Defence Science Journal, Vol. 55, No. 1, January 2005, pp. 37-42

REVIEW PAPER

Compliant Materials for Drag Reduction of High-speed Submerged Bodies

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ABSTRACT

This paper briefly discusses the possibility of employing the compliant materials on underwater bodies for the drag reduction. Recent studies in the area of hydrobionics all-over the world have drawn the attention of hydrodynamicists for using the compliant materials on underwater body surfaces, similar to that found in fast aquatic animals like dolphins, towards achieving drag reduction and increased speeds of underwater vehicles and weapons[1]. Some basic principles of hydrobionics in drag reduction have been presented with special emphasis on the control of turbulent boundary layer characteristics of flow over the compliant material surfaces and induce delay in transition. Various researchers have estimated that the use of such compliant material surfaces can lead to an overall drag reduction of the order of 10-12 per cent over drag of the rigid surface. This is a considerable drag reduction and should arouse keen interest among the underwater weapon and vehicle designers as the next stage of technological advancement in underwater hydrodynamic technology.

Keywords: Compliant materials, drag reduction, hydrobionics, turbulent boundary layer, skin friction drag, compliant walls, underwater bodies, torpedoes, submarines, turbulence suppression mechanisms, drag

1. INTRODUCTION

So little is known about the nature of turbulent boundary layers and so much benefit would accrue to aviation from a reduction in turbulent skin friction, that all avenues for its reduction should be thoroughly examined. The scenario today is not different from that in 1964 when Schairer[1] made this observation with regard to the knowledge of the nature of turbulent boundary layers. A recent study[2] reports that a 20 per cent drag reduction in commercial aircraft can lead to an annual savings of $1 billion in the US alone. Similarly, for underwater bodies, such as torpedoes and submarines, a 20 per cent drag reduction can lead to an increase in the speed to 6.8 per cent. Although modest, these savings can be of vital importance in military applications. The drag reduction of underwater bodies, such as torpedoes and submarines is especially relevant for naval application and it strongly influences the hydrodynamic design of such vehicles. In normal operating conditions, these bodies have predominantly skin friction drag, and therefore, any amount of frictional drag reduction that can be achieved, especially using turbulence suppression mechanisms, would be of great value and can lead to significant increase in speed, endurance, payload, and stealth of the vehicles.

Revised 01 April 2004

2. DRAG REDUCTION & HYDROBIONICS

The total drag of the underwater bodies can be divided into two categories: (i) skin friction drag, which is the integral sum of all the tangential, streamwise forces due to shear stresses on the surface of the body and (ii) pressure drag, which is the integral sum of the forces due to the pressure distribution on the surface of the bodies. The drag reduction would involve reducing one or both of these components.

Recently, hydrodynamicists have begun paying attention to the drag reduction phenomenon exhibited by hydrobionts, such as dolphins and other fast aquatic animals, and to the possibility of adapting such techniques for the man-made underwater bodies. Interest in the hydrodynamics of hydrobionts came to the limelight with the publication of Gray's book[3], "Animal Locomotion", in 1961. It then became known that the energy level of dolphins is incompatible to the swimming speeds attained by them. Later in 1966, Hertel[4] identified technical applications of hydrodynamic principles. However, it is only in the recent times that more efforts are being put in the research leading to the application of hydrodynamic principles for drag reduction of high speed underwater bodies.

The most commonly studied hydrobionts are the cetaceans, and among them, especially the dolphins. This is especially so because of the extremely high speeds attained by them in comparison to the power available at their disposal. The energy studies of the cetaceans have shown that these creatures have similar comparative energy levels as the Olympic athletes, land animals, such as horses, etc. This makes their very high swimming speeds an extraordinary achievement. The hydrobionts generally have three speeds of operation. Slow speeds at which they can coast along for long periods of time, cruise speeds at which they can travel for 20-30 min, and high speeds at which they can travel for a few seconds. While the low speeds are well in line with the energy levels their body can generate, the cruise and high speeds are not. Babenko[5] has described some of the principles of drag reduction of hydrobionts.

The laminarised airfoil sections used for airplane wings have up to 90 per cent laminar boundary layer, leading to minimum frictional drag, minimum boundary layer thickness, and minimum wake behind the aerofoil. Almost all hydrobionts have similar body geometry as these airfoil sections and are the bodies of revolution. The fins and tails of these cetaceans also correspond to the best airfoils[5]. However, the drag reduction afforded by this laminarised shape does not account for the high-speed levels exhibited by the cetaceans. The skins of the cetaceans are enriched with nerve endings, which actively sense the turbulent pressure fluctuations and the vortical perturbations within the boundary layer and readjust the pressure field by active movement of the derma, which promotes relaminarisation of the boundary layer. The cetaceans are also able to adjust the propulsion mechanism, such as the movement of fins, tail, and body according to the flow around the body, and thereby achieve maximum propulsive efficiency.

The skin covers of the cetaceans are compliant by nature in the sense that these are able to adapt to the external hydrodynamic fluctuations. The hydrodynamic study of boundary layers over the compliant skin has reported that during active swimming, the turbulent fluctuations of velocity are much smaller than those over the rigid bodies. However, this is not the case for the slow-speed locomotion. The transition from laminar to turbulent in the case of compliant surfaces occurs at a much higher Reynolds number when compared to the rigid surfaces.

3. COMPLIANT SURFACE

Extensive and unbiased studies about hydrobionics[5] have shown that the active mechanisms have a much greater role to play in the drag reduction of the hydrobionts than the passive mechanisms employed by these. The contribution of the passive mechanism, however, is not insignificant and there is enough scope for adaptation of such a mechanism for underwater bodies. The compliant skin over the cetaceans may be likened to a viscoelastic material. The flow over such a surface investigated by Kramer[6], and subsequently by others, show how the integral characteristics of flow over bodies with compliant coatings differ from the flow over the rigid bodies. The drag reduction studies by Gad-el-Hak[7], *et al.* and Bushnell[8], *et al.* have shown that a compliant surface can be used as an effective drag reduction mechanism. The existing experimental and theoretical data indicate that up to 10-12 per cent drag reduction can be achieved using compliant surfaces.

Physically, the compliant wall is nothing but a flexible surface affixed on to a rigid body. The complaint wall acts in such a way so as to dampen the instabilities existing within the turbulent boundary layer, and thus delaying transition. There are evidences[9] to show that compliant walls also help in suppressing turbulence in a turbulent boundary layer. Rubber like materials have been used in the past to study the wall interference with the boundary layer vortical mechanisms and instability mechanisms.

3.1 Causes for Drag Reduction

The drag reduction on the compliant surfaces is understood to be the outcome of two phenomena, viz, delay in transition, and the interaction of the turbulent boundary layer with the compliant surface. The latter, however, is not a well-understood phenomenon and researchers are actively investigating the response characteristics of the interaction between the turbulent boundary layer and the compliant surface as well as the instability modes leading to transition from laminar to turbulent flow. However, some qualitative features of the flow have emerged from the past research in this area.

A detailed description of the mechanisms of transition in flow over compliant walls is presented by Carpenter[10]. The transition from laminar to turbulent flow takes place through the instabilities in the flow. The Tollmein-Schlichting (T-S) waves, which are flow-based instabilities, play a major role in the flow over rigid flat plates. Although it is modified by compliance, essentially its characteristics remain unchanged. The T-S waves are attenuated by transfer of energy to the compliant wall. The travelling-wave flutter is a flow-induced surface instability caused by the travelling waves in the viscoelastic medium caused by flow-induced hydrodynamic forces. The response of this instability to energy transfer is opposite to that of the T-S waves, in the sense that the higher flexibility leads to earlier transition due to the travelling-wave flutter. Divergence is also a flow-induced surface instability but it is static in nature, ie, it does not propagate on the surface. This instability can be compared to the buckling of a strut, as it is caused when the restorative forces of the surface are exceeded by the hydrodynamic forces induced due to disturbances generated in the flow.

3.1.1 *Transitional Mode*

Sometimes, the T-S waves and the travelling-wave flutter instabilities coalesce to form a powerful instability referred to as transitional mode. This instability has the characteristics of both the flow-based and the flow-induced surface instabilities.

3.2 Interaction between Turbulent Boundary Layer & Compliant Wall

The interaction of the turbulent boundary layer with the compliant wall is still not so clearly understood. Researchers are at work to identify the mechanism of these interactions. Rozumnuik[11], *et al.* reported the development of a numerical code based on a Reynolds stress-transfer model and some qualitative results have been presented in this study. The laminar sub-layer thickness is found to have increased. The turbulent energy maximum, which is shifted away from the compliant wall, is about 20 per cent less in the boundary layer over a compliant surface than on a rigid surface. In the near-wall region, the shear stresses are less and these approach maximum values much more smoothly than on a rigid surface. The dissipation velocity is less in the near-wall region than on a rigid surface. The production of normal component of Reynolds stress tensor is found to decrease. There is an observed deceleration of the boundary layer thickness growth. All these factors lead to an increased degeneration of turbulence, and lesser frictional drag on a compliant surface.

4. MATERIAL PROPERTIES OF COMPLIANT WALLS

In the past, many experimental studies have been carried out with the compliant walls, some of which have been shown[10,12] in Fig.1. Conceptually,

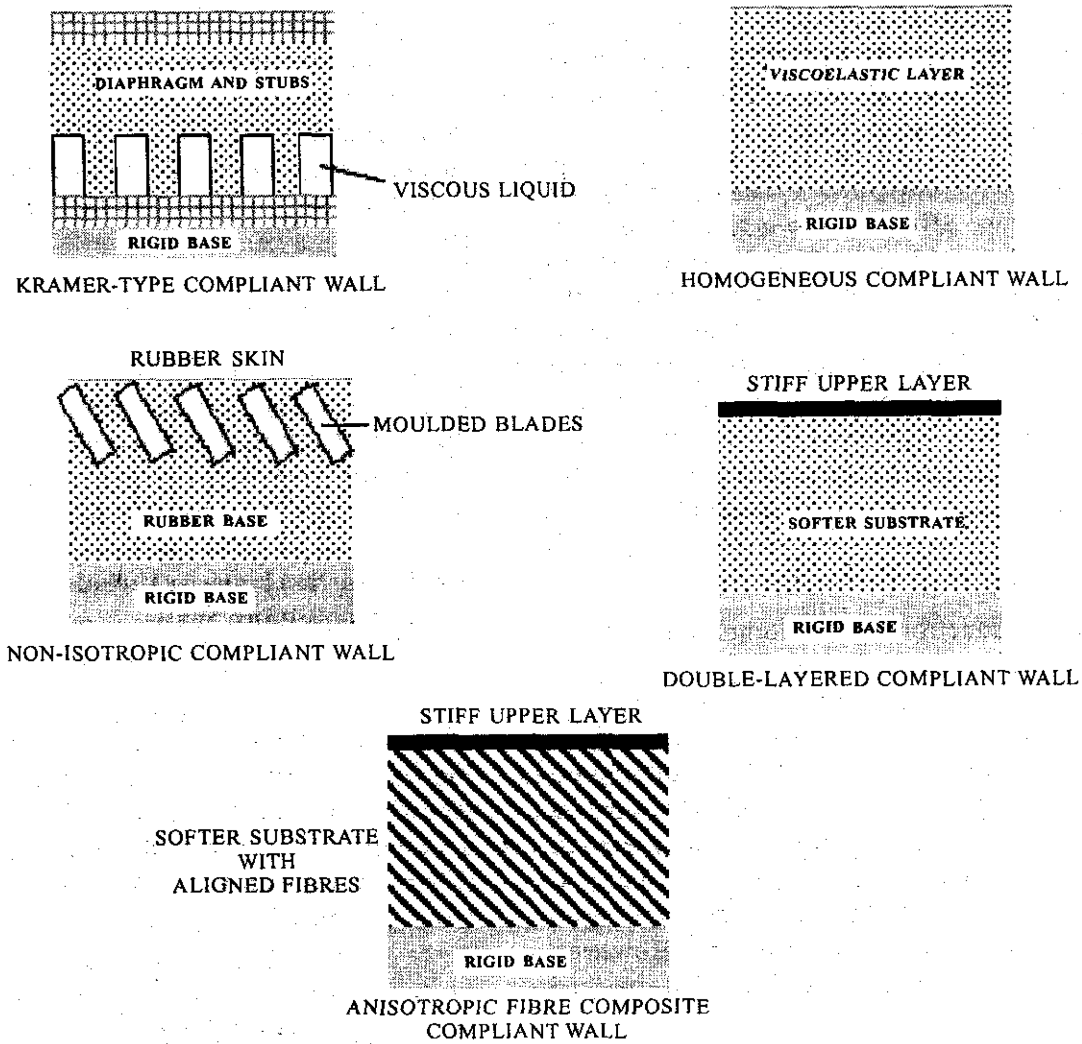

Figure 1. Different types of compliant walls

the simplest compliant surface is a homogenous viscoelastic layer. This has been extensively studied by Hansen[13], *et al.* and Gad-el-Hak[7], *et al.* Most often, soft silicone rubbers have been used as the compliant materials. However, later researchers had found that the soft silicone rubber was too delicate and so they covered it with a thin layer of harder latex rubber. It was later found that this arrangement also improved the performance of the compliant wall. Gaster[14] has suggested that the main dynamic effect of the protective covering is to restrict the horizontal motion of the compliant wall. In general, compliant surfaces are the network polymers in a rubbery state.

5. CONCLUSION & FUTURE RESEARCH

It has been concluded that the use of compliant walls on underwater bodies is a viable mean of drag reduction. As the technology is in its burgeoning stages and of military value, not much technological expertise would be available from the external sources. Development of this technology indigenously would provide a definite fighting edge in the deep waters. A brief review of the research work in this area, as it stands today, has been presented. Indigenous development of the compliant materials would involve a dedicated research activity. The work would involve a detailed study of the drag reduction mechanisms and optimisation of material properties of the compliant walls by computational and experimental hydrodynamics experts. The manufacturing and testing methods for the compliant materials would have to be devised by the material scientists. It is expected that a minimum of 12 per cent drag reduction can be achieved using this technology.

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