Modeling and Control of a Pneumatic Air Muscle Actuator

Byron Seaberg, Raymond Turrisi, Joshua Rathinaraj

Acknowledgements to Peter Morice

Outline

- Objective
- Pneumatic Air Muscles (PAMs) - Working Principles
- Experimental Setup
- Modeling
    - Simplified mass-spring-damper model
    - Linearization Results
- Next Steps
    - Controller Design - beyond lumped spring mass damper
    - Observer - application in industrial systems

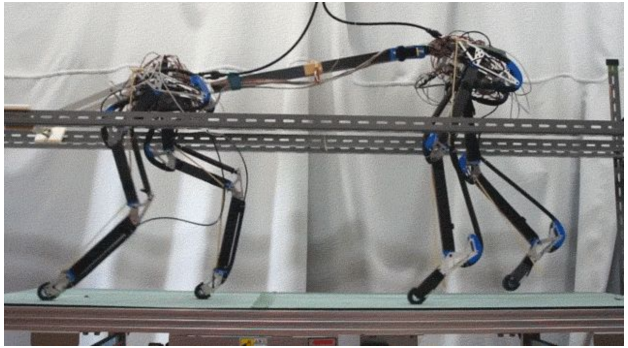


Fig. 2: Quadruped actuated by PAMs [src]

Objectives

- Develop a model and controller for a Pneumatic Air Muscle (PAM) Actuator
- Conduct parameter and system identification
- Develop a controller complementing industrial applications
    - Measure pressure and displacement feedback
    - Control PAM for tracking complex motions. (eg. sinusoidal motion)
- Compare performance with other models in literature

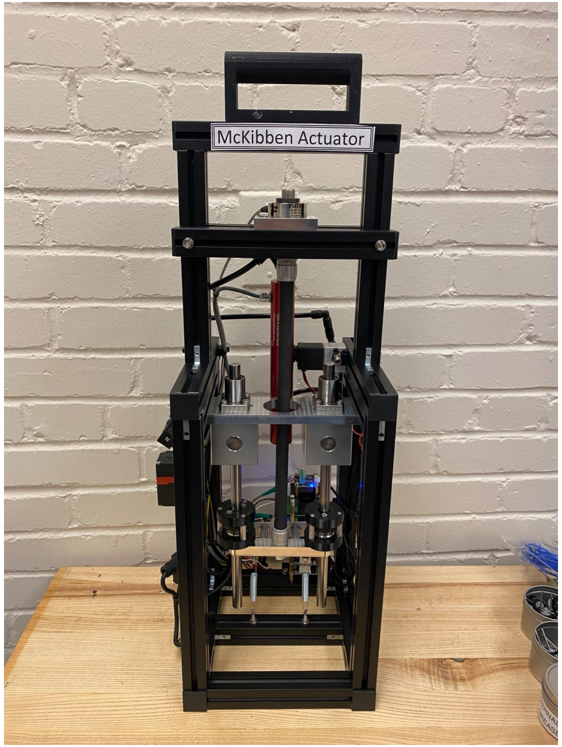
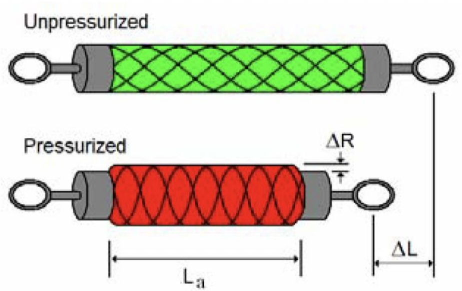


Fig. 3: Experimental setup

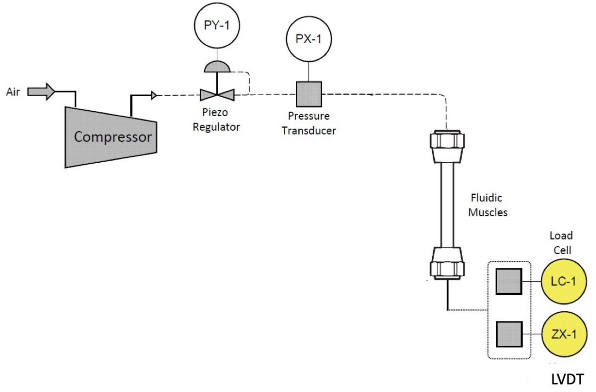
Pneumatic Air Muscle

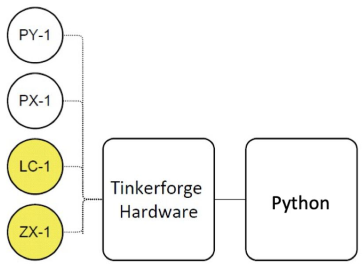
The air muscle compresses as it is pressurized.



Kang, B.S. et al. In *2009 IEEE International Conference on Robotics and Automation* (pp. 182-187). IEEE.

Outline of the experimental setup.





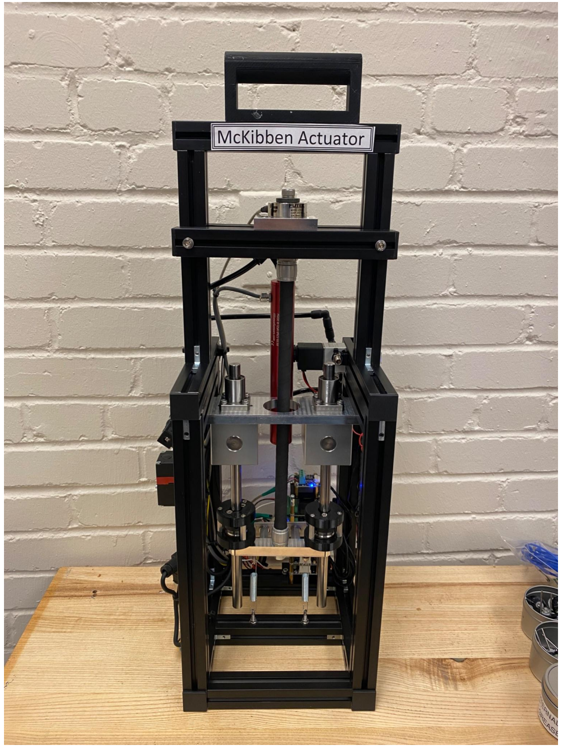


Fig. 3: Experimental setup

Mathematical Modeling - Work in Progress

- Finding system parameters
- Linearizing the nonlinear theoretical force equation
- Tuning parameters and identifying acceptable operating regions

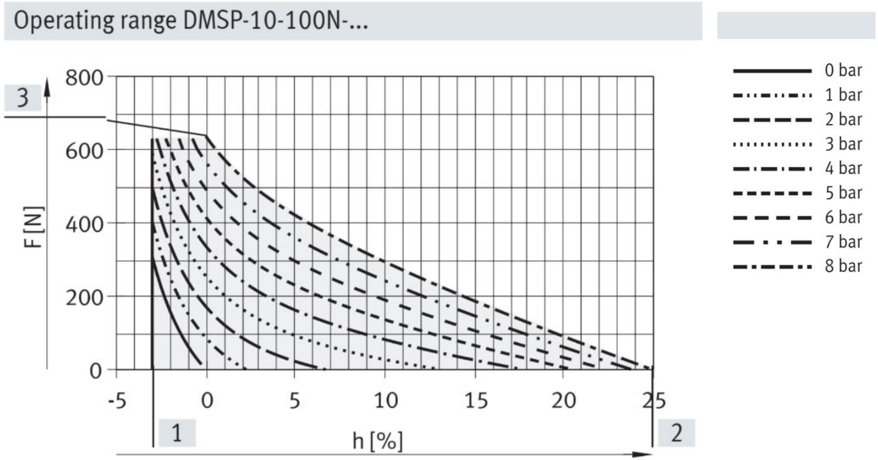


Fig. 4: Strain/Force/Pressure relations for our PAM, from manufacturer's datasheet [src]

Theoretical Nonlinear Force Equation - 1

- Correction factors & parameters
  - C_q1 and C_q2:
    - 3 and -0.000002 respectively
  - Braid angle: 23 degrees
  - Actuator length: 30 cm
  - Actuator diameter: 1 cm

$$q = 1 + C_{q1} e^{(C_{q2} P_g)}$$

$$\epsilon = \frac{L_A - L}{L_A}$$

$$F_a = P_g \frac{dV}{dL} = P_g \cdot \frac{D_0^2 \pi}{4} \cdot \left[\frac{3(1 - q\epsilon)^2}{tan^2(\alpha_0)} - \frac{1}{sin^2(\alpha_0)} \right]$$

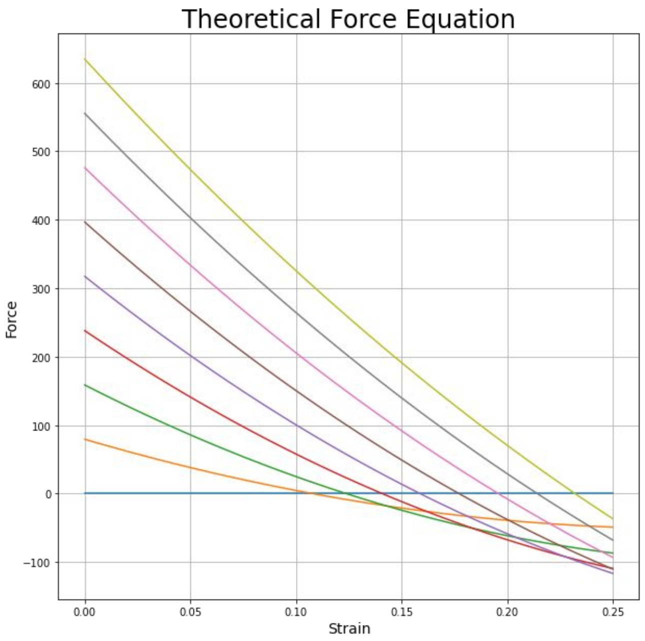


Fig. 5: Theoretical force equation for varying pressures and strains.

Theoretical Nonlinear Force Equation - 2

- Interpolated data from the datasheet and compared with theoretical nonlinear equation

- Notice the highly nonlinear force relationships at low pressures and low strains

- Later we discuss hysteresis

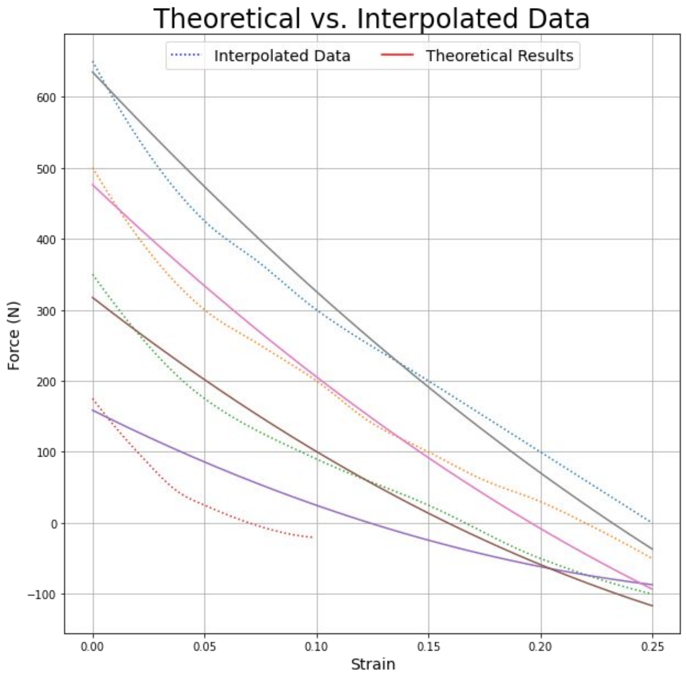


Fig. 6: Interpolated data vs. Theoretical results after parameter tuning

Theoretical Nonlinear Force Equation - 3

Linearized in the following form

$$\delta F_a = \frac{\partial F_a}{\partial P_g} \cdot \delta P_g + \frac{\partial F}{\partial L} \cdot \delta L$$

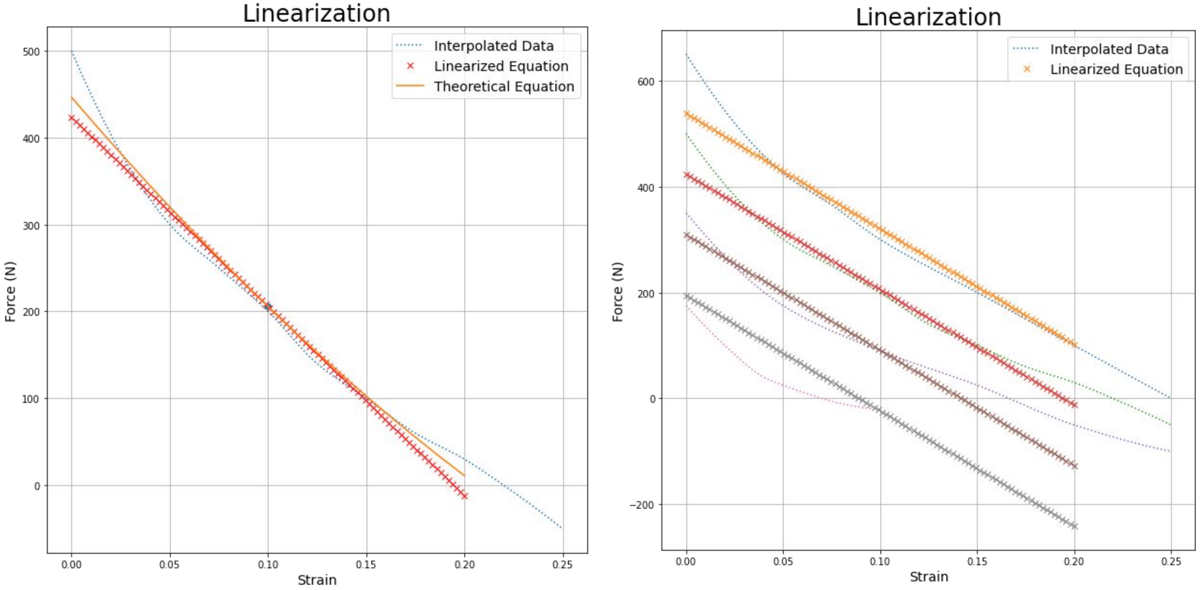
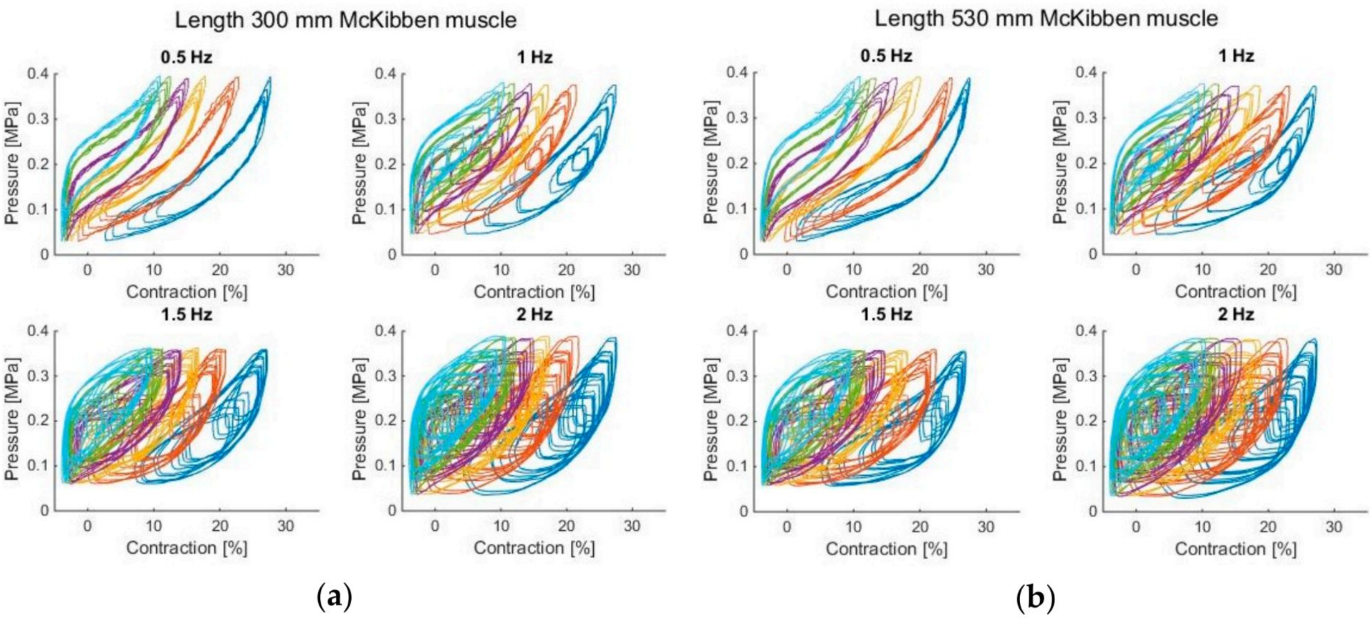


Fig. 7: Linearization about 6 bar and 10% strain. Coefficients are 5.7238e-5 and 8061.8 respectively.

Hysteresis



M. A. Mat Dzahir and S. Yamamoto, *Applied Sciences, vol. 9, no. 12, p. 2538, Jun. 2019*, doi: 10.3390/app9122538.

Fig. 8: Hysteresis for two lengths of PAMs. Observe how state trajectories vary significantly depending on the frequency in which the actuator is driven.

Dynamic model

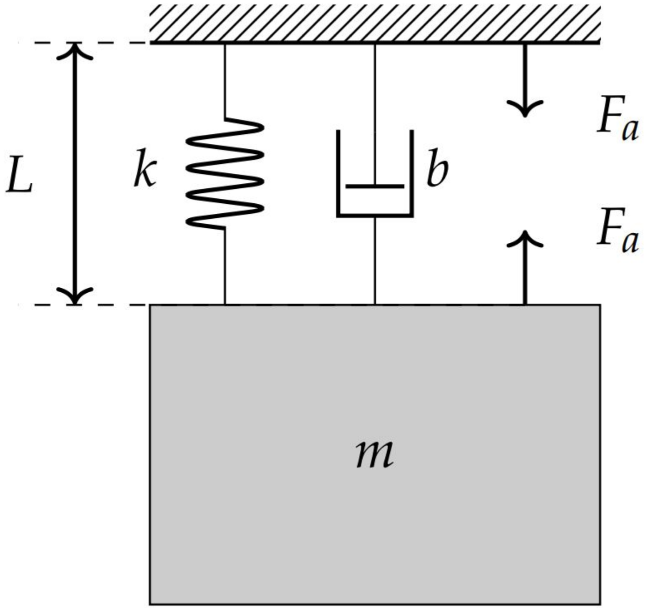


Fig. 9: Lumped mass preliminary model

__Linearized force__

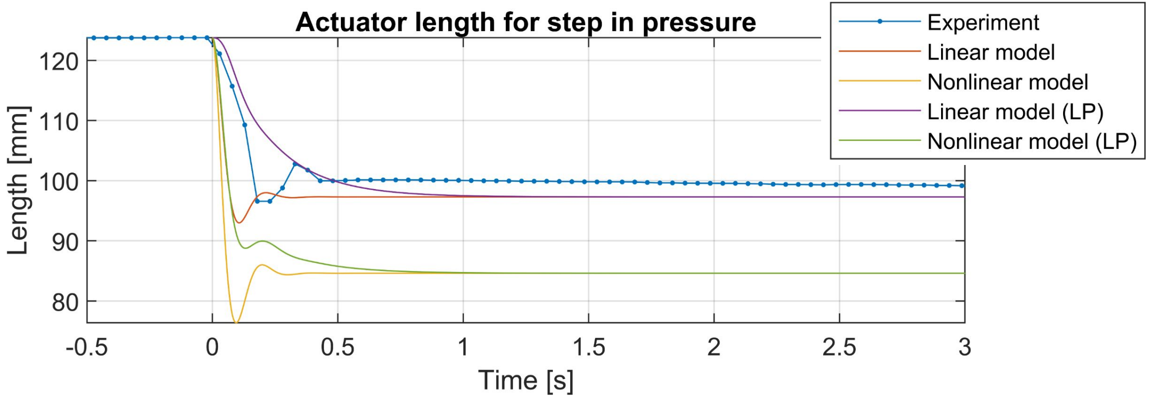
$$F_a = F_o + C_1 dP_g + C_2 dL$$

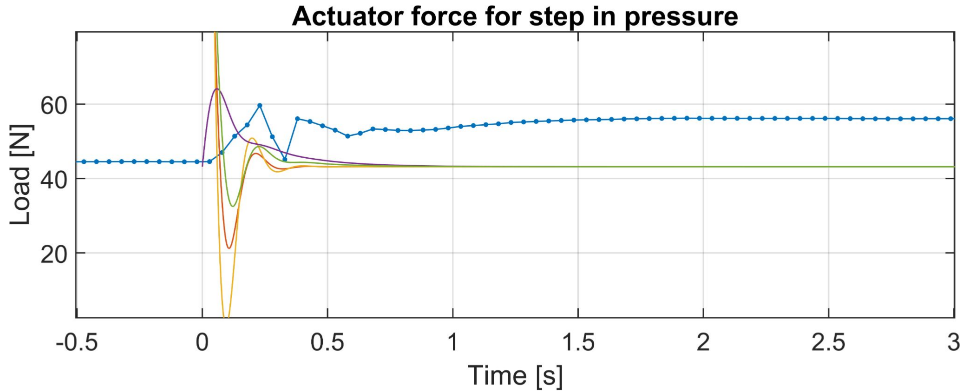
__State space equations__

$$\frac{d}{dt}\begin{bmatrix} P_g \\ L \\ \dot{L} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau} & 0 & 0 \\ 0 & 0 & 1 \\ -\frac{C_1}{m} & -\frac{C_2+k}{m} & -\frac{b}{m} \end{bmatrix} \begin{bmatrix} P_g \\ L \\ \dot{L} \end{bmatrix} + \begin{bmatrix} \frac{1}{\tau} \\ 0 \\ 0 \end{bmatrix} P_{in}$$

Dynamic step response

- Pressure step input
  - 2.5 bar -> 4.5 bar
- Concerns with data
  - Suspect force response
  - Faster sampling required





Next steps

- Develop an observer to predict the force output on the actuator
    - In industry this reduces the costs for which these devices can be employed at scale

- Develop low-level software interfaces to improve sampling rate (10 Hz -> 80 Hz <)

- Compose and analyze frequency response data for our setup

- Look for applications which can sufficiently improve complexity/add challenges to the project

References

- [1] B. Kang, C. S. Kothera, B. K. S. Woods, and N. M. Wereley, "Dynamic modeling of Mckibben pneumatic artificial muscles for antagonistic actuation," 2009 IEEE International Conference on Robotics and Automation, pp. 182–187, 2009.
- [2] M. A. Mat Dzahir and S. Yamamoto, "Dynamic Modeling of McKibben Muscle Using Empirical Model and Particle Swarm Optimization Method," Applied Sciences, vol. 9, no. 12, p. 2538, Jun. 2019, doi: 10.3390/app9122538.