Nonlinear transduction and dynamic buckling of dielectric elastomer actuators

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Abstract. Recent advances in the design and fabrication of power-dense dielectric elastomer actuators (DEAs) have enabled agile soft robotic locomotion such as flight. In contrast to most existing DEAs that optimize output energy density, the new DEAs maximize output power density through operating at high frequencies (>200 Hz). Under the dynamic conditions, the DEAs experience nonlinear transduction and dynamic buckling, which reduce DEA performance and lifetime. We characterized these nonlinear dynamic modes and developed mechanical designs to mitigate these effects. Our works resulted in the first soft-actuated aerial robot that can demonstrate controlled hovering flight, acrobatic manoeuvres, as well as in-flight collision-recovery.

Introduction

Dielectric elastomer actuators (DEAs) are soft artificial muscles that have shown promise in a wide range of applications such as haptics, microfluidics, and robotics. Traditionally, researchers aim to maximize DEAs' net energy density through developing soft elastomeric materials of high dielectric strength. Existing DEAs have achieved large deformation (>1000%), and many studies [1] have investigated nonlinear actuation modes and phenomena such as pull-in stability. However, while DEA static nonlinearities have been extensively studied, there lacks accurate models for describing dynamic nonlinearities. In this work [2], we developed DEAs that can operate in the 300 – 500 Hz range. The DEAs drive a flapping-wing robot at system resonance conditions, where they need to overcome large aerodynamic and inertial loads. We identified two unique nonlinear dynamic properties: dynamic buckling and nonlinear transduction. To overcome these effects, we developed mechanical designs and driving strategies to suppress nonlinear modes. For the first time [2], we demonstrated a soft-actuated robot can achieve feedback-controlled hovering flights.

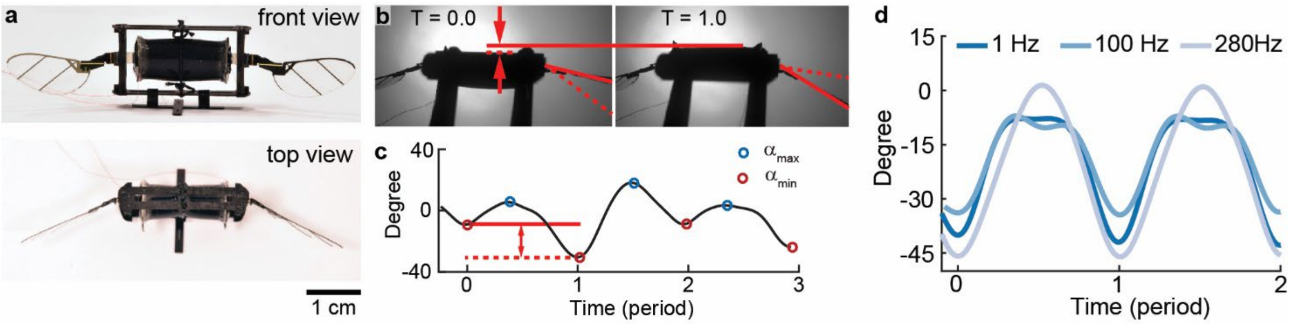

Figure 1: A DEA driven aerial robot and the dynamic nonlinearities associated with the soft actuator. (a) Images of a 155 mg robot. (b) Images that highlight dynamic buckling. (c) Measured wing stroke motion that corresponds to the experiment in (b). The asymmetric peaks illustrate dynamic buckling. (d) Asymmetric wing motion due to nonlinear transduction at different operating frequencies.

Results and discussion

We designed a flapping-wing aerial robot that is driven by a DEA (Figure 1a). When the robot operates at peak conditions (300 Hz and 1400 V), the large aerodynamic load on the DEA causes the actuator to buckle (Figure 1b). We observed period doubling in the corresponding flapping-wing motion (Figure 1c). This period doubling limits the net flapping amplitude, which causes a reduction of system lift force. In addition, buckling leads to large DEA deformation, which causes local dielectric breakdown (self clearing) and reduces actuator performance. This problem can be mitigated by constraining the buckling mode. We constrain the DEA's central plane by tying thread around the DEA. The tension in the thread constrains the DEA from buckling. Furthermore, we measured nonlinear actuation as a function of different operating frequencies. Since a DEA's deformation is proportional to the square of the applied electric field, the robot's output motion does not follow the input waveform. At dynamic conditions, each harmonic component is amplified differently. Consequently, the output wing motion does not resemble sinusoidal driving functions at most operating frequencies (Figure 1d). The asymmetry between upstroke and downstroke motions can cause a 40% reduction of net lift force. To mitigate actuation nonlinearity, we operate the robot near system resonance and remove higher harmonic contributions. Figure 1d shows that at 280 Hz, the robot's flapping-wing motion becomes approximately sinusoidal. Based on these designs, we demonstrated the first controlled flight of an insect-scale soft aerial robot [2], which highlights the potential of applying soft artificial muscles in agile and robust robotic systems.

References

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[2] Chen, Y., Zhao, H., Mao, J., Chirarattananon. P., Helbling, E.F., Hyun, N.P., Clarke, D.R., and Wood, R. J. (2019) Controlled flight of a microrobot powered by soft artificial muscles. *Nature* 575., **7782**: 324-329.