9:00

1aPA3. Understanding and exploiting acoustic field-microswimmer interactions in acoustofluidic devices. J. Mark Meacham (Mech. Eng. & Mater. Sci., Washington Univ. in Saint Louis, 1 Brookings Dr., Jubel Hall, Rm 203K, Saint Louis, MO 63130, meachamjm@wustl.edu), Minji Kim, Mingyang Cui (Mech. Eng. & Mater. Sci., Washington Univ. in Saint Louis, Saint Louis, MO), and Rune Barnkob (Heinz-Nixdorf-Chair of Biomedical Electronics, Tech. Univ. of Munich, Munich, Bavaria, Germany)

Acoustic microfluidic devices offer exquisite control for manipulation of objects sized from tens of nanometers to tens of microns. Our work focuses on applying various acoustofluidic solutions to understand microswimmer behavior and the mechanisms underlying the beating of propulsive cilia/flagella. Ultrasonic trapping in bulk acoustic wave (BAW) and substrate acoustic wave (SAW) fields enables observation of swimming without constraining rotational degrees of freedom and without damaging the cells. Here, we summarize recent studies using biciliate *C. reinhardtii* algae cells, including three-dimensional body motion, synchronization/asynchronization of *cis* and *trans* cilia waveforms, and thermal and fluid-property effects. Acoustofluidic approaches provide unprecedented flexibility as a tool to investigate cell motility. Conversely, acoustic field-microswimmer interactions can also be exploited by applying the *C. reinhardtii* cells as dynamic probes to assess acoustofluidic device performance. We have previously reported use of these cells to identify optimal resonant frequencies of operation and to qualitatively map the strength of the acoustic field in BAW devices. Here, we extend the method to quantify the acoustic energy density of a straight microchannel operating at the first half-wavelength resonance, achieving agreement within 1 % to a standard method based on passive particle tracking. New applications for SAW devices are also presented.

9:30

1aPA4. Theory for attenuation and dispersion of acoustic propagation through a muddy medium. Allan D. Pierce (Retired, PO Box 339, 399 Quaker Meeting House Rd., East Sandwich, MA 02537, allanpierce@verizon.net)

Mud as a medium typically consists of clay particles, small silt particles (primarily quartz), and water. The clay particles lock together in what is called a card-house configuration, and the silt particles are held in suspension by the card house. The low frequency velocity of sound waves appears to be well-predicted by the Mallock-Wood theory that gives weighted averages of bulk compressibility and material density. At low frequencies, the attenuation is caused by the viscous dag of the water on the suspended silt particles, and the attenuation varies as the frequency squared. The deviation of the phase velocity from the low frequency limit at low frequencies is less well-understood but appears to vary as the frequency to the three-halfs. At higher frequencies, the dominant mechanism appears to be a relaxation mechanism associated with the card house. Each clay particle carries a net electrical charge and the resulting repulsion forces the clay particles to be spatially separated. However, the particles tend to stick together edge to face, and the van der Waals attraction between the clay particles tends to dominate over the electrostatic repulsion. However, the passage of a sound wave temporarily breaks some van der Waals bonds and they subsequently recombine as the acoustic pressure ebbs. The present paper seeks to quantify the effects of the relaxation processes. It is demonstrated that the latter leads to an attenuation that, at higher frequencies, varies nearly linearly with frequency. [Work supported by ONR.]

10:00–10:15 Break

Contributed Papers

10:15

1aPA5. Modulation of acoustofluidic parameters to assess effect on molecular loading in human T cells. Connor Centner (Bioengineering, Univ. of Louisville, 580 S Preston St., Louisville, KY 40214, connor.centner@louisville.edu), John Moore, Mary Baxter (Bioengineering, Univ. of Louisville, Louisville, KY), Mariana Vinseiro Figueira (Chemical Eng., Ohio State Univ., Columbus, OH), Zachary Long (Bioengineering, Univ. of Louisville, Louisville, KY), Clinton Belott, Michael Menze (Biology, Univ. of Louisville, Louisville, KY), Paula Bates (Medicine, Univ. of Louisville, Louisville, KY), Kavitha Yaddanapudi (Surgery, Univ. of Louisville, Louisville, KY), and Jonathan A. Kopechek (Bioengineering, Univ. of Louisville, Louisville, KY)

T-cell therapies are rapidly emerging for treatment of cancer and other diseases but are limited by inefficient non-viral delivery methods. Acoustofluidic devices are in development to enhance non-viral delivery to cells. The effect of acoustofluidic parameters, such as channel geometry, on molecular loading in human T cells was assessed using 3D-printed acoustofluidic devices. Devices with rectilinear channels (1- and 2-mm diameters) were compared directly with concentric spiral channel geometries. Intracellular delivery of a fluorescent dye (calcein, 100 μg/ml) was evaluated in Jurkat T cells using flow cytometry after ultrasound treatment with cationic microbubbles (2.5% v/v). B-mode ultrasound pulses (2.5 MHz, 3.8 MPa output pressure) were generated by a P4-1 transducer on a Verasonics Vantage ultrasound system. Cell viability was assessed using propidum iodine staining (10 μg/ml). Intracellular molecular delivery was significantly enhanced with acoustofluidic treatment in each channel geometry, but treatment with the 1-mm concentric spiral geometry further enhanced delivery after acoustofluidic treatment compared to both 1- and 2-mm rectilinear channels (ANOVA $p < 0.001$, $n = 6$/group). These results indicate that 3D-printed acoustofluidic devices enhance molecular delivery to T cells, and channel geometry modulates intracellular loading efficiency. This approach may offer advantages to improve manufacturing of T cell therapies.

10:30

1aPA6. Acoustic radiation force and torque on objects with continuous and discrete inhomogeneity. Thomas S. Jerome (Appl. Res. Labs. and Walker Dept. of Mech. Eng., The Univ. of Texas at Austin, 10000 Burnet Rd., Austin, TX 78758, tsjerome@utexas.edu) and Mark F. Hamilton (Appl. Res. Labs. and Walker Dept. of Mech. Eng., The Univ. of Texas at Austin, Austin, TX)

At the Fall ASA meeting in 2019, the Born approximation was extended to acoustic radiation force and torque on objects of arbitrary shape with spatially varying density and compressibility [*Proc. Meet. Acoust.* **39**, 045007 (2020)]. This model is applied here to a standing plane wave incident on objects either with continuously varying material properties or composed of connected homogeneous regions with different material properties. The approximation for inhomogeneous objects is subject to the same restrictions on incident field structure, scatterer size, and material contrast as for homogeneous objects. Results are presented for cylinders with a variety of strongly asymmetric inhomogeneity distributions. Closed-form expressions are obtained for a sphere with material properties that vary linearly with distance from its center and for a sphere surrounded by concentric spherical layers. Results for the latter case are shown to be in close agreement with existing theory for the radiation force on a nucleated cell modeled as a multilayered compressible sphere [Wang *et al.*, *J. Appl. Phys.* **122**, 094902 (2017)]. The Born approximation thus proves convenient for determining