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14. ABSTRACT This report describes the development of an aeroelastic model capable of representing in an approximate manner the fundamental nonlinear aeroelastic behavior of flapping wing micro air vehicles in hover. The approximate nature of the model is due to an approximate nonlinear two dimensional unsteady aerodynamic model based on a vortex approach that accounts for the leading edge vortex shed from the leading edge of the flapping wing. This approximate aerodynamic model is coupled with a nonlinear structural dynamic model based on the MARC analysis package that is part of the NASTRAN code. The aeroelastic response solution is obtained from an updated Lagrangian approach for flapping wings with prescribed root motion that resembles insect or hummingbird wing flapping motion. It is shown that wing flexibility modifies the aeroelastic response of the wing, however these changes are relatively modest.					
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A FUNDAMENTAL STUDY OF NONLINEAR AEROELASTIC PHENOMENA IN FLAPPING WING MICRO AIR VEHICLES

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Introduction and Problem Statement

Micro air vehicles (MAVs) are flight vehicles with geometric dimensions less than 15 cm and weight less than 100 grams [1]. The need for such vehicles is motivated primarily by unmanned military and civilian missions that involve closed spaces (such as buildings) or short distances. Existing MAV designs may be classified into three categories: fixed, rotary, or flapping wing. While fixed and rotary wing designs benefit from the existing technologies, flapping wing designs are fundamentally different and are inspired from biological flyers such as insects, and small birds and bats. In particular, flapping wing designs that operate at low Reynolds number ($10^2 < Re < 10^5$) and low forward flight speed (7-17 m/s) have received considerable attention due to the exceptional flight capabilities observed in insects [1-3].

A significant portion of research on flapping wing MAVs has focused on the mechanisms that generate the unsteady aerodynamic forces. This research [1-7] has identified the predominant force generating mechanisms as leading edge vortices (LEVs), combined with wing rotation, and wake capture as a result of wing-wake interaction. Attempts to model the aerodynamic loads have employed two approaches: (1) computational fluid dynamics (CFD) based on solutions of the Navier-Stokes (NS) equations, and (2) approximate aerodynamic models based on potential flow solutions. Descriptions based on CFD [7-10] offer the best resolution of the unsteady flow field; however these approaches are expensive when parametric studies are of interest. Approximate models, on the other hand, offer a compromise between accuracy and computational efficiency; therefore such approaches are best suited for trend and design type studies. Historically, simple steady and quasi-steady models were used; however, these models consistently underestimated forces generated by flapping wings [1]. Unsteady aerodynamic formulations used for flapping wing problems can be

classified as assumed (or prescribed) wake and free wake models. Assumed wake models, developed originally for aeroelastic studies of fixed wing vehicles [11], are two-dimensional linear thin airfoil theories that are valid for small plunge (bending) and pitch (torsional) displacements. Recent studies [12,13] have attempted to incorporate the effect of the LEV in assumed wake formulations. These approaches involve modifying Theodorsen's theory by using a leading edge suction analogy [14] that was originally derived for steady separated flow on delta wings for moderate angles of attack (typically less than 40 degrees). Free wake models include unsteady panel methods [10] and discrete vortex methods [15–17]. These approaches, which account for evolution of the wake, provide a reasonable approximation to the development of the unsteady wake during a flapping cycle. A two-dimensional panel method was used in Ref. [10], and reasonably good agreement was found with CFD simulations for the range of parameters considered. However, LEVs were not accounted for in this study. Two dimensional discrete vortex formulations that account for flow separation have been considered in Refs. [15–17]. The model developed in Ref. [15], which accounts for separation close to the leading edge, compared well with experimental data for airfoils in steady flow. In this approach the chordwise location of the separation point, which may be obtained using independent computations or experiments, is explicitly incorporated into the formulation. Comprehensive treatment of an unsteady aerodynamic model based on a discrete vortex method that is applicable to insect-like flapping wings in hover is presented in Refs. [16,17]. The model was used to simulate rigid wings, and for the cases considered, compared well with experimental data on flapping wings.

The importance of wing flexibility in enhancing the performance of flapping wings has been mentioned in a number of studies; however, only a limited number of studies [13,18,19] have attempted to address this issue in a systematic manner. In the earliest study, where a linear finite element model of the wing was coupled with an unsteady panel method [18], the wing model was based on experimentally obtained geometric and inertial data on Moth wings. More recent computational studies have considered wing models based on Euler-Bernoulli beam theory coupled with CFD [20], or membranes reinforced by metal or composite frames [13] coupled with Theodorsen's theory modified using Polhamus leading edge suction analogy. These studies [13,18,19], which considered wing flexibility in a linear manner, concluded that wing flexibility had a favorable effect on lift, and that the effect of flexibility cannot be ignored when computing aerodynamic loads.

Thus, the overall objective of the research carried out in the framework of the current grant was to determine the effect of flexibility on the performance of anisotropic flapping wings in hover and forward flight. The specific objectives were as follows:

- (1) Develop a nonlinear aeroelastic model to study flexible anisotropic flapping wings.
- (2) Conduct systematic validation studies to develop confidence in the model.
- (3) Explore the effect of wing flexibility on aeroelastic response and unsteady loads generated by flapping wings.

Nonlinear Aeroelastic Model

The aeroelastic model is obtained by coupling MARC, a commercially available nonlinear finite element code, with the approximate aerodynamic model that was developed in Refs. [16,17]; a description of this model is presented in Ref. [20].

Structural Dynamic Model

The structural dynamic model of a bio-inspired wing, depicted in Fig. 1, (*note: all figures are provided at the end of the report*) consists of beam and shell elements capable of undergoing large rigid body rotations as well as moderate-to-large flexible deformation. The elements have compatible degrees of freedom so that beam stiffened shell structures may be constructed [21]. Furthermore, the elements support a variety of constitutive laws so that isotropic as well as anisotropic wings can be modeled. Wing kinematics consists of large amplitude, prescribed, time dependent rigid body rotations imposed at the base (root) of the wing. In MARC, rotations may be prescribed either using a time dependent rotation vector [21] or as displacements at two or more nodes.

Aerodynamic Model

The approximate aerodynamic model is based on potential flow and uses a circulation/vorticity approach to compute the aerodynamic loads. The formulation accounts for leading edge separation and subsequent vortex formation, incorporates the effect of wing thickness and camber, and includes a free wake model. The model is two-dimensional and is applied in a strip theory manner. Furthermore, each airfoil cross-section is assumed to interact only with its own shed wake. At each time step, vorticity shed into the wake is computed by enforcing a Kutta condition at the trailing edge and a stagnation condition at the leading edge. The evolution of the wake is governed by the Rott-Birkhoff equation, which is derived from the Biot-Savart law for two-dimensional flow. The unsteady aerodynamic loads are computed using the vortex impulse method and the unsteady Bernoulli equation. It is important to note that the formulation [16,17] was originally developed for rigid wings for the case of hover; its implementation for wings that have both span-wise and chord-wise flexibility is described in Ref. [20].

Coupled Fluid-Structure Model

The aeroelastic response is obtained using an updated Lagrangian (UL) method [22] wherein the equations of motion at each time step are formulated by using the equilibrium configuration computed at the previous time step as the reference. A schematic description of the approach is shown in Fig. 3. The coupled fluid-structure problem is modeled in MARC via user-defined load subroutines [21] whereby time dependent pressure loads that are computed from the wing motion are imposed on the structure. The user subroutine is called from the main program for each Newton-Raphson iteration of the UL method thereby ensuring convergence of the structural displacements and aerodynamic loads within each time step. Schematic of the aeroelastic solution in MARC is depicted in Fig. 4. Finally, the resulting equations of motion are integrated using a suitable numerical scheme.

Results and Discussion

Validation of the structural dynamic model

Important considerations in the structural modeling of MAV wings are (1) implementation of prescribed, large amplitude, rigid body rotations that are representative of wing kinematics, and (2) accurate capture of the dynamic or centrifugal stiffening effect in flexible structures undergoing prescribed rotary or flapping motion. Note that all the results that follow were obtained by integrating the equations of motion using a single step Houbolt scheme [23].

Implementation of large amplitude rigid body rotations in MARC was examined by imposing kinematics of a dragonfly wing on a rigid rectangular plate shown in Fig. 2. The results [20], shown in Fig. 5, indicated that wing kinematics can be accurately implemented as displacements, but produce significant error when implemented as a time dependent rotation vector.

The effect of centrifugal stiffening was examined by considering the spin-up motion of a flexible plate; details of the test case are given in Ref [24]. The results, shown in Fig. 6, indicate that this effect is accurately modeled in MARC.

Validation of the aerodynamic model

The aerodynamic model was validated for (1) cases of attached flow over the airfoil, and (2) cases where flow separation from the leading edge was observed.

The force coefficients for a NACA0012 airfoil undergoing prescribed plunge motion are shown in Fig. 7. Figure 9 shows a comparison of lift coefficients obtained for a rigid flat plate airfoil undergoing prescribed plunge motion in near hover conditions. Parameters: Chord = 1.0 m, plunge frequency = 0.064 Hz, Reynolds number = 1000, plunge amplitude = 0.5m. The CFD results were obtained by implementing laminar NS equations in CFD++, a commercially available CFD code, using a grid that had approximately 150,000 cells with 240 points on the airfoil. Results using the approximate model were obtained by assuming flow separation at the leading edge. This result indicates that the approximate model shows reasonable agreement with CFD for the case considered.

Aeroelastic response results

Preliminary aeroelastic results that examined the effect of flexibility on force generation by wings undergoing prescribed motion have been presented in Ref. [20]. The calculations were performed by assuming leading edge separation for a zero free stream velocity, thereby simulating conditions of hover. The results, which were obtained for wings that had different spanwise stiffness [20], were consistent with the finding of previous studies and indicated that flexibility had a comparatively small but favorable impact on force generation and that the effect of aerodynamic loads on wing deformation was small compared to the effect of inertia loads. Sample results of lift and chord-normalized tip displacements are shown in Fig. 10.

Concluding Remarks and Accomplishments

The research performed during the period of this grant resulted in the development and comprehensive testing of a nonlinear aeroelastic model that is suitable for the analysis of flexible anisotropic MAV wings for the case of hover;

this work [20] was presented at the 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference held in April 2008 in Schaumburg, IL.

Currently, the model is being extended in the frame work of the multi-university research initiative (MURI) to include effects of forward flight, finite span and tip vortices. Furthermore, a separation and re-attachment criterion will also be included so that the aeroelastic model can be used for both hover and forward flight for a range of angles of attack.

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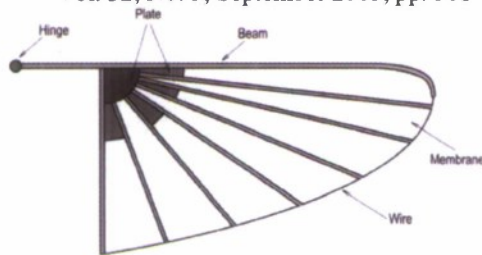


Figure 1: Structural dynamic model of a bio-inspired MAV wing

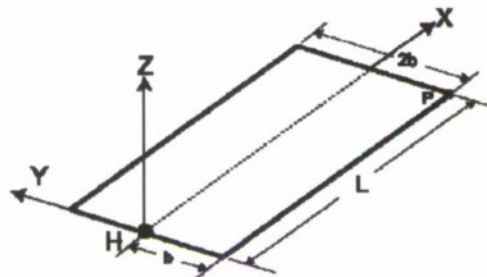


Figure 2: Rectangular plate used for preliminary studies

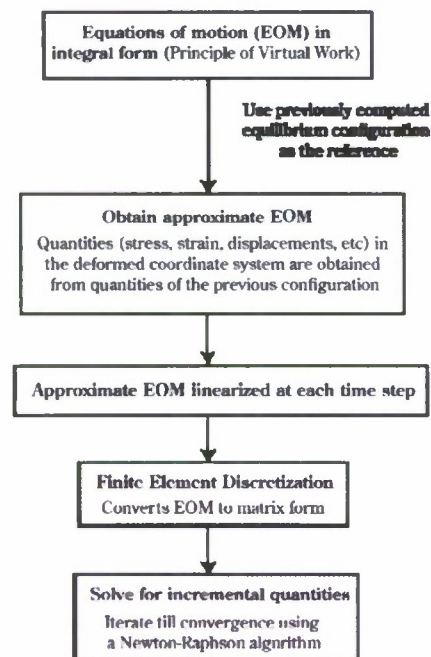


Figure 3: Schematic of the updated Lagrangian method

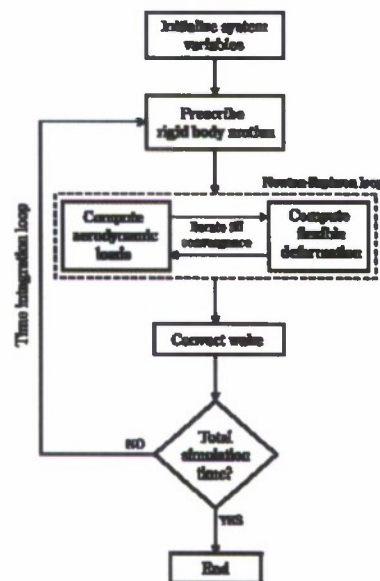


Figure 4: Schematic of the aeroelastic solution in MARC

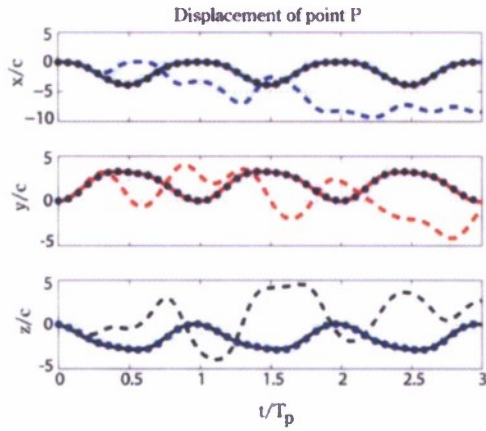


Figure 5: Implementation of wing kinematics: solid line – MATLAB computation, dashed line – rotation vector in MARC, circles – displacements in MARC

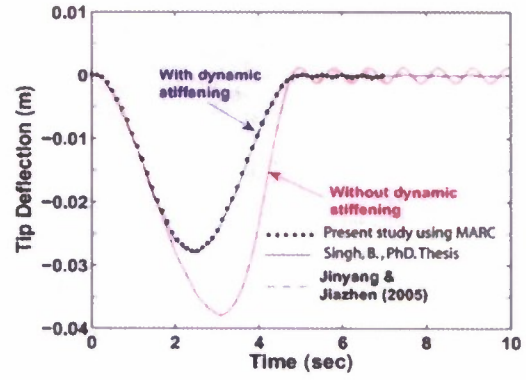


Figure 6: Effect of centrifugal stiffening. Results from Jinyang and Jiazhen presented in Ref. [24].

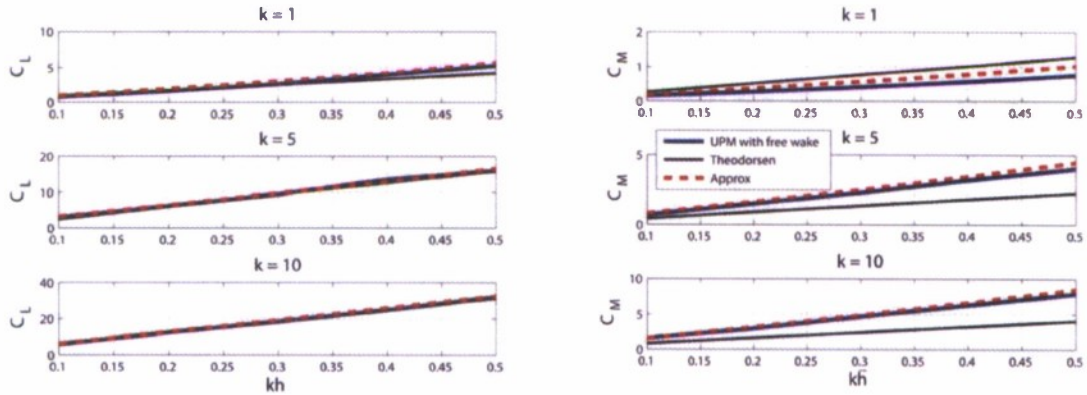


Figure 7: Lift and moment coefficients for a NACA0012 airfoil undergoing prescribed plunge motion. UPM results were obtained from Ref [10]. k and $\bar{h}$ denote reduced frequency and chord-normalized plunge amplitude respectively.

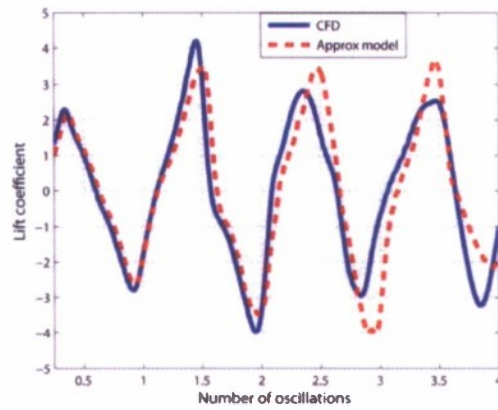


Figure 9: Lift coefficients for a rigid flat plate airfoil undergoing prescribed plunge motion in near hover conditions.

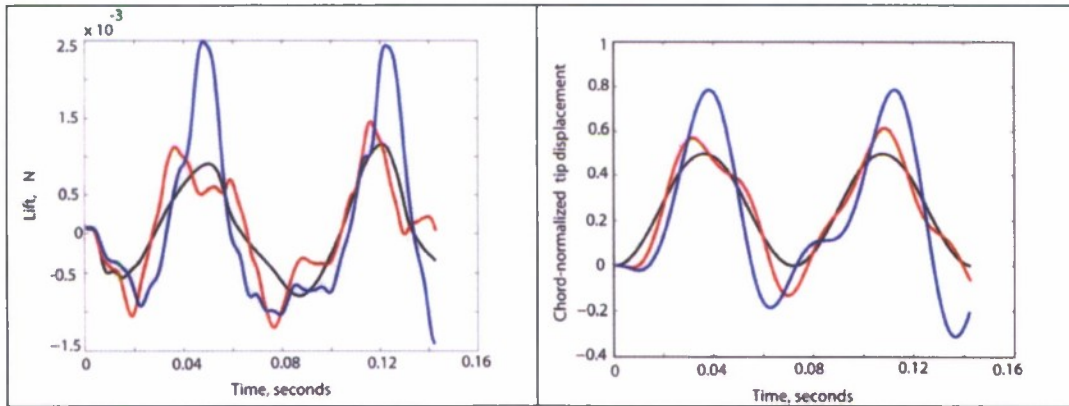


Figure 10: Lift and chord-normalized tip displacement of wings undergoing prescribed plunge motion for the case of hover [20]. Black – rigid wing, Red and Blue – flexible wings; Blue line corresponds to the most flexible configuration tested.