COMPLIANT COATINGS: A DECADE OF PROGRESS

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Appeared in *Applied Mechanics Reviews*, 49, no. 10, part 2, pp. S147–S157, 1996.

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ABSTRACT

This brief article reviews the important developments in the field of compliant coatings that took place in the past ten years. During this period progress in theoretical and computational methods somewhat outpaced that in experimental efforts. There is no doubt that compliant coatings can be designed to delay transition and to suppress noise on marine vehicles as well as other practical hydrodynamic devices. Transition Reynolds numbers that exceed by an order of magnitude those on rigid-surface boundary layers can be achieved. There is renewed evidence of favorable interactions of compliant coatings even for air flows and even for turbulent boundary layers, but more research is needed to confirm these latest results.

1. INTRODUCTION

For close to forty years the subject of compliant coatings has fascinated, frustrated and occasionally gratified scientists and engineers searching for methods to delay laminar-to-turbulence transition, to reduce skin-friction drag in turbulent wall-bounded flows, to quell vibrations, and to suppress flow-induced noise. The present author wrote a review on the subject ten years ago (Gad-el-Hak, 1986a), and was invited to update that article for the present special volume of the *Applied Mechanics Reviews.* Other reviews that appeared since 1986 include those by Gad-el-Hak (1987), Riley *et al.* (1988), Carpenter (1990), and Metcalfe (1994).

Compliant coatings offer a rather simple method to delay laminar-to-turbulence transition as well as to interact favorably with a turbulent wall-bounded flow. In its simplest form, the technique is passive, relatively easy to apply to an existing vehicle or device, and perhaps not too expensive. Unlike other drag reducing techniques such as suction, injection, polymer or particle additives, passive compliant coatings do not require slots, ducts or internal equipment of any kind (Gad-el-Hak, 1989). Aside from reducing drag, other reasons for the perennial interest in studying compliant coatings are their many other useful applications, for example as sound absorbent materials in noisy flow-carrying ducts in aero-engines, and as flexible surfaces to coat naval vessels for the purposes of shielding their sonar arrays from the sound generated by the boundary-layer pressure fluctuations and of reducing the efficiency of their vibrating metal hulls as sound radiators.

The original interest in the field was spurred by the experiments of Kramer (1957) who demonstrated a compliant coating design based on dolphin's epidermis and claimed substantial transition delay and drag reduction in hydrodynamic flows. Those experiments were conducted in the seemingly less-than-ideal environment of the Long Beach Harbor, California. Subsequent laboratory attempts to substantiate Kramer's results failed, and the initial interest in the idea fizzled. A similar bout of excitement and frustration that dealt mostly with the reduction of skin-friction drag in turbulent flows for aeronautical applications followed. Those results were summarized in the comprehensive review by Bushnell *et al.* (1977). During the early 1980s, interest in the subject was rejuvenated mostly due to modest investment in resources by the Office of Naval Research in the United States and the Procurement Executive of the Ministry of Defence in Great Britain.[§] Significant advances were made during this period in numerical and analytical methods to solve the coupled fluid-structure problem. New experimental tools were developed to measure the minute yet important surface deformation caused by the unsteady fluid forces. Coherent structures in turbulent wall-bounded flows were routinely identified, and their modulation by the surface compliance could readily be quantified.

Careful analyses by Carpenter and Garrad (1985) and well-controlled experiments by Gaster (1988) have, for the first time, provided direct confirmation of the transition-delaying potential of compliant coatings, convincingly made a case for the validity of Kramer's original

[§] Through all the ups and downs in the West, compliant coating research continued at more or less steady pace in the former Soviet Union, but open-literature publications resulting from this work, either in English or in Russian, are rather scarce (for some valuable references, see, for example, the books by Aleyev, 1977, and Choi, 1991, and the article by Carpenter and Garrad, 1985).

claims, and offered a plausible explanation for the failure of the subsequent laboratory experiments (see also Willis, 1986; Lucey and Carpenter, 1995). There is little doubt now that compliant coatings can be designed to delay transition and to suppress noise on marine vehicles and other practical hydrodynamic devices. Transition Reynolds numbers that exceed by an order of magnitude those on rigid-surface boundary layers can be achieved. Although the number of active researchers in the field continues to dwindle, new promising results are being produced. There is recent evidence of favorable interactions of compliant coatings even for air flows and even for turbulent boundary layers.

The present article reviews the significant compliant coating research that took place during the last ten years and suggests avenues for future research. Because of the limited space apportioned by the editor of the present special volume, this article will not detail any of the recent achievements in the field but will mostly serve as a navigation tool to access the available literature. Following these introductory remarks, a brief description of the myriad of instabilities that can develop in the coupled fluid-solid system is given in Section 2. Sections 3 and 4 describe, respectively, transitional and turbulent boundary layers in the presence of pliable surfaces. In Section 3, the linear stability theory, optimization procedures, practical examples and the dolphin's secret are discussed. Recommendations for future research and a personal commentary are given in Section 5. Finally, brief concluding remarks are made in Section 6.

2. SYSTEM INSTABILITIES

From a fundamental viewpoint, a rich variety of fluid-structure interactions exists when a fluid flows over a surface that can comply with the flow. Not surprisingly, instability modes proliferate when two wave-bearing media are coupled. Some waves are flow-based, some are wall-based, and some are a result of the coalescence of both kind of waves. What is most appealing about compliant coatings is their potential to inhibit, or to foster, the dynamic instabilities that characterize both transitional and turbulent boundary layer flows, and in turn to modify the mass, heat and momentum fluxes and change the drag and the acoustic properties. While it is relatively easy to suppress a particular instability mode, the challenge is of course to prevent other modes from growing if the aim is, say, to delay laminar-to-turbulence transition. From a practical point of view, it is obvious that an in-depth understanding of the coupled system instabilities is a prerequisite to rationally designing a coating that meets a given objective.

There are at least three classification schemes for the fluid-structure waves, each with its own advantages and disadvantages. The original scheme is due to Benjamin (1960) and divides the waves into three classes according to their response to irreversible energy transfer to and from the compliant wall. Both class *A* and class *B* disturbances are essentially oscillations involving conservative energy exchanges between the fluid and solid, but their stability is determined by the net effect of irreversible processes such as dissipation in the coating or energy transfer to the solid by non-conservative hydrodynamic forces. Class *A* oscillations are Tollmien-Schlichting waves in the boundary layer modified by the wall compliance, in other words by the motion of the solid in response to the pressure and shear-stress fluctuations in the flow. T-S waves are stabilized by the irreversible energy transfer from the fluid to the coating, but destabilized by dissipation in the wall. Class *B* waves reside in the wall and result from a resonance effect much the same as wind-induced waves over a body of water. Their behavior is the reverse of that for class *A* waves, stabilized by wall damping but destabilized by the non-conservative hydrodynamic forces. Essentially class *B* waves are amplified when the flow supplies sufficient energy to counterbalance the coating internal dissipation. Finally, class *C* waves are akin to the inviscid Kelvin-Helmholtz instability and occur when conservative hydrodynamic forces cause a unidirectional transfer of energy to the solid. The pressure distribution in an inviscid flow over a wavy wall is in exact antiphase with the elevation. In that case, class *C* waves can grow on the solid surface only if the pressure amplitude is so large as to outweigh the coating stiffness. Irreversible processes in both the fluid and solid have negligible effect on class *C* instabilities.

If one considers the total disturbance energy of the coupled fluid-solid system, a decrease in that energy leads to an increase in the amplitude of class *A* instabilities, class *B* is associated with an energy increase, and virtually no change in total energy accompanies class *C* waves. In other words, any non-conservative flow of activation energy from/to the system must be accompanied by disturbance growth of class *A/B* waves, while the irreversible energy transfer for class *C* instability is nearly zero.

The second classification scheme is due to Carpenter and Garrad (1985; 1986). It simply divides the waves into fluid-based (Tollmien-Schlichting instabilities, TSI) and solid-based (flow-induced surface instabilities, FISI). FISI are closely analogous to the instabilities studied in hydro- and aeroelasticity, and include both the traveling-wave flutter that moves at speeds close to the solid free-wave-speed (class *B*) and the essentially static, and more dangerous, divergence waves (class *C)*.[§] The main drawback of this classification scheme is that under certain circumstances the fluid-based T-S waves and the solid-based flutter can coalesce to form a powerful new instability termed transitional mode by Sen and Arora (1988). According to the energy criterion advanced by Landahl (1962), this latest instability is a second kind of class *C* waves. In a physical experiment, however, it is rather difficult to distinguish between the static-divergence waves and the transitional ones.

The third scheme to classify the instability waves considers whether they are convective or absolute (Huerre and Monkewitz, 1990). An instability mode is considered to be absolute if its group velocity is zero. On the other hand, the unstable development of a disturbance is said to be convective when *none* of its constituent modes posses zero group velocity. Both classes *A* and *B* are convective, while class *C* divergence and transitional modes are absolute. As Carpenter (1990) points out, the occurrence of absolute instabilities would lead to profound changes in the laminar-to-turbulence transition process. It is therefore pointless to consider reducing their growth rate or postponing their appearance to higher Reynolds number; nothing short of complete suppression will work. Figure 1 combines and summarizes all three classification schemes.

[§] Static-divergence waves were erroneously interpreted in the past as being class A (*e.g.*, Gad-el-Hak *et al.*, 1984; Duncan *et al.*, 1985; Yeo, 1992). The confusion occurs when divergence is treated as a convective instability, when in fact it is an absolute one (Carpenter, 1990).

3. TRANSITIONAL FLOWS

3.1 Linear Stability Theory

Both the hydrodynamic and the hydroelastic stability theories have reached an impressive level of maturity during the last two decades. The linear theories can be handled, for the most part, analytically, while the nonlinear stability theories are more computer intensive. Perhaps no one has contributed more to the recent application of the stability theory to compliant coatings than Peter W. Carpenter, originally with the University of Exeter and now with the University of Warwick. His list of relevant publications includes 65 papers and growing; obviously only a selected few will be cited in the present short article.

Within the framework of the linear stability theory, two-dimensional small disturbances are assumed to be superimposed upon a steady unidirectional mean flow. The nonlinear, partial Navier-Stokes equations are then reduced to the well-known Orr-Sommerfeld equation which is a fourth-order,[§] linear, ordinary differential equation. The major difficulty in integrating the Orr-Sommerfeld equation is that it is highly stiff and unstable, which makes it virtually impossible to apply conventional numerical schemes. Explicit codes with step size that is commensurate with the global behavior of the solution lead to numerical instabilities, and alternative routines have been developed to handle this stiff eigenvalue problem.

An added difficulty when the walls are compliant is the interfacial conditions which require continuity of velocity and stress. Those boundary conditions can also be linearized, but special care should still be exercised in handling them. Appropriate equations must be used for the compliant walls to be able to fully couple the fluid and solid dynamics. Those models can be either surface-based or volume-based (Figure 2). The former model reduces the spatial dimensions by one, and is therefore less computationally demanding. An example is the thin plate-spring model used by Garrad and Carpenter (1982), Carpenter and Garrad (1985; 1986), Domaradzki and Metcalfe (1987), and Metcalfe *et al.* (1991), among others, to simulate Kramer-type coatings. The

[§] The order of this equation increases when additional complexities are included in the problem. For rotating-disk flow, for example, Coriolis and streamline-curvature terms are incorporated leading to a sixth-order stability equation.

volume-based models are based on the Navier equation and include single and multi-layer coatings (*e.g.*, Fraser and Carpenter, 1985; Buckingham *et al.*, 1985; Duncan *et al.*, 1985; Yeo, 1988) as well as isotropic and anisotropic materials (*e.g.*, Duncan, 1988; Yeo, 1990; 1992). The equations describing the stability of the coupled system form a numerical eigenvalue problem for the complex wavenumber of the disturbance. Duncan (1987) offers a useful comparison between the results obtained from a surface-based model and a corresponding volume-based one.

Compliant walls do suppress the Tollmien-Schlichting waves, but solid-based instabilities proliferate if the coating becomes too soft. For the class *A* T-S waves, the wall compliance reduces the rate of production (via Reynolds stress) of the disturbance kinetic energy. Simultaneously, the viscous dissipation is increased and thus the balance between the energy production and removal mechanisms is altered in favor of wave suppression.

Experimental validation of the stability calculations is rather difficult and requires well-controlled tests in a quiet water or wind tunnel. Several careful experiments to test the flow stability to two-dimensional as well as three-dimensional controlled disturbances have been reported in the past few years (Daniel *et al.*, 1987; Gaster, 1988; Lee *et al.*, 1995, 1996). The last two papers report the results of wind tunnel experiments and actually demonstrate the stabilizing potential of compliant coatings in aerodynamic flows; a remarkable achievement that has been deemed impractical in the past (Bushnell *et al.*, 1977; Carpenter, 1990).

Excellent agreements are reported between the results of the stability theory and the hydrodynamic experiments (see, for example, Willis, 1986; Riley *et al.*, 1988; Carpenter, 1990; Lucey and Carpenter, 1995). The last paper, in particular, applies the linear stability theory to predict the experimentally observed evolution of both Tollmien-Schlichting waves and traveling-wave flutter in water flows. For the wind tunnel experiments, P.W. Carpenter (private communication) is planning to conduct the corresponding calculations. In here, we show one example of the suppression of T-S waves in an air boundary layer developing on top of a silicone elastomer-silicone oil compliant surface. Figure 3 depicts the wind tunnel results of Lee *et al.* (1995). The coating in Figure 3a was made by mixing 91% by weight of 100 mm^2/s silicone oil with 9% of silicone elastomer. In Figures 3b, 3c and 3d, the corresponding mix was 90% and 10%, yielding about 35% higher modulus of rigidity. As compared to the rigid wall, the single-layer, isotropic, viscoelsatic compliant coating significantly suppresses the rms-amplitude of the artificially-generated Tollmien-Schlichting waves across the entire boundary layer, for a range of displacement-thickness Reynolds numbers. Reductions in the maximum rms-amplitude of as much as 40% are observed for the softer coating (Figure 3a), which may lead to delayed transition.

3.2 Coating Optimization

If a compliant coating is to be designed for use on an actual vehicle, a relevant question might be what are the optimum wall properties to give the greatest transition delay? The large number of available parameters makes it imperative that a rational (*i.e.,* one derived from first principles) selection process be conducted. For obvious reasons, the trial-and-error empirical approach used in the past *(if it is soft, let us try it!)* should not be even contemplated. This should be particularly true now that rational optimization procedures are becoming readily available as described below.

A wall that is too compliant (*i.e.,* too soft) can substantially delay transition via TSI by shrinking its unstable region in the frequency-Reynolds number plane, but rapid breakdown can occur through the amplification of wall-based instabilities (Lucey and Carpenter, 1995). Both kinds of FISI are potentially harmful. The divergence instabilities are absolute, nearly static, and yield to wholesale deformations of the surface which are likely to trigger premature transition due to a roughness-like effect (Figure 4). Flutter instabilities, though convective, are also dangerous. As shown in the stability diagram in Figure 5, their narrow band of unstable frequencies extends indefinitely as Reynolds number increases downstream. Thus, once these instabilities are encountered at some downstream location, sustained growth follows. This is unlike the broad-band Tollmien-Schlichting instabilities which grow then decay as the different waves travel downstream and pass through the lower and upper branches of their neutral-stability curve (Figure 5).

A workable strategy for coating optimization suggested by Carpenter (1988) is to choose a restricted set of wall properties such that the coating is marginally stable with respect to FISI (both flutter and divergence). The remaining disposable wall parameters can then be varied to obtain the greatest possible transition (via TSI) delay. For the plate-spring, surface-based model, for example, there are two disposable parameters: the wall damping and the critical wavenumber for divergence. The downstream location of the transition region is estimated from an e^n criterion, where n is typically chosen in the range of 7-10. The lower exponent represents the approximate limit of validity of the linear stability theory for a low-disturbance environment, and provides a rather conservative calculation.

Although wall dissipation destabilizes Tollmien-Schlichting waves, a viscoelastic coating with moderate level of damping leads to greater delay in transition as compared with purely elastic surfaces. Apparently the stabilizing effects of wall damping on traveling-wave flutter allow a softer wall to be used, and thus more than offset the adverse effects of coating dissipation on TSI.

Coating optimization with respect to TSI growth rate is performed at a rather narrow range of Reynolds numbers. On a growing boundary layer, the Reynolds number increases monotonically, and a compliant coating will not be optimum over the whole length of a vehicle. Carpenter (1993) suggests that a multiple-panel wall, placed in series, with each panel optimized for a particular range of Reynolds numbers, is likely to produce larger transition delays than a single-panel wall. His calculations for a two-panel, plate-spring-type compliant wall indicate an additional performance improvement of over 30% over an optimized single-panel wall.

It seems reasonable that a large number of panels, say 10, in series would lead to superior performance, but of course the calculations involved become prohibitive very quickly. An additional benefit from using multi-panels is that shorter panels are more resistant to both static-divergence waves and traveling-wave flutter (Lucey and Carpenter, 1993), thus allowing softer panels to be used which further suppress TSI and improve the coating performance.

Work on nonlinear stability theory has recently been in the forefront and confirms that transition-delaying coatings, optimized using the linear theory, maintain their beneficial effects into the latter stages of transition to turbulence (Metcalfe *et al.*, 1991; Joslin and Morris, 1992; Thomas, 1992a; 1992b). Lee *et al.* (1996) studied experimentally the effects of a compliant surface on the growth rates of both the subharmonic and three-dimensional fluid-based instabilities of a laminar boundary layer in air. Their results suggest that a delay of the excitement of the secondary instability could be achieved by suppressing the growth of the primary waves using surface compliance.

3.3 Practical Examples

Most of the theoretical as well as experimental compliant coating research has been concerned with canonical boundary layers. Nevertheless, an attempt is made in here to estimate the potential benefit of applying the technique for field applications where strong three-dimensional and pressure-gradient effects and, for aeronautical applications, compressibility effects could be present. The typical Reynolds numbers, based on vehicle speed and overall length, for a hydrofoil, a torpedo and a nuclear submarine are, respectively, of the order of 10 million, 50 million and 1 billion. Applying an e^n-type calculations (with the exponent chosen conservatively to be $n = 7$) to an optimum two-panel, plate-spring-type compliant wall, Carpenter (1993) computes a transition Reynolds number of 13.62×10^6, as compared with 2.25×10^6 for a rigid wall.[§] This means that the laminar region that would normally extend over 23%, 5% and 0.2% of the respective vehicle lengths would, with the use of an optimum coating, extend over a larger length of 100%, 27% and 1%. Computing the corresponding overall drag coefficients using standard methods for a mixed laminar-turbulent boundary layer over a flat plate, the potential reduction in skin-friction drag using the optimum two-panel compliant wall could be as much as 83%, 19% and 0% for the three respective vehicles. Obviously the large submarine does not benefit, as far as drag reduction is concerned, from the use of transition-delaying compliant coating but the smaller vehicles do. However, extending the laminar region on a submarine even by 1 m could be

[§] Contrast this six-fold increase to the 30% higher transition Reynolds number reported in the experiments of Gaster (1988), who did not attempt to optimize his single-panel, two-layer, silicone rubber/latex rubber coating. Theoretical calculations by Dixon *et al.* (1994) indicate that an optimum Gaster-type coating would provide a 500% higher transition Reynolds number.

significant for sonar applications requiring longer quiet regions of the boundary layer.

The estimates above were made for a simple plate-spring model. Using more than two panels could provide further transition delay. More complex compliant surfaces, particularly anisotropic ones designed specifically to suppress the Reynolds stress fluctuations, could conceivably offer more spectacular savings. Such custom-designed coatings could also favorably interact with fully-turbulent flows. Even for laminar flows, the calculations involved when complex, wall-based models are used, though straightforward in principle, are quite demanding in practice.

For aeronautical applications, a cruising commercial jet aircraft has a fuselage Reynolds number of the order of 1 billion and a wing Reynolds number of the order of 50 million. Again, increasing the transition Reynolds number by a factor of 5 or so is significant for the wing but not for the fuselage. Skin-friction reduction of the order of 20% is achievable for the wings (whose skin-friction drag accounts for about 50% of the skin friction of the entire aircraft and 25% of the total drag). Finding a compliant coating that would reduce the turbulent skin-friction drag would of course be very beneficial for both the typical fuselage and long submarine.

3.4 The Dolphin's Secret

The ability to swim or to fly with minimum skin-friction and pressure drag is of extreme importance to the Darwinian survival of certain nektonic and avian species. *Homo sapiens* interested in building the fastest submarine or the most fuel-efficient aircraft have much to learn about alternative drag-reduction approaches from their humble earthlings. As M. O. Kramer has remarked close to 40 years ago, a school of porpoises, including the young and the old, the weak and the strong, showing off its seemingly effortless glide along a fast ocean-liner is a sight to behold.

Cetaceans appear to possess unusually low overall drag coefficients. This is the basic for the so-called Gray's (1936) paradox, in which a steady-state energy balance based on the anticipated muscle power of various nektons, including the dolphin, failed to explain their unusually fast swimming speeds. Transition delay is of course an obvious albeit arduous technique for achieving about an order of magnitude lower skin-friction drag, but does the dolphin posses an exotic means by which such difficult flow control goal can be accomplished? Obviously the dolphin is not sharing its secrets with other fellow mammals.

Kramer's (1957; 1961) invention of a compliant coating tried to mimic the dolphin's epidermis and claimed drag reduction of as much as 60%. His explanation for the dolphin's secret is that their skin, like his successful compliant coating, is capable of substantially delaying laminar-to-turbulence transition. Kramer's work was discredited for a while but now seems to be back in vogue as remarked in the Introduction. The calculations presented in Section 3.3 indicate that it is quite conceivable to design a Kramer-type coating that delay transition by a factor of 4-6 in Reynolds number and that drag reduction of the order reported by Kramer is also quite possible. Does the dolphin or other similar fast swimmers posses such a coating?

In a recent article, Bushnell and Moore (1991) quote the relevant energetic and controlled swimming studies, but conclude by supporting the explanation offered by Au and Weihs (1980) that dolphins, which must periodically breath air, achieve high-speed swimming by simply *porpoising, i.e.,* momentarily leaping out of the water thereby reducing their drag force by a factor of 800 (density ratio of air and water). This more than pays for the additional interfacial or wave drag and accounts for the abnormally low apparent drag-coefficients inferred from the assumption of fully-submerged travel.

The present author, however, does not concur with the above *final solution* to the Gray's paradox. Dolphins have been clocked at sustained and burst speeds of close to 10 and 20 m/s, respectively. *Delphinus delphis* has a typical length of 2 m. This leads to sustained and burst Reynolds numbers based on the overall length of the order of 20 million and 40 million, respectively. Carpenter (1993) reports the results of optimizing a rather simple plate-spring coating. Using a single panel, as compared with a rigid surface a 4.6-fold increase in transition Reynolds number is estimated, which leads to a drag reduction of 36% at the typical dolphin's sustained speed and 20% at burst speed. Using a mere two-panel coating, the transition Reynolds number becomes 6.1 times the value for a rigid surface, and the potential drag reductions for the sustained and burst speeds are now 52% and 30%, respectively.

These lower levels of skin friction are compatible with the available muscle power for a dolphin of the size used above. Admittedly, the above estimates were made for a flat-plate boundary layer and might not hold when pressure-gradient and other shape effects are taking into account. Additionally, the dolphin has also pressure drag on top of the (much larger) skin friction. On the other hand, cetaceans have had millions of years of evolutionary adaptations to hone their coatings for maximum speed and efficiency, and it is quite conceivable that their epidermis is quite more complex, and hydrodynamically beneficial, than the simple ones computed in the examples above. Moreover, each portion of the skin could have been optimized for the appropriate range of local Reynolds numbers. Therefore, the dolphin's apparent success is not incompatible with having optimum compliant coatings to substantially delay laminar-to-turbulence transition, and therefore to attain inordinately low coefficients of drag.

Other fascinating questions related to the amazing swimming abilities of the dolphin include the possibility that its excreted mucin is a drag-reducing additive. Is there a hydrodynamic advantage to the warm-blooded cetaceans because their epidermis temperature is higher than the ambient one (in which case the near-wall water viscosity is lowered and the turbulent boundary layer might be relaminarized)? Does the dolphin's particular body shape during coasting (with no attendant overall body deformation) or actual swimming (accompanied by appropriate body oscillations) offer additional drag-reducing advantages? Also, what are the potential benefits to the porpoise when it uses ship-generated bow waves for body surfing? These subjects, though related to the above discussion, are outside the scope of the present brief and are therefore left for another circumstance.

4. TURBULENT WALL-BOUNDED FLOWS

Unlike the laminar and transitional flows investigated in sections 3.1 and 3.2, compliant coating effects on turbulent boundary layers are rather difficult to study theoretically. In fact *any* turbulent flow is largely unapproachable analytically. For a turbulent flow, the dependent variables are random functions of space and time, and no straightforward method exists for analytically obtaining stochastic solutions to the governing nonlinear, partial differential equations. The statistical approach to solving the Navier-Stokes equations always leads to more unknowns than equations (the closure problem), and solutions based on first principles are again not possible. Direct numerical simulations (DNS) of the canonical turbulent boundary layer have so far been carried out up to a very modest momentum-thickness Reynolds number of 1410 (Spalart, 1988).

How would one go about rationally choosing a coating to achieve a particular control goal for a turbulent boundary layer? Analytical optimization procedures such as those used to delay transition (Section 3.2) would not work for fully-turbulent flows. In order to analyze the full problem, direct numerical simulations of the turbulent boundary layer should be coupled to a finite-element model of the compliant coating, a task that is extremely time consuming, expensive and taxes the fastest supercomputer around. Modeling the turbulence by an eddy-viscosity or even a more sophisticated closure scheme is less computationally demanding, but there is no guarantee that turbulence models developed primarily for rigid surfaces would work for a compliant surface. In fact, it is not difficult to argue that closure models based on mean quantities miss completely the all important spectral contents of a fluid-solid interaction, and will therefore never work.

A turbulent boundary layer is characterized by a hierarchy of coherent structures. Near the wall, the dynamics are dominated by the quasi-periodic bursting events (Robinson, 1991). A crude albeit resourceful attempt to model a turbulent boundary layer interaction with a single-layer, isotropic, viscoelastic coating has been advanced by Duncan (1986). He approximates the turbulent flow over the coating by a potential flow with a superimposed pressure pulse, convecting downstream, that mimics the pressure footprint of a single bursting event. In order to relate the problem to a real turbulent flow, the pressure pulse characteristics are taken from actual boundary layer measurements and the potential flow is modified to incorporate the reduced magnitudes and phase shifts found experimentally in boundary layer flows over moving wavy walls. At low flow speeds (relative to the transverse-wave speed in the solid), the coating response to the pressure pulse is stable and primarily localized under it. At intermediate speeds, the response is still stable but includes a discernible wave pattern tagging along behind the pressure pulse. At the highest speed studied, large-amplitude, unstable waves develop on the compliant surface, much the same as the FISI observed experimentally. Duncan and Sirkis (1992) have recently extended the above model to anisotropic compliant coatings. They report that certain anisotropic surfaces provide more effective control over the amplitude and angular extent of the generated stable response pattern. Larger amplitudes are generated as compared with isotropic surfaces, thus providing for greater potential for modifying the turbulence.

Whenever the flow speed in a turbulent boundary layer becomes sufficiently large compared with the transverse free-wave speed in the solid, flow-induced surface instabilities proliferate. The pressure fluctuations within the flow are an order of magnitude larger than the normal and tangential viscous stresses, and drive the coating response. In laminar wall-bounded flows it is difficult to observe the hydroelastic waves in their unstable state. As soon as flutter or divergence waves grow, rapid breakdown to turbulence takes place in the boundary layer and the flow is no longer laminar.

Most of the experimental studies concerning compliant coating effects on turbulent boundary layers focused on documenting the unstable flow-induced surface instabilities. When divergence waves or flutter are unstable, the effects, though adverse, are pronounced and are somewhat easier to document. Only recently few hardy souls have attempted to investigate the wall-bounded flows when these FISI are stable or neutrally stable. Obviously the latter kind of studies have to await the development of refined techniques to measure the minuscule surface deformation and the associated coherent structure modulation when the FISI are neutrally stable.

Both Gad-el-Hak (1986b) and Hess *et al.* (1993) introduce nonintrusive methods for the point measurement of the instantaneous vertical surface-displacement of a compliant coating, while Lee *et al.* (1993a) offer an optical holographic interferometer, in connection with an interactive fringe-processing system, to capture whole-field random topographic features. The latter technique is more expensive to set up but offers higher spatial resolution, of the order of 1 micron, and yield simultaneous surface displacement information on a large section of the compliant coating. Both the local and global methods were initially employed to document the unstable surface response to the pressure fluctuations in turbulent boundary layers. The holographic interferometer was recently used to record the surface topography in the presence of *stable* flow-induced deformations (Lee *et al.*, 1993b).

The onset speed and wave characteristics of the solid-based class *B* and *C* instabilities were systematically documented in a series of towing-tank experiments (Gad-el-Hak, 1986b). Divergence waves were observed on a single-layer viscoelastic coating made from a PVC plastisol. The flutter appeared on an elastic coating made from common household gelatin, but, in the absence of damping, its threshold speed was consistently lower than that for divergence. The damping in the PVC coating stabilized the traveling-wave flutter and hence only divergence was observed there.[§] For the elastic coating, flutter appeared first and dominated the observed surface deformation. For both kind of waves, the threshold speed decreases with coating thickness, in other words thin surfaces (relative to the displacement thickness of the boundary layer) are less susceptible to hydroelastic instabilities than thick ones.

Typical profiles of unstable class *B* and *C* waves were also recorded in the same hydrodynamic experiments using a laser displacement gauge. The vertical displacement at a point associated with the slow moving, asymmetric, large-amplitude divergence waves contrasts the faster, more-or-less symmetric, smaller-amplitude flutter. Both waves cause roughness-like effect, but the static divergence is the more dangerous instability. The phase speed of the static-divergence waves is of the order of 1% of the freestream speed, and their wavelength is about 5-10 times the coating thickness. The corresponding quantities for the flutter are 40% and 1.5-3, respectively.

Hess (1990) and Lee *et al.* (1993b) also investigated compliant coating effects on turbulent boundary layers. Both experiments were conducted in the same water tunnel, but the second paper

[§] Parenthetically, this and similar earlier observations led Gad-el-Hak (1986b) and others to the wrong conclusion, as stated in the footnote in Section 2, regarding the classification of the divergence waves. To reiterate, the class B flutter is stabilized by damping, while the class C divergence is largely unaffected.

focused on the stable interaction between the fluid and a single-layer, homogeneous, viscoelastic coating made of a mixture of silicone rubber and silicone oil. Lee *et al.*'s coating was chosen based on the criterion established by Duncan (1986). In the presence of a stable wave pattern on the compliant surface, the flow visualization experiments indicated low-speed streaks with increased spanwise spacing (by as much as 80%; see Figure 6) and elongated spatial coherence compared with those obtained on a rigid surface. More significantly, for the particular compliant coating investigated an intermittent relaminarization-like phenomenon was observed at low Reynolds numbers. Lee *et al.* (1993b) also report a slight thickening of the buffer region and viscous sublayer and an upward vertical shift in the compliant law-of-the-wall. The streamwise turbulence intensity, the local skin-friction coefficient and the Reynolds stress across the boundary layer were all reduced, indicating a possible interruption of the feedback loop which allows the turbulence to be self-sustaining. Thus, potentially favorable interaction between a compliant coating and a turbulent boundary layer has been demonstrated for the first time.

5. THE FUTURE

The diminishing pool of researchers remaining active in the field of compliant coatings includes teams from the University of Warwick, Johns Hopkins University, University of Houston, and University of Maryland. A larger pool was involved during the early 1980s, but the realities of research funding led to the present decline.

Few suggestions for future research are given in here. The optimization procedures discussed in Section 3.2 have not been validated experimentally. Gaster-type experiments should be repeated using optimized coatings, including multi-panel ones.

The results of the transitional boundary layer, wind-tunnel experiments reported by Lee *et al.* (1995; 1996) are intriguing and fly in the face of the conventional wisdom. They indicate that compliant coatings are capable of delaying transition even for air flows. Past calculations using a plate-spring model and considering the extremely large density of typical walls compared with the density of air indicated that very flimsy coatings would be required to achieve transition delay and that the situation gets worse as the air speed increases. This led Carpenter (1990) among others to conclude that the use of wall compliance is impractical for aeronautical applications. But the plate-spring results do not apply in any straightforward way to the homogeneous, single-layer walls studied by Lee *et al.* (1995). Validating the recent favorable results using both independent experiments and numerical simulations would open the door for aerodynamic applications, something that was seriously considered but later abandoned by NASA and the aerospace industry. The optimization procedures developed by Carpenter (1988) for transitional hydrodynamic flows should be extended to air flows. Experiments should be conducted using the resulting optimized coatings.

More complex coatings could potentially yield superior performance as compared with the relatively simple walls studied thus far. Multi-panels, multi-layers, anisotropic coatings and combinations thereof should be investigated. In any such research program, experiments has to be guided with theoretical results. As already mentioned, trying to pick a compliant coating by trial and error is a very inefficient use of limited resources and will perhaps never work.

Favorably modulating a fully-turbulent flow, in contrast to merely delaying transition, is also of great practical importance. The experimental results reported by Lee *et al.* (1993b) are very encouraging, but the coating used was chosen based on a rather simplistic model of the turbulent pressure fluctuations. In order to custom-design compliant coatings to achieve particular control goals for turbulent wall-bounded flows, direct numerical simulations of the coupled fluid-structure system have to be performed. Turbulence modeling via classical closure schemes, while sufficient for some simple flows over rigid surfaces, will perhaps not yield reliable results for compliant walls. DNS, on the other hand, requires extensive computer resources and is quite expensive to carry out. The bottom line is that relatively large investment in resources are required for this task, but the enormous potential payoffs could easily justify the expenditure.

Most of the research thus far has considered incompressible, zero-pressure-gradient, flat-plate boundary layers. Effects of compressibility, pressure gradient and three-dimensionality on the performance of compliant coatings are largely unknown. Such studies will yield invaluable information for field application of the control technique for both air and water flows. Most practical aerodynamic flows are in the moderate-to-high Mach number regime, and compressibility effects must therefore be investigated before compliant coatings are used on actual aircraft. Related to the pressure-gradient effects is the question of separated flows: Does compliant coating affect separation favorably or adversely? Other stability modifiers, such as favorable pressure-gradient, suction or heating/cooling, do delay transition as well as prevent separation. It is not known whether compliant coatings also have this dual benefit, and it may be beneficial to research the possibility. Finally, real flows are three-dimensional and involve complex geometries. A model problem for three-dimensional flows is the rotating disk. Few experiments were conducted using a rotating disk with a compliant face (see, for example, Hansen and Hunston, 1974). More recently, Cooper and Carpenter (1995) analyzed the cross-flow (type *I*; inviscid) as well as the viscous (type *II)* fluid-based instabilities which develop in the same three-dimensional flow. The preliminary results are encouraging and indicate that compliant coatings can suppress the more dangerous type *I* instabilities.

Active compliant coatings is an emerging area deserving of further research. Energy expenditure is required to drive the wall, but the potential for significant net drag reduction is higher than that for passive coatings. The feasibility of the concept for stabilizing laminar boundary layers has been shown through numerical experiments (Metcalfe *et al.*, 1986). Active coatings could also be used to suppress the Reynolds stress and reduce the skin-friction drag in turbulent wall-bounded flows, but any realistic field application of the technique has to await further development of reasonably-priced and rugged microfabricated sensors and actuators (Gad-el-Hak, 1994; 1996).

I would like to end this section with a personal commentary. There is a growing impatience among our fellow citizens with the glacial pace of transferring knowledge from the laboratories to the factories, getting back the invested research dollars of yesterday in the form of stronger industrial competitiveness tomorrow. In his closing remarks on the occasion of the presentation of the 1990 American Physical Society Fluid Dynamics Prize, Lumley (1992) lamented that the United States is a curiously unsympathetic environment for a theoretician, or *any* scientist interested in fundamental work. Through all its ups and downs, compliant coating research provides a good case study. Although in the general scheme of things this basic research is but a drop in the ocean, its triumphs and debacles are not untypical. The usual five-year cycle for academic research is just enough to get off the ground. When this research program was re-ignited in the early 1980s, few veterans from the 1960s and 1970s were around to share their valuable experiences, and the newcomers have had to climb the learning curve from its bottom. Nevertheless, we now know how to carry out stability calculations, solve fully coupled fluid-solid problems, numerically simulate turbulent flows, conduct well-controlled experiments for both transitional and turbulent flows, reliably measure surface deformation, identify as well as quantify coherent structures, optimize a coating for a particular task using first principles, ... In other words, the compliant coating research community has now most of the tools it needs for significant further progress. Unfortunately, this community has recently been forced into an early retirement.

As amply illustrated in this brief, compliant coating research offers the potential for substantial transition delay and favorable interactions with turbulent boundary layers. It requires modest commitment of resources, but the payoff is extraordinary. It might be worth recalling that a mere 10% reduction in the total drag of an aircraft translates into a saving of $1 billion in annual fuel cost for the commercial fleet in the United States alone. Contrast this benefit to the annual cost of less than $2 million for the 5-year compliant coating research program that was sponsored by the U.S. Office of Naval Research in 1980. Private capital will not and can not step in place of the government to support leading-edge research with long-term promise but without short-term return. Do we have the will, desire, patience and resources to continue the journey towards real-life applications? In so many similar circumstances in the past, the answer was no. Scarce resources were spent for five years only to be hastily diverted to newer areas, long before the fruits of our labor have even had a chance of being reaped. But even in these difficult times of trying to reduce the federal budget deficit, one hopes for a different road to prosperity--and I do not mean for the researchers involved--this time around. And while we are at it, cutting funds for basic research in general might be popular but certainly unwise. Reducing spending on current outlays is one thing, but investing less in the country future is an entirely different matter. The overall detrimental impact of reducing government funding for basic research probably will not be felt for a generation, but it will be felt.

6. CONCLUDING REMARKS

The last ten years witnessed renewed interest in compliant coatings as a means to achieve beneficial flow control goals. Significant advances were made in numerical and analytical techniques to solve the coupled fluid-structure problem. Novel experimental tools were developed to measure the stable as well as the unstable surface deformations caused by the pressure fluctuations in the boundary layer. In turbulent wall-bounded flows, coherent structures were routinely identified and their modulation by wall compliance could be quantified.

The coupled system instabilities are now well understood, and compliant coatings can therefore be rationally designed to achieve substantial transition delay in hydrodynamic flows. Most significant results thus far were obtained when a strong cooperation existed between theory and experiment. Recent experiments indicate favorable compliant coating interactions even for aerodynamic flows and even for turbulent boundary layers. More research is needed, however, to confirm these latest results.

ACKNOWLEDGMENT

The author's compliant coating research during the early 1980s was sponsored by the Office of Naval Research and monitored by Michael M. Reischman. Peter W. Carpenter, Dennis M. Bushnell, Mihir Sen and Albin A. Szewczyk have read the manuscript and provided useful comments. James H. Duncan and Ralph W. Metcalfe have shared useful, difficult-to-obtain papers. To all I extend my sincere appreciation.

Different versions of this paper have been presented at the *Forty-Eighth Annual Meeting of the Division of Fluid Dynamics of the American Physical Society*, Irvine, California, 19-21

November 1995, and the *Workshop on Flow Control Fundamentals and Practices,* Corsica, France, 1-5 July 1996.

REFERENCES

Aleyev, Yu.G. (1977) *Nekton*, DR. W. Junk b.v. Publishers, the Hague, the Netherlands.

Au, D., and Weihs, D. (1980) "At High Speeds Dolphins Save Energy by Leaping," *Nature* **284**, pp. 548-550.

Benjamin, T.B. (1960) "Effects of a Flexible Boundary on Hydrodynamic Stability," *J. Fluid Mech.* **9**, pp. 513-532.

Buckingham, A.C., Hall, M.S., and Chun, R.C. (1985) "Numerical Simulations of Compliant Material Response to Turbulent Flow," *AIAA J.* **23**, pp. 1046-1052.

Bushnell, D.M., and Moore, K.J. (1991) "Drag Reduction in Nature," *Annu. Rev. Fluid Mech.* **23**, pp. 65-79.

Bushnell, D.M., Hefner, J.N., and Ash, R.L. (1977) "Effect of Compliant Wall Motion on Turbulent Boundary Layers," *Phys. Fluids* **20**, pp. S31-S48.

Carpenter, P.W. (1988) "The Optimization of Compliant Surfaces for Transition Delay," in *Turbulence Management and Relaminarisation*, eds. H.W. Liepmann and R. Narasimha, pp. 305-313, Springer-Verlag, Berlin.

Carpenter, P.W. (1990) "Status of Transition Delay Using Compliant Walls," in *Viscous Drag Reduction in Boundary Layers*, eds. D.M. Bushnell and J.N. Hefner, *Progress in Astronautics and Aeronautics*, vol. 123, pp. 79-113, AIAA, Washington, D.C.

Carpenter, P.W. (1993) "The Optimization of Multiple-Panel Compliant Wall for Delay of Laminar-Turbulence Transition," *AIAA J.* **31**, pp. 1187-1188.

Carpenter, P.W., and Garrad, A.D. (1985) "The Hydrodynamic Stability of Flow over Kramer-Type Compliant Surfaces. Part 1. Tollmien-Schlichting Instabilities," *J. Fluid Mech.* **155**, pp. 465-516.

Carpenter, P.W., and Garrad, A.D. (1986) "The Hydrodynamic Stability of Flow over Kramer-Type Compliant Surfaces. Part 2. Flow-Induced Surface Instabilities," *J. Fluid Mech.* **170**, pp. 199-232.

Choi, K.-S. (editor) (1991) *Recent Developments in Turbulence Management*, Kluwer, Dordrecht, the Netherlands.

Cooper, A.J., and Carpenter, P.W. (1995) "The Effects of Wall Compliance on Instability in Rotating Disc Flow," AIAA Paper No. 95-2257, American Institute of Aeronautics and Astronautics, Washington, D.C.

Daniel, A.P., Gaster, M., and Willis, G.J.K. (1987) "Boundary Layer Stability on Compliant Surfaces," Final Report No. 35020, British Maritime Technology Ltd., Teddington, United Kingdom.

Dixon, A.E., Lucey, A.D., and Carpenter, P.W. (1994) "The Optimization of Viscoelastic Compliant Walls for Transition Delay," *AIAA J.* **32**, pp. 256-267.

Domaradzki, J.A., and Metcalfe, R.W. (1987) "Stabilization of Laminar Boundary Layers by Compliant Membranes," *Phys. Fluids* **30**, pp. 695-705.

Duncan, J.H. (1986) "The Response of an Incompressible, Viscoelastic Coating to Pressure Fluctuations in a Turbulent Boundary Layer," *J. Fluid Mech.* **171**, pp. 339-363.

Duncan, J.H. (1987) "A Comparison of Wave Propagation on the Surfaces of Simple Membrane Walls and Elastic Coatings Bounded by a Fluid Flow," *J. Sound Vibration* **119**, pp. 565-573.

Duncan, J.H. (1988) "The Dynamics of Waves at the Interface between a Two-Layer Viscoelastic Coating and a Fluid Flow," *J. Fluids Structures* **2**, pp. 35-51.

Duncan, J.H., and Sirkis, J.S. (1992) "The Generation of Wave Patterns on Isotropic Coatings by Pressure Fluctuations in a Turbulent Boundary Layer," *J. Sound Vibration* **157**, pp. 243-264.

Duncan, J.H., Waxman, A.M., and Tulin, M.P. (1985) "The Dynamics of Waves at the Interface between a Viscoelastic Coating and a Fluid Flow," *J. Fluid Mech.* **158**, pp. 177-197.

Fraser, L.A., and Carpenter, P.W. (1985) "A Numerical Investigation of Hydroelastic and Hydrodynamic Instabilities in Laminar Flows over Compliant Surfaces Comprising One or Two Layers of Viscoelastic Material," in *Numerical Methods in Laminar and Turbulent Flow*, ed. C. Taylor *et al.*, pp. 1171-1181, Pineridge Press, Swansea, United Kingdom.

Gad-el-Hak, M. (1986a) "Boundary Layer Interactions with Compliant Coatings: An Overview," *Appl. Mech. Rev.* **39**, pp. 511-524.

Gad-el-Hak, M. (1986b) "The Response of Elastic and Viscoelastic Surfaces to a Turbulent Boundary Layer," *J. Appl. Mech.* **53**, pp. 206-212.

Gad-el-Hak, M. (1987) "Compliant Coatings Research: A Guide to the Experimentalist," *J. Fluids Structures* **1**, pp. 55-70.

Gad-el-Hak, M. (1989) "Flow Control," *Appl. Mech. Rev.* **42**, pp. 261-293.

Gad-el-Hak, M. (1994) "Interactive Control of Turbulent Boundary Layers: A Futuristic Overview," *AIAA J.* **32**, pp. 1753-1765.

Gad-el-Hak, M. (1996) "Modern Developments in Flow Control," *Appl. Mech. Rev.* **49**, pp. 365-379.

Gad-el-Hak, M., Blackwelder, R.F., and Riley, J.J. (1984) "On the Interaction of Compliant Coatings with Boundary-Layer Flows," *J. Fluid Mech.* **140**, pp. 257-280.

Garrad, A.D., and Carpenter, P.W. (1982) "A Theoretical Investigation of Flow-Induced Instabilities in Compliant Coatings," *J. Sound Vibration* **85**, pp. 483-500.

Gaster, M. (1988) "Is the Dolphin a Red Herring?," in *Turbulence Management and Relaminarisation*, eds. H.W. Liepmann and R. Narasimha, pp. 285-304, Springer-Verlag, Berlin.

Gray, J. (1936) "Studies in Animal Locomotion. VI. The Propulsive Powers of the Dolphin," *J. Exp. Biol.* **13**, pp. 192-199.

Hansen, R.J., and Hunston, D.L. (1974) "An Experimental Study of Turbulent Flows over Compliant Surfaces," *J. Sound Vibration* **34**, pp. 297-308.

Hess, D.E. (1990) "An Experimental Investigation of a Compliant Surface beneath a Turbulent Boundary Layer," Ph.D. Dissertation, the Johns Hopkins University, Baltimore, Maryland.

Hess, D.E., Peattie, R.A., and Schwarz, W.H. (1993) "A Nonintrusive Method for the Measurement of Flow-Induced Surface Displacement of a Compliant Surface," *Exp. Fluids* **14**, pp. 78-84.

Huerre, P., and Monkewitz, P.A. (1990) "Local and Global Instabilities in Spatially Developing Flows," *Annu. Rev. Fluid Mech.* **22**, pp. 473-537.

Joslin, R.D., and Morris, P.J. (1992) "Effect of Compliant Walls on Secondary Instabilities in Boundary-Layer Transition," *AIAA J.* **30**, pp. 332-339.

Kramer, M.O. (1957) "Boundary Layer Stabilization by Distributed Damping," *J. Aeronaut. Sci.* **24**, pp. 459-460.

Kramer, M.O. (1961) "The Dolphin's Secret," *J. Am. Soc. Nav. Eng.* **73**, pp. 103-107.

Landahl, M.T. (1962) "On the Stability of a Laminar Incompressible Boundary Layer over a Flexible Surface," *J. Fluid Mech.* **13**, pp. 609-632.

Lee, T., Fisher, M., and Schwarz, W.H. (1993a) "The Measurement of Flow-Induced Surface Displacement on a Compliant Surface by Optical Holographic Interferometry," *Exp. Fluids* **14**, pp. 159-168.

Lee, T., Fisher, M., and Schwarz, W.H. (1993b) "Investigation of the Stable Interaction of a Passive Compliant Surface with a Turbulent Boundary Layer," *J. Fluid Mech.* **257**, pp. 373-401.

Lee, T., Fisher, M., and Schwarz, W.H. (1995) "Investigation of the Effects of a Compliant Surface on Boundary-Layer Stability," *J. Fluid Mech.* **288**, pp. 37-58.

Lee, T., Fisher, M., and Schwarz, W.H. (1996) "An Experimental Study of the Boundary-Layer Nonlinear Instability over Compliant Walls," *J. Fluid Mech.*, to appear.

Lucey, A.D., and Carpenter, P.W. (1993) "The Hydroelastic Stability of Three-Dimensional Disturbances of a Finite Compliant Panel," *J. Sound Vibration* **165**, pp. 527-552.

Lucey, A.D., and Carpenter, P.W. (1995) "Boundary Layer Instability over Compliant Walls: Comparison between Theory and Experiment," *Phys. Fluids* **7**, pp. 2355-2363.

Lumley, J.L. (1992) "Some Comments on Turbulence" *Phys. Fluids A* **4**, pp. 203-211.

Metcalfe, R.W. (1994) "Boundary Layer Control: a Brief Review," in *Computational Fluid Dynamics '94*, eds. S. Wagner, J. Periaux and E. Hirschel, pp. 52-60, Wiley, New York.

Metcalfe, R.W., Battistoni, F., Ekeroot, J., and Orszag, S.A. (1991) "Evolution of Boundary Layer Flow over a Compliant Wall during Transition to Turbulence," in *Proc. Boundary Layer Transition and Control Conference*, pp. 36.1-36.14, Royal Aeronautical Society, Cambridge, United Kingdom.

Metcalfe, R.W., Rutland, C.J., Duncan, J.H., and Riley, J.J. (1986) "Numerical Simulations of Active Stabilization of Laminar Boundary Layers," *AIAA J.* **24**, pp. 1494-1501.

Riley, J.J., Gad-el-Hak, M., and Metcalfe, R.W. (1988) "Compliant Coatings," *Annu. Rev. Fluid Mech.* **20**, pp. 393-420.

Robinson, S.K. (1991) "Coherent Motions in the Turbulent Boundary Layer," *Annu. Rev. Fluid Mech.* **23**, pp. 601-639.

Sen, P.K., and Arora, D.S. (1988) "On the Stability of Laminar Boundary-Layer Flow over a Flat Plate with a Compliant Surface," *J. Fluid Mech.* **197**, pp. 201-240.

Spalart, P.R. (1988) "Direct Simulation of a Turbulent Boundary Layer up to $R_\theta = 1410$," *J. Fluid Mech.* **187**, pp. 61-98.

Thomas, M.D. (1992a) "On the Resonant Triad Interaction in Flows over Rigid and Flexible Boundaries," *J. Fluid Mech.* **234**, pp. 417-442.

Thomas, M.D. (1992b) "On the Nonlinear Stability of Flows over Compliant Walls," *J. Fluid Mech.* **239**, pp. 657-670.

Willis, G.J.K. (1986) "Hydrodynamic Stability of Boundary Layers over Compliant Surfaces," Ph.D. Thesis, University of Exeter, United Kingdom.

Yeo, K.S. (1988) "The Stability of Boundary-Layer Flow over Single- and Multi-Layer Viscoelastic Walls," *J. Fluid Mech.* **196**, pp. 359-408.

Yeo, K.S. (1990) "The Hydrodynamic Stability of Boundary-Layer Flow over a Class of Anisotrpic Compliant Walls," *J. Fluid Mech.* **220**, pp. 125-160.

Yeo, K.S. (1992) "The Three-Dimensional Stability of Boundary-Layer Flow over Compliant Walls," *J. Fluid Mech.* **238**, pp. 537-577.

FIGURE CAPTIONS

Figure 1. Summary of all Three Classification Schemes.

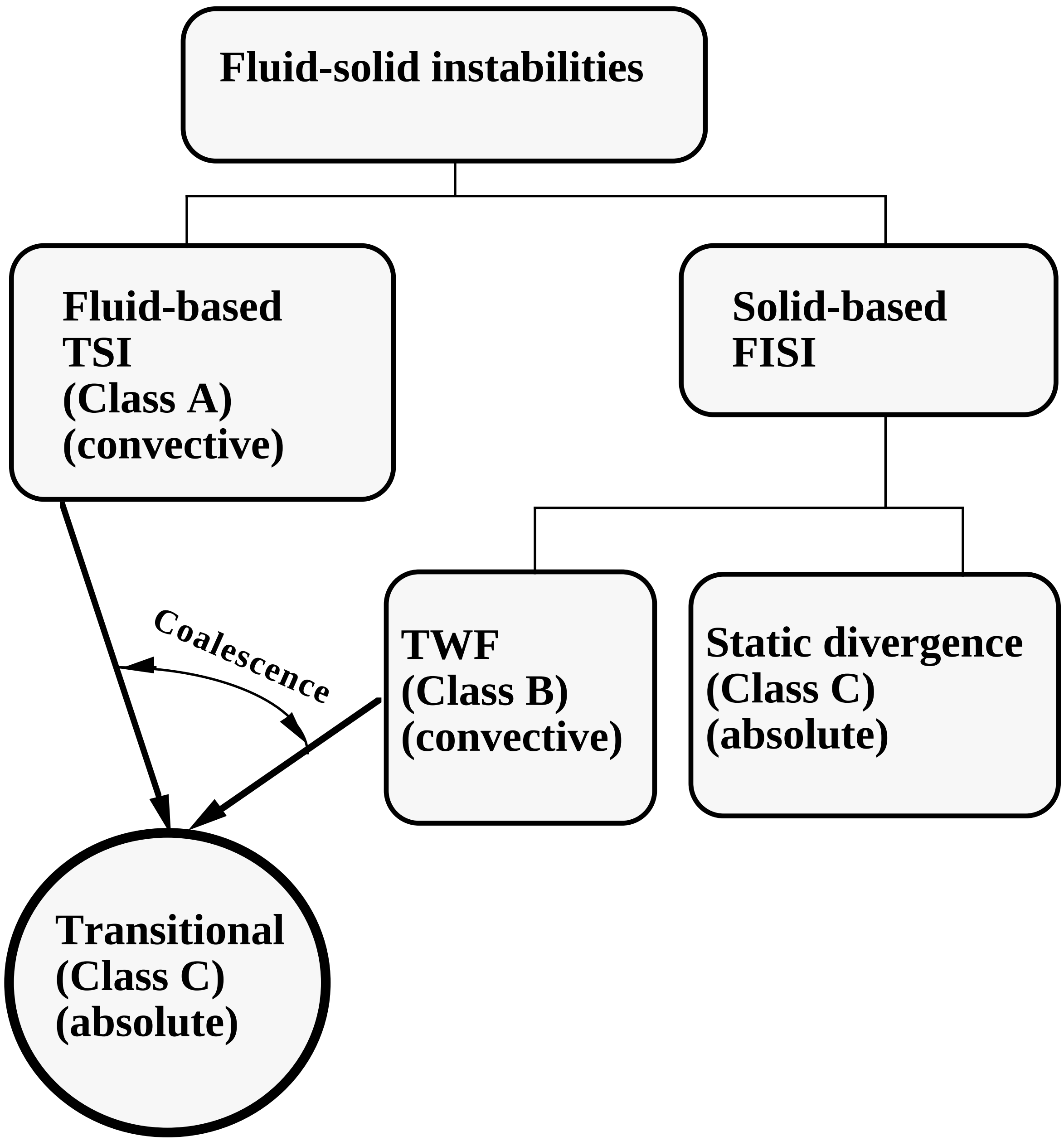
Figure 2. Volume-based and surface-based models of compliant coatings. (From Carpenter, 1990.)

Figure 3. Comparison of distribution of rms-amplitude of the TSI of rigid surface and compliant surface across boundary layer. Wind tunnel experiments of Lee *et al.* (1995). ❑, rigid surface; ■, compliant surface. (a) R_{δ^*} = 1274; (b) R_{δ^*} = 1105; (c) R_{δ^*} = 1225; (d) R_{δ^*} = 1350. Inset shows locations of ribbon (solid symbol) and probe (open symbol) relative to neutral-stability curve.

Figure 4. Static-divergence waves on a single-layer viscoelastic coating subjected to the pressure fluctuations of a turbulent boundary layer. Freestream velocity is 6.3 times the transverse-wave speed in the solid. (From Gad-el-Hak *et al.*, 1984.)

Figure 5. Typical neutral-stability curves for Tollmien-Schlichting waves and for traveling-wave flutter. The solid is a double-layer, Gaster-type compliant coating. (From Lucey and Carpenter, 1996.)

Figure 6. Variations of mean dimensionless spanwise spacing of the low-speed streaks in a turbulent boundary layer. ●, rigid surface; ▲, compliant surface, friction velocity u_* obtained from rigid-surface mean-velocity measurements; ■, compliant surface, u_* obtained from compliant-surface mean-velocity measurements. These data are from the water tunnel experiment of Lee *et al.* (1993b). Other symbols in the figure are from classical rigid-surface measurements.



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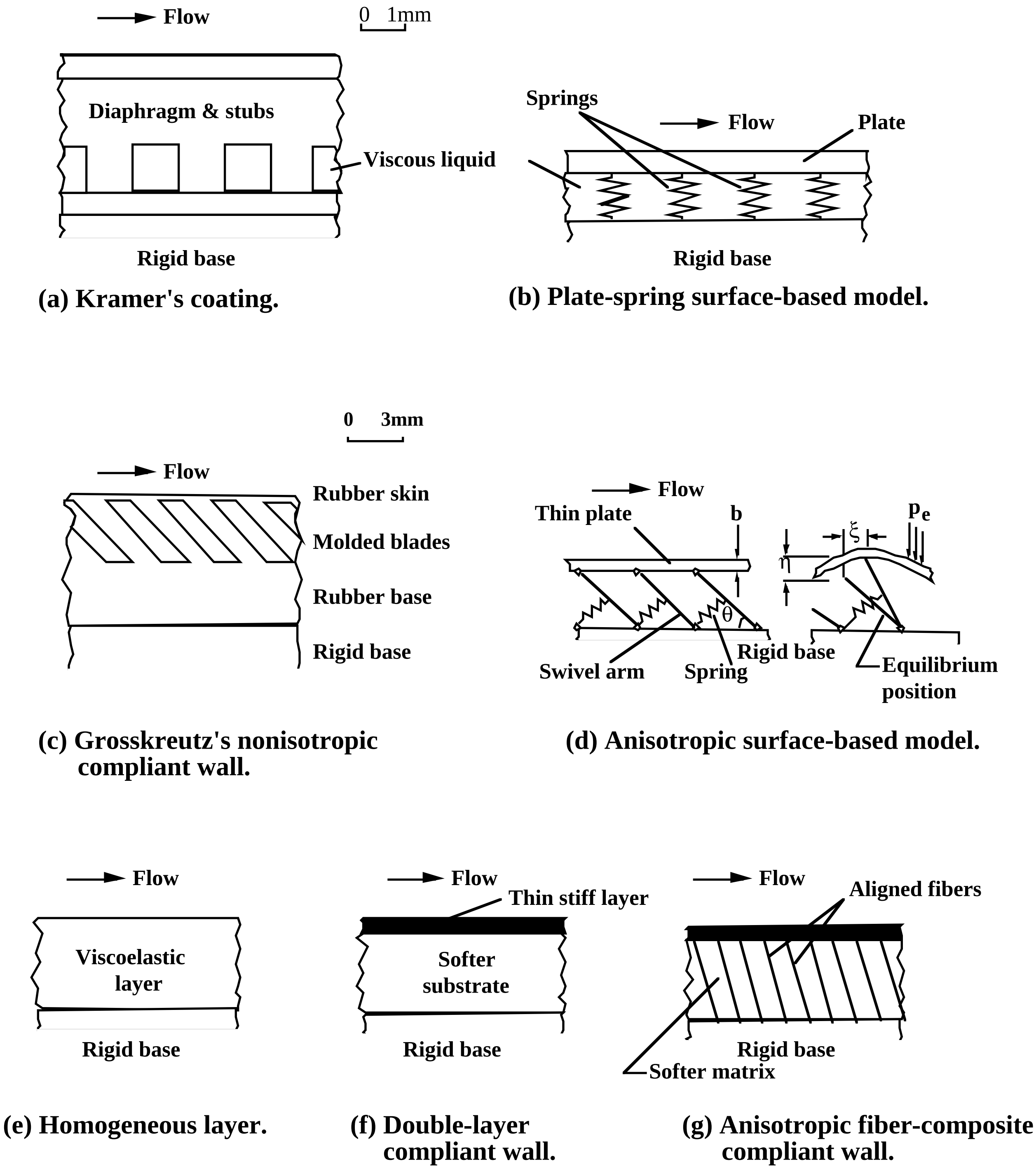

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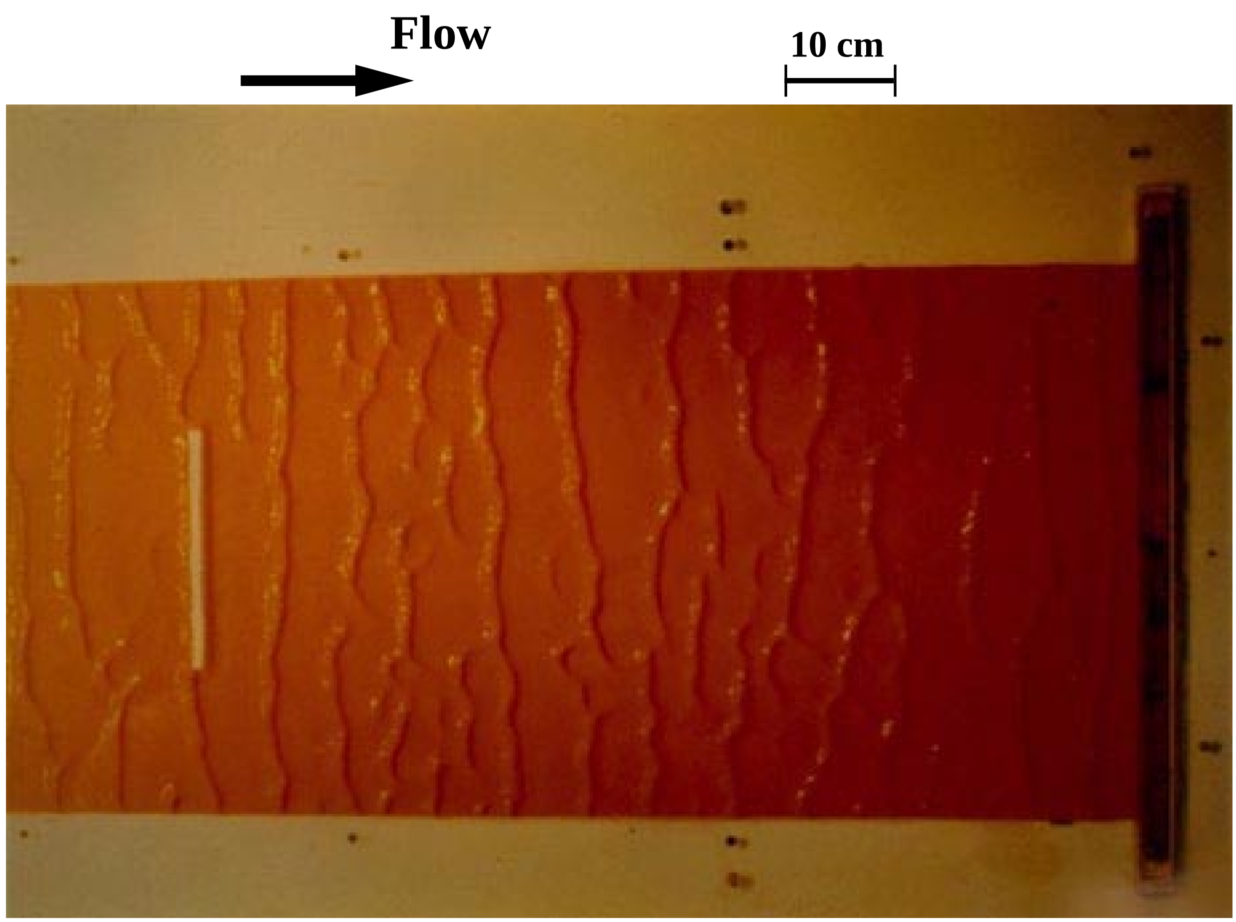

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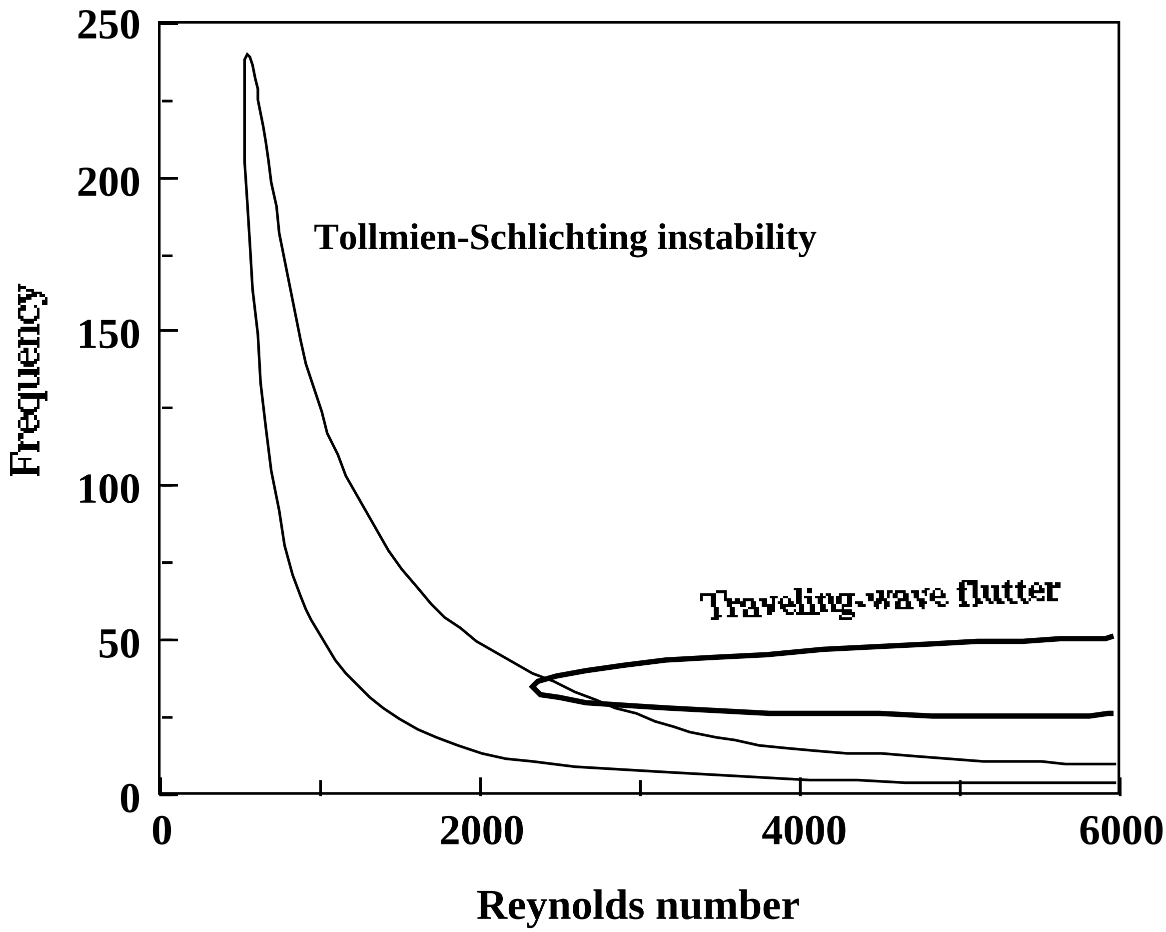

Figure 5. Typical neutral-stability curves for Tollmien-Schlichting waves and for traveling-wave flutter. The solid is a double-layer, Gaster-type compliant coating. (From Lucey and Carpenter, 1996.)