Hydrodynamics of dolphin skin and other compliant surfaces

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Abstract

The research on the hydrodynamics of compliant walls was originally inspired by dolphins. In particular, much research on the use of wall compliance for drag reduction was motivated by *Gray's Paradox*, namely the belief that specific power output of the propulsive muscles must greatly exceed the mammalian norm in order to achieve the observed swimming speeds if some sort of laminar-flow control were not involved. The full assessment of Gray's Paradox is a highly multidisciplinary undertaking and remains controversial. Here the emphasis will be placed on the hydrodynamics of compliant walls and its bearing on the possible laminar-flow and turbulence-suppression properties of the dolphin epidermis. The mechanics of the various types of compliant wall and their equations of motion will then be considered. This is followed by a discussion of the hydrodynamics of compliant walls, including hydroelastic instabilities and the effect of wall compliance on laminar-turbulent transition and fully turbulent flow. Finally the structural features of dolphin skin of possible hydrodynamic significance will be considered together with their relationship with analogue dolphin skins with possible technological applications.

1 Introduction

Both scientists and artists have long been interested in dolphin hydrodynamics. Interest in the possible drag-reducing properties of the dolphin skin dates back to the seminal paper of Gray [1]. Using then-accepted hydrodynamic principles Gray calculated the power required to overcome the drag of a 'rigid' dolphin at its assumed sustained swimming speed of around 10 m/s. He then went on to estimate the specific power required from the propulsive muscles and concluded that it was about seven times greater than the mammalian norm. This discrepancy became known as *Gray's Paradox.* If the boundary layer were to remain laminar no such discrepancy would exist. Accordingly, Gray, and others subsequently, have inferred that dolphins must be able to maintain laminar flow by some extraordinary means.

Gray's paradox remains controversial and so far definitive resolution has eluded us. Intriguingly, a strong difference of opinion developed between the Soviet Union and the USA that mirrored the ideological disputes of the Cold War. The Soviet view, which has continued into the current

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era and is typified by Babenko and Surkina [2] and Romanenko [3], is that dolphins do possess an extraordinary laminar-flow and low-drag capability. The American school of thought, as typified by Fish *et al.* [4, 5] and Fein [6], broadly is that they do not. A full assessment of Gray's paradox would be highly multidisciplinary. A recent review is given in chapter 13 of [7] and a rather different view is to be found in [5].

If Gray's method of drag estimation were used, the muscle power of a typical bottle-nosed dolphin (*Tursiops truncatus*) would be sufficient for a sustained swimming speed of about 5.6 m/s [7], as opposed to 10 m/s. What has been clear for some time is that Gray over-estimated the drag by assuming the transition point corresponds to the transitional Reynolds number for a flat-plate boundary layer. It is now known that transition is likely to occur near the point of minimum streamwise pressure, which for a dolphin is located midway along its body. This leads to a revised drag estimate that raises the estimated maximum sustained swimming speed to 6.6 m/s [7]. However, maintaining laminar flow over the whole body would raise it to 12 m/s [7]. All these estimates neglect the swimming motion of dolphins. Lighthill [8] estimated the skin-friction drag of swimming fish and dolphins to be three to five times the rigid-body value, owing to boundary-layer thinning. However, this effect will also favour laminar flow and Lighthill ignored the effects of a change in flow state. In their experimental study of the boundary-layer characteristics of swimming fish, Anderson *et al.* [9] observed the predicted boundary-layer thinning, but, owing to laminarization, the drag was only about 1.5 times the rigid-body value. At larger scale, Barrett *et al.* [10] actually observed a 50% drag reduction for their swimming robot tuna compared with the rigid-body value.

Some authors [5] have used swimming theory to estimate the thrust produced by a dolphin. They thereby concluded that the drag of a swimming dolphin is many times larger than that of a passive dead dolphin! The many pitfalls with this type of analysis can result in gross overestimates of the dolphin drag [3, 7]. In many ways, however, ever since Gray, there has been a misplaced emphasis on the dolphin's need for low drag to achieve high swimming speeds. The fact is that when dolphins swim fast they need to breath more frequently and consequently spend more time near the surface where their drag is necessarily very high. For this reason when their swimming speed exceeds around 4 m/s, it is more energy-efficient to adopt a swimming mode consisting of alternate leaping and submersion, sometimes known as 'porpoising' [7]. Like many marine mammals, dolphins exhibit deep-diving behaviour. In order to conserve energy they 'glide' for up to 80% of the duration of the dive [11]. As argued in [7], it is during the glide phase of these deep dives that a laminar-flow capability would be most essential.

Whatever the remaining uncertainty and doubts about Gray's paradox and the dolphin's laminar-flow capability, there is no doubt that analogue dolphin skins, namely compliant walls, can maintain laminar flow. It was shown in [12] that the laminar-flow capabilities claimed by Kramer [13] for his analogue dolphin skin were perfectly feasible. Later the hydrodynamic stability theory used in [12] and by many others since was verified in detail by Gaster's experimental study [14, 15]. Accordingly for the remainder of this paper the emphasis will be on these compliant walls and what they can tell us about the possible laminar-flow properties of the dolphin epidermis. A recent review of all aspects of the hydrodynamics of compliant walls can be found in [7].

2 Mechanics and hydrodynamics of compliant walls

2.1 Types of compliant wall

The term compliant wall has been applied to a wide variety of flexible walls. In our view it should be restricted to those *passive* flexible walls that have properties tuned to (compliant with) the flow properties. The first such example was Kramer's [13] compliant coatings (Fig. 1) that were

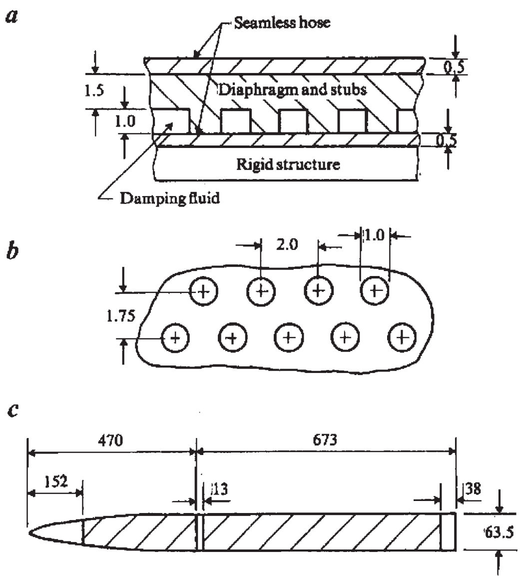

Figure 1: Kramer's compliant coating and model. All dimensions are in mm. Drawings based on those given in [13]. (*a*) Cross-section; (*b*) cut through stubs; (*c*) model: shaded regions were coated. (Based on fig. 1 of [12].)

closely modelled on the dolphin epidermis. In [12] Kramer's coatings were modelled theoretically by an elastic plate supported by a spring foundation; there was also damping in the form of a viscous fluid substrate as well as the viscoelastic damping of the elastomeric material used to fabricate the coatings. The equation of motion for such a wall can be written as [12]:

$$b\rho_{\mathrm{m}}\frac{\partial^2\eta}{\partial t^2} + B\nabla^4\eta + \left[K - g(\rho_{\mathrm{f}} - \rho_{\mathrm{s}})\right]\eta = -(p_{\mathrm{f}} - p_{\mathrm{s}}), \tag{1}$$

where ρ_{m}, ρ_{s} and ρ_{f} are, respectively, the densities of the plate material, the substrate damping fluid and the mainstream fluid; b and B are, respectively, the plate's thickness and flexural rigidity; K is the spring stiffness; g is the acceleration due to gravity; and p_{f} and p_{s} are the pressure perturbations in the mainstream and substrate fluids. Viscoelastic damping is introduced by employing complex values for B and K; viscous damping is present when there is a fluid substrate. The sole dependent variable, η, is the vertical wall displacement, and the biharmonic operator ∇^4 only involves the two spatial coordinates parallel to the wall; thus this model is embodied in a relatively simple equation with two spatial variables (only one, if the fluid flow is two-dimensional). It is coupled to the boundary-layer flow through the pressure term and by requiring continuity of velocity at the solid–fluid interface.

The plate-spring model is reasonably representative of the dynamics of most compliant walls with good laminar-flow properties, including dolphin skin. In his experimental study Gaster [14] used a compliant wall comprising two layers of elastomeric material: an outer, stiff, thin layer backed by a much thicker, much less stiff, inner layer. Such walls can be modelled accurately [15] using the Navier equations; the governing equations for the wall now become fully three-dimensional with three dependent variables, namely the three components of the displacement vector. What makes the plate-spring or two-layer walls compliant is the fact that they are characterized by two stiffnesses, namely the bending stiffness, which is effective on short waves, and the spring stiffness or lower layer, which is effective against long waves. Thus such walls can be tuned by adjusting the ratio of the stiffnesses. Most experimental studies, however, have used single-layer viscoelastic walls. It is arguable whether such walls are truly compliant; however, their dynamics can be modelled relatively simply by means of the Navier equations. Finally, inspired, perhaps, by certain features of the dolphin skin (see Fig. 3), anisotropic walls have been proposed [16, 17]. Theoretically, at least, these seem potentially to have further enhanced laminar-flow capabilities.

2.2 Hydroelastic instabilities

The dynamics of a compliant wall interacting with a fluid flow are complex [12, 18]. Essentially, two wave-bearing media are involved. The laminar boundary layer supports Tollmien–Schlichting waves and more complex dynamical systems exist in turbulent flow. These will be briefly discussed in the following two sections. The origin of hydroelastic instability lies in the wall dynamics. There are two main types: divergence and travelling-wave flutter. The latter is driven by irreversible energy transfer to the wall due to work done by the fluctuating pressure force [18]. The result is a fast wave travelling slightly slower than the mainstream. It was the main route to transition for the Gaster compliant walls [15]. The mechanism for divergence is simpler. When a disturbance causes a slight drop in fluid pressure it tends to cause a local surface displacement that is resisted by the structural forces. The pressure force increases with flow speed whereas the resisting structural force remains fixed. Ultimately a flow speed will be reached where the pressure force exceeds the resisting structural force and divergence, usually in the form of very slow, downstream travelling waves, will occur. Normally, divergence is only seen with turbulent flow [19, 20]. It has been observed on the underside and rear of dolphins when they swim at high speed for short durations [21]. It has also been seen on the original Kramer coatings [19]. In laminar flow it appears that divergence is replaced by another absolute instability that is formed when travelling wave flutter and Tollmien–Schlichting waves coalesce [12, 19]. In practice it would be difficult to distinguish one from another.

2.3 Effects of wall compliance on laminar–turbulent transition

It has been established theoretically, experimentally and computationally [12–15, 17, 19] that appropriately designed compliant walls can suppress the growth of Tollmien–Schlichting waves, thereby maintaining laminar flow or greatly postponing laminar–turbulent transition. The close agreement between Gaster's experimentally measured growth rates and theory for both Tollmien–Schlichting waves and travelling-wave flutter [15] almost puts this beyond doubt. In order to design compliant walls with good laminar-flow properties it is important to ensure that hydroelastic instability does not occur. On the other hand one wants as great a degree of compliance as is otherwise possible. Travelling-wave flutter is very sensitive to wall damping [18, 19] and it is likely that the damping in Kramer's coating played a role in suppressing it, rather than damping the Tollmien–Schlichting waves as he thought.

Tollmien–Schlichting waves are the main route to transition in low-noise environments, such as free flight. In a marine environment, freestream turbulence and particulate matter have an important effect on transition. Algebraically growing, streaky structures, known as Klebanoff modes [22, 23], play an important role in such cases. Ali [24] has shown recently that boundary layers over compliant walls are very much less receptive to Klebanoff modes and to particle-generated disturbances.

2.4 Effects of wall compliance on turbulent flows

There is a considerable body of experimental evidence showing that compliant walls reduce skin-friction drag in fully turbulent flow (see chapter 12 of [7]) by up to 20–30%. Theoretical and computational studies are less common, but there has been considerable recent progress (see chapters 10 and 11 of [7]). Here we will focus on the recent simplified computational study of Ali [24]. He developed a theoretical model of the sub-layer streaks that was based on the concept of the Klebanoff mode. For simulating freestream turbulence he placed at the edge of the boundary layer a streamwise vorticity source of the form:

$$F \cos(\beta y)\delta(x - x_s)\delta(z - z_s), \tag{2}$$

where x, y, z are the streamwise, spanwise and wall-normal coordinates, δ denotes a Dirac delta function, and x_s, z_s are the coordinates of the vorticity source. Such a vorticity source generates a streamwise vortex sheet with strength varying periodically in the spanwise direction. The boundary layer is not receptive to spanwise vorticity sources. Vorticity sources of the form (2) generate classic Klebanoff modes in the laminar boundary layer. They can also be used to represent the hairpin vortices seen in the buffer layer of a turbulent boundary layer. In this case the undisturbed flow field is taken to be the mean turbulent velocity profile and the source has to be located within the boundary layer, the strongest response being found at $y^+ \cong 18$. If the vorticity source is present throughout the simulation, the streaks will continue to elongate. Initially they will grow in strength, but will eventually level off. For the simulation of turbulent streaks the vorticity source was switched off after $t^+ = 15$, a time period chosen to match that of the localized suction used in [25] to generate sub-layer streaks artificially. In this case the streaks continue to grow in strength for some time after the vorticity source is removed, but eventually decay. The spanwise wave number is then optimized to give the strongest streaks. The resulting optimal streak wavelength is plotted in Fig. 2 for rigid and compliant walls where it is compared with the experimental data of Lee *et al.* [26]. There is remarkably good agreement between theory and experiment. As well as predicting that the streak spacing increases as wall compliance rises, the theory also predicts that the streaks weaken greatly. This is also corroborated by experiment. These results suggest that compliant walls can have a strong favourable effect on the sub-layer streaks.

3 Structure of dolphin skin and its possible hydrodynamic function

Kramer [13] carried out a careful study of the dolphin epidermis and his compliant coatings were designed to incorporate what he regarded as its key characteristics. A comparison between Figs 1 and 3 reveals a close resemblance in terms of dimensions. But the optimal mechanical properties of dolphin skin vary with flow speed (chapter 13 of [7]). And Kramer's greatest drag reductions were obtained at a speed of 18 m/s that is twice the normally assumed maximum swimming speed of dolphins. Accordingly, the ideal mechanical characterization of the Kramer coatings would by no means be identical to that of dolphin skin. Moreover, the studies of Babenko and Surkina [2] and others [7] suggest Kramer's understanding of the dolphin epidermis was faulty. In fact, it appears that there is not a universally accepted, coherent view of the structure.

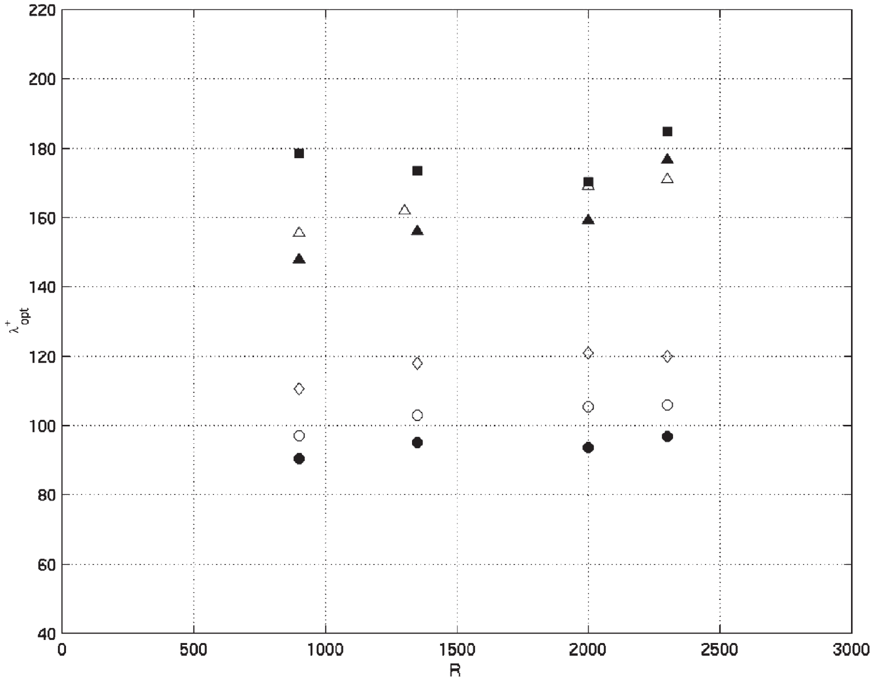

Figure 2: Spanwise spacing of sub-layer streaks as a function of Reynolds number based on displacement thickness. The open symbols correspond to computed optimized streaks; the black ones correspond to mean streak spacing found in experiments [26]. Key: ○, ●, rigid wall; ◊, Kramer-type compliant wall [12, 13]; ■, ▲, △ compliant wall [26]. (This figure is taken from Ali [24].)

Figure 3 gives a schematic composite view of the dolphin epidermis and upper dermal layer based on several sources [19].

The upper epidermal layer forms a comparatively dense elastic membrane capable of transmitting all pressure fluctuations to the underlying layer. This lower layer and the dermal papillae are made of loose, more hydrated tissue, including fat cells. The dimensions and orientation of the cutaneous ridges [7, 27] and the angle made by the dermal papillae to the surface vary over the body [2, 7]. These angles of inclination vary from 10° to 80° and appear to be correlated with the gradients of the hydrodynamically generated tractions acting on the body. The dermal papillae extend outwards from, and are supported by, the longitudinal dermal ridges which appear to be aligned with the streamlines close to the surface [7]. Sokolov [28] describes the development of the epidermis during ontogenesis. It is thought that the common characteristics shared by a wide range of species appear at an earlier stage of the embryo's development than more specialized ones. Accordingly, it can be deduced that the dermal ridges and papillae evolved comparatively recently. Millions of years ago dolphins probably had similar skin to present-day humans. The recent modifications are also consistent with adaptation for skin-friction drag reduction.

Fairly complex mechanical models have been proposed for the dolphin epidermis (chapter 13 of [7]). However, one can evoke a mechanical equivalent of Thévenin's theorem for electronic circuits to reduce complex models to the simpler plate-spring model [see eqn (1)]. This allows us to compare the free wave speeds of theoretical compliant walls optimized for greatest transition

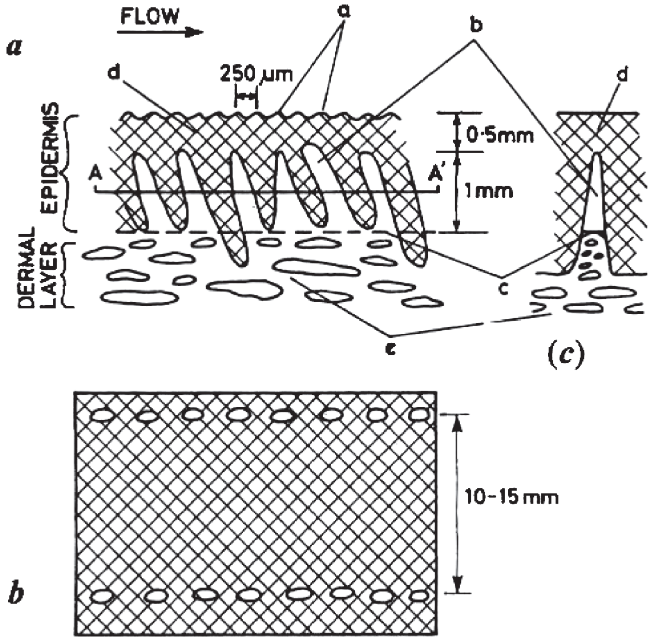

Figure 3: Structure of dolphin skin. (*a*) Cross-section; (*b*) cut through dermal papillae at AA′; (*c*) front view. Key: a, cutaneous ridges; b, dermal papillae; c, dermal ridge; d, upper epidermal layer; e, fatty tissue. (Taken from fig. 2 of [19].)

delay [17] with measurements made on live dolphins [29]. It is found theoretically that for compliant walls optimized for the suppression of Tollmien-Schlichting waves, the speed of the free surface waves is around 70% of the freestream flow speed [19]. For both the theoretical model and the actual dolphin skin the speed of the free surface waves varies with frequency. However, at frequencies typical of Tollmien–Schlichting waves the measured values over most of the body were 6.5 ± 0.5 m/s, suggesting that the dolphin epidermis is optimized for a flow speed of around 9 m/s. Similarly, Fitzgerald and Fitzgerald [30] measured various mechanical properties of pilot-whale blubber. Among other things they found that the shear-wave speed was approximately 9 m/s.

The cutaneous ridges of dolphin skin have been noted by a few authors [2, 27]. No function, hydrodynamic or otherwise, has hitherto been proposed for them. However, recently Ali [24] carried out numerical simulations showing that they help to suppress Tollmien–Schlichting waves. His work will be briefly summarized below. In his simulations he drove the laminar boundary layer with a vorticity source similar to eqn (2) except that its amplitude, F, varied periodically with time. When the frequency lay within the correct range Tollmien–Schlichting waves were generated. For smooth rigid walls the fastest-growing Tollmien–Schlichting waves are quasi-two-dimensional with wave crests perpendicular to the direction of propagation. In this case the presence of a fixed wave in the surface acted like surface roughness, as expected, and promoted faster growth and earlier transition. Over compliant walls, the fastest-growing Tollmien–Schlichting waves are three-dimensional with oblique wave fronts in accordance with previous theory [31]. For each frequency the forcing has an optimum spanwise wave number, β. In Fig. 4 the optimized growth rates are plotted against frequency for smooth compliant walls and those with fixed waves

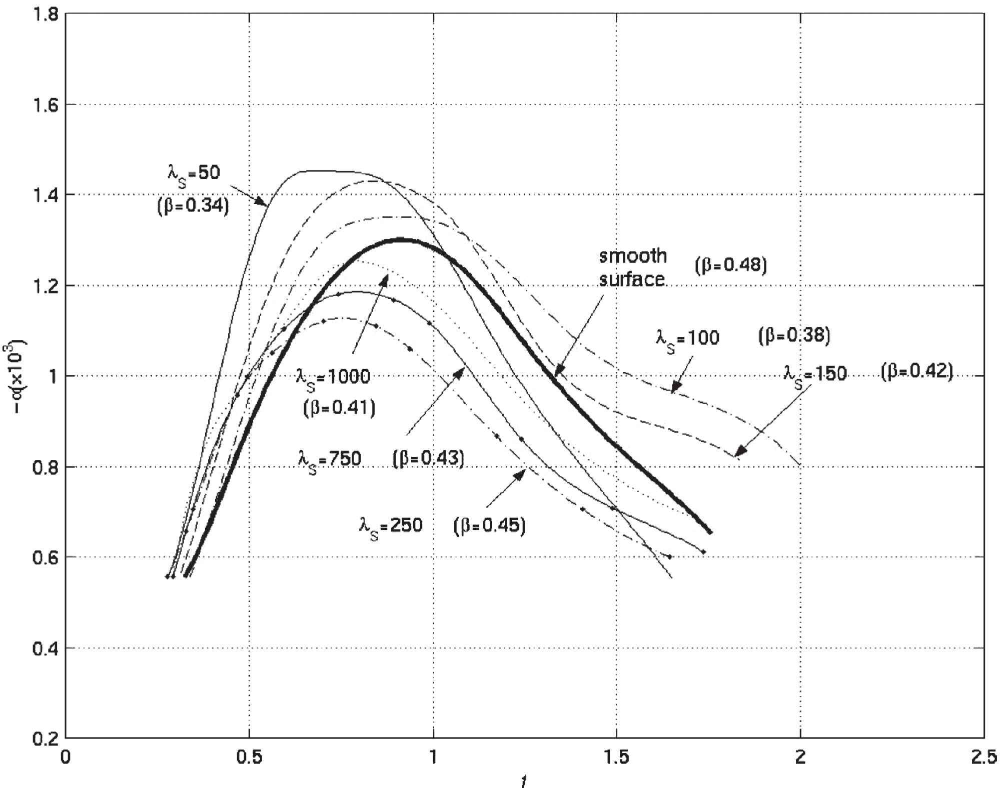

Figure 4: Dimensionless growth rates of oblique TS waves over Kramer-type compliant walls versus their frequency. The values of β correspond to optimal values for growth; λ_S denotes the wavelength in micrometres of the analogue cutaneous ridges, their amplitude is 50 μm throughout, and the Reynolds number based on displacement thickness is 750. (Taken from Ali [24].)

(analogue cutaneous ridges). It can be seen that for a smooth wall the maximum non-dimensional growth rate of around 0.0013 occurs at a non-dimensional frequency just below 1. This growth rate is already considerably less than the rigid-wall value of around 0.00175 at the same Reynolds number of 750 (the favourable effect is much stronger at the higher Reynolds numbers more typical of transition). In contrast to the rigid wall what we see is that for a range of analogue cutaneous ridges the TS growth rate is substantially lower than for the smooth wall. The greatest favourable effect occurs for cutaneous ridges with wavelengths between 5 and 10 ridge amplitudes, exactly the range found for the dolphin epidermis.

This suggests that the cutaneous ridges of dolphins have been adapted for laminar flow. Certainly they are completely different from the cutaneous ridges on shark's scales [32] that are oriented in a streamwise direction and function like riblets to reduce turbulent skin friction by a few percent. It is, perhaps, worth noting that with its dermal ridges, the dolphin epidermis has structures aligned in the streamwise direction that, presumably, could have evolved into riblets. But their actual characteristic spacing is at least two orders of magnitude too large. More direct evidence for laminar flow over dolphins is reviewed in chapter 13 of [7].

4 Concluding remarks

There is little doubt that properly designed analogue dolphin skins in the form of compliant walls possess a laminar-flow capability and also reduce skin-friction drag in turbulent flows. For example, their use is banned under America's Cup rules. The fact that their application in aeronautical engineering is impractical, the difficult, multidisciplinary nature of experimental studies relevant to real applications, and the multi-million-dollar investment in materials science and manufacturing techniques required to produce a practical technology explain, in part at least, why they are not more widely used. There is also convincing evidence that dolphins possess a laminar-flow capability. However, nature does not surrender her secrets easily and it is important in assessing the evidence to ask the right questions. It should also be borne in mind that all features of an organism such as the dolphin are multifunctional and interactive. In this paper we have focussed almost entirely on dolphins. However, compliant walls are probably widely distributed in the natural world; for example, the compliance of shark scales is discussed in [32]. On the whole, though, only dolphins have been much studied in connection with the hydrodynamics of compliant walls.

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