AN ATTEMPT TO CONTROL BOUNDARY LAYER TURBULENCE WITH NONISOTROPIC COMPLIANT WALLS

R. GROSSKREUTZ
Physics Department, University of Dar es Salaam.

Abstract

A review of turbulence production in boundary layers leads to a new approach to boundary layer control by means of nonisotropic compliant walls. Suitably constructed coatings were tested and demonstrate that the concept is basically valid.

Introduction

Since Kramer's studies of the dolphin's skin and his experiments with artificial reproductions (Kramer 1960 and 1969), boundary layer control by means of compliant coatings is one of the methods under discussion for drag and noise reduction in hydrodynamics (Benjamin 1964). Two basically different approaches have been followed up. Kramer himself aimed at a stabilisation of laminar boundary layers and retardation or even complete avoidance of the transition to turbulent flow. He hoped to achieve this by means of energy absorbing coatings with the task of extracting and eradicating immediately any energy from upspringing flow instabilities. Not very encouraging theoretical investigations (Landahl 1962) and disappointing attempts (many of which remained unpublished) to reproduce Kramer's experimental successes caused later investigators to concentrate more on the interaction between fully developed turbulent flow and compliant walls (e.g. Dinkelacker 1966, Carstensen 1967, Blick et al 1969). Because of the complexity of this problem these latter approaches were mainly empirical.

The work outlined in this paper is based on a reconsideration of the mechanism of turbulence production, which led to the development of a new concept for boundary layer control using compliant walls with nonisotropic elasticity. Suitably designed walls have been built and tested. Technical details of the lengthy process of production and other particulars, which are not presented here, are available from the author's dissertation (Grosskreutz 1971).

Concept of the nonisotropic compliant wall

The increased power requirements for turbulent boundary layer flow as compared with laminar flow are due to increased internal friction and dissipation of turbulent energy, which, in the case of steady flow, is produced at the same rate as it is dissipated. The production is effected by a lateral transfer of fluid elements into regions of higher or lower mean velocity, respectively. In the turbulent energy equation the production term therefore reads $-\rho\,\overline{uv}\,dU/dy$, where ρ is the density, U the mean streamwise velocity, u the instantaneous streamwise velocity, v the instantaneous normal velocity, y the normal distance from the wall and the bar denotes time average. (For a simple derivation see appendix.)

The instantaneous product uv may sometimes be positive; the time average, however, is generally negative resulting in a continuous production of turbulent energy. A device aimed at reducing drag must therefore primarily reduce the negative correlation between u and v in the region of maximum turbulence production, which in all boundary layers is found very near the wall, just outside the viscous sublayer. It would be of even greater advantage if such a device could impose positive correlation between u and v.

The same conclusion is suggested by a consideration of the shear stress. Immediately at the wall there is only viscous stress due to the non slip condition. And viscous stress $\mu\,dU/dy$ is predominant throughout the adjacent viscous sublayer up to $y \simeq 10\,\mu\rho^{-\frac{1}{2}}\,\tau_o^{-\frac{1}{2}}$ (where μ denotes dynamic viscosity and τ_o wall shear stress). Beyond that, however, the turbulent shear stress $-\rho\,\overline{uv}$ becomes predominant, the sum of both being practically constant throughout the inner part of the boundary layer (Hinze 1959 pp. 491/92). If to all this a positively correlated wall motion

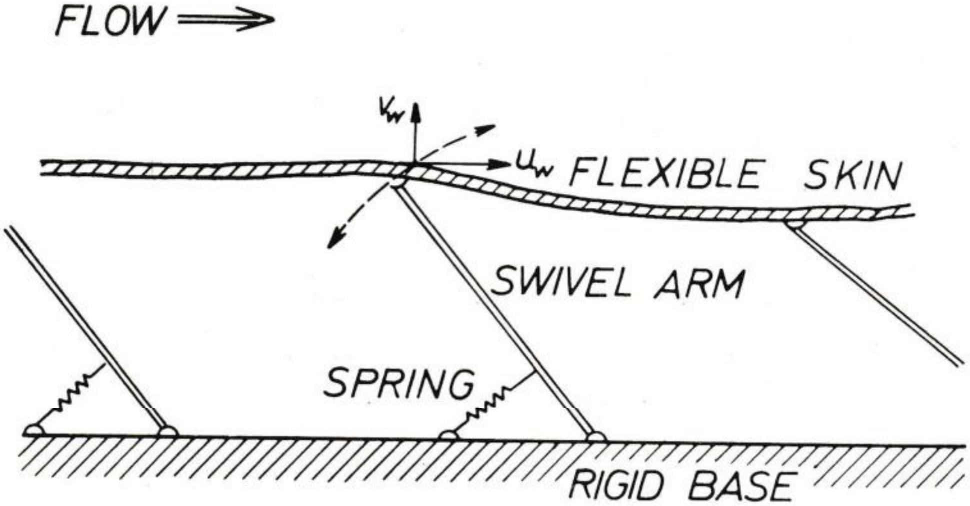

Fig. 1 Sketch of a compliant wall with restricted surface mobility, illustrating the principle proposed to ensure positively correlated surface motion $u_W v_W > 0$.

$u_w v_w > 0$ is added by means of a suitably constructed wall, one can hope that, in first order approximation, the viscous wall shear stress remains unchanged and thus the total wall shear stress is reduced to $\tau_w = \tau_o - \rho u_w v_w$ (where the index w denotes compliant wall).

From these considerations our aim was to construct a compliant wall with nonisotropic elastic response to wall pressure and wall shear stress fluctuations, such that an outward motion of any surface element is automatically combined with a streamwise motion and vice versa. Fig. 1 shows a possible nonhomogeneous realisation of this concept. By virtue of the non slip condition, this wall will generate a positively correlated motion in the near wall region of the boundary layer.

The same result could also be achieved by means of a suitable homogeneous material with nonisotropic elastic response. And enhanced efficiency may be expected from walls whose elements are moved by external forces, e.g. by electromagnetic forces (active wall).

Experimental tests

The conception presented in Fig. 1 can be materialized in a comparatively simple way by utilisation of pliable stalks or blades instead of swivel arms and springs, thus combining the function of two construction elements in only one. Based on this concept several compliant walls have been constructed, all parts of which, including the top membrane were cast from soft silicone rubber (Abformmasse produced by Wacker Chemie,

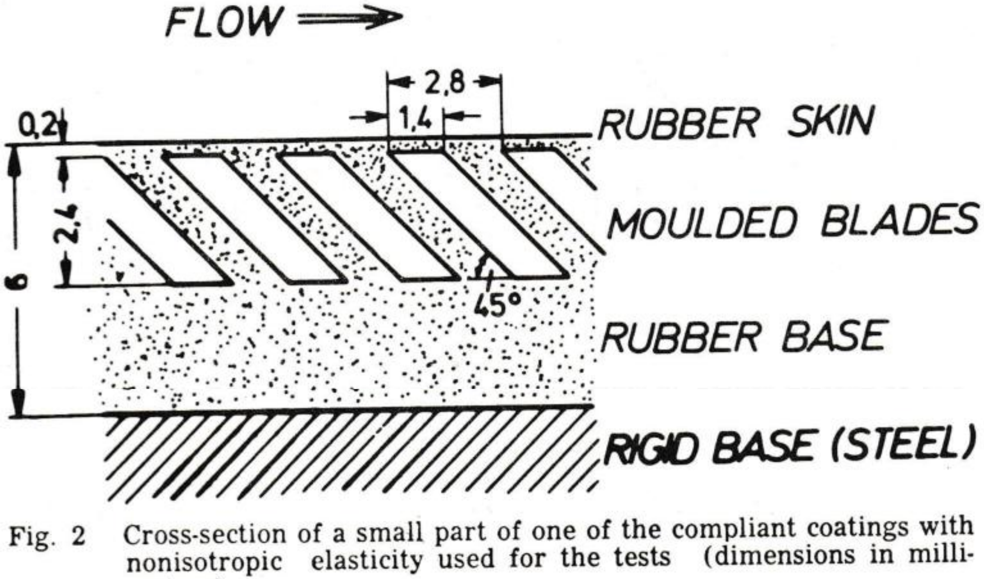

Fig. 2 Cross-section of a small part of one of the compliant coatings with nonisotropic elasticity used for the tests (dimensions in millimeters).

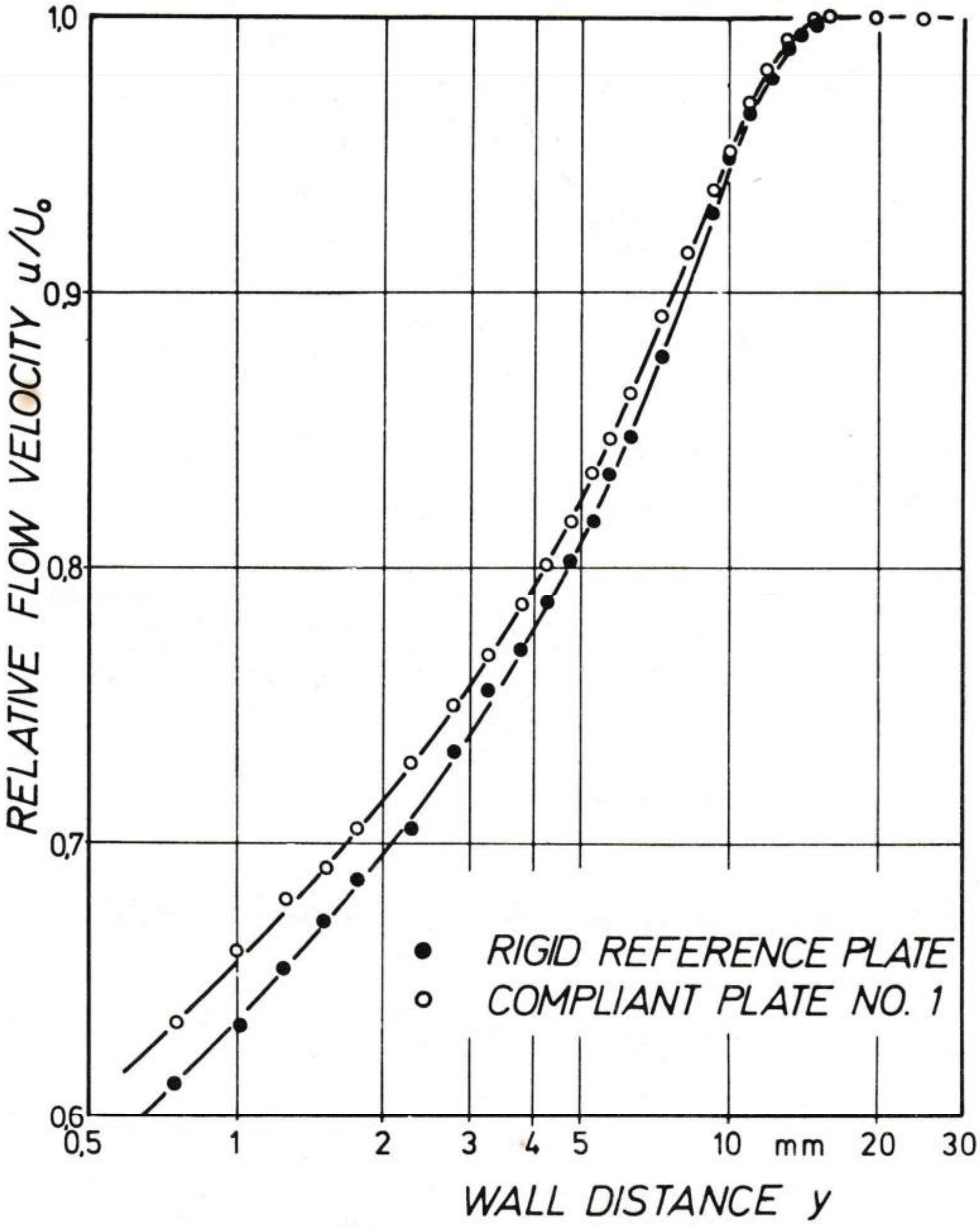

Fig. 3 Normalized velocity profiles of the flow over a compliant plate and over a rigid reference plate (U_o = 163 cm/sec, measuring position x = 68.8 cm, temperature 23°C pressure gradient $dp/dx \approx 0$, Reynolds number $\rho x U_o/\eta = 1.2 \cdot 10^6$).

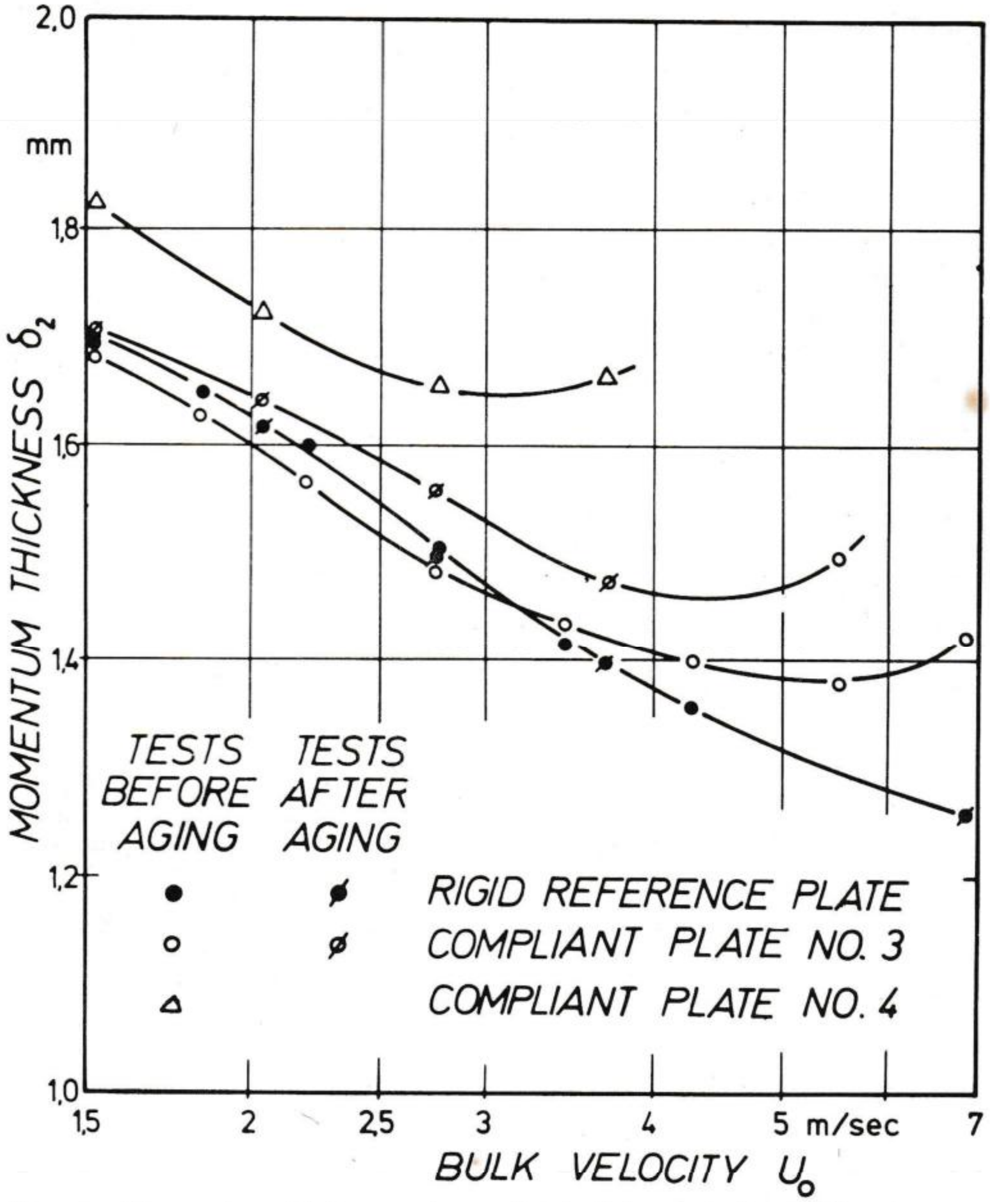

Fig. 4 Momentum thickness of compliant plates and of a rigid reference plate as calculated from velocity profiles The decrease in momentum thickness obtained with fresh compliant plates is lost after 6 weeks of aging of the silicon rubber. ($x = 68.8$ cm, $T = 23°C$, $dp/dx \simeq 0$, $1.1 \cdot 10^6 < \rho x U_0 / \eta < 5.2 \cdot 10^6$).

München). Fig. 2 shows a sketch with some typical dimensions. Rubber sheets (65 cm x 21 cm) of this structure were carefully mounted in strong metal frames. The resulting smooth flat plates were equipped with a device allowing a continuous adjustment of the inside air pressure to the outside pressure. They were then, together with a rigid reference plate of the same outer dimensions, tested in a water tunnel with adjustable pressure gradient.

By means of hot-wire anemometry it was carefully checked that the transition from laminar to turbulent flow occurred in all cases at the beginning of the metal frame of the plates in a small region of adverse pressure gradient. To compare the flow over the compliant and rigid plates, velocity profiles were measured using a Pitot tube of 1.3 mm inner diameter (about a tenth of the boundary layer thickness at measuring position). An example of such velocity profiles is given in Fig. 3. The profile measured at the reference plate is in agreement with a profile calculated from standard formulas (Hinze 1965 p. 480). The profile obtained from the compliant plate is different in shape, and the momentum thickness calculated from it is about 5% smaller than that of the rigid plate. In the case of zero pressure gradient this is equivalent to a 5% reduction in the total drag upstream of the measuring position (see appendix). This effect is believed to be genuine, although the same wall produced a somewhat reduced effect, when it was tested again half a year later. Further polymerisation of the silicone rubber and small amounts of water which found their way into the ducts within the rubber coating may be responsible for this change.

Later investigations of plates with slightly modified flexible coatings were more detailed. The results, however, which are represented in Fig. 4, were less encouraging. Again a strong aging effect was observed. One of the tested plates (Plate No. 4) which had an extremely thin top membrane (0.1 mm), even showed an increase of the total upstream drag by 7%. This can be attributed to the fact that since the top membrane was so ductile, it produced a wavy hydrodynamically rough surface. It is believed that also the favourable results obtained with less delicate coatings suffered to a certain extent from a similarly caused surface roughness.

Discussion

The experiments show that the compliant coatings tested here can lead to a decrease as well as to an increase in momentum thickness and thus to a decrease or an increase of drag. From this it is concluded that the proposed concept is basically valid, but in certain cases the favourable effect is compensated or overcompensated by adverse effects which are also caused by the compliant coatings. The adverse effects are understandable because the tested coatings had a few serious drawbacks : (i) The elastic qualities changed with aging (compare Fig. 4). (ii) The coatings used were fairly rigid with respect to high-wavenumber fluctuations. This has been confirmed experimentally (Grosskreutz 1971) for one of the tested plates by means of a very sensitive Schlieren-optic (Viering & Meier 1972) and is probably due to the fact that small-scale elastic deformations are controlled mainly by the elasticity of the top membrane, and not by the elastic blades (compare Fig. 2). (iii) The tested plates had a tendency to form hydraulically rough surfaces, especially when the top membrane was very thin (plate No. 4). It is hoped that further development of the coatings, e.g. the use of homogeneous nonisotropic materials, combined with a more detailed knowledge of the turbulence generation mechanism can lead to successful application of the proposed concept.

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Appendix : Derivation of basic formulas

1. The production rate of turbulent energy in boundary layers along flat plates can be found by working out the turbulent energy density in a given volume element at the beginning and at the end of a short time interval dt. At the beginning it is

$$\frac{1}{2}\,\rho\,(u-U)^2 + \frac{1}{2}\,\rho\,v^2$$

(the average normal velocity V being zero). After the time dt. the same volume element has — due to its normal velocity v — moved into a layer of different mean stream velocity U + dU/dy v dt. Consequently its turbulent energy density is now

$$\tfrac{1}{2}\,\rho\,(u-U-dU/dy\cdot v\cdot dt)^2 + \tfrac{1}{2}\,\rho\,v^2.$$

and therefore has increased by

$$-\,\rho(u-U)v\cdot dU/dy\cdot dt.$$

Thus, in time average, the production rate of turbulent energy is given by

$$-\,\rho\overline{uv}\cdot dU/dy$$

since Uv = Uv = 0.

2. The shear stress due to turbulent motion can be found by calculating the time rate at which momentum density ρu is transported through a fictitious plane parallel to the wall by action of the normal velocity v. This time rate is ρuv and — according to Newton's 2nd law — equal and opposite to the shear stress, which, in time average, therefore turns out to be $-\rho\overline{uv}$

3. Also the relationship between total upstream drag $D = \int \tau_0\, dx$ and momentum thickness $\delta_2 = U_0^{-2} \int U\,(U_0-U)dy$ at a position x is a consequence of Newton's 2nd law. For its derivation one has to find the net rate of momentum loss in a rectangular volume enclosing the whole of the boundary layer from the leading edge down to position x. The flat plate is chosen as the base of this volume; its height may be called h.

The mass and the momentum entering the volume per time at the leading edge are

$\rho\int U_0 dy$ and $\rho\int U_0^2 dy$ respectively.

Similarly the mass and momentum leaving at x are

$\rho\int U\, dy$ and $\rho\int U^2 dy$ respectively.

Neither mass nor momentum can leave through the bottom formed by the plate. Due to continuity, however, mass, and therefore also momentum, must be leaving through the top. The mass leaving is just the difference between influx at the leading edge and outflux at x and therefore

$$\rho\int(U_0 - U)\, dv\cdot$$

Its velocity is the main stream velocity U and therefore it is carrying a momentum

$$\rho\int(U_0 - U)U_0\, dy.$$

The total loss of momentum per time in the boundary layer is therefore

$$\rho\int(U_o - U)U_o\,dy + \rho\int U^2\,dy - \rho\int U_o^2\,dy = -\rho\int U(U_o - U)\,dy = -\rho U_o^2\,\delta_2$$

Thus total upstream drag and momentum thickness are proportional:

$$D = \rho U_o^2\,\delta_2.$$