Introduction to Animal Locomotion

The marvelous diversity in nature is, of course, reflected in the wide variety of ways that animals have developed to propel themselves in a fluid. In this treatise on fluid mechanics it is only possible to highlight a few of the fundamental propulsion mechanisms used in nature. We focus only on the simplest environments, namely those of Newtonian fluids (principally air and water) without any nearby solid surfaces. Moreover we will confine these notes to mechanisms used for straight-line propulsion while noting that there are many circumstances in nature where maneuverability is equal or more important than straight-line velocity. Some animals, like a tuna fish or a peregrine falcon, are beautifully adapted for straight-line speed. Other designs that have been have modified for a secondary purpose, for example the owl's need to minimize the aerodynamics sound it generates. Many land animals, like a cheetah, have a marvelously streamline design to minimize its drag and maximize its speed.

But we will also touch on the great variety of designs used by the very small animals in nature. Both prokaryotic (bacteria) and the larger eukaryotic microrganisms have their own spectacular variety of propulsion mechanisms which we touch on later. This prompts us to mention that one of the pervasive features of all animal locomotion is the way in which the various mechanisms correlate with the Reynolds number, $Re = U\ell/\nu$, of the desired locomotion as characterized by the speed, U, of propulsion, the typical dimension, ℓ, or length of the animal and the kinematic viscosity, ν, of the fluid in which they are moving. The Reynolds numbers seen in nature range all the way from 10^{-3} for bacteria up to 10^{8} for large whales. It is most remarkable that most of the propulsion at high Reynolds numbers, 10^{2} and higher, utilizes mechanisms that take full advantage of the effectiveness and efficiency of the lift force rather than the drag force. Even at low Reynolds numbers (less than 10^{-2}) many propulsive devices use small filaments and an orientation of those filaments that maximizes their propulsion. In both of these regimes, the best motions are fairly steady in order to minimize wasted energy. However, in the central regime, between Reynolds number of 0.1 and 10, where flows are typical quite unsteady, it is notable that animals have developed propulsion mechanisms that are also quite unsteady and take advantage of the peculiar fluid flow processes that occur in that regime. An example might be the unsteady jet propulsion method deployed by shrimp.

Of course, the evolution of almost all these methods of propulion, has been limited by other mechanical and biological constraints. For example, almost all livings things animals have had to cope with the inability to generate continuous rotary motion, a feature that we humans have extensively used in developing our inanimate machines. The remarkable exceptions are prokaryotic animals, the bacteria who utilize filaments (flagella) that rotate continuously relative to the body; indeed the structures at the junction look remarkable like an electric motor with an armature and bearings. One of the truly intriguing questions is why nature was unable to scale up this mechanism for use in larger animals; of why it was necessary to jump sideways to cope without continuous rotary motion as eukaryotic microorganisms universally do.

This brief venture into the realm of the biologist and zoologist will survey just some of the dominant features of animal propulsion in the high and low Reynolds number regimes. In particular, we review the swimming of the most efficient fish and cetaceans and the flying of birds and insects. We follow that with a brief review of microrganism locomotion using flagella and cilia.