

Active and passive components of the dolphin's hydrodynamic advantage

The legendary fast swimming speed of dolphins, that suggests maintenance of laminar flow resistance at high swimming speeds (Gray's paradox ¹), may be due to active and passive biophysical epidermal mechanisms. Kramer's experiments suggested that the structure of the compliant dolphin skin prolonged laminar flow passively by distributed damping.²

The primary shear waves of transition – boundary layer flutter waves

Linear boundary imperfections can create stationary waves in flowing water.³ These waves represent the paths along which laminar flow “flutters” along at the speed of flow. An anatomic feature of the dolphin skin is that there are periodic cutaneous ridges transverse to the flow and these may similarly arrest the the wavy paths along which boundary layer laminae flutter along at their individual laminar velocities, while maintaining their alignment normal to the flow (which, coincidentally, is the alignment of the ridges).

(Notably, Carpenter et al., while accepting Schubauer and Skramstad's interpretation of Tollmien-Schlichting boundary layer oscillations, described “a flow-induced surface instability – traveling wave flutter,” suggesting that “the role of Kramer's coatings was to control this “traveling wave flutter” ⁴).

Schubauer and Skramstad made a monumental discovery when they discovered simple harmonic boundary layer **velocity** oscillations that coincided with the onset of transition. However, they erred in their analysis of the boundary layer fluid shear waves that created these velocity oscillations. As noted in “Order in Chaos,” boundary layer “flutter waves” are flowing at the rate of flow of each lamina, always in phase, with the rapidly flowing flutter waves creating both the velocity oscillations and the slower-moving simple harmonic wavy paths they follow..

Because seawater is incompressible the flutter waves are layered – in identical simple harmonic wavy paths, as boundary layer flutter waves – with wave fronts of all flutter waves descending in phase, striking at the boundary, before returning (rebounding) upwards, generating simple harmonic sound normal to the flow. The faster the flow, the harder they strike at the boundary and the greater is the sound amplitude, transverse to the flow.

Flutter waves flow in laminar sheets – at the speed of flow – snaking along simple harmonic wavy paths in the “laminar membranes” (the tracks along which they flow), with these wavy paths moving much more slowly than the flowing flutter

¹ Gray J: Studies in animal locomotion. VI. The propulsion powers of the dolphin. The Journal of Experimental Biology (1936); 13:p. 192

² Kramer MO: Boundary layer stabilization by distributed damping. American Society of Naval Engineers Journal (1960); 72: pp. 25-33

³ Hamilton G: Order in Chaos – The Physics of Transition to Turbulence. Aylmer Express (2011): Stationary standing MM waves caused by boundary irregularity: Figure 19a, p.147,

⁴ Carpenter PW, Davies C and Lucey: Hydrodynamics and compliant walls: Does the dolphin have a secret. Current Science (2000); 6: 758-764

waves. These simple harmonic wavy paths may be stationary – as they are in the dolphin epidermis – but the laminar flutter waves flow at the rate of flow of each individual lamina.

These flutter waves, all in phase, would create periodic zones of high pressure along the boundary as they strike at the boundary, interspersed by similar periodic zones of low pressure as the flutter waves rebound. These pressure fields are exactly what would occur if the high pressure zones, interspersed with low pressure zones, were to represent a standing wave sound field sliding along the boundary. If a standing wave sound field were present, and if one sprinkled particulate matter, like tiny glass beads along the boundary, the particles should accumulate at simple harmonic intervals, as in the classic Kundt's tube experiment, as the simple harmonic boundary layer flutter waves appear as transition occurs. Thomas, using tiny glass beads, proved that this was the case, with the periodic glass bead waves sliding along the base of a shiny glass tube ⁵ at a speed much slower than the rate of flow.

Similarly, if a stationary long crested standing wave sound field were to develop as transition onsets along a flat stretch of sand (another compliant boundary), one might expect that sand would accumulate at simple harmonic intervals on beaches or streams of flowing water. Bagnold proved that this does occur.⁶ Thomas compared his simple harmonic glass bead waves to Bagnold's sand waves, believing that, somehow, there was a similar physical explanation for the coherent glass bead waves and the sand waves.

Furthermore, Bagnold's photographs showed sand particles being ejected normal to the flow from the troughs, descending at shallow angles to be deposited on the crests, just as one might expect when a standing wave sound field is present in wind or water flow. A standing wave sound field experiment, with a layer of particles in a Kundt's tube, exhibits, particles ejected from areas of the troughs (the loops of sound waves) and deposited on the crests (the standing wave nodes). Similarly, one should rightly expect snow "particles" to accumulate in simple harmonic fashion on flat stretches of snow as transition occurs in wind flow.

S and S came close to the truth when they considered whether their boundary layer velocity oscillations were caused by sound waves, but rejected this idea because the velocity of the waves was far less than the speed of sound. They noted: "...disturbances in the stream, possibly acoustic as well as turbulent, give rise to oscillations, which are not themselves sound waves."⁷ However, S and S did not consider whether the waves could be manifestations of standing wave sound that was sliding along the shiny flat plate boundary as a "traveling" stationary sound wave field.

⁵ Thomas DG: Periodic phenomena observed with spherical particles in horizontal pipes. *Science* (1964); 144: pp. 534-536

⁶ Bagnold RA: *The Physics of Blown Sand and Desert Dunes*. Butler and Tanner, Frome and London (1971, reprint of 1941 edition): pp. 31-37

⁷ Schubauer GB and Skramstad HK: Laminar-boundary-layer-oscillations and transition on a flat plate. Advance Confidential Report. National Advisory Committee to Aeronautics (1943): pp. 1-70

Kramer's coatings were designed to imitate compliant dolphin skin. The materials were specifically chosen because of their ability to damp boundary layer sound (specifically, standing wave sound)⁸. The compliant dolphin epidermis should be able to damp, passively – rather than simply reflect and propagate – these boundary layer flutter waves.

A potential neurovascular feedback active damping mechanism

Essapian suggested that cutaneous blood vessels might be involved in cutaneous standing wave formation by changing the stiffness of the skin,⁹ in the same way as blood vessel engorgement changes the compliance of mammalian erectile tissue in the genitalia and nipples. Furthermore, Essapian showed photographically that, at high speeds, simple harmonic ring-like waves appeared along the epidermis, normal to the flow, proposing that these waves might be related to the preservation of laminar flow.

Carpenter proved that the damping of periodic slat-like panels, aligned perpendicular to the flow, could extend laminar flow to very high Reynolds numbers.¹⁰ If there were a mechanism of selective neurovascular feedback control of dermal compliance in ring-like panels corresponding to Essapian's coherent ring-like waves, then it might be possible for the dolphin to exert active prolongation of laminar flow.¹¹

There is an array of extremely sensitive pressure / vibration sensory nerve endings in the skin of the dolphin forehead. Returning sonar echoes are detected by this nerve network, with the impulses processed in the large temporal lobes of the dolphin brain. This endows the dolphin with sonovision with a resolving power that approaches mammalian optic vision.

Thus, it is not much of a stretch of evolutionary specialization to imagine similar pressure / vibration sensitive nerve endings, aligned under the dermal ridges along the dolphin body, that are capable of creating selective simple harmonic ring-like waves of increased / decreased dermal compliance, in response to feedback from nerve impulses to erectile vessels in ring-like bands of dolphin epidermis.¹²

There may be another compliance modifying mechanism in being able to change the compliance of the subcutaneous fat. Mammalian fat is liquid at body temperature. This is responsible for the devastating complication of fat embolism that sometimes occurs in tissue trauma associated with severe bone fractures, when

⁸ Kramer MO: Boundary layer stabilization by distributed damping. American Society of Naval Engineers Journal (1960); 72: pp. 25-33

⁹ Essapian FS: Speed-induced skin folds in the bottle-nosed porpoise, *Tursiops truncatus*. Breviora, Museum of Comparative Zoology (1955); 43: pp. 1-4.

¹⁰ Carpenter PW, Davies C and Lucey AD: Hydrodynamics and compliant walls: Does the dolphin have a secret. Current Science (2000); 6: 758-764

¹¹ Essapian FS: Speed-induced skin folds in the bottle-nosed porpoise, *Tursiops truncatus*. Breviora, Museum of Comparative Zoology (1955); 43: pp. 1-4.

¹² Hamilton G: Order in Chaos – The Physics of Transition to Turbulence. Aylmer Express (2011): p. 47

liquid fat enters torn veins. Mammalian fat tissue (as seen in the butcher shop) is solid at room temperature (or seawater temperature), but liquid when normal circulation maintains it in the liquid state at body temperature.

If feedback from pressure / vibration sensitive nerve impulses cause vasoconstriction in simple harmonic ring-like bands, the dermal blood supply could become markedly reduced in banded ring-like panels, the subcutaneous fat temperature would rapidly drop in vaso-constricted bands in response to cold boundary layer seawater (just as one's fingers get cold in air under the influence of adrenaline output when stressed by fear). Alternating bands of increased and decreased vascularity should be discernible as simple harmonic bands of increased and decreased temperature, respectively, by sensitive infrared photography. (A few years ago, some home video cameras were so infrared sensitive that the increased blood circulation in unwary people's pubic areas could be imaged through light clothing).

Conclusions

These are left for the reader to decide.