DESIGNING AND MATURATING DOPPLER LIDAR SENSORS FOR GUST LOAD ALLEVIATION: PROGRESS MADE SINCE AWIATOR

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This paper gives an overview of the work performed by DLR on lidar-based gust load alleviation during the CleanSky and CleanSky 2 programmes. This work is put in relation with the work that was performed in the AWIATOR project, which is still the most advanced lidar-based gust load alleviation demonstration programme that has been undertaken in Europe. Compared to the system that was designed and demonstrated within AWIATOR, various improvements could be made by DLR and demonstrated in simulation. In order to properly evaluate the load alleviation performance for a given system (including lidar sensor, measurement processing, and load alleviation functions) and its sensitivity to the design parameters a coupled simulation environment is being developed. This environment is still an on-going development but it already permits to perform concurrent engineering studies of the complete lidar-based gust load alleviation system.

ABBREVIATIONS

ATTAS	Advanced Technologies Testing Aircraft System (former DLR research aircraft)
AWIATOR	Aircraft Wing with Advanced Technology Operation
BFGS	Broyden-Fletcher-Goldfarb-Shanno (algorithm)
CRM	Common Research Model
CS, CS2	CleanSky, CleanSky 2
CS25	Certification Specifications for Large Aeroplanes
DLM	Doublet Lattice Method
DLR	Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center
EU / EC	European Union / Commission
FP5	5th Framework Programme of the European Commission
GBJA	Generic Business Jet Aircraft
GLRA	Generic Long Range Aircraft
GN	Gauss-Newton (algorithm)
LOS	Line of Sight
RANS	Reynolds-Averaged Navier-Stokes
SFWA	Smart Fixed Wing Aircraft
VLM	Vortex Lattice Method
XRF1	Airbus-provided industrial standard multi-disciplinary research test case representing a typical configuration for a long range wide body aircraft

1. INTRODUCTION

In order to be competitive and to address the challenges of the fight against global warming transportation systems need to be energy-efficient. Depending on the type of vehicle considered various characteristics play a role in the overall efficiency of a given vehicle. The drag force, opposed to the vehicle's direction of motion, is dissipating energy and therefore must be kept as low as possible to prevent unnecessary high power consumption. For typical airliners in cruise conditions roughly 50% of the aerodynamic drag is so-called "induced drag" and corresponds to the drag that results directly from the generated lift, which itself is equal (in steady horizontal flight) to the aircraft mass. Additionally, a snowball effect will be triggered as the additional energy consumption resulting from the additional drag (itself coming from the additional mass of the airplane) forces to carry more fuel, which itself increases the weight. This effect is well-known and more significant for long-range missions.

In order to keep the aircraft mass as low as possible, the structure must be designed and built as light as possible. At the same time, the structure must be sized such that the aircraft can be operated safely. For this a whole part (Part C) of the certification requirements for large aeroplanes CS25 [1] deals with the requirements on the aircraft structure. These requirements involve a series of very specific criteria and acceptable means of compliance for the different parts of the airplane. The experience over several decades has shown that the combination of these requirements and regular inspections permits to ensure a very high level of safety. Statistically, air transportation accidents linked to structural failures are almost negligible and the few occurrences of such accidents are linked with maintenance problems rather than design problems. When analyzing the maximum loads on each part of the structure of various modern airliners, it appears that, usually, the maximum loads for large portions of the wing structure result from the so-called gust and turbulence loads. These loads are the results of the dynamic excitation of the aircraft structure when flying into turbulent/gusty conditions. As a result, a reduction of the loads under these conditions enables the use of lighter structures and thereby the design of more energy-efficient aircraft.

Apart from avoiding the turbulence areas (if possible), two main ways of reducing the gust and turbulence loads exist: passive and active gust load alleviation. The passive load alleviation focuses on the design of a structure whose deformation under loads tends to reduce the aerodynamic forces and moments that caused this deformation in the first place. Active gust load alleviation works by using sensors to sense the gusts or their effects and automatically reacting to them by means of actuators (e.g. control surfaces). It should be noted that passive and active load alleviation technologies can be combined.

One of the limiting factors for active load alleviation systems lies in the difficulty to react early or quickly enough to significantly alleviate the loads. The typical aircraft sensors are measuring the effects of the gusts/turbulence (e.g. through inertial accelerations at various places of the airframe) or the gusts/turbulence itself, i.e. the wind speed. Compared to measurements at the wing, a direct detection of the gusts/turbulence at the aircraft nose enables a somewhat better load alleviation performance. However, it can be shown that, for typical airliners, with slightly more anticipation a significant improvement of the load alleviation performance can be obtained [2]. This fact has been known for at least 25-30 years, but measuring the gusts/turbulence ahead of the aircraft nose is technically challenging.

Doppler lidar sensors might provide a viable way to measure the gusts ahead of the aircraft. Various past research programs, starting with the US American developments in the 1970s [3], developed or used Doppler lidar sensors to measure wind velocities remotely [4] [5] [6]. Regarding the use of Doppler lidar sensors aboard large airplanes for load alleviation purposes, one particular project stands out: the European FP5 AWIATOR project. It aimed, among many other objectives, at developing and demonstrating exactly the type of sensors needed for gust/turbulence load alleviation purposes. This project ended more than ten years ago, but this work remains nowadays a reference through the quality of work accomplished and the fact that it is well-known in the European aeronautics community. An overview of the accomplishments of AWIATOR regarding the use of Doppler lidar sensors for load alleviation purposes is provided in the next section. After that, section 3 explains the improvements proposed by DLR since AWIATOR (among others within CleanSky Smart Fixed Wing Aircraft, CleanSky 2 Airframe, and the German national project LuFo-V-2-Con.Move/NEKON). Finally, the authors' view regarding the required, and partly already on-going, efforts for further maturing this technology using concurrent engineering is given in section 4.

2. ACHIEVEMENT OF THE AWIATOR PROGRAMME ON LIDAR-BASED GUST LOAD ALLEVIATION

During the AWIATOR programme a new direct detection Doppler lidar sensor has been developed, built, and tested. Reference [4] gives a good overview of the preliminary design of the lidar sensor, of its processing electronics, and of the preliminary tests that were performed onboard the DLR VFW-614 ATTAS research airplane. Based on these flight tests various modifications were made to the system in order to improve the sensor measurements. Eventually, the improved system was integrated and tested on an Airbus A340-300 aircraft [5]. The sensor accuracy shown in [5] is significantly better than in [4], which is explained to be mainly the result of an increased laser power (about ten times higher). All in all the accuracy figures shown in [5] may be considered as sufficient for a lidar-based gust load alleviation function.

These two references ([4] and [5]) also provide a valuable insight into the ideas underpinning the lidar sensor design made in AWIATOR. It was decided to use Rayleigh scattering with a 355 nm wavelength (in the ultraviolet spectrum) in order to have a sensor system providing measurements even in the absence of aerosols (i.e. when flying through clean air, which regularly happens at typical jet airplane cruise altitudes). To the best of this paper's authors' knowledge this is the right choice for the application to a gust load alleviation function which shall enable the design of lighter aircraft structures and whose availability shall not depend on the presence of aerosols.

Another aspect that was considered in the design of the AWIATOR sensor was the need for large longitudinal and temporal resolutions. The design of the AWIATOR sensor already went quite far in that direction and the need for sufficient longitudinal and temporal resolutions was a main concern for the authors of [4] and [5]. The experience gained in simulation by the authors of the present paper led to the conclusion that even larger resolutions than those used in AWIATOR (even if at the cost of an increase in measurement noise) would be beneficial for the overall load alleviation performance.

Overall, the work performed in AWIATOR on the sensor has provided a very valuable experience and reference for the following projects on lidar-based feedforward gust load alleviation. This is also why the AWIATOR system is taken here as reference.

3. BEYOND AWIATOR

3.1. Identifying Potential Improvements

Whilst the AWIATOR sensor was the reference in Europe at the beginning of the CleanSky project in 2008, it became relatively quickly clear that the exploitation of the lidar measurements could be improved significantly. Two main steps for which possible improvements were identified: 1) the determination of the wind and gusts ahead of the aircraft based on the lidar sensor measurements (i.e. the wind reconstruction) and 2) the use of this wind information by active load alleviation functions. Additionally, the mentioned improvements in terms of longitudinal (spatial) and temporal resolution play a critical role. These three aspects are detailed in the following subsections.

3.2. Wind Reconstruction Algorithm

The determination of the wind components in the lidar sensor measurement post-processing algorithm of AWIATOR also consists of two main sub-steps.

First, the inertial motion of the aircraft is compensated; which was and remains a straightforward step.

Second, several line-of-sight (LOS) wind velocity measurements (i.e. the projections of the wind velocity vectors onto the sensor LOS that are measured via the Doppler effect) are combined to estimate the three-dimensional wind vector. For this, in the AWIATOR solution, four successive measurements taken in four different directions are combined. Here, in DLR's recent works, a significantly improved processing of the measurements could be achieved.

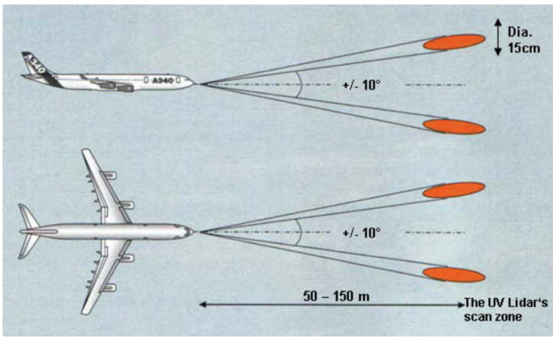

Figure 1: Measurement geometry used in AWIATOR with four beam directions (top-left, top-right, bottom-left, bottom-right) forming effectively a 14° angle with the mean direction (through the combination of 10° angles both vertically and horizontally)

The wind reconstruction algorithm of AWIATOR (see [5]) performs a wind estimate based on four measurements with different directions (see geometry in Figure 1) and repeats this process for the next group of four measurements, which then correspond to a location in space a bit further along the aircraft's flight path. The same process is repeated over time for each group of four measurements. The fact that these four measurements were taken successively at a rate of 60 Hz and therefore do not perfectly correspond to the same location in space was not taken into account in the wind estimation of AWIATOR. The groups of four measurements were also considered separately and the neighboring groups were not considered during the estimation. Besides, when encountering turbulence the aircraft "moves" (either the whole aircraft or as excitation of its flexible modes), which can significantly affect the distribution of the measurement locations and LOS directions and should be taken into account in the wind estimation process.

As a consequence a more advanced wind reconstruction algorithm was developed which considers all recent measurements (stored in a buffer that gets updated with new measurements and too old measurements get dropped) [7] [8]. The variations of measurement geometry (locations and LOS directions of each measurement) are taken into account. It is also not restricted to / derived for a particular measurement geometry which

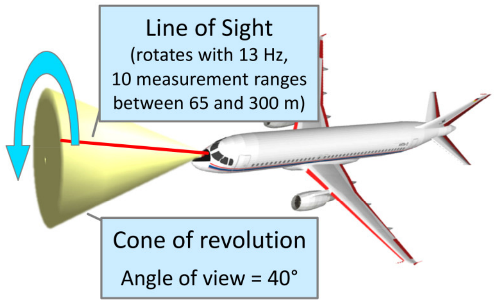

Figure 2: Possible alternative scanning geometry investigated during CS SFWA

permits to easily investigate which geometry / scanning strategy is best suited for reconstructing the wind field ahead of the aircraft. For instance a continuously rotating beam with several measurements at various distances was tested during CleanSky Smart Fixed Wing Aircraft (CS SFWA) (see Figure 2 and [7] [8] [11]).

The output of the wind reconstruction is not the wind estimates for a "mean location" but rather a wind profile along the flight path. It is provided as a series of wind estimates for a series of locations along the flight path (each time the coordinates of these locations and the corresponding wind estimates are provided). The algorithm integrates smoothing parameters in form of Tikhonov regularization terms which can be useful for reducing the impact of the sensor noise on the wind estimates. A first version of this algorithm was developed in CS SFWA. Once the principles were validated in simulation a new implementation was made in CleanSky 2 (in the Airframe Integrated Technology Demonstrator) as it appeared that it could be made much faster and fully deterministic in terms of computational effort and memory footprint. Figure 3 shows the linear complexity of the wind reconstruction algorithm with the size of the problem (i.e. number of lidar measurements considered simultaneously).

In the AWIATOR post-processing algorithm, based on four measurements, the noise in LOS direction resulted in a noise level amplified by a factor 2.9 on the transversal wind components (i.e. perpendicular to the middle axis of the four LOS directions). This led to very noisy wind estimates which then could be filtered with a low-pass filter. It should be noted that by integrating regularization terms directly within the wind reconstruction algorithm it is possible to obtain behaviors that cannot be obtained with a recursive filter (i.e. taking one measurement at a time). Outliers in the measurement buffer could easily be identified and potentially rejected. When treating the measurements four by four, as noted by the authors of [5], a quality index can be computed as only three (non-collinear) measurements would be required to estimate a three-dimensional vector. If one of the four measurements deviates more than the others from the correct value, it remains impossible to determine which one of the four is wrong, at least unless the value is extremely far from the range of plausible values.

The wind reconstruction algorithm based on a buffer of measurements can also directly exploit the specificities of some lidar sensor designs that are able to perform measurements at various distances: the algorithm can directly make the fusion between these different measurements and account for the possible differences in terms of noise levels between them. For instance a sensor could make relatively good measurements at a relatively short distance (e.g. 50 m) and less good measurements at a longer distance (e.g. 150 m): the former ones provide precise information in the short-term whereas the latter ones give a general idea of the longer-term trend of the wind such that an effective pitching strategy can be used. Such processing can directly be handled by the authors' wind reconstruction algorithm but could not be handled with the original design of the AWIATOR wind estimator.

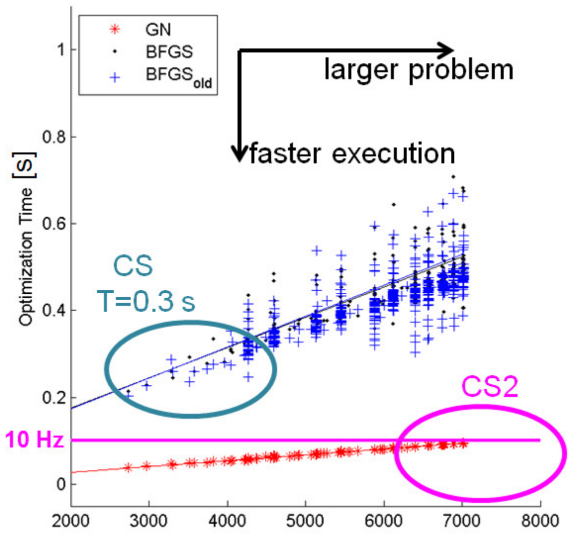

Figure 3: Improvement to the wind reconstruction algorithm allowing the detection of gusts based on Doppler LIDAR measurements. Details can be found in [8].

3.3. Load Alleviation Function Design

Once the wind ahead of the aircraft has been estimated based on the Doppler lidar measurements and the inertial motion of the aircraft, this information can be used for actively alleviating the gust and turbulence loads. Various load alleviation functions were investigated during the course of the AWIATOR project, however it appears that due to the significant time that had to be spent developing the lidar sensor itself and due to its low maturity level at the time, most of the load alleviation function design work focused on solutions that did not require a lidar sensor (see for instance [12]). During AWIATOR, former colleagues of the authors already started investigating the best way to use the gust information provided by the lidar sensor, combined with the air data measurements at the nose of the aircraft, for feedforward load alleviation functions [13]. Whilst these investigations brought various new ideas and reflections on this topic, significantly more capable solutions were developed later on during CleanSky and CleanSky 2.

Over the course of CS SFWA a multi-objective controller design scheme was used to design both a feedforward load alleviation function and a feedback load alleviation function. The feedforward function permitted to anticipate the forthcoming gusts/turbulence whereas the feedback function increased the damping of the flexible modes and could also reject effectively the largest gusts [8] [11].

An unconventional feedforward controller structure has been developed [10] specifically for the needs of the application to the GLRA-XRF1 test case provided by Airbus. It permits to easily combine time-frequency-separated sub-functions to obtain the strongly nonlinear behavior that had been implicitly specified by Airbus in CS SFWA. The motivation for this structure was twofold. First, it was desired to enforce by design a strict bandwidth limit for the feedforward pitching actions. Second, low-amplitude disturbances were neither to be alleviated by means of the pitching actions nor by means of the spoilers. These differences in load alleviation behavior/strategy depending on the amplitude of the disturbance represent a strongly nonlinear behavior. Using such a controller structure for the load alleviation function can restrict the maximum achievable alleviation performance [10]. However, this structure permits to decompose the load alleviation functions into several sub-functions, each of which having much simpler tasks to accomplish and thereby can be tuned very easily, even "by hand".

Combining the improved wind estimate with this feedforward control structure and manually tuned (sub-)controllers already permitted to obtain very promising results towards the end of CleanSky Smart Fixed Wing Aircraft, with significant load reduction potential obtained with simple controller sub-functions.

CleanSky 2 contribution

Even if the results obtained in CS SFWA were already showing the promising potential of lidar-based gust load alleviation, a more systematic load alleviation function design methodology was required. The maximum achievable load alleviation performance for a given lidar sensor design cannot be determined based on a manual tuning approach and as a consequence fair comparisons between different lidar sensors were virtually impossible. Moreover, if this approach was used for systems engineering studies, the number of manual tunings (one for each sensor configuration) would grow rapidly and become excessively time-consuming and costly.

This observation led to developing a more systematic methodology for the development of (quasi)-optimal load alleviation functions. The same methodology can be used in two versions: 1) an automatized version for system/concurrent engineering studies (see next section) and 2) a version involving human interaction for fine tuning of the necessary trade-offs between the various conflicting requirements, e.g. load alleviation performance, robustness, and required control authority.

A natural and effective way to design a control function that alleviates the peak loads caused by the turbulence is to minimize the H_∞ norm of the transfer functions from the gust/wind input of the model to its load outputs. This results from the fact that the H_∞ norm can be interpreted as the peak gain of a transfer function across all frequencies and input directions. Using the H_∞ norm the gust load alleviation problem can therefore be formulated mathematically as an optimization problem type for which very powerful algorithms exist.

When considering discrete gusts, the certification criteria (cf. CS25.341) require to consider different maximum amplitudes for the different gust lengths, which means that a frequency-weighting should be multiplied to the gust/wind input to account in the frequency domain for the change in amplitude specified in the certification requirements for large aeroplanes (see [14] for the details on the weighting function). For typical flexible large airplanes improvements are typically needed in the frequency range between 0.3 and 10 Hz (critical or close to critical gust lengths divided by the true airspeed).

Over the last decade (2010-2020) new H_∞ algorithms based on nonsmooth optimization algorithms have become widely available through their inclusion in one of the most popular control design software packages: the Robust Control Toolbox of MATLAB. These algorithms were not available during the AWIATOR project and constitute very valuable tools for the design of gust/turbulence load alleviation functions. In particular, they provide additional possibilities to design directly reduced-order controllers (i.e. controllers with lower order than the system they control), with a given structure, and on multi-channel/model problems. These new capabilities are of utmost importance for the load alleviation applications, because the required aeroservoelastic models as well as the required weighting functions are of fairly high order. With the more classical H_∞ control design algorithms high-order controllers would be obtained and a far-from-trivial controller reduction would have to be made afterwards, with no guarantee of being able to keep the controller performance. Moreover, the design load alleviation involves making trade-offs between the loads at various locations of the structure and it is often not possible to properly express the desired priorities in only one single H_∞ performance channel (restriction of the classical H_∞ control design algorithms based on Riccati equations or linear matrix inequalities).

Many advanced control design algorithms are sensitive to the model size and its numerical conditioning. This is also the case with H_∞ control design algorithms. Consequently when dealing with complex or high-order systems a model reduction step is often necessary. This is in particular the case when using this type of algorithms on aeroelastic models that are derived from the coupling of a complex structure model and some aerodynamic computational method (DLM, VLM, RANS, etc.). With the recent reduced-order H_∞ synthesis algorithms, a model reduction step prior to the control synthesis is often still required for numerical reasons. However, the order (and representativeness) of the model can in practice often be kept higher as the model order does not condition the order of the controller anymore.

In addition to benefiting from the recent improvements of the H_∞ algorithms, a new preview control formulation has been developed to better exploit the wind information coming from the wind reconstruction algorithm. In particular, the entire reconstructed wind profile is now considered by the controller at each point in time. This is a rather unusual formulation of the so-called “preview control” disturbance rejection problem whose main advantage is that improved wind estimates can be provided to the controller over time. Indeed, in a classical preview control formulation, the measurements are made in advance and directly provided to the controller which can “save/remember” all or part of the information using its internal states. However, once this information was taken into account it cannot be updated if better measurements/estimates become available. The formulation proposed by the authors in [9] [10] addresses this, by ensuring that the controller “preview memory” is made explicitly and can be manipulated / updated. In the case of the wind reconstruction based on lidar measurements the wind estimates at a given location become more precise as the aircraft approaches this location and this new preview control formulation permits to account for that in a simple and practical way. Note that such an update could also be performed using a model predictive control (MPC) approach as proposed in [15]. A similar solution was investigated by the authors at the beginning of CS SFWA but it was ultimately rejected due to the issues related to the required online optimization step (certification, worst-case execution time, etc.) and to the fine tuning of the load alleviation functions. By using a preview control scheme no real-time implementation issues are to be expected as all heavy computations are done offline. Moreover, the fine tuning and trade-off between conflicting requirements with multi-channel H_∞ are also easier and more powerful than in the MPC case.

3.4. Sensor Improvements

A key for improvement of the whole sensor-reconstructor-controller-actuator chain is the wind data yield itself. On that topic, DLR is also contributing its competence in airborne and spaceborne lidar technologies and Doppler wind lidars. Namely, the enhancement in terms of spatial and temporal resolution may be addressed by several technical innovations that are available today and have not been at the time of AWIATOR. Optical component manufacturing allows fabricating novel spectral analyzers with several advantages. This allows novel detector technology for working at higher signal-to-noise levels on fewer individual detection elements. Also recent fiber technology enables further reductions of the noise and the systematic error. These aspects have permitted to develop [6] a demonstration prototype yielding high performance in terms of LOS wind speed determination from the lidar spectral analyzer data [16].

4. SYSTEMS ENGINEERING STUDIES OF COMPLETE LIDAR-BASED GUST LOAD ALLEVIATION SYSTEMS

In order to enable the maturation of lidar-based gust load alleviation systems a simulation environment coupling the various components/disciplines involved is currently being developed. The main components of the coupled simulation environment are described in the following subsections. Finally, the way this coupled simulation environment will be used for systems/concurrent engineering studies is described in subsection 4.5.

4.1. Flexible Aircraft Models

In order to be able to assess the benefit of lidar-based load alleviation systems, the load alleviation potential of these systems must be evaluated with high-quality aeroservoelastic models. Currently two types of aircraft are considered: long-range airliners and business jets. Two Generic Long Range Aircraft (GLRA) models are used in the present CS2 work: the GLRA-XRF1 model, derived from the Airbus XRF1 configuration, and the GLRA-CRM, derived from the Common Research Model from [17] [18]. Regarding the business jet applications, Dassault Aviation provided a Generic BizJet Aircraft (GBJA) aeroservo-elastic model to DLR and ONERA in the framework of CS2 [19].
With these models the load alleviation figures can be computed, but additional work is required in order to convert these figures into mass savings for the aircraft. On the GBJA, the computation of mass savings figures requires Dassault Aviation proprietary information. One version of the GLRA-XRF1 model has been modified by DLR in such a way that mass saving figures cannot only be computed by Airbus but also by DLR.

4.2. Baseline Flight Control Laws

Whichever combination of sensors (lidar + inertial, inertial + air data, etc.) is used by load alleviation functions their potential interactions with the basic "rigid-body" flight control laws / autopilot modes must be investigated. Ideally, the basic flight control system will even be directly taken into account in the design of the load alleviation functions. In any case the performance of an active load alleviation function often should be assessed in combination with the baseline control system.
A baseline control law is available for the GBJA model. For all other models, representative control laws had or have to be added separately.

4.3. Lidar Sensor Models

In order to be able to assess the performance of lidar-based load alleviation functions, representative lidar sensor simulation models are also required. Two different types of lidar sensor models are necessary and described hereafter.

Physics-Based End-to-End Simulation of the Lidar Sensors

The first type of lidar sensor simulation that is required is called "physics-based end-to-end" simulation because it describes the sensor based on all physical processes that take place in the sensor subsystems: from the generation of the photons in the laser source, to their travel through the optical system and the air, their backscattering, capture by the detector, and evaluation of the Doppler shift. Within this simulation model each of these processes is sufficiently finely modeled to permit variations of the main properties of each sensor subsystem. Further, statistic noise processes are represented at all relevant stages of the detection process. Details on this model were published in [6], but the development has been pursued continuously since then. Ground experiments have been performed [16] and will be performed over the next years to provide validation data for this model.

Surrogate Models of the Lidar Sensors

The surrogate model of the lidar sensor is significantly simpler than the physics-based end-to-end model. It aims at representing the performance of one particular lidar sensor configuration at a macroscopic / flight mechanical level. It relies on a limited set of parameters to describe measurement geometry, noise, bias, etc. whose values need to be determined using the physics-based end-to-end simulation model. Its simplicity makes it extremely fast which permits to integrate it in the complete aircraft + controllers + load alleviation + lidar simulation environment.

4.4. Lidar-Based Load Alleviation Function

The aim of the simulation environment described here is to permit the evaluation of the load alleviation potential of lidar-based load alleviation functions. The corresponding functions must therefore also be integrated in this environment. As described in section 3, these functions typically involve two main parts: first, a wind reconstruction module, and second, the load alleviation controller. The wind reconstruction algorithm designed by DLR in CS and improved in CS2 is implemented in C++ and integrated in the Simulink-based simulation environment as an s-function. For simplicity both the surrogate lidar sensor simulation and the wind reconstruction algorithms were integrated in a single s-function. This simplifies the data handling between these two modules, as otherwise all lidar sensor measurements and their metadata would have to be passed from the lidar sensor to the wind reconstruction algorithms via Simulink signals. That would result in very large interfaces for each of these s-function blocks and numerous unnecessary copy operations. The tuning parameters of the wind reconstruction algorithm (e.g. resolution of the mesh and smoothing parameters) are made available through external parameters of this s-function. This way they can be controlled by the users directly from MATLAB.

The second part, i.e. the load alleviation controllers, consists usually simply of one or several dynamical systems that can be programmed with standard Simulink blocks. This said, the unusual time-frequency-based signal decomposition made in CS-SFWA for the XRF1 application was easier to program in code than with block diagrams and therefore was integrated in a separate s-function (also written in C++).

4.5. Required Systems Engineering Studies

Based on the coupled simulation environment previously described and currently well advanced, systems engineering studies will be performed during the next years. This way the best combination of sensor technologies, their configuration, wind reconstruction algorithms, and load alleviation controllers will be searched. All these components partly behave in a strongly nonlinear way (e.g. with saturations), which makes the described coupled environment crucial for such investigations as the overall system performance cannot easily be derived from the performances of each individual component.

In a first step the aircraft dynamic behavior, flexible modes, etc. will be kept constant and the variations considered for the concurrent engineering studies are focused on the sensors, the measurement processing, and the actuators.

On the actuator side, the choice of control surfaces used for the load alleviation function, the authority that the load alleviation has on each of the control surfaces, and the properties of the actuators (e.g. bandwidth and rate limiters) are the main parameters that will be varied.

On the sensor side, the choice of sensor type, their positions, and the sensor characteristics are the relevant parameters to investigate. In particular the design space for Doppler lidar sensors is quite large and various solutions compete for the various subsystems. This leads to a relatively high number of possible designs among which the best designs remain to be identified. The various subsystems of the “lidar sensor” that could be selected or varied include, on a very rough scale, characteristics like power-aperture-product, overall electro-optical efficiency, lidar Doppler scheme, scan envelope and aircraft integration constraints. On a finer scale, when advancing the level of detail, these figures may be broken up into laser type, power, pulse rate, receiver type and aperture (for power-aperture-product) and so forth.

The dependency of the lidar sensor performance on these parameters is complex, which is why the physics-based end-to-end lidar simulation model is crucial for the overall systems engineering of a lidar-based load alleviation system.

The complete chain, from the sensor measurements to the commands sent to the actuators, also contains a wind reconstruction algorithm [7] [8] and the load alleviation function. The wind reconstruction algorithm has a few parameters that can be tuned. These parameters define the level of smoothing of the reconstructed wind profile and their optimal values depend on the lidar sensor characteristics. Consequently, they need to be considered and adjusted along with the lidar sensor during systems engineering studies.

The design of the load alleviation functions also provides some tuning possibilities such as: the desired alleviation performance (for each load type and station), the trade-off with some other criteria, and the thresholds under which the function will not be active (e.g. to prevent unnecessary actuator cycles in the presence of low turbulence levels). It could even be imagined to opt for a blending of a more passenger comfort-oriented function for low turbulence levels and of a more peak load-oriented function for larger turbulence levels.

All in all, the coupled simulation environment shall permit to search efficiently (easily and with a reasonable effort) throughout the design space defined by the aforementioned parameters to find the most interesting system designs. As an example, the impact of change in lidar sensor range on the load alleviation performance typically resembles the curve shown in Figure 4, with first a fairly sharp decrease in the loads but with greater measurement distance (i.e. preview length in preview-control sense) the improvement in terms of load reduction is always shallower and tends to a lower bound that reflects the limits that can be reached for a given aircraft type and sensor/actuator system. In that example, depending on the relative weighting β of the two criteria (comfort and loads), one of these criteria might increase whenever it is not critical and helps reducing the critical one (see for instance the comfort in the case $\beta = 2$).

This task will be performed in a concurrent

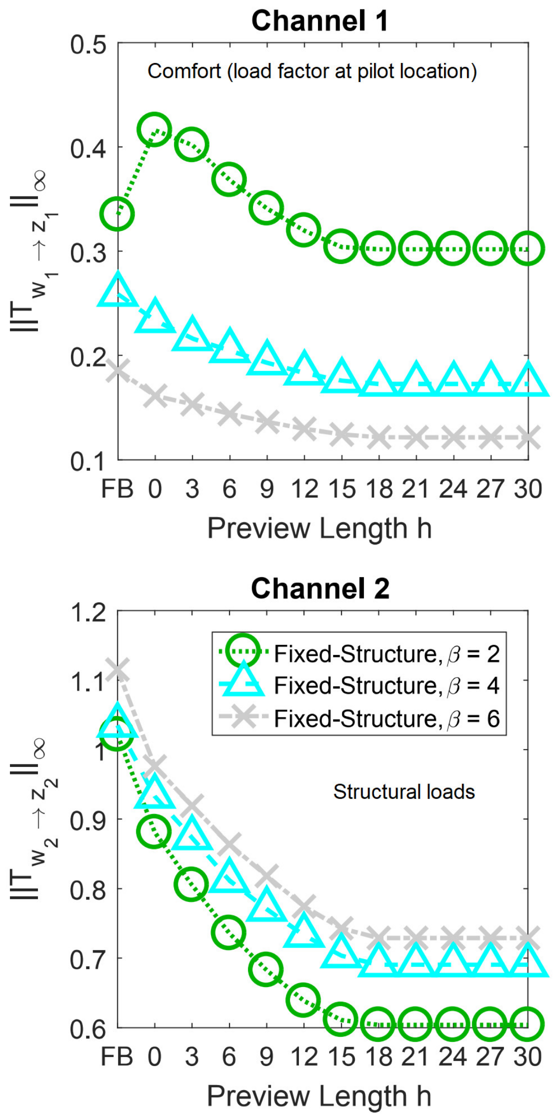

Figure 4: Example for load alleviation performance improvement with the increase of the preview length taken from [10]. The preview length corresponds here to the number of samples with which the wind is known before it acts on the aircraft wings, which – for a given true airspeed – directly correlates to the range of the lidar sensor.

engineering fashion. For this, most computations should be sufficiently automatized and fast to permit a large batch of computations. The determination of trends and sensitivities must also be reliable enough to permit the use of gradient-based optimization techniques. The automation of such tasks was the main driver for the design of an automated control synthesis workflow for the load alleviation controllers (cf. end of section 3.3).

5. SUMMARY AND OUTLOOK

This paper shows an overview of the work DLR has done in CleanSky and is still pursuing in CleanSky 2 on lidar-based gust load alleviation. This work extends the great work that has been performed during the AWIATOR project and both activities should rather be seen as complementary. AWIATOR still remains today the reference work in that area in Europe, even if the authors have identified and developed various improvements to the AWIATOR system. Even if some improvements are needed, in their current state the tools that were developed in CleanSky and CleanSky 2 are already permitting to better assess the system design trade-offs at the overall aircraft level.

The authors are convinced that the Doppler lidar sensor technology has tremendous potential for active load alleviation and is worth investigating further. Discussions have started with various European partners with the aim of defining a cost-efficient technology maturation roadmap. The first estimates led to a roadmap over 8 to 10 years, which addresses in a systematic fashion all aspects and technologies with remaining uncertainties. This roadmap involves a series of lab tests, ground tests (possibly at high altitude in the mountains), as well as full-scale flight demonstrations. A compressed roadmap could be considered but is expected to be less cost-efficient. The CleanSky scheme seems to be the most adequate European research programme for executing the considered long-term lidar-based load alleviation technology maturation.

With the experience gained through AWIATOR and the complementary work performed in CleanSky and CleanSky 2, a full-scale closed-loop flight demonstration at the end of a CleanSky 3 seems achievable to the authors, provided that the right consortium of partners is constituted. Potential partners are kindly invited to contact the authors.

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