Moshen Zayernouri

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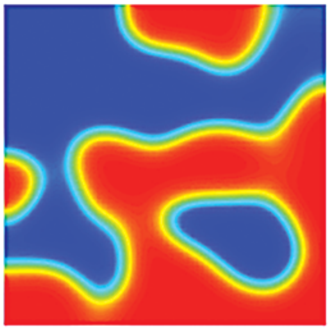
BIO SKETCH

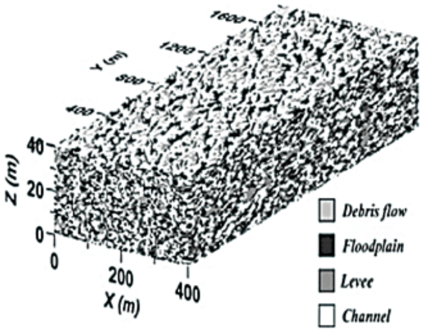
Mohsen Zayernouri joined the MSU faculty in August 2015 with joint appointments in the Department of Computational Mathematics, Science, and Engineering, and the Department of Mechanical Engineering. He is also the director of the Fractional Mathematics for Anomalous Transport and Hydromechanics (FMATH) group at MSU.

The overarching theme of research in FMATH is to bring to bear advanced computational tools from applied mathematics and data sciences to develop multi-fidelity and predictive simulation tools for challenging engineering problems, including: stochastic Lévy processes in turbulent flows, shock and interface problems in reacting and multi-phase flows, anomalous transport in porous and disordered materials, sub-/super-diffusion processes in the human brain, and complex bio-materials and tissue engineering. The main thrust of research in FMATH is on fractional-order modeling, numerical analysis (FEM, spectral methods, and spectral element methods), computational fluid dynamics, data-driven algorithms for fractional PDEs, stochastic PDEs, and high-performance computing.

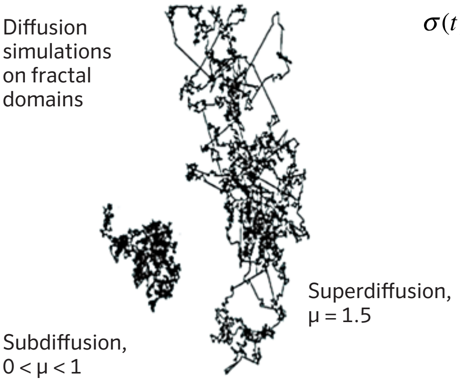
Dr. Zayernouri obtained his M.Sc. in mechanical engineering from Tehran Polytechnic, Iran. Subsequently, he joined the University of Utah, where he acquired his first Ph.D. in mechanical engineering. He then joined Brown University, where he received his second Ph.D. in applied mathematics under Professor George Em Karniadakis. Prior to joining MSU, Dr. Zayernouri was a postdoctoral research associate in the Division of Applied Mathematics at Brown University.



Random sharp interfaces in multiphase flows

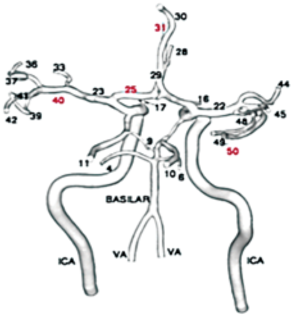


Anomalous disperson in porous media (Merschaert et al. 2010)



Stochastic (Levy) processes (Ozarslan et al. 2006)

$$\sigma(t)+\tau_{\sigma 0}^{\alpha C} D_t^{\alpha}\sigma(t)=E\left[\varepsilon(t)+\tau_{\varepsilon 0}^{\alpha C} D_t^{\alpha}\varepsilon(t)\right]$$



Fractional-order continuum mechanics

RESEARCH INTERESTS

Numerical analysis (FEM, spectral, and spectral element methods), nonlocal continuum mechanics for anomalous transport, stochastic modeling and uncertainty quantification, computational fluid dynamics, high-performance computing

LAB(S)/GROUP(S)

Fractional Mathematics for Anomalous Transport and Hydromechanics (FMATH)

WEBSITE

https://cmse.natsci.msu.edu/directory/faculty/mohsen-zayernouri/

GROUP MEMBERS

PH.D. STUDENT: Anna Lischke (Brown University, externally co-advised). COLLABORATING FACULTY: George Em Karniadakis (Brown University), Mark Meerschaert (MSU), Mark Ainsworth (Brown University), Jan Hesthaven (EPFL), Anastasios Matzavinos (Brown University), Marco L. Bittencourt (Unicamp, Brazil), Jorge Suzuki (Unicamp, Brazil), Hong Wang (University of South Carolina), Guang Lin (Purdue University), Farzad Sabzikar (Iowa State University).

CURRENT RESEARCH FOCUS

In FMATH, we are particularly interested in physical problems that exhibit anomalous (sub- or super-) diffusion, nonlocal interactions, self-similar structures, long memory dependence, and power-law effects. Applications include: non-Gaussian (Levy) processes in turbulent flows, non-Newtonian fluids and rheology, non-Brownian transport phenomena in porous and disordered materials, and non-Markovian processes in multi-scale complex fluids and multi-phase problems. In such applications, fractional PDEs naturally appear as the right governing equations leading to high-fidelity modeling and predictive simulations, which otherwise cannot be achieved using the standard integer-order PDEs.

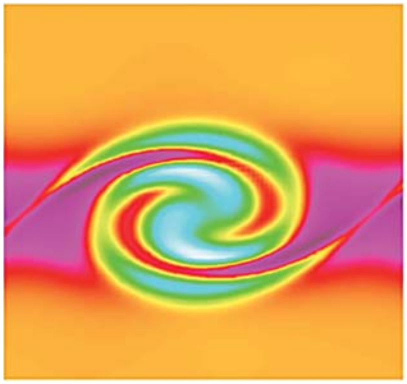
Our main research objective is to develop an integration of theory and algorithms for data-driven FPDEs, and we envision a combined mathematical-computational framework where the underlying operators are formulated based on available data. To this end, the focus of research in FMATH group is on the following three inter-related areas:

1. Fractional-order modeling. This area composes the research foundations of the FMATH and scientifically feeds the next two areas of interest. The research structure in this area is hierarchical and integrated with the following three main aspects:

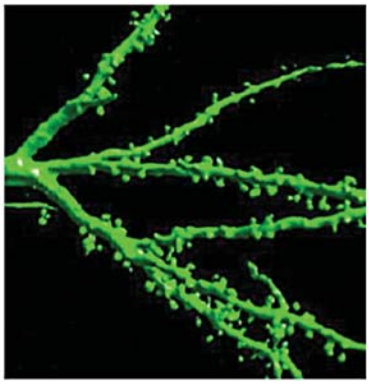
1-1. Fractional-order continuum mechanics. We employ a new class of nonlocal constitutive laws that generalize the existing ones to fractional and/or distributed-order constitutive laws. Next, we incorporate them in the context of elasticity, viscoelasticity and fluids mechanics. This is a significant step to rigorously derive fundamental conservation laws in the context of existing models such as Navier and Beltrami-Mitchell equations in elasticity, Kelvin and Maxwell models in viscoelasticity and rheology, and Stokes equation in viscous dominating flows and Navier-Stokes equations for diverse fluids problems. There are several open questions of mathematical interest regarding the nature of these models, as well as the existence and uniqueness of the solutions of FNS equations.

1-2. Turbulence LES modeling for anomalous transport. In the presence of non-Gaussian (Levy jump) stochastic processes in turbulent flows, the existing models for large eddy simulation (LES) of such flows may fail to provide the satisfactory statistics, particularly the probability density function (PDF) and higher moments of the field solutions. Along this research area at the FMATH, we will focus on anomalous subgrid scale models to properly model the eddy viscosity, which is physically adapted to the anomalous nature of diffusion processes at high frequencies.

1-3. Multi-phase flows and gas dynamics. Multi-phase flows, particularly nucleating steam, naturally lend themselves to being modeled using FPDEs. Hypothetically, fractional-order models are exceptional candidates to capture the sharp interface between the gas and liquid phases, which accounts for the non-equilibrium (anomalous) heat transfer between the phases. We aim to propose such fractional condensation models for a variety of applications in aerodynamics and energy systems, e.g., vapor nozzles, steam turbines, etc.



Nonlocal turbulent mixing



Sub-diffusion in nerve cells (B. Henry)

2. Data-driven and stochastic FPDEs. In data-driven applications, we need to take into account the uncertainty in our knowledge of material properties, as well as in topological (boundary) constrains. Moreover, such physical systems are often subject to random excitements, which naturally cast underlying fractional PDE models in a stochastic framework. In addition, data-driven simulations rely heavily on fine-tuning of differential orders (fixed, variable, and distributed) in fractional PDEs. This necessitates a systematic framework for uncertainty quantification (UQ) in fractional PDEs. To this end, we will focus on a new technique, operator-based UQ, which renders the order of a given fractional PDE stochastic. Then we could treat the order of the differential operator as either a random number or a stochastic process across all scales.

3. Scientific computing. The first and second areas of research at the FMATH naturally compel development of efficient and accurate numerical algorithms. FMATH will conduct ongoing and strategic research efforts on formulating high-order methods (spectral/hp-element methods) for fractional fixed-, variable-, and distributed-order PDEs for a range of applications. Moreover, we will introduce our schemes to the community by developing open-source computational platforms for high-performance and parallel computing.

RECENT PUBLICATIONS

M. Zayernouri, S.W. Park, D.M. Tartakovsky, G.E. Karniadakis, "Stochastic Smoothed Profile Method for Modeling Random Roughness in Flow Problems," *Computer Methods in Applied Mechanics and Engineering*, 263, 99–112 (2013).

M. Zayernouri, G.E. Karniadakis, "Fractional Sturm-Liouville Eigen-Problems: Theory and Numerical Approximations," *Journal of Computational Physics*, 47-3, 2108–2131 (2013).

M. Zayernouri, G.E. Karniadakis, "Exponentially Accurate Spectral and Spectral Element Methods for Fractional ODEs," *Journal of Computational Physics*, 257, 460–480 (2014).

M. Zayernouri, M. Ainsworth, G.E. Karniadakis, "A Unified Petrov-Galerkin Spectral Method for Fractional PDEs," *Computer Methods in Applied Mechanics and Engineering*, 283 (1), 1545–1569 (2015).