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Dynamic contraction behaviour of pneumatic artificial muscle

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A B S T R A C T

The development of a dynamic model for the Pneumatic Artificial Muscle (PAM) is an imperative undertaking for understanding and analyzing the behaviour of the PAM as a function of time. This paper proposes a Newtonian based dynamic PAM model that includes the modeling of the muscle geometry, force, inertia, fluid dynamic, static and dynamic friction, heat transfer and valve flow while ignoring the effect of bladder elasticity. This modeling contribution allows the designer to predict, analyze and optimize PAM performance prior to its development. Thus advancing successful implementations of PAM based powered exoskeletons and medical systems. To date, most muscle dynamic properties are determined experimentally, furthermore, no analytical models that can accurately predict the muscle's dynamic behaviour are found in the literature. Most developed analytical models adequately predict the muscle force in static cases but neglect the behaviour of the system in the transient response. This could be attributed to the highly challenging task of deriving such a dynamic model given the number of system elements that need to be identified and the system's highly non-linear properties. The proposed dynamic model in this paper is successfully simulated through MATLAB programing and validated the pressure, contraction distance and muscle temperature with experimental testing that is conducted with in-house built prototype PAM's.

1. Introduction

The PAM is a pneumatically powered unidirectional actuator whose structure and functionality differs significantly from traditional pneumatic actuators (i.e. cylinders). In its most common design, the PAM is made of an elastic bladder that is enclosed in a double helically braided sleeve. Both bladder and sleeve are held airtight at their ends using mechanical fixtures. Fig. 1 shows an example of the PAM prototype that was previously designed and developed by Doumit et al. [1] and used for this research.

With reference to Fig. 1, θ is the braid angle of the sleeve, β is the sleeve inclination angle at muscle ends, ΔL is the muscle contraction distance, and F is the muscle force. The muscle operation is simple, as the bladder is inflated, using an external fluid flow through the end fixture, the muscle pressure increases and results in two types of stresses acting on the muscle's thin inner walls, namely, hoop and longitudinal stresses [2]. The hoop stresses will yield to a force that would radially expand the muscle. Subsequently due to the sleeves structural properties this will longitudinally contract the muscle. The longitudinal stresses will yield to a force that will longitudinally stretch (relax) the muscle. An unbalance of these two forces (radial and longitudinal) yields to a muscle motion such as contraction or relaxation. Neglecting all other forces such as fric-

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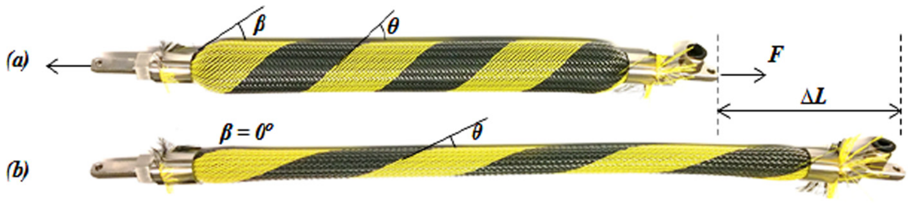

Fig. 1. PAM prototype: (a) pressurized state (b) deflated state.

tion, the maximum contraction distance of the muscle coincides with the equilibrium state of both radial and longitudinal forces. If the muscle contraction is externally resisted, the muscle produces a substantial contraction force that is called the muscle force. However, the muscle does not produce any expansion force if the relaxation motion is resisted, and thus the PAM is a unidirectional actuator.

The earliest reference of the PAM dates back to 1941, Johnson and Pierce patented the "Expansible Cover" which is also referred to as a mining tube or a cartridge [3]. This was used in coal mines where the device was inserted in a rock seam and upon inflation, its radial expansion would cause the rock to crack open. Later in 1949, De Haven revealed the longitudinal contraction ability of the device by patenting the tensioning device for producing a linear pull [4]. This was applied to a crash belt apparatus and was operated by a sudden release of compressed air that was triggered by a charge of gun powder. However, it was not until 1955 that the device was proposed as an actuator by Gaylord who patented the fluid actuated motor system and stroking device [5]. The PAM is also referred to as the McKibben muscle after the physicist Joseph L. McKibben. In 1957, McKibben introduced the PAM to the field of orthotic medicine by using the PAM to control a Wrist-Driven Wrist-Hand Orthosis [6]. Whereas, the PAM was perceived as a great innovation in this era, it was not a flawless success. This was attributed to the PAM's structural reliability, pneumatic power storage system, controls as well as other factors. After the letdown of the PAM, there was a period of approximately two decades before it was reintroduced by the industry and researchers. Among the pioneers, in the mid 1980's, Bridgestone Rubber introduced a PAM version called Rubbertuators for robotic applications [7]. Bridgestone offered two separate PAM models (i.e. RASC and Soft Arm robots); however, they were unsuccessfully commercialized and became obsolete in 1990. Despite this failure, researchers and industry continued their work on improving the PAM performance and proposed new designs of muscles. As an example, in 2002, Festo Corporation introduced the fluidic muscle MAS [8] which infuses the sleeve into the bladder. This design claimed to improve the fatigue life of the muscle. Another new design called the Pleated Pneumatic Artificial Muscle (PPAM) [9] was also proposed to eliminate muscle's hysteresis and to improve muscle contraction distance and force.

Nowadays, the success of the PAM is in applications where other forms of actuations such as electric and hydraulic are not optimum or feasible. The distinctive properties of the PAM also make it very appealing for the biomedical field. It has been used for human motion rehabilitation devices [10,11]. This is attributed to the PAM compliant behaviour, high force to weight ratio, high contraction ratio as well as human safety interaction behaviour.

2. Prior PAM models

A literature survey has shown that the PAM has been extensively studied and tested by researchers [12]; however, most PAM analytical models analyze the muscle force F for static condition only. Most models developed to predict the PAM dynamic behaviour are either based on lumped parameter approaches or are empirical in nature where the values of the model parameters are experimentally determined.

The first PAM analytical model was developed by Gaylord [5] for the muscle force F in static condition and later by Schulte et al. [13] as follows:

$$F = \frac{P\pi D_{90^\circ}^2}{4}(3\cos^2\theta - 1) \tag{1}$$

where P is the muscle pressure, and D_{90} is the diameter when the braid angle θ is 90°. Many similar static models were later developed by other such as Chou et Hannaford [14].

Tondu and Lopez [15] further modified the aforementioned static model by including a PAM dynamic force F_{dyn} for the case of the PAM suspended vertically. This term takes into consideration the static muscle force and the friction forces. The model's governing equation is:

$$F_{dyn} - mg = m\ddot{x} \tag{2}$$

where m is the mass of the hanging load, g is the gravitational constant and x is the muscle contraction distance. The parameters of this lumped model are selected and adjusted based on experimental results. Due to model simplification, Tondu and Lopez have noted that the model given by (2) is less accurate when the muscle pressure is low (200 kPa).