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Deployable wing model considering structural flexibility and aerodynamic unsteadiness for deployment system design

Keisuke Otsuka [a,*], Yinan Wang [b], Kanjuro Makihara [a]

[a] Department of Aerospace Engineering, Tohoku University, 6-6-01 Aramaki-Aza-Aoba, Aoba-Ward, Sendai 980-8579, Japan
[b] Department of Aeronautics, Imperial College, London SW7 2AZ, United Kingdom

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ABSTRACT

In future, wings will be deployed in the span direction during flight. The deployment system improves flight ability and saves storage space in the airplane. For the safe design of the wing, the deployment motion needs to be simulated. In the simulation, the structural flexibility and aerodynamic unsteadiness should be considered because they may lead to undesirable phenomena such as a residual vibration after the deployment or a flutter during the deployment. In this study, the deployment motion is simulated in the time domain by using a nonlinear folding wing model based on multibody dynamics, absolute nodal coordinate formulation, and two-dimensional aerodynamics with strip theory. We investigate the effect of the structural flexibility and aerodynamic unsteadiness on the time-domain deployment simulation.

1. Introduction

Currently, it is difficult to improve the flight ability of airplanes by only exploitation of lightweight materials and optimization of the wing shape. One of the practical ways to advance flight ability is the use of morphing wings [1]. A morphing wing transforms depending on the flight condition to provide better flight ability and to save storage space. In particular, a deployment-type morphing wing, illustrated in Fig. 1, is gaining attention because it transforms much more drastically than the morphing wings proposed in the past. The concept of the deployment-type morphing wing has been proposed by several organizations. Thus, the wing has several names, such as multisegmented hinged wing, multisegmented folding wing, folded wing, and deployable wing. This paper utilizes the name "deployable wing". Lockheed Martine proposed a servo-actuated deployable wing, as mentioned in [2]. In this scheme, the deployable wing can be folded/deployed any number of times in the flight by using the servo actuator. The servo-actuated deployable wing proposed by Lockheed Martine is the most widely used research subject in the area of deployable wings. In comparison, the Japan Aerospace Exploration Agency (JAXA) attempts to utilize a spring-actuated deployable wing for the Mars-airplane [3]. The Aerial Regional-scale Environmental Survey (ARES) [4] is also building a Mars-airplane with a spring-actuated deployable wing. A spacecraft and a rocket are generally utilized as carriers to take the Mars-airplane from the earth to Mars. However, the carriers do not have a large storage space to store the airplane. Thus, the Mars-airplane requires deployable wings to save

* Corresponding author.
E-mail addresses: otsuka@ssl.mech.tohoku.ac.jp (K. Otsuka), yw3@hotmail.co.uk (Y. Wang), makihara@ssl.mech.tohoku.ac.jp (K. Makihara).

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Nomenclature

A	section area of beam [m^2]
$\mathbf{A}_{mn}$	elastic force matrix due to axial deformation (m, n = 1, 2)
b	half chord [m]
$\mathbf{B}_{mn}$	elastic force matrix due to bending deformation (m, n = 1, 2)
e_i	generalized nodal coordinate (i = 1–10)
$\mathbf{e}$	vector of generalized nodal coordinates
$\mathbf{e}_\mathrm{f}$	vector of generalized nodal coordinates of flexible structural model
$\mathbf{e}_\mathrm{p}$	vector of generalized nodal coordinates related to planar axis motion
$\mathbf{e}_\mathrm{r}$	vector of generalized nodal coordinates of rigid structural model
$\mathbf{e}_\mathrm{t}$	vector of generalized nodal coordinates related to torsion
F_θ	actuator torque [N m/rad]
$\mathbf{F}_\mathrm{actuator}$	generalized force vector due to actuator force
$\mathbf{F}_\mathrm{aero}$	generalized force vector due to aerodynamic force
$\mathbf{F}_\mathrm{elastic}$	generalized force vector due to elastic force
h	height of heaving motion of airfoil [m]
$\mathbf{i}$	unit vector of x-axis of local coordinate system of element
$\mathbf{j}$	unit vector of z-axis of local coordinate system of element
J	moment of inertia [kg m^2]
l	element length [m]
L	aerodynamic lift or body length [N]
m	mass per unit length of the beam [kg/m]
M	aerodynamic pitching moment [N m]
$\mathbf{M}$	mass matrix
$\mathbf{r}$	position vector of node
$\mathbf{r}_x$	vector perpendicular to cross section at node
t	time [s]
T	kinetic energy [J]
$\mathbf{T}$	elastic force matrix due to torsional deformation
U	airspeed of free stream [m/s]
X_r	X coordinate of center of gravity of body
Y_r	Y coordinate of center of gravity of body
α	angle of attack, which also equals torsional angle of beam [rad]
$\boldsymbol{\gamma}$	terms obtained from second order differential of constraint vector $\boldsymbol{\Phi}$
θ	angle between tangential line of point on beam and X-axis of inertial frame [rad]
$\boldsymbol{\lambda}$	vector of Lagrange's undetermined multipliers
Π	elastic energy [J]
Π_axial	elastic energy due to axial deformation [J]
Π_bending	elastic energy due to bending deformation [J]
Π_torsion	elastic energy due to torsional deformation [J]
μ	linear density of beam [kg/m]
ρ	air density [kg/m^3]
$\boldsymbol{\Phi}$	constraint vector
$\boldsymbol{\Phi}_\mathrm{after}$	constraint vector after latching
$\boldsymbol{\Phi}_\mathrm{before}$	constraint vector before latching
$()_\mathrm{Body\ 1}$	value related to body 1
$()_\mathrm{Body\ 2}$	value related to body 2
$()_\mathbf{e}$	$\partial/\partial\mathbf{e}_\mathrm{f}$ or $\partial/\partial\mathbf{e}_\mathrm{r}$
$(\ )_\mathrm{r}$	value related to rigid structural model
$(\ )_t$	$\partial/\partial t$
$(\ )_\mathrm{total}$	value related to superimposed matrix and vector
$(\ )_x$	$\partial/\partial x$
$(\ )^\mathrm{A}$	value related to node A
$(\ )^\mathrm{B}$	value related to node B
$(\ )^\mathrm{S}$	value related to steady aerodynamic force
$(\ )^\mathrm{QS}$	value related to quasi-steady aerodynamic force

storage space. The spring-actuated deployable wing concept is also utilized on the Earth. The flying radar target (FLYRT) mentioned in [5] and the Wide area surveillance projectile (WASP) mentioned in [6] are the representative spring-actuated deployable wings utilized in aircrafts for earth-related applications. In these cases, the wing is folded, and then the airplane is stored in a shell. The shell is launched to a distant area by a canon. The shell releases the airplane over the distant area. The airplane deploys the wing during its flight. When the wing is completely deployed, the wing components are latched to prevent wing reversal in the folding direction.

To design a model-based deployment system, the deployment motion has to be simulated in the time domain using a numerical wing model. Several models of the servo-actuated deployable wing of Lockheed Martine have already been proposed to perform frequency-domain flutter analyses [7–9]. The models are linear, which suggests that the model is limited to the small elastic deformation. Further, the models cannot be applied to the time-domain deployment simulation because the deployment motion includes not only the elastic deformation but also the large rigid body rotation around the joint. To express the mixed motion involving the elastic deformation and rigid body motion, the wing model has to be nonlinear. The formulation of such a nonlinear model is considered an important research subject by the current aerospace community. In 2010, Palacios et al. [10] and Su and Cesnik [11] presented nonlinear models for the next-generation highly-flexible-wing airplanes that included the mixed motion of elastic deformation and rigid body motion. These nonlinear models are useful for various time-domain simulations of the next-generation airplanes such as gust response control [12] and aeroelastic energy harvesting [13].

Recently, nonlinear models of the deployable wing were proposed by using multibody dynamics (MBD) [14] for the time-domain deployment simulation. MBD is a theory to systematically derive the numerical model of a multibody system that is composed of many bodies connected by various joints. Then, the dynamic motion of the numerical multibody model can be simulated by using computer-based techniques. MBD was developed in the mid-1960s by Hooker and Margalies [15] and