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On dynamic stiffness of spacecraft flexible appendages in deployment phase

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ABSTRACT

Deployment inertial effects of a spacecraft appendage on its flexible dynamics are investigated. The Euler–Bernoulli beam theory and the actual deployment profile, in which appendage axial motion accelerates from static state and then decelerates to end at zero velocity and acceleration, are employed. The study is concentrated on the arm dynamic stiffness introduced by inertial effects of the arm deployment, and the resultant effects on the arm flexible motions. Lagrange's equations and some appropriate shape functions in the series approximation method are employed to study the arm lateral elastic displacements. Finally a system of ordinary differential equations with time varying coefficients governing the system dynamics is developed. Solving the equations of motion reveals the importance of dynamic stiffness effects in precise positioning of appendages tip-payloads. The results indicate that the effects of deployment dynamic stiffness, however, vary significantly with the payload mass and arm deployment time. This investigation can help designers to understand in-depth the effects of axial inertial forces during arm deployment for trajectory planning and designing efficient deploying profile to increase the performance of the control devices.

1. Introduction

Axially moving robot arms appear in a wide range of space applications such as robot manipulators, deploying antennas and inspection booms. These robot arms may carry a payload such as inspection devices. For the sake of clarity, this work refers to such complete deploying devices as "system" in this paper. The tip responses of such arms, during a typical deployment, may affect the payload safety and operation; thus it is required to clearly identify the system dynamics through appendage deployment profile. Deployment acceleration imposes some inertial forces on arm and affects its lateral dynamic responses. In order to have a clear understanding of the overall system dynamics, the inertial effects of deployment profile are required to be investigated; the results provide design considerations for deployment profile of the mechanisms. In this work a flexible link traveling through its ideal frictionless joint while carrying a tip mass on its free end is considered. This work would like to investigate the deployment inertial effects on the arm elastic dynamics during unfolding. For such a problem, however, there are not many works in the literature that address the complete physical phenomenon and focus on the induced dynamic stiffness. Tabarrok et al. [1] have provided studies on the dynamics of the flexible beam in constant velocity deployment. In the same line, Wang and Wei [2,3] studied the deployment of no tip mass flexible robot arm through Newton's second law while left out certain terms. Moreover, Kalaycioglu and Misra [5] provided the approximate analytical solutions for the equations of motion of no tip mass deploying beam while the effect of the axial acceleration on the total potential energy has not been simulated. On the other hand, Kim and Gibson [4], Stylianou and Tabarrok [6] and Al-Bedoor and Khulief [7] applied the finite element approach to model a sliding flexible link. Stylianou et al. [6] modeled the tip mass on the arm through finite element method (FEM) by developing elements with time-varying domains. While, Esmailzadeh and Nakhaie-Jazar [8], Esmailzadeh and Jalili [9] and Rastgoo et al. [10] studied the vibration of beams with tip mass and constant length due to base motion, following the assumed mode method. There are some works which have concentrated on suppressing tip vibration of spacecraft booms. In this line for constant length booms, Hu and Ma [11] have simulated the spacecraft as a hub with a cantilever flexible beam appendage which can undergo a single axis rotation; they have investigated the boom vibration reduction during attitude maneuver. As well, tip-position control of a deployable space structure has been investigated by Oh and Bang [12] to minimize the effect of bending vibration in a deployable manipulator. Due to the importance of the ap-

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pendage vibration in spacecrafts, some researches have analyzed thermally induced vibrations of spacecraft deployable appendages; for example, Shen et al. [13] and Li and Wang [14] applied the absolute nodal coordinate formulation to analyze the flexible body dynamics of deployment structures under different temperatures to simulate space environments. The concentration of these references is not on the spacecraft appendage deploying phase and in the most of them the vibration of the deployed appendages has been analyzed. Considering arms with time varying length, Bagheri Ghaleh et al. [15] have suggested a new approach to find the semi-analytical solutions for the deploying arm carrying tip mass. In addition, Wang et al. [16] and Tang et al. [17] investigated the dynamics of deploying flexible arm without tip mass. The previous researches investigating deploying arms applied some usual mathematical functions to explain deployment profiles while factual trajectory of deployment and retraction has not been completely considered. An operational deployment should start at axial static state and after attaining the final required length then the axial movement comes back at rest. In this line, Bagheri and Malaek [18] have presented a real continues trajectory for the arm deployment and they applied it in their other studies on dynamics of spacecraft deploying appendages [19,20]. If the factual deployment profile is not employed in the system simulation then the final axial positioning of the arm tip will not be stable due to the existence of the axial velocity and acceleration. While none of the previous researches have been concentrated on investigating inertial effects of the arm deployment profile on the system dynamics through factual trajectory of deployment and retraction; the main contribution of this work is to investigate the inertial effects of a factual Axial Deployment Speed Profile (ADSP) and to present the resultant phenomenon which reveals the importance of the corresponding stiffness terms and the produced errors while ignoring them. Generally in the present work the flexible robot arm with end mass during actual deployment is studied. Inertial effects of the axial acceleration profile impose tension and compression forces on the arm which cause positive and negative stiffness effects, this dynamic stiffness (DS) is taken into account through deriving the equations of motion in the suggested deployment profile and investigated completely in this study.

In the next sections, following an approach the equivalent dynamic system is developed such that common shape functions of the without tip mass arm could be employed in the simulation of the carrying tip mass arm by assumed mode method. Finally using these shape functions, the series form is applied to mathematical simulation of the lateral elastic displacement and the equations of motion are derived as a system of ordinary differential equations (ODE) with time varying coefficients. Moreover, following the approach outlined by Stylianou and Tabarrok [6], an alternative simulation by finite element method is done and the solutions are compared to demonstrate the validity of the obtained arm response at the considered ADSP. Solving the equations of motion, the effects of DS on the arm response are investigated while various deployment time and various payload masses are studied. In addition, the effects of deployment/retraction time and tip payload mass on the number of appropriate terms to series convergence are investigated.

2. Approach

A flexible link that can be modeled as an Euler–Bernoulli beam is considered while undergoes deployment from a large spacecraft and carries a tip mass on its free end (see Fig. 1). The in-orbit deployment is considered for the arm and therefore the gravity free condition is assumed in this simulation. The arm length which varies with time, t, is denoted by $L(t)$. It is supposed that the arm is thin and 'inextensible' with a constant cross-sectional area A,

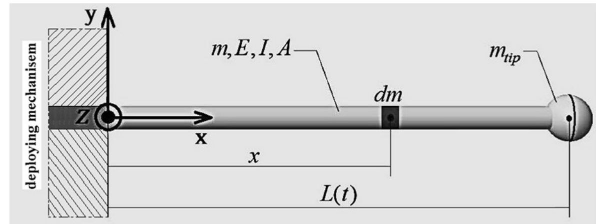

Fig. 1. Deploying flexible arm carrying payload.

moment of inertia I, mass per unit length m and modulus of elasticity E. The deploying arm carries a payload at its free end which can be modeled as a lumped mass, m_{tip}, concentrated on the arm tip. In addition, as the total system response may affect the arm axial velocity and acceleration then it is assumed that robust design of deploying mechanisms provides the considered deployment profile.

2.1. Equations of motion

The arm lateral displacements at the distance x from the root are denoted by w and v in the y and z directions, respectively. For very flexible and long arms, significant axial displacement is resulted from large transverse deflections. The axial displacement u of an element at distance x is obtained from the following equation in which v_x and w_x denote differentiation of v and w with respect to x.

$$u(x,t) = \int_0^x \left[(v_x)^2 + (w_x)^2\right] dx \tag{1}$$

As can be seen, u is a second order quantity with respect to the transverse displacements v and w; and its effect could be neglected when the transverse displacements v and w are small quantities. While non-spinning spacecraft is considered, the transverse displacements remains small with respect to the beam length through the supposed loading condition; therefore the axial displacement u is neglected and therefore a beam element, dm, has a velocity vector, $\mathbf{V}$, which can be presented by

$$\mathbf{V} = [\dot{L} \quad \dot{v} + \dot{L} v_x \quad \dot{w} + \dot{L} w_x]^T \tag{2}$$

the total kinetic energy will be as

$$K = \frac{1}{2}\int_0^L m\left(\left(\frac{\partial v(x,t)}{\partial t}\right)^2 + \left(\frac{\partial w(x,t)}{\partial t}\right)^2 + \dot{L}^2\right) dx \tag{3}$$

Here v_{xx} and w_{xx} denote the second order differentiation of v and w with respect to x, the total potential energy is

$$U = \frac{1}{2}\int_0^L EI\left[(v_{xx})^2 + (w_{xx})^2\right] dx + \frac{1}{2}\int_0^L P_x\left[(v_x)^2 + (w_x)^2\right] dx \tag{4}$$

The second term in the total potential energy of the arm produces dynamic stiffness (DS) effects; in which P_x is the axial force at any section. Here, it is caused by the inertial effects of the arm axial acceleration through the deployment phase, which is

$$P_x = -\left(m\left(L(t) - x\right) + m_{tip}\right)\ddot{L}(t) \tag{5}$$

The elastic displacements w and v are expanded in series approximation as follows [2,5,16]:

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