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Mechanism reliability of bistable compliant mechanisms considering degradation and uncertainties: Modeling and evaluation method

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ABSTRACT

The bistable compliant mechanism has been widely used in the field of micro-electromechanical systems, industrial lines, and daily necessities. Enhancing mechanism reliability is helpful to prolong product life and to reduce the maintenance costs of bistable compliant mechanisms. This paper proposes one method to evaluate the mechanism reliability of the bistable compliant mechanism considering degradation and uncertainties of the parameters. The new method can be subdivided as follows: first, the pseudo-rigid body model is used to calculate the motion precision of the mechanism. Second, by introducing the degradation of stiffness and the randomness of the bending line into the kinematic equations, the other equilibrium position can be calculated with respect to the service duration. Third, by using the health index to judge the status of the mechanism, a large sample of failure time is generated and processed by the Kaplan–Meier estimator to characterize the mechanism reliability of the bistable compliant mechanism. A case studied in this paper reveals the mechanism reliability of a typical bistable compliant mechanism under different health indices and provides clues for the reliability evaluation and performance improvement of bistable compliant mechanisms.

1. Introduction

In the research field of mechanical engineering, compliant mechanisms are flexible mechanisms that transfer an input force or (angular) displacement to another point through elastic body deformation [1–6]. Notably, these mechanisms are usually monolithic (single-piece) or jointless structures with certain advantages over the rigid-body or jointed mechanisms, such as reduced manufacturing and assembly time and cost [6–8]. Considering the lack of joints, the universal “friction” embedded in the conventional joints between two parts of a rigid body is absent, thereby making the compliant mechanism expanding to more areas. Currently, compliant mechanisms are widely employed in micro-electromechanical

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systems, including the micro-accelerometers and electro-thermal micro-actuators [7]. The concept and synthesis method of the bistable compliant mechanism was first proposed by Howell [3]. The mechanism has two equilibrium positions in the potential mapping with respect to the angle. As a main branch of the compliant mechanism, the bistable compliant mechanism is useful in switches, gates, and other applications as it provides two stable configurations for actual use. A number of papers have discussed the design and analysis method of the bistable compliant mechanism, and some of them are involved in reliability-based issues [4]. Thus, the bistable compliant mechanism, regarded as the general bistable mechanism, is selected as the main objective in this paper. Typically, two approaches known in the literature for the systematic syntheses of compliant mechanisms are the kinematics based approach and the structural optimization based approach [5–8]. Generally, the pseudo-rigid model is most widely used in the kinematic-based approach [5]. Now the modeling method has evolved into the more accurate ones, such as the finite element modeling, the corrected finite element modeling and other modeling methods [9,10].

Given the increasing requirement of tasks and the complexity of missions, more emphases are placed on research related to the stability and maintainability of bistable compliant mechanisms [4]. Scholars first focused on the problem of fatigue and devoted themselves to seeking effective ways to prolong the longevity of the compliant mechanism by controlling the process of fatigue. Howell et al. [4] considered fatigue as the major concern in many compliant mechanisms because of the cyclic stresses induced on the flexible members, and they proposed one method for the probabilistic design of the bistable compliant mechanism. Xu examined the design of compliant hinges for compliant joints and concluded that elliptical profiles have the advantage of achieving a long fatigue life, but the corner-filleted design offers the highest flexibility [2]. Research related to reliability evaluation and health management has also been conducted [5–8].

Although bistable mechanisms are eliciting increasing attention from engineers, failures have occurred during application, and thus designers have been impelled to extensively investigate the failure mechanism, reliability evaluation, and maintenance methods of bistable compliant mechanisms [11–12]. With the improvement of material properties and the enhancement of manufacturing technology, fracture caused by fatigue rarely occurs within the anticipated life of the bistable compliant mechanism. The bistable compliant mechanism has two stable working states, and the main concern of its performance properties is its ability to accurately form the two operating configurations. On the one hand, to meet the requirement of more accurate output, the ability of exporting precision kinematic output is the most important performance indicator of the bistable compliant mechanism. On the other hand, the motion accuracy decreases when cracks grow on the compliant hinges. When the bistable compliant mechanism cannot meet the requirement of motion accuracy, the structure may become intact without the failure of fracture in the hinges. Therefore, at present, a general direction of engineers' main concern is how to improve the reliability of motion accuracy caused by stiffness degradation rather than the problems associated with fatigue fracture. This concern can be referred to as the theme of the so-called "mechanism reliability".

Mechanism reliability is the ability of a certain mechanism to maintain the output accuracy under consistent conditions. Mechanism reliability is a comprehensive indicator that reflects the operating characteristics of one mechanism used in the machinery industry [13]. As far as we know, the concept of mechanism reliability was first defined by Feng [13]. He indicated that two parts of research should be focused on: the reliability of structures and the reliability of output properties. The reliability of output properties is concerned with mechanism reliability, which is the main topic of this paper. Although certain papers have introduced the methodologies of traditional mechanism reliability evaluation [13–15], the methodologies of evaluating the mechanism reliability of bistable compliant mechanisms have been scarcely reported.

As regards mechanical engineering facing practical problems, the characteristics of uncertainties and degradation have drawn much attention [14–16]. Many scholars have focused on system performance to evaluate reliability rather than the traditional binary states, namely, normal and abnormal [17–22]. Based on the abovementioned literature, certain obstacles must be overcome in the mechanism reliability evaluation of the bistable compliant mechanism. First, a dynamic modeling that considers parametric uncertainties and degradation must be conducted to obtain the output motion property of the mechanism. However, the mathematical modeling and solution method have yet to be reported. To examine the methods of improving the kinematic properties of the mechanism, Luo and Sun [23] proposed the direct probability method (DPM) to evaluate motion reliability. Given the law of motion, this method can provide the kinematic properties of the displacement, velocity, and acceleration (as well as the angular displacement, angular velocities, and angular accelerations) of a particular component. In addition, DPM can be used to calculate the probability that kinematic parameters lie in a specified interval, and it has been used in the probabilistic design of the bistable compliant mechanism [8]. Particularly, the widely used DPM can only be applied when the output properties have the explicit analytical form. Second, the classic method for reliability evaluation needs to obtain a certain amount of failure samples. Targeted at the mechanism reliability evaluation of the bistable compliant mechanism, the approach on how to obtain these samples has not been clearly identified in previous studies. Third, how to explore the failure data to obtain the reliability properties is not presented. Consequently, the main objective of this paper is to evaluate the mechanism reliability of the bistable compliant mechanism using a large sample of simulation data considering the uncertainties and degradation of the parameters.

This paper is structured as follows. Section 2 introduces the operational principle of the bistable compliant mechanism, and the basic equations of geometry, force, and potential energy are examined. The concrete method of evaluating the mechanism reliability of the bistable compliant mechanism is proposed in Section 3. Section 4 presents a case study of evaluating the mechanism reliability of a typical bistable compliant mechanism. The last section concludes the paper.