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A Bistable Artificial Muscle Actuator

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Abstract:

We present an artificial muscle actuator based on the axially compressed buckled beam of bending actuator material. Thus natural bistable structure helps to overcome some problems found in the new materials used for artificial muscle actuators, such as relaxation and non-repeatability. Without electrical stimulation the buckled beam remains in one of two stable positions. Actuating the structure causes it to switch from one state to the other, thus giving a versatile element that can be used as an actuator, mechanical switch or adjustable structural element. The structure can be partially actuated in order to move the actuator with respect to one of the stable states without actually switching state. Likewise a variable force can be generated. We show how initial study of the standard buckled beam model suggests a method for segmenting bending actuator materials such as ionic-polymer metal composites (IPMC) in order to switch between states through low energy paths. We also show how such a structure can be used to construct a cilium-like actuator that generates the standard envelope of power stroke and recovery stroke using a one-degree of freedom input.

1. INTRODUCTION

Modern materials used for artificial muscles are at the cutting-edge of engineering and material science. Unfortunately, like many other state-of-the-art technologies, these materials suffer from a number of “teething” problems. Problems with bending actuators include such undesirable properties as relaxation after actuation [2], low repeatability [3], and the need for power and active control to maintain a constant actuated state. To use these imperfect materials one is forced to spend time building a mathematical model in order that a suitable controller can be constructed. Unfortunately such a model is often very complex and difficult to implement. Another approach, utilized in this paper with specific relevance to bending-type actuators, is to build naturally stable structures. Here we approach the problem from the structural mechanics point of view, in an attempt to link these new materials with real-world applications. The bistable actuator presented here, and shown in Fig. 1, is just such an important building block that can expand application areas and help realize practical devices. These stable structures provide easily measured equilibrium points from which to start actuation or between which to switch.

There are a number of advantages that mark these self-bending bistable actuators as different from previous bending actuator structures:

- Post actuation relaxation is reduced since the actuator always falls into the same stable shape
- Actuation is repeatable because the natural stress distribution is the same whenever the structure is in one of the stable shapes.
- No energy is required to maintain the stable shapes.

Compared to other bistable actuator structures [4][5][6], the presented self-bending structures have the following advantages:

- No external force is needed to change state.
- The state transition path can be optimized with respect to a desired property, e.g. time, energy, etc.
- The structure can bend in a controlled manner around a stable state without actually changing state, thus creating local actuation.
- The structure can be made to adapt to a changing environmental or loading conditions.

In the sequel we present the self-switching bistable buckled beam actuator. We describe a segmentation schema based on buckling mode shapes and show initial actuation data. We also present an embodiment of the structure as an artificial muscle that drives a beating element similar to bacterial cilia. The bistability of the structure generates a two-dimensional cyclic swimming motion comprising a power stroke and a recovery stroke from only a single input signal.

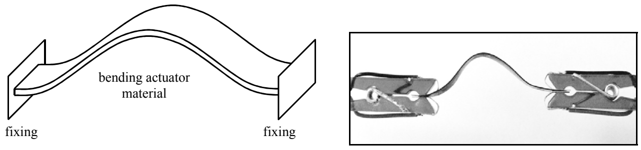

Fig. 1 The basic buckled beam actuator shape, and a sample Au/Nafion test actuator

2. BUCKLED BISTABLE BEAMS

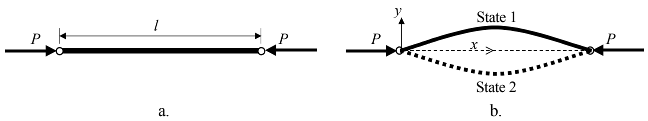

Fig. 2 Buckling of a pinned beam

2.1 Buckling modes in clamped beams

Consider the pinned beam of length l as shown in Fig. 2 [7]. Under axial loading P the beam initially deforms axially (Fig 2a.) Once the critical load is exceeded, the beam deforms sideways into the buckled "bow" shape (Fig 2b,) characterized by the equation,

$$\frac{d^2y}{dx^2} = -\frac{P}{EI}y, \tag{1}$$

where E is the Young's modulus, I is the moment of inertia, and y is the deflection along length x. In this case the boundary conditions are, $y=0|x=0$ and $y=0|x=l$. The resulting deflection equation of the buckled beam has the form:

$$y = A\sin(kx) + B\cos(kx), \tag{2}$$

where, $k^2 = P/EI$

In Fig. 2b we can clearly observe the two stable buckling states for a beam with rectangular cross section. The disadvantage of the pinned beam is the difficulty of mounting such a beam to ensure free end rotation. In order to develop a more convenient, mountable, bistable structure we now consider the double clamped beam in Fig 3. Here the ends are fixed such that rotation is eliminated.

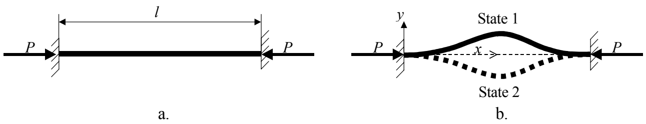

Fig. 3 Buckling of a clamped beam

Equation (1) still applies, but boundary conditions now become, $\{y=0, y'=0\}|x=0$ and $\{y=0, y'=0\}|x=l$. Now (1) results in the deflection equation of the clamped buckled beam of the form,

$$y = A\sin(kx) + B\cos(kx) + \frac{M_0}{P}, \tag{2}$$

where M_0 is the bending moment at the clamps.

In order to obtain non-zero solutions to this equation we must satisfy the following condition:

$$\sin\left(\frac{kl}{2}\right)\left(\tan\left(\frac{kl}{2}\right) - \frac{kl}{2}\right) = 0, \tag{3}$$

This yields two families of solutions for the displacement equation [2],

$$y = C\left(1 - \cos\left(\frac{(j+1)\pi x}{l}\right)\right) \tag{4}$$
$$j = 1, 3, 5, \ldots$$

$$y = C\left(1 - 2\frac{x}{l} - \cos(kx) + \frac{2\sin(kx)}{kl}\right) \tag{5}$$
$$kl = 2.86\pi,\ 4.92\pi,\ 6.94\pi,\ 8.95\pi,\ 10.96\pi, \ldots$$

Equation (4) defines symmetric buckling shapes and (5) defines asymmetric shapes. Fig. 4 shows the first three solutions from (4) and (5), commonly referred to as buckling modes 1, 2 and 3. Note the reflexive symmetry of modes 1 and 3.

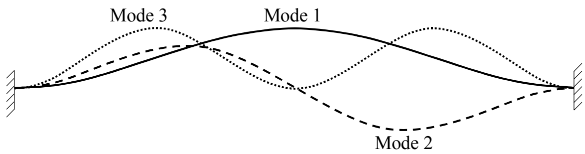

Fig. 4 The first three buckling modes

By constraining movement at various key points along the length of the beam, or by applying specific critical loads, the different buckling modes can be forced to develop.

2.2 Restricting buckling modes

Traditional applications of bistable beams restrict movement to a small subset of these modes [6], and most usually only one [4][5]. This is a constraint imposed by the fairly rigid materials used and the inflexibility of the actuation method. It is clear that, while such mode restrictions may be necessary for passive beam structures they would unnecessarily constrain the active self-bending structures proposed in this paper. Further, it may be advantageous to utilize such alternative buckling modes since they can provide pointers to low-energy state transition paths. Indeed, the ability of bending actuators to change the shape of the buckled structure means that it may be possible to move through more optimal paths than are possible with the best-designed passive structures.

In the next section we discuss the switching of state through intermediate shapes, including alternate buckling modes.

3. SELF-BENDING BISTABLE BEAMS

Given a pre-stressed (or at least pre-deflected) bending actuator that exhibits the simplest buckling mode (mode 1) we now consider movement paths from one state to the complimentary state. Figs. 5 and 6 show two possible actuation paths that pass through alternative buckling solutions. In Fig. 5 the actuator in state A bends under electrical stimulation until is resembles the mode 2 buckle B. This is the snap-through region of a passive bistable beam and only a little further actuation is required to force the actuator into state C, again in buckling mode 1. Likewise, the same state switching may be achieved by passing through buckling mode 3 as shown in Fig 6.

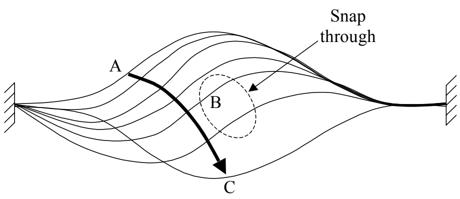

Fig. 5 State change via intermediate buckling mode 2

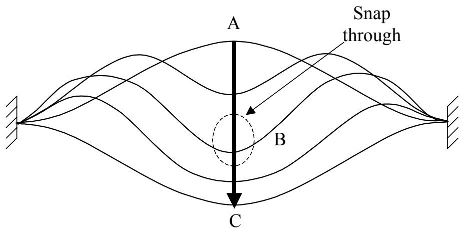

Fig. 6 State change via intermediate buckling mode 3

There are advantages in choosing each of these transition paths. For example, the mode 2 shape has a lower potential energy and is therefore a more suitable intermediate shape for applications requiring lower energy actuation. The mode 3 shape, on the other hand, is characterized by the vertical motion of the center of the structure. This vertical motion may be extremely important in applications where the beam contacts another object.

4. Actuator Segmentation

Consider the typical bending actuator, such as an IPMC, that bends under electrical stimulation. Typically the actuator bends with constant curvature r, as shown in Fig. 7.

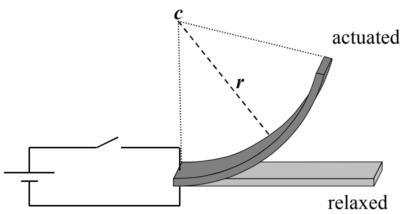

Fig. 7 IPMC bending with constant curvature

When a beam of uniform material is forced into the first buckle mode shape (Fig. 3) the structure does not have constant curvature. Crucially there are three distinct regions where the curvature has the same direction, i.e., $0 \leq x \leq l/4$, $l/4 < x \leq 3l/4$, $3l/4 < x \leq l$, as shown in Fig. 8. The boundary points $x=l/4$ and $x=3l/4$ coincide with the points of zero stress in the structure where,

$$\frac{d^2y}{dx^2} = 0 \tag{6}$$

If we superimpose three curves with constant radius r and with centers at C_1, C_2 and C_3 onto the buckled beam in Fig. 10 we can see that there is a very close correspondence between the bending of three IPMC actuators represented by these curves and the natural curvature of the bistable beam. Thus it is natural to consider this buckled structure as three joined, but electrically independent, bending actuators.

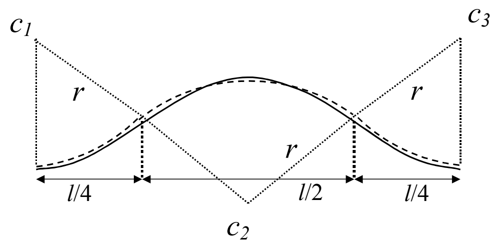

Fig. 8 Distinct bending regions in a buckled beam

Actually we need only to electrically segment a single actuator strip to achieve the same effect. Segmentation of a polymer actuator can be achieved by cutting or etching the electrodes upon one or both sides of the actuator. The base polymer material (e.g. Nafion) is unaffected and provides the necessary mechanical linkage from one segment to the next. Segmentation is therefore an electrical construct that has a consequent mechanical effect through the actuator transduction mechanism.

To enable self-actuation between states we desire that the actuator bend efficiently in the region of the stable state. This is possible only if we supply the same polarity voltage to sections of the buckled structure that have bending moments in the same direction. The worst case exists when part of the region is bent one way and part of the region is bent in the opposite direction, such as in an ‘s’ shape. These observations give us some valuable information about how and where to segment a single bending actuator to make a buckle beam actuator that can change state effectively.

Our initial approach is to segment the actuator electrodes at the points of minimal internal stress (i.e. minimum bending) such as the $x=l/4$ and $x=3l/4$ points in Fig. 8. Unfortunately, during actuation these points are not stationary along the length of the actuator. That is, the points of minimum stress move and change number. If we determine, however, that actuation should involve transition through, for example, the mode 2 buckle shape we can use this known shape as a further indicator as to where to segment the actuator.

4.1 Actuation of a 3-segment beam

It may be that in many applications the optimum number of segments and their precise segmentation is not required. This may be, for example, in order to simplify the control strategy or the manufacturing process. As such, a simple segmentation schema may provide the needed actuation.

Consider, for example, the three-segment beam in Fig. 9. Here the beam has been split into three segments at the previously discussed positions of $l/4$ and $3l/4$. When forced into the mode 1 buckling its shape resembles that in Fig. 8. Now let us actuate this structure with a single varying voltage *Vs*. For simplicity of control we connect the drive signal *Vs* as shown in Fig. 9 where the middle segment is connected in reverse polarity with respect to the end segments. This reverse polarity connection scheme matches the natural polarity of bending in each segment. That is, the end segments bend in the opposite direction to the middle section.

In actuation this structure will bend into a symmetric intermediate shape resembling the mode 3 buckle. State transition thus substantially resembles that shown in Fig. 6.

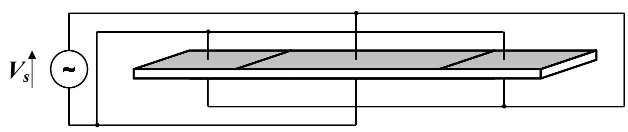

Fig. 9 a three-segment test beam

An actuator with this structure was manufactured from gold plated IPMC material with a base of Nafion 117 and dimensions 4mm × 38mm × 0.175mm. The beam was clamped at both ends and given a slight axial load to force the formation of a mode 1 buckle shape. The voltage signal *Vs* in Fig. 10 was applied to each segment using the connections shown in Fig. 9 At the same time the displacement of the center of the buckle beam was recorded using a Keyence laser displacement meter. Displacement of the center point *D* is also show in Fig.10.

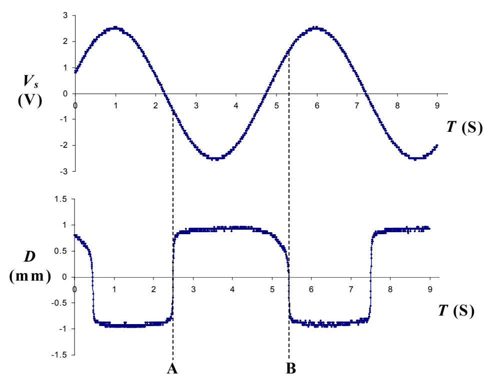

Fig. 10 Driving voltage and displacement signals

We can clearly see that the displacement of the actuator is a near square wave in response to the sine wave input. This is a typical displacement response for a bistable buckled beam. Note the switching events at A and B. As time *T* approaches point A the input voltage falls below zero but structural stability keeps the actuator in its stable shape. At point A the input is sufficient to cause the structure to rapidly change state to the complimentary shape, as shown by the very high gradient of displacement. The structure stays in this stable state until a half cycle of the input has passed when, at point B, the reverse state-switching event occurs.

If we plot displacement *D* against input *Vs* we have a clearer illustration of the state switching action. Fig. 11 shows this graph with an inset showing the direction of progress with time. Fig. 11 shows the classic hysteresis plot of a bistable device. Note the asymmetry resulting mainly from imbalance in the end clamps but also partly from manufacturing effects.

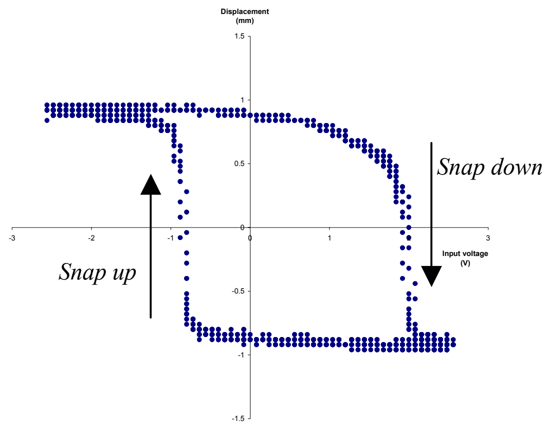

Figure 11. Actuation hysteresis for a three-segment Nafion buckled beam actuator

5. A Cilium-like Structure

Cilia are structures used by microorganisms such as bacteria to propel themselves. The small size of these organisms and the resulting low Reynolds number [9] means that other propulsion mechanisms, such as anguilliform swimming, are not possible. Swimming at small Reynolds numbers involves exploiting viscous forces rather than the inertia forces present at higher Reynolds numbers. Cilia generate thrust by separating motion into two distinct phases, or strokes. Fig. 12 shows the typical motion of a bacterial cilium and clearly illustrates the power stroke and the recovery stroke. This cyclic motion is fundamentally different from the symmetrical side-to-side motion of a fish's tail.

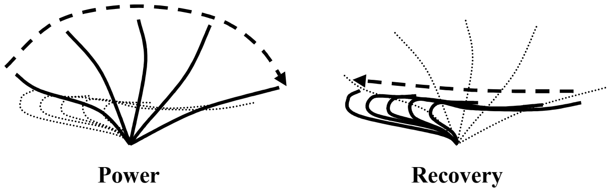

Figure 12. Bacterial Cilia showing power and recovery strokes (reproduced from [9])

It follows that if we are to make swimming robots on the micro scale we need to adopt an appropriate propulsion mechanism such as beating cilia.

In order to generate this cilia-like motion from a single bending actuator we would need an actuator with two segments, each with separate control. In effect we would be generating a two-dimensional cyclic motion and would thus need a two-dimensional control signal. Such an actuator is shown as a simplified coupled rod model in fig 13.

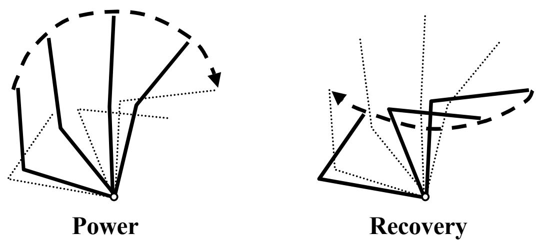

Figure 13. Example of two-segment cilia-like actuator

Utilizing the bistable bending structure, on the other hand, we can generate a two-dimensional actuation envelope like a beating cilia from a single control signal. Fig 14. shows a structure comprising a buckled bistable beam and a paddle, or fin, appendage mounted perpendicularly at the center of the structure.

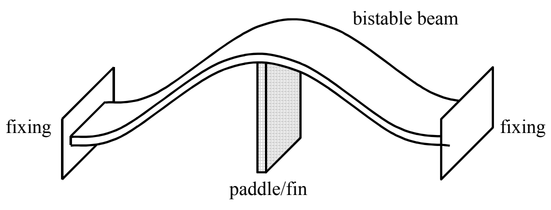

Figure 14. Possible embodiment of flexible paddle cilia

If the bistable beam is appropriately segmented we can force it to switch state through the mode 2 buckle shape. The paddle will follow the movement of the buckled beam as it actuates and the paddle will sweep a path through space. Fig. 15 shows the cyclic path (seen from the side) swept by the paddle as the bistable actuator changes state.

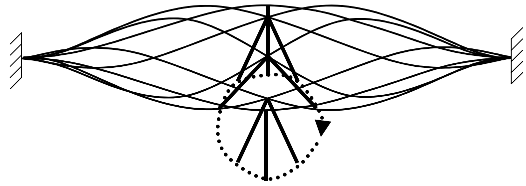

Figure 15. Cilia-like actuator with rigid paddle

This is shown more clearly in Fig. 16 where a full cycle of the structure is shown in eight steps, P1-P8 and states P1 and P5 are the two stable states of the structure. The structure actuates through two strokes; P7→P8→P1→P2 corresponds to the recovery stroke and P3→P4→P5→P6 corresponds to the power stroke.

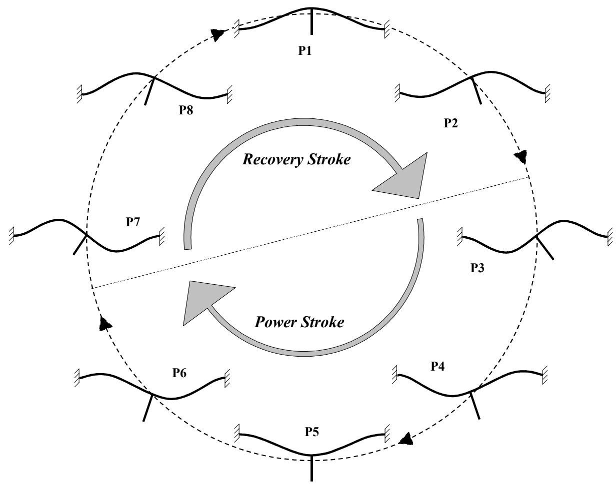

Figure 16. Cilia-like actuator showing power and recovery strokes

Of course, with the natural snap-through behavior of the bistable beam structure the actuation path may more closely resemble that shown in Fig. 17, which shows the predicted two-dimensional displacement of the end point of the paddle in response to input voltage V.

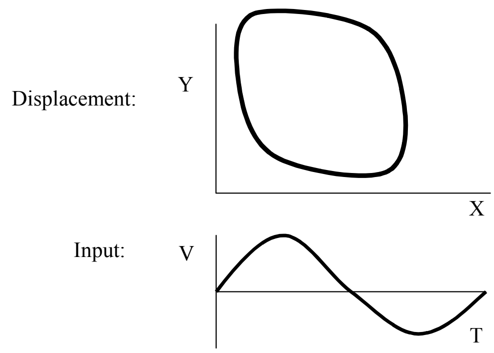

Figure 17. Cyclic motion from one input

We can modify the biomimetic cilia structure to shift the balance of power between the two strokes in the cycle. For example, we can make the center paddle out of active bending material and we can even substitute a passive material for half of the bistable beam. Such a modified structure is shown in a relaxed, unmounted, state in Fig. 18.

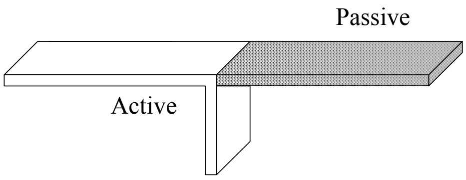

Figure 18. Possible embodiment of flexible paddle cilia

Now as this structure goes through actuation the paddle made out of active bending material bends at the same time as the main buckled beam. Fig 19 illustrates the expected activation cycle of this modified cilia structure. It is clear that the power stroke has been made longer and the recovery stroke has been made shorter.

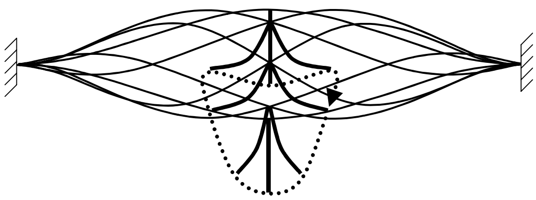

Figure 19. Cilia-like actuator with flexible 'paddle'

Given a smooth time-varying actuation signal (such as a sine wave) the actuation forms a cycle consisting of a power stroke followed by a recovery stroke. This is much like the power and recovery strokes found in the beating action of some bacterial cilium. Such a structure could be used to provide motive power for micro swimming or micro walking robots.

CONCLUSIONS

We have presented a new approach to artificial muscle actuators and smart structures based on stable physical structures. Our examples have focused on the clamped buckled bistable beam as the simplest form of bistable structure suitable for realization with bending type actuators such as IPMCs. By analysis of stresses in the characteristic buckling modes we propose a segmentation schema where the bending actuator is electrically segmented at points corresponding to minimal stress in one or more buckling mode shapes. We also propose that actuation from one stable state to another can be optimized with respect to some desired quantity such as time, space, or energy.

As an example embodiment of the buckled beam we present a biomimetic swimming fin inspired by the bacterial cilia. We show that the actuation hysteresis of a buckled beam can lead to a cyclic actuation path. Thus a beating cilium is constructed that exhibits a power stroke and a recovery stroke in response to a simple input signal.

It is clear that bi- and multi-stable structures made from bending actuator material have great potential in practical applications ranging from electrical relays to Braille displays and swimming muscles. Future work will involve further modeling of stresses in buckled actuator materials such as IPMCs especially when under external load (in an active damper configuration) or applying a force. We will also investigate multi-stable bending actuators made from multi-beam and diaphragm structures.

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