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PARAMETRIC NONLINEAR FLUTTER ANALYSIS OF THE SEMI-AEROELASTIC HINGES DURING MANOEUVRES AND GUST ENCOUNTERS

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Abstract: A recent consideration in aircraft design is the use of semi-aeroelastic hinges, with the aim of enabling higher aspect ratio wings with less induced drag but also meeting airport gate limitations. Of particular interest is the concept of using in-flight free-floating wingtips in order to reduce aircraft gust and manoeuvre loads. On a previous work, a multibody formulation was introduced to account for finite rotations of rigid folding wingtips attached through flared hinges on a flexible airframe structure including aerodynamic follower forces for the folding wingtip components. This study uses the same formulation to investigate the effect of geometric nonlinearities on the aircraft aeroelastic stability. A time marching flutter analysis is used to depict how the stability of the aircraft varies during static and dynamic conditions like manoeuvres and gusts. It is shown that the aeroelastic stability of the aicraft is strongly influenced by the aicraft deformed shape leading to a reduction of stability the higher the tips coasting angles. Preliminary results show the emergence of unstable flutter mechanisms which have the tendency to become more and more unstable the higher the wing deformation and wingtip coasting angle. The aim of the paper is to show in which scenarios, such a degradation might be critical.

1 INTRODUCTION

Much effort has been made to design aircraft to optimize fuel consumption through the reduction of aerodynamic drag. A sizable contribution (usually 30–40%) to the overall drag is lift-induced drag, which could be reduced by increasing the wingspan, but such a design solution has well-defined limits imposed by the maximum aircraft dimensions allowed at airports, as well as the increase in bending moments along the wing. A possible solution to the first issue is the use of folding wings that can be employed on the ground, similar to the retractable wings used on aircraft-carrier-borne aircraft. The inclusion of such a design feature raises the question as to whether such a folding device could also be used to enable load reduction on the aircraft during the flight. Recent works [1, 2, 3, 4] have been aimed at studying the benefits of using a flexible wing-fold device for load alleviation and considering how it would be implemented on civil jet aircraft. It was shown that the orientation of the hinge line relative to the airflow is a key parameter to enable successful load alleviation. When the hinge line is rotated outboard of the streamline, folding the wingtip up introduces a decrease in the local angle of attack [1]; such an effect provides a means to reduce the loads acting on the wing, leading to the possibility of achieving a wingtip extension with limited or even minimal impact on wing weight. Previous works have demonstrated that a floating wingtip is necessary to maximise load alleviation performance [1]. However, zero hinge stiffness leads the wingtip to be deflected during

straight and level cruise flight due to the static trim loads and, furthermore, to a continuous oscillating motion due to unsteady aerodynamic loads. Such deflections and continuous motions are undesirable because they will be detrimental to aerodynamic performance and may lead to undesired rigid body dynamic motion. Ideally, the wingtip should not deflect during cruise, but should operate only once a significant gust is encountered or an high G manoeuvre is initiated. Such a concept is called Semi-Aeroelastic Hinge (SAH). During cruise, the wingtip is kept in place using a dedicated blocking mechanism. When a triggering event is detected, the wingtip is actively released, and the tip device then acts as a passive load alleviation system, which is purely driven by the aerodynamic and inertial forces. After the load event has finished, an actuator is engaged to bring the wingtip back to the initial clean configuration.
Previous works focused on the impact of the SAH on the loads, flutter stability [1, 2, 3] and handling qualities [4] of a typical commercial jet aircraft using a linear aeroelastic model. Such a modelling approach was based on the assumption of small wingtip deflections under static and dynamic loads. However, the numerical results have shown that the Folding Wingtips (FWT) could reach angles of 45 degrees and over. This raised the question of whether a linear aeroelastic formulation was appropriate for modelling floating wingtips.
Conti et al. [5] investigated the effects of geometric nonlinearities, due to large FWTs rotations, on the quasi steady aeroelastic response of a floating FWT. A nonlinear dynamic multibody formulation was developed to describe the kinematic of the aircraft and the two folding wingtips. However, the aerodynamic forces were introduced using a quasi steady formulation which is not suitable for gust response and dynamic stability analyses.
This formulation has been extended by Mastracci et al. [6] to introduce unsteady aerodynamic forces accounting for local tip geometric nonlinear effects. This opened the possibility to assess the sensitivity of the aircraft steady and unsteady aeroelastic response (including gust response, stability and limit cycle oscillations) to different parameters such as hinge orientation, tip mass and flight condition.
Experimental studies were conducted by Healy et al. in [7, 8]. The experiments demonstrated the aeroelastic static and dynamic behaviour of a wing with flared folding wingtips, confirming the trends reported in the numerical studies mentioned above.
The present paper uses the same formulation introduced in [6] to investigate the effect of geometric nonlinearities on the aircraft aeroelastic stability in operative conditions. A time marching flutter analysis is used to depict how the stability of the aircraft varies during static or dynamic conditions like manoeuvres and gusts. It is shown that the aeroelastic stability of the aircraft can be degraded by the increased wingtips coasting. Preliminary results show the emergence of unstable flutter mechanisms which have the tendency to become more and more unstable the higher the wing deformation and wingtip coasting angle.

2 NONLINEAR AEROELASTIC FORMULATION

A multibody formulation is introduced in order to account for geometric nonlinearities due to the FWTs finite rotations. Fig. 1 shows a simplified schematic of the physical system. The FWTs are modeled as rigid bodies connected through hinges to the main airframe structure. It is assumed that the local deformation of the FWTs are negligible with respect to the tips rigid body rotation around the hinges. The main airframe is modeled as a linearly flexible body in which rigid-body motion is not accounted. The related physical displacements are then defined via a set of mode shapes. The wingtips instead, are treated as concentrated masses, their dynamics is analytically represented solving the equations of motion in a hinge-oriented non inertial frame of reference. The interaction between main airframe and wingtips is accounted via the imposition of forces and displacements at the hinges.

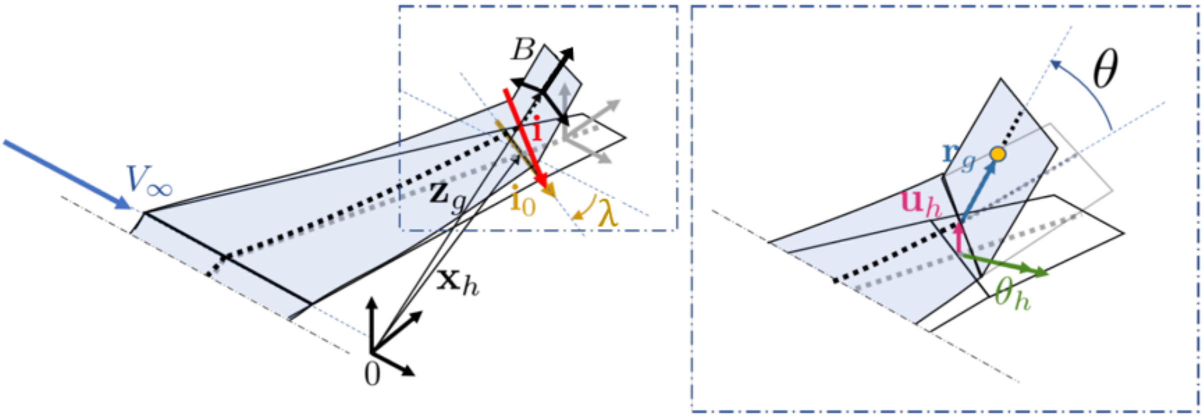

Figure 1: Simplified schematic of the aircraft/FWT assembly

The aeroelastic model is eventually completed with the addition of aerodyamic forces as described by the doublet lattice method (DLM). Such method is able to produce generalized aerodynamic forces taking as an input only the normalwash distribution of the aerodynamic mesh. A completely linear approach is used for the normalwash definition of the main airframe while the true, nonlinear, normalwash distribution is applied over the wingtips aerodynamic panels. A rational function approximation is required to describe such dynamic forces in the time domain. To account for geometrical nonlinearities, for each instant of time, the aerodynamic forces acting on the wingtips are projected onto the panels' actual position. For further details on the used formulation, please refer to [6].

3 NUMERICAL RESULTS

In this section, we present findings derived from the nonlinear model mentioned earlier. This formulation is implemented using Matlab&Simulink® based on a Nastran finite element model of a business jet.

Initially, the nonlinear model is compared to linear Nastran solutions to illustrate how geometric nonlinearities impact aeroelastic dynamic behavior. Subsequently, the model is utilized to demonstrate how aeroelastic stability varies with changes in the aircraft loading factor. Finally, an investigation is carried out to study the stability of the aircraft in a dynamic environment by observing how aeroelastic modes evolve over time when the aircraft experiences disturbances such as elevator inputs (e.g., manoeuvres) or gusts.

3.1 The impact of a steady loading onto the linear stability

The aeroelastic stability of the nonlinear model is compared to a linear Nastran solution (SOL145). In order to perform a comparable flutter analysis, the nonlinear model is linearized at various dynamic pressures (speeds) around a fixed undeformed aircraft shape, maintaining a constant Mach number.

Figure 2a presents the damping and frequency of the aeroelastic modes as a function of speed for both Nastran and the nonlinear model. In this case, the stability is studied around an aircraft shape with 0 degrees coasting angle. This comparison is a key evidence to validate the nonlinear code capability to study the stability of the aircraft, and the results show that both models yield consistent and comparable results when analysing the same aircraft conditions.

Figure 2b illustrates a similar flutter study, but this time using an aircraft shape with a 30 degrees SAH coasting angle. When the wingtips are deflected, an hard flutter coupling is present in the analysed range of speeds. This flutter mechanism is given by a coupling of the wingtip flapping and inner wing first in-plane bending modes. This mechanism emerges because, when the wingtip is deflected, the resulting vertical offset of the wingtip center of gravity enhances the coupling between wing in-plane bending and wing torsion. Such a coupling mechanism is strongly dependent on the deformed wing shape and thus it cannot be captured by the linear model which assumes a flutter analysis around the undeformed geometry. It is important to note that, as shown in Fig. 3, for the nonlinear model the wingtips, and thus the related aerodynamic panels, are rotated around the actual hinge axis, which is flared. Hence a positive coasting angle of the wingtip creates a pitch-down rotation of the aerodynamic panels. Whereas for the linear model, the aerodynamic panels can only be rotated around the global longitudinal axis due to the limitation introduced by the DLM Nastran formulation. Such a geometric effect leads the folding wingtip to generate a lift with a non zero x component in the case of the nonlinear model. Therefore, when the model is linearized around the deformed shape, the wingtip flapping mode would not only generate aerodynamic forces increments in z and y (as for the linear model) but also in x. This latter aerodynamic component is a key driver in the coupling between the wingtip flapping and inner wing in plane modes coupling, and thus plays an important role in the stability of the system.

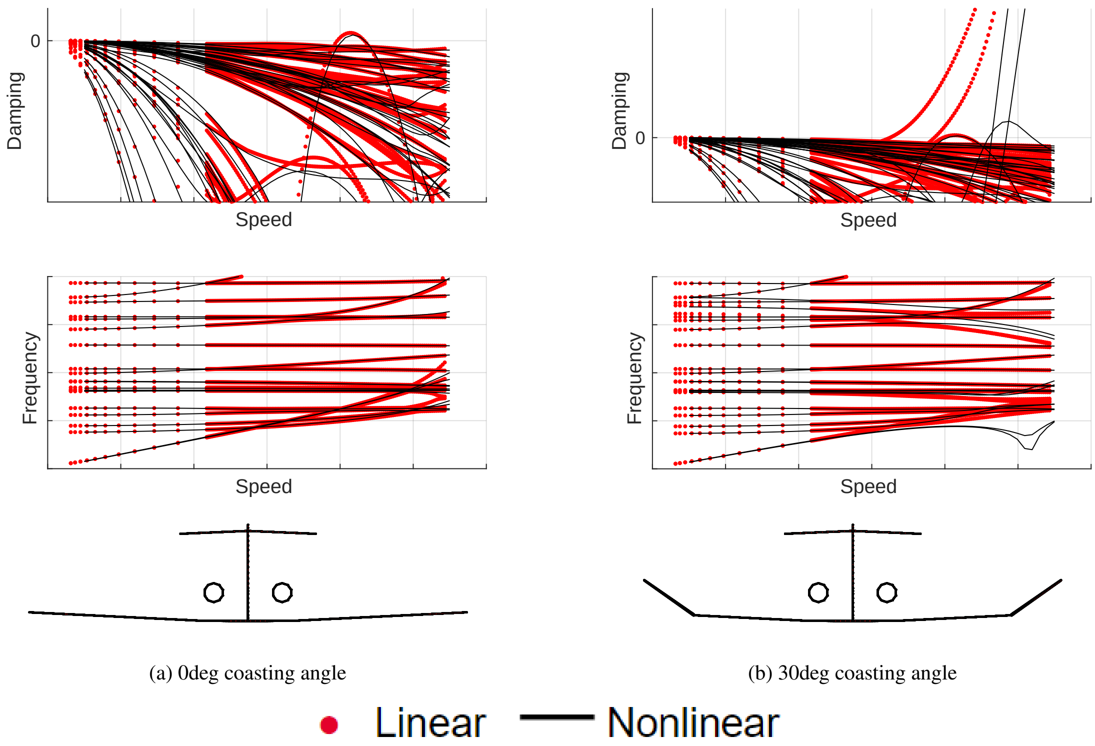

Figure 2: VG-VF Plots, comparison against Nastran

3.2 The trimmed flutter analysis

As indicated in the preceding paragraph, there exists a tendency for the aeroelastic stability of an aircraft to deteriorate when a non-zero SAH coasting angle is present. Previous works [6] show that the static coasting angle is bigger as the angle of attack increases. This prompts the question on whether a higher loading factor (which raises the aircraft angle of attack) could potentially induce flutter due to the amplified coasting angle.

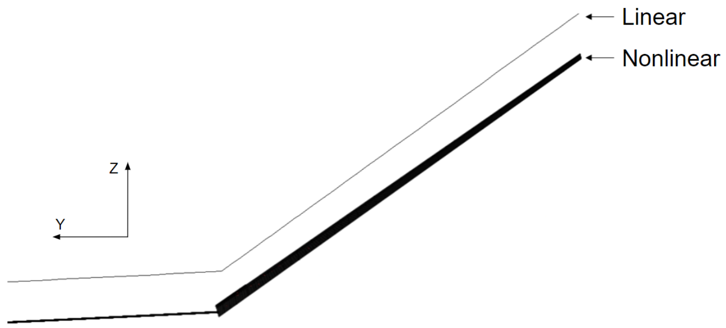

Figure 3: Comparison between the aerodynamic meshes of Nastran and the nonlinear model

In order to study such a condition a trimmed flutter analysis is required. To do so, for a given loading factor, the nonlinear model is trimmed and linearized about the trimmed condition at various dynamic pressures. When using this method, the aircraft's shape adjusts as its speed varies. Specifically, for a given loading factor, as dynamic pressure increases, the angle of attack needed for trim decreases, and the coasting angle decreases consistently.

Figure 4 reports the results of the trimmed flutter analysis for different loading factors. Damping and frequency of the aeroelastic modes is reported as a function of the speed, as well as the coasting angle at trim. The drawing represents the aircraft shape at a sample speed (not V^*). It is shown that increasing the loading factor, a new hard flutter mechanism appears. This mechanism is a coupling between wing modes and the wingtip flapping mode. Similarly to what introduced in the previous paragraphs, this interaction is created by the increased coasting angle and wing bending. Figure 5 reports the flutter speed drop due to the increased load factor.

3.3 The stability of the aircraft during a manoeuvre

The relationship between flutter and the coasting angle of semi-aeroelastic hinges, described in the previous paragraphs, might lead to a flutter event during a manoeuvre. Depending on the flight conditions, there may be instances where increasing the loading factor leads to instability of the aircraft.

For instance, if we examine a flight condition at speed V^* and 1G (as shown in Figure 4c, see also Fig. 5), initiating a 2.5G manoeuvre from this state will lead to a flutter condition. Such a finding leads to the introduction of the concept of a critical coasting angle, with the assumption that the coasting angle is the key parameter for the aircraft stability at a fixed speed. This critical angle corresponds to the stable wingtip angle at 1G and flutter speed. At this velocity, whenever the coasting angle exceeds this value due to external perturbations (such as manoeuvres or gusts), the aircraft may experience aeroelastic instability.
A simulation of this scenario is presented in Figure 6. In this time simulation, the aircraft is initially trimmed at 1G. An elevator input is then introduced to increase the load factor (NZ). The NZ is kept constant for a specific duration, after which the system is returned to its initial configuration. The aircraft aeroelastic response is calculated and, for each time step, a stability analysis is performed by linearizing the system about the current aircraft configuration. The stability analysis is reported as time histories of damping and frequency of the aeroelastic modes. By examining the time histories of frequency and damping, as well as the time history of the coasting angle, it becomes apparent that flutter is gradually developing as soon as the coasting angle exceed the critical value. However, stability is restored as soon as the loading factor is returned to 1G. The flutter onset is also visible in the time histories of coasting angle and loading

factor.

3.4 The stability of the aircraft during a discrete gust

As the coasting angle turned out to be the key parameter for flutter in the analysed wing configuration, it is important to understand what happens if the wingtip angle is varied due to a gust perturbation.
In all simulations proposed in this section, the aircraft is initially trimmed at V^* and 1G loading factor (see Fig. 4c) and then perturbed by a "1-cosine" gust profile. The aircraft aeroelastic response is calculated and, for each time step, a stability analysis is performed by linearizing the system about the current aircraft configuration.

Figure 7a reports the response of the aircraft to a medium length (compared to aircraft size) and light intensity gust. The time histories of damping and frequency of the aeroelastic modes, as well as the coasting angle and the gust profile are depicted. As shown by the results, with a small gust the coasting angle does not exceed the critical value, hence no positive damping (unstable aeroelastic modes) is seen in the damping plot, the aircraft does not develop a flutter. Figure 7b reports the response to a more intense gust. In the present case, the coasting angle crosses multiple times the critical value and for these instances a positive damping (unstable aeroelastic modes) is calculated. However, the time for which the coasting angle exceeds the critical value is very short, hence there is not enough time for a flutter to develop.

Figure 8 reports the sensitivity to various discrete gust conditions, to try to analyse different scenarios.

- Figure 8a shows a negative gust, tuned with the frequency of the flutter mode, is simulated. In this case, the dynamics around the excited frequency is lowly damped, and a periodic crossing of the 0 damping is visible in the response.
- Figure 8b depicts the response to a medium-length and high-intensity gust ($\sim$ 10 times higher than the prescribed value of CS25). Although some modes show positive damping during the excitation, no major flutter oscillation is seen in the coasting angle time histories.
- Figure 8c reports the case of a very long gust. As previously analysed, this case is important to understand if in a long gust there is enough time for a flutter to develop. In this case, the coasting angle does not exceed the critical value, mainly because with a slow excitation the aircraft naturally changes the pitch attitude. Also in this case, some modes are calculated to have a positive damping during the excitation, but no major flutter oscillation is seen in the coating angle time histories.

4 CONCLUSION

The here presented analysis was helpful to assess the possibility of experiencing a flutter degradation with increasing semi-aeroelastic hinge coasting angles.

This degradation is due to the presence of an hard flutter, mainly driven by the vertical offset of the wingtip with respect to the wing plane. The greater the offset, the stronger the coupling between in-plane bending and flapping modes, and this leads to a degradation of the flutter speed. This feature resulted to be very important in manoeuvres, where the increase of loading factor leads to a degradation of the stability margins. Conversely, it has been seen that a 1-cosine gust is not long enough to sustain an increase of coasting angle beyond the critical value long enough for the studied flutter coupling to develop.

The study also addresses the needs of having a nonlinear aeroelastic model capable of capturing geometric nonlinearities when studying the semi-aeroelastic hinges stability. The use of a trimmed stability analysis was also helpful in considering the right aircraft shape (equilibrium position) for each dynamic pressure.
Furthermore, this approach could be applied more broadly to highly flexible wings that experience significant displacements during trim conditions. It is worth considering that, similar to observations from the here presented model, static loading might impact the dynamic behavior of these very flexible wings, even when semi-aeroelastic hinges are not present.

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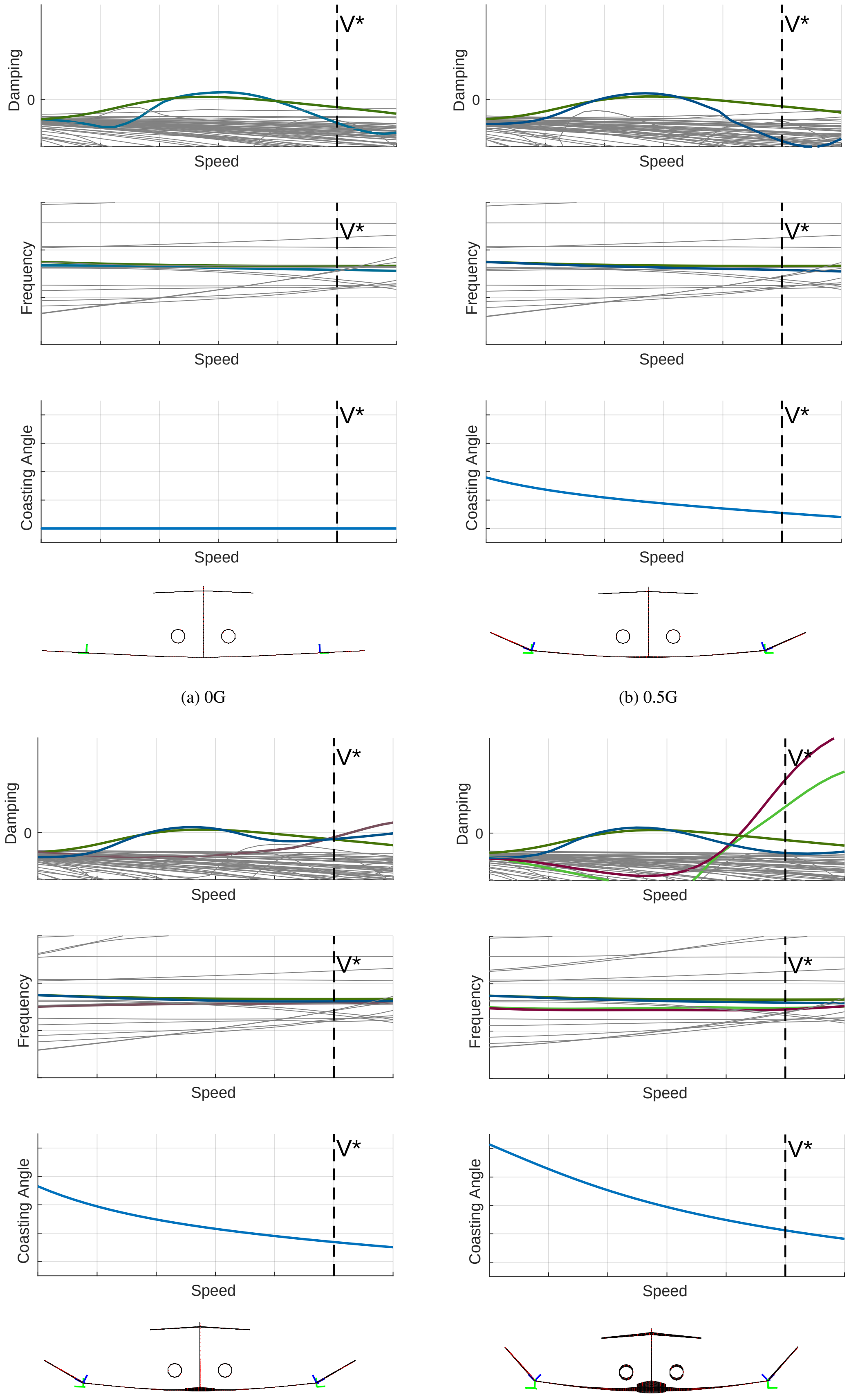


(a) 0G

(b) 0.5G

(c) 1G

(d) 2.5G

Figure 4: VG-VF Plots, trimmed flutter analysis

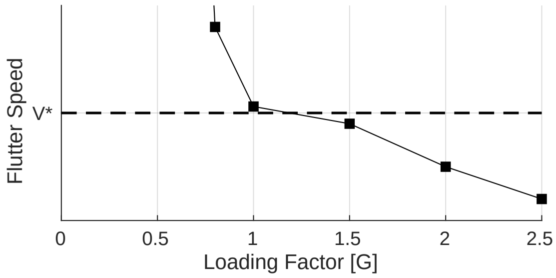


Figure 5: Flutter speed as a function of the loading factor

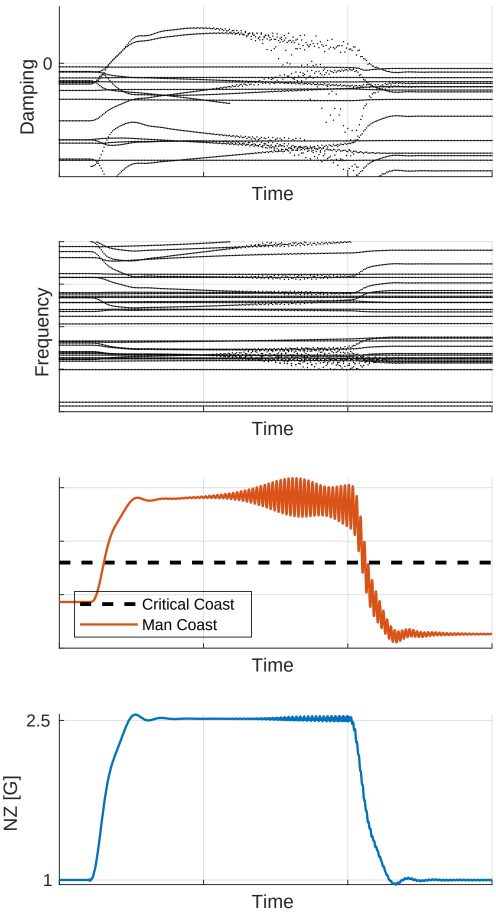
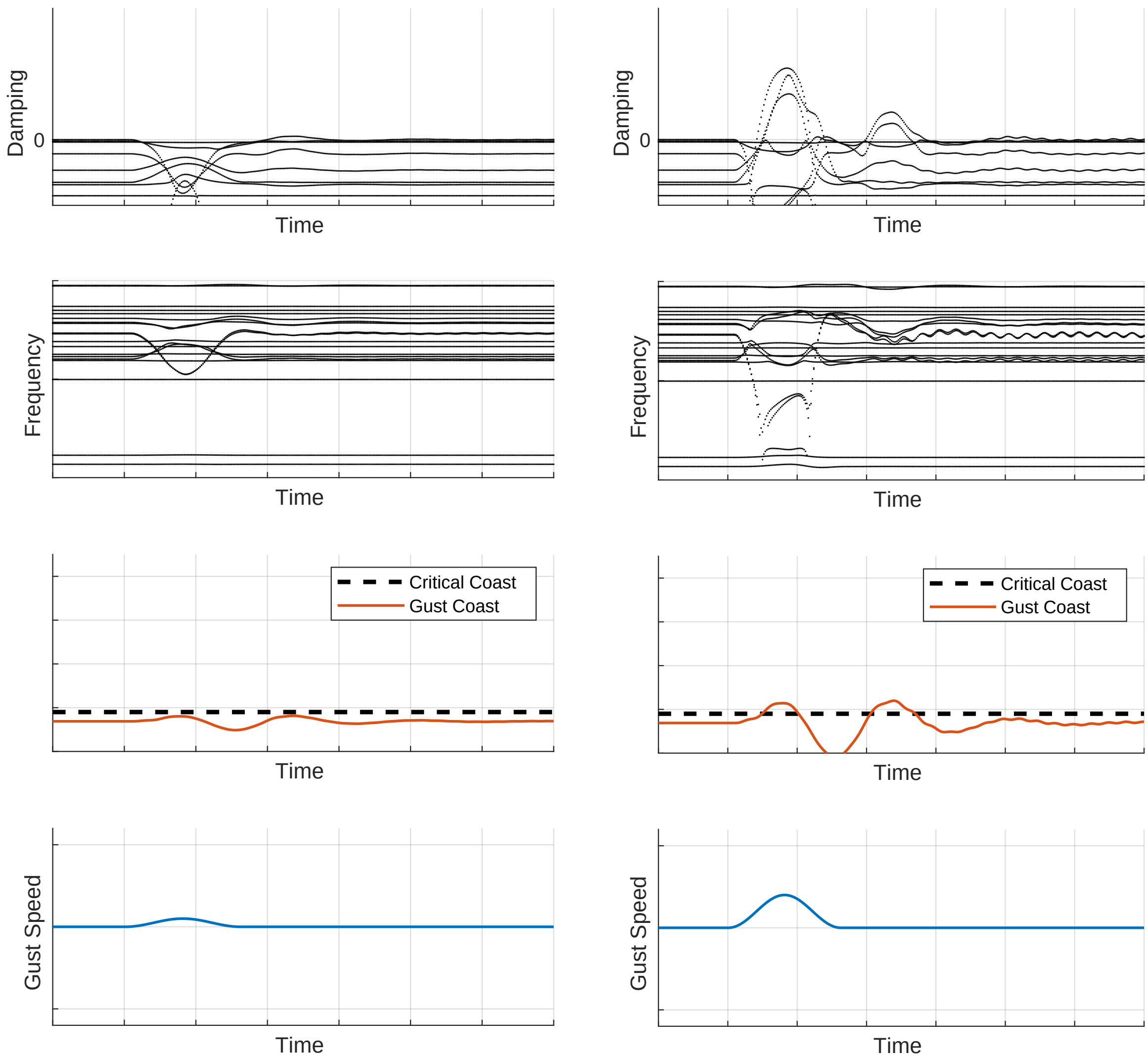


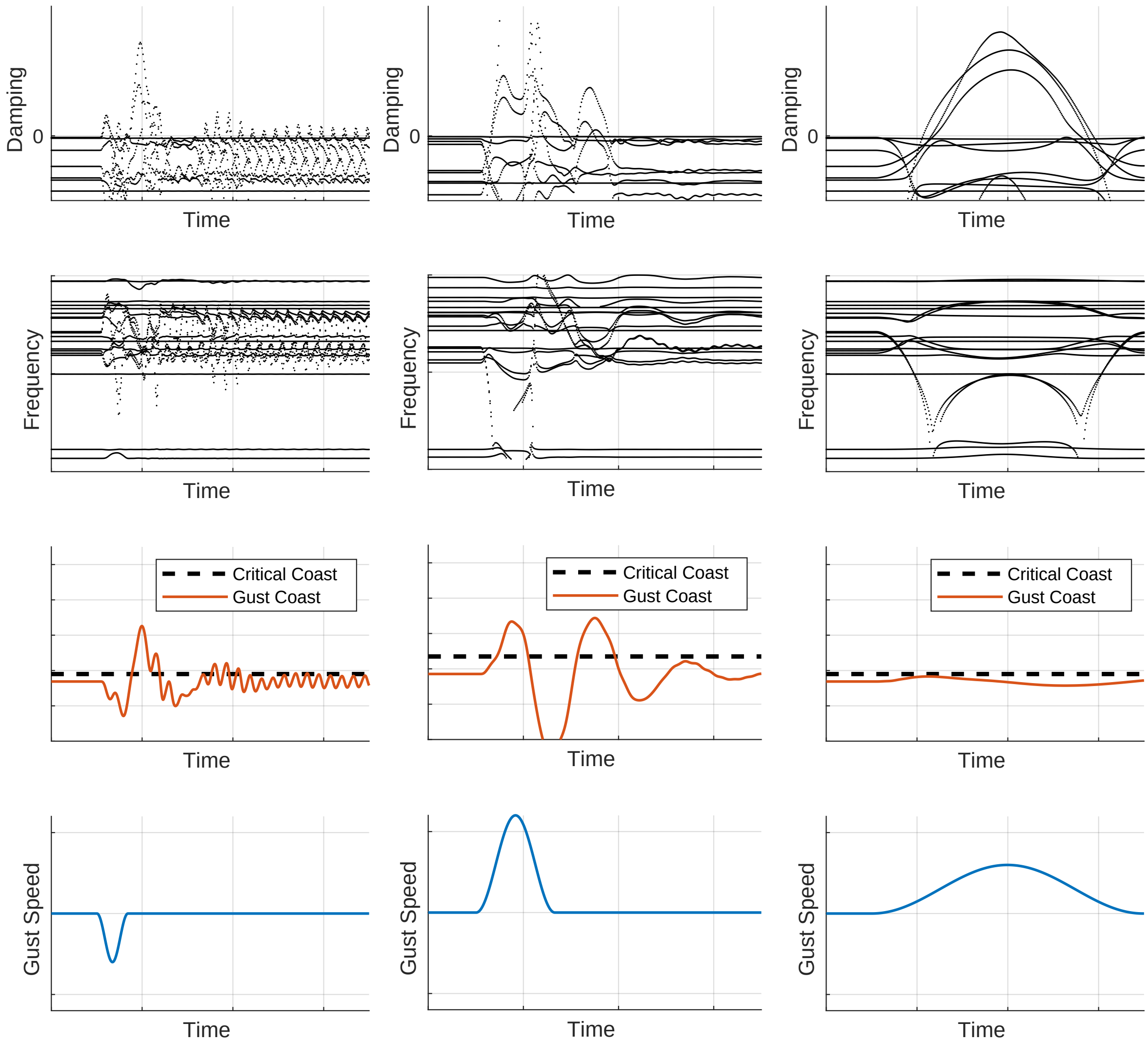
Figure 6: Flutter analysis during a manoeuvre



(a) Small intensity gust

(b) Large intensity gust

Figure 7: Flutter analysis during a gust



(a) Gust tuned on the critical frequency (b) Large intensity gust ∼10x CS25 value (c) Long gust

Figure 8: Flutter analysis during a gust