Making Waves: the Mechanics of Oscillations in Cilia and Flagella

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Cilia and flagella are slender organelles that beat rhythmically to move fluid or propel cells. The mechanism that produces the autonomous, propulsive oscillations of cilia and flagella remains mysterious. The common cytoskeletal structure the "9+2" axoneme comprises nine outer doublet microtubules surrounding a central pair of microtubules, connected by radial spokes and circumferential links. Dynein molecules form cross-bridges between pairs of microtubule doublets, exerting active forces on each doublet. These active forces combine with the reactions from passive structural elements (doublets, nexin links and radial spokes) to produce bending. Since dynein activity on opposite sides of the axoneme produces opposing (antagonistic) bending moments, it is widely believed that dynein activity must be dynamically regulated (switched or modulated) to produce oscillatory waveforms. This concept has been explored in a number of theoretical studies. For example, analyses and simulations have shown that oscillations can arise from: (i) control of dynein activity by axoneme curvature to; (ii) feedback from the speed of inter-doublet sliding to dynein force; or (iii) regulation of dynein by the transverse force between each doublet pair (the "geometric clutch" hypothesis). Using mathematical models of flagella mechanics, we show that a much simpler interaction between dynein and the passive components of the axoneme, can also produce oscillations. Steady, distributed axial forces, acting in opposite directions on coupled beams in viscous fluid, lead to oscillatory, wavelike motion. This phenomenon, termed "viscoelastic flutter," is a classic dynamic instability, related to, but different from, the well-known static instability, buckling. Flutter also occurs in aircraft wings exposed to steady air flow, and in flexible pipes conveying fluid. Flutter, rather than buckling, generally occurs when forces follow elastic bodies as they deform. We use two different, but complementary, mathematical methods to explore this mechanism of oscillation: (i) analysis and simulation of partial differential equations (PDE) describing axoneme mechanics; and (ii) detailed 3D mechanical (finite-element, or FE) models of the axoneme. By both methods, we find that dynein does not need to change magnitude, switch direction, or turn on and off, to produce autonomous oscillations. Instead, these models show that, in principle, steady dynein activity above a critical threshold force is sufficient to generate propulsive waves.

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Short Biography

Philip V. (Phil) Bayly is The Lilyan and E. Lisle Hughes Professor of Mechanical Engineering and Chair of the Department of Mechanical Engineering and Materials Science at Washington University in St. Louis. Dr. Bayly earned an A.B. in Engineering Science from Dartmouth College, an M.S. in Engineering from Brown University, and a Ph.D. in Mechanical Engineering from Duke University. He has been a member of the faculty at Washington University since 1993. His research involves the study of waves, instability, and oscillations in mechanical and biological systems, using imaging and image processing to understand the mechanics of cells and biological tissues. Dr. Bayly's research in brain biomechanics and flagellar oscillations has been funded by the National Science Foundation, the National Institutes of Health, and the Office of Naval Research