



NUMERICAL INVESTIGATION OF PASSIVE AND ACTIVE ALLEVIATION OF DYNAMIC LOADS ON HIGH-ASPECT-RATIO-WING VEHICLES

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Abstract

We investigate basic gust load alleviation strategies in three very flexible aircraft, each belong to a different vehicle class. First, we investigate floating wingtips as a potential passive load alleviation in two different low-speed lightweight air vehicles, each corresponding to a span-loaded and a high wing load configuration. Subsequently, we present the design process of an active load alleviation system on a subsonic aircraft. The aeroelastic solver, based on a geometrically nonlinear multibody formulation, and the vehicle models, are made available in an accompanying open-source repository.

Keywords: High-aspect-ratio wings; nonlinear aeroelastic modelling; multibody dynamics; gust load alleviation

1. Introduction

Dynamic loads are a major limiting factor in the design of wings with very high aspect ratio for low induced drag. Gust load alleviation (GLA) systems that simultaneously provide large load reduction and robust performance will therefore very likely play a key role in the development of such wings. While the basic GLA system architecture and design methods are by now well established [1], they are tailored towards current-generation air vehicles. This paper reports on an effort to build a more general simulation environment for GLA design that deals with: 1) Passive solutions with large moving parts, such as flared folding wing tips. 2) Large wing deflections in both (static) trim conditions and (dynamic) gust response. 3) More complex geometries, as in truss-braced wings. 4) Advanced control architectures, including disturbance preview and nonlinear algorithms. 5) Fast computation of time-transient simulations, at least as fast as current industry-standard analysis tools.

We are addressing points 1-4 above with the development of SHARPy [2], a nonlinear simulation environment for flexible aircraft dynamics and control, and point 5 with the development of a new solver, FENIAX [3], built on vectorization that exploits modern computational architectures. The focus on this paper is on the former. SHARPy's modelling strategy uses a finite-element solver with multibody constraints based on geometrically-nonlinear composite beams [4], unsteady vortex-lattice aerodynamics with polar corrections [5], and real-time data transfer libraries for integration with control software (e.g., Simulink) [6]. Solutions include nonlinear trim equilibrium, time-marching of the nonlinear equations as well as the linearised in tangent space, dynamic stability analysis around nonlinear equilibrium, etc. Computational effort in the linearised dynamics is reduced using several model order reduction methods. All methods and their implementations have been extensively verified and validated and are freely available under a permissive open-source license. See §6 for details.

The core formulation underlying SHARPy has been reported in Refs, [1, 2, 4, 5], amongst others. The objective of this paper is to consolidate several aircraft models with high-aspect-ratio wings for

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studies of gust load alleviation with geometric nonlinearities. All SHARPy models have been updated to the latest version and are made openly available in a single repository, which can again be found in §6.

2. X-HALE

We consider first the University of Michigan X-HALE remotely piloted aircraft [7]. The baseline SHARPy model was developed for a code-to-code comparison with UM/NAST by Carre and Teixeira [8] and the main results have been summarised in §9.4 of Palacios and Cesnik [1]. A optimal aerodynamic discretisation has been developed for this that increases numerical performance without penalising accuracy. Figure 1 shows the UVLM model for the aircraft, assuming a prescribed wake with varying panel size in the streamwise direction.

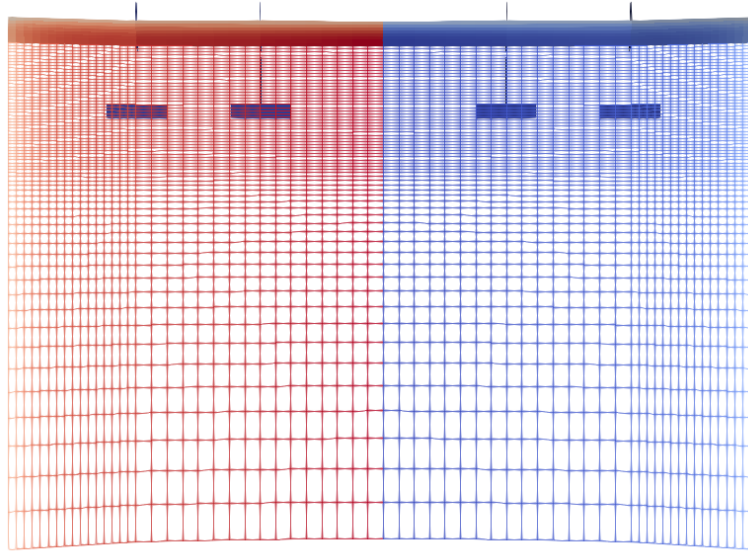


Figure 1 – Aerodynamic discretization of the X-HALE using a streamwise discretization.

The hinge is flared with respect to the streamwise direction. The associated aerodynamic grid is sketched in Figure 2, thus exploiting the versatility of the UVLM to represent arbitrary (planform) geometry and kinematics. The dotted line in the figure indicates the beam axis, and the beam node at the hinge is duplicated to allow for multibody constraints.

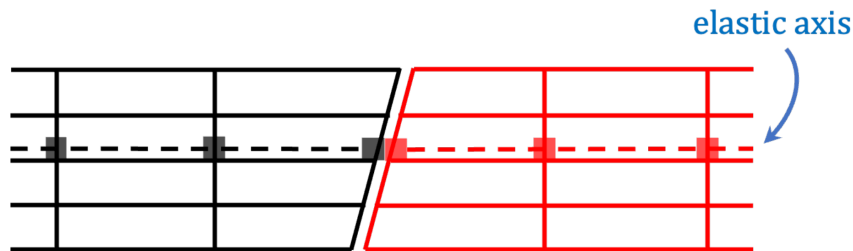


Figure 2 – Detail of wing discretization of a flared hinge in the UVLM.

As a verification exercise, Figure 3 compares the root strains in a discrete gust encounter obtained by this model with those in Ref. [1]. Simulations are for sea-level flight with $U_\infty = 14$ m/s. The gust is a "1-cos" of 15-chord length and intensity $.15U_\infty$. The original SHARPy model is identified as v1.0, while the current results are v2.2. Results for a prescribed wake (as in the v1.0 model) and free wake are included. Out-of-plane bending strains are exactly reproduced with the free-wake model, while the longer wake length used now results in slightly increased torsional strains.

As a potential passive load alleviation mechanism, a flared folding wing tip is introduced with hinges located 0.125 m outboard of the outer fuselages. The modified vehicle is referred to as the HX-HALE

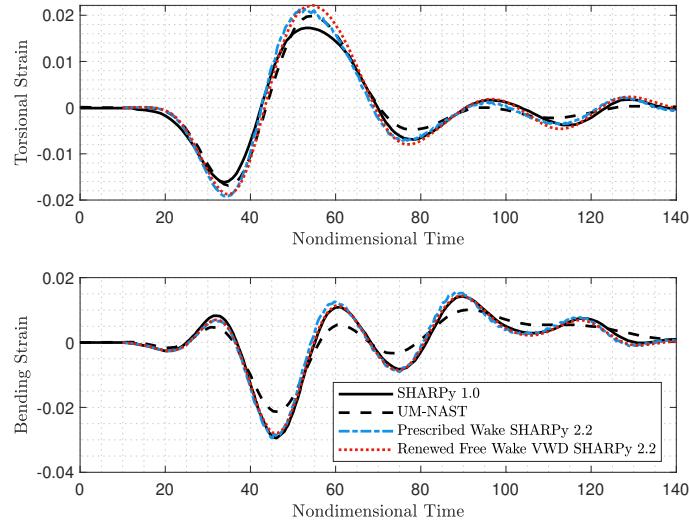


Figure 3 – Wing root strains of the X-HALE under a "1-cos" vertical gust.

and the multibody solver developed in Ref. [4] is used for the study. Figure 4 shows the forces applied on the beam nodes in forward flight for a flare angle of 10 deg.

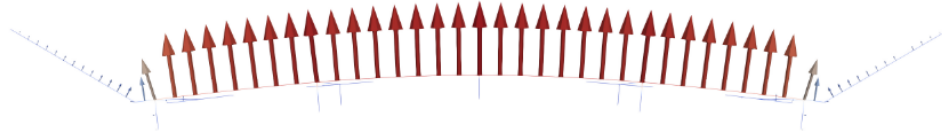


Figure 4 – Point forces on the deformed HX-HALE with 10-deg flare angle in forward flight.

The response to discrete gust is shown in Figure 5, where the root moments are shown for increasing gust lengths. As a reference, Figure 6 shows the same results for the original X-HALE configuration. It can be observed how the floating wing tips reduced the initial peak but then drive the dynamics of the aircraft resulting in overall larger load levels. This can be explained because the original X-HALE is a span-loaded vehicle, for which a constant gust is mostly absorbed by inertia relief. The redistribution of load that appears when the floating wing tip is introduced, results in larger stresses on the wing during the gust encounters.

3. T-TAIL HALE

The second platform is a simplified configuration of a very flexible solar-powered aircraft, which has been introduced in Refs. [9, 10], amongst others. This vehicle has around 32 m span, a total mass of 78.25 kg and a cruise speed of $U_\infty = 10$ m/s. Due to the relatively simplicity in its definition, it was chosen as one of the tutorials for SHARPy². As with the previous example, floating wing tips have been introduced on this model by Cheng [4] and a snapshot of the aerodynamic grid in a 1-cos gust encounter is shown in Figure 7. The hinge flare is parameterised by its angle with the streamwise direction as β . We refer to this model as the H²ALE.

Figure 8 shows the phase plot between the bending and torsion bending moments at the wing root for the H²ALE with $\beta = 10$ deg ('f10'). In this case, the gust length is fixed ($H = 15$ m) and the intensity (the maximum vertical velocity) of the gust profile is increased from 10% of the freestream to as much as $1.60U_\infty$. While this is an unrealistic condition, it helps to highlight the nonlinearities in the aircraft

²A sample python notebook is available at https://ic-sharpy.readthedocs.io/en/latest/content/example_notebooks/nonlinear_t-tail_HALE.html

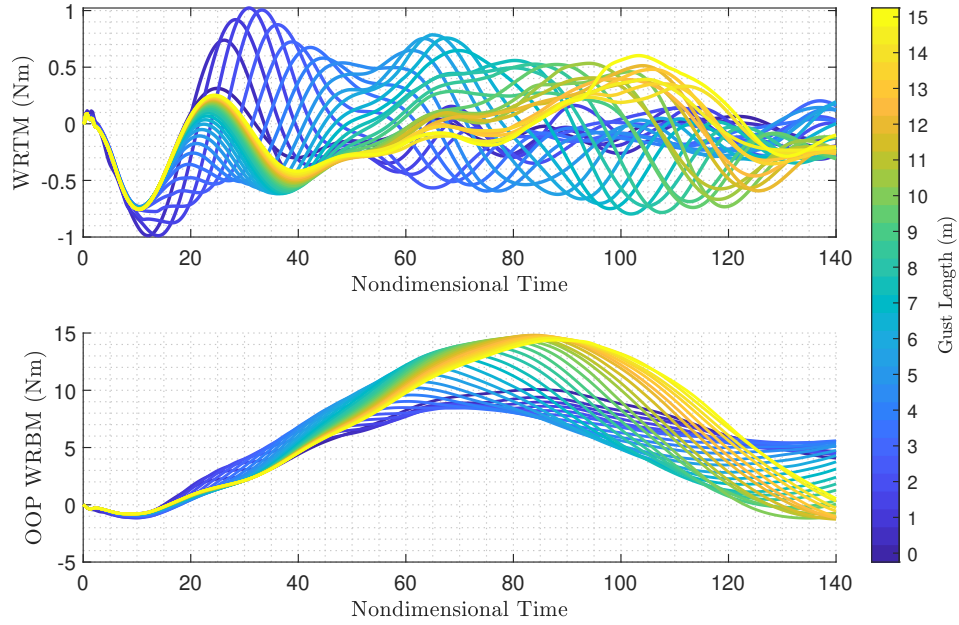


Figure 5 – Root moments (in Nm) for the HX-HALE with 10-deg flare for discrete vertical gusts of intensity $0.15U_\infty$ and varying lengths.

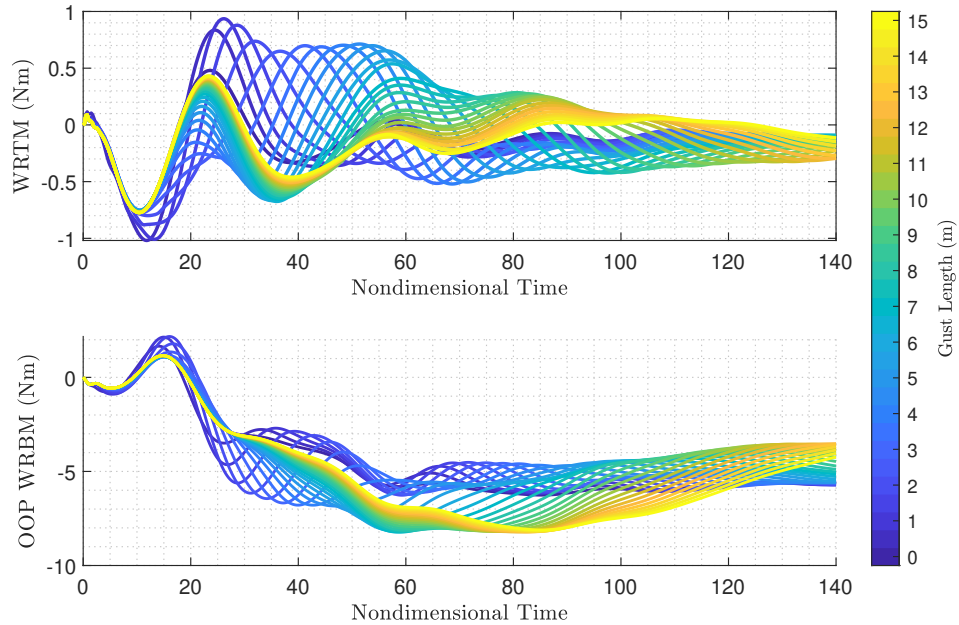


Figure 6 – Root moments (in Nm) for the X-HALE for discrete vertical gusts of intensity $0.15U_\infty$ and varying lengths.

response. The figure also includes two version of the original platform (denoted as the HALE) in which the outer wing either remains extended ('d00') or is rotated with with a fixed angle equal to 90 degrees ('d90'). Those configurations define two limit cases that seemingly bound the loads with the floating wing tips. Three main observations can be made from these results. Firstly, the floating wing tips produce a large alleviation in the steady loads with respect to the extended wing ('d00'). This can be seen in the shift towards the left between the ('d00') and ('f10') results in Fig. 8. The alleviation is of nearly 50% of the root bending moment in the equilibrium conditions. Secondly, the load reductions in the gust encounter are mostly in the wing-root torsional moment, which becomes

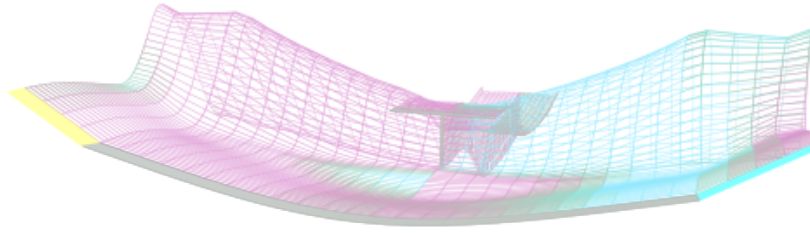


Figure 7 – Aerodynamic discretization of the T-Tail HALE with floating wing tips.

comparable to the wing with folded wing tips ('d90'). Finally, the nonlinearity in the response defines a load envelope that is not uniquely defined by the maximum gust intensity case. Intermediate values are necessary to identify the worst case of combined loading.

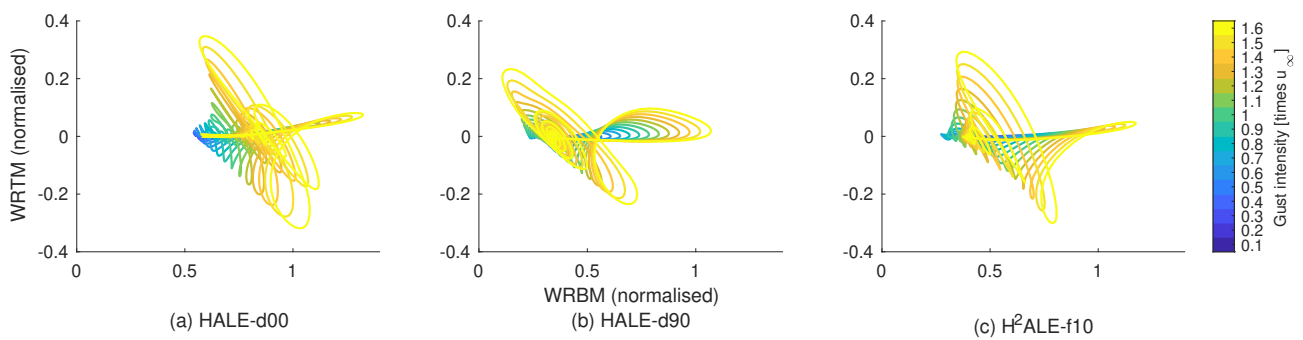


Figure 8 – Instantaneous values of normalised wing root bending and torsional moment over range of gust intensities, gust length = 15 m

It is also interesting to assess the wing tip dynamics under lateral gusts. This is shown in Figure 9, which shows the instantaneous hinge fold angle on both wings, for discrete lateral gusts coming from the port (left) wing. A fixed gust intensity of $0.5U_\infty$ is considered with multiple gust lengths. The amplitude of the response increases with the gust length within the range considered, but shows both a nonlinear response, and a strongly asymmetric response, and the larger swing on each wing occurs in a different phase of the response (corresponding to aircraft rolling to right and back, respectively).

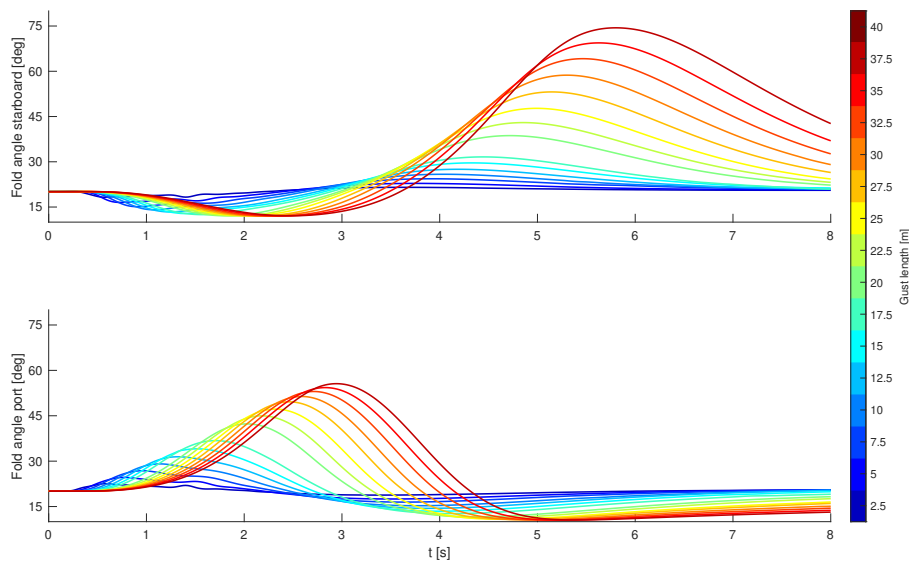


Figure 9 – Time histories of hinge fold angle port and starboard at various lateral gust lengths, gust intensity = $0.5U_\infty$

4. FLEXOP

The last platform is a modified version of the FLEXOP UAV [11, 12]. This is a 7-m span vehicle with a total mass of 65 kg that was built to investigate active flutter suppression strategies. The SHARPy model includes the original mass and geometry but has reduced stiffness constants to increase wing flexibility. We refer to the resulting aircraft configuration with 30% of the original stiffness as the SuperFLEXOP [6]. Figure 10 shows the aerodynamic surfaces in the UVLM model of this aircraft.

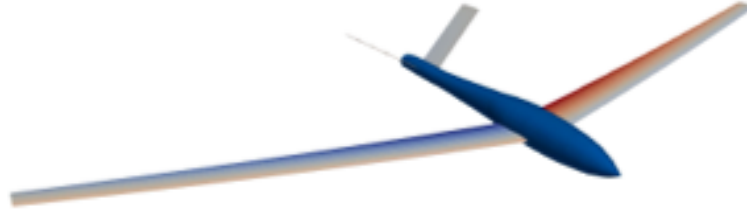


Figure 10 – SHARPy model of the FLEXOP UAV.

The open-loop response of the free-flying vehicle with $U_\infty = 45$ m/s to '1-cos' gusts is exemplified in Figure 11. The figure shows the instantaneous tip vertical displacement for vertical gusts of increased length (5, 10, 20, and 40 m, respectively) and intensity equal to $0.1U_\infty$. Dotted lines correspond to linear results, while continuous lines are for results including geometrically nonlinear effects. A very small difference between both modelling fidelities can be observed.

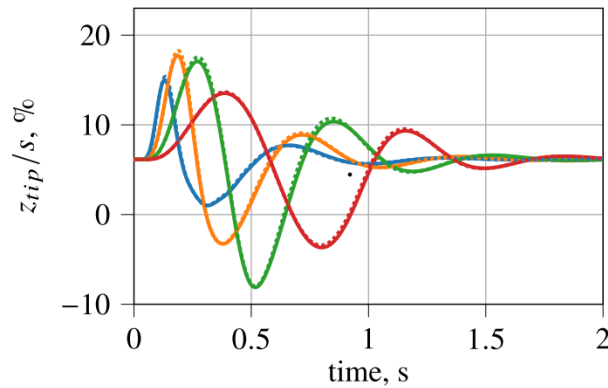


Figure 11 – Wing tip displacement of linear and nonlinear SuperFLEXOP model to discrete gusts.

A LQG controller is now designed using a reduced-order linear model defined in SHARPy around the static aeroelastic equilibrium conditions. The four trailing-edge control surfaces in each wing are deflected together and the wing tip displacement is used as a proxy sensor for the bending moments. Figure 12 shows the results on a vehicle clamped at the wing root for the same gust conditions considered above. The closed-loop results are obtained on both the full nonlinear model and the linearised model. A good load reduction is demonstrated without saturating the control surfaces. It is also interesting to observe that the small differences in the open-loop between the linear and the nonlinear model has been amplified in the closed-loop analysis.

5. Conclusions

Three full-vehicle aeroelastic models are presented for UAVs of different scales and complexities. They are used to illustrate the recent capabilities of the SHARPy solver to explore passive and active concepts for gust load alleviation in very flexible aircraft.

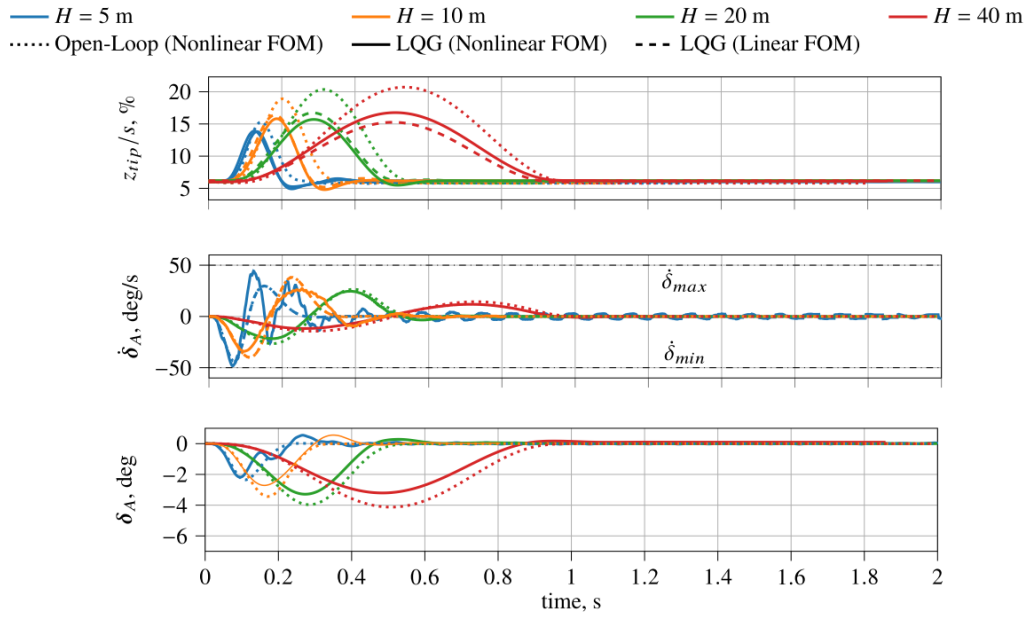


Figure 12 – Open and closed-loop response of the SuperFLEXOP model to discrete gusts.

6. Software and data statement

All simulations in this report have used SHARPy, which is available as open source under a BSD 3-clause permissive license at <https://www.imperial.ac.uk/aeroelastics/sharpy>. Test cases are all available at https://github.com/ImperialCollegeLondon/sharpy_tests.

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