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Mitigation of Detrimental Torsion in Ionic Polymer–Metal Actuators via Coupled Electrochemical–Mechanical Simulation

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Abstract

In this paper, a Multiphysics framework is proposed for the analysis and mitigation of torsion in ionic polymer–metal composite (IPMC) actuators, where both viscoelastic and electroactive effects of the material are considered simultaneously. The governing equations were first derived based on Euler–Bernoulli beam theory and the principle of minimum energy, and then coupled with the Nernst–Planck–Poisson electrochemical relations to obtain the torsional moment induced by ion migration under an electric field. To account for material softening, the mechanical moduli were formulated as combined models dependent on both time and electric field. Numerical simulations reveal that, under an applied voltage of 5 V and a thickness of 1 mm, the shear modulus decreases by nearly 85% within about 10 seconds; however, by introducing transverse stiff layers and symmetric longitudinal excitation, the torsional moment drops to less than 5% of its initial value and the torsional angle is effectively eliminated. Empirical coefficients were introduced to represent the sensitivity of the moduli to the electric field, whose values may vary with changes in membrane or electrode material. A stability analysis was performed through the definition of a specific index that simultaneously captures the influence of time, electric field intensity, and boundary constraints. The numerical results demonstrate that while modulus reduction over time and with higher voltages decreases the shear and bending stiffness and increases viscous energy, the imposition of boundary conditions at the edges suppresses torsion even under severe softening. Geometrical sensitivity analysis further indicated that variations in length and width have only a limited effect on viscous energy, whereas boundary conditions play a decisive role in torsion control. This framework can therefore serve as a reliable tool for the design of torsion-free actuators in soft robotics and biomedical systems.

Keywords: Ionic Polymer-Metal Composite (IPMC) Actuators, Euler-Bernoulli Beam, Energy Method, Nernst-Planck Equation, Poisson Equation, Torsion.

1. Introduction

Ionic Polymer–Metal Composites (IPMCs), due to their light weight, high flexibility, and low-voltage responsiveness, are among the most important smart materials used in soft robotics and multifunctional sensors. Although early research primarily focused on bending behavior, torsion has recently gained attention as a key degree of freedom for replicating natural motion. It has been shown that increasing the electrode spacing can significantly enhance the twist angle [1]. Recent studies have focused on the design of dual-mode actuators that combine both bending and twisting motions; for instance, an angular velocity exceeding 300°/s at 3.75 V has been reported [2]. Furthermore, several one-dimensional and three-dimensional models have been developed to describe the torsional response and large bending deformations, demonstrating high accuracy in reproducing experimental behavior [3,4].
On the other hand, both experimental and numerical analyses have revealed the crucial influence of geometry, electrode symmetry, and boundary conditions in controlling undesired torsion [5,6].
The innovation of the present research lies in the development of a Multiphysics framework in which the time- and electric-field-dependent behavior of the Young's and shear moduli is modeled, combining the Poisson–Nernst–Planck equations with the Euler–Bernoulli beam theory.

2. Methodology

The strain energy of the system (π) can be expressed by Equation (1) [7]:

$$\pi = \frac{1}{2}\iiint_V (\sigma_{xx}\varepsilon_{xx} + \sigma_{yy}\varepsilon_{yy} + \sigma_{zz}\varepsilon_{zz} + \sigma_{xy}\varepsilon_{xy} + \sigma_{yz}\varepsilon_{yz} + \sigma_{zx}\varepsilon_{zx}) = \frac{1}{2}\int_0^l EI\left(\frac{d^2w}{dx^2}\right)^2 dx \quad (1)$$

The strain energy resulting from viscous stress is calculated using Equation (2):

$$U_{vis} = \int_V \eta\left(\frac{\partial v}{\partial y}\right)^2 dV = \eta \iiint \left(\frac{\partial v(x,y,z)}{\partial y}\right)^2 dx\, dy\, dz \quad (2)$$

The total potential energy of the system, which combines the energy induced by viscous stress (torsional energy) and the energy generated by electrical excitation, is expressed in Equation (3):

$$\pi = U_{vis} + U_{elec} \quad (3)$$

$$\pi = \eta \iiint \left(\frac{\partial v(x,y,z)}{\partial y}\right)^2 dx\, dy\, dz - \int_0^L \int_{-\frac{b}{2}}^{\frac{b}{2}} \left[M_{elec}^{(w)}(x) \cdot \frac{d^2w}{dx^2} + M_{elec}^{(v)}(y) \cdot \frac{d^2v}{dy^2}\right] dxdy$$

According to the principle of minimum potential energy, $\delta\pi = 0$ for any arbitrary δv, which can be expressed by Equation (4).

$$\eta\frac{\partial^2 v}{\partial y^2} + \frac{1}{A_x}\frac{d^2 M_{elec}^{(v)}(y)}{dy^2} = 0 \quad (4)$$

The final governing equation, based on the energy minimization principle, is obtained from Equation (3) with respect to v, as shown in Equation (5).

$$\eta\frac{\partial^2 v}{\partial y^2} + \frac{d^2 M_{elec}^{(v)}(y)}{dy^2} = 0 \quad (5)$$

Similarly, based on the same principle, differentiation of Equation (3) with respect to w gives Equation (6).

$$\frac{d^2 M_{elec}^{(w)}(x)}{dx^2} = 0 \quad (6)$$

The boundary conditions for the viscous term are expressed by Equation (7),

$$\iint \left(\frac{\partial v}{\partial y}\delta v\right)_{y=-\frac{b}{2}}^{y=\frac{b}{2}} dx\, dz = 0 \quad (7)$$

and likewise, the boundary conditions for the viscous electrical moment term are expressed by Equation (8).

$$\int \left[M_{elec}^{(v)}(y)\frac{d\delta v}{dy}\right]_{y=-\frac{b}{2}}^{y=\frac{b}{2}} dx = 0 \quad (8)$$

The deformation behavior of Ionic Polymer–Metal Composites (IPMCs) under an electric field can be described using the Nernst–Planck equation, which governs ion transport and is given by Equation (9) [ʌ]:

$$J = -D\left[\nabla C + \frac{zF}{RT}C.\nabla V\right] \quad (9)$$

To relate the potential field to the ion concentration (ion distribution), the Poisson equation is employed [8].

$$\nabla^2 V + \frac{\rho}{\varepsilon} = \frac{zF(c - c_0)}{\varepsilon} \quad (10)$$

The velocity gradient plays a crucial role in torsional behavior. As shown in Equation (2), if $\partial v/\partial y \neq 0$, the viscous energy is positive, indicating resistance to motion and the generation of torsion. If $\partial v/\partial y = 0$, the viscous energy becomes zero, corresponding to the absence of shear forces and torsion.

By applying physical boundary conditions at the upper and lower edges ($y = \pm b/2$):

$$\left.\frac{\partial v}{\partial y}\right|_{-\frac{b}{2}}^{\frac{b}{2}} = 0 \quad (11)$$

If the structure is designed such that the displacement $\boldsymbol{v}$ is symmetric with respect to the $y - axis$, reaches a maximum at $y = 0$, and becomes zero at $y = \pm b/2$, then the velocity gradient at the boundaries vanishes, minimizing viscous energy.

When $\partial v/\partial y = 0$ at $y = \pm b/2$, integrating by parts yields Equation (12).

$$\iiint \frac{\partial v}{\partial y}\frac{\partial \delta v}{\partial y} dx\, dy\, dz \rightarrow \iiint \frac{\partial^2 v}{\partial y^2}\delta v dx\, dy\, dz + \underbrace{B.C.}_{=0} \quad (12)$$

Since $\partial v/\partial y = 0$ at the boundaries, the boundary term becomes zero—meaning that no net torsional force acts at the edges, and torsion is eliminated.

Table 1 shows how different boundary conditions affect torsional behavior and viscous energy.

Table 1. Effect of Boundary Conditions on Torsion

Boundary Condition	Physical Interpretation	Effect on Torsion
$\partial v/\partial y = 0$ at $y = \pm b/2$	No shear stress at edges	Elimination of viscous torsional energy
Constant or very small v at edges	Limited transverse displacement	Negligible torsion

For simplicity in analysis and to enable modeling of coupled phenomena, it is assumed that this dependency follows an exponential relation combining both time and electric field intensity.

The equations are proposed as an analytical model, intended to explore the general system behavior under this simplified assumption rather than to provide an exact empirical fit (Equations (13)– (18)).

Accordingly, these parameters can be expressed as functions of the electric field intensity (E_f):

$$E(E_f) = E_0 e^{-\gamma E_f} \quad (13)$$

$$G(E_f) = G_0 e^{-\delta E_f} \quad (14)$$

If time dependency is also considered, a viscoelastic model can be adopted.

$$E(t) = E_0 + E_1 e^{-\frac{t}{\tau}} \quad (15)$$

$$G(t) = G_0 + G_1 e^{-\frac{t}{\tau}} \quad (16)$$

Since both time and electric field influence E, it can be written as Equation (17).

$$E(t, E_f) = \left(E_0 + E_1 e^{-\frac{t}{\tau}}\right) e^{-\gamma E_f} \quad (17)$$

Similarly, the shear modulus (G) is defined in Equation (18).

$$G(t, E_f) = \left(G_0 + G_1 e^{-\frac{t}{\tau}}\right) e^{-\delta E_f} \quad (18)$$

Table 2. Effect of Variable Shear Modulus on Torsion

Parameter	Influence on Torsion
Decreasing $G(t, E_f)$	Reduced shear resistance may increase or decrease torsion (depending on boundary conditions)
Boundary condition $\partial v/\partial y = 0$ at edges	Suppression of shear flow at edges reduces or eliminates torsion
Combination of both	Formation of a parabolic deformation profile naturally eliminates torsion

Table 2 illustrates how various factors influence the torsional behavior of the composite. Using the proposed models (Equations (17) and (18)), a numerical criterion for the torsional stability/sensitivity index is defined as Equation (19).

$$S(t, E_f, \alpha) = (1 - \alpha)\frac{G_0}{G(t, E_f)} \quad (19)$$

3. Results and Discussion

Figure 1 presents the variation of the shear modulus $G(t, E_f)$ over time for different voltage levels.

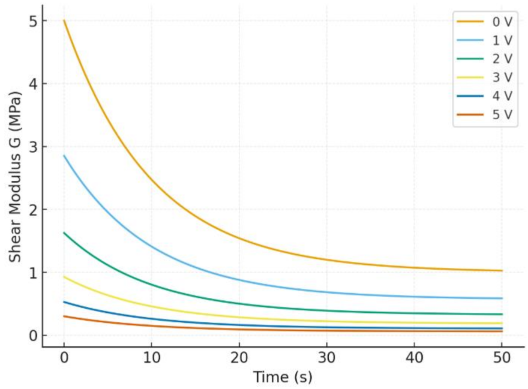

Figure 1. Shear modulus versus time at different voltages

Figure 2 shows the Young's modulus $E(t, E_f)$ as a simultaneous function of time and electric field.

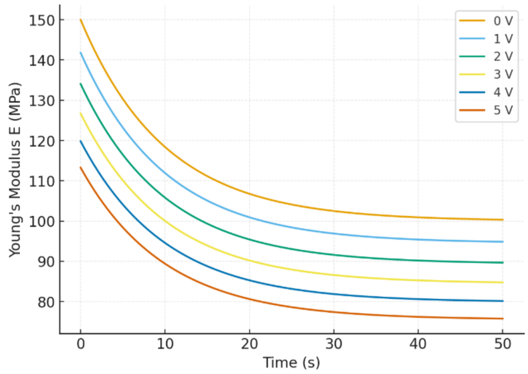

Figure 2. Young's modulus versus time and electric field

Figures 3–7 illustrate the stability analysis under varying boundary conditions.

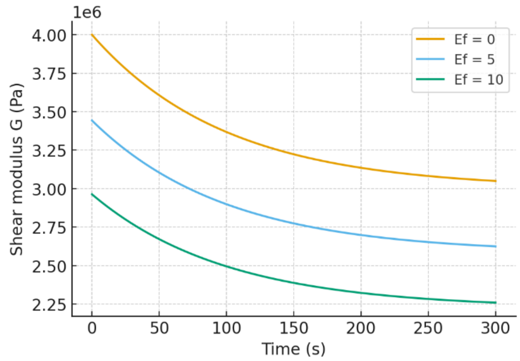

Figure 3. Decrease of shear modulus with time and electric field

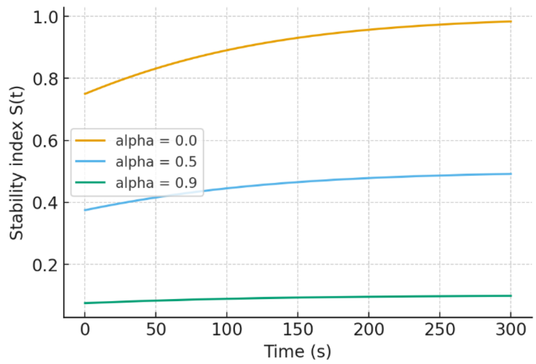

Figure 4. Stability index versus time for multiple boundary conditions

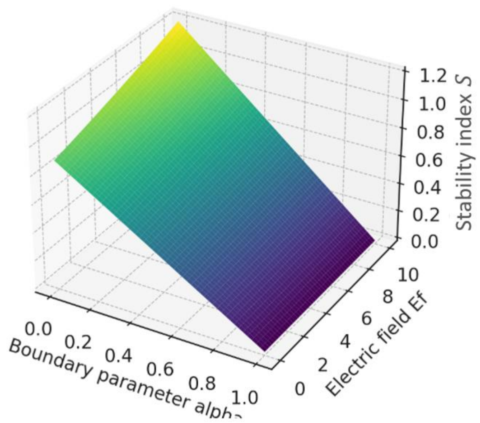

Figure 5. Surface plot of the stability index at t = 100

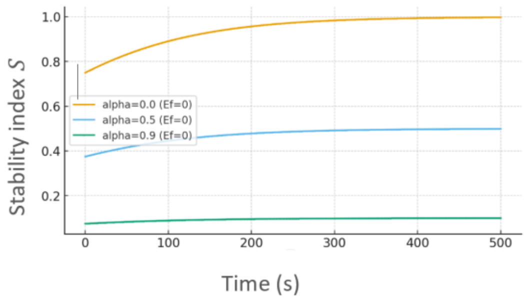

Figure 6. Stability index versus time under various boundary conditions

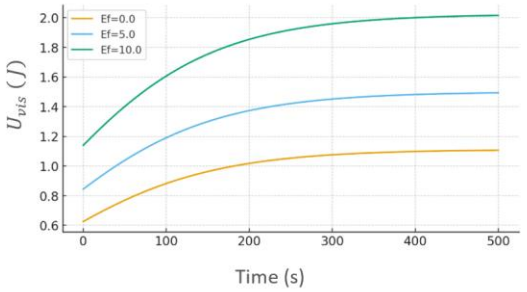

Figure 7. Variation of viscous energy with time and electric field

4. Conclusions

In this study, a comprehensive Multiphysics framework was developed to analyze the origin of torsion in Ionic Polymer–Metal Composite (IPMC) actuators and to propose strategies for its reduction or elimination. Using the Euler–Bernoulli beam theory and the principle of minimum potential energy, the bending strain energy and the viscous energy contribution associated with shear stresses along the $yz-plane$ were derived.

Subsequently, the coupled Nernst–Planck–Poisson equations were integrated to describe ion transport, enabling the derivation of the electro-torsional moment as a function of potential gradient and ion concentration.

The proposed model demonstrates that torsion in IPMC beams arises from the interaction of three key factors: Viscoelastic behavior, Electro-induced softening, and Mechanical boundary conditions.

This insight provides a solid foundation for designing torsion-free or torsion-controlled IPMC actuators with enhanced stability, durability, and energy efficiency for applications in soft robotics, biomedical devices, and micro-actuation systems.

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