Abstract

Studies have revealed that insect like flapping flight can serve as a benchmark in designing Micro Aerial Vehicles (MAV) owing to its power efficiency and high maneuverability. Primarily envisioned as agents facilitating in surveillance and reconnaissance missions, flapping wing-based MAV (FWMAV) can also be employed for a host of other applications ranging from _re fighting, rescue missions and biochemical sensing. Recently, few prototypes of FWMAV have successfully been realized owing to the recent technological progress. However, the present state of the art is still at a nascent stage and the ultimate goal of designing fully autonomous FWMAVs appears staggering, which demands contemporaneous developments in several disciplines. In particular, being the sources of lift generation, propulsion and maneuvers, the flexible wings of FWMAVs need special attention for the successful design of this class of vehicles. To this end, the development of a low dimensional aeroelastic framework describing the interaction of the flexible wing structures of FWMAVs with the surrounding fluid medium has special importance as it would guide the synthesis of control laws - a key step towards the development of autonomous FWMAVs. The work embodied in this thesis essentially presents two low dimensional analytical models describing the aeroelasticity of a flexible insect wing undergoing the flapping light. The analytical models can serve as a ready-to-use framework for obtaining responses of insect-like flexible flapping wing under different operating fight conditions.

After a brief introduction on the topic followed by a thorough survey of relevant literatures in Chapter 1, Chapter 2 presents a framework for quasi-steady aeroelasticity of a flapping wing structure in hover, which essentially is the first part of the dissertation. For this purpose, the revised quasi-steady aerodynamics model of Sane and Dickinson is used after making suitable modifications to the model to accommodate the effect of wing flexibility. The idealized flapping kinematics parameterized by the wing-sweep angle and the angle of attack is prescribed at the wing root. The flexible wing structure is idealized as the bending-torsion coupled Hodges-Dowell beam. Ramifications are made to the existing beam model to describe the time varying pitching motion of the insect wing. The bending displacement and the twist are the two unknowns to be solved for. One term approximation of the bending displacement and twist are made respectively in terms of the first bending mode of Euler-Bernoulli beam and the

first torsional mode of circular bar with each expression having one multiplicative unknown coefficient. The Rayleigh-Ritz method is then taken recourse to wherein the expressions of the kinetic energy, the potential energy and the virtual work due to the aerodynamic loads are obtained in terms of the unknown coefficients of the bending and torsion expressions. An ordering scheme is invoked which segregates terms within the expressions energy and virtual work having different orders of magnitude, thereby retaining only the significant terms. The governing equation of motion of the coupled system is obtained using the Lagrange's method.

Notwithstanding the conciseness of the quasi-steady model, the second part of the study, comprising of Chapters 3-6, focuses on the development of a full unsteady aeroelastic model of insect fight, which would essentially capture the underlying complex flow physics keeping the same structural model earlier developed. Chapter 3 and 4 discuss the development of an unsteady blade element theory for the aerodynamics of insect flight based on the finite state air-load theory by D.A. Peters. The motivation stems from the requirement of a low order aerodynamics model, which can be developed from the first principle unlike most of the existing theories that are constructed empirically. Chapter 3 reports the development of the quasi-steady framework. The model developed is validated against the Robofly data. The framework is then used to model the forward flight of a rigid wing. The simplest case of locomotion along a straight line in one principal direction is considered. Chapter 4 reports the development of a wake model. For this purpose, the three-dimensional Peter-He inflow model is adapted to describe the wake shed by the wing and, more importantly, for modeling the interaction of wing with the wake shed during previous wingbeat cycles. A time domain formulation with ten wake states is developed based on the Peter-He inflow theory. The modularity of the finite state framework air-load theory allows us to incorporate the effect of the shed wake by coupling it with the quasi-steady framework developed in chapter 3. Once the unsteady framework is developed, the unsteady lift force computed is again validated with the Robofly data. Noteworthy to mention that chapter 4 presents the first ever attempt to adapt the formulation of Peter-He inflow theory for the wake modeling of insect-like flapping flight. Chapter 5 presents a low-dimensional aeroelastic framework based on the unsteady blade element theory developed in the previous two chapters. The finite state blade element theory is modified at the outset to incorporate the effect of wing flexibility by introducing variables such as the velocity of the wing flapping and the angular velocity due to wing pitching. The wing model used for the quasi-steady aeroelasticity analysis is used again. Virtual work done due to the aerodynamics loads is computed. The energy expressions are obtained similarly to the quasi-steady problem enumerated in chapter 2. Procedures similar to that of Chapter 2 is followed to arrive at the governing equations of motion. Simulations for both the quasi-steady and unsteady cases are carried out and lift forces obtained from each case is compared with one another and with the rigid wing lift data obtained from the finite state aerodynamics. Responses of a flapping wing structure under gust load are very important owing to the light weight and diminutive size of the vehicle. Chapter 6 presents the framework for obtaining aeroelastic responses of the wing in hover when impinged with the wind gust, which is modeled as a transient velocity pulse acting vertically to the wing surface. Different standard forms of global gust-pulse are considered. This is for the first time that a low-dimensional framework for obtaining aeroelastic response under gust is being reported. Apart from being an useful tool for stability analysis and synthesis of control laws, the low dimensional aeroelastic models introduced in the dissertation may also provide useful insights into the complex physics of the flapping flight.