Mechanics of Materials 79 (2014) 1–14

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

A multiscale co-rotational method for geometrically nonlinear shape morphing of 2D fluid actuated cellular structures

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ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form 6 August 2014
Available online 27 August 2014

Keywords:
Fluid actuated
Cellular structures
Geometrically nonlinear analysis
Multiscale finite element method
Co-rotational formulation

ABSTRACT

This work investigates geometrically nonlinear shape morphing behaviors of the adaptive bio-inspired fluid actuated cellular structures. An efficient multiscale co-rotational method based on the multiscale finite element framework is proposed for the geometrically nonlinear analysis of the fluidic cellular structures composed of periodical microscopic fluid inclusions. In this method, the multiscale base functions are firstly constructed to establish the relationship between the small-scale fluctuations of the microstructures and the macroscopic deformation on the coarse scale mesh. And then the co-rotational formulation is integrated to the multiscale method to decompose the geometrically nonlinear motion of the coarse-grid element into rigid-body motion and pure deformational displacements. With these formulations, the large displacement-small strain nonlinear problems of the fluid actuated cellular structures can be resolved on the multiscale co-rotational coarse-grid elements with little work. The numerical results indicate that the present multiscale algorithm is simple, accurate and highly efficient and can provide an alternative to model the fluid actuated actuators for morphing wings.

1. Introduction

Biologically inspired actuators have receiving growing interest in recent year. Plants such as *Dionaea muscipula* (Venus flytraps) possess structural and shape adapting functions by actively altering the cell pressures. The leaves of these plants are hydraulic actuators that do not require any complex controls and keep an energy efficiency which is unmatched by natural or artificial muscles (Pagitz et al., 2012; Stahlberg, 2009). Therefore, the bio-inspired fluidic cellular materials that develop pressure and hence strain similar to plants, possess some special features, such as light weight, strong energy absorption capability, adaptive ability and large actuation (Luo and Tong, 2013a). These attractive features make the fluidic cellular structures to be useful for smooth shape control. For instance, their potential applications to morphing flexible aircraft wings have been experimentally validated by several authors (e.g. Barbarino et al., 2011; Barrett and Barrett, 2014; Bowman et al., 2007; Gomez and Garcia, 2011; Matthews et al., 2006; Stanewsky, 2001).

With the inspiration of the cellular fluid systems in natural plants, the adaptive pressure cellular materials/structures have recently appeared. In the plants, the fluid pressure difference amongst adjacent cells can be generated by the fluid deliver system of the biological membrane. These pressure differences can result in individual

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http://dx.doi.org/10.1016/j.mechmat.2014.08.004
0167-6636/

cell to expand or shrinkage and hence accumulate deformations over all cells in the plants. In other words, the structural morphing of the plants can be obtained by adjusting the differential pressure amongst adjacent cells. Several researchers have been utilized the morphing mechanism of the plants in the design of adaptive structures. Matthews et al. (2006) studied the bioenergetics of a prototype nastic structural system which consists of an array of cylindrical micro-hydraulic actuators embedded in a polymeric plate. Thereafter, Freeman and Weiland (2009) further designed the nastic materials to mimic bulk deformation similar to nastic movements in the plant kingdom. In their works, the controlled transport of charge and fluid across a selectively permeable engineering membrane employing biological process was employed to achieve bulk deformation. And their experiments demonstrated that the bio-inspired actuator can provide large mechanical force from chemical energy and can response quickly. In addition to the above works, some other researchers have also proposed different schemes on this subject. For instance, Shan et al. (2006) and Philen et al. (2007) designed a type of flexible composite material whereby internal fluid pressure was used to cause extension, contraction or twisting motions. Shan et al. (2008) developed a plate consisting of multiple fluidic flexible matrix composites.

In the applications of the bio-smart fluidic cellular materials, Vos and Barrett (2011) and Vos et al. (2011) developed adaptive pressurized cellular structures for morphing wings. In their work, the cellular structures were composed of complaint honeycomb cells and could exhibit great strains by relying on a pressure differential to alter the structural stiffness. Pagitz et al. (2012), Pagitz and Bold (2013) and Pagitz and Hühne (2014) proposed a novel pressure actuated cellular structure that was inspired by the nastic movement of plants. The main idea of this structure is to connect prismatic cells with tailored pentagonal and/or hexagonal cross sections such that the resulting cellular structure morphs into given target shapes for certain cell pressures. Vasista and Tong (2012) designed and tested the pressurized cellular planar morphing structures to offer a solution to the challenges faced in designing morphing aircraft structures. Li and Wang (2013) investigated a cellular adaptive structure consisting of a string of fluid-connected fluidic flexible matrix composite cells with different properties. Luo and Tong (2013a,b) designed and validated the adaptive bio-inspired pressure cellular structures for shape morphing optimum designs for cellular structures.

Another area worth exploring is the simulation and design methods for the fluid actuated cellular structures with multiple fluid inclusions. In real applications, the fluidic cellular structures commonly consist of a large number of microcapsules, since the size of the components of the motor cells in the cellular structure is generally limited to a small scale level, such as the biological membrane in nastic materials (Sundaresan and Leo, 2006). Due to the difficult to solve such problems by the direct methods (e.g. standard finite element method), some novel multiscale methods have been developed. Zhang and Lv (2011) developed a coupled two-scale model based on the homogenization theories to simulate nastic structures with periodically arranged fluid-filled cells. Similarly, Ma et al. (2011) proposed an analytical micromechanics model and an asymptotic homogenization-based finite element model to investigate the effective properties of the cellular structure containing pressurized fluid-filled pores. Guiducci et al. (2014) utilized a numerical homogenization and a micromechanical model based on the Born model to simulate cellular materials filled with a variable pressure fluid phase. On the other hand, a new hierarchical multiscale method based on the multiscale finite element framework is developed to simulate linear behaviors of the closed liquid cellular structures with multiscale features (Zhang et al., 2010). The developed multiscale method can efficiently compute the multiscale problems on a relative coarse scale mesh and can easily recover the small-scale information of the microstructures by a downscale technique. Recently, this multiscale method has been successfully extended to perform the shape and topology designs of the fluid actuated morphing structure (Lv et al., 2014). However, these works mainly concentrated on the elastic properties of the fluid actuated cellular structures.

In current research, we will focus on the numerical methods to predict the nonlinear characteristics of the fluid actuated cellular structure. In real applications, the fluidic cellular structure often shows large and nonlinear deformations in non-muscular engines, such as snapping motion of the Venus flytrap as illustrated in Fig. 1 (Forterre et al., 2005; Pagitz et al., 2012). The research by Vos et al. (2011) indicated that the adaptive pressurized cellular structures can provide large actuation strains up to 12.5%. As a result, the direct methods for linear problems will show some drawbacks in situations where the problems to be solved contain nonlinear features. Recently, Ma and his coworkers (Ma et al., 2014) successfully developed a micromechanics model and a computational homogenization method to examine the macroscopic elastoplasticity and yield behavior of closed-cell porous materials with varied inner gas pressure. However, this work is limited to the material nonlinearity of the fluid actuated cellular structure with multiple inclusions. On the other hand, due to the geometrical nonlinear behaviors of the bio-inspired smart materials, it will be an interesting and

Fig. 1. Illustration of geometrically nonlinear behaviors in the snap motion of the Venus flytrap (Pagitz et al., 2012).