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PROPULSION AND LOCOMOTION IN COMPLEX FLUIDS

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ABSTRACT

Flagella beating in complex fluids are significantly influenced by viscoelastic stresses. Relevant examples include the ciliary transport of respiratory airway mucus and the motion of spermatozoa in the mucus-filled female reproductive tract. Although biologists have been characterizing the structure and rheology of such complex fluids for many years, not much is know on the quantitative impact of these non-Newtonian stresses on the kinematics and energetics of transport and locomotion. We consider here a number of prototypical examples where a detailed analysis is possible.

We first consider the simplest model of propulsion and transport in a complex fluid, a waving sheet of small amplitude free to move in a polymeric fluid with a single relaxation time. We show that, compared to self-propulsion in a Newtonian fluid occurring at a velocity U_N, the sheet swims (or transports fluid) with velocity [1]

$$\frac{U}{U_N} = \frac{1 + \mathrm{De}^2 \eta_s/\eta}{1 + \mathrm{De}^2}, \tag{1}$$

where η_s is the viscosity of the Newtonian solvent, η is the zero-shear-rate viscosity of the polymeric fluid, and De is the Deborah number for the wave motion, product of the wave frequency by the fluid relaxation time. Similar expressions are derived for the rate of work of the sheet and the mechanical efficiency of the motion. These results are shown to be independent of the particular nonlinear constitutive equations chosen for the fluid, and are valid for both waves of tangential and normal motion. The generalization to more than one relaxation time is also provided.

In stark contrast with the Newtonian case, these calculations suggest that transport and locomotion in a non-Newtonian fluid can be conveniently tuned without having to modify the waving gait of the sheet but instead by passively modulating the material properties of the liquid.

We then consider the extension of this result for biological swimmers of finite size. Using an extension of Lorentz's reciprocal theorem, we demonstrate that the effect of (nonlinear) viscoelastic stresses on the small-amplitude locomotion of finite-size swimmers can be quantified by a surface integral on the swimmer body. This result is then exploited to demonstrate that Eq. 1 remains valid for a swimmer of finite extent.

Finally, we consider the use of viscoelastic fluids to escape of constraints of Purcell's scallop theorem [2]. We show that a flapping-like reciprocal actuation on a viscoelastic fluid (Oldroyd B) allows to

exploit normal stress differences in the fluid and generate net flow and forces. The flow is calculated explicitly for small-amplitude oscillations of the flapper. Some other examples of reciprocal swimmers are also presented.

These results suggest that primitive actuation mechanisms which would not be effective in Newtonian flow can harness non-Newtonian stresses for propulsion and pumping purposes.

REFERENCES

[1] E. Lauga. "Propulsion in a viscoelastic fluid". *Phys. Fluids*, Vol. **19**, 083104, 2007.

[2] E. M. Purcell. "Life at low Reynolds numbers". *Am. J. Phys.*, Vol. **45**, 3-11, 1977.