ADVANCED GUST LOAD ALLEVIATION SYSTEM FOR LARGE FLEXIBLE AIRCRAFT

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OVERVIEW

The effects of gusts and turbulence do not only affect adversely the passenger comfort but also create significant aircraft loads. That's why gust load alleviation plays an important role for the development of load control strategies. DLR has a comprehensive know-how in the field of control systems design for aerospace applications especially the design of gust load alleviation systems, their demonstration and assessment. Based on this experience a gust load alleviation system (GLAS) was designed within the frame of the European AWIATOR project based on a feed-forward disturbance compensation. To follow this concept the determination of the disturbances respective the gusts/turbulence is essential. Assuming to have direct lift control surfaces available the reduction of vertical accelerations and alleviation of loads can be envisaged. Thus, it is not necessary to determine the complete three dimensional air mass motion but to compute precisely its vertical fluctuation. This can be done by using simplified fight mechanics relations. The computed vertical gust component is used to trigger the GLAS.

The principle design of the GLAS is focused on reduction of vertical accelerations (nz) caused by turbulence. This design is mainly related to the improvement of passenger comfort. Simulation results have shown that this design yields an overcompensation of structural loads caused by turbulence. To avoid this overcompensation, we performed an optimization based tuning of the GLAS. The simulation results for this advanced GLAS show very good performance for load alleviation and also improvement of passenger comfort. However, depending on the flight case it may be interesting to choose between different parameterizations of the GLAS, e.g. focus on passenger comfort improvement in cruise condition and focus on load alleviation on points of the flight envelope where already high loads arise (sizing cases). In addition, Pareto-bounds were calculated to allow a choice between compromise solutions for wing load and HTP load reduction. The advanced GLAS also contains dynamic filters to consider the structural modes and to avoid the unintentional excitations of the aircraft structure stimulated by the gust and turbulence or by GLAS itself.

1. INTRODUCTION

Aircraft operations at low altitudes are often affected by strong gusts and turbulence producing aerodynamic forces and moments. They result in additional aircraft accelerations combined with an unpleasant impact on pilot and passengers and extra structural loads. Active control systems [1][2][3] for the alleviation of gust and manoeuvre loads as well as of structural vibrations are an important means for the reduction of critical loads as well as for the improvement of ride comfort and handling qualities. Load reduction increases aircraft efficiency by the possibility to reduce structural weight. Effective gust load alleviation in normal direction can be obtained only if the wing has extra control surfaces for direct lift variation, such as special flaps at the trailing edge, symmetrical ailerons or spoilers.

In [3] a Gust Load Alleviation System (GLAS) has already been successfully flight tested on the DLR test aircraft ATTAS. Standard deviations of the load factor n_z could be reduced by more than 50%, which means a remarkable improvement of the passenger comfort. As ATTAS is a relatively small and stiff aircraft (compared to an Airbus A340) the aero-elastic modes only play a minor role and the gust load alleviation system was focused on the reduction of the turbulence influence on the rigid body modes. For the measurement and estimation of the turbulence a nose-boom was employed, thus allowing a forward looking measurement and estimation of the turbulence, which was required for the application of the feed-forward control law. However the small forward looking distance limited the application of this system to low speed flight.

In the AWIATOR project of the 5th European framework programme, DLR developed a gust load alleviation system for the Airbus A340 aircraft. Due to the large dimensions of the A340, there exists a coupling between rigid body and aero-elastic modes, which both had to be considered during the design of the GLAS. Furthermore, an airborne LIDAR system [4] was available on the test aircraft, which provides sufficient forward looking distance for the application of the GLAS during cruise, which is important to improve safety when clear-air turbulence occurs. The active control system developed by DLR mainly consists of two components (see FIG 1):

1) A Gust Computation System (GCS) to perform a

sufficiently accurate real-time estimation of gust and turbulence. The main aspects during the development of the GCS were the: a) integration of an angle of sideslip information to allow an accurate wind estimation also during roll manoeuvres, b) adaptation/calibration of the system using flight test data and flight path reconstruction techniques, c) improvement of the LIDAR accuracy using a sensor fusion algorithm.

2) A feed-forward GLAS to alleviate structural loads and to improve passenger comfort. To ensure robustness with respect to different load cases and flight conditions a multi-model approach was employed. Furthermore a multi-objective formulation of the control goal allowed to simultaneously improve a large set of structural load and comfort criteria. For conflicting criteria we could easily calculate 2d Pareto bound plots which – depending on the cruise condition or sizing cases - allow to choose between different controller parameterizations.

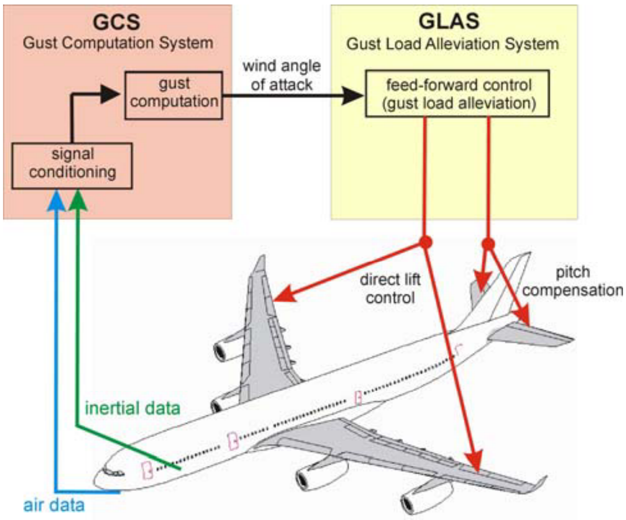

FIG 1. Structure of active control system

2. GUST COMPUTATION SYSTEM (GCS)

In accordance with the available control surfaces of the AWIATOR test aircraft and with respect to the predominating gust and turbulence effect on aircraft, it was decided to compensate only for vertical gusts. The variation of the aircraft's angle of attack due to a vertical gust can be expressed by the wind angle of attack

$$(1)\quad \alpha_W \approx -\arcsin\left(\frac{w_W}{V_{TAS}}\right)$$

This wind angle of attack can be computed from the following equation[1]

$$(2)\quad \alpha_W \approx \cos(\Phi)\left[\arcsin\left(\frac{V_z}{V_{TAS}}\right) - \Theta + \cos(\Phi)\cdot\left(\alpha + \frac{q\cdot r_{AoA}}{V_{TAS}}\right) + \sin(\Phi)\cdot\left(\beta - \frac{r\cdot r_{AoS}}{V_{TAS}}\right)\right]$$

where Φ is the roll angle, V_z is the inertial vertical speed of the aircraft, V_{TAS} is the true airspeed, Θ is the pitch angle, α is the angle of attack, q is the pitch rate, r_{AoA} is the distance between the centre of gravity and α-sensor, β is the angle of sideslip, r is the yaw rate, and r_{AoS} is the distance between the centre of gravity and β-sensor. This computation algorithm even is valid during manoeuvring flight with high dynamic aircraft behaviour.

2.1. Validation of the GCS

FIG 2 shows the time histories of a nonlinear simulation to validate the described algorithm. The figure illustrates an uncoordinated bank manoeuvre in a constant updraft wind field of w_{Wg} = *-3m/s*. The manoeuvre starts from trimmed conditions of a straight descending flight (γ = *-3°*) with wings level. Within a few seconds the bank angle was increased up to $\Phi \approx 40°$ and back to wings level. Although, the aircraft response is strongly affected by the manoeuvre the computed vertical wind calculated from the above equations is very accurate and shows only small deviations as indicated by FIG 3.

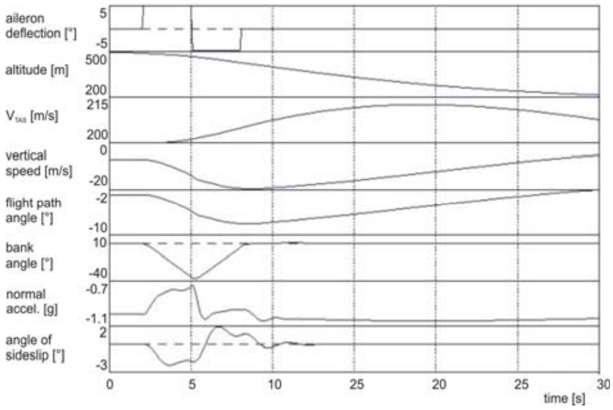

FIG 2. Time histories of a simulated flight in an updraft windfield

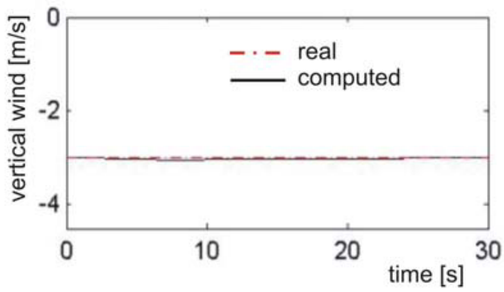

FIG 3. Comparison of real and estimated wind

Equation (2) is not only valid in constant wind fields but also can be applied for dynamic gusts. FIG.4 shows the encounter of a 1-cos gust during a horizontal turn with a bank angle of $\Phi \approx 45$. The importance of the correct processing of α and β-signal is evident. The wind angle of attack calculation only based on the α-signal (blue line) will result in significant deviations compared with the exact time history of wind angle of attack (red line). The computation using Equ. (2) is illustrated by the green broken line and shows no noticeable deviation from the exact values.

[1] DLR patent

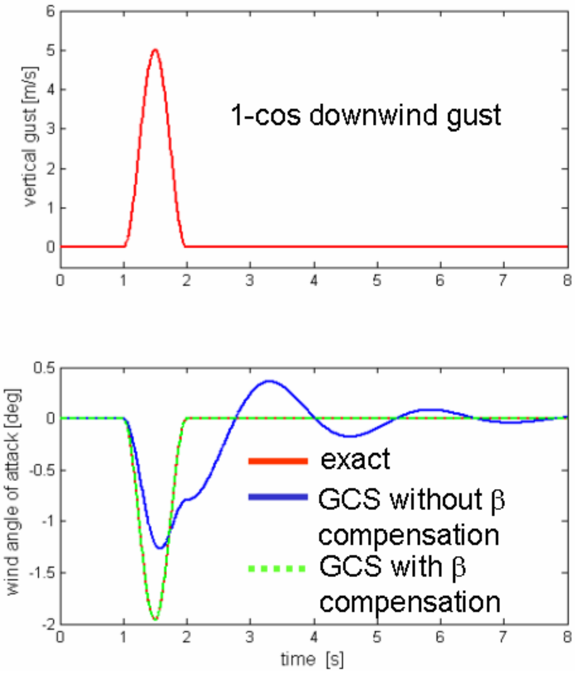

FIG 4 Effect of sideslip angle on the calculation of the wind angle of attack

2.2. Adaptation to real world measurement system

Considering real world sensors one has to accept that their positions will not be known exactly and that the measured data will not be error-free. The required signal inputs for α_W computation are provided by different sensors having different characteristics and pre-filters. To remove errors from the resulting time shifts of the signals their individual time delays and time responses have to be synchronized. All the available pre-knowledge of sensors and measurement systems was used for signal conditioning and processing to provide the best possible signal accuracy. Finally, a first order high-pass filter (with time constant of 10s) was introduced to eliminate low frequency wind effects (mainly affecting the aircraft's energy state) and a possible bias in the estimated wind angle of attack.

The final validation of the CGS was performed using flight test data. Since the real gusts and turbulence during flight were not known, parameter identification methodology based on flight path reconstruction (FPR) [8] was used to determine the most probable gust and turbulence. Generally, the FPR procedure utilizes a mathematical model which is embedded in an optimization process to minimize a predefined cost function, here depending on the quadratic differences of measured and re-simulated time dependent data. The FPR model consists of 6-DoF aircraft kinematics including co-ordinate transformations and rules to enable the signal re-calibration and synchronization. Mostly, in-flight measured accelerations and angular rates serve as inputs into the FPR model, and numerical integration is used to re-simulate the output variables to be compared to the respective flight data. The inertial reference system (IRS) data were assumed to be correctly calibrated and synchronised and serve as reference for the calibration and synchronization of all other signals. Using the above described methodology input and output signals were re-calibrated and time shifted where necessary, rules for estimation of sensor alignment and position errors as well as of non-linear additions, e.g., to airflow signals were furnished. A comparison of the computed wind angle of attack with basic and recalibrated GCS is given in FIG 5. It can clearly be seen that the pre-knowledge based basic GCS is able to compute the gusts and turbulence (at least the variations) but it shows some deviations from the results based on the application of parameter identification.

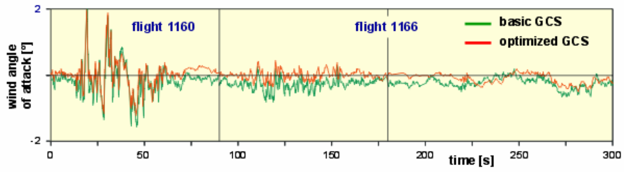

FIG 5 Comparison of the wind angle of attack from the basic GCS and the GCS optimized by parameter identification methodology

2.3. Sensor fusion to improve the accuracy of the forward looking turbulence sensor

Due to time delays in the aircraft control system and a limited performance of the control surface actuators, the wind/turbulence sensor signal must be available early enough (200-300ms before the turbulence reaches the aircraft wing) to allow a signal processing for estimating the vertical turbulence and to initiate the deflection of the control surfaces such that the optimal deflection is reached exactly when the turbulence passes the aircraft wing. Hence, for the measurement of the turbulence at Mach numbers between 0.5 and 0.86, a forward looking LIDAR sensor is used, which measures turbulence at about 50m in front of the aircraft.

Unfortunately the accuracy of the currently available LIDARs is not sufficient to apply them for precise gust computation. The AWIATOR LIDAR [4] accuracy in line of sight is approximately of 1m/s, which yields an accuracy of 2.8m/s for the measurement of vertical wind. Simulations have shown that for the application of the GLAS a wind signal with an accuracy of about 1-1.5m/s is necessary. Hence, the accuracy of the actual LIDAR sensor must be improved by a factor of two.

A sensor fusion algorithm is proposed by DLR[2], which performs a fusion of the forward looking LIDAR signal with the more accurate wind measurement of the alpha vane sensor at the aircraft nose. The objective of the algorithm is to obtain a wind signal, which has an accuracy of about 1.5m/s, while keeping the forward looking property of the LIDAR signal. The principle of the concept is based on the calculation of a time derivative $\dot{w}$ of the gust information w computed from the LIDAR signal w_{LIDAR} and the signal w_{Vane} from the conventional angle of attack sensor

$$(3) \qquad \dot{w} = \frac{w_{LIDAR} - w_{Vane}}{T}.$$

T is the aircraft speed dependent time delay between the LIDAR sensor and the alpha-vane sensor measurement

[2] DLR patent

points. The time derivative $\dot{w}$ of the vertical wind is filtered, corrected by a feedback loop, and integrated to get *good and ahead* estimation w_g of the gust (see FIG 6).

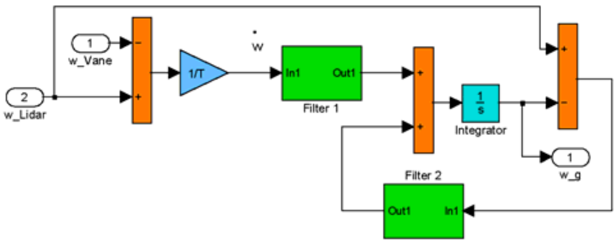

FIG 6 Block diagram of Sensor Fusion algorithm

The accuracy improvement using the sensor fusion algorithm is illustrated in FIG 7 and FIG 8 and the standard deviation of the noise/error content in the signal w_{LIDAR} could be reduced by almost 50%. Hence the more accurate estimated wind signal w_g may be directly used for the GLAS.

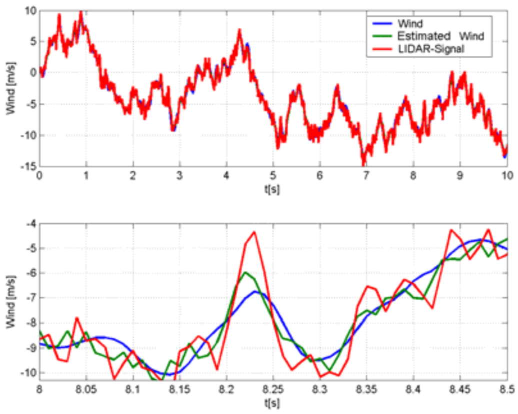

FIG 7 Simulation results of wind w, estimated wind w_g and LIDAR signal w_{LIDAR}

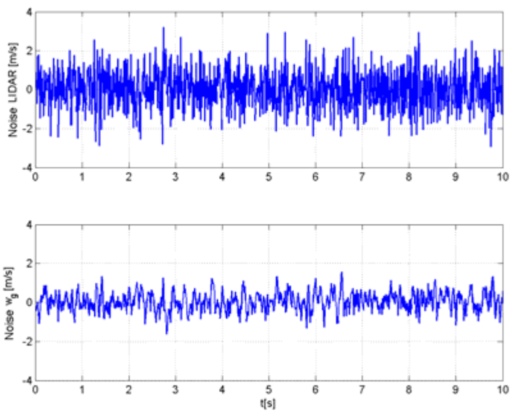

FIG 8 Comparison of noise in w_{LIDAR} and w_g

3. GUST LOAD ALLEVIATION SYSTEM (GLAS)

To maintain an undisturbed flight in gusty weather conditions several actions have to be taken. Presuming that the wind-angle of attack representing the wind disturbance is calculated and provided by the GCS, the GLAS performs a coordinated deflection of the direct lift control devices (symmetric ailerons/mini-TEDs) to reduce the wing bending moment and the vertical aircraft accelerations. Furthermore, the pitching moment belonging to the deflections of the direct lift control devices at the wing has to be compensated by the elevator.

One of the most important points is that the control surface deflections must be synchronized with the moment at which the measured wind disturbance reaches the aircraft wing. Therefore the time shift between the measured wind disturbance at the position of the angle of attack sensor and its arrival at the wing has to be taken into account. When the changed downwash of the wing and also the gust itself reaches the elevator, additional elevator deflections are required to avoid pitching moments. The principle concept of the GLAS is sketched in FIG 9, where $\tau_{AoA-wing}$ denotes the time delay between the angle of attack sensor and the wing, $\tau_{wing-HTP}$ is the time delay between the wing and the HTP. K1, K21, K22, K23 and K24 denote the different linear filters of the control system.

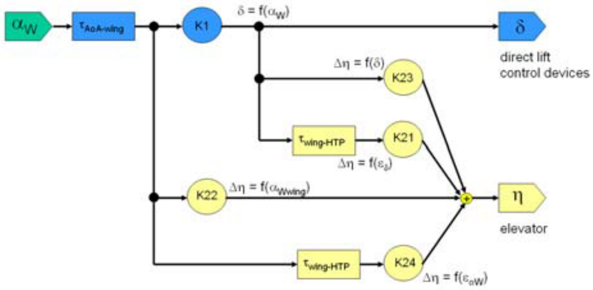

FIG 9 Principle structure of the GLAS

3.1. Pre-deflection and forward-looking distance

The actuator dynamics of the control surfaces of the AWIATOR test aircraft were approximated with the transfer function $T_{act} = 1/(0.2s+1)$, which describes quite slow dynamics. Therefore one main problem was the delayed/slow reaction of the control surfaces, yielding a bad synchronization of the aileron and mini-TED deflections with the wind at the aircraft wing.

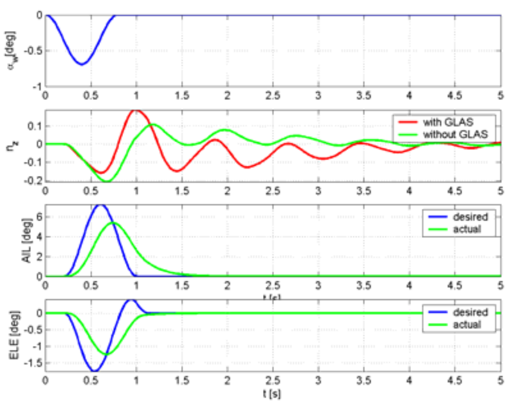

FIG 10 GLAS without pre-deflection

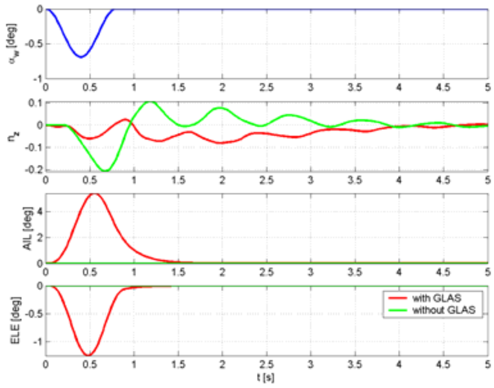

FIG 11 GLAS with pre-deflection

This is obvious in FIG 10, where a clear difference between the desired and the actual aileron and elevator deflections yield no reduction of the vertical acceleration n_z at the centre of gravity.

To solve this problem, one possibility would be to use faster actuators for the aircraft. However, this will be a very big effort and probably not realizable. One simple solution to improve the performance of the GLAS was to make use of the fact that we know the wind information before the wind reaches the aircraft wing. Hence, to counteract the slow actuator dynamics, we can start deflecting the control surfaces in advance in order to have a better synchronization of the control surface deflection and the vertical wind at the aircraft wing.

Using optimization, the best results for the GLAS were obtained using a “pre-deflection”-time of about 190ms and this time was almost independent from the flight case and the type of turbulence/gust that was used, i.e. this time mainly depends on the actuator dynamics. The clearly improved reduction of vertical accelerations using the GLAS with optimal pre-deflection time can be seen in FIG 11. In addition we can realistically assume that due to sensor delays and computation time it takes 110ms until the actual value of the estimated wind is available in the flight control computer. Therefore, to obtain the optimal performance of the GLAS, it is necessary that the measurements of the wind sensor are performed at least 300ms (190ms+110ms) before the wind reaches the wing aerodynamic chord, which is located at 31.47m behind the aircraft nose. This allows a rough estimation of the minimal distance $d_{\min}$ between the wind measurement point and the wing aerodynamic chord and the required forward looking distance $d_{LIDAR} = d_{\min} - 31.47$ of the LIDAR sensor, which are both shown in TAB 1.

V_{tas} (Mach)	$d_{\min}$	d_{LIDAR}
103m/s (M 0.5)	30.9 m	-0.57 m
248m/s (M 0.82)	74.4 m	42.93 m
254m/s (M 0.86)	76.2 m	44.73 m

TAB 1 Locations of wind measurement point required for GLAS

The results show that at high speed cases (e.g. Mach 0.86) the wind measurement point is ahead of the aircraft (e.g. 44.73m, for the A340) and therefore the usage of a LIDAR sensor will be necessary.

3.2. Dynamic feed-forward

The first design of the GLAS was a purely static control system, which already resulted in a very good alleviation of the wing root bending moment M_x (see green result in FIG 12). However, the static GLAS does not consider the aircraft elasticity and a quite remarkable excitation of the first wing root bending moment still occurs. Therefore, we extended the static GLAS by adding dynamic filters, which allow alleviating the loads and vibrations at the frequency of the first wing root bending mode (blue result in FIG 12).

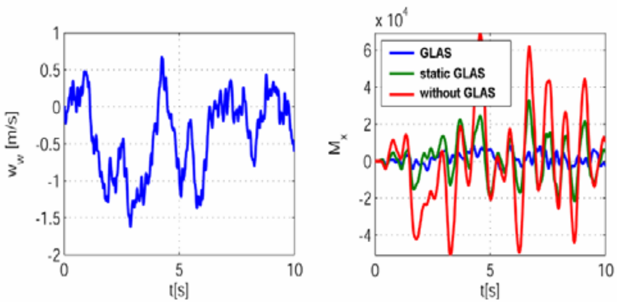

FIG 12 Reduction of wing root bending moment M_x in continuous turbulence (w_w)

3.3. Multi-objective, multi-model optimization

A fixed structure was chosen for the GLAS [5][6] with a dynamic order of 2 and the controller coefficients were designed using multi-objective optimization. To ensure robustness, a multi-model formulation was used, such that for each Mach number only one controller parameterization was synthesized, which guarantees robust stability and performance for all available flight cases.

3.3.1. Optimization criteria

For the multi-objective design the following load and comfort criteria were used:

- Load: fatigue (E_{M_x}) and peak (P_{M_x}) load at wing root (2 criteria), fatigue ($E_{M_x\_HTP}$) and peak ($P_{M_x\_HTP}$) load at HTP root (2 criteria)
- Safety and Comfort: peak vertical acceleration (P_{nz_cg}) at CoG (1 criteria), comfort criteria British standard for sitting (C_{st}) and standing (C_{std}) persons in the front and rear of the aircraft (4 criteria)

Therefore, 9 criteria were simultaneously considered for one flight case. As for each Mach number 5 flight cases were available, an overall set of 45 criteria were considered during the multi-objective design of the GLAS.

3.3.2. Resulting criteria improvements

In FIG 13 to FIG 18 the relative improvements of the criteria are presented. The black line at one represents the normalized criteria values for the aircraft without GLAS and a criterion value less than one describes the relative improvement of the criterion. To identify the effectiveness of different control surfaces two designs of the GLAS were investigated. One design uses only mini-TED and the other only symmetric aileron deflections for direct lift control and wing load alleviation. It is obvious that the mini-TEDs (blue lines) have a larger direct-lift effect compared to the ailerons (red lines), which results in a better comfort improvement. On the other hand, the ailerons have more effect on the wing bending moment and therefore allow a better load alleviation.

The performance specification of the GLAS designs seen in FIG 13 to FIG 18 was to improve the wing loads, with the constraint to keep at least the same level (compared to the aircraft without GLAS) for all the other criteria. This specification had to be fulfilled for three types of turbulence/gust: 1) continuous turbulence with Dryden spectrum, turbulence scale length L=2500ft and standard deviation σ=30ft/s, 2) discrete gust with length L=30ft and amplitude of 60ft/s, 3) discrete gust with length L=350ft and amplitude of 60ft/s. Furthermore the specification had to be robustly fulfilled for the five flight cases under consideration. Altogether four sets of controller parameters were synthesized: 1) using only mini-TEDs for load alleviation at Mach 0.5, 2) using only mini-TEDs for load alleviation at Mach 0.82, 3) using only symmetric ailerons for load alleviation at Mach 0.5, 4) using only symmetric ailerons for load alleviation at Mach 0.82.

Note, that for the GLAS using mini-TEDs we assumed that (in simulation) these can be deflected up- and downwards, which allowed an easy comparison of the different control systems. In reality they could only be deflected downwards and therefore a combination of the GLAS using mini-TEDs with the GLAS using ailerons will be necessary. Furthermore, for discrete gusts the comfort criteria are not calculated as these are only defined for continuous turbulence.

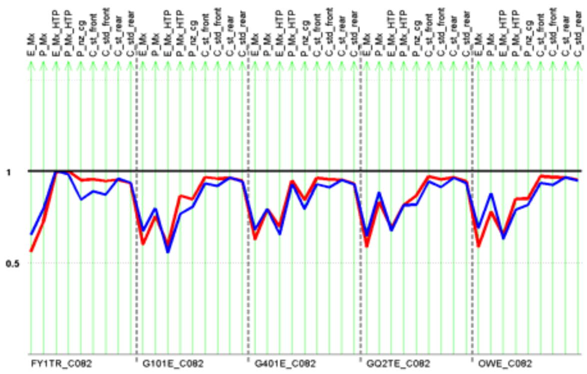

FIG 13 Relative improvements of criteria at Mach 0.82 for five flight cases in continuous turbulence (L=2500ft, Dryden, σ=30ft/s)

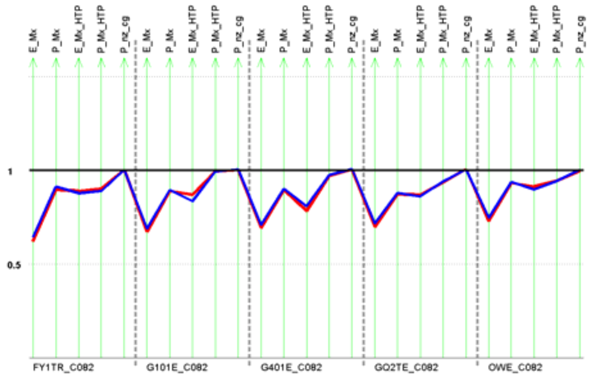

FIG 14 Relative improvements of criteria at Mach 0.82 for five flight cases in discrete gust (L=30ft, Amplitude=60ft/s)

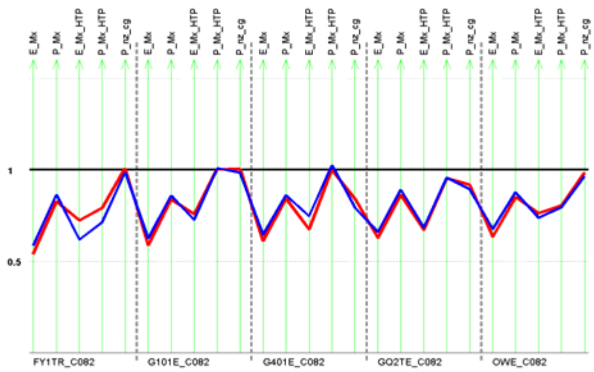

FIG 15 Relative improvements of criteria at Mach 0.82 for five flight cases in discrete gust (L=350ft, Amplitude=60ft/s)

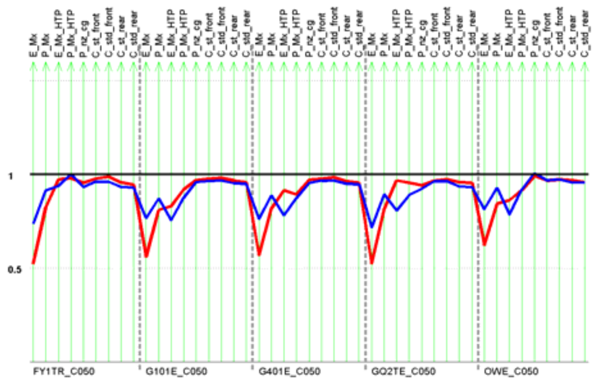

FIG 16 Relative improvements of criteria at Mach 0.5 for five flight cases in continuous turbulence (L=2500ft, Dryden, σ=30ft/s)

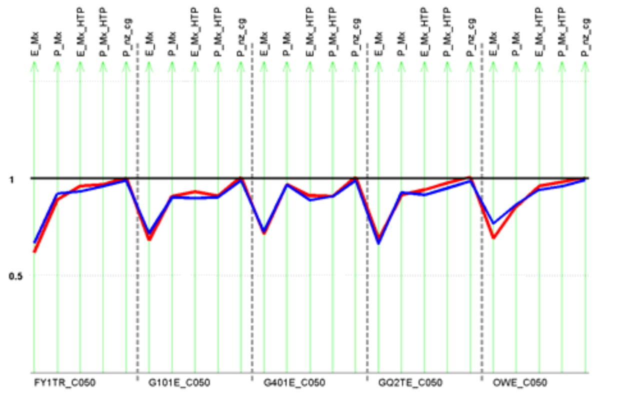

FIG 17 Relative improvements of criteria at Mach 0.5 for five flight cases in discrete gust (L=30ft, Amplitude=60ft/s)

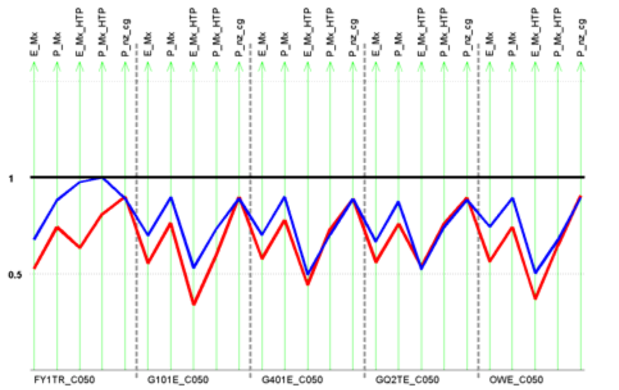

FIG 18 Relative improvements of criteria at Mach 0.5 for five flight cases in discrete gust (L=350ft, Amplitude=60ft/s)

3.3.3. Compromising and Pareto optimal solutions

During the multi-objective control design we were confronted with the problem of conflicting criteria, i.e. improving one criterion means that another criterion becomes worse. Therefore a proper weighting of the different criteria is necessary and also offers the freedom to find different compromise solutions depending on the flight case. For example, one may choose a special parameterisation of the GLAS during cruise (focus on safety by reducing vertical accelerations when clear air turbulence occurs) and another parameterisation during takeoff and approach (focus on load reduction when encountering wake vortices).

Depending on the flight case (sizing cases) it may also be important to improve the HTP loads. To illustrate this, the Pareto bounds for two loads criteria are shown in FIG 19. From this figure one may easily chose a proper parameterisation of the GLAS depending on the flight case. For example, if for a certain flight case one can tolerate up to 30% increase of the HTP loads, then one can reduce the wing loads by almost 60%. In case that no increase of HTP loads is allowed, one may still be able to reduce the wing loads by about 45%. Again, the different effectiveness of ailerons and mini-TEDs for load alleviation is obvious in FIG 19.

These 2d plots give a deep insight into the underlying multi-objective control problem and can be easily generated from the Multi-Objective Parameter Synthesis (MOPS) [7] software that was used to parameterize the GLAS.

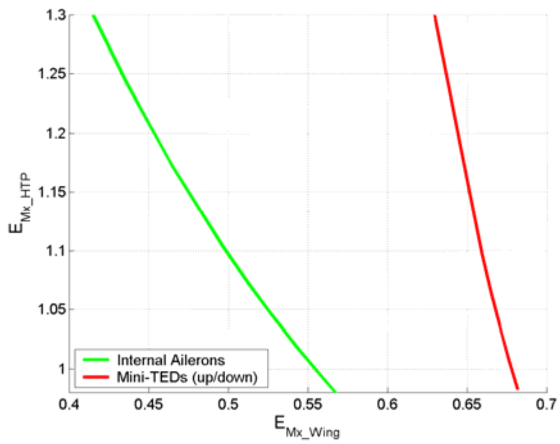

FIG 19 Pareto bounds for fatigue loads at wing and HTP in continuous turbulence (L=2500ft, Dryden, σ=30ft/s) at Mach 0.82

3.4. Simulation results

FIG 20 and FIG 21 show some representative simulation results in continuous turbulence and for a discrete gust, respectively. The results show the vertical wind input, aileron (internal and external) and elevator deflections and the bending moments at wing and HTP root. The aircraft response without GLAS is shown in red. Despite the large wind amplitudes (standard deviation of 30ft/s in continuous turbulence and amplitude of 60ft/s for the discrete gust) the control surface deflections and deflections rates do not exceed the given limits.

4. CONCLUSIONS

The combined Gust Computation Algorithm (GCA) and Gust Load Alleviation System (GLAS) developed by DLR within the AWIATOR project allows an accurate estimation of vertical wind disturbances and performs a coordinated deflection of the control surfaces to alleviate structural loads and to improve passenger comfort and safety. The benefits of including the angle of sideslip information (measurement or estimation) and a sensor fusion algorithm into the real-time estimation of wind disturbances have been impressively demonstrated. The multi-objective, optimization based design of the simple GLAS structure (dynamic order of the controller is two) provides a lot of freedom in choosing appropriate weightings for the different criteria, thus allowing to easily derive different controller parameterisations for different flight/sizing cases. The parameterisation derived within the AWIATOR project was focused on wing load reduction, while keeping the same level of HTP loads. With this GLAS, a reduction of 30-40% of structural loads at wing root and an improvement of the passenger comfort around 5-10% could be achieved.

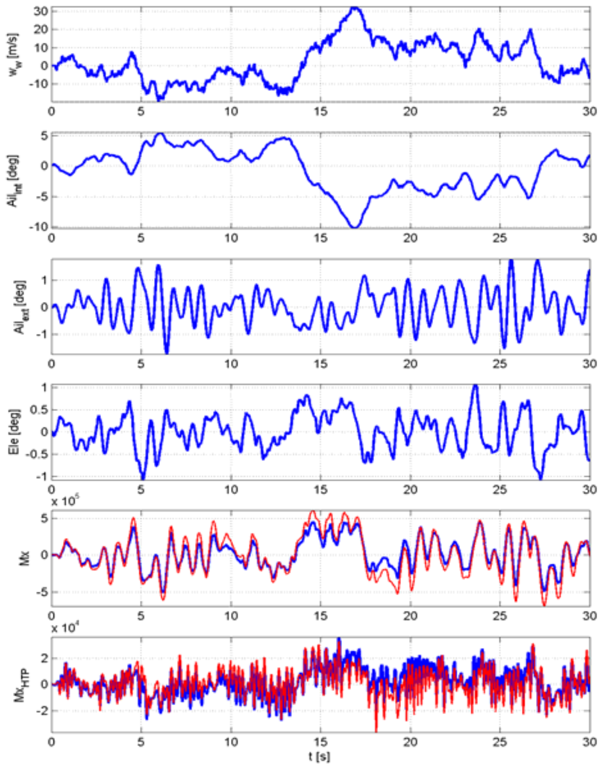

FIG 20 Continuous turbulence, Mach 0.82, GLAS using ailerons

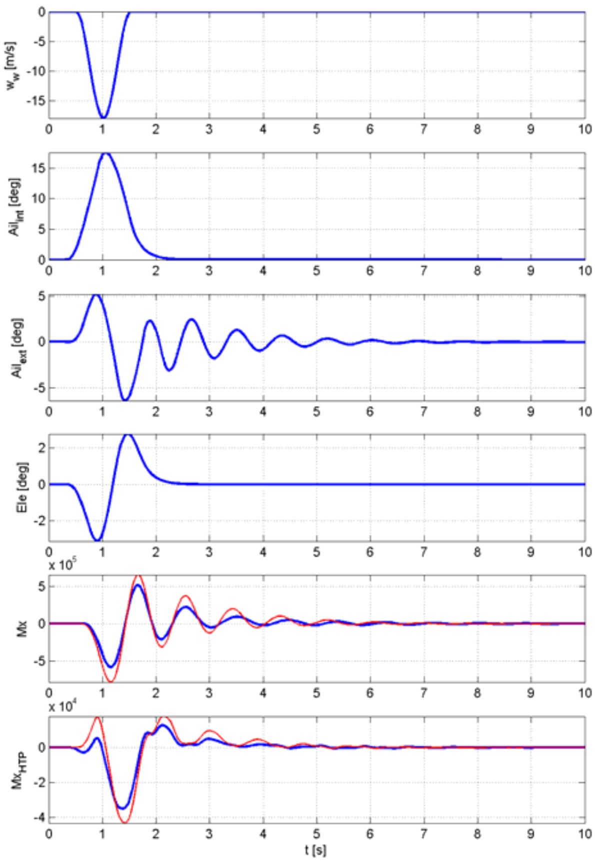

FIG 21 Discrete Gust with L=350ft, Mach 0.5, GLAS using ailerons.

5. REFERENCES

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