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ScienceDirect
Sensors and Actuators A 134 (2007) 231–238
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Design of fully compliant, in-plane rotary, bistable micromechanisms for MEMS applications

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Received 1 March 2006; accepted 11 April 2006
Available online 2 June 2006

Abstract

A fully compliant bistable micromechanism (hereafter identified as an in-plane rotary bistable micromechanism or IPRBM) is designed to perform in-plane rotary motion with two stable positions. The micromechanism consists of four identical bistable mechanisms arranged in a cyclic symmetry manner about a central proof mass. This new class of micromechanism can be used in several microelectromechanical system (MEMS) devices such as gate valve, optical shutter, and mechanical lock. Two types of IPRBMs have been developed in this paper, called as the outside IPRBM and the inside IPRBM. These two mechanisms differ by their relative orientation of bistable mechanisms with respect to the central proof mass. The micromechanisms are fabricated by electroplating a soft magnetic material—Permalloy (80% Ni, 20% Fe) into their photoresist mold. The minimum feature size is 4 μm, which corresponds to the width of compliant linkages used in the mechanism. The fabricated micromechanisms are tested for their torque-deflection response by using an image-based force sensing method. The test results are compared with simulation results. A pseudo-rigid-body model as well as a finite element model of IPRBM is developed to simulate the mechanical response of the mechanism. The micromechanisms are shown to reversibly undergo 10–20° of in-plane rotation and required a maximum torque of 1–2 μN m depending on the design. The experimental results showed good overall agreement with the design. The testing of each type of IPRBM is performed on three different design cases between which the tether width and aspect ratio was varied. The study showed a relative advantage of slender tethers with high aspect ratio in minimizing out-of-plane deflection. Also, the anchor distance between bistable mechanisms is significant.

Keywords: MEMS; Micromechanism; Rotary; Compliant; Bistable; Microvalve; Electromagnetic actuation; Finite element analysis; Torque measurement; Pseudo-rigid-body model

1. Introduction

Micromechanisms are an important component of numerous MEMS devices, which are integrated with an actuation system to achieve the desired on-chip motion. Micromechanisms can be classified into rigid-body mechanisms or compliant mechanism depending on the type of linkages and joints used. As opposed to a rigid body mechanism, which consists of rigid links connected by movable joints, a fully compliant mechanism derives all its motion from the deflection of flexible link(s) that are connected at fixed joint(s). This class of mechanisms has greater advantages in MEMS technology such as ease of microfabrication, reduced wear, and high precision motion [1].

Numerous microcompliant mechanism designs have been used by researchers to obtain different types of on-chip motion. The most commonly used compliant micromechanisms—microcantilevers and diaphragms perform out-of-plane linear motion [2–4]. Another type of motion is performed by the Digital Micromirror Devices (DMD^{TM}), developed by Texas Instruments (Dallas, TX), which use a pair of torsional hinges to tilt each micromirror out-of-plane. Several different designs of compliant micromechanisms have been developed to perform in-plane linear motion that is needed for sensing acceleration, on-chip object manipulation, and switching [5–8]. Another class of micro compliant mechanisms that perform in-plane rotary motion has great potential applications in MEMS. Such a mechanism has mechanical advantage to provide a wide range of displacements from the same design by simply changing the radial dimension. Large displacements are possible with small angular displacement of the compliant segments. In microfluidic system, it can be incorporated in a gate valve design, which

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0924-4247/$ – see front matter
doi:10.1016/j.sna.2006.04.030

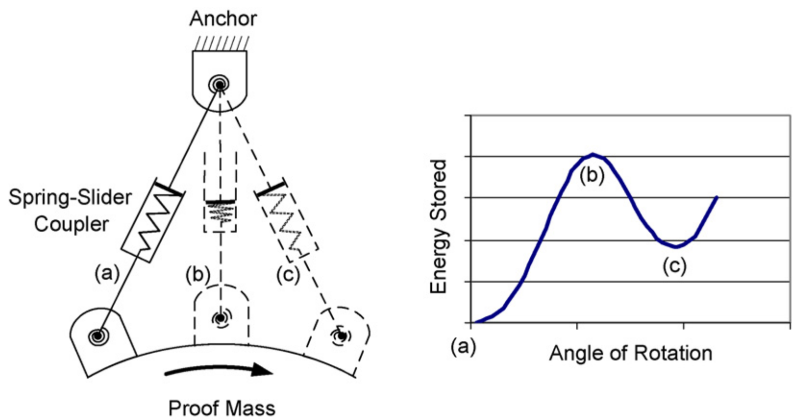

Fig. 1. Schematic of compliant bistable mechanism showing the three equilibrium positions and a qualitative graph of total energy stored in the mechanism at these positions.

is under investigation by the authors. In optical system, the micromechanisms could perform the function of an optical shutter [9]. It also has applications in mechanical locking devices [10].

So far researchers have concentrated on using rigid body mechanisms such as microgear train to perform in-plane rotary motion [11]. However, minimal work has taken place towards developing a fully compliant micromechanism that would perform this type of motion. Walters et al. [12] developed a rotary gate valve design in which he used a pair of compliant mechanism to suspend the diaphragm. However, they utilized a pin joint to obtain rotational motion. This paper reports the development of a new class of fully compliant in-plane rotary bistable micromechanism (IPRBM) [13]. The mechanism is designed to have two stable states of equilibrium (bistable). Devices such as microvalves and microswitches, which have two operating states (on and off states) greatly benefit from bistability. It allows the device to operate at low energy input and also provides precision motion. Different designs of IPRBM have been fabricated and tested for in-plane rotary motion and bistability. The experimental method to estimate actual torque required to rotate the mechanism is described and the test results are presented. The experimentally measured torque is compared with the simulated values-obtained from a finite element model of the mechanism. Furthermore, the micromechanism structure, fabricated with soft magnetic material—Permalloy (80% Ni and 20% Fe) [14], is integrated with armatures and actuation posts to investigate on-chip electromagnetic actuation.

2. Development of the micromechanism

2.1. Concept

The basic concept behind the design of a bistable rotary mechanism is shown in Fig. 1. The mechanism consists of a suspended central proof mass that is connected to the base anchor by a system of compliant linkages. The spiral springs at the joints indicate that the compliant linkages are rigidly connected to both fixed base and proof mass. The system of compliant linkages is designed to perform the functionality of a linear spring-slider system. Therefore, as the central proof mass is rotated clockwise in the plane from its initial position (a), the proof mass joint moves closer to the fixed base joint resulting in the compression of the spring-slider system. This continues till the proof mass is rotated to position of unstable equilibrium (b). At this position, the two joints (base anchor and proof mass anchor) are closest possible. The amount of energy stored in the mechanism is maximum at this point. Beyond this, the joints start to move apart resulting in decompression of the spring-slider system. A local minima in energy stored exists at position (c), which is the second stable position of the mechanism. In absence of any external load, the mechanism will remain in this state. The energy stored at this position results from the flexural energy stored in the compliant linkages due to the rotation. The stiffness of the flexural joints should be much smaller than that of the spring-slider system to achieve bistability in the design. The ratio of the energy required to reach the unstable equilibrium position (b) from second stable position (c) and initial stable position (a), defines the bistability ratio (BSR). As evident from the definition, BSR values lie between 0 and 1. Also, higher the BSR, more stable the mechanism is in its second stable position.

Another design requirement is to constrain the central proof mass to perform rotary motion. One possible approach is to use a pin joint at the center of the proof mass, which will allow only rotational degree of freedom. However, use of pin joint is not recommended due to its high wear, complex fabrication process, and large pin clearance requirement. Therefore, in order to design a fully compliant mechanism, a set of four identical bistable mechanisms is arranged in a cyclically symmetric geometry about a central proof mass as shown in Fig. 2. This arrangement helps in evenly suspending the central proof mass above the base and allows only rotational degree of freedom. Other types of motion are limited due to high spring stiffness in those directions.

2.2. Design

Two types of IPRBMs have been developed, which have different configuration of bistable mechanisms with respect to the proof mass. In the first design (“outside IPRBM”); the