UNCERTAINTY QUANTIFICATION IN AUTOMATED MODAL SHAPE SENSING OF A HIGH-ASPECT-RATIO WING

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ABSTRACT

Monitoring the evolution of modal parameters during flight is essential for detecting changes induced by varying operational conditions or by deformation. The latter becomes particularly important for high-aspect-ratio wings, whose increased flexibility leads to pronounced deformation and stronger modal variations. Since these modal changes are tied to the underlying displacement field, obtaining an accurate online estimate of the structural shape is very beneficial for assessing the modal properties of aeroelastic systems. The displacement reconstruction of wing-like structures based on strain, commonly denoted as shape sensing, enables the monitoring of the deformation state whenever a direct measurement is not feasible. Among the available approaches, modal shape sensing superposes displacement mode shapes using modal coordinates obtained from a regression of measured in-situ strain against strain mode shapes. Given that the selected modes represent the actual deformation state, this method has proven efficient and accurate, especially in view of the limited number of required strain measurements.

Both numerical mode shapes computed from a finite element model or mode shapes obtained from experimental testing can be employed in the shape sensing; a hybrid combination is possible as well. Using experimentally identified modes is promising in applications where the relevant modes of the structure and their changes with respect to different deformation states are monitored continuously during operation, and local strain measurements are available in parallel. This is the case in wind tunnel or flight test scenarios close to the dynamic stability boundary [1].

In contrast to their numerical counterparts, experimental modes inherently reflect real boundary conditions, structural imperfections, and operational variability including non-linear effects which are present in real flight test data but not captured in linear simulation models. This potentially leads to more accurate displacement estimations. On the other hand, identification results inevitably exhibit variability due to sensor installation tolerances, measurement noise, and scatter caused by linear identification techniques applied to non-linear and time varying aeroelastic systems like aircraft in flight. The measured strains are also subject to uncertainties. To account for this, the uncertainty of the estimated displacement due to mode shape and strain variability has been investigated in [2].

Present research applies the aforementioned uncertainty quantification on measurements conducted on a high-aspect-ratio wing (AR=17) which is clamped to a structural dynamics test rig (cf. Fig. 1). The wing exhibits a length of 5m and features sweep and taper; it is instrumented with 33 uniaxial accelerometers and 20 strain gauges. Using an electric motor, static forces can be induced to the wingtip via load frames to deform the wing. A draw wire displacement sensor is attached at the tip that serves as a reference for the shape sensing estimates.

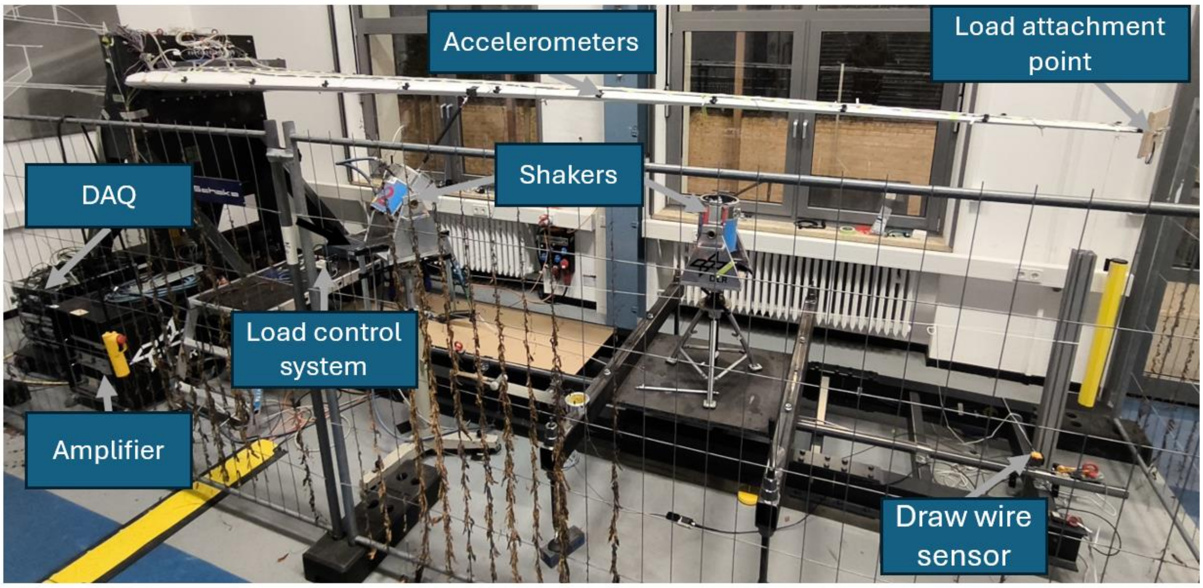

Figure 1: Experimental setup

The experimental uncertainty quantification is carried out as follows. Under broadband random excitation from an electrodynamic shaker, the response signals of the sensors are used to identify displacement and strain mode shapes relevant to the shape sensing at different deformation states. Using the DLR online monitoring toolbox (OLM), the identification is accomplished based on a sliding time buffer and modes are newly identified every few seconds. By means of a mode shape buffer from consecutive identifications, the variability of both displacement and strain mode shapes is determined and then propagated through the modal shape sensing method according to the methodology presented in [2].

With this approach, not only are the displacements estimated at any given point in time, but an indication of the uncertainties of this estimate is also provided. In the scope of the OLM, parameters such as the time buffer length and the number of modes in the mode shape buffer can be varied to investigate their impact on the uncertainty of the displacement output. Furthermore, the accuracy of the shape sensing and the uncertainty trends can be studied under various deformation levels.

The demonstrated capability to derive displacement estimates together with their associated uncertainties under realistic boundary conditions emphasizes the maturity of the proposed approach for application in wind tunnel and flight testing. In such environments, where both deformation levels and modal characteristics evolve during operation, the combined use of in-situ strain data and continuously updated operational modes enables reliable tracking of modal parameter changes and the detection of possible modal coupling attributed to wing deformation. This offers a pathway for more insight when monitoring the aeroelastic behavior of increasingly flexible wing designs anticipated in future aircraft configurations.

[1] Volkmar, R., Soal, K.I., Govers, Y., and Böswald, M. (2023). Experimental and operational modal analysis: Automated system identification for safety-critical applications. *Mechanical Systems and Signal Processing*, **183**(109658).

[2] Gundlach, J., Böswald, M., and Sodja, J. (2025). Uncertainty quantification for the modal shape sensing of structures undergoing geometrically non-linear deformation. *Mechanical Systems and Signal Processing.* **239**(113249).