nature physics

ARTICLES

PUBLISHED ONLINE: 21 AUGUST 2017 | DOI: 10.1038/NPHYS4225

Nonlinear flow response of soft hair beds

José Alvarado[1], Jean Comtet[1], Emmanuel de Langre[2] and A. E. Hosoi[1]*

We are 'hairy' on the inside: beds of passive fibres anchored to a surface and immersed in fluids are prevalent in many biological systems, including intestines, tongues, and blood vessels. These hairs are soft enough to deform in response to stresses from fluid flows. Yet fluid stresses are in turn affected by hair deformation, leading to a coupled elastoviscous problem that is poorly understood. Here we investigate a biomimetic model system of elastomer hair beds subject to shear-driven Stokes flows. We characterize this system with a theoretical model that accounts for the large-deformation flow response of hair beds. Hair bending results in a drag-reducing nonlinearity because the hair tip lowers towards the base, widening the gap through which fluid flows. When hairs are cantilevered at an angle subnormal to the surface, flow against the grain bends hairs away from the base, narrowing the gap. The flow response of angled hair beds is axially asymmetric and amounts to a rectification nonlinearity. We identify an elastoviscous parameter that controls nonlinear behaviour. Our study raises the hypothesis that biological hairy surfaces function to reduce fluid drag. Furthermore, angled hairs may be incorporated in the design of integrated microfluidic components, such as diodes and pumps.

General background introduces the topic in a way that a larger audience can understand. In this example, the authors do not emphasize the need or importance of the topic itself, they do mention its relevance to the audience (as in increasing area of research).

Mechanics has become increasingly soft: research interest in largely deformable structures has increased over the past decades. Whereas stiff structures typically deform according to linear mechanical frameworks, global deformations of soft structures often incur geometrical nonlinearities, even while local strains remain small, in the range of linear response[1]. One driver of interest in deformable structures comes from the observation that deformability characterizes many biological systems[2]. Studying the nonlinear deformation of biological structures can supplant qualitative descriptions with quantitative physical models in a wide range of systems, such as embryo development[3] and microorganism locomotion[4]. Mimicking biological behaviour in the lab has furthermore led to novel engineering designs, such as soft robotic locomotion[5] and anisotropic surface adhesion[6].

Specific background connects the general background to the contribution. This section builds on current understanding and other works to frame the knowledge gap and contribution.

One prominent example of soft structures in biology is beds of anchored, elastic fibres (or hairs), which are often immersed in fluids. Small (~1 to 100 μm) hairs coat many biological surfaces. Examples include brush-border microvilli[7], papillae of tongues[8], primary cilia of kidney cells[9,10], and hyaluronans of blood vessels' glycocalyx[11–13]. These hair beds are usually immersed in fluids, and sufficiently deformable to bend in response to fluid flow. Seminal work by Vogel on flexible tree leaves subject to aerodynamic forces described how fluid stresses induce reconfiguration, or nonlinear deformations that reduce drag forces[14]. This work has inspired a body of research into the reconfiguration of various plants[15–17] as well as idealized systems[18–26]. However, these studies have been performed at high Reynolds number (Re), where inertial effects dominate. In contrast, viscous effects dominate the physics of low-Re fluid flows near small biological hairs. We anticipate rich nonlinear behaviour when deformable solids interact with fluid viscous effects[27–29]. Yet the reconfiguration problem of hair beds at low Re remains largely unsolved.

Knowledge gap clearly explains the lack of understanding in the research area.

Here we investigate a bio-inspired model system of deformable hairs subject to low-Re fluid flows. Even though hairs and fluids are described by linear constitutive properties, we find the flow response of hair beds can exhibit two types of nonlinearities: a drag-reducing nonlinearity, which we characterize by the rescaled flow impedance $\widetilde{Z}$; and a rectification nonlinearity, which we find for angled hairs, and which we characterize by the impedance ratio Z_+/Z_- comparing flow with and against the grain. These two nonlinear responses are functions of the dimensionless parameter $\widetilde{v}$, which compares fluid and elastic effects.

Here we show... section explicitly states findings that fill the knowledge gap.

[1]Hatsopoulos Microfluids Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. [2]Hydrodynamics Laboratory, CNRS UMR 7646, Department of Mechanics, École Polytechnique, 91120 Palaiseau, France. *e-mail: peko@mit.edu