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Flexible pneumatic micro-actuators: analysis and production

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Abstract

Compliant pneumatic micro-actuators are interesting for applications requiring large strokes and forces in delicate environments. These include for instance minimally invasive surgery and assembly of microcomponents. This paper presents a theoretical and experimental analysis of a balloon-type compliant micro-actuator. Finite element modeling is used to describe the complex behavior of these actuators, which is validated through prototype experiments. Prototypes with dimensions ranging from 11mm x 2mm x 0.24mm to 4mm x 1mm x 0.12mm are fabricated by a newly developed production process based on micromilling and micromolding. The larger actuators are capable of delivering out-of-plane strokes of up to 7mm. Further, they have been integrated in a platform with two rotational and one translational degree of freedom.

Keywords: Micro-actuator; Flexible actuator; Pneumatic actuator

1. Introduction

Flexible fluidic actuators are increasingly gaining attention in medical and biological applications, due to their remarkable actuation characteristics [1, 2, 3, 4]. As opposed to electrostatic, electromagnetic and thermal actuators, they avoid the use of high electric fields, currents or heat which are potentially harmful for living organisms. Another advantage of flexible actuators is that they are intrinsically safe for handling cells, tissues or other delicate objects. This paper focuses on a particular type of flexible fluidic actuators introduced by Suzumori et al. [5]. These actuators, called pneumatic balloon actuators (PBA's), consist of two flexible layers with different bending stiffnesses, which are connected at their rim to form a cavity. The actuation is generated by the differential bending of the two layers when pressurizing the cavity (see fig. 1). In this paper, the difference in bending stiffness between the two layers is achieved by altering layer thicknesses of polydimethylsiloxane (PDMS). Despite the unique properties of these actuators such as large actuation strokes, robustness, and low fabrication cost, little theoretical analysis has been

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performed on PBA's [6]. The next section will present a model, based on the finite element method (FEM), which will be validated by tests on prototypes.

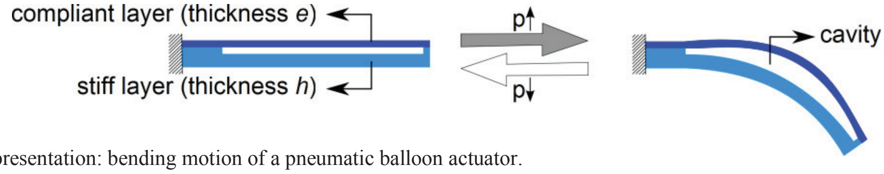
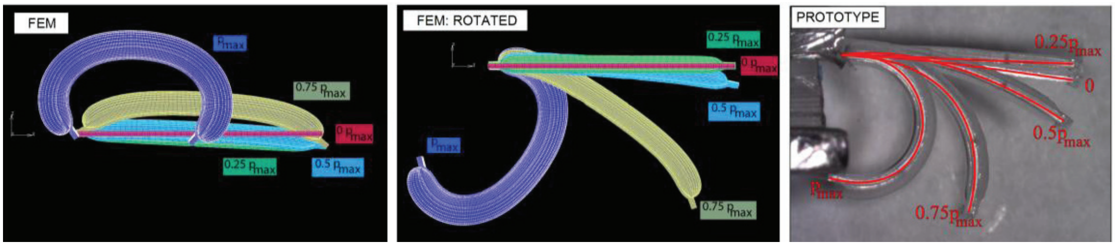


Fig. 1. 2D representation: bending motion of a pneumatic balloon actuator.

2. Theoretical analysis

A 3D FEM model is created with outer dimensions 11mm x 2mm x 0.23mm and a ratio of layer thicknesses of 2.6 (stiff layer thickness to compliant layer thickness). The pressurized cavity has dimensions 10mm x 1mm x 0.05mm. For the modeling of the PDMS, a second order Ogden model is used, as suggested by Kim et al. [7]. This model is solved using software package MSC Marc. Numerical problems appear when constraining the model at multiple points to simulate a clamping at the edge (see fig. 1). This can be solved by constraining the translation of only one point at the edge. As can be seen by fig. 2(a), this solution shows, on top of the actuator deformation, a rotation of the actuator as a whole around the fixed point, because this rotation is not prohibited by any constraints. Manually restoring the rotation, as in fig. 2(b), shows that actuator deformation is in good agreement with tests on prototypes, as can be seen on fig. 2(c). The restoring manual rotation is justified because the deformation of an actuator only subjected to internal pressure, is not influenced by how it is clamped at the edge. Values of p_{max} (pressure when the deformation is a half circle) vary from 20kPa in the FEM model to 70kPa for test on a prototype with the same dimensions, which is an improvement compared to previous results [8].



(a) (b) (c)

Fig. 2. Results from analysis: deformation of a PBA for different pressures: 3D FEM model with single translation constraint (a), 3D FEM model with restoring rotation (b), prototype (c).

3. Prototype testing

To verify the actuator deformation of the FEM model, tests on prototypes are essential. Therefore a new production method is developed based on micromolding of PDMS (Sylgard 184 with base polymer to current agent ratio 10:1) where a compliant and stiff layer with accurate thickness can be produced.

3.1. Production process

The compliant layer with thickness *e* is produced through a spin coating process. Afterwards this layer is cured at 90°C for 15min. In our design, the cavity is molded in the stiff layer, which therefore cannot be produced by spin coating. In literature, this stiff layer with thickness *h* is usually being fabricated by an open mold, where excess PDMS is spun off [9]. With this technique, there is little control of layer thickness, which is undesirable. Instead, we propose a closed mold, produced by means of micromilling, which gives accurate control of the stiff layer thickness. Curing of PDMS in this mold is done at 100°C for 1h. Both stiff and compliant layer are bonded together after oxygen plasma activation in a RIE-chamber (50W for 20s). A detailed overview of the production process can be seen in fig. 3, and an actuated PBA is shown in fig. 4.

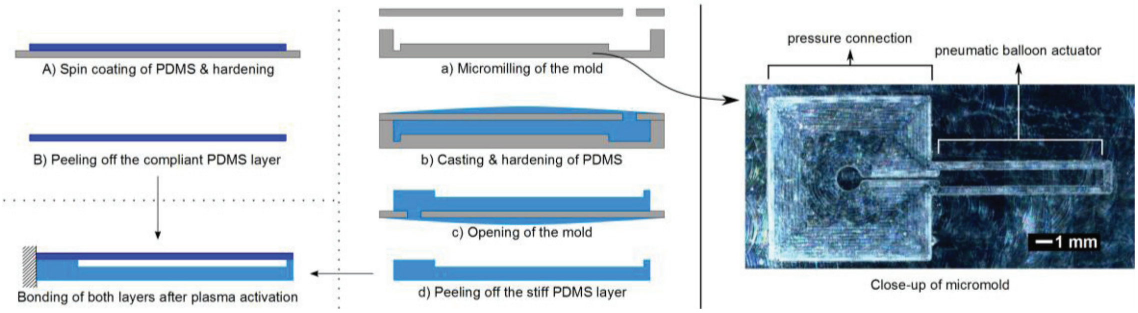


Fig. 3. Production process: overview.

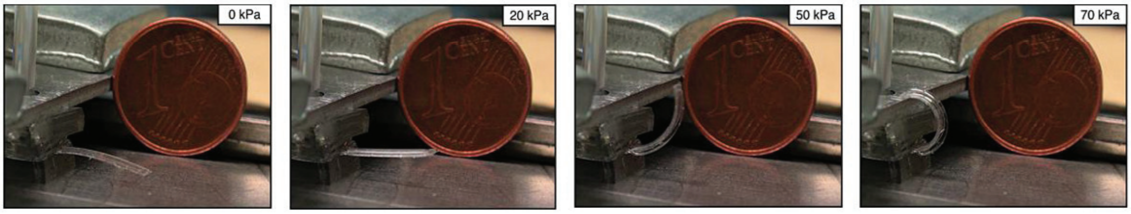


Fig. 4. Deformation of a PBA when pressurized (outer dimensions: 11mm x 2mm x 0.24mm).

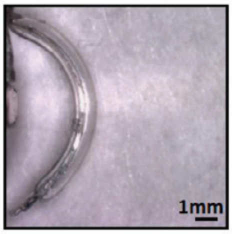
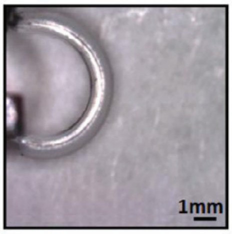
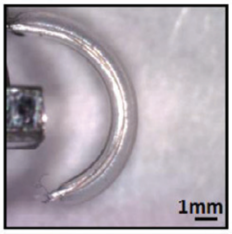
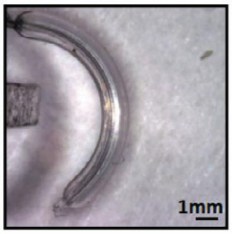
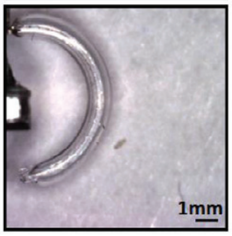
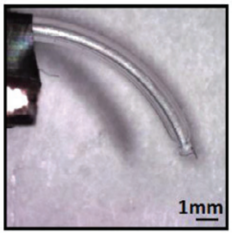
3.2. Test results

In order to maximize the deflection of PBA's, an optimal ratio of compliant layer thickness to stiff layer thickness must be found. Therefore, actuator prototypes with different layer thicknesses are produced with compliant layer thickness e ranging from 50µm to 85µm, and stiff layer thickness h ranging from 80µm to 210µm. An optimum in deflection can be seen in table 1, where three actuators are pressurized at 70kPa and the others at 100kPa. These measurements show that the optimal ratio h/e is about a factor 2 to 3. Tests also indicate that actuators with a small compliant layer thickness deflect more than actuators with a large compliant layer thickness for a given pressure.

4. Applications

The question remains: are these actuators capable of being implemented in systems with industrial or medical applications? Fujiwara et al. [10] combined two PBA's together to produce a linear movement to actuate a surgical gripper and Watanabe et al. [2] constructed a device that is capable of producing a predetermined 3D motion for transplanting eye tissue. In an attempt to generate complex 3D motion, we combined three balloon actuators to form a pneumatic actuated platform (see fig. 5). The three actuators are bonded to a lightweight aluminum end effector with PDMS. Pressure is provided through three tubes so that each PBA can be actuated separately to produce 3D movement. For instance, fig. 5(right) shows the end effector being tilted to the left by 15°.

Table 1. Influence of layer thickness on deformation behavior (*e*: compliant layer thickness, *h*: stiff layer thickness).

		h [µm]		
		80 – 90	120 – 140	+ 140
e [µm]	50 (p = 70kPa)			
	85 (p = 100kPa)			

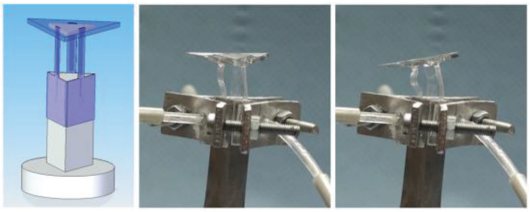


Fig. 5. Combining 3 PBA's in a pneumatic actuated platform.

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