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# Developing a reduced order model from structural kinematic measurements of a flexible finite span wing in stall flutter

Ethan C.E. Culler [a], Casey Fagley [b], Jürgen Seidel [b], Thomas E. McLaughlin [b], John A.N. Farnsworth [a,*]

[a] Aerospace Engineering Sciences Department, University of Colorado Boulder, Boulder, CO 80309, United States
[b] Aeronautics Research Center, Department of Aeronautics, United States Air Force Academy, USAF Academy, CO 80840, United States

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ABSTRACT

Experiments were conducted on a flexible, finite-span cyber–physical wing model in the wind tunnel to study the structural kinematics for a wing undergoing stall flutter. The wing model was designed to be weak in torsion and stiff in bending to exhibit stall flutter oscillations. The physical deformation of the wing surface was mapped at 38%, 58%, 78%, and 98% span using a stereo vision motion tracking system. From these measurements, the wing motion is decomposed and shown to consist of a principally torsional (pitching) oscillation consistent with the first mode for a cantilevered beam in free vibration. A two equation empirical model of the wing motion was then developed and compared to the measured stall flutter motion.



## 1. Introduction

Designers are increasingly utilizing high aspect ratio wings in wind turbines, Unmanned Aerial Vehicles, high efficiency piloted aircraft, and High Altitude Long Endurance (HALE) aircraft. The choice to utilize high aspect ratio wings is driven in part by the increased aerodynamic efficiency that high aspect ratio wings can provide due to their lower induced drags. Unfortunately, in conjunction with these efficiency gains, there can be a significant decrease in structural robustness due to increased wing flexibility and the larger aerodynamic moments acting along the span of the wing. These two factors couple to increase the structure's susceptibility to large deformations, oscillations, and flutter. For an example of the types of catastrophic fluid structure interactions (FSI) which can occur in flexible, high aspect ratio wing structures, simply consider the NASA Helios prototype which was destroyed over the Pacific Ocean after encountering unexpected turbulence (Noll et al., 2007).

To mitigate these damaging FSI instabilities and improve the performance of future aircraft systems, a novel research program has been undertaken to investigate the viability of aerodynamic flow control as a method for suppressing unstable aeroelastic excitation in wing structures. In order to apply closed-loop control, the wing motion must be well understood so that deformations can be predicted in-situ. The wing structure utilized in this program is modeled experimentally using the cyber–physical system developed by Fagley et al. (2015, 2016). The investigation reported here focuses on capturing and modeling the structural kinematics of the cyber–physical wing system when excited in a stall flutter type motion for a flexible, finite span wing.

Flutter is an aeroelastic instability that results from the coupling of a wing's structural mechanics with its aerodynamics. This coupling can result in sustained wing vibrations with an amplitude that either stabilizes into limit cycle oscillations

* Corresponding author.
*E-mail address:* john.farnsworth@colorado.edu (J.A.N. Farnsworth).

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(LCOs) or diverges until structural failure occurs. In subsonic flows two types of flutter are generally considered: classical and stall, with the primary difference between them being the existence of flow separation.

Generally wing motion can be characterized as structurally vibrating in either a bending mode, a torsional mode, or some coupling thereof. Note that these motions are equivalent to aerodynamic plunging and pitching, respectively. In classical flutter, these two structural modes couple together to induce greater wing deformations and thus a large positive feedback to the system. As a result, classical flutter is generally initiated from small amplitude disturbances at small angles of attack where the flow is fully attached over a wing section. In this region, linear models of the wing's aerodynamic response are adequate and often used in predicting flutter (Theodorsen, 1934).

In stall flutter, as suggested by the name, the wing stalls and the flow becomes separated from the wing surface producing an inherently nonlinear response (Dowell, 2015). Generally, stall flutter is associated with large changes in angle of attack occurring in a periodic or cyclic fashion which produces an aerodynamic response akin to dynamic stall in rigid bodies. For the wing to exhibit this cyclical stalling behavior, the structure is most typically excited in a purely torsional or pitching mode to produce the large changes in angle of attack. Furthermore, the existence of stall at large angles of attack produces a dramatic loss in lift that can work to limit the amplitude and growth of the oscillations allowing them to stabilize from cycle to cycle in repeatable LCOs. From an aerodynamic controls perspective, these LCOs present a logical starting test-bed as they provide an experimentally repeatable phenomenon with an identified mechanism to target and control, i.e. flow separation.

A review of the literature shows a large body of previous work discussing the stall flutter problem, however in much of this work two dimensional rigid, non-deforming, wing models have been tested (Halfman et al., 1951; McCroskey, 1981; Ekaterinaris and Platzer, 1996; Dimitriadis and Li, 2009; Razak et al., 2011). Furthermore many of these studies utilized sinusoidal, motor driven oscillations of these rigid models as a paradigm for studying "free", aeroelastically driven, stall flutter (Halfman et al., 1951; McCroskey, 1981; Ekaterinaris and Platzer, 1996). In reality, aircraft wing structures are three dimensional and will deform in a spanwise varying fashion that can be expected to introduce gradients along the fluid–structure boundary. Additionally, the motion is not guaranteed to be perfectly sinusoidal in time, and constraining it as such could significantly alter the aerodynamic development and coupling. Tang and Dowell (2001, 2002) allowed for both three dimensional deformations and non-sinusoidal, free-flutter motions, in their studies of high-aspect-ratio wings. In fact they found that the stall aerodynamics dominated the non-linear structural response in the developed model. Unfortunately, they were constrained to a single set of structural parameters and could not explore the larger structural parameter space. Arena et al. (2013) developed a nonlinear flutter model, to understand post-flutter behavior of high aspect ratio wings, and validated its behavior against the work of Tang and Dowell (2001, 2002). This work demonstrates the necessity for using unsteady aerodynamic models when predicting flutter, as quasi-steady approximations can lead to overly conservative estimates. Finally, in terms of modal analysis in flutter applications, the literature shows that while a large body of work exists, it primarily focuses on modal representations of the flow field: (Bryant et al., 2013; Zhang et al., 2015; Zhang and Ye, 2007).

In order to experimentally replicate a stall flutter type motion, a flexible model is utilized which constrains the motion to a predominantly pitching mode, and allows for intermediate wing twist angles along the span. This was achieved through the implementation of a cyber–physical wing system as previously discussed by Fagley et al. (2015, 2016). In this work the authors investigated the performance of the cyber–physical wing system across a large parameter space to quantify the different aeroelastic flutter regimes in which the model can operate.

The current work focuses on a single set of operating conditions within the stall flutter regime where the wing kinematics are studied in detail. The wing kinematics are experimentally captured using a stereo vision optical reconstruction technique relying upon the open-source software developed and documented by Hedrick (2008). The captured motion is decomposed by projecting onto the linear eigenmode shapes for a cantilevered beam in free vibration. This work seeks to address whether this modal decomposition, utilizing the eigenmode shapes as a fundamental basis, can accurately capture the large amplitude torsional deflections of the wing observed during stall flutter excitation. If accurate, using such a decomposition could allow the entire wing deformation to be determined from a single spatially located measurement along the span, such as the tip position measurement made in the cyber–physical system.

A discussion of the experimental setup is provided in Section 2, followed by a detailed description of the modal decomposition technique in Section 3. The wing kinematics are then thoroughly presented and analyzed in Section 4.

## 2. Experimental set-up

The current experiments were conducted in the United States Air Force Academy's Subsonic Wind Tunnel, which is a single leg recirculating type with a 0.91 m by 0.91 m by 1.83 m test section. It is capable of attaining speeds up to Mach numbers of $M = 0.5$, however for the current tests the wind speed was limited to $U_\infty = 26$ m/s or $M = 0.08$. The test geometry consisted of a finite span, rectangular NACA 0018 wing model cantilevered up from a splitter plate mounted to the tunnel floor as shown in Fig. 1. Note that the splitter plate was utilized to isolate the influence of the tunnel boundary layer from the wing model aerodynamics. Additionally, the wing had a chord and span of $c = 0.1$ m and $b = 0.6$ m, respectively.

The stall flutter limit cycle oscillations of the wing model were tuned using the position-feedback cyber–physical control system developed by Fagley et al. (2015, 2016) and pictured in Fig. 1. The embedded controller was designed to take the form of a second-order mass–spring–damper system:

$$J\ddot{\theta} + \eta\dot{\theta} + k_\theta\theta = \tau. \tag{1}$$