Aeronautics lidar revisited – Towards lidar-based gust and turbulence measurement for aircraft load alleviation control

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Abstract: We give an overview of the authors' and their institutions' latest R&D activities regarding Direct-Detection Doppler-Wind-Lidar (DD-DWL) for the usage as remote flow sensor on civil aircraft. The purpose of such a lidar, when flying through Clear Air Turbulence (CAT) at cruise altitudes, is delivering sufficient turbulent wind information for feeding a chain of gust reconstruction, control and command modules. Hence, aerodynamic effects on the aircraft structure shall be mitigated.
The long-standing record of the ONERA and DLR lidar groups in aeronautics' application lidar allowed us recently to team up in the European Clean Aviation Joint Undertaking (CAJU) co-financed project UP Wing with the agenda of maturing the critical technologies (like laser, Doppler spectrometric receiver, etc.) and validating these at component and system level with extensive ground and also airborne tests.
Here, we present the main bricks of this technology suite, an overview of some prior and actual achievements and some perspective.

1. Introduction

The use of lidar on aircraft, in particular as remote flow sensor, has been under discussion since the very early days of laser and lidar [5]. Particular emphasis has always been on turbulence encounter which still is the second major cause (after system or component failure) [1] of enroute accidents in civil aeronautics, with an increasing trend [2]. As outlined in [3], tomorrow's civil aircraft will have to be up to the challenges of increasing turbulence encounter [4,5,6] due to climate change, higher structural vulnerability, e.g., due to more slender wing geometry (high aspect ratio) and the ever-relevant economic-commercial competitiveness.

Thus here, we are focusing on lidar-based feed-forward flight control systems for mitigation of effects of aircraft encounter with turbulence, gusts and wake vortices.

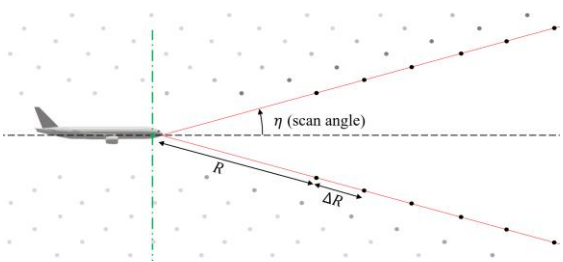

Figure 1: Scheme of airborne forward-pointing scanning DWL for determining vertical wind speeds from LOS wind measurements (black dots actual, grey dots past measurements).

In contrast to state-of-the-art feedback control schemes, such feed-forward methods are based on ahead wind information, ultimately to be delivered by a Doppler lidar system [7,8]. Thereby the low and unknown occurrence of aerosol in cruise flight altitudes dictates the usage of direct-detection DWL [9]. European activities in this context have been pioneered by the seminal AWIATOR lidar subproject [10,11] led by Airbus that as a first employed a forward-pointing UV-DD-DWL based on a fringe-imaging Fabry-Perot interferometer. From the numerous lessons-learned of this and other aeronautics lidar projects at ONERA and DLR (such as [12,13]), in particular regarding risks due to system complexity, our groups developed a – in our view – firm risk-resilient approach [14,15] for advancing the whole scheme of lidar-based feed-forward flight control systems (i.e., raising the technology-readiness-level TRL) far enough for future uptake by airframe manufacturers or tier-one suppliers.

This programme is addressed in the CAJU co-financed project UP Wing and based on three pillars: (i) technology development in terms of hardware and simulative modeling, together with prospective evaluation of novel techniques and successive maturation; (ii) early demonstration of the main technology components and systems and the validation of the simulations; (iii) a thorough evaluation of the performance in terms of gust load alleviation for generalized or specific airframes using the validated simulation tools. Thus, the different aspects and sub-systems of the overall lidar-based GLA scheme, their dependencies, interrelations and the necessary requirements optimization to come to a sufficient, reliable, and affordable lidar-based gust load alleviation system shall be assured.

In this conference contribution, we want to give an overview of the many parallel and intertwined past and present activities and highlights. We will however, for ease of reading, desist from attributing each activity to the numerous projects on institution-internal, national and European level.

2. General architecture and requirements optimization

A DWL-based remote gust and turbulence alleviation control scheme as depicted in Figure 1 is based on the take-up of the DWL-determined wind data by a reconstruction algorithm (WRA) for use in the subsequent control functions [3,7]. A critical criterion for the performance of the whole chain is the dispersion of the lidar wind measurements (or averaged measurement sets) which may be very roughly described by [3]:

$$\sigma_{v_{LOS,av}}{}^2 = k_{lid} \cdot k_{atm} \cdot \frac{R^2 \cdot r_{refresh}}{P.A.P. \cdot \Delta R} \quad (1)$$

where k_{lid} and k_{atm} are lidar system and atmosphere-related “constants” whereas the fraction includes (apart from distance R) the main lidar design parameters, the data rate $r_{refresh}$ delivered to the WRA, the laser power - lidar telescope aperture (that are equivalent to a certain extent) product $P.A.P.$ and the spatial resolution (often termed range gate length) ΔR. While this relationship in reality is far more complex and has to be determined with physics-based end-to-end simulations, Eq. 1 may, as a surrogate, however be used in the full lidar-based aeroservoelastic simulation [16] as described in Section 5. The approximate fidelity of Eq. 1 to physical-technical reality therefore is regularly re-checked by comparison to different levels of end-to-end simulations and field measurements with a DD-DWL prototype [3,17,18]. Full lidar-aeroservoelastic simulations allow for mutually optimizing lidar system requirements as laser power, averaging times and lengths, scanning angles etc. and are therefore crucial for not-overspecifying the subsystems.

3. Lidar system and subsystems

Stemming from such a requirement iteration, DLR has been developing an adapted UV laser of the solid-state MOPA (master oscillator, power amplifier) type yielding a UV (355 nm) output power of > 5 W at 3 kHz pulse rate. Its further characteristics (pulse length 7 ns, single mode, linewidth < 400 MHz) allow for the use with DLR’s Doppler spectrometric receiver prototype [3,19,20] based on a fringe-imaging Michelson interferometer (FIMI) and will as such be combined with it in the near future. Following the philosophy of our contribution to the mentioned actual UP Wing project regarding a parallel and complementary approach for risk reduction, ONERA is currently developing a hybrid fiber laser, i.e. with a possible boost free-space amplification stage and solid-state IR-UV frequency conversion. Its specifications are also optimized for the combination with ONERA’s development of a Doppler receiver based on a quadri-channel Mach-Zehnder (QMZ) [21,22].

Furthermore, our activities include the optimization of scanning angle and scheme [22,23] as well as the study of adapted opto-mechanical beam directing systems.

4. Demonstration and validation

The second pillar of this activity within CAJU UP Wing is the early, repeated and thorough testing, demonstration and validation of different versions and combinations of a UV DD-DWL. This ranges from on-site ground over high-altitude ground to airborne wind and turbulence measurements. So far, DLR has completed a first high-altitude test campaign on a mountain-based environmental research station for proof-of-concept of its DD-DWL prototype (configuration as described in [3]) in low-aerosol and otherwise very diverse meteorological conditions (see Figure 2 and [18,24]), while ONERA is about preparing for the first local demonstration of the QMZ-configuration.

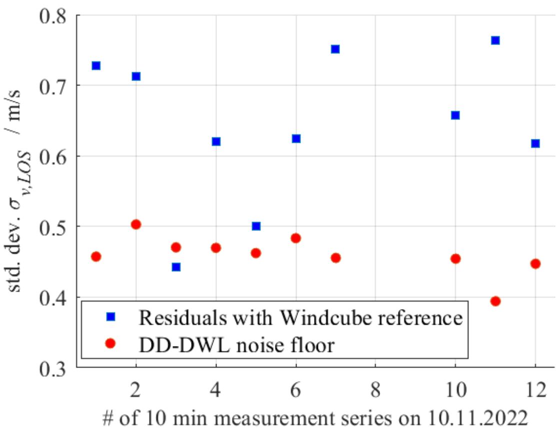

Figure 2: Wind measurement dispersion of DLR's DD-DWL prototype determined at $R = 300$ m, $\Delta R = 50$ m and $r_{refresh} = 2$ Hz (at laser $PRF = 100$ Hz), as compared to C-DWL Windcube© for 10 min measurement series over some hours of comparable meteorological and low aerosol conditions.

Such high-altitude demonstrations shall be repeated over the course of the project(s). Furthermore, an inflight demonstration (of only uni-axial LOS wind measurement) is planned onboard NLR's research aircraft Cessna Citation II PH-LAB, very much relying on modifications and equipment developed for the EC FP7 project DELICAT [12,25,26]. This will allow for a raise of the TRL of such a UV DD-DWL sensor due to operation in the relevant environment.

5. Feed-forward control

Since the times of AWIATOR, various improvements have been performed within the Clean Sky 1/2 and now Clean Aviation programmes by DLR regarding the overall simulation toolchain, the gust identification (WRA), the use of diverse aeroelastic aircraft models (i.e., generating descriptive state space models of reduced order), and the feed-forward controller itself, with the controller design based on a new multi-channel structured discrete time H_∞ formulation [27]. A complete run of this multi-domain toolchain with the DLR configuration (new laser as above and spectral receiver with foreseeable realistic performance in terms of opt. efficiency etc.) yields that turbulence-induced aerodynamic loads might be decreased such that they are not sizing the structural design anymore (e.g. maneuver-loads being higher). This is when flying through standard certification (CS25.341 [28]) turbulence with a typical short-to-medium range passenger aircraft. Such a control performance would allow for effectively reducing the mass of these aircraft structures (e.g., wing root).
Such kind of full simulations may be run for any kind of sensor-aircraft-flight point combination for optimization of the requirements (as addressed in Section 2).

6. Conclusion and outlook

We gave an overview of past and ongoing activities by ONERA and DLR for the advancement of critical lidar technology projected for the use in novel feed-forward load control of civil transport aircraft which shall increase their efficiency in terms of structural mass reduction. The many given references (also planned, in this conference and beyond) of our own activities might invite to dig deeper into the subject. The authors are confident to finally open up the (commercial) aerospace sector for the use of atmospheric lidar technology.

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Disclaimer

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