DEVELOPMENT OF AEROELASTIC PITCH-HEAVE WING TEST RIG WITH NONLINEAR DAMPER-FREEPLAY MECHANISM

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ABSTRACT

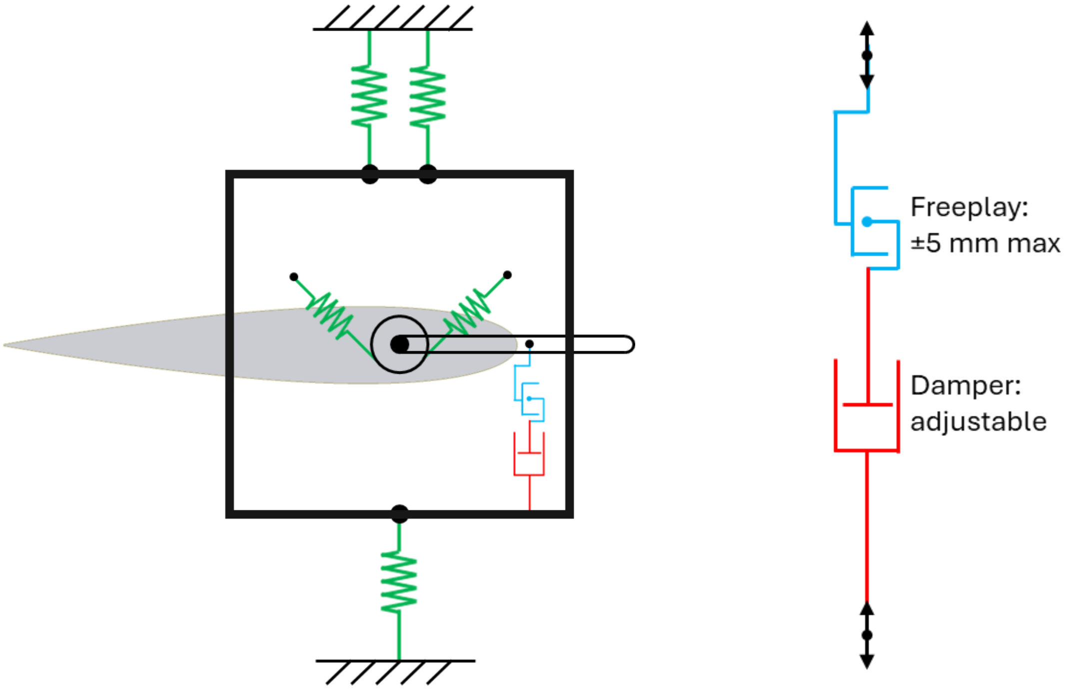
Freeplay nonlinearity is one of the most common and significant causes of limit-cycle oscillations (LCOs) and dynamic bifurcations in aeroelastic systems [1]. In aircraft wings, for example, freeplay can occur because of wear in joints and bearings of control surfaces, or failures in their actuation systems, causing dangerous dynamics. The assessment of the unwanted behaviour of the full aeroelastic system emerging from the presence of freeplay requires validated predictive models that can accurately simulate the complex nonlinear dynamics of system. However, accurate and robust experimental characterisation of such freeplay behaviour in laboratory-based aeroelastic tests remains challenging, primarily due to its intrinsic sensitivity to manufacturing clearance, dynamic hysteresis, and presence of experimental constraints such as friction, contact dynamics and damping nonlinearity.

This paper presents the development, characterisation, and preliminary testing of a novel heave-pitch wing-based aeroelastic rig [2] with a damper-based freeplay mechanism (see Fig. 1). The setup enables carefully controlled investigation to study the effects of freeplay size and damping on the nonlinear behaviour of the wing in both wind-off and wind-on conditions.

The development of the apparatus focuses on the establishment and validation of a complete and repeatable mechanical system from component-level behaviour to whole-system dynamics. This includes defining the required geometry and clearances for the adjustable freeplay, designing and validating the bracket layout through sizing and stiffness considerations, and ensuring that the damper's nonlinear response can be introduced into the pitch degree of freedom (DoF) conveniently, while introducing minimal additional changes or unwanted constraints to the baseline rig.

The freeplay apparatus is based on a modified commercially-off-the-self hydraulic damper, equipped with custom-designed mounting brackets that allow adjustable dead-zone size, enabling a range of freeplay from zero to ± 5 mm (see Fig. 2). The damper provides velocity-dependent energy dissipation and asymmetric response characteristics, which offers test conditions closer to real-world behaviour compared to conventional pin-hinge or spring-based configurations.

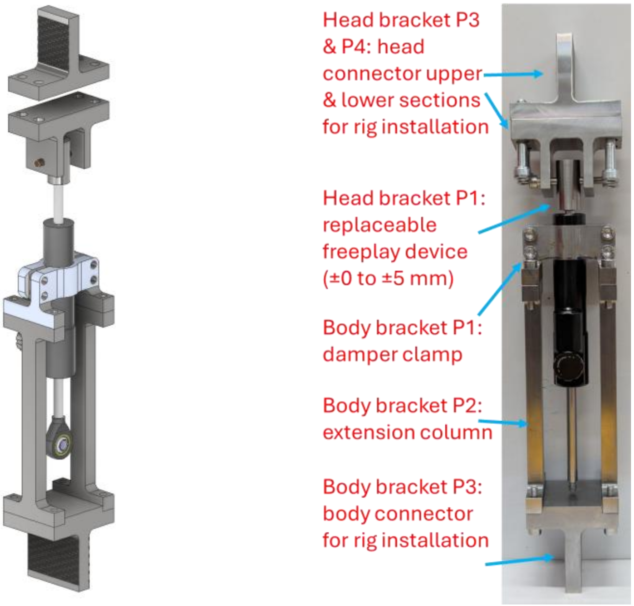
Tension-compression tests are performed using Instron Servo-hydraulic Fatigue Testing Systems to generate force-velocity diagrams in order to quantify the damping and freeplay behaviours, such as motion onset, hysteresis, initial stiction, and the nonlinear damping. These results establish a detailed mechanical characterisation of the designed system, which provides essential baseline parameters for subsequent numerical modelling and experimental testing.



(a) (b)

Figure 1: Schematic diagram for the 2DoF apparatus with the freeplay system: (a) the aeroelastic rig with the freeplay-damper, and (b) the damper-based freeplay mechanism.

To ensure the nonlinear damping and freeplay are introduced purely in the pitch DoF, the freeplay system is installed onto the aeroelastic rig following the arrangement shown in Fig. 3. The head bracket shown in Fig. 1 is used to clamp onto an existing handle arm connected to the central shaft of the rig. The body bracket is installed to an additional appendix plate attached to the side support plate of the rig.



(a) (b)

Figure 2: The damper-based freeplay mechanism: (a) CAD model, and (b) physical structure

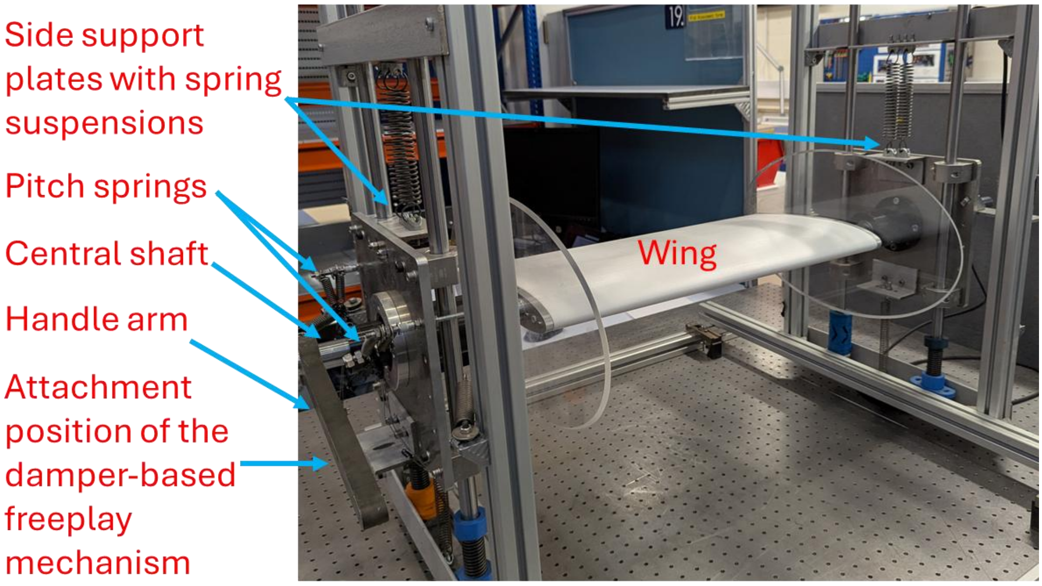
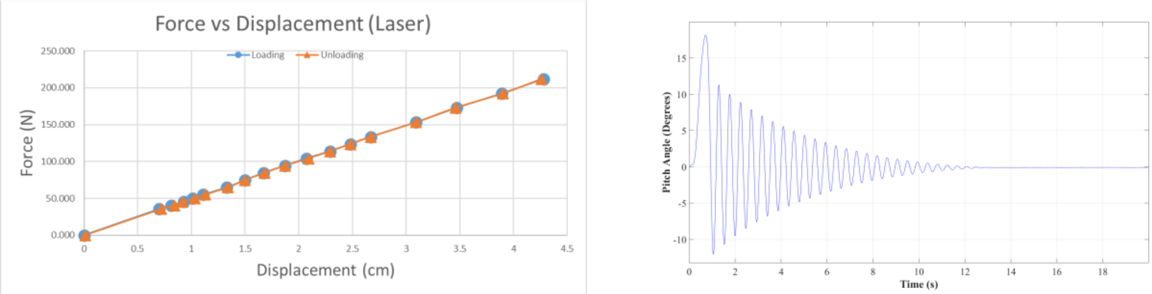


Figure 3: The aeroelastic wing apparatus.

To investigate how the freeplay system modifies the behaviour of the rig once installed, the study follows a structured set of identification steps. These begin with static and free response tests of the original rig in both heave and pitch DoF, which are repeated with the freeplay mechanism installed, allowing direct comparison of parameters before and after installation. This staged approach ensures that the influence of each substructure is fully understood before evaluating the combined nonlinear response.

More specifically, the static and free response tests are conducted to extract essential rig information including stiffness, damping ratios, and natural frequencies (see Fig. 3). The measured responses are useful not only to establish the underlying dynamic characteristics of the rig, but also to assess the presence of any other unwanted nonlinearity in the system.



(a) (b)

Figure 3: Baseline rig characterisation test without freeplay mechanism results: (a) static test in heave DoF, (b) free response test in pitch DoF.

The developed apparatus provides a mechanically robust, repeatable, and easily adjustable platform for systematic exploration of nonlinear aeroelastic phenomena, such as LCO onset, and the relationship between structural damping, stiffness, and freeplay effects at various wind speed conditions. The results will allow producing the bifurcation diagram for the various freeplay and damper parameters.

Future work will involve integration of the rig within a low-turbulence wind tunnel at the University of Bristol to perform free response and forced tests under aerodynamic loading.

Combined experimental-numerical studies will then be conducted to validate reduced-order nonlinear models and investigate transition mechanisms between small-amplitude oscillations and large-large LCOs in relation to freeplay size and damping nonlinearity.

References

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[2] I. Tartaruga, D. A. W. Barton, D. Rezgui and S. A. Neild, “Experimental bifurcation analysis of a wing profile,” in *International Forum on Aeroelasticity and Structural Dynamics (IFASD)*, Savannah, Georgia, USA, 2019.