Saxena, Shashank; **Barreto, Darius Diogo**; **Kumar, Ajeet**

Extension-torsion-inflation coupling in compressible electroelastomeric thin tubes. (English)

Zbl 1446.74122
Math. Mech. Solids 25, No. 3, 644-663 (2020).

Summary: We present an axisymmetric and axially homogeneous variational formulation to obtain coupled extension-torsion-inflation deformation in compressible electroelastomeric tubes in the presence of axial and radial electric fields. We show that such deformations occur under the following two conditions: (1) only the axial electric field is imposed, with the electric poling direction in the tube (if present) lying in the radial plane; and (2) only the radial electric field is imposed within the tube, with the electric poling direction (if present) also along the radial direction. The poling direction in condition (1) generates helical anisotropy in the tube. We then obtain the governing differential equations necessary to solve the above deformation problem for thick tubes. We further apply the thin tube limit to obtain simplified algebraic equations to solve the same deformation problem. The effect of applied electric field parameters on the extension-inflation coupling and induced internal pressure vs. imposed inflation behavior is finally presented through numerical solution of the above obtained algebraic equations. The study will be useful in designing soft electroelastic tubular actuators.

MSC:

74F15 Electromagnetic effects in solid mechanics
74B99 Elastic materials
74G65 Energy minimization in equilibrium problems in solid mechanics

Keywords:

nonlinear electroelasticity; extension-torsion coupling; extension-inflation coupling; helical anisotropy; thin tube

Full Text: DOI

References:

[1] Jaffe, H, Berlincourt, DA. Piezoelectric transducer materials. Proc IEEE 1965; 53(10): 1372-1386.

[2] Ayers, W, Hirsch, J. General Dynamics Corp. Method and means for sensing strain with a piezoelectric strain sensing element. US Patent 3,750,127, 1973.

[3] Crawley, EF, De Luis, J. Use of piezoelectric actuators as elements of intelligent structures. AIAA J 1987; 25(10): 1373-1385.

[4] Shahinpoor, M . Continuum electromechanics of ionic polymeric gels as artificial muscles for robotic applications. Smart Mater Struct 1994; 3(3): 367.

[5] Kim, J, Seo, YB. Electro-active paper actuators. Smart Mater Struct 2002; 11(3): 355.

[6] Bossis, G, Abbo, C, Cutillas, S, et al. Electroactive and electrostructured elastomers. In: Electro-rheological fluids and magneto rheological suspensions. World Scientific, 2000, 18-27.

[7] Toupin, RA . The elastic dielectric. J Ration Mech Anal 1956; 5: 1956849915.

[8] Hutter, K . On thermodynamics and thermostatics of viscous thermoelastic solids in the electromagnetic fields: a Lagrangian formulation. Arch Ration Mech Anal 1975; 58(4): 339-368. · Zbl 0332.73095

[9] Hutter, K . A thermodynamic theory of fluids and solids in electromagnetic fields: Arch Ration Mech Anal 1977; 64(3): 269-298. · Zbl 0366.73001

[10] Maugin, G.A. Continuum mechanics of electromagnetic solids (Vol. 33). Amsterdam: Elsevier, 2013.

[11] Eringen, AC . Nonlinear theory of continuous media. New York: McGraw-Hill, 1962.

[12] Eringen, AC, Maugin, GA Electrodynamics of continua I: foundations and solid media. Berlin: Springer Science \& Business Media, 2012.

[13] Pao, YH . Electromagnetic forces in deformable continua. In: Mechanics today, vol. 4. New York: Pergamon Press, 1978, 209-305. · Zbl 0379.73100

[14] Trimarco, C . A Lagrangian approach to electromagnetic bodies. Technische Mechanik 2002; 22(3): 175-180.

[15] Dorfmann, A, Ogden, RW. Nonlinear electroelasticity. Acta Mechanica 2005; 174(3-4): 167-183. · Zbl 1066.74024

[16] Dorfmann, A, Ogden, RW. Nonlinear electroelastic deformations. J Elast 2006; 82(2): 99-127. · Zbl 1091.74014

[17] Dorfmann, L, Ogden, RW. Nonlinear theory of electroelastic and magnetoelastic interactions. New York: Springer, 2014. · Zbl 1291.78002

[18] Ogden, RW, Steigman, D. Mechanics and electrodynamics of magneto- and electro-elastic materials. Udine: CISM International Centre for Mechanical Sciences, 2011.

[19] Varga, Z, Filipcsei, G, Szilàgyi, A, Zrínyi, M. Electric and magnetic field-structured smart composites. In: Macromolecular Symposia, 2005.

[20] Bustamante, R, Ogden, RW. Universal relations for nonlinear electroelastic solids. Acta Mechanica 2006; 182(1-2): 125-140. · Zbl 1111.74014

[21] Bustamante, R . Mathematical modelling of non-linear magneto-and electro-active rubber-like materials. Doctoral dissertation, University of Glasgow, Glasgow, 2007.

[22] Kashani, MR, Javadi, S, Gharavi, N. Dielectric properties of silicone rubber-titanium dioxide composites prepared by dielectrophoretic assembly of filler particles. Smart Mater Struct 2010; 19(3): 035019.

[23] Carpi, F, Gallone, G, Galantini, F, De Rossi, D. Silicone-poly (hexylthiophene) blends as elastomers with enhanced electromechanical transduction properties. Adv Funct Mater 2008; 18(2): 235-241.

[24] Jensen, H . Determination of macroscopic electro-mechanical characteristics of 1-3 piezoceramic/polymer composites by a concentric tube model. IEEE Trans Ultrason Ferroelectr Freq Control 1991; 38(6): 591-594.

[25] Kim, SH, Haines, CS, Li, N, et al. Harvesting electrical energy from carbon nanotube yarn twist. Science 2017; 357(6353): 773-778.

[26] Calabrese, L, Frediani, G, Gei, M, et al. Active compression bandage made of electroactive elastomers. IEEE/ASME Trans Mechatron 2018; 23(5): 2328-2337.

[27] Melnikov, A, Ogden, RW. Finite deformations of an electroelastic circular cylindrical tube. Zeitschrift für angewandte Mathematik und Physik 2016; 67(6): 140. · Zbl 1354.74024

[28] Ren, J, Wang, C. Electromechanical responses and instability of electro-active polymer cylindrical shells. Appl Math Mech 2016; 37(8): 1067-1076.

[29] Kumar, K, Kumar, R. Torsional effect on the nonlinear electroelastic response of a circular cylinder. In: Proceedings of the World Congress on Engineering, 2012.

[30] Lu, T, An, L, Li, J, et al. Electro-mechanical coupling bifurcation and bulging propagation in a cylindrical dielectric elastomer tube. J Mech Phys Solids 2015; 85: 160-175.

[31] Mehnert, M, Hossain, M, Steinmann, P. On nonlinear thermo-electro-elasticity. Proc R Soc London, Ser A 2016; 472(2190): 20160170. · Zbl 1371.82161

[32] Goulbourne, NC . A mathematical model for cylindrical, fiber reinforced electro-pneumatic actuators. Int J Solids Struct 2009; 46(5): 1043-1052. · Zbl 1236.74059

[33] Zhu, J, Stoyanov, H, Kofod, G, et al. Large deformation and electromechanical instability of a dielectric elastomer tube actuator. J Appl Phys 2010; 108(7): 074113.

[34] Dorfmann, L, Ogden, RW. Nonlinear response of an electroelastic spherical shell. Int J Eng Sci 2014; 85: 163-174. · Zbl 1423.74305

[35] Singh, R, Kumar, S, Kumar, A. Effect of intrinsic twist and orthotropy on extension-twist-inflation coupling in compressible circular tubes. J Elast 2017; 128(2): 175-201. · Zbl 1374.74017

[36] Singh, R, Singh, P, Kumar, A. Unusual extension-torsion-inflation couplings in pressurized thin circular tubes with helical anisotropy. Mathematics and Mechanics of Solids 2019; 24(9), 2694-2712.

[37] Steinmann, P . 2011. Computational nonlinear electro-elasticity: getting started. In: Mechanics and electrodynamics of magneto- and electro-elastic materials. Vienna: Springer, 2011, 181-230. · Zbl 1213.74139

[38] Pan, E, Heyliger, PR. Free vibrations of simply supported and multilayered magneto-electro-elastic plates. J Sound Vib 2002; 252(3): 429-442.

[39] Blatz, PJ, Ko, WL. Application of finite elastic theory to the deformation of rubbery materials. Trans Soc Rheology 1962; 6(1): 223-252.

[40] Barreto, DD, Kumar, A, Santapuri, S. Extension-torsion-inflation coupling in compressible magnetoelastomeric thin tubes with helical magnetic anisotropy (communicated). 2019. · Zbl 1440.74064