New insights on limit cycle oscillations due to control surface freeplay

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Abstract. A new experimental wind tunnel test-bed has been developed for the study of limit cycle oscillations induced by control surface freeplay. Studies of the effects of a single nonlinearity, made possible by the new horizontal tail plane, are described here. Several effects are considered, starting from a reference configuration: the effect of changes in inertia and stiffness, a time-varying gap size, and an aerodynamic preload due to an angle of attack. Both time marching simulations and describing functions analytical methods have been used to understand the experimental measurements and study the capability of the methods to capture the physical behavior. Good agreement was found in all cases and physical insights are gained from the mathematical models. Limitations of the analytical tools are also addressed, focusing on the important difference between the self-excited dynamics of the nonlinear system and its forced response to external excitations.

Introduction

Research on limit cycle oscillations (LCO) and other nonlinear aeroelastic mechanisms due to control surface hinge nonlinearities has gained significant traction since the 1990's. The drivers include the prevalence of the problem in many aeroelastic flight vehicle systems, the growing number of large dynamically actuated control surfaces where keeping tight tolerances on the freeplay over time can be demanding, the growing power of simulation capabilities (in computing hardware and the theory involved), and major developments over the last forty years or so in the area of nonlinear dynamic systems. The challenge has been known and tackled for years in analysis, simulation, as well as wind tunnel and flight tests. Recent reviews include [1], [2] and the technically thorough [3]. Those three sources cite many, if not most, of the works on control surface freeplay and on aeroelastic nonlinear behavior in the years prior to their publication, providing a state of the art view of the field.

An examination of the work done in this area so far reveals needs for more work in a few particular areas. First, the effects of time-dependent freeplay gap variation, the effects of interacting multiple local nonlinearities, and the effects of control / actuator freeplay on the active control of aeroelastic systems, including gust load alleviation and flutter suppression. Some research on interacting multiple structural nonlinearities has been reported over the years (see [4]–[9]). This area, however, still lacks sufficient experimental work.

Very little work has been reported on the time varying freeplay gap problem, and never in the context of an actuation failure [10].

Driven to cover by analytical and experimental work areas in which not enough research has been done to date, a new project was launched by the Politecnico di Milano (POLIMI) and the University of Washington (UW) to study realistic aeroelastic systems, representing real aircraft, and investigate the effects of multiple control surface hinge nonlinearities, time-varying freeplay gaps, a wide range of freeplay gaps from the very small to the large, and the effects of control surface freeplay on active flutter suppression.

A series of studies, using systems of increasing complexity, tackled first a system with a single nonlinearity and a constant gap size [11], then a system where the gap size was dynamically changing with time [12], and finally the same system subject to preload. Meanwhile, the development of a wind tunnel model of a full aircraft configuration, designed to have multiple nonlinearities, was carried out, and wind tunnel tests were performed in February of 2023. The work with the full-configuration wind tunnel model will be described in future papers. In the present paper, a review of the results obtained with the single nonlinearity system is presented. Building on the results previously presented previously by the authors, the effect of aerodynamic and mechanical preload on the LCO is investigated. Recent advances in the Describing Function (DF) technique are used to shed light on the phenomena observed in the simulations and in the test. The effect of gravity is discussed as a source of natural quenching of the nonlinear phenomena. Finally, the sensitivity of different systems to perturbations is established by studying the effects of different angles of attack of the lifting surface.

The results presented here for the case of single nonlinearity will be the base for the upcoming analysis and test results considering multiple nonlinearities.

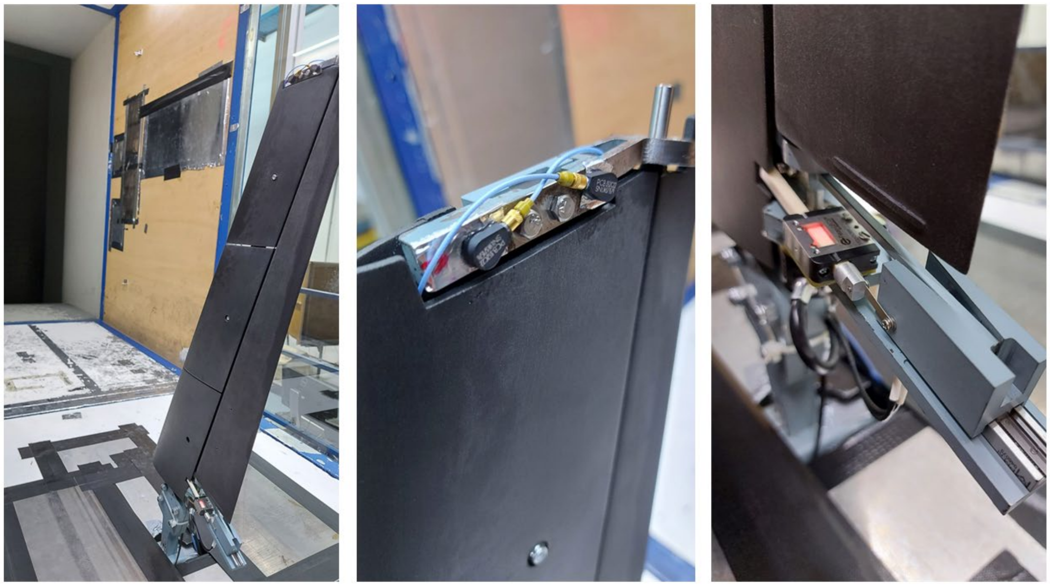

Figure 1: Photo of the test model, installed in the wind tunnel

Test models

The test model is the right horizontal tail of the modified X-DIA, with a nonlinearity in the elevator's hinge attachment rotation. The test model is shown above. At the root of the model a hinge nonlinearity-generating mechanism can be seen. A close up view of this mechanism is also presented. The model was designed to create an accurate freeplay gap, taking into account production and mounting tolerances, which can also be dynamically or statically varied. The gap-generating mechanism also allows for the accurate measurement of the hinge movement itself. The entire mechanism is held by two structural ribs, 18 millimetres apart. Both ribs host a radial bearing, which sustains the same shaft, glued to the elevator aerodynamic surface.

Selected results

As mentioned in the introduction, several studies have been performed to understand the effect of different parameters on the LCO. These include the effect of different gap sizes, different inertial and elastic configurations, time varying gap sizes, and different preloads. Here, as an example, the experimental measurements related to the effect of the angle of attack are reported. In figure below, the experimental LCO amplitude, computed as the RMS rotation, normalized by the gap size, is reported for various gap sizes and for two angles of attack (0.5° and 1.0°).

The angle of attack has the immediate effect of quenching the LCO in some conditions. By looking at the freeplay values for which LCO is completely quenched, it can be noticed that in a practical application, with a realistic gap size, the control surfaces that are usually at some angle of attack will often show no LCO due to this quenching effect. However, during maneuvers when the aerodynamic moment (and thus aerodynamic preload) disappears, LCO reappears, leading to vibrations that can range from the uncomfortable to dangerous.

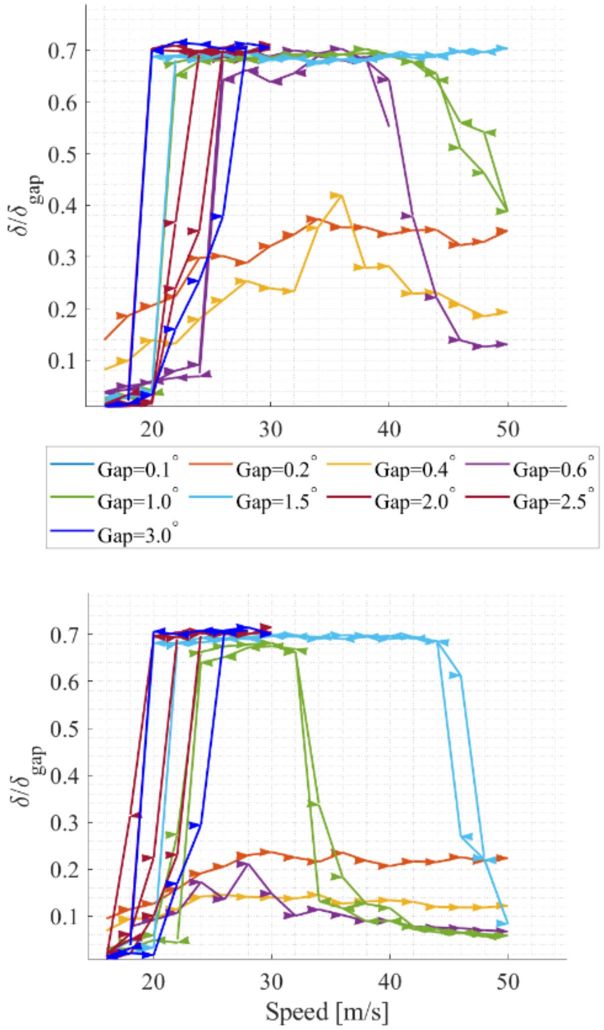

Figure 2: Effect of angle of attack on the LCO amplitude

With an angle of attack as small as half of a degree, LCO due to freeplay is quenched for freeplay gaps smaller than 0.4°, thus well within the limits imposed by regulatory agencies. In the middle of the plot it can be seen how the green and red curves are not overlapping with the others and are placed at a significantly smaller amplitude. This is signifying the disappearance of LCO and the start of a forced response movement of smaller amplitude due to external excitation.
An angle of attack of a degree quenches LCOs with a gap smaller than 0.6° and significantly limits the range of speed for which some larger gaps are creating the limit cycle oscillations. This is an important consideration for practical applications, but it must be approached with care. As previously mentioned, LCO can indeed develop with small gaps, including those within the regulations, if no angle of attack is present.

Relatively large gap values were also tested, up to a value of 3.0°. Due to the important vibrations transmitted to the main structure in those cases, the wind speed was limited to preserve the model integrity.

Summary

In this presentation, a comprehensive overview of the physics of limit cycle oscillations is provided. Several effects affecting the LCO amplitude and frequency are explored. The obtained conclusions will serve as a foundation for further work, exploiting a more complex system, with multiple nonlinearities.

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