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# Nonlinear flow response of soft hair beds

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**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.**

In Nature, as in some other journals, the writing style emphasizes a narrative more strongly than distinct sections.
As a result, methods (high-level), results, and discussion are all interwoven throughout the main text.
Here, I've picked out some of the good writing choices for results sections:
- strong topic sentences that motivate what comes next
- honest descriptions of observations & results
- Explicit statement of the logically derived conclusion, which flows into the next results paragraph.

## Drag reduction

T[illegible]nvestigate the feedback between hair deformation and fluid [illegible] we develop an experimental model system of elastomer hairs [illegible]ersed in high-viscosity fluids (Fig. 1; Methods). We mount hair beds onto the inner rotor of a Taylor–Couette geometry (Supplementary Fig.1; Methods) and determine shear stress $\tau$ [illegible] function of velocity $v$ of the hairy surface. Upon first [illegible]ce, rheometry experiments appear to exhibit shear thinning [illegible]2a). For low velocities up to 0.01 m s$^{-1}$, shear stress $\tau$ scales [illegible]rly with $v$. But at higher velocities, $\tau$ deviates from linearity. We rule out shear thinning of the fluid because we observe nonlinearity at $\dot{\gamma} = (v/H - L) > 12.5\ \mathrm{s}^{-1}$, well below the fluid's known $\dot{\gamma}_{\mathrm{crit}} = 10{,}000\ \mathrm{s}^{-1}$. Instead, the measured nonlinear response arises from hair deformation.

To characterize this nonlinear behaviour, we develop a simple model to illustrate how fluid flow affects hair deformation. In Fig. 1d, we consider a stationary planar surface coated with hairs, immersed in fluid, and facing a smooth surface moving with velocity $v\mathbf{e}_x$ and separated by a distance $H$, measured from the hair base $z = 0$. No-slip boundary conditions hold at the moving surface. We further assume no-slip boundary conditions at the plane $z = h$ containing hair tips, which holds as long as the hair bed is sufficiently dense. The resulting flow profile $u(z) = v((z - h)/(H - h))$ is equivalent to the Couette problem of shear-driven flow between two plates—except that stresses from fluid flows cause hairs to bend (or reconfigure). As a result, the position of the hair-tip plane $h$ depends on shear stress $\tau$. At the same time, $\tau$ depends on $h$, because lowering the hair-tip plane increases the gap width $H - h$ and decreases the shear stress. This interdependency reflects the elastoviscous coupling between deformable hair beds and fluid flows.

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