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Nonlinear analysis of two-phase flow dynamics in a polymer electrolyte fuel cell cathode

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In polymer electrolyte fuel cells (PEFCs), proper water management is required for optimal fuel cell performance. Product water is needed to hydrate the membrane and decrease its ionic resistance, but too much water can flood the cathode and increase the transport resistance of the gaseous reactants. Efficient water management maintains the proper balance of water with a minimal parasitic load for reactant delivery and water removal.

The highly nonlinear and chaotic system dynamics associated with water accumulation and removal, shown in Figure 1, add significant complexity to water management optimization. In this work, we apply a nonlinear analysis to the voltage output of a 50 cm^2 PEFC with an 18μm Gore membrane operating under varying levels of water accumulation and removal to identify fundamental nonlinear quantities.

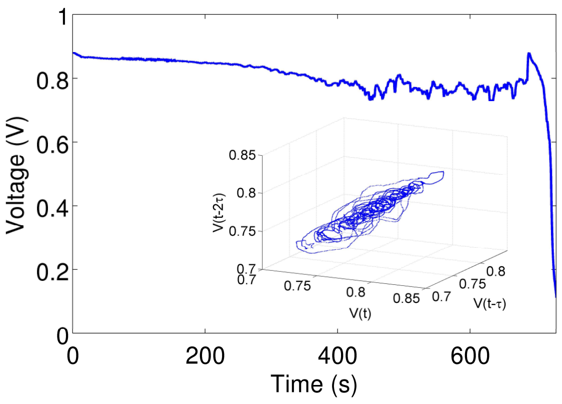

Figure 1: PEFC voltage signal under low-current low-air flow rate conditions. The onset of instability induced by cathode flooding can be witnessed at about 400 seconds, after which the voltage signal is completely lost around 700 seconds. The inset shows the time-delay embedded strange attractor of the 400-700 second window with a fractal dimension of ~3.4.

After using a nonlinear noise reduction scheme in the time-delay embedded state space [1], we estimate chaotic invariants indicative of the health of the fuel cell. One estimated invariant is the fractal correlation dimension, a measure of the degrees of freedom, or complexity, of the dynamics [2]. Additionally, we identify scale-invariance in the frequency power spectra that is correlated with the degrees of dynamical freedom, shown in Figure 2.

A second invariant is the correlation entropy, an estimator for Kolmogorov entropy [3]. It is an information-theoretic entropy indicative of the amount of prior information needed to specify the current dynamical state, with less stable dynamics exhibiting higher entropy. We propose to use the maximal Lyapunov exponent of the return map as an indicator of the dynamical stability of the fuel cell, Figure 3. The results can be used in the design of an optimal water management scheme.

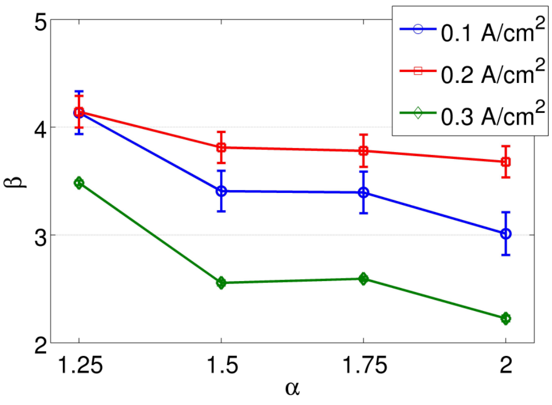

Figure 2: Frequency power law exponent β vs. air stoichiometric ratio α for different current densities. The trend in β for each current density is consistent with estimated correlation dimensions.

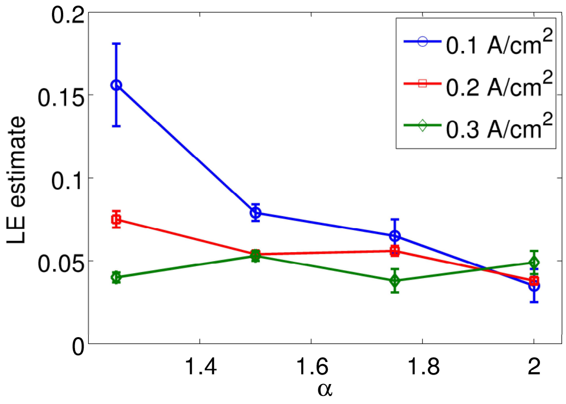

Figure 3: Lyapunov exponent (LE) estimates for the voltage return map vs. air stoichiometric ratio α for different current densities. The least stable operation occurs at low α and low current.

References

[1] H. Kantz and T. Schreiber, *Nonlinear Time Series Analysis*, 2000.
[2] P. Grassberger and I. Procaccia, “Measuring the strangeness of strange attractors,” *Physica D: Nonlinear Phenomena*, 1983.
[3] P. Grassberger and I. Procaccia, “Estimation of the Kolmogorov entropy from a chaotic signal,” *Physical Review A*, 1983.