Aeronautics Application of Direct-Detection Doppler Wind Lidar: Alleviation of Airframe Structural Loads Caused by Turbulence and Gusts

P. Vrancken[1], N. Fezans[2], D. Kiehn[2], O. Kliebisch[3], Ph. Linsmayer[1], J. Thurn[3]
(1) Institute of Atmospheric Physics, German Aerospace Center (DLR), 82234 Weßling, Germany
(2) Institute of Flight Systems, German Aerospace Center (DLR), 38108 Braunschweig, Germany
(3) Institute of Technical Physics, German Aerospace Center (DLR), 70569 Stuttgart, Germany
Email: patrick.vrancken@dlr.de

Introduction

The use of lidar in the domain of aeronautics, namely in airborne operation, has been one of the earliest fields of application, endeavored shortly after the invention of the laser itself (Franken, Jenney and Rank, 1966). Such efforts, in particular aiming at turbulence in cruise flight (clear air turbulence CAT), have long been pioneered by the US (cited in Vrancken, 2016), but achievements have also been made in Japan (Inokuchi, Akiyama and Sasaki, 2018) and in Europe (AWIATOR, cf. Schmitt *et al.*, 2007; Rabadan *et al.*, 2010) where efforts have come to a halt in the early 2000s.

At DLR however, these activities have been continuously pursued. In a recently started project, we aim for the use of a Doppler Wind Lidar (DWL) as the central wind speed sensor for a real-time control scheme aboard civil passenger aircraft. This control loop shall use the wind information ahead for derivation of significant turbulent gusts and their counteraction with fast feed-forward actuation of the aircraft's control surfaces (elevators, ailerons, spoilers etc.). An exemplary maneuver could be a subtle 'nose down' pitch when detecting a vertical gust ahead. This scheme could significantly decrease the loads associated with cruise-flight turbulence encounter. Previous simulations (Fezans and Joos, 2017; Fezans, Joos and Deiler, 2019) show that the loads in the wing and fuselage structures may be reduced to a level where such a system is becoming economically attractive.

Evidently, a future commercially viable system for this type, and likewise its prior full airborne demonstration (in an R&D context), poses strong requirements on each of the ingredients of this control scheme: on the DWL laser transmitter and receiver as well as the gust identification and control function. In the presentation/poster, we give insights to the current status, latest achievements and potential of each of these crucial elements.

Activities and status

At the ELC2020 we have introduced (Vrancken and Herbst, 2020) a concept and prototype of a direct-detection DWL based on a fringe-imaging technique based on a skewed Michelson interferometer. The requirements of the described control scheme, sub-m/s precision, high data repetition rate (few to several tens of Hz), high spatial resolution (20 to 50 m), close measurement ranges (50 to 300 m) as well as sensitivity to both mixed molecular/aerosol and pure molecular backscatter (without knowledge on the ratio thereof in terms of backscatter ratio) are all adequately addressed by our design. After the general demonstration of the lidar's functionality (Vrancken and Herbst, 2019/2020) we now have identified the main drivers for absolute and relative (in terms of photon budget) improvement of the systems wind speed measurement dispersion as well as for its residual bias. The first deduced technical improvements are currently (summer 2021) counter-checked in ground-based wind measurements.

In parallel, simulation models (both a simplified analytical and a more physical end-to-end) of a realistic evolution of the lidar are used within an iterative simulation setup particularly including gust identification and the aircraft (rudder command generating) controller.

Notably, it is the module "wind reconstruction algorithm" (WRA) that significantly lowers the requirements on the lidar in a way that (direct-detection) DWL altogether may come into play with significant impact. The WRA analyzes the line-of-sight wind measurements (taken at some angle from the flight direction axis) in a maximum-likelihood estimation using a matching wind (gust) field continuously being updated. The algorithm integrates smoothing parameters in form of Tikhonov regularization terms for reducing the impact of lidar measurement noise.

The third block within the simulation ensemble is the feedforward gust load alleviation (GLA) controller itself, which is currently matched to a "generic business jet" aircraft aero-elastic model, envisioning a future demonstration on a European flight test aircraft (such as the DLR ISTAR Falcon 2000 LX or similar). The controller design is based on a new multi-channel structured discrete time H_∞ formulation (Khalil and Fezans, 2021).

The iterative analysis of this model covers the four main components of the overall system: including the lidar model, the WRA, the feedforward GLA controller and the aircraft aeroservoelastic model. It is deemed to allow identifying a reasonable set of requirements, in particular on the lidar (with receiver, laser and scan / beam director system), all based on a reasonable and useful level of load alleviation (Fezans et al., 2020). In other words, over-specification of any sub-component is thus avoided.

Among the set of requirements, many crucial ones concern the laser transmitter. As pointed out at ELC2020, within our current ground prototype DWL we employ an existing powerful Nd:YAG UV-source (Vrancken *et al.*, 2016), however not adapted to a future GLA scenario. Previous (Herbst and Vrancken, 2016) and latest simulation results hint at low kHz laser systems as the optimum design point. For this reason, a dedicated laser development effort has been started, taking a master oscillator power amplifier (MOPA) scheme as a workhorse basis for the envisioned future airborne demonstration of the whole GLA loop. In parallel, further technology routes with lower technology readiness level (TRL), but possibly higher industrialization capability, such as fiber and semiconductor laser technology, shall be kept track of.

Challenges and discussion

Evidently, the development of such an advanced DWL system comes with many challenges and thus the authors will be pleased and eager to discuss the details, pitfalls and known unknowns of the whole scheme, in particular concerning laser, spectral analyzing receiver and scanning system. We also embrace potential future cooperations to tackle this European aeronautics domain subject.

Acknowledgements

Part of the work has been funded within the framework of the European CleanSky2 Joint Technology Initiative – Airframe (Grant Agreement Number CS2JU-AIR-GAM-2014-2015-01 Annex 1, Issue B04, October 2nd, 2015) being part of the Horizon 2020 research and innovation framework programme of the European Commission.

References

Fezans, N. *et al.* (2020) 'Designing and Maturating Doppler Lidar Sensors for Gust Load Alleviation: Progress Made Since AWIATOR', in. *Aerospace Europe Conference 2020*, Bordeaux, France.

Fezans, N. and Joos, H.-D. (2017) 'Combined Feedback and LIDAR-Based Feedforward Active Load Alleviation', in *AIAA Atmospheric Flight Mechanics Conference*. Denver, Colorado: American Institute of Aeronautics and Astronautics. doi: 10.2514/6.2017-3548.

Fezans, N., Joos, H.-D. and Deiler, C. (2019) 'Gust load alleviation for a long-range aircraft with and without anticipation', *CEAS Aeronautical Journal*, 10(4), pp. 1033–1057. doi: 10.1007/s13272-019-00362-9.

Franken, P., Jenney, J. and Rank, D. (1966) 'Airborne investigations of clear-air turbulence with laser radars', *IEEE Journal of Quantum Electronics*, 2(4), pp. 147–147. doi: 10.1109/JQE.1966.1073867.

Herbst, J. and Vrancken, P. (2016) 'Design of a monolithic Michelson interferometer for fringe imaging in a near-field, UV, direct-detection Doppler wind lidar', *Applied Optics*, 55(25), p. 6910. doi: 10.1364/AO.55.006910.

Inokuchi, H., Akiyama, T. and Sasaki, K. (2018) 'Flight demonstration of a long range onboard Doppler lidar', in *31st Congress of the International Council of the Aeronautical Sciences (ICAS 2018)*, pp. 3960–3966.

Khalil, A. and Fezans, N. (2021) 'A multi-channel H_∞ preview control approach to load alleviation design for flexible aircraft', *CEAS Aeronautical Journal*, 12(2), pp. 401–412. doi: 10.1007/s13272-021-00503-z.

Rabadan, G. J. *et al.* (2010) 'Airborne Lidar for Automatic Feedforward Control of Turbulent In-Flight Phenomena', *Journal of Aircraft*, 47(2), pp. 392–403. doi: 10.2514/1.44950.

Schmitt, N. P. *et al.* (2007) 'The AWIATOR airborne LIDAR turbulence sensor', *Aerospace Science and Technology*, 11(7–8), pp. 546–552. doi: 10.1016/j.ast.2007.03.006.

Vrancken, P. *et al.* (2016) 'Airborne forward-pointing UV Rayleigh lidar for remote clear air turbulence detection: system design and performance', *Applied Optics*, 55(32), p. 9314. doi: 10.1364/AO.55.009314.

Vrancken, P. (2016) 'Airborne remote detection of turbulence with forward-pointing LIDAR', in Sharman, R. and Lane, T. (eds) *Aviation Turbulence*. Springer International Publishing. doi: 10.1007/978-3-319-23630-8.

Vrancken, P. and Herbst, J. (2019) 'Development and Test of a Fringe-Imaging Direct-Detection Doppler Wind Lidar for Aeronautics', in *EPJ Web of Conferences. 29th International Laser Radar Conference*, Hefei, People's Republic of China.

Vrancken, P. and Herbst, J. (2020) 'A Novel Direct-Detection Doppler Wind Lidar Based on a Fringe-Imaging Michelson Interferometer as Spectral Analyzer', in *European Lidar Conference*. Granada, Spain (online).