Chapter 1

Introduction

Overview of Aeroelasticity

An aeroelastic system results from couplings between the aerodynamic forces and structural response whereby the aerodynamic forces cause elastic structural motions and the deformed configuration affects the aerodynamic forces. In some cases, it is possible that the aerodynamic forces and elastic forces balance each other causing the system to settle into a stable equilibrium. In other cases, the structural response can undergo large amplitude motions which may result in structural failure. Aeroelastic effects can be observed in many natural phenomena and in many manmade structures. For example, during strong winds, tree leaves curl up which reduces the aerodynamic force on them. If this aeroelastic mechanism was absent, the leaves would detach from the tree during a summer gale rather than remain until the fall. In air vehicles, aeroelastic effects are not so beneficial. They can be responsible for control surface reversal or flutter among other effects, which are detrimental to aircraft stability [1].

Aircraft design requires both crude calculations and detailed analysis. This can be thought of as “power” and “finesse”. The “power” constraints represent the most obvious limitations: aircraft efficiency, payload, and range. These were dealt with early on by the Wright brothers. Since then, many tools have become available to aid in the design of power plants, control surfaces, and estimate aircraft stability under ideal conditions. Once these problems have been investigated and gains have been made, the next layer of subtlety and synergy should be considered. The “finesse” required to characterize aeroelastic effects is currently the focus of a great deal of research.

The first methods of estimating aeroelastic stability were pioneered by Von Schlippe in 1935 [2]. In these tests, an aircraft was excited at its natural frequency while being flown at successively higher air speeds. Structural damping was estimated from the resulting oscillations, and the flutter speed was inferred when the damping approached zero. The process of aeroelastic analysis bears many of the same characteristic today as it did in 1935 [2]. Aeroelasticity gained exposure as a significant design constraint in 1973 when W. Swan remarked during an airfoil test that changes in the pitching moment due to aeroelastic effects were of the same order of magnitude as the effects of the rigid tests [3, 4]. This subtle aspect of aircraft behavior has become a significant obstacle to expanding flight envelopes.

An airplane represents a continuously changing system. The weight of fuel, configuration of the wing, and flight conditions are all variables which affect the fluid structure interaction. It is prohibitive to test all the different combinations of wing configurations and ambient pressure and altitude [5]. Yet these varying conditions determine when the wing is prone to aeroelastic oscillations and when it is not. For these reasons, the analysis of aeroelastic phenomena requires specialized tools [6]. Both wind tunnel testing and numerical analysis add time and expense to the design process with the further disadvantage that once an aeroelastic instability is identified, the tests do not necessarily give an indication of how the problem might be rectified. Both linear and nonlinear similarity analyses are required for accurate aeroelastic characterization. The identification of physical nonlinearities gives insight into the physics of the system and can suggest design changes that may mitigate nonlinear coupling and the ensuing limit cycle oscillations.

The importance of the need to identify nonlinear aeroelastic aspects for different wing configurations cannot be underestimated. Chabalko, Mook, Hajj, and Silva [7] showed a subcritical instability in the Nonlinear Aeroelastic Testbed Apparatus (NATA). This model is expected to experience LCO if the free stream speed is above the linear flutter speed which, in this case is about 9.2 m/s. However, there is an interval of speeds where the model can transition from steady conditions into sudden LCO with a sufficient perturbation, as shown in Figure 1. As such, linearization of the system would obfuscate subcritical instabilities [8]. This presents the need to develop sophisticated tools capable of the identification of nonlinear aeroelastic effects [9].

A reduced-order model that incorporates the actual nonlinearities of the system can be used to characterize aeroelastic effects. Reduced-order models of certain physical phenomena have been

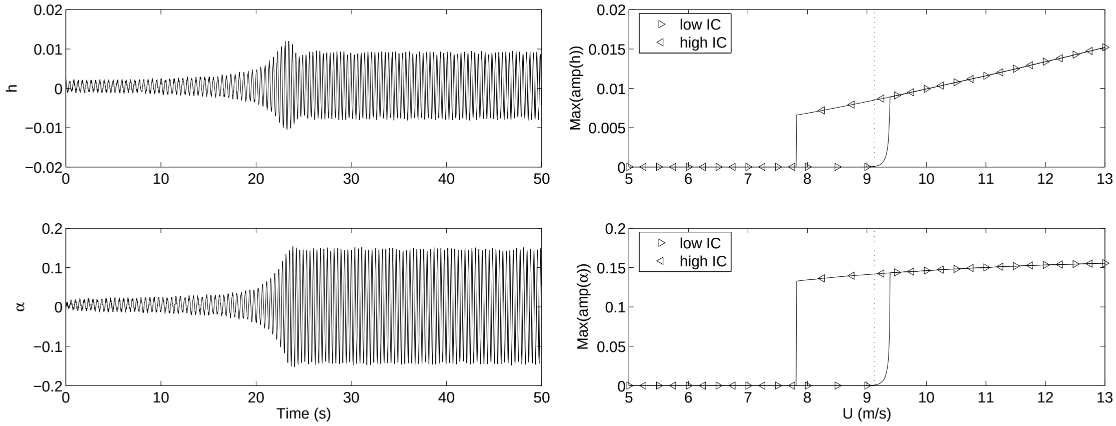

Figure 1.1: Subcritical instability in the NATA model. For this model, LCO can be encountered at speeds below that predicted by linear analysis. Identification and modeling the jump phenomena at the lower speeds require nonlinear analysis.

successfully developed using higher-order spectral moments and perturbation techniques. Reduced-order models for the lift and drag on inline and transversely oscillating cylinders are given by Qin [10]. Hajj et al. [11] combined higher order spectral moments with approximate solutions of governing equations to characterize nonlinear damping in vibrating structures. Suleiman et al. [12] applied the same analysis procedure to model ship motions in large amplitude waves. In relation to aeroelastic response of aircraft wings, Stearman and Powers [13] successfully implemented higher order spectral moments to identify nonlinearities present in the limit cycle oscillations caused by a damaged wing, and separately, by wing stores on an F-16.

The overall goal of this work is to gain a complete understanding of the mechanism that causes limit cycle oscillations in the two aircraft subsequently analyzed. This is achieved through the identification of nonlinearities responsible for the LCO. This knowledge can be used to develop an aeroservoelastic control algorithm which is responsible for mitigating flutter by actuating aileron inputs [14]. Such an algorithm can be executed independently of the pilot. Furthermore, the sensors and computer power necessary for such a control system are already in place on most aircraft. The additional sensors and control algorithms would add minimal weight and space to an aircraft while allowing that same aircraft to be lightened structurally and simultaneously more reliable under varying flight conditions. The understanding gained might also be used to mitigate LCO in the design phases.

Mitigation of aeroelastic effects, by design changes or aeroservoelastic control methods, would benefit air vehicles and the customer. Air frames could be made lighter by selective reinforcement rather than bulk reinforcement and performance and safety could be enhanced by an expansion of the operational envelope. With advanced analysis tools, perhaps designers will welcome nonlinearities rather than avoid them. It should be noted that commercial airliners are thoroughly tested against flutter [2]. Stiff and relatively heave wings are tested to more than the maximum theoretical loads. With fuel prices and efficiency requirements on the rise, optimization of airframes should be of great interest.

The importance of complete data characterization and the limitations of linear analysis are illustrated by Anscombe's quartet [15] presented in Tufte [16]. The four ensembles *I*, *II*, *III*, and *IV*, shown in Table 1.1a, share the same linear statistics, as calculated in Table 1b, including their best fit lines ($Y = 0.5X + 3$). After examining the data sets as plotted in Figure 1.2, the differences are obvious. The need for a more robust analysis is clear, especially when the system has a suspected quadratic nonlinearity, as in set *II*.

Table 1.1: Anscombe's quartet [16] and statistics.

I		II		III		IV	
X	Y	X	Y	X	Y	X	Y
10.0	8.04	10.0	9.17	10.0	7.46	8.0	6.58
8.0	6.95	8.0	8.14	8.0	6.77	8.0	5.76
13.0	7.58	13.0	8.74	13.0	12.74	8.0	7.71
9.0	8.81	9.0	8.77	9.0	7.11	8.0	8.84
11.0	8.33	11.0	9.26	11.0	7.81	8.0	8.47
14.0	9.96	14.0	8.10	14.0	8.84	8.0	7.04
6.0	7.24	6.0	6.13	6.0	6.08	8.0	5.25
4.0	4.26	4.0	3.10	4.0	5.39	19.0	12.50
12.0	10.84	12.0	9.13	12.0	8.15	8.0	5.56
7.0	4.28	7.0	7.26	7.0	6.42	8.0	7.91
5.0	5.68	5.0	4.74	5.0	5.73	8.0	6.89

(a) The Four Data Sets of Anscombe's quartet [16]

$N = 11$
$\overline{X} = 9.0$
$\overline{Y} = 7.5$
$\sigma(X) = 3.31$
$\sigma(Y) = 2.03$
Regression Line: $Y = 0.5X + 3.0$
Residual Sum Sq. (Y) = 13.7
$\rho_{X,Y} = 0.816$
$R^2 = 0.66$

(b) Linear Statistics

Fourier-Based Spectral Analysis

The Fourier-based power spectrum became a practical tool for signal analysis shortly after Cooley and Tukey developed the Fast Fourier Transform (FFT) algorithm in 1965 [17]. With the

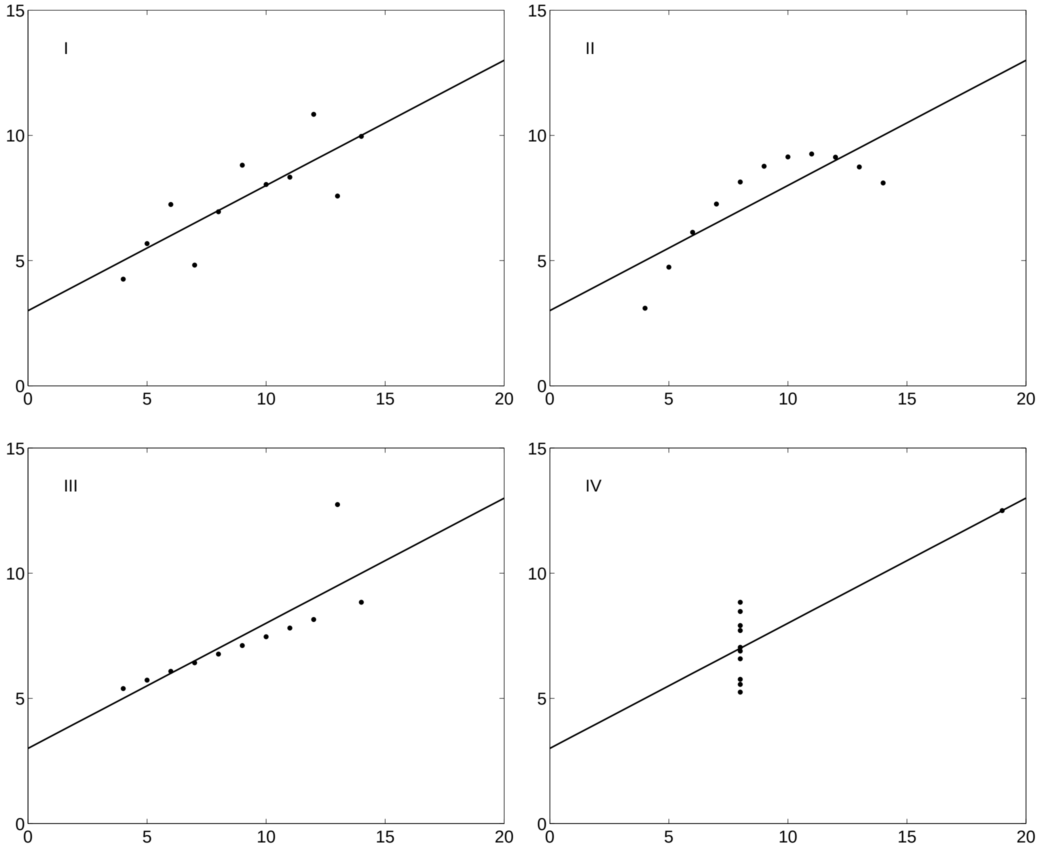

Figure 1.2: Anscombe's quartet with a best fit line. The four data sets have the same linear statistics including best fit line. The obviousness of the differences in the data presents the need for higher-order analysis tools.

increasing speed of personal computers, Fourier analysis is now a part of almost every study that involves periodic oscillations. The Fourier-based power spectrum and linear coherence are natural tools for the examination of aeroelastic systems. Frequency content becomes instantly apparent when using these tools. However, systems analyzed in this work require a more robust set of tools capable of nonlinear characterization which is necessary to develop an understanding of the physics governing their behavior.

Powers and Im [18] present a discussion of Fourier-based higher order spectral moments that can be viewed as natural extensions of the power spectrum and linear coherence. These tools are suited to identify phase coupling in quadratic and cubic systems. Higher order spectral analysis was successfully applied by Hajj, Miksad, and Powers [19] to identify quadratic interactions in the transition to turbulence of mixing layers. A similar analysis was used by Hajj and Janajreh [20] to identify the energy transfer of unstable modes to their sum and difference frequencies in the transition to turbulence of plane wakes.

These tools were also applied to the identification of quadratic nonlinearities in the pressure record of the High Speed Civil Transport by Hajj and Silva [21]. Although Fourier-based higher order spectral analysis is powerful, it has one major drawback. Because of the many ensemble averages required in calculating the moments, signal stationarity is a requirement. On the other hand, aeroelastic phenomena can be intermittent which makes the implementation of Fourier-based higher order spectral moments inappropriate. This leads to the need for the development of more robust time/frequency analysis procedures for the identification of transient and intermittent aeroelastic phenomena.

Wavelet-Based Spectral Analysis

Because of the averaging required, traditional Fourier analysis cannot simultaneously resolve intermittent small scale and large scale events. The short time Fourier transform (STFT) was developed to overcome this limitation by applying the Fourier transform over a short window. The inherent conflict remains: a short window is too short to resolve a large scale feature, while a long duration window is too long to isolate small scale features. The continuous wavelet transform is a multiresolution time/frequency analysis that overcomes these deficiencies. Wavelet analysis allows for the signal energy to be characterized simultaneously in both time and frequency. The ability of the wavelet transform to characterize intermittent events of various scales has been applied in fields ranging from the analysis of turbulence to speech recognition [22] and [23]. Lusk implemented the continuous wavelet transform to quantify amplitude and phase modulations in the transition of mixing layers [24]. The wavelet transform was also used to measure the time scale of intermittent pressure events over low rise structures by Chabalko [25] and Hajj, Jordan, Tieleman, and Chabalko in [26]. A similar analysis was conducted by Palumbo and Chabalko to measure the duration and length scale of persistent structures in a turbulent boundary layer [27]. A unique feature of the continuous wavelet transform is that it allows the choice of the most appropriate basis function for the analysis. Chabalko, Jordan, Hajj and Tieleman [26] showed that, in the case of an intermittent pressure event, both the Paul and Morlet wavelet basis functions yield equivalent time scales. Wavelet-based higher order spectral moments were defined by van Milligen et al. [28]. The result is a powerful set of tools that can be used to identify nonlinearities in nonstationary signals.

Aeroelasticity in the High Speed Civil Transport

The prototype Boeing 2707, an outcropping of the National Supersonic Transport program (1963), was the first US government supported venture into civilian supersonic transport [29]. The program examined many aspects of a supersonic transport, with efficiency and environmental effects being the primary focuses of research [30]. Although the program was canceled in 1971, two other supersonic transport airplanes, namely the French/English Concorde and the Russian TU-144 were successfully developed. Some of the complexities that make supersonic transport impractical are the poor efficiency of supersonic wings in subsonic flight, and the noise generated at takeoff and acceleration by engines powerful enough to maintain supersonic flight. Since weight plays a pivotal role in the commercial viability of a high speed civil transport, a great deal of effort was made to reduce weight. However, the less rigid materials that usually accompany a weight reduction may have detrimental aeroelastic effects

The NASA based High Speed Research program (HSR) was introduced in 1990 in order to develop a high speed civil transport (HSCT) for the twenty-first century [31]. The effort considered all aspects of the proposed supersonic aircraft including materials, airframe, propulsion, and environmental effects. The ultimate goals of the HSR program were to develop an aircraft that was capable of sustained flight at Mach 2.4; a speed that is only incrementally higher than that of the Concorde. However, the HSR vehicle would have twice the range and three times the seating capacity [4]. The HSCT airplane was expected to be approximately 50% lighter than originally estimated in 1990 due to advances in design and material properties [32]. The program was phased out in 1999 due to a change in the political climate and projected increases in operating expenses including fuel prices. Over the lifetime of the HSR, valuable research was conducted through computer simulations and wind tunnel tests. The designers decided on a single wing planform designated as reference H, in order to focus their developmental efforts [31].

The aeroelastic response of the reference H configuration were assessed from two 1/12 scale rigid and flexible models. Tests were conduced at the NASA Transonic Dynamics Tunnel (TDT) at Langely Research Center (LaRC) in Langely, Virginia. Both models were extensively instrumented in order to study their aerodynamic and structural properties. The first model was the Rigid Semispan Model (RSM) which was used to estimate the lift and drag coefficients. A flutter model, designated as the Flexible Semispan Model (FSM), was developed to determine all possible flutter mechanisms exhibited by the proposed HSCT [33]. After extensive analysis in both wind tunnel tests and matched computer simulations, the flexible semispan model failed suddenly during a "hard" flutter event.

The FSM was skinned with Fiberglass 108 which was the thinnest and most flexible material available that met the structural requirements of wind tunnel testing. The nonlinear properties of Fiberglass 108, including creep and relaxation, added uncertainty to the FEM of the structure. After structural vibrational tests were completed, the FEM models, computed with both NASTRAN and IDEAS, were tuned to match the experimentally determined vibrational modes [34]. This deficiency of the computer models underscores the value of physical testing and data reduction.

Experimental analysis conducted by Silva et. al. [33] showed evidence of pressure variations near the trailing edge of the wing at $\eta = 60\%$. The difference between the max, min, and mean of the pressure record was found to have a large scatter under tunnel conditions, $M = 0.947$ and $q = 149.2$ psf, where computational analysis predicted steady conditions.

Hajj and Silva [21] conducted a more in depth analysis of the experimental data leading up to the "hard" flutter event. Frequency shifts in the wing bending frequency were determined by Fourier-based spectral analysis of strain gage data. During the run just before "hard" flutter, the model showed a significant bending mode at 14.2 Hz. In addition, evidence of shock formation was determined from the sudden increase in mean C_p just after $x/c = 70\%$ at $\eta = 60\%$ and $\eta = 95\%$ in all runs. Fourier-based bicoherence of the pressure at tap location $x/c = 80\%$ showed slight nonlinearities, however, they were not associated with a specific physical phenomena.

In this work, wavelet-based higher order spectral moments are implemented to identify the nonliear dynamics that lead to the "hard" flutter and loss of the FSM. This objective is a part of NASA's ultimate goal of developing aeroservoelastic control laws to suppress flutter as well as gust loads. The results presented here, in the form of physical and quantitative descriptions of the nonlinearities in the wing are a necessary first step for the development of robust control laws that are capable of suppressing flutter instabilities.

Aeroelasticity in the F-16

The Air Force's SEEK EAGLE program was established 1987 to "ensure new warfighter capabilities through the application and transfer of aircraft-store compatibility expertise" [35]. Wing store functions include fuel tanks, armaments, surveillance, and electronic counter measures. The combination of stores on the wing influences the aerodynamics as well as the structural loading of the wing. For example, the loading caused by a fuel tank will decrease steadily as the fuel is burned, while the deployment of a 2000 lb. bomb results in a sudden unloading. A change in the wing loads of the aircraft may result in Limit Cycle Oscillations (LCO). Several techniques have been used to clear store configurations, however, the number of different store combinations has increased from 500 in 1997 to over $24,000$ in 2007 [36]. This increase has outpaced the ability to predict the flight stability of store combinations. Because of cost and time constraints only a small portion of those combinations can be flight tested. The Air Force's SEEK EAGLE program averages only 25 flight tests per year [36]. While this method of testing gives reliable results and flight envelopes, no insight into the physical mechanism of the Limit Cycle Oscillations is gained.

Mission planners must be aware of the store configuration and flight conditions that are required during a sortie. The store configuration at the commencement and end of the mission can be anticipated although unanticipated maneuvers might be necessary. The parallel ridge crossing described by Updike [37], shown in Figure 1.3, requires a windup turn followed by an increase in altitude and several other maneuvers. The windup turn maneuver can cause LCO as shown in Chapter 4. Although flight paths are chosen to avoid exciting LCO, uncertain situations can arise. In these situations, it is necessary to have a robust understanding of the aeroelastic limits of the air vehicle to ensure mission integrity. The ability to predict LCO with a "flutterometer" [38] is an additional goal of this effort.

Researchers have used several different methods including, analytical analysis, CFD/FEM, and reduced-order modeling to predict the onset of LCO. While each of these techniques has advantages and disadvantages, all are necessary for a complete understanding of LCO behavior. For a method to be capable of accurately predicting LCO stability it should be able to accurately predict the onset of LCO for various store configurations. Moreover, the method should be capable of identifying aeroelastically similar store configurations and flight conditions i.e. similar physical

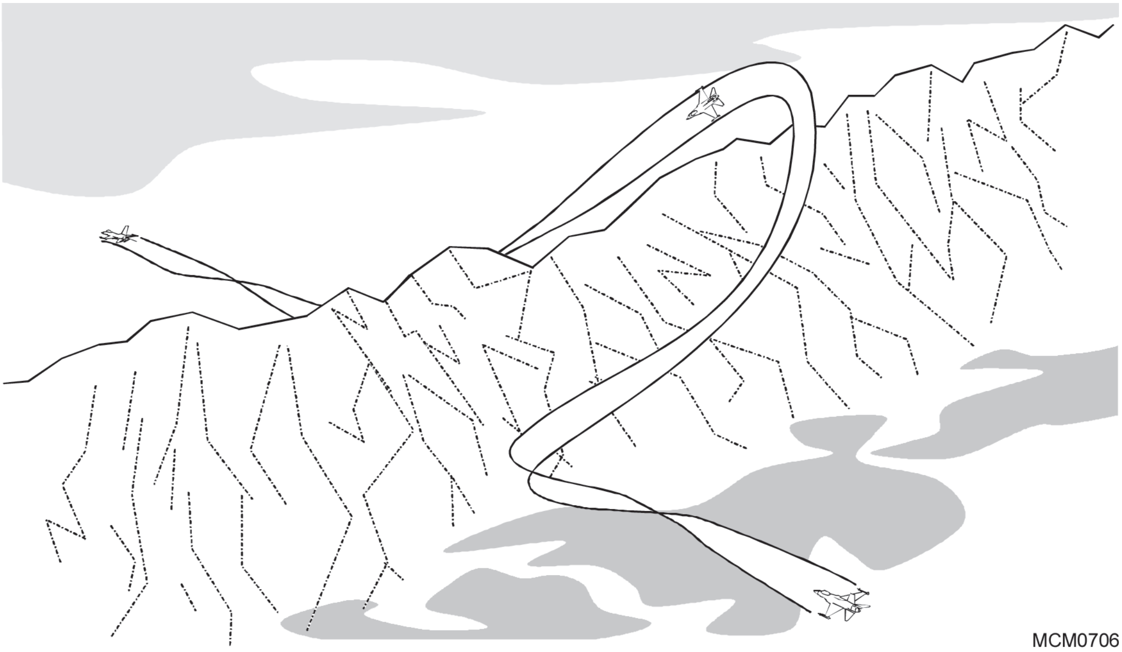

Figure 1.3: Parallel ridge crossing maneuver which requires a wind up turn that is followed by an increase in altitude [37]. The wind up turn can cause LCO.

phenomena. If such similarities were identified, a single representative flight test could admit many store combinations and flight conditions by model analogy. Finally, the method should be able to predict combinations and conditions of instability. Such predictions would help focus flight tests and maximize the benefit of those tests.

A high fidelity computational aerodynamic solver can take several weeks to run a combination of cases [39]. In addition, the solution is only as good as the conditions it models. Computational models are complicated by uncertainties such as: structural/fluid nonlinearities, gusting, and moisture content of the air. If such nonlinearities are unknown or incompletely modeled, the numerical solution can be compromised. A solution that is highly dependent on one specific parameter is also undesirable. In addition, wing mode shapes vary with increasing Mach number and requiring robust structural algorithms [40]. With such considerations, the computational solution may have limited validity.

Neural networks have also been used to predict the the flutter speed for various store combinations. While some success was demonstrated by Pitt [41] the neural network solutions yield no physical understanding of the system. In addition, the network must be trained using verified data, and its predictions become suspect if the conditions that cause LCO are significantly different from those it was trained on.

Several attempts have been made to characterize limit cycle oscillations and associate them with different parameters. Denegri et al. refers to LCO as either typical or non-typical [42]. Typical LCO is characterized by an increase in amplitude with increasing Mach number. Non-typical LCO does not exhibit a consistent amplitude trend with increasing Mach number. While such classifications are useful in grouping LCO by suspectedly similar mechanisms, such an analysis does not give insight into the physics of those mechanisms.

A reduced-order model may properly predict the onset of LCO in certain cases, however, if the model does not properly account for the nonlinear interactions that take place throughout the entire aircraft/store system, it remains of limited use [36]. In order to maximize the benefit of reduced-order modeling, accurate physical interactions, linear and nonlinear, must be incorporated. The question remains, what mechanism causes LCO and how can that mechanism be identified? Robust characterization of LCO is a required first step for an accurate modeling endeavor.

The characterization of LCO would benefit the most from a complete family of reduced-order models that are valid across many store configurations and flight conditions. The tools presented above have the ability to analyze actual flight data. A reduced-order model constructed from flight data has the advantage of including all nonlinearities including those of unknown origin [43]. Higher order spectral analysis tools that were discussed earlier have the ability to identify nonlinearities in aerodynamics, structural dynamics, and fluid/structure interactions. Based on a complete set of nonlinear identifications, a reduced-order model can be constructed which could satisfy the criteria of the SEEK EAGLE program.

In this work, wavelet-based higher order spectral moments are used to identify nonlinearities in the wing/store system of a specially outfitted F-16 aircraft. Significant differences in nonlinear couplings are determined between maneuver-induced and mechanically-forced LCO. The new insight gained by this analysis will aid in the reduced-order modeling effort. This is a necessary step for a complete understanding of the physical interactions that take place during LCO.

Organization

The organization of this thesis is as follows. In chapter 2, examples of “phase coupling” among two and three frequency components are presented to show how higher-order spectra can be used to detect quadratic and cubic nonlinearities. Higher order spectra are presented as a natural extension of Fourier-based moments. Special emphasis is given to the bicoherence and tricoherence since they are extremely useful in this work. A novel method of visualizing the tricoherence is presented as well. Next, the continuous wavelet transform is defined with several examples demonstrating the advantages of the continuous wavelet transform over the Fourier-based power spectrum. The higher order spectral moments presented earlier are subsequently defined in terms of wavelet-based quantities. The chapter concludes with an exercise that establishes the benefits of wavelet-based higher order spectra over Fourier-based higher order spectra.

An analysis of the High Speed Civil Transport flexible semispan model is presented in Chapter 3. Pressure profiles and accelerations near the failed region are presented as the model approaches the "hard" flutter conditions. Quadratic coupling between the pressure and accelerations is identified as the cause of "hard" flutter.

Limit cycle oscillations of the F-16 "Fighting Falcon" are analyzed in Chapter 4. Through the use of wavelet-based higher order spectra, couplings present during maneuver-induced LCO are determined to be significantly different from couplings resulting from mechanically-forced LCO. The flaperon motions are treated as an input to the wing/store system which results in quadratic coupling at some, but not all, locations of the wing/store system during mechanically forced LCO. The chapter concludes with an example showing how wavelet-based higher order spectra can be used to identify the decoupling of quadratic nonlinearity from limit cycle oscillations. The significance of using this analysis in a "flutterometer" application are described.

The conclusions of this work are summarized in Chapter 5 and the bibliography follows.