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Dynamics of conducting polymer actuators

Mehrdad Bahrami-Samani
University of Wollongong

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DYNAMICS OF CONDUCTING POLYMER ACTUATORS

A thesis submitted in fulfilment of the
requirements for the award of the degree

Doctor of Philosophy

From

University of Wollongong



By

Mehrdad Bahrami-Samani, B. Sc., M. Sc. (Mech. Eng.)

School of Mechanical, Materials and Mechatronic Engineering

2007

CERTIFICATION

I, Mehrdad Bahrami-Samani, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Mehrdad Bahrami-Samani

July 21, 2007

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GLOSSARY

σ	Stress
ε	Strain
k_r	Relaxed stiffness coefficient
k_t	Total stiffness coefficient
k_i	Maxwell's i^{th} stiffness coefficient
η_i	Maxwell's i^{th} viscosity coefficient
ε_{ech}	Electrochemical generated strain
ρ	Charge transferred density
q	Charge transferred
ΔF	Frequency change
ΔR	Admittance change
f_0	Resonance frequency of bare crystal
L_u	Inductance of unloaded crystal
ρ_q	Density of the quartz crystal
μ_q	Shear modulus of the quartz crystal
ρ_f	Film density
ρ_l	Liquid density
η_l	Liquid viscosity
h_f	Film thickness
G	Shear modulus of the film

PUBLICATIONS

- **Samani, M.B.**, G.M. Spinks, and C. Cook. "*Mechanical performance of PPy helix tube microactuator*". in Smart Materials III. 2004. Sydney, Australia: SPIE.
- **Samani, M.B.**, Spinks, G. M., Whitten, P. G. and Cook, C. "*Modelling of Polypyrrole Actuators*". in Electroresponsive Polymers and Their Applications. 2005: Mater. Res. Soc. Symp. Proc. 889, Warrendale, PA, 2005.
- Spinks, G., Xi, B., Campbell, T., Whitten, P., Mottaghitalab, V., **Samani, M. B.** and Wallace, G. G. "*In pursuit of high-force/ high-stroke conducting polymer actuators*" (Invited Paper). in Smart Structures and Materials 2005: Electroactive Polymer Actuators and Devices (EAPAD). 2005. San Diego, CA, USA: SPIE.
- **Samani, M.B.**, Whitten, P., Spinks, G. and Cook, C. "*Viscoelastic study of conducting polymers using quartz crystal microbalance*". in Smart Structures and Materials 2006: Electroactive Polymer Actuators and Devices (EAPAD). 2006. San Diego, CA, USA: SPIE.
- Spinks, G.M., Mottaghitalab, V., **Bahrami-Samani, M.**, Whitten, P. G. and Wallace, G. G., "*Carbon-Nanotube-Reinforced Polyaniline Fibers for High-Strength Artificial Muscles*". Advanced Materials, 2006. 18(5): p. 637-640.
- **Samani, M.B.**, Spinks, G. M., Whitten, P. G. and Cook, C. "*Effect of Actuation on Viscoelastic Parameters of Conducting Polymer Actuators*". ready to submit.
- **Samani, M.B.**, Cook, C., Madden, J. D., Spinks, G. M., Whitten, P. G. and "*Quartz Crystal Microbalance Study of Mass Changes and Modulus Shifting in Electrochemically Switched Polypyrrole*". Thin Solid Film, accepted.

ABSTRACT

Considerable research has been carried out to develop actuator technologies such as shape memory alloys, piezoelectric actuators, magnetostrictive actuators, contractile polymers and electrostatic actuators to use in devices such as human-like robots, micro robots and artificial organs for medical applications place of conventional actuators. Though there have been great advances, one or more of high electrical power, low efficiency or low strain limit the application of these new actuator technologies.

Recently, conducting polymers have drawn considerable attention as a new class of advanced functional material for many applications based on the unique properties of electro-activity, conductivity and other physical or chemical properties. The applications being considered include batteries, photovoltaic devices, electro-chromic devices, ion selective membranes, electromagnetic interference shielding, radar absorption, electrical wires, corrosion inhibitors, electrochemical sensors and actuators.

For actuator applications a comprehensive electro-chemo-mechanical model is needed to predict the mechanical output (displacement or force) from the electrical input (current and voltage) to enable control engineers to use these actuators in mechanical systems, new models which describe the dynamic response (actuator output/actuator input) as a function of time and frequency are required. The research in this thesis shows how such models can be derived by exploiting standard control theory analysis tools using Laplace transforms and State-Space techniques. For conducting polymers, such a model needs to include a description of the chemical process occurring between the conducting polymer, dopant and electrolyte. Such a model will enable the application of conducting polymer actuators in automation and robotic applications in which a predictive model is needed to design the control system and also identify the system performance to optimise the actuator characteristics. The aim of the research presented in this thesis is to create a comprehensive predictive model in order to track the output of a typical high-performance conducting polymer actuator: Polypyrrole Helix Tube Fibre Composite Actuator.

The review of literature has revealed that previous models of polypyrrole actuators have been based on the 'strain to charge ratio' parameter, which has been assumed to be constant. In this work, it is shown that the strain to charge ratio is not always constant,

particularly when a wide potential window is used. A master calibration curve approach has been devised to model the mechanical output when the strain to charge ratio is not constant. Secondly, the polypyrrole helix tubes were found to be viscoelastic, so the model was modified to include the viscoelastic (time-dependent) responses. Finally, the model was further modified to allow the viscoelastic parameters to vary with the applied potential. The latter two additions to the model greatly improve its predictive ability when the applied load is changing.

To further investigate the effect of applied potential on the mechanical properties, a measurement method based on Quartz Crystal Microbalance technique has been developed. This method enables the thickness and shear modulus variation of polypyrrole thin films under electrochemical doping and un-doping (oxidation and reduction) to be studied. A complicated 'Modulus Shifting' phenomenon in polypyrrole is revealed by these studies which depend strongly on the electrolyte.

Finally, the results present a full description of the electromechanical characterisation of polypyrrole helix tubes considering the interacting effects of electrochemical and electromechanical parameters. This description may enable further optimization of the design and performance of polypyrrole helix tube actuators.

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