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Analytical and numerical study of the buckling of planar linear array deployable structures based on scissor-like element under its own weight

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A B S T R A C T

This paper aims at investigating the buckling load of fully deployed linear array deployable structure based on scissor-like element (SLE) under its own weight. The deployable structure has been widely researched both in geometric configurations and structural dynamic characteristics. However, when the number of elements or degree of deployment exceeds the predetermined range, even if there is no external load, deployable structure will automatically collapse under its own weight. To address this issue, this paper derives a new stability model based on linear elastic analysis and energy method to compute the buckling load caused by its own weight for avoiding the structural instability, which can be applied to a linear array deployable structure with n SLEs. In the process of calculation, the first SLE is taken for mechanical analysis and the results are extended to any unit. In the sequel of this process, the scissor deployable structure is equivalent to a uniform solid column and its buckling condition under self-weight is obtained based on the principle of potential energy. Also, the effect of various parameters that affect the instability of the structure, such as the number of elements, bar length and degree of deployment is investigated, and the results of the theoretical analysis are verified through a comparison with the simulation results in ANSYS, which show that the new stability model proposed here can predict the buckling load of scissor deployable structure.

1. Introduction

Deployable mechanism is the basic system of general spatial deployable structure, which is the basic structural mechanism element that helps to implement the morphological changes and expansion-folding process of the structural mechanism [1]. The scissor deployable structure researched in this paper is one of the linear deployable mechanisms where scissor-like element (SLE) with the movement contractive function is the basic unit, which consists of pairs of straight bars connected by pivots. A SLE unit is any "X" unit where all of the joints are revolute joints which allow the pairs of bars to rotate freely about a pivot but restrains all other degrees of freedom. Meanwhile, its end points can be hinged to the end points of other SLEs forming a complicated linear array structure, namely a SLE column. A number of representative foldable

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structures are composed of SLEs, such as planar deployable mast, three-dimensional cylinder grid system, square cross-section mast and so on [2].

Since the beginning of the 1960s [3], many applications for deployable structures have been found ranging from architecture [4] (such as opening and closing dome, disaster relief housing), aviation [5] (such as retractable apron, temporary hangar), aerospace [6,7] (such as large-diameter antenna, solar sail) and in other areas. In the field of aerospace, deployable structures have been widely surveyed and utilized by many research institutions and scholars [8] with the increasing needs of complex space missions [9–11]. Because the volume of the space structure which needs to be carried has become increasingly large and the storage of the launch vehicles is limited, the spatial structure is sent to space with a compact shape and stably expanded as desired geometric configurations after reaching the predetermined spatial orbit. Therefore, the research associated with deployable structure has become a hot topic recently.

Chew and Warnaar [12] studied the procedure of conceptual design of deployable structures systematically by way of a mathematical technique known as graph theory, and the resulting approach brought about all possible conceptual designs based on a given number of links and nodes within a module of a deployable structure. Kipe et al. [13] proposed a new linkage type for resizing polygonal and polyhedral shapes and analyzed its kinetic characteristics, indicating that the reasonable choice of the linkage type during expected deployment was very important. On the basis of the basic module [14–16], Guest and Pellegrino [14] presented a model which consisted of identical triangular panels on a helical strip and had a small internal displacement inextensional mechanism. Also, it has been shown broadly that many triangulated cylinders can be folded down to a compact stack of plates, where only small strains are imposed during folding. Gantes et al. [15] presented a new concept of self-stabilizing deployable structures featuring stable, stress-free states in both deployed and collapsed configuration. Also, he used a large displacements/small strains finite element formulation to trace the nonlinear load–displacement curve, and to obtain the maximum internal forces that occur in the members of the structure during deployment. Chen and Guan [16] designed a large deployable hexapod paraboloid antenna for space application, of which the most significant feature was that no mechanism is locked during the deployment compared with previous varied deployable units. From the dynamic stability point of view [17,18], Li et al. [17] dealt with the effects of joint clearance and link flexibility on the dynamic characteristics of deployable space structures (DSS) using a virtual experimental modal analysis (VEMA) method. Also, he analyzed the effects of clearance size and gravity on the dynamic characteristics of the DSS. Meanwhile, Zhang et al. [18] took into account the stability and stabilization of a deployable flexible beam. The boundary controllers were proposed for the structure, which may dissipate the unwanted vibration and rotation energy of the structure, thus stabilizing the structure during all the motion phases.

In addition, the current research on the deployable structures has mainly concentrated on the geometric configurations [19–22] and structural dynamic characteristics [23–25], especially in its expandable performance. Chen [26] explored the possibilities of systematically constructing large structural mechanisms using existing spatial overstrained linkages with only revolute joints as basic elements. Moreover, following the mathematical derivation, the problem of connecting two similar Bennett linkages into a mobile structure, which other researchers were unable to solve, has also been solved in her dissertation. Zhong and Pellegrino [27] extended and generalized the standard trellis-type foldable structure consisting of two sets of parallel straight rods connected by hinges using a new two-dimensional foldable structure. Their discovery can be exploited to investigate the structural layouts of flat and curved structures. Sun et al. [28,29] extended the screw theory to analyze the mobility and dynamics of the deployable structure with scissor-like element. They also derived an efficient solution formulation and provided the theory guidance for complex multi-closed loop deployable structure. Furthermore, Cai et al.[30] did the mobility analysis of generalized angulated scissor-like elements with the reciprocal screw theory. It has been proven that both types of generalized angulated element (GAE) are movable because the terminal constraints exerted to the common joint by the two linkages are equal. In addition, the dynamic performance of deployable structure constituted by scissor unit mechanisms with clearance joint was investigated precisely by Li et al. [31]. He used an improved Gonthier nonlinear continuous contact force model and LuGre model to evaluate the effect of clearance on the structure. Also, a considerable amount of experimental and theoretical works associated with clearance joints have been the subjects of many investigations.[32–34] Moreover, the influences of the clearance size, clearance position, bar flexibility, and number of clearance joints on the dynamic responses of multibody systems have been quantified by various references [35–37]. Muvengei et al. [35] used a slider-crank mechanism as a demonstrative example to study the nine simultaneous motion modes at two revolute clearance joints together with their effects on the dynamic performance of the system. Also, the parametric effects of differently located frictionless revolute clearance joints on the overall dynamic characteristics of a multi-body system was studied by Muvengei et al. [36]. Clearances of joints and flexibility of members were considered by Yan et al. [37] in modeling dynamic equations to accurately capture dynamic performances of deployable structures used for spacecrafts in orbit. It should be highlighted that the magnitude of impact force is reduced due to the flexibility of members, and the deployment angle of deployable structure is disturbed by the joint clearance.

However, there are few studies on the stability and critical load of deployable structure, especially the instability caused by the weight of the structure. Actually, since the elastic curve and the buckling load of the slender column were expounded by Euler, the influence of the stability on the structure performance has already attracted wide attention of scholars [38,39]. Raskin and Roorda [40] studied the nonlinear characteristic of a uniform pantographic column in compression, indicating that the axial stiffness of the pantographic column is greatly increased and the snap-through buckling considerably postponed if one additional constraint is introduced. Li et al. [1] established a structural instability limit load expression of SLE based on the analysis of the elastic deformation of bar, and the expression was extended to the array combination of deployable structure. He also pointed out that the structural stability gradually decreased with the increase of the number of units or the bar flexibility, and the degree of deployment cannot be used separately as the bases for judging structure

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