

# Framework for Efficient and Robust Prediction of Freeplay Induced Limit Cycle Oscillations with Consideration of Preloading

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## ABSTRACT

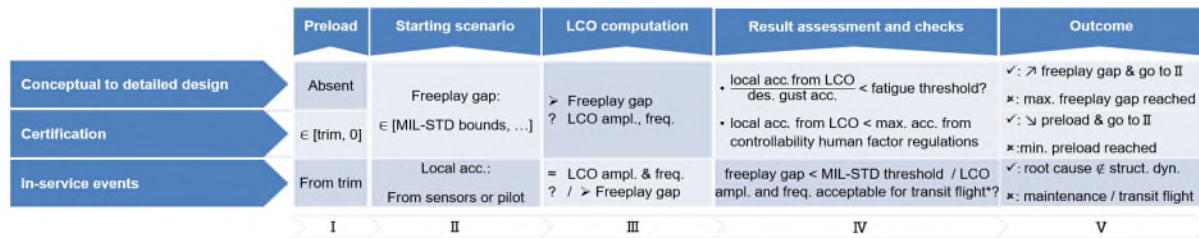
Backlash on worn actuation chains is a major challenge for design/certification, installation, and maintenance of aircraft moveable surfaces. Indeed, aeroelastic Limit Cycle Oscillations (LCOs), might take place at this off-design condition [2, Chapter 6]. Aeroelastic LCOs are dynamic instabilities arising from geometrical, structural, aerodynamic, or control system nonlinearities. LCOs may set in at smaller airspeed compared to linear flutter. Flexible structures undergoing LCOs feature stable, self-sustained, and bounded single harmonic sinusoidal motions. LCO effects include: i) fatigue life shortening, up to structural failure, if limit loads are exceeded; ii) discomfort / reduced controllability. Freeplay is a discontinuous nonlinearity on the actuator stiffness, and therefore a potential source of LCOs.

Certification specifications [4] require the minimum flutter speed for the linear nominal system (i.e., w/o freeplay) to be at least 15% larger than the dive speed, therefore outside the flight envelope. Because linear dynamic aeroelastic instabilities must be prevented by design, technology and standard work for flutter free systems are in place and industrialized. LCOs cannot be detected by linear flutter assessments instead, and might set in inside the flight envelope. The freeplay gaps allowed by certification standards are meant to admit at most negligible LCOs, if at all present. Indeed, the certification bounds for freeplay gaps range from  $10^{-2}$  to  $10^{-1}$  degrees, depending on the moveable surface. If the freeplay gap is proven to fulfill the certification specifications, no LCO assessment is prescribed. However, complying w/ certification thresholds requires complex and time/resource demanding procedures, from early design stages throughout the whole aircraft life cycle. If freeplay is outside the normative bounds, detrimental LCOs might take place, and must be assessed. The freeplay bounds can be relaxed (and installation maintenance and repair efforts importantly reduced) if the impact of LCOs on fatigue and comfort/controllability is proven to be safe. Technology to assess LCOs and demonstrate the feasibility of larger freeplay gaps is not mature for industrial application and is not part of the standard work yet.

The present work proposes a framework w/ methods, tools and process for aeroservoelastic LCO assessments on lifting and control surfaces, from early design through service, up to end of life. The framework deals with LCOs induced by freeplay at the present stage. However, its modular architecture enables any structural concentrated nonlinearity to be incorporated. Additionally, the framework can be easily extended to aerodynamic and control system nonlinearities. Figure 1

displays the framework process for the different design phases. Preload is excluded up to detailed design, as its absence is mostly conservative for the LCO prediction [1]. For certification, preload values between the trim angle and zero are considered. Stages II. to IV. are the same for certification and design phases. Freeplay is modelled on one moveable surface at a time. Multiple freeplay is less likely and left as an outlook to the present work. The workflow is executed for all linear flutter mass configurations and flight points. The freeplay gap is set to increasing values, starting from the military standard bounds. For the design phases, if fatigue (or limit load) thresholds are exceeded, or if local accelerations from LCO are beyond human factors bounds, then the maximum freeplay gap has been overcome. If both checks are negative, the process is executed again from stage II. For certification, if the checks are both negative, preload is decreased and the process is started from stage II. Otherwise, the minimum preload at the current freeplay gap has been reached.

For in-service events, the preload comes from trim recording/information in flight. Estimations of local accelerations come from pilot reports and human factors references. Freeplay gap is either known from backlash tests or estimated. Results are checked for certification limitations exceedance, after ruling out modelling weaknesses. If the freeplay is within thresholds, then the root cause of the event is unrelated to structural dynamics. Otherwise LCOs are checked for fatigue and structural damage, and aircraft maneuverability. Actuator replacement or transit flight clearance are mandated.



**Figure 1:** Steps of LCO assessment framework

The framework leverages three formulations for predicting (two-domain and three-domain) LCOs. see e.g. [3]. The frequency-domain Equivalent Linearization (EL) offers the highest computational speed but the lowest accuracy, making it suitable for initial LCO screening. Harmonic Balance (HB) is a trade-off between speed and accuracy for frequency-domain LCO assessments. The time-domain integration identifies chaotic and aperiodic behaviors but is computationally demanding. The synergistic use of these methods according to Figure 2 enables efficient flight envelope screening and detailed LCO assessments.

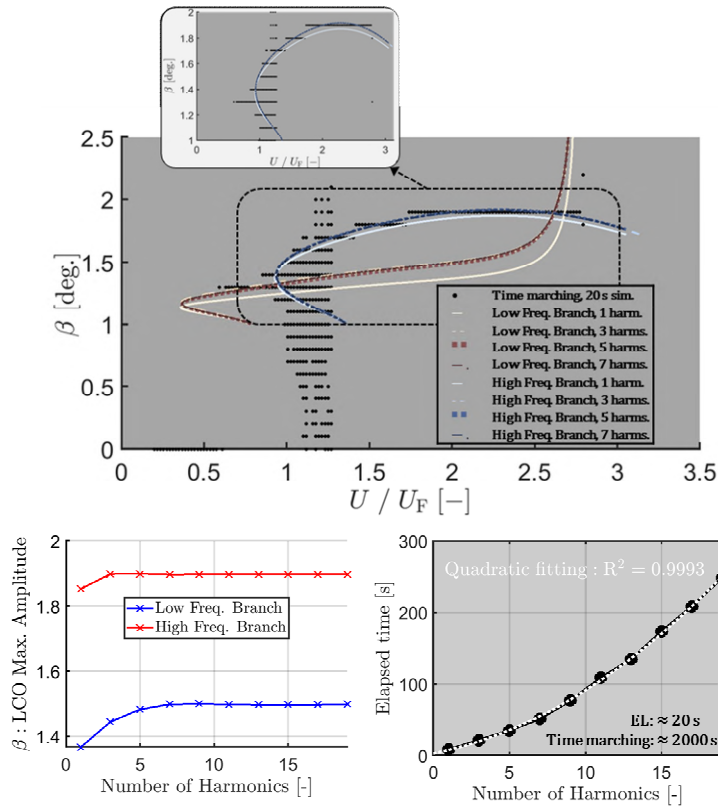
	Frequency domain		Time domain
Modules / Formulations	EL - Equivalent Linearization	HB - Harmonic Balance	Numerical integration of system ODEs
Functionality	LCO screening	LCO assessment	Identification of aperiodic / chaotic behaviors
Speed	■ ■ ■	■ ■ ■	■ ■ ■
Accuracy	■ ■ ■	■ ■ ■	■ ■ ■
Logical sequence	1	2	3 (w/ support of 1 and 2)
Conditional execution statement	--	LCO screening returns positives	LCO assessment returns coexisting branches

**Figure 2:** Formulations for LCO assessment process

These formulations, together with tailored numerical methods, were developed, verified and validated on a 2D typical section model, w/ plunge, pitch, and control surface degrees of freedom (DoFs). The robustness of the single formulations to various freeplay gaps and preloads was checked. Figure 3 is an example of these assessments for a scenario w/ freeplay on the control surface DoF ( $\beta$ ). The bifurcation diagrams of LCO amplitudes for the nonlinear DoF from time marching and HB<sup>1</sup> of various orders are displayed on the top. The HB convergence w/ increasing number of harmonics is shown on the bottom left. The time elapsed by harmonic balance versus the number of harmonics is displayed on the bottom right. The following is observed:

- Gap to time marching results decreases w/ increasing harmonic order
- Convergence is achieved w/  $\approx 7$  harmonics (for this scenario)
- HB elapsed time grows quadratically w/ number harmonics
- Time marching elapsed time is  $\approx 10\times$  HB wall clock time (and  $100\times$  EL)

<sup>1</sup> Pseudoarclength continuation w/ Euler prediction and Newton Raphson correction is used here.



**Figure 3:** Bifurcation diagram of control surface amplitude (top); HB order convergence (bottom left); elapsed time for HB computation versus harmonic order, and comparison to EL and time marching (bottom right).

These formulations will be extended to isolated wings and to full aircraft models w/ controller dynamics. Validation against high fidelity CFD-CSM and experimental data will be performed. The framework will be introduced into standard work, to relax freeplay gap bounds for certification. Directives for flight tests, maintenance, and in service events will be updated.

## References

- [1] Chen, P. C., and Lee, D. H. (2006, May 1 - 4). Flight-Loads Effects on Free-play Induced Limit Cycle Oscillation. 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference.
- [2] Dimitriadis, G. (2017). Introduction to Nonlinear Aeroelasticity. Wiley.
- [3] Liu, L., & Dowell, E. H. (2005). Harmonic Balance Approach for an Airfoil with a Freeplay Control Surface. AIAA Journal, 43(4), 802--815. DOI: 10.2514/1.10973
- [4] MIL-A-8870C (Ed.). (1993). Airplane strength and rigidity vibration, flutter, and divergence.