CHAPTER I.

LITERATURE REVIEW AND MODELING CONSIDERATIONS

1.1 Introduction

As the requirements for higher flexibility on high speed aircraft increase, so do the challenges of developing innovative design solutions. Whereas the increased flexibility is likely to provide enhanced aerodynamic performance, the aircraft must also be able to fulfill a multitude of missions in complex environmental conditions and to feature an expanded operational envelope and longer operational life. To achieve such ambitious goals, advanced concepts resulting in the enhancement of static and dynamic response of the multimission, highly flexible aircraft should be developed and implemented. One way of achieving such goals consists of the integration of advanced composite materials in the aircraft structures [1]. In this regard, it should be stressed that the directionality property featured by anisotropic composite materials is capable of providing the desired elastic couplings through the proper selection of the ply-anlge. However, such a technique is passive in nature in the sense that, once implemented, the structure cannot respond to the variety of conditions in which it must operate.

The above situation can be mitigated by incorporating into the host structure adaptive materials able to respond actively to changing conditions. In a structure with adaptive capabilities, the natural frequencies, damping and mode shapes can be tuned to reduce the vibration so as to avoid structural resonance and flutter instability, and in general to enhance the dynamic response characteristics. The adaptive capability is achieved through the converse piezoelectric effect, which consists of the generation of localized strains in response to an applied voltage. This induced strain field produces, in turn, a change in the dynamic response characteristics of the structure. It is proposed here to enhance the free vibration and dynamic response to external excitations of cantilevered structures by incorporating the adaptive capability referred to as induced strain actuation in conjunction with structural tailoring. Under consideration is a cantilevered structure, modeled as a thin/thick-walled closed cross-section beam made of anisotropic material. Implementation of the control laws relating the applied electric field to selected mechanical quantities characterizing the response of the host structure according to a prescribed functional relationship and/or state feedback results in eigenvalue/boundary-value problems. The solution consists of closed-loop eigenvalues/dynamic response characteristics, which are functions of the applied voltage, i.e., of the feedback control gain.

In this research, the task of enhancing the free and forced vibration characteristics of cantilevered structures made of advanced composite materials is accomplished through the synergistic combination of above mentioned control methodologies.

1.2 System Modeling Considerations and Nonclassical Effects

The great possibilities provided by advanced anisotropic composite materials can be used to enhance the response characteristics of cantilevered structures, in general and lifting surfaces of space vehicles, in particular. Due to their outstanding properties, such as high strength/stiffness to weight ratios, fiber-reinforced laminated thick/thin-walled structures are likely to play an increasing role, among others, in the design of advanced aircraft wings. Another reason for employing advanced composite materials in flight vehicle design lies in the fact that they permit the use of specific lay-up and fiber orientations so as to induce preferred elastic couplings [1-7]. In this context, a number of elastic couplings resulting from anisotropy and the ply-angle sequence of composite material structures can be exploited so as to enhance the response characteristics.

In the previous works [1, 8, 9],the wing structure was modeled as an anisotropic solid beam combining, in a coupled form, both Bernoulli-Euler bending and St.Venant twist features. The Bernoulli-Euler beam theory is based on the assumption that the cross-sections, after deformation, remain plane and normal to the bent axis of the beam and also postulates a linear strain distribution across the cross-section and ignores the influence of transverse shear deformations. As concerns torsion, within St. Venant's theory, it is assumed that the cross-sections of the beam maintain their original shape although they are free to warp in the axial direction. The warping displacement is postulated to be proportional to the rate of twist, which is assumed to be constant along the beam axis. However, these classical theories of bending and torsion may result in erroneous predictions, especially when the warping constraint is present. Within the warping constraint beam model, the rate of twist can not be assumed to remain constant along the axis of the beam. In contrast to this modeling of the wing structure, many researchers [2, 10-13] developed a more refined and more realistic model which consists of a thin/thick-walled closed section cantilevered beam. For such anisotropic cantilevered beams (of either solid or thin/thick-walled cross section), the warping inhibition induced by the restraint of torsion requires the discard of the St. Venant twist concept. In their works [6, 7, 14], Crawley *et al.* have contributed to the study of warping restraint effect to torsional vibration with bending-torsion coupling. Later on, Kaza and Kielb [15] have investigated the torsional vibration of rotating pretwist beams as aspect ratio was varied, including the warping effect. They suggested that the structural warping term must be accounted for modelling of blades even if isotropic materials were used. Song and Librescu [10] incorporated the effects of primary and secondary warping restraint in the study of composite thin-walled beam structure. Primary warping was referred to warping displacement of the middle surface. In addition, in these works, the necessity of incorporating transverse shear effect was underlined. It should be stressed here that the necessity of incorporating transverse shear effects arises not only from the fact that composite beams tend to be thicker than the standard metallic counterpart, but also from the fact that the advanced fiber composite materials exhibit high flexibilities in transverse shear, which, among other features, significantly lowers the natural frequencies [2, 15-17].

Timoshenko [18] has considered transverse shear deformation in the beam modeling. Later, Davis [19] and Jacobsen [20] have studied the effect of this term on natural frequencies of uniform metallic cantilever beams. Mindlin [21] and Reissner [22] have extended Timoshenko beam model to isotropic elastic plates. Kruszewski [23] has considered both transverse shear and rotary inertia terms in his vibration analysis of a uniform beam. Trail-Nash and Collar [24] have found that the effect of shear flexibility was more significant than that of rotary inertia. In all the above investigations, most of the papers included both effects of transverse shear and rotary inertia, however, warping constraint effect was not considered in spite of its importance. Reissner and Stein [25] introduced the effect of constraint against axial warping on the problem of coupling between bending and torsion of isotropic cantilever plates. Later Librescu *et al.* [26] have accounted this restraint in the aeroelastic divergence of multicell metallic wings.

One of the goals of this work is to incorporate, in a unified way, several essential effects which have importance in the design and the analysis of composite thin-walled beam structures, namely :

Transverse shear deformation

Composite material structures exhibit great flexibility in transverse shear, contradicting the usual assumption of infinite rigidity in transverse shear postulated by the classical theory. As a result, the transverse shear effect constitues an important factor in the behavior of composite thin-walled beams and, hence this effect will be taken into account in the analysis.

Warping restraint effect

As is well known, torsion related nonuniform warping occures when a section is restrained against out of plane deformation and/or when a non-uniform distributed torque is applied along the span of the beam. Therefore, as was reported [6, 14, 25, 27], the free warping assumption may result in erroneous predictions of the behavior of cantilevered type structures (such as, e.g. of airplane wings). Consequently, the warping restraint effect will be incorporated in this work.

Secondary warping

For the metallic thin-walled beam structures, the warping displacement of the middle surface (which is referred to as the primary warping) is usually more predominant than the secondary warping which is assumed to vary across the thickness [28]. As a result, warping displacement is usually assumed to be constant across the thickness and the secondary warping effect was often neglected in the previous analyses. However, when the thickness of the wall is not so small compared with the other dimensions of the beam and/or for composite structures which in general exhibit a weak rigidity in transverse shear, the secondary warping may constitute a dominant part of the warping displacement. In addition, for special shapes of the cross-section of beams (e.g. circular cross-section) for which the primary warping displacement vanishes, the secondary warping still exists [29]. In the present work, this effect will also be included.

The structure intended to be studied is that of a cantilevered beam, which among others, is specific to the aircraft wing type structure. It is clear that, for an accurate prediction of flight vehicle response characteristics, comprehensive structural models must be used. In the present work, the beam is modeled as a thin/thick-walled closed cross-sectional cantilevered beam composed of advanced composite material whose constituent layers feature elastic anisotropic properties. For illustrations purpose, a profile typical of supersonic wing airplanes is adopted, namely, the biconvex one [2].

1.3. Structural Tailoring Technique

Implementation of structural/aeroelastic tailoring has revealed great promise toward improving static and dynamic response characteristics, preventing vibration resonance and enhancing aeroelastic behavior.

For thin-walled composite beams, tailoring was carried out in a number of recent studies [2, 11] in which the possibility of generating desired elastic couplings beneficial to specific aeronautical problems was examined. For thin-walled beams the pioneering work was done by Rehfield and his co-workers [4, 5, 17]. These structural configurations are categorized circumferentially uniform stiffness (CUS) and circumferentially asymmetric stiffness (CAS) according to the lay-up of laminae on opposing flanges. For CUS configuration characterized by ply-angle distribution $\theta(y) = \theta(-y)$, the extensional, bending and extension-bending coupling stiffnesses are constant throughout the cross section and hence its CUS configuration was adopted by Atilgan (1989), Rehfield and Atilgan (1989), Hodges *et al* . (1989) and Rehfield *et al.* (1990). For a box beam, the ply layups on the opposite sides yielding such couplings are of reversed orientation and hence the name antisymmetric configuration was adopted by Chandra *et al.* (1990) and Smith and Chopra (1990, 1991) whereas circumferentially asymmetric stiffness (CAS) is characterized by ply-angle distribution $\theta(y) = -\theta(-y)$ which is also referred to as symmetric ply layup by Chandra *et al.* (1990) results in bending twist coupling. In this case extensional, bending-extension coupling and bending stiffness have constant magnitude around the upper cross section but different sign on the lower side.

1.4. Dynamic Response of Composite Wing Structures

A great deal of interest for a better understanding of the dynamic response behavior of composite structure subjected to time-dependent external excitations is manifested in the literature. This interest is due to the increased use of advanced composite materials in the various fields of the modern technology. In an earlier work, Bank and Kao [30] have analyzed free and forced vibration of thin-walled fiber reinforced composite material beams in the framework of the Timoshenko beam theory. It was shown that the effect of the shear deformation causes different prediction as compared to that obtained within the Euler-Bernoulli beam theory. Lee and Chao [31] considered the small-amplitude, undamped transverse vibration of a double-tapered circular beam with a linearly varying wall thickness attached to a central mass. The steady-state vibration produced by a harmonic force applied to the central mass was used to investigate the vibration absorption capabilities of the composite beam. Librescu, Meirovitch and Song [2] have developed a structural model and solution methodology for the advanced wing structure and later Song and Librescu [15] worked on the study of the bending vibration response of laminated composite cantilevered thin-walled box beam subjected to a harmonically oscillatory concentrated load. The main body of the available research works was devoted entirely to study the response behavior of composite plate and shell structures (see e.g. 32). Whereas a good deal of research work was devoted to the study of the eigenvalue problem of thin-walled composite beam [33, 34], little work has been done toward the study of the dynamic response of thin-walled beams in general and of their counterparts, with closed cross-section contour, in particular. The absence of such results is more intriguing as this structural model is basic when dealing with a number of important constructions such as airplane wing, fuselage, helicopter blades and turbine blades as well as many other ones widely used in mechanical engineering.

In this work the control of dynamic response characteristics of thin-walled composite beam using smart material technology will be investigated. The control capabilities achieved by a dynamic control law relating the piezoelectrically induced bending moment with selected dynamic response characteristics of the structure are implemented, which results in a closed-loop eigenvalue problem.

It is also clear that, for accurate prediction of structural response under complex static and dynamic excitations, powerful analytical tools are needed. As analytical tools, two methods of solution were explored and proved to be extremely efficient. The first is based on the Laplace transform technique [35] in the spatial domain and the second, referred to as the Extended Galerkin Method [42], is an approximate technique yielding results in excellent agreement with the ones obtained by means of the Laplace transform, but with less effort. The analytical developments in this work are general in the sense that they are valid for arbitrary beam cross sections.

It should be stated here that investigation of static and dynamic control of aircraft wing structures via the simultaneous implementation of induced strain actuation and structural tailoring is of recent vintage. Among the few investigations using both techniques, we single out Refs. 3 and 36. The present research, consistent with the approach in Refs. 37 and 38, represents a clear departure from the approach in Refs. 3, 39 and 40, in the sense that here a dynamic feedback control strategy is implemented. This enables us to control the free and forced vibrations and avoid the resonance phenomenon without weight penalties.

The following Chapters contain the details of a comprehensive research efforts devoted to this goal. The global constitutive equations of thin-walled beam wing structures made of advanced composite materials and incorporating active capabilities are first derived. Then, based on related work [2], the equations of motion and the associated boundary conditions for composite adaptive structures are derived and discretized via the Extended Galerkin's Method. The obtained results underline the fact that the simultaneous implementation of tailoring and active control technology can enhance the dynamic response characteristics of flight vehicle structures significantly.

Furthermore, this study has in view an assessment of the implications played on natural frequencies and dynamic response of thin-walled composite beam wing structure by the elastic coupling, transverse shear and warping restraint. With these facts in mind, the present work is intended to incorporate essential non-classical effects which are of considerable importance towards the accurate prediction and control of the vibrational behavior of composite wings.