NONLINEAR AEROELASTIC ANALYSIS OF ROTOR-STRUCTURE INTERACTION WITH PITCH-YAW FREEPLAY

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ABSTRACT

Rotor-nacelle systems can be susceptible to aeroelastic instabilities, such as whirl flutter, which arise from complex interactions between aerodynamic forces, structural flexibility, and gyroscopic effects. These instabilities are further influenced by structural and aerodynamic nonlinearities, making their prediction and control particularly challenging. Whirl flutter, in particular, can lead to severe structural fatigue and even catastrophic failure in propeller-driven aircraft, underscoring the need for accurate modelling and experimental validation. Historically, most of research efforts have concentrated on predicting the onset of whirl flutter using linear methods, which often fail to capture the full spectrum of nonlinear behaviours observed in practice. Some recent developments have introduced experimental rigs - such as ATTILA [1], the Maryland rotor rig [2], W-Wing [3], and Bristol early experimental test rigs [4,5] - primarily aimed at validating linear stability predictions and measuring modal characteristics in the stable region or near the flutter boundary. However, these studies have largely overlooked the influence of nonlinearities, which can significantly alter stability margins and dynamic response regimes.

This paper presents a numerical investigation of the nonlinear dynamics of newly developed **Bristol Whirl Flutter Rig (BWFR)**, designed for experimental testing in the Bristol University Vertical Wind Tunnel, see Fig.1(a). The analysis focuses on the role of **freeplay nonlinearity** in the pitch and yaw degrees of freedom, which introduces discontinuities in stiffness and fundamentally changes the aeroelastic response. Unlike previous studies that emphasize linear stability or explored nonlinear whirl flutter of a theoretical model, this work explores how freeplay modifies stability boundaries, induces bifurcations, and triggers complex oscillatory behaviours of a physical experimental rig. The BWFR is modelled as a two degree-of-freedom system comprising a spinning propeller powered by a small motor and mounted, via a rigid shaft, on a universal joint (see Fig.1(a)-(b)). The rig is modelled in a vertically suspended configuration to replicate the physical setup and eliminate asymmetric gravitational effects. The investigation employs a combination of **time-domain simulations, frequency-domain analysis,** as well as **advanced continuation** and **bifurcation techniques** to map stability landscapes and identify nonlinear bifurcation points. Parametric studies are

conducted across a range of rotational speeds, wind speeds, freeplay gaps, and stiffness configurations to assess the topology of the underlying bifurcation diagrams.

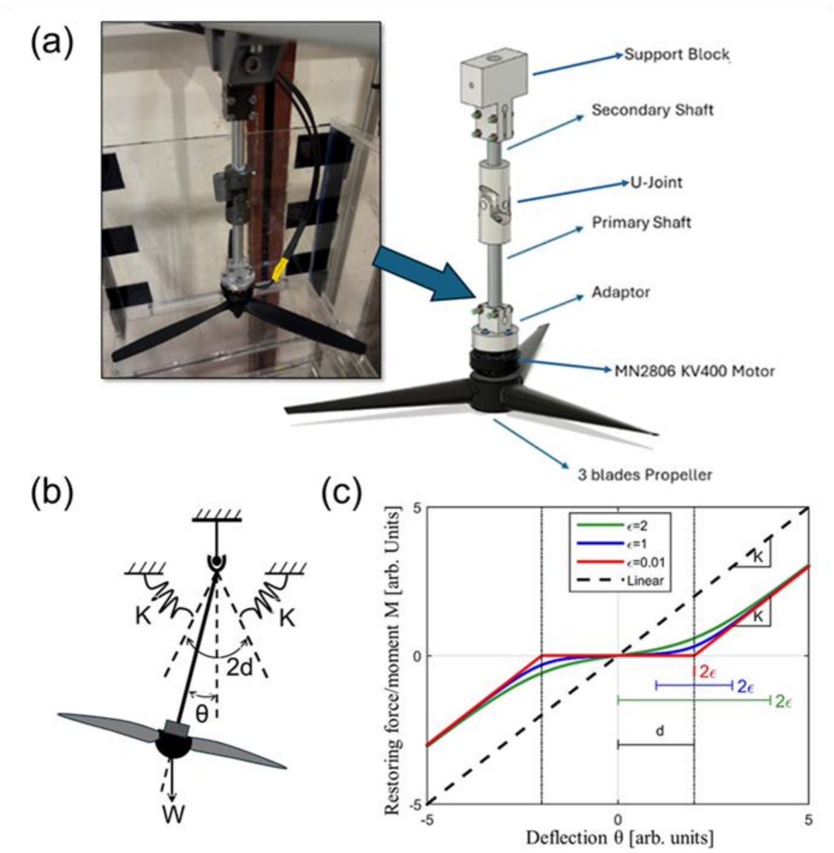

Figure 1: (a) The Bristol Whirl Flutter Rig (BWFR), (b) Schematic of the BWFR model, (c) Sample freeplay stiffness profiles.

The freeplay in stiffness is modelled using an arctangent function, with a tuning parameter ε controlling the turning radius at the edges of the deadband (Fig. 1(c)). More details of the freeplay model can be found in our previous works [6]. The initial results reveal that freeplay nonlinearity significantly alters aeroelastic stability. Even small freeplay gaps destabilize regions previously considered safe under linear analysis, inducing whirl flutter and generating multiple equilibrium states (see Fig. 2). The system exhibits transitions through saddle-node and Hopf bifurcations, leading to **limit cycle oscillations (LCOs)** of varying amplitude and frequency. These nonlinear effects highlight the inadequacy of conventional linear prediction methods and emphasize the necessity of incorporating nonlinearities into the design.

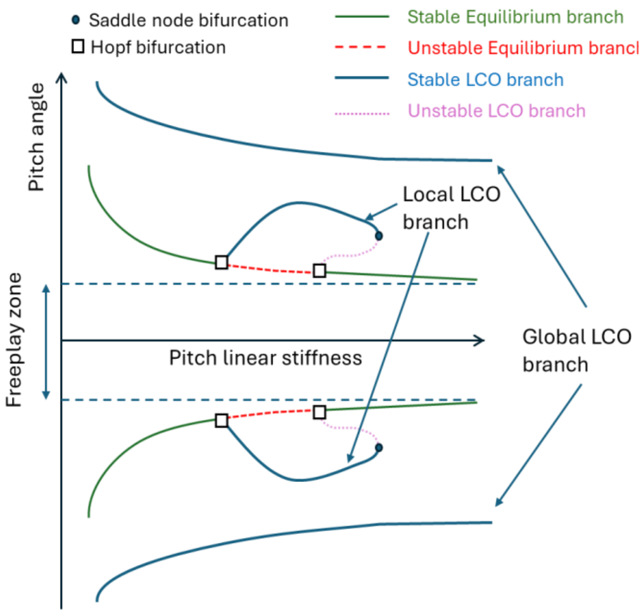

Figure 2: Typical bifurcation diagram for a basic whirl flutter model with a freeplay in pitch.

The findings provide critical insights for guiding the design of the BWFR and similar experimental rigs. By deliberately introducing and controlling freeplay, the rig can be tuned to exhibit rich nonlinear dynamics within the constraints of physical testing, allowing a systematic exploration of phenomena such as multi-stability which is essential for validating advanced nonlinear aeroelastic models. Furthermore, the study establishes benchmark data for future experimental campaigns and contributes to the development of robust prediction tools for rotor-nacelle systems operating in nonlinear regimes. The full paper will present the detailed results and associated discussion of the nonlinear analysis.

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