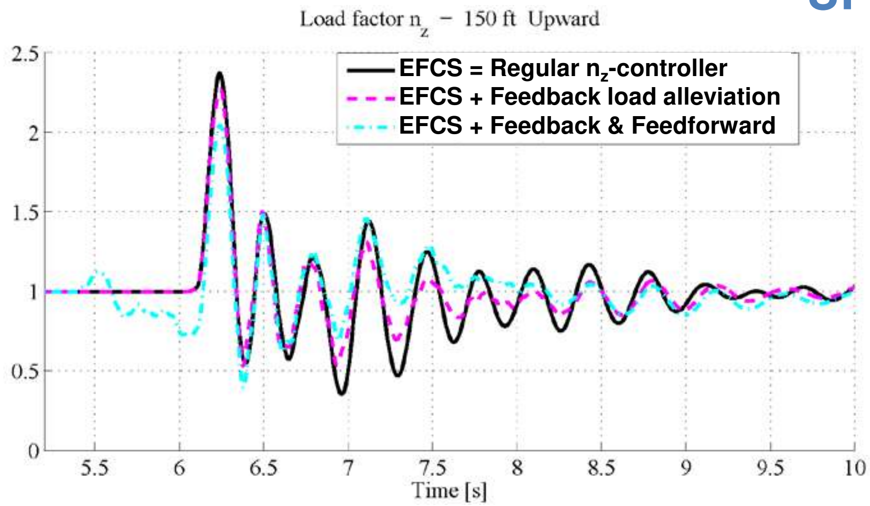


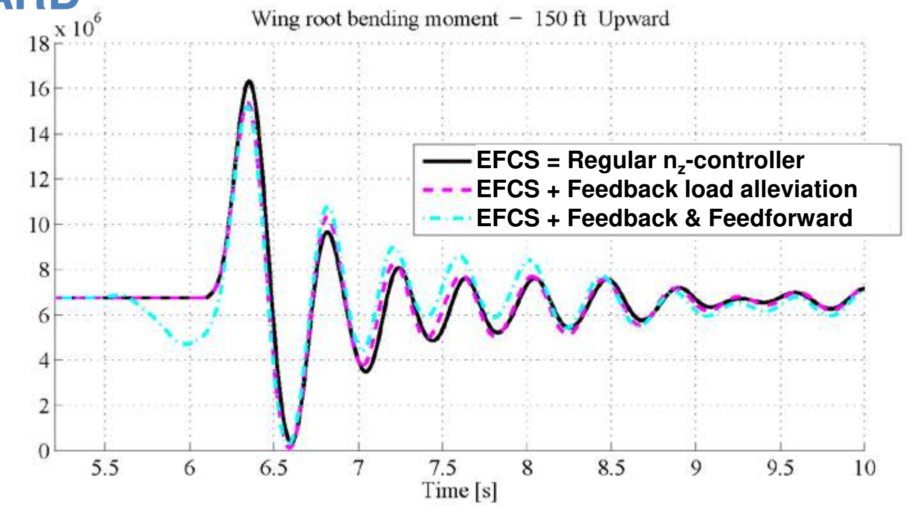


DOWNWARD

Results – Time Simulation 150 ft Gust

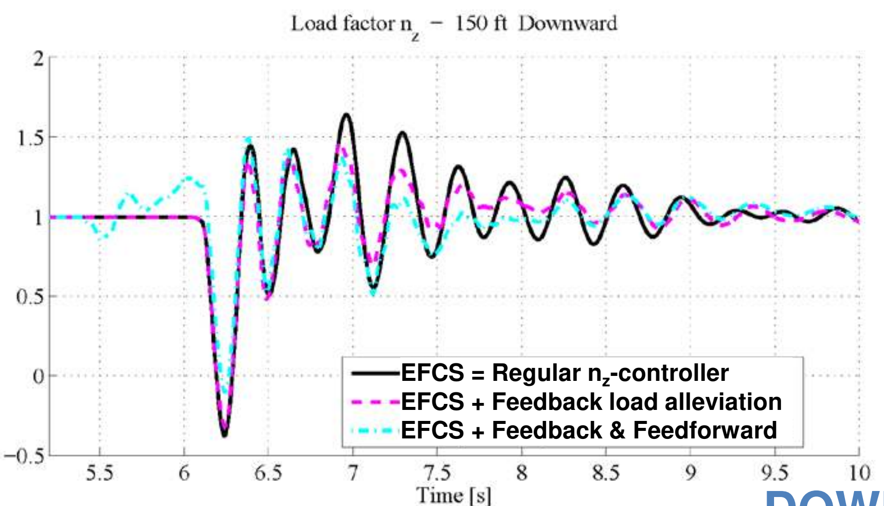
UPWARD

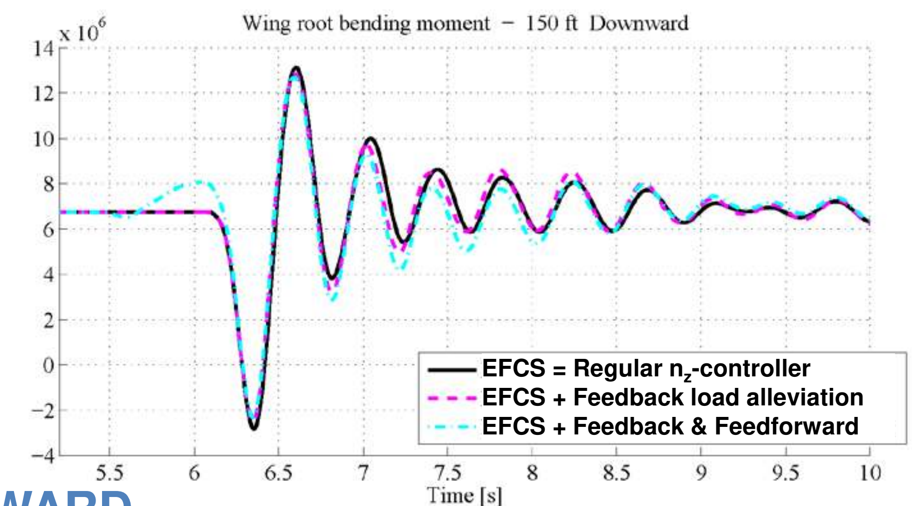




Nz

Wing root bending moment

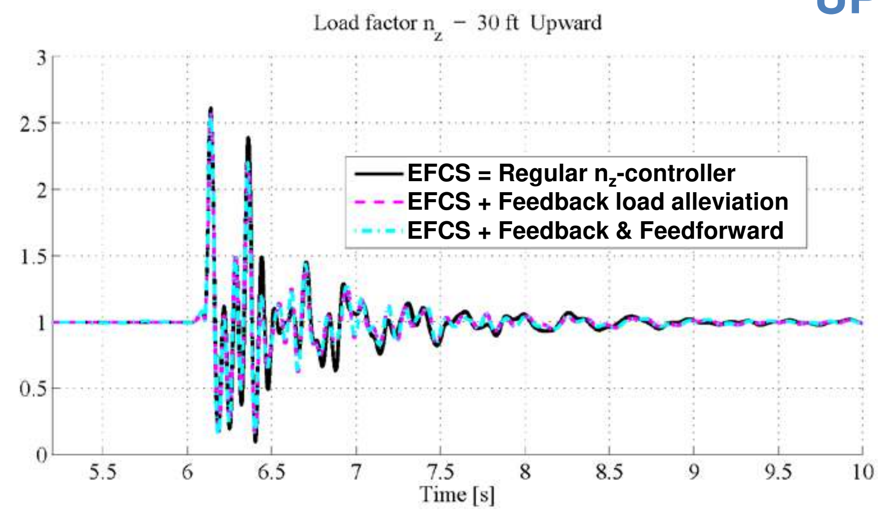


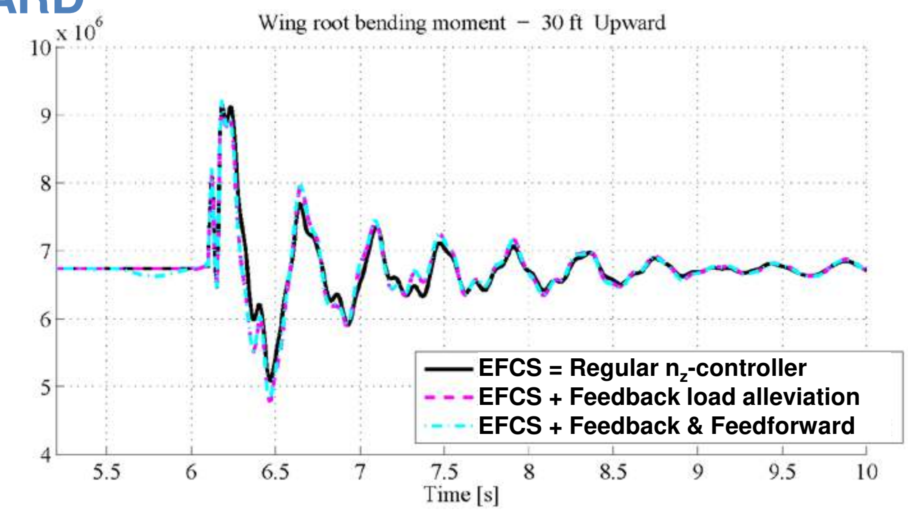


DOWNWARD

Results – Time Simulation 30 ft Gust

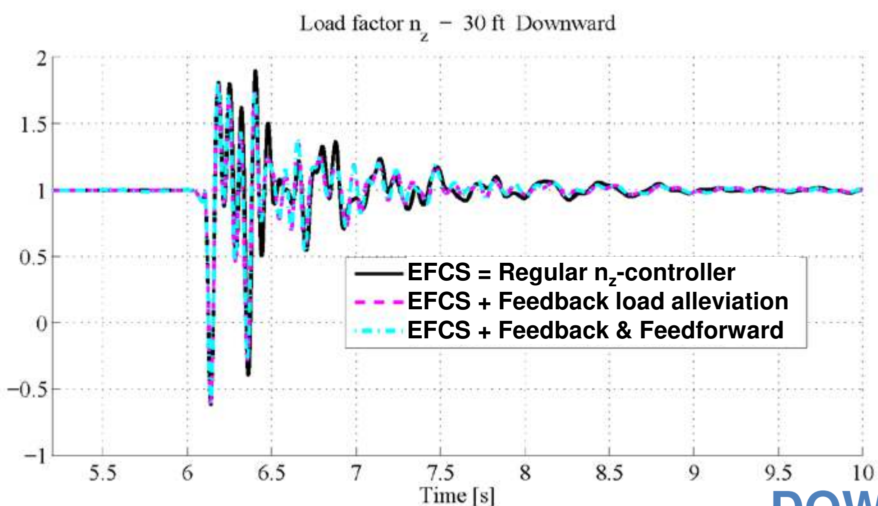
UPWARD

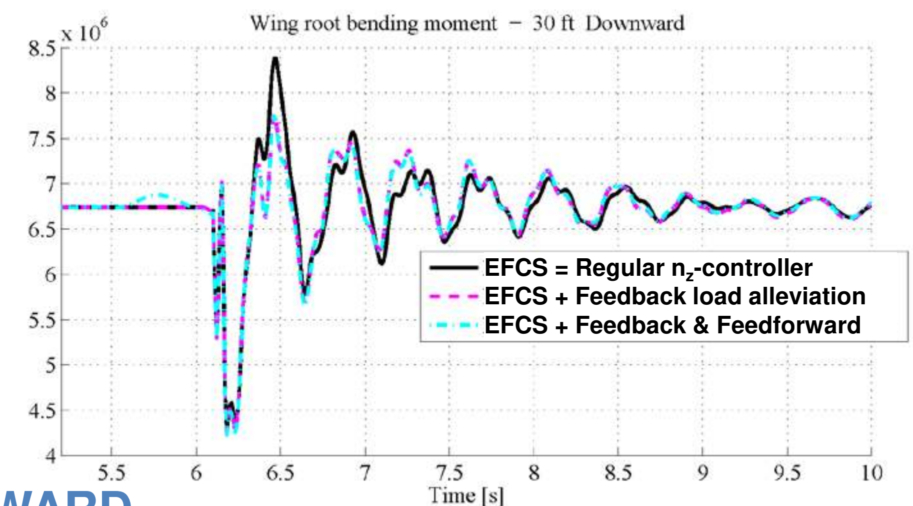




Nz

Wing root bending moment





DOWNWARD

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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** European research 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 *(see details in the 1st author's CEAS Journal paper of June 2017)*
        - Interested in demonstrating in flight test, possible cooperation?
        - An original feedforward control structure was designed specifically for this application *(see details in the 1st author's CEAS EuroGNC 2017 paper)*
- Further developments going on within the European CleanSky 2 Research Framework (Airframe-ITD) and also for business jets in addition to large passenger aircraft