Introduction:

- Dielectric elastomers (DE) have demonstrated promising properties for applications ranging from actuation, sensing, and energy harvesting [1]. By placing a compliant electrode on either side of these materials, one can apply voltage across the material thickness causing large electrostriction (i.e., electric field induced strain on the order of 100%).
- Considering the light weight properties of DE and its compact actuation mechanism, these soft materials are well suited for various platforms, including multi-modal legged robots, micro air vehicles, energy harvesting, biomedicine, and flexible electronics.
- Legged robots struggle to move on different surfaces as their components are typically designed for a single terrain. If a compliant structure could be incorporated into the leg mechanism, it could potentially allow for seamless transfer on to different terrains.
- In the area of flow control, one can similarly control the membrane’s structure with an electrostatic field to alter the fluid-structure interactions. A more compliant membrane (as a result of electrostriction) will be significantly influenced by the surrounding flow physics.
- DE offer a route towards accomplishing these goals; however, adaptive structure designs and real-time control require accurate and computationally efficient predictions of the constitutive behavior and dynamic structure response. Whereas advanced electrostriction has been demonstrated, these electrostatic materials produce rate dependent behavior which has largely been neglected.

Approach:

Beginning from a nonlinear rate-dependent model we integrate the constitutive equations into a finite deforming electroactive membrane structure. From there we compare with experiments and use Bayesian uncertainty quantification to assess model uncertainty and error propagation. We use information gained from the uncertainty analysis to reassess our material model and continue improving our overall structural model.

Material Modeling:

Total Energy Density:
\[
\psi = \psi_u(f_u, \theta) + \frac{1}{2} f_u \theta^T J_2 \theta
\]

Total Stress:

Nonlinear Hyperelastic Free Energy [4]:

\[
\psi_u = \frac{1}{2} \mu \int \left( \frac{\lambda_1 - 1}{\lambda_1^{3/2}} + \frac{\lambda_2 - 1}{\lambda_2^{3/2}} - 2 \right) \, dV
\]

Nonlinear Viscous Energy:

Membrane Structure Modeling:

Transverse load [5]:

\[
F = 2 \varepsilon \sin(\phi) + \varepsilon_0
\]

where \( \varepsilon \) is Cauchy stress in radial direction. Application of electric field in transverse direction decreases the Cauchy stress [6,7].

Relative permissivity, \( \varepsilon_0 \), is assumed independent of deformation. The nonlinear hyperelastic stress is

\[
\psi_u = \frac{1}{2} \mu \int \left( \frac{\lambda_1 - 1}{\lambda_1^{3/2}} + \frac{\lambda_2 - 1}{\lambda_2^{3/2}} - 2 \right) \, dV
\]

Inverse problem using Baye’s Relation:

\[
\theta = \frac{\int \left( \frac{\lambda_1 - 1}{\lambda_1^{3/2}} + \frac{\lambda_2 - 1}{\lambda_2^{3/2}} - 2 \right) \, dV}{\int \varepsilon \sin(\phi) + \varepsilon_0 \, dV}
\]

Reliable parameter estimation (a priori knowledge of the parameter values) is needed. Likelihood of model given parameters

\[
\psi_u = \frac{1}{2} \mu \int \left( \frac{\lambda_1 - 1}{\lambda_1^{3/2}} + \frac{\lambda_2 - 1}{\lambda_2^{3/2}} - 2 \right) \, dV
\]

Bayesian Uncertainty Quantification [8]:

Parameter Estimation:

Markov Chain Monte Carlo – MCMC

Assume unknown model parameters are random variables.

- Uniaxial, viscoelastic model: \( \beta = [\xi, \zeta, \alpha, \omega, \gamma, \eta] \)
- Transverse load model: \( \beta = [\xi, \zeta, \alpha, \omega, \gamma, \eta, \rho] \)

Electric displacement model: \( \beta = [\xi, \zeta, \alpha, \gamma, \eta] \)

Experiments:

- Uniaxial load/unload cycles using Very High Bond (VHB) 4910.
- Transverse loading of membrane structure (See Figure 6).

Effect of electric displacement applied on membrane structure in non-deformed configuration. Placed in Sawyer Tower circuit with a known capacitor.

Conclusion:

- It was shown that the nonlinear viscoelastic model quantified the rate-dependent deformation of VHB 4910 with the greatest accuracy, as it accounted for the behavior at all stretch rates with a single set of hyperelastic parameters.
- The time response of the nonlinear viscoelastic model follows a power law with respect to the deformation rate (See Figure 11). This opens up opportunities to explore origins for the power law based on the underlying network physics.
- Uncertainty associated with model prediction in nonlinear rate dependent regimes is quantified using Bayesian statistics and its errors are propagated through the model to assess model accuracy with respect to experiments.
- Those results show potential for applying controls to a robotic platform as the electroactive behaivior causes significant change in the membrane stiffness as a function of applied field. Effective application of controls could assist a robot in adjusting to different terrains simply by applying different fields across the membrane.
- Determining the appropriate parameters to enhance a robotic platform is currently under investigation to quantify fatigue behavior under electromagnetic loading. The use of Bayesian statistics is ideal to determine if posterior parameter densities evolve during fatigue which would lead to developments of more robust control algorithms and filter designs.

References:


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