Hydrodynamics and compliant walls: Does the dolphin have a secret?

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This paper reviews recent progress on understanding the effects of compliant walls on boundary-layer instabilities and laminar-turbulent transition. Aspects of the structure and properties of dolphin skin are also considered insofar as they have influenced the work on the hydrodynamics of compliant walls. The question of whether the work on this subject can shed any light on the supposed laminar-flow capability of dolphin skin is also examined.

Do some dolphin species (e.g. the bottle-nosed dolphin *Tursiops truncatus*) possess an extraordinary laminar-flow capability? Certainly mankind has long admired the swimming skills of this fleet creature. Scientific interest in dolphin hydrodynamics dates back at least as far as 1936 when Gray[1] published his analysis of dolphin energetics. It is widely accepted (although there is expert dissenting opinion[2,3]) that *Tursiops truncatus* can maintain a sustained swimming speed of 9 m/s. Gray followed the usual practice of marine engineers and modelled the dolphin's body as a one-sided flat plate of length 2 m. The corresponding value of Reynolds number, Re_L, based on the body length was about 20×10^6. Even in a very low-noise flow environment the Reynolds number, Re_{xt}, for transition from laminar to turbulent flow does not exceed 2 to 3×10^6 for flow over a flat plate. Accordingly, Gray assumed that if conventional hydrodynamics were involved, the flow would mostly be turbulent and the dolphin body would experience a large drag force. So large, in fact, that at 9 m/s its muscles would have to deliver about seven times more power per unit mass than any other mammalian muscle. This led him and others to argue that the dolphin must be capable of maintaining laminar flow by some extraordinary means. This hypothesis has come to be known as *Gray's Paradox*.

Little in detail was known about laminar-turbulent transition in 1936 and Gray would have been unaware of the effect of the streamwise pressure gradient external to the boundary layer. We now know that transition is delayed in favourable pressure gradients (accelerating flow) and promoted by adverse ones (decelerating flow)[4]. Thus, for the dolphin, the transition point would be expected to occur near the point of minimum pressure. For *Tursiops truncatus* this occurs about half way along the body[5] corresponding to $Re_{xt} = 10 \times 10^6$. When this is taken into account the drag is very much less and the required power output from the muscles only exceeds the mammalian norm by no more than a factor of two. There is also more recent evidence that dolphin muscle is capable of higher output[2,3]. So after re-examination of Gray's paradox there is now much less to explain. Nevertheless, the dolphin may still find advantage in a laminar-flow capability. Moreover, there is ample evidence, which we will review in the present paper, that the use of passive artificial dolphin skins – compliant walls – can maintain laminar flow. We will also review the information on those features of the dolphin epidermis which may be of hydrodynamics significance. In particular, we will consider whether the study of compliant walls can offer any evidence that dolphin skin has laminar-flow properties.

Structure of dolphin skin and its artificial analogues

In the late 1950s, Kramer[6–8] carried out a careful study of the dolphin epidermis and designed compliant coatings closely based on what he considered to be its key properties. Figure 1 shows his compliant coatings and test model. Certainly, from his photographs[8] of sections through dolphin epidermis, it appears that his coatings bore a considerable resemblance to dolphin skin, particularly with respect to dimensions (see also Figure 2). According to Babenko *et al.*[9–11], however, Kramer's photographs are misleading and his understanding of the structure of dolphin epidermis faulty. In fact, it appears that there is still not a universally accepted, coherent view of the structure. Figure 2 attempts to give a composite schematic view of the main structural features of the dolphin epidermis and upper dermal layer drawn from several sources[5,9–13]. Some authors[10,13] have noted the presence of microscales or cutaneous ridges

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The first author does not know Prof. Dhawan well, but has had the pleasure of hearing him lecture on two occasions. We hope that our paper which combines stability and transition with dolphin hydrodynamics will serve as a modest tribute to his work.

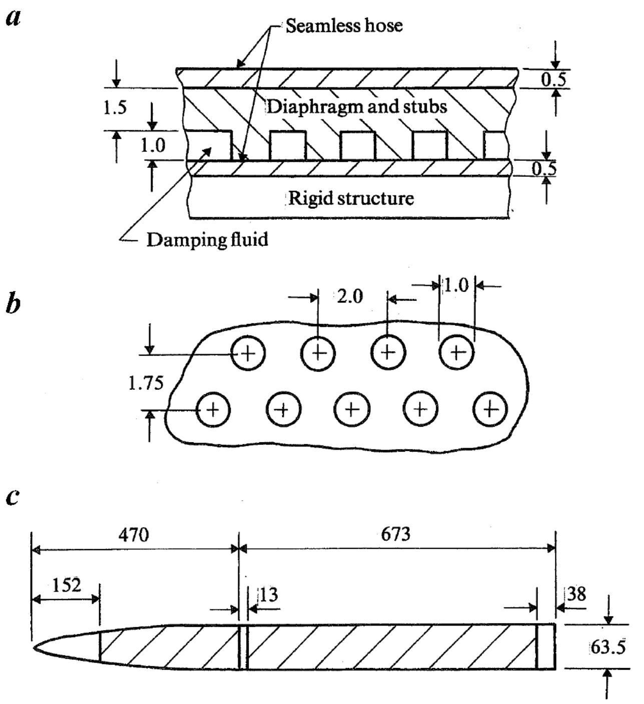

Figure 1. Kramer's compliant coating and model. All dimensions in mm. (Drawings based on those given in ref. 7.) ***a***, Cross-section; ***b***, Cut through stubs; ***c***, Model: shaded regions were coated. (Based on figure 1 of ref. 17.)

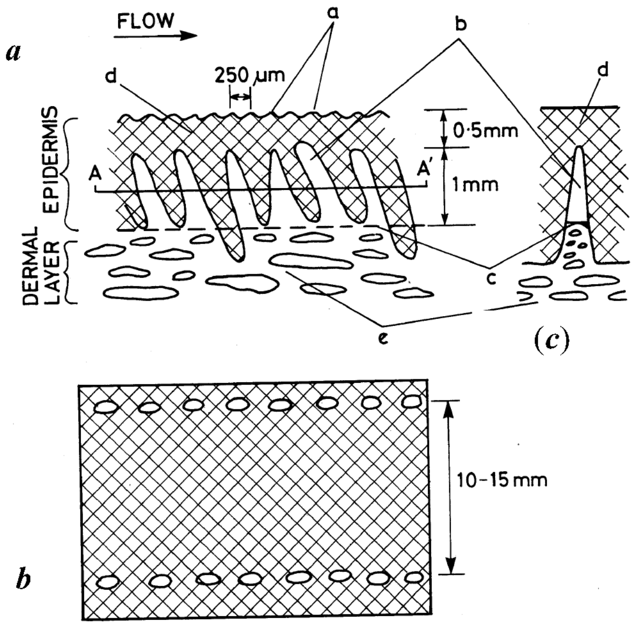

Figure 2. Structure of Dolphin skin. ***a***, Cross-section; ***b***, Cut through dermal papillae at AA'; ***c***, Front view. Key: a, cutaneous ridges or microscales; b, dermal papillae; c, dermal ridge; d, upper epidermal layer; e, fatty tissue.

running approximately normal to the flow direction. The effect of the cutaneous ridges on the hydrodynamics is unknown. The upper epidermal layer forms a comparatively dense elastic membrane and is considered capable of transmitting all pressure fluctuations to the underlying layer. This layer and the dermal papillae are made of looser, more hydrated tissue, including fat cells. The angle the dermal papillae make to the vertical varies over the body from 10 to 80 degrees[10]. They extend upwards from the dermal ridges which run roughly in the streamwise direction[10,12] and can be clearly discerned through the translucent upper epidermal layer by the naked eye. Babenko *et al.*[9–11] also suggested that the blood flow through the dermal papillae could be varied, thereby allowing the viscoelastic properties of the papillary layers, and perhaps the skin as a whole, to be regulated by the nervous system. This implies that dolphin skin is subject to a certain amount of active control unlike the purely passive compliant walls.

Kramer's compliant coatings were manufactured from very soft natural rubber and he mimicked the effect of the fatty, more hydrated tissue, by introducing a layer of highly viscous silicone oil into the voids created by the short stubs. He achieved drag reductions of up to 60% for his best compliant coating compared with the rigid-walled control in sea-water at a maximum speed of 18 m/s. Both the grade of natural rubber and the viscosity of the silicone oil were varied to obtain the best results. (The optimum viscosity was found to be about 200 times that of water.)

Effects of compliant walls on instability waves

Although no evidence existed beyond the drag reduction, Kramer believed that his compliant coatings postponed laminar-turbulent transition. For the low disturbance levels found in the natural marine environment the route to laminar-turbulent transition for boundary-layer flows like those over flat plates is via the amplification of quasi-two-dimensional, small-amplitude, Tollmien-Schlichting (T/S) waves[4]. After extended exponential growth along the boundary layer, these waves eventually grow sufficiently large for nonlinear effects to set in. Transition proper follows shortly thereafter. Its final stage is characterized by the formation of turbulent spots and any vestige of T/S waves has disappeared. However, this final stage of transition can only take place following the amplification of the small-amplitude waves which occupies approximately 80 or 90% of the total transition length. This initial phase is well described by linear hydrodynamic stability theory.

Kramer's view was that compliant coatings reduced or suppressed the growth of the small-amplitude T/S waves, thereby postponing transition to much higher Reynolds numbers or even eliminating it entirely. This also remained the goal of much subsequent research. Kramer believed that the fatty tissue in the upper dermal layer of the dolphin and the silicone oil in his compliant coatings acted as damping to suppress the growth of the waves. This must have seemed eminently reasonable at the time. Surprisingly, however, the early theoretical work by Benjamin[14,15] and Landahl[16], while showing that wall compliance can indeed suppress the growth of T/S waves, also showed that wall damping itself promoted wave growth (i.e. the waves grew faster for a high level of damping than for a low level). Because the theory contradicted his concept of the role of damping and also owing to the failure of other investigators to confirm his results, few believed that Kramer's coating had a laminar-flow capability. But Benjamin and Landahl's theory was rather general and they had made no attempt to model Kramer's coatings theoretically. A theoretical assessment of his coatings was carried out much later by Carpenter and Garrad[17,18] who modelled the coatings as plates supported on a spring foundation with the effects of visco-elastic damping and the viscous damping fluid included. Their results broadly confirmed that the Kramer coatings were capable of substantially reducing the growth of T/S waves.

Experimental confirmation was still lacking for the stabilizing effects of wall compliance on T/S waves. This was provided by Gaster[19]. A schematic diagram of his compliant panel and experimental set-up is shown in Figure 3. The compliant wall was simpler than Kramer's and less obviously like dolphin skin. It consisted of two-layers: a thin, outer, plate-like covering surmounting a much softer and thicker layer. The test model was a flat plate with a compliant-panel insert. The T/S waves were created by a driver located ahead of the compliant panel's leading edge and they were measured at its trailing edge by a surface hot-film foil gauge. Close agreement was found between the measured growth and that predicted by suitably modified linear stability theory.

Flow-induced surface instabilities

A compliant wall is itself a wave-bearing medium. If it is subject to an impulsive line load in the absence of fluid flow, surface waves travel outward along the surface to the left and the right of the point of impact. These are the free surface waves. It has been found that for compliant walls with good transition-delaying properties these waves travel at about 0.7 times the flow speed[20,21]. In fact, a good definition of a compliant wall is that the free-surface waves travel at speeds comparable to the flow speed. It follows therefore that a particular passive flexible wall can only be compliant for a certain range of flow speeds. In the presence of fluid flow the free-surface waves can develop into instabilities. They can also interact with other waves to form instabilities.

The existence of these flow-induced surface instabilities adds much to the interest and challenge of the subject, and their importance was fully appreciated in the seminal papers of Benjamin[14,15] and Landahl[16]. Benjamin's discovery of the unexpected effect of wall damping on the T/S waves, led him and Landahl to introduce a new concept to science. They classified waves according to how they responded to irreversible energy transfer. Class A waves (now called *Negative Energy Waves* – NEW – after terminology introduced later in plasma dynamics[22]) are destabilized (stabilized) by irreversible energy transfer out of (into) the system due, for example, to wall damping. T/S waves belong to this class. (One needs to be a little cautious in this regard as strictly the concept can only be applied to conservative base states.) Class B waves (*Positive Energy Waves* – PEW) are more conventional in that they are stabilized (destabilized) by energy transfer processes having the opposite effect on the NEW. In their pure forms the NEW and PEW can only become convective instabilities[22], i.e. they grow exponentially (until nonlinear effects intervene) as they propagate downstream, but do not grow with time at a fixed location. Owing to their opposite energy requirements, however, NEW and PEW can combine to form a truly self-sustained, temporally-growing instability, known as an *absolute* instability[22]. Once they form, these instabilities are indifferent to irreversible energy transfer. Examples of such instabilities found in flow over compliant walls are discussed below.

An interesting, and highly significant, observation made in Gaster's experimental study was that for the two most compliant of his three panels, the route to transition was not amplification of T/S waves. Unlike the relatively gradual process found for the rigid control, transition occurred suddenly when a critical speed was reached. Moreover, when this happened the signal from the hot-film foil gauge located at the panel's trailing edge oscillated at a much higher frequency than the driver. It was later shown by Lucey and Carpenter[23] that a flow-induced surface instability – *traveling-wave flutter* – set in at the observed transition speed. (This instability is included schematically in Figure 3).

Traveling-wave flutter is a PEW and it is destabilized by irreversible energy transfer to the wall due to the work done on it by the fluctuating pressure. If the boundary layer were absent it would be found that the fluctuating pressure generated in an unsteady potential flow when a surface wave propagates along a compliant surface is exactly 90 degrees out of phase with the vertical velocity of the wall. Thus no network would be transferred over the wave period. If the boundary layer can shift this phase difference away from 90 degrees then there would be a possibility of irreversible energy transfer to the wall. Benjamin[15] showed that a mechanism originally identified by Miles in connection with water waves could also apply to waves on compliant walls. He showed that the required phase change in pressure occurred at the critical point where the local

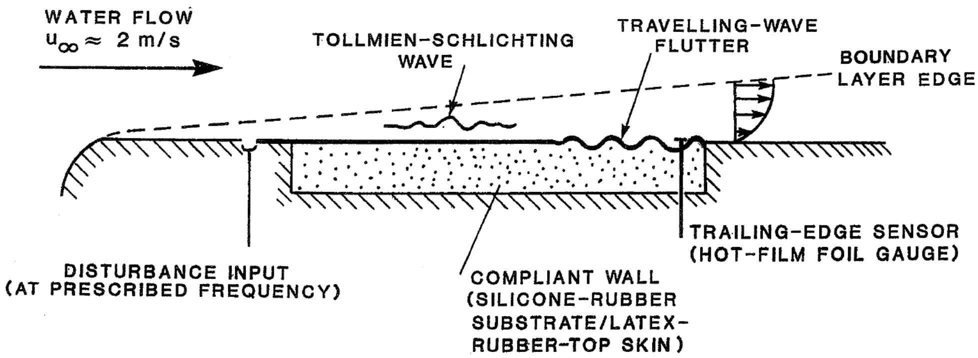

Figure 3. Set-up for Gaster[19] experimental investigation.

velocity in the boundary layer equals the wave speed. Thus, although viscous effects were required to create the boundary layer, the mechanism is otherwise inviscid. A knowledge of this mechanism allowed simple and accurate estimates to be made for the critical wave-number and flow speed of traveling-wave flutter in the case of the plate-spring model[18]. A more rigorous analysis based on asymptotic techniques and including other irreversible mechanisms was developed by Carpenter and Gajjar[24]. This was later extended to the more complex case of Gaster-type two-layer walls[21,23].

To summarize the attributes of traveling-wave flutter: it is a convective instability that travels at speeds of the order of 0.7 U_∞; it is stabilized by irreversible energy transfer to the wall, whereas energy transfer out of the wall, such as damping, has the opposite effect and can be used to control it. It is much more sensitive to wall damping than T/S waves and it appears that the true role of the damping fluid in Kramer's coatings was to control traveling-wave flutter[17]. Figure 4 presents the results of a numerical simulation of traveling-wave flutter propagating in the boundary layer over a finite compliant panel of plate-spring type. The figure shows ray paths traced out by a propagating wave-packet initiated by creating a small bump on the left of the domain which is then allowed to relax. It can be seen that, in fact, two separate wave-packets are present. Despite appearances, the right-hand one becomes dominant at later times. The computations were carried out using our novel discrete-vortex method[25,26]. Traveling wave flutter is now well understood and can be confidently predicted with existing theory.

The other commonly observed flow-induced surface instability is *divergence*. This is a simple instability to understand. Imagine a small disturbance in the form of a bump is somehow created on a compliant surface. There will be a pressure drop as the flow passes over the bump, thereby creating a suction force. If the flow speed is steadily increased this suction force will rise and at a sufficiently high flow speed it will outweigh the restorative structural force in the wall causing the bump to grow until checked by the rise in the structural force due to nonlinear effects. Thus the physical mechanism is conservative and does not require any viscous effects at all; it can occur even in a potential flow[27]. In fact, simple estimates for the critical wave-number and flow speed were derived for potential flow over the plate-spring compliant-wall model[28]. These appeared to give reasonable agreement with the experimental data then available. According to this model, divergence is a static wave at the point of instability and slowly travels downstream at supercritical flow speeds[27,28]. It has been observed on the underside and rear of dolphins when they swim at high speed for short durations[5,29]. It has also been seen on the original Kramer compliant coatings[30].

The phenomenon is not quite so straightforward for the Gaster-type, two-layer walls and for the simpler one-layer walls (Gaster walls with the top plate-like layer removed). For example, Duncan *et al.*[31] found that the critical wavelength was infinitesimally small for the single-layer walls. Divergence on such walls was investigated in detail in a seminal experimental study by Gad-el-Hak *et al.*[32]. They found that the divergence waves traveled slowly downstream at speeds between 0.02 U_∞ and 0.05 U_∞. The waves exhibited sharp crests with broad valleys between each wave. Perhaps the most significant finding was that the divergence waves only occurred when the flow was turbulent. This is most dramatically illustrated in their figure 10 which showed a wedge of turbulence created by a local roughness element surrounded by laminar flow. The divergence waves were only found within the turbulent wedge. Duncan *et al.* explained that the presence of the shear flow in the boundary layer reduced the magnitude of the pressure fluctuations. This shear-sheltering effect would have to be much greater for laminar boundary layers compared with turbulent ones in order to explain the observations of Gad-el-Hak *et al.* In a subsequent experimental study using an ultra-low-damping material, Gad-el-Hak[33] was also able to produce traveling wave flutter on a single-layer wall, but not divergence in this

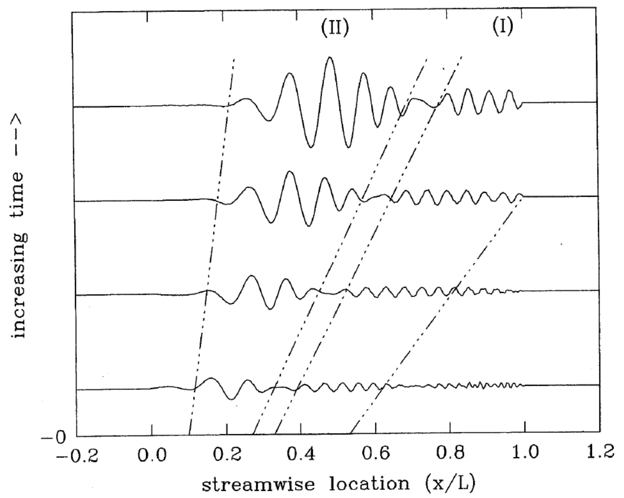

Figure 4. Wall displacement profiles obtained by numerical simulation of traveling-wave flutter produced by a relaxing bump located near the leading edge of the compliant panel. The flow is from left to right. (Based on figure 2 *b* of ref. 26.)

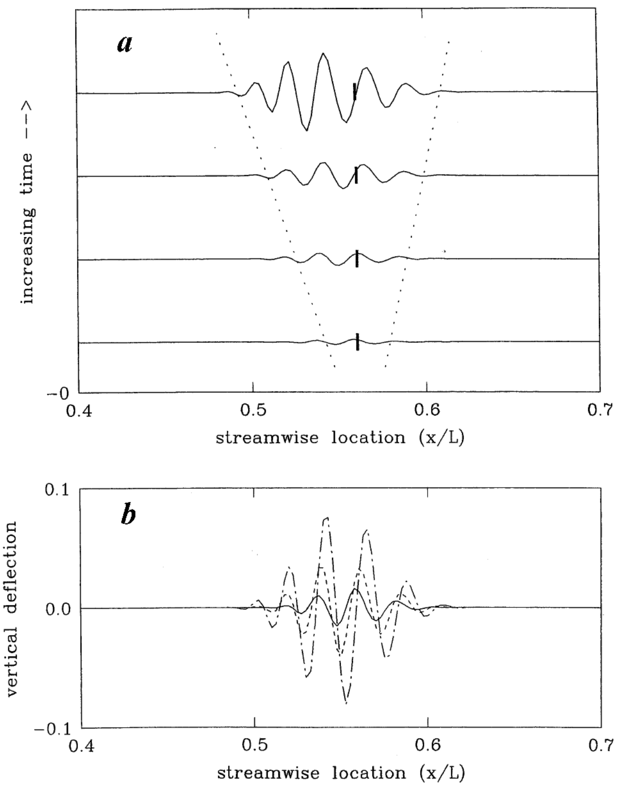

Figure 5. Numerical simulation of divergence: ***a***, space-time form; ***b***, wall displacement profiles at successive times. (Based on figure 4 of ref. 26.)

case. In contrast to the previous case, the wave-forms were much closer to the sinusoid form and traveled at around 0.5 U_∞.

Figure 5 presents a numerical simulation of divergence which can be compared with Figure 4. The same technique was used and, as before, the disturbance is created by a relaxing bump, this time located in the centre of the domain. The main difference between the two figures is that the flow conditions are now such that the flow/wall system is unstable with respect to divergence. It can be seen that the ray patterns and displacements are quite different from Figure 4. Now the wave-packet does not propagate downstream but spreads in both directions from the point of initiation. This is characteristic of an absolute instability. In fact, Yeo *et al.*[34] have shown rigorously that divergence is an absolute instability. By means of our numerical simulations we have been able to confirm that the pressure fluctuations are reduced to a much greater extent in a laminar boundary layer than for a comparable turbulent one[26] owing to the smaller shear thickness of the latter. The peculiar shape of the divergence waves revealed in the experiments of Gad-el-Hak *et al.*[32] has recently been explained by Lucey *et al.*[35]. They showed that it is necessary to include nonlinear effects in both the fluid and wall dynamics. When this was done the hydrodynamic stiffness became increasingly peaky, similar to the wave-forms observed in the experiments, as the wave amplitude increased.

Under certain circumstances the NEW T/S waves can coalesce with the PEW traveling-wave flutter instability to form a much more powerful instability[36] which has been termed a *transitional mode* by Sen and Arora[37]. It appears that excessive use of wall damping to control traveling-wave flutter can give rise to this instability[17]. Thus it sets an upper limit on the level of damping that can be used to control traveling-wave flutter. But wall damping is not essential for its existence. The group velocity is zero and it appears to have the attributes of an absolute instability. Davies and Carpenter[38] have shown that this transitional mode replaces divergence for laminar plane channel flow. It is now known that this also happens for the flat-plate boundary layer[39]. In practice, an experimentalist would find it difficult to distinguish between divergence and the transitional mode as they are both absolute instabilities.

Compliant walls can also support *evanescent modes*[20,22,40]. These are spatially-developing, attenuating waves which usually have the phase and group velocities in opposite directions. Figure 6 displays a numerical simulation of a T/S wave which is incident on a finite compliant panel. The spectrum in Figure 6 *a* shows that two other modes are present over the compliant panel as well as the T/S wave. These are both convective eigenmodes of the coupled boundary-layer/compliant-wall system. One mode has a similar wavelength to the T/S wave and propagates upstream from the panel's trailing edge. The other is a lightly damped, near-neutral, much longer, wave which propagates downstream from the panel's leading edge. Some evanescent modes may also coalesce with other waves to form powerful absolute instabilities[27,34]. A good example is found in the three-dimensional boundary layer over a rotating disk. Lingwood[41,42] has shown that for the rigid rotating disc an absolute instability formed from a coalescence of the Type I cross-flow vortices and the evanescent Type III mode may well be the route to transition in such flows. Wall compliance has been shown to have a strong stabilizing influence on this absolute instability[43,44].

Designing compliant walls for laminar flow

Carpenter and Morris[20,45] have developed a methodology for designing plate-spring-type compliant walls to achieve the greatest possible transition delay. The essential concept underlying the optimization procedure is to use theoretical estimates for the onset speeds of traveling-wave flutter and divergence in order to restrict the choice of wall properties to those corresponding to marginal stability with respect to these two flow-induced surface instabilities at the design flow speed. The e^n method[46] of transition prediction was then used to select the properties with the greatest transitional Reynolds number. (A conservative value of $n = 7$ was used as this corresponds approximately to the limit of linear stability theory.) Later Dixon *et al.*[21] developed similar procedures for the more difficult two-layer, Gaster-type walls using methods based in part on those of Yeo[47]. In both cases the optimum wall design could achieve in excess of a five-fold delay in transition compared with a rigid wall. There was also an optimal level of wall damping required to control the traveling-wave flutter.

Figure 2 gives some idea of the complex structure of the dolphin skin. Babenko *et al.*[9] attempted to develop an equivalent mechanical model, but even if this were feasible there is a lack of knowledge about the mechanical properties of the various components of the dolphin skin. However, just as complex electrical circuits can be shown by Thevenin's and Norton's theorems to be equivalent to very simple circuits, one could argue that there is an mechanical analogue whereby the complex dolphin skin could be shown to be hydrodynamically equivalent to a simpler plate-spring or two-layer compliant wall. Certainly there are two characteristics of such optimized two-layer compliant walls which can be compared directly with live dolphins[48]. Firstly, the wavelength of divergence observed on dolphins can be estimated from the photographs given by Essapian[29]. It is found to be close to that predicted for the optimum compliant walls designed for a flow speed of 9 m/s. Secondly, the free-wave speed of optimized compliant walls is found to be close to $0.7\ U_\infty$. This quantity has been measured on live dolphins by Madigosky *et al.*[49] for a limited number of locations on the dolphin's body. For most of these locations the free-wave speed was found to be around 6.5 m/s, although it was higher than this at a few locations. The above estimate of $0.7\ U_\infty$ would therefore imply that the dolphin skin is optimized for laminar flow at speeds of about 9 m/s. In both these instances, then, there is indirect evidence that the dolphin skin is adapted for laminar flow control. The fact that divergence occurs when the dolphin swims for short durations at substantially higher speeds is also suggestive, as divergence normally only occurs when the boundary layer is turbulent.

Carpenter and Morris[20] have also shown that so-called anisotropic compliant walls have much better transition-delaying properties than the (isotropic) ones discussed above. The anisotropic compliant-wall model was based on a concept first suggested by Grosskreutz[50]. The basic idea is that the structure of the wall is arranged so that rather than being displaced up and down by the fluctuating pressure it is displaced in a direction making a substantial angle to the vertical, thereby generating a negative Reynolds stress at the compliant surface. (Alternative designs of anisotropic compliant wall were also proposed by Yeo[51] and these were predicted to have superior transition-delaying capability.) Again there is a possible link to the dolphin skin. As mentioned above, the dermal papillae make an angle to the vertical which varies over the body from 10 to 80 degrees[10].

The design optimization methods discussed above used estimates of the critical speed for divergence based on assuming potential flow. It is now known, see above, that these estimates are very conservative for laminar boundary layers because of the very considerable reduction in the magnitude of the fluctuating pressure due to shear-sheltering. When this is taken into account, it is possible to design compliant walls which completely suppress the T/S waves for a range of Reynolds numbers[40]. It is possible to shift the range of complete suppression to higher or lower Reynolds numbers by choosing the wall properties appropriately. This has led to our proposition that transition can be completely suppressed to indefinitely high Reynolds numbers by the use of a series of appropriately designed compliant panels, each with its properties selected to suit the local flow environment. The suggestion that it may be possible to maintain laminar flow by passive means at indefinitely high Reynolds numbers may seem highly unorthodox. But there is no law of physics that dictates the inevitability of turbulent flow. In fact, with regard to T/S waves, the maximum growth rate is reached at a comparatively low Reynolds number, and in certain respects it should become easier to maintain laminar flow when this Reynolds number is exceeded. The idea of locally tailored compliant-wall properties is also reflected in dolphin skin, the properties of which, as already noted, vary over the body.

To be really effective at suppressing T/S waves theory indicates that fairly short compliant panels should be used, so that the properties could be kept well-tailored to the local flow environment. (Short compliant panels bring yet further advantages because they are less vulnerable to flow-induced surface – i.e. hydroelastic – instabilities[52].) But boundary-layer stability theory is based on the approximation of a spatially homogeneous flow (the so-called parallel-flow approximation) which perforce has to also assume an infinitely long compliant wall. An obvious question therefore arises. Do panels as short as a few, or even one, T/S wavelengths retain their capability to suppress T/S waves? This question has been investigated in detail by means of numerical simulation by Davies and Carpenter[39,40]. Figure 6 is based on one of these simulations. As discussed earlier, it can be seen that the compliant panel exhibits a complex response. It is typical of a case where the frequency of the T/S wave is above the cut-off frequency of the panel. The spectrum displayed in Figure 6 *a* shows that the response is a superposition of the incident T/S wave and two wall-based eigenmodes. Despite this complex response, the compliant panel in Figure 6 does suppress the growth of T/S waves because they emerge from the panel's trailing edge with a much-reduced amplitude.

In many respects Figure 6 depicts a rather extreme example. No wall damping was included and hinged end conditions were assumed at the leading and trailing edges. The use of more realistic clamped end conditions considerably reduces the extreme behaviour at the panel's leading edge. Including light wall damping also reduces the complexity of the response. From our studies it appears that compliant panels as short as one T/S wavelength remain effective at suppressing T/S waves. This strongly suggests that multiple-panel compliant walls can maintain laminar flow indefinitely.

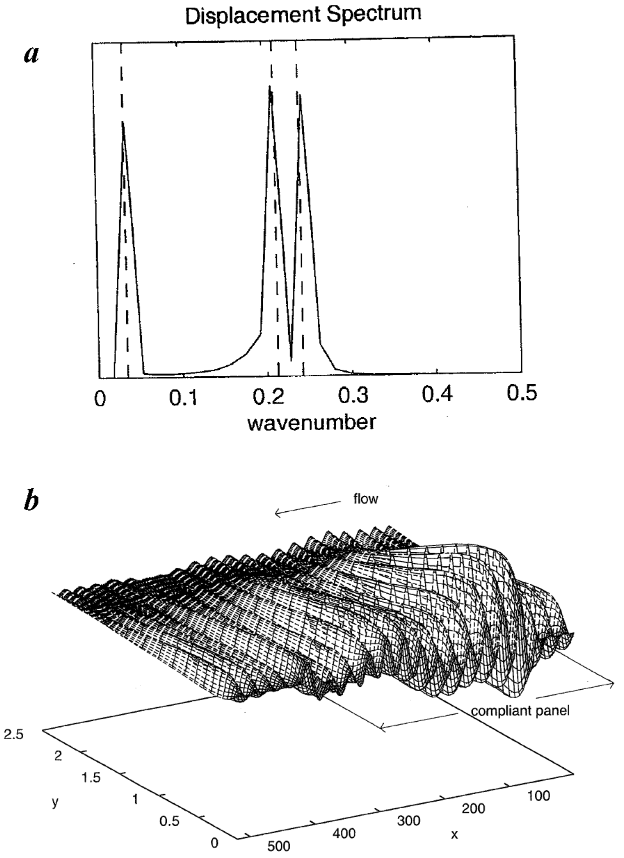

Figure 6. Numerical simulation of a Tollmien-Schlichting wave propagating in a laminar flat-plate boundary layer over a finite compliant panel of plate-spring type. ***a***, Power spectrum obtained by analysing the instantaneous profile of wall displacement; the vertical broken lines correspond to eigenmodes of the coupled Orr-Sommerfeld/compliant-wall eigenproblem. ***b***, Instantaneous spatial variation of the streamwise velocity perturbation plotted along and normal to the wall.

Conclusions and prospects

Most aspects of the hydrodynamics of compliant walls are now well-understood. Detailed comparisons between theory and experiment have confirmed that both the effect of wall compliance on Tollmien-Schlichting waves and the flow-induced surface instabilities can be reasonably well predicted. The theory suggests that substantial postponement of laminar-turbulent transition is possible through the use of properly designed compliant walls. It further suggests that laminar flow may be maintained to indefinitely high Reynolds numbers through the use of multiple-panel compliant walls tailored for the local flow environment. A comparison is made between certain characteristics of dolphin skin and those of the corresponding theoretical compliant walls designed for maximum transition delay. This provides some indirect evidence for the laminar-flow capability of dolphin skin.

Although further experimental investigation remains desirable, the most important gap in knowledge concerns the effects of compliant walls on receptivity mechanisms, particularly those involving the generation of boundary-layer disturbances by freestream turbulence and suspensions of particles. This is the subject of our current research.

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