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A method for nonlinear aeroelasticity trim and stability analysis of very flexible aircraft based on co-rotational theory

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ABSTRACT

Very flexible aircraft with high aspect ratio wings subjected to aerodynamic loads undergoes large deformation, which will lead to distinct changes on the mass distributions, stiffness characteristics and aerodynamic characteristics of the complete aircraft. The aeroelasticity and flight dynamics of such aircrafts are nonlinear and the linear elastic theory model cannot be used. A new method is developed for the analysis of nonlinear aeroelasticity and flight dynamics of very flexible aircraft through combining the co-rotational beam theory with the modified ONERA dynamic stall model. Based on a form of co-rotational technique which is external to the element, a spatial two-node beam element, which depicts the geometrically nonlinear dynamic characteristics of the flexible wing, is developed. Both tangential stiffness matrix and mass matrix of the beam element are formulated to establish the nonlinear dynamic equations. In addition, the modified ONERA dynamic stall model is adapted to evaluate the unsteady nonlinear aerodynamic loading of the very flexible wing. Using the present method, the nonlinear aeroelastic response, trim and stability characteristics of a very flexible aircraft are predicted in this paper. The obtained results show a good agreement to the literature, which indicates that the present method is accurate and efficient.

1. Introduction

HIgh-altitude and ultra-long-endurance solar-powered unmanned aerial vehicles (UAVs) which can fill the gap between low-orbit satellites and conventional fuel-powered UAVs, are designed to perform a very large spread of low cost continuous coverage of a geographic area missions, such as meteorological monitoring, coastal surveillance, tele-communication relay, and so on (Flittie and Curtin, 1998; Cestino, 2006; Romeo et al., 2004; Noll et al., 2004; Min et al., 2010; Wei et al., 2014). As the energy available from solar cells is very limited, the flexible structural design strategy is usually introduced to minimize the structural weight and to maximize aerodynamic efficiency of high aspect ratio wings. For example, the conventionally

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Nomenclature

A_ρ	mass per unit length
A_a	angular acceleration in body attached frame
D	drag
e	unit vector of coordinate system
f_l	local nodal generalized forces
f	global nodal generalized forces
f_{mass}	inertial force vector
g	gravitational acceleration
I	unit matrix
I_{xyz}	global reference coordinate system
J_ρ	mass moment of inertial tensor
J_{trim}	criterion function
k	linear momentum per unit length
L	lift of aerodynamics
M	moment of aerodynamics
K_l	linear stiffness matrix
K_T	tangential stiffness matrix
$K_{T\sigma}$	geometric stiffness matrix
N	interpolation function
p_l	local nodal displacements
p	global nodal displacements
R	rotation matrix
$S_{k,T}$	Jacobian matrix
S	skew-symmetric matrix
S_m	first moment area of a section
T	transformation matrix
u	aircraft body attached reference coordinate system
u_l	axial deformation
$\dot{u}$	linear velocity
V	flow velocity
δW	virtual work
w	angular velocity in body attached frame
π	angular momentum per unit of length
γ	pseudo-vector
Δ	increment
$\dot{\vartheta}$	angular velocity in inertial frame
$\ddot{\vartheta}$	angular acceleration in inertial frame
α,β,r	integration parameters
Γ	vortex strength
ρ	density of air

Subscript

i,j	nodal number of beam element
m	'mean configuration' coordinate system
e	element coordinate system
l	local

powered high altitude long endurance (HALE) UAV of Global Hawk has an aspect ratio of 25 and a surface density of the wing structure of 53 kg/m^2. While, the aspect ratio of the solar-powered UAV of Helios is 31 and the surface density of the wing structure is only 3.2 kg/m^2. High aspect ratio wings with extremely low weight will undergo large deformation during normal flight, which will lead to distinct changes on the structural stiffness characteristics, the mass and the aerodynamic loading distribution of the aircraft. In that case, nonlinearity coupling arising from large wing deflection may play an important role on the vehicle aeroelasticity and flight dynamics, as it was sadly illustrated by the mishap of NASA's Helios. Due to the complexity of the problem, these nonlinear problems are still hotspots of research. Therefore, precise analysis methods for nonlinear aeroelasticity and flight dynamics of high aspect ratio flexible aircraft need urgently to be developed to deal with its nonlinear aeroelastic, trim, flight stability and other characteristics (Noll et al., 2004).

The elastic deformation of a very flexible wing under aerodynamic loads belongs to typical geometrically nonlinear problems with large displacement but small strains. Currently, there are three main kinds of approaches to analyze the flexible structure with the geometric nonlinearity, which are all based on finite element method (FEM) but with every one choosing a different selection of independent degrees of freedom including displacements, strains, and combined velocities and internal forces of the intrinsic formulation (Palacios et al., 2010). The intrinsic beam model was used to describe the geometrically large deformation of flexible wing (Hodges, 2003). Combining intrinsic beam equations with finite-state induced flow model (Peters, 1985), Patil and Dowell (2001), Patil and Hodges (2006), Chang (2008), and Patil et al. (1999) developed a nonlinear aeroelastic trim and stability analysis method that was suitable to HALE aircraft, and their computation codes are referred as NATASHA. In literature (Zhang and Xiang, 2008), Zhang researched the nonlinear aeroelastic response of a very flexible wing based on intrinsic beam element and ONERA dynamic stall model (McAlister and Lambert, Petot).

Further, in the development of nonlinear aeroelastic and flight dynamics analysis tools, Cesnik and Su (2005), Su and Cesnik (2006), Shearer and Cesnik (2007) Shearer and Cesnik (2008), and Su (2008) developed the University of Michigan's Nonlinear Aeroelastic Simulation Toolbox (UM/NAST) which combines nonlinear strain-based beam model, unsteady aerodynamics with simplified stall model and a six degree of freedom flight dynamic formulation.

Other research works include: Shams et al. (2012) and Zhao and Ren (2011) established a geometrically nonlinear model of flexible wing structure through using nonlinear general flexible Euler–Bernoulli beam equations and multi rigid body theory, separately. The advantage of relatively low order of intrinsic beam theory or strain-based theory can provide significant reduction in computation cost of solving dynamics problems. However, its independent variants are not straightforward and lead to this method being less versatile than the displacement based element method (Patil and Dowell, 2001).

Presently, there are three main methods for the solving of displacement based beam element, which are Total Lagrangian (TL), Update Lagrangian (UL) and Co-rotational (CR) formulation, respectively. Based on the linearization of UL methods, Yang et al. (2012) (Chuan and Chao, 2011) studied the nonlinear aeroelastic and flight load characteristics of a very flexible