Chapter 10
Interplay of Light, Mechanics, and Material in Light-powered Actuation of Fibers

Alireza Ahmadi and Neda Maghsoodi

Abstract We investigate the self-sustained oscillatory behavior of azo-dye-doped liquid crystal elastomer (azo-LCE) cantilevers under constant illumination. A coupled photomechanical model is developed to capture photo-isomerization dynamics, light absorption, and the resulting nonuniform strain distribution driving bending and flapping motion. Our simulations reveal that the system evolves into a steady-state oscillation at frequencies close to the natural resonance of the structure. The results highlight the interplay of light absorption, self-shadowing, and mechanical response in producing periodic motion, offering insights into designing light-powered actuators and soft oscillators.

Keywords Photomechanical materials · Light-induced bending · Periodic motion

Introduction

Self-sustained oscillation occurs when periodic motion is generated and maintained by a power source that is not inherently periodic. Self-sustained oscillations are non-equilibrium phenomena that interconvert between two or more kinetically stable and metastable states of soft actuators [1]; the actuators directly sense a constant stimulus, deform to a position away from the stimulus source, and autonomously return to their initial state based on an embedded negative feedback loop to obtain regular energy to maintain their periodic motion [2, 3]. Interestingly, the frequency of oscillations depends only on the inherent parameters of the structure [4, 5]. Recent developments in active materials have introduced new possibilities for designing self-sustained oscillators. Liquid crystal elastomers (LCE) are one example of such materials that can respond to incident light when proper photo-responsive moieties (like azobenzene molecules) are incorporated into their structure (Fig.1). The mechanism by which azo-LCEs respond to light depends on illumination wavelength. Exposure to UV radiation at 365 nm prompts the azobenzene linkage to transition from its *trans* to *cis* form, leading to macroscopic deformation (Fig.1). The goal of this work is to investigate the photo-induced self-sustained oscillations of high modulus, glassy, monodomain azo-LCE cantilevers via a self-shadow-induced negative feedback loop.

Methods

Consider an inextensible and unshearable monodomain long and thin LCE strip with a rectangular cross-section subjected to the planar incident light intensity I_0 (Fig. 1). Let s denote the coordinate along the centerline of the strip. The balance of linear and angular momenta can be expressed as [6, 7]

$$m\frac{\partial^2 \mathbf{R}(s,t)}{\partial t^2} = \frac{\partial \mathbf{f}(s,t)}{\partial s} + \mathbf{f}_{\text{ext}}(s,t) \tag{1}$$

$$\Pi\frac{\partial^2 \theta(s,t)}{\partial t^2} = \frac{\partial q(s,t)}{\partial s} + (\hat{\mathbf{t}}(s,t) \times \mathbf{f}(s,t)).\hat{\mathbf{e}}_3 + q_{\text{ext}}(s,t) \tag{2}$$

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Kristin B. Zimmerman, PhD (eds.), *Structural Health Monitoring, Metamaterials, Metastructures and Additive Manufacturing and Dynamics of Biomedical and Bioinspired Systems, 2026, Vol. 10*, Conference Proceedings
of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-8-743-81449-8_10

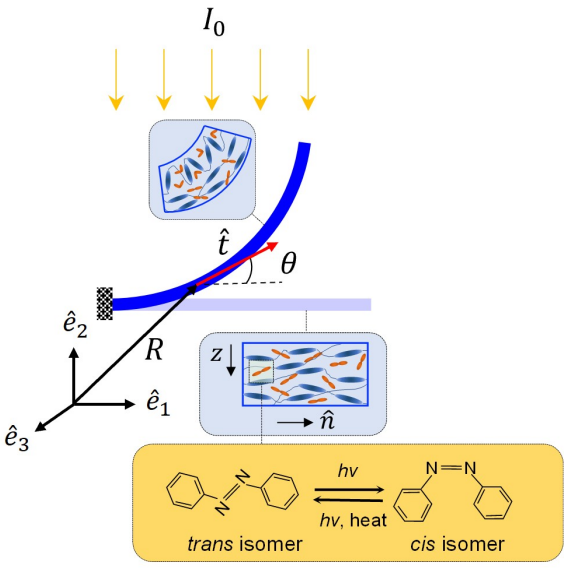

Fig. 1 Azo-LCE deformation under light.

where $\mathbf{f}$ and q are the internal force vector and moment, respectively, $\mathbf{f}_{\text{ext}}$ and q_{ext} are any external force vector and moment per unit length applied to the strip, respectively, m and Π denote the mass and rotational moment of inertia per unit length, respectively. Let n_c denote the fraction of azo molecules in the *cis* state and n_t denote the fraction of azo molecules in the *trans* state. At a depth z at time t, the rate of change of the *cis* volume fraction is [8]

$$\frac{\partial n_c(s,z,t)}{\partial t} = A_t I(s,z,t) n_t(s,z,t) - A_c I(s,z,t) n_c(s,z,t) - \frac{n_c(s,z,t)}{\tau} \tag{3}$$

where $n_t + n_c = 1$ and I is the absorbed light intensity at depth z at time t and point s. At any point s, the light intensity diminishes with depth as it is absorbed by the azo molecules

$$\frac{\partial I(z,t)}{\partial z} = \frac{-I(z,t)}{d_0} \tag{4}$$

where d_0 is the penetration depth. For the definition of utilized parameters, refer to [7, 9]. The photo-isomerization of the azo molecules leads to a light-induced spontaneous axial strain $\varepsilon_0(z,t) = \lambda n_c(z,t)$ in the material where λ is a material constant. The non-uniform distribution of light-induced axial strain at each cross-section causes the strip to bend. Note that any part of the strip may block light from reaching another part, a phenomenon known as *self-shadowing*. In the self-shadowed region, $I = 0$; therefore, the cis molecules relax to the $trans$ state, causing the strip to thermally relax in the shadowed area. The initial-boundary-value problem above for a photomechanical strip is solved via a finite difference method by discretizing the equations in both space and time.

Results and Discussion

Figure 2 shows the simulation results for a monodomain LCE cantilever illuminated perpendicularly from above with a light intensity of $I_0 = 4000\ \text{W/m}^2$. Other simulation parameters are listed in Table 1. Figure 2A shows that, beyond a critical illumination intensity, the rod reaches a steady-state flapping motion with a frequency of 19 Hz. Interestingly, this value is very close to the natural frequency of a clamped-free rod, which in this case is 18 Hz. Our analysis shows that the strip largely bends up and makes shadow on the illuminated section near the clamped end, so the strip unbends to relax the bending energy. Indeed, self-shadowing plays the role of negative feedback loop in self-sustained oscillation. As expected, the oscillation frequency is independent of external stimulus (illumination intensity). Figures 2B, C also show that the steady-state response, once reached, is symmetric, but as the velocity curve clearly shows, the symmetry point is not exactly at $x = 0$. This is because the rod is initially placed in the positive x direction, and since it is clamped at one end, it cannot bend completely to the other side, leading to a small asymmetry. Figure 2D shows the evolution of photo-induced

spontaneous strain. As can be seen in this figure, the steady state photo-strain at the centerline is very small and can be neglected, showing that the assumption of the rod's inextensibility is correct. There are multiple parameters that can affect the motion of the rod and its time scale. A more detailed analysis can lead to interesting results, paving the way towards a self-sustained motion using light.

Table 1 Simulation parameters

Parameter (symbol)	Value
Young's modulus (E)	4 GPa
Poisson's ratio (ν)	0.3
Mass density (ρ)	1400 kg/m^3
Strip thickness (H)	15 μm
Strip width (W)	1 mm
Strip length (L)	15 mm
$trans$ absorption coefficient (A_t)	5 $\times 10^{-3}$ m^2/J
cis absorption coefficient (A_c)	5 $\times 10^{-4}$ m^2/J
Thermal relaxation time (τ)	0.2 s
cis-strain proportionality (λ)	-0.05 [10]

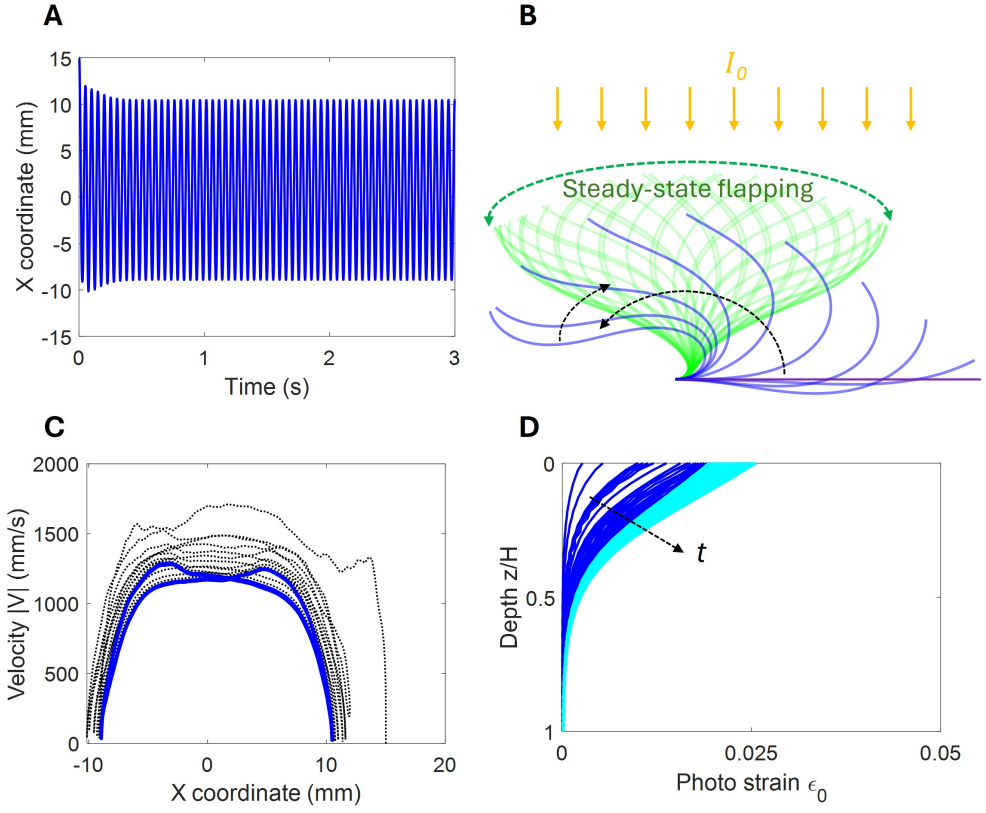

Fig. 2 Self-sustained flapping of the Azo-LCE under constant light illumination using typical parameters for Azo-LCE. (A) The x coordinate of the end-point vs. time, (B) the transient and steady-state flapping of the rod. The red line indicates the initial configuration, blue lines indicate the transient response, and green lines show the self-sustained steady-state flapping of the rod. (C) The velocity of the end-point vs. the x coordinate. The dotted lines show the response in the transient state and the solid blue lines show the steady-state response, (D) the evolution of the light-induced spontaneous strain ϵ_0 in depth and time, showing a very small strain at the centerline of the rod ($z/H = 0.5$, where H is the thickness of the rod). The light blue lines indicate the steady-state response.

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