

Fatigue Characteristics of McKibben Artificial Muscle Actuators

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ABSTRACT

The McKibben artificial muscle is a pneumatic actuator whose properties include a very high force to weight ratio. This characteristic makes it very attractive for a wide range of applications such as mobile robots and prosthetic appliances for the disabled. Typical applications often require a significant number of repeated contractions and extensions or cycles of the actuator. This repeated action leads to fatigue and failure of the actuator, yielding a life span that is often shorter than its more common robotic counterparts such as electric motors or pneumatic cylinders. In this paper, we develop a model that predicts the maximum number of life cycles of the actuator based on available uniaxial tensile properties of the actuator's inner bladder. Experimental results, which validate the model, reveal McKibben actuators fabricated with natural latex rubber bladders have a fatigue limit 24 times greater than actuators fabricated with synthetic silicone rubber at large contraction ratios.

1 INTRODUCTION

Modern industrial robots excel at tasks requiring repetitive movements with accurate position control in highly restricted environments. These robots have deeply penetrated the automotive and consumer electronic industries. Future growth in other industries such as construction, agriculture, ocean and space exploration, and human welfare depend on advances in robotics which allow contact with uncontrolled environments. One approach for developing such advanced robots involves emulating human and animal models as both regularly interact with the environment in a robust manner.

The "Biorobotic" approach involves integrating known aspects of neuromuscular physiology and biomechanics into the design of robotic sensors, actuators, circuits and processors, and control algorithms. Of the various actuators that could be used, the McKibben artificial muscle comes closest to achieving the performance of human skeletal muscle

[6]. The pneumatic McKibben actuator is made from an inflatable inner bladder sheathed with a double helical weave which shortens lengthwise when expanded radially (see figure 1). The dimensions of the inner bladder, exterior braided shell, and the resting length angle of the double helix have significant effects on the actuator's performance. The contraction stroke length, force generated, and air volume consumption are some of the actuator properties dependent on geometry. A number of investigators have studied the design and control of these muscle-like actuators using classical engineering techniques [3-6, 8, 9, 12, 14, 15]. While these authors have identified relationships between force, length, and pressure, none have attempted an analysis of the fatigue or life cycle characteristics of the actuator.

Among the various failure modes of a McKibben actuator, the most common mode we have experienced is rupture of the inner elastic bladder. The bladder can be fabricated from a number of commercially available elastic tubes using various types of rubber (both natural and synthetic). While the fatigue limit of McKibben actuators is far below that of human skeletal muscle, we hope to design better actuators that are capable of reasonable service lives. This paper describes the mechanism of fatigue failure of rubber materials, develops a theoretical relationship between uniaxial tensile testing and the multi-axial loading of a pressurized McKibben actuator, and provides experimental results from two types of rubbers which validate the proposed theoretical relationship. We conclude with suggestions for further extending the fatigue limit.

2 THEORY

Mechanical fatigue in rubber materials is the result of slow crack growth during cyclic loading or deformations. The initial crack, thought to arise as the result of natural defects or flaws in the material, typically has a length on the order of 10 μm . As the rubber is dynamically loaded or deformed, this initial crack grows in length until fracture occurs. For a given rubber material, the engineer is most interested

in the factors which accelerate or impede crack propagation (see table 1).

Table 1: Factors that affect the rate of crack propagation in rubber materials.

Mechanical	Magnitude and direction of load or deformation
Chemical	Exposure to petroleum products
Environmental	Operational temperature Presence of ozone Exposure to ultraviolet radiation

2.1 Fatigue Limit for Uniaxially Loaded Specimens

For a crack of length c , the crack growth per cycle $\left(\frac{dc}{dn}\right)$ is related to the tearing energy G which, for moderate to large strains, approximates a power law relationship given by

$$\frac{dc}{dn} = BG^\beta \quad (1)$$

where B and β are material constants [7]. The exponent β for most rubbers lies between 2 and 6. For specimens loaded in uniaxial tension, the tearing energy is given by

$$G = 2(k_{ut})Wc \quad (2)$$

where

$$k_{ut} = \frac{\pi}{\sqrt{\lambda_1}} \quad (3)$$

and W is the strain energy density and λ_1 is the stretch ratio along the axis of loading

$$\lambda_1 = \frac{l_i}{l_o} \quad (4)$$

Substituting equations (2) and (3) into equation (1) and integrating across limits C_0 (initial crack size) to C_f (crack size at failure), the fatigue limit or number of cycles (N) until failure can be derived:

$$N = \frac{1}{(\beta - 1)(B)(2kW)^\beta (C_0)^{\beta-1}} \quad (5)$$

when $C_f \gg C_0$. Examination of equation (5) reveals only k and W are dependent on the magnitude and direction of load (or deformation), while β , B , and C_0 are properties of the material.

Fatigue limit data for uniaxial tensile tests is available in the literature for different types of latex

rubber [e.g. 4, 10]. We will now develop a relationship between the uniaxial tensile load case and the multi-axial load condition of the inflated McKibben actuator. This relationship will allow estimates of the fatigue limit for McKibben actuators based only on uniaxial tensile data.

2.1.1 Normalized Crack Length

To find the relationship between the uniaxial load case and the multi-axial case of the McKibben actuator, we begin by making two assumptions that are reasonable for both synthetic and natural rubbers. We assume the material is isotropic in the unstressed state and is incompressible (i.e. the product of the stretch ratios from each of the principal axes (λ_1 , λ_2 , and λ_3) is equal to unity under all possible deformations). Furthermore, the relationship between the stretch ratios for the uniaxial tensile case is well known [e.g. 16] and is given by

$$\lambda_2 = \frac{1}{\sqrt{\lambda_1}} \quad (6)$$

When a crack develops in a uniaxial tensile specimen, its orientation is perpendicular to the load path. As the specimen elongates, its width becomes smaller as demonstrated by equation (6), and thus affects the length of the crack. The function of parameter k (equation 3) is to normalize the crack length with respect to the amount of deformation.

The relationship between the stretch ratios for the McKibben actuator and its crack length is more complicated and is dependent on actuator geometry. The inner bladder of the actuator is kinematically constrained by an exterior sheath formed from a double helical weave. This exterior shell forces the inflated bladder to shorten lengthwise when expanded radially. As reviewed in Chou and Hannaford [5, 6], there is a specific relationship between the length of the actuator and its circumference. Within the exterior braided shell, the lengths of the threads remain almost constant regardless of the state of the actuator. Only the angle between the threads forming the double-wound helix changes as the actuator contracts. The relationship between length and circumference at various states of inflation can be determined with the Pythagorean theorem (see figure 2):

$$(l_o)^2 + (2\pi Tr_o)^2 = (l_i)^2 + (2\pi Tr_i)^2 = b^2 \quad (7)$$

where l_o and r_o are the resting length and radius of the actuator, l_i and r_i a contracted length and radius, b is the length of an individual thread within the braided shell (a constant), and T is the number of

turns the thread makes around the longitudinal axes of the actuator (also a constant).

Using the longitudinal (λ_1 , equation 4) and circumferential (λ_2) stretch ratios, given by

$$\lambda_2 = \frac{r_i}{r_o} \quad (8),$$

and equation 7, we can derive the relationship between the principal stretch ratios:

$$\lambda_2^2 = 1 + a(1 - \lambda_1^2) \quad (9a)$$

where

$$a = \left(\frac{l_o}{2\pi T r_o} \right)^2 \quad (9b).$$

For one of our typical actuators, we measured $l_o = 14.00$ cm, $r_o = 0.38$ cm, and $T = 1.94$, such that

$$\lambda_2 = \sqrt{9.6 - 8.6\lambda_1^2} \quad (10).$$

Note that for the McKibben actuator, when the inner bladder is inflated, the actuator shortens such that $0.7 \leq \lambda_1 \leq 1.0$.

The most common mode of failure for McKibben actuators is one in which the bladder fails as a result of a fatigue related crack propagation in the bladder. The orientation of the crack is perpendicular to the circumferential axis and is the result of "hoop stress." As the actuator contracts during normal operation, a developing crack will shorten in length. We propose to normalize the crack length using

$$k_{McK} = \pi \sqrt{9.6 - 8.6\lambda_1} \quad (11).$$

2.1.2 Strain Energy Density

Research to describe the behavior of non-linear elastic materials subjected to large deformations was conducted by several investigators in the 1940's and 1950's [e.g. 11, 13]. The relationship between stress ($\bar{\sigma}$) and strain ($\bar{\epsilon}$) is given by

$$\bar{\sigma} = \frac{\partial W}{\partial \bar{\epsilon}} \quad (12)$$

where W is the strain energy density function (also known as the work per unit volume or the stored-energy function). If the strain energy density function is known, one can measure the strains and then calculate the applied stresses.

Using the assumptions of initial isotropy and incompressibility, the strain energy density W can be described as a function of two strain invariants (I_1 and I_2):

$$W = \sum_{i=0, j=0}^{\infty} C_{ij} (I_1 - 3)^i (I_2 - 3)^j \quad (13)$$

where C_{ij} are empirical constants [13]. The strain invariants are functions of the stretch ratios of the deformed specimen along its principal axes (λ_1 , λ_2 , and λ_3) and are given by

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \quad (14)$$

$$I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2 \quad (15).$$

Using the relationships between the principle stretch ratios for both the uniaxial tensile case (equation 5) and the multi-axial load case of the McKibben actuator (equation 11), the strain invariants for both cases can be plotted (see figure 3) over typical deformation ranges. Importantly, the strain invariants of the uniaxial tensile test characterize nearly the same region of $\{I_1, I_2\}$ space as the strain invariants of the McKibben actuator. Thus, without actually finding the constants C_{ij} , we can determine the necessary stretch ratios of a uniaxial tensile specimen that gives the equivalent strain energy density as a contracting McKibben actuator. For a McKibben actuator capable of contracting up to 30 percent of its resting length ($0.7 \leq \lambda_1 \leq 1.0$), the equivalent strain energy densities can be achieved on a uniaxial test specimen through a lengthwise deformation ($1.0 \leq \lambda_1 \leq 2.4$).

2.2 Fatigue Limit for McKibben Actuators

Using equation (5) and canceling like parameters, we can solve for a fatigue limit ratio relating the uniaxial limit (known from published data) to the McKibben limit:

$$\frac{N_{McK}}{N_{UT}} = \frac{(2k_{UT}W)^\beta}{(2k_{McK}W)^\beta} \quad (16).$$

If we apply appropriate stretch ratios to insure equivalent strain energy densities (W), and substitute for parameter k with equations (3) and (11), we find

$$\frac{N_{McK}}{N_{UT}} = \frac{\left(\frac{1}{\sqrt{\lambda_{1, UT}}} \right)^\beta}{\left(\sqrt{9.6 - 8.6\lambda_{1, McK}^2} \right)^\beta} \quad (17).$$

Using published fatigue limit data from natural latex rubber [4], we estimated the fatigue limit for McKibben actuators. To test our predictions, we conducted 14 fatigue limit experiments on two

different types of rubber material used in McKibben actuators.

3 MODEL VALIDATION

To validate the hypothesized relationship between uniaxial and McKibben fatigue limits (equation 17), we repetitively cycled McKibben actuators from their resting length (typically 14 cm) to a specified contraction ratio until failure. Our experimental setup used air from a portable compressor whose pressure (maximum 4 bar) was regulated to achieve the desired contraction ratios. To test several actuators simultaneously, we used an electronically controlled gang valve (Festo, Germany) to cycle the actuators from resting to pressurized conditions. The gang valve was triggered by a function generator and electronically counted (Tektronix, OR). The actuators were cycled at 1 Hz with no external load applied.

The inner bladder of a McKibben actuator can be made from a variety of commercially available elastic tubing. We tested two types of tubing: (1) a synthetic, silicone rubber tube (Manosil™ Silicone Rubber, Barnant Co., Barrington, IL) and (2) a natural latex rubber (p/n 402R, Biddle and Crowther Co., Seattle, WA). However, we were only able to find published uniaxial fatigue limit data for the natural latex rubber.

The results of these experiments are shown in figure 4. The model prediction (using $\beta=3$ in equation 17) coincides well with the McKibben fatigue limit data for natural latex rubbers. The fatigue limit for both kinds of rubber monotonically increased as the actuator stretch ratio (λ_1) approached 1.0 (its resting length). The fatigue limit for the synthetic, silicone rubber (N=8) was significantly less than the natural latex rubber (N=6) over the entire range of actuator contractions. Using a linear regression, we tabulated the data at specified contraction ratios for the both the silicone rubber ($r^2=0.94$) and the latex rubber ($r^2=0.70$) as shown in table 2. For large contractions ($\lambda_1=0.75$), the fatigue limit for latex bladders was 24 times that of silicone bladders. However, for smaller contractions, the fatigue limit for latex bladders was slightly less than twice that of the silicone bladders.

4 SUMMARY and FUTURE DIRECTIONS

A number of conclusions can be drawn from these results. Importantly, the fatigue limit for a McKibben actuator can be accurately predicted from a conventional test procedure (uniaxial tension) for

Table 2: Fatigue limit for McKibben actuators fabricated with silicone or latex rubber bladders tabulated by the amount of actuator contraction.

Actuator Contraction λ_1	Typical Pressure (bar)	Silicone Rubber N (cycles)	Latex Rubber N (cycles)
0.75	3.6	180	4320
0.80	3.0	480	6140
0.85	2.3	1290	8730
0.90	1.6	3490	12400
0.95	0.9	9440	17620

which data may already be available. This was demonstrated by the close relationship between the prediction using data from Cadwell et al. [2] and the experiments we conducted with McKibben actuators. A second conclusion is that the magnitude of actuator contraction has a significant effect on the fatigue limit. Smaller actuator strokes result in higher fatigue limits. Lastly, over the entire range of contractions tested, actuators fabricated with a natural latex rubber bladder had a higher fatigue limit those fabricated with a synthetic silicone rubber. This material effect was most notable at large contractions, where the fatigue limit of the natural latex rubber was 24 times that of synthetic silicone rubber.

The fatigue limit of McKibben actuators can most obviously be extended by selecting a bladder material which has a slow crack growth rate and by limiting the contraction or stroke length as much as possible. Further gains may be made by using compressed gas of controlled composition and by maintaining a minimum strain on the actuator bladder. We currently use compressed air to pressurize our actuators, but data from Baramboim[1], who tested styrene-butadiene rubber, indicates the fatigue limit at room temperature can be doubled when cycled in a nitrogen environment. Larger gains (several orders of magnitude) may be achieved by maintaining a minimum deformation between cycles (i.e. not cycling through a relaxed, un-pressurized state) as demonstrated by Lake [10] on natural latex rubber specimens in uniaxial tension.

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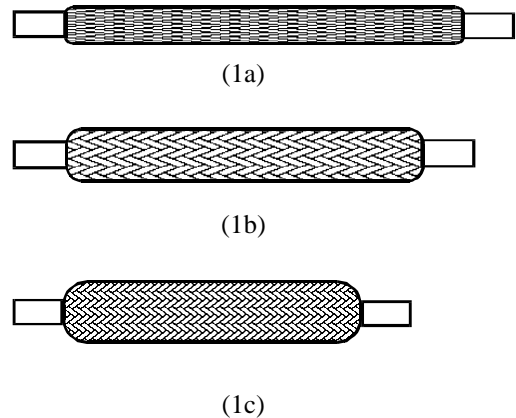


Figure 1: McKibben actuators are fabricated from two principle components: an inflatable inner bladder made of a rubber material and an exterior braided shell wound in a double helix. At one end of the actuator, a common pneumatic fitting (a hose barb) is used to provide pressure input. At ambient pressure, the actuator is at its resting length (a). As pressure increases, the actuator contracts proportionally (b) until it reaches its maximally contracted state at maximum pressure (c).

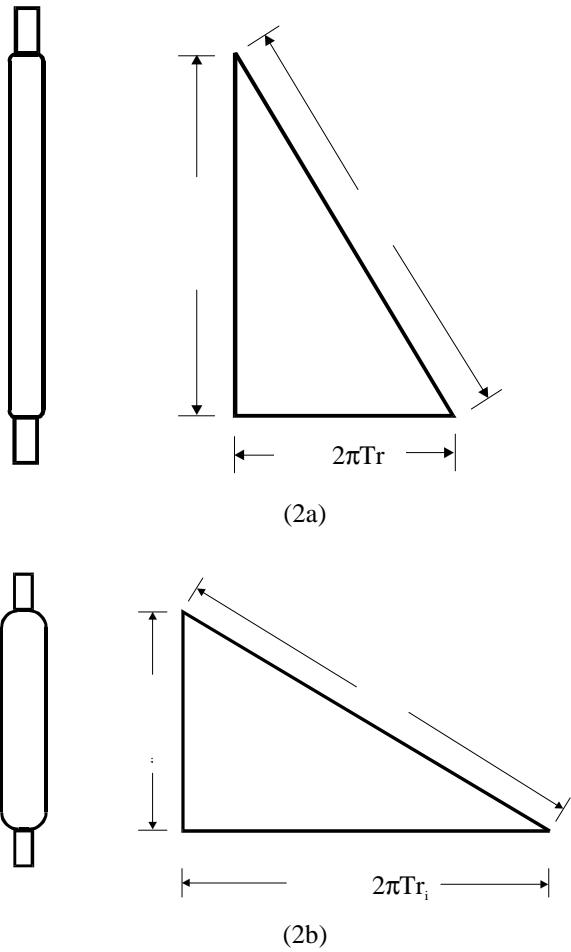


Figure 2: The geometry of McKibben actuator's exterior braided shell. (a) An actuator at ambient pressure with a schematic diagram indicating the relationship of a single fiber (hypotenuse 'b') to the actuator's length and circumference (see text for details). (b) The same actuator with a single fiber diagram at maximum contraction.

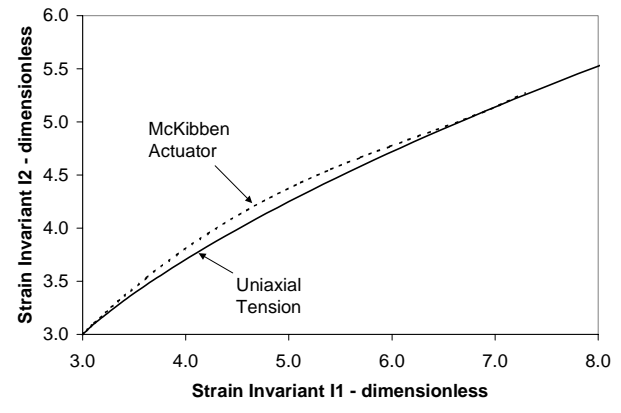


Figure 3: The strain invariants (I_1 and I_2), independent variables of the strain energy density function, are remarkably similar for the uniaxial tensile load case and the multi-axial load case of the McKibben actuator.

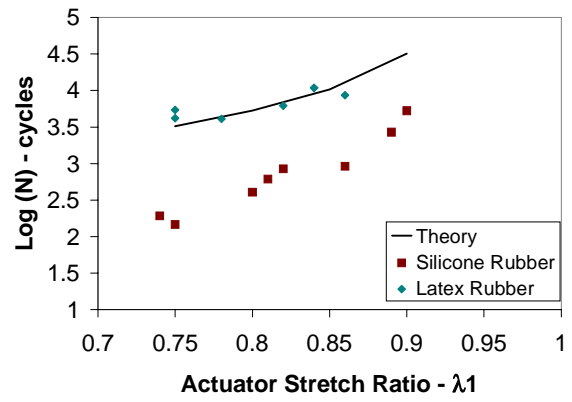


Figure 4: Theoretical prediction and experimental data of the fatigue limit (base 10 logarithm) for McKibben actuators versus the magnitude of the actuator contraction. The line (using $\beta=3$ from equation 17) represents the theoretical prediction of the fatigue limit for natural latex rubber. Data necessary to predict the fatigue limit for silicone rubber is unavailable in the literature. The squares (actuators fabricated with silicone rubber bladders) and diamonds (actuators fabricated with natural latex rubber bladders) each represent a single actuator cycled repetitively until failure.