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EXPERIMENTAL INVESTIGATION OF DRAG REDUCING MECHANISM OF COMPLIANT COATING WITH OPTIMAL VISCOELASTIC PROPERTIES

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ABSTRACT

In this study, a wind tunnel experiment has been performed to investigate the effect of the dynamic viscoelastic properties of a silicone RTV rubber on the drag reducing efficiency in turbulent boundary layer. A specially designed flat plate was mounted vertically over the center line in the wind tunnel of the Pusan National University. The plate is 2 m long, 0.8 m high and 8 cm thick. The measurements were performed in velocity range from 15 to 30 m/s. Removable insertions of 0.55x0.25m2 size were mounted in the trailing part of the plate. The following set of the insertions was designed and manufactured: metal standard with polished surface and coated with a compliant material of different thickness. The compliant coatings were manufactured of a silicone rubber Silastic® S2 (Dow Corning Inc.). To modify the viscoelastic properties of the rubber, its composition was varied: 90% of the rubber + 10% catalyst (standard), 92.5% + 7.5% (weak), 85% + 15% (strong). Modulus of elasticity, the loss tangent and Poisson's ratio were measured in detail for these materials in the frequency range from 40 Hz to 3 KHz using the proposed innovative technique. The skin friction drag was measured by the strain balances mounted in the trailing part of the plate over removable insertions. The development of velocity profiles measured at all four surfaces under study are found to be self-similar. The strong compliant coating achieved 5% drag reduction within a velocity range 20~40 m/s.

INTRODUCTION

Experimental verification of drag reduction by compliant coatings is a long-standing actual problem. After Kramer's report on a significant (~60%) drag reduction (Kramer 1957) no experiment was able to repeat the result. A review of these tries is given in (Bushnell et al. 1977; Gad-el-Hak, 1996), where mostly experiments with "soft" coatings (either a sponge material covered by a thin film or a gel-like substances) are analyzed. In the experiments the coatings showed only drag increase, while the coating surface experienced λ-shape folds moving with a velocity much smaller than a base flow velocity (Gad-el-Hak et al. 1984). However, certain theoretically substantiated (Carpenter, 1990) success in laminar-turbulent transition delay, rather than turbulent drag reduction, was achieved in experiments with the soft compliant coatings.

For the turbulent drag reduction practically important can be "hard" compliant coating consisting of a viscoelastic layer with relatively large modulus of elasticity ($E > 1$ MPa). Experiments with such coatings of a towing model performed at velocities 10 – 20 m/s in a natural basin (Kulik and Semenov, 1991) showed the drag reduction about 20%. A try to repeat these results in laboratory conditions was undertaken in a cavitation tunnel of Newcastle University (Choi et al. 1997). A drag reduction of about 7% were found. Unfortunately, the experiments were carried out in a different velocity range (1-5 m/s) a long time after the coating manufacturing. The effect of coating aging was studied in Bandyopadhyay et al. (2005).

Kornilov et al. (2004) tested a "hard" compliant coating in a wind tunnel at velocities from 7 to 30 m/s. Despite a significant decrease of intensity of interaction of the coating with the turbulent pressure fluctuations proportional to the density of the fluid, 5% drag reduction was obtained. Positive effect is confirmed by increase of sublayer thickness and corresponding decrease of turbulent velocity pulsations.

The present paper based on detail determination of the coating properties, a prediction of flow velocity range where an intensive interaction of the coating with the flow is expected. Results of experimental investigation of turbulent boundary layer characteristics and comparison of the results with the prediction are given.

COMPLIANT COATING MATERIAL

A silicon rubber Silastic S-2 (Dow Corning) was used to manufacture the coatings. This is a low-molecular polydimethylsiloxan with the structural formula [-O-Si(CH3)2-] which looks like a very viscous liquid (μ= 90 Poise). The standard composition consists of 90% of the main material and 10% of catalyst (standard). To modify the viscoelastic properties the amount of the catalyst was increased to 12.5% (strong composition) and reduced to 7.5% (weak composition). The mixture was poured to a cylinder with a plunger served for injecting it into the moulds. As depicted in Fig. 1, the coating mixture (2) was poured in the mould (3), with internal sizes 550×250×3 mm^3. The prepared mixture through a pipe (6) is poured until the material penetrated through the channels (5) reaches the middle of the dilators (4). This prevents formation of cavities inside the coating at the material contraction during its polymerization. To provide a sufficient adhesion the mould surface was washed by a special solution 24 hours before the coating manufacturing. A film was placed between the base plate (1) and the removable insert (2) to provide the smoothness of the outer coating surface and simplify the coating removing.

The compliant coating and the samples to measure the viscoelastic properties were prepared from the same mixture. Figure 2 shows frequency dependence of the modulus of elasticity and the loss tangent for three compounds under study measured 15 days after their manufacturing.

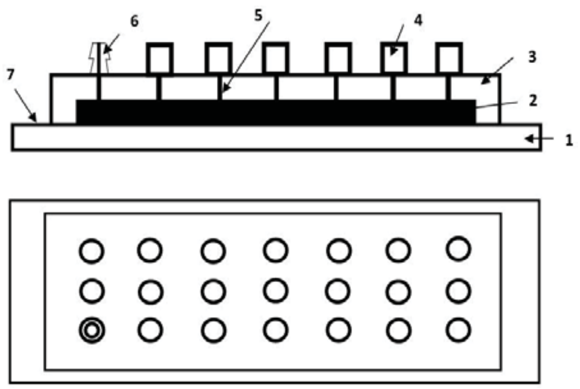

Fig. 1: The mould to prepare the compliant coating.

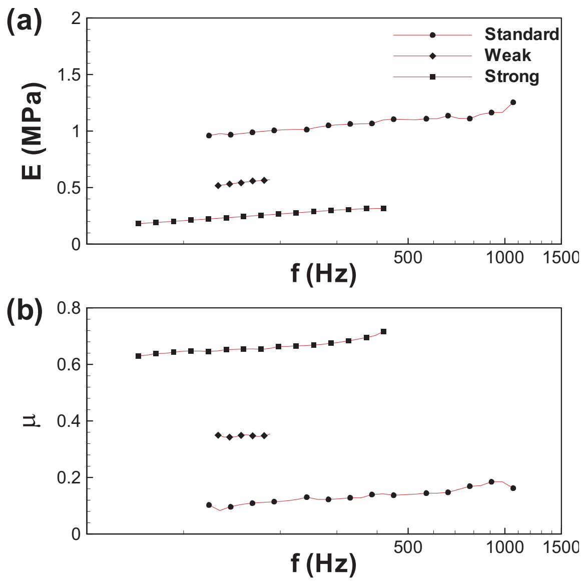

Fig. 2: Modulus of elasticity (a) and the loss tangent (b) vs. frequency. ▲ – "standard"; • - "weak"; + - "strong" compositions.

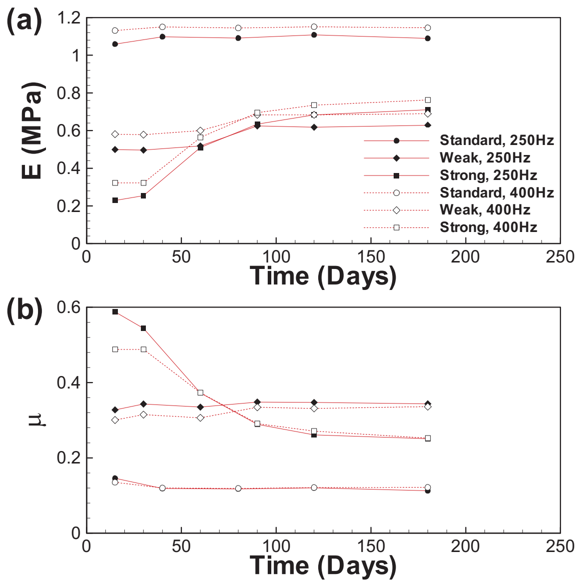

Fig. 3: Changing of the modulus of elasticity (a) and loss tangent (b) with time.

The standard composition has the properties dependent on time only slightly. With the proportion of the resin and the catalyst (90:10) recommended by manufacturer has the largest modulus of elasticity and the smallest loss tangent. The viscoelastic properties slow down their variations and become stable with time. Viscoelastic properties of the weak composition are more stable and more differs from the standard composition in the initial period of aging; hence this variant seems most promising.

The response of the compliant coating to an external forcing was studied in (Duncan et al. 1985; Kulik et al.

2005). Deformation amplitude of the "hard" compliant coating surface is less than the thickness of the laminar sublayer (Kulik et al. 2005), hence, the coating is always hydraulically smooth. However, in the frequency range of the coating and flow interaction (in the vicinity of the resonant frequency of the coating) the speed of its movement is comparable with the turbulent velocity pulsations near the wall.

According to the Semenov's interference theory (Semenov) the wall movement changes the generation of the Reynolds stresses in the boundary layer above the coating

$$\tau = \rho\left\langle (u_{flow} + u'_{coat})(v_{flow} + v'_{coat}) \right\rangle \quad (1)$$

where u_{flow}, v_{flow} are undisturbed velocity pulsations of the flow along and normal to the wall; u'_{coat}, v'_{coat} are the disturbances introduced by the compliant coating in corresponding velocity components. The value and the sign of the changes in the Reynolds stresses depend both on the amplitude of the introduced velocity disturbances and the phase shift between them. To produce the drag reduction Semenov (1996) based on the model of viscous sublayer (Sternberg, 1962) and one-dimensional model of the coating deformation derived the condition for choosing the resonant frequency f_0 of the coating

$$6.3\times10^{-3} \le f_0 \nu / u_\tau^2 \le 1.9\times10^{-2} \quad (2)$$

The intensity of interaction is the largest when the frequency of interaction is equal to the resonant frequency of the coating. In the case of a running pressure wave an additional condition of the interaction optimality consisted in equality of the convective velocity of pressure pulsation transport and the velocity of propagation of disturbances in the compliant coating was obtained in (Kulik et al. 2005), i.e.

$$V = U_C = 0.7 \sim 0.9U \quad (3)$$

According to two-dimensional model of deformation of viscoelastic covering (Kulik et al. 2008), the resonance frequency is determined by the formula

$$f_0 = (0.357 + 0.312\sigma) C_t / H \quad (4)$$

where $C_t = \sqrt{E/2\rho(1+\sigma)}$ is the velocity of propagation of the shear deformations.

Hence, the essential condition to obtain a positive effect (the drag reduction) is the condition of the optimal interaction of the covering with the flow, namely

- temporal factor : Eq. (2)
- spatial factor : Eq. (3).

The conditions are essential, rather than sufficient for the drag reduction. In a series of studies (Amphilokhiev et al. 2000) a large influence of the level of flow turbulence on the drag reduction was pointed out. Probably, this is related to the requirement that the pressure pulsations of the turbulent flow should have certain coherence (Kulik et al. 2005). Otherwise the compliant coating has no time to react to the applied forcing and the surface deformation will be negligible.

Table 1 contains the results of calculations of the flow velocity at which the optimal interaction of the coating with the flow and the drag reduction are expected. It is supposed also the aging of the cylindrical samples and the plane coating is the same, i.e. the aging is independent on the shape and the size of a sample. Therefore, the modules of elasticity obtained at the corresponding resonant frequencies and the following parameters equal for all coatings under study, $\rho=1.13\times10^3$ kg/m^3, H=3 mm, σ =0.3 were taken.

Table 1: Expected effective flow velocities.

Material	*E*, MPa	C_t, m/s	f_0, kHz	Spatial factor	Temporal factor
Standard	1.15	19.41	3.02	30.0 ~ 38.6	38.8 ~ 71.6
Weak	0.6	14.02	2.18	21.8 ~ 28.0	32.5 ~ 60.0
Strong	0.3	9.94	1.54	15.4 ~ 19.8	26.8 ~ 49.4

As seen, no surface satisfies completely to the requirements, i.e. there is no region of intersection of the velocity ranges. For the "weak" coating, at 25 m/s the wavelength of the coating deformation at its resonant frequency coincides with the convective length of the pressure pulsations at this frequency. Hence, the covering interacts optimally with the flow, but the frequency of the pressure pulsations is out of the frequency range where the drag reduction is expected. However, the coating produced from the Standard mixture is more promising. With this covering a drag reduction at the flow velocity at the upper bound of the spatial factor and at the lower bound of the temporal factor is possible.

In order for the region of intersection to appear, the following is necessary:

I. To raise the bounds of the regions determined by the spatial factor. Meanwhile, $U \sim 1.8\sqrt{E/2\rho(1+\sigma)}$ is independent of the thickness and hence it is necessary to enlarge the modulus of elasticity or to reduce the density.

II. To lower the bounds of the regions determined by the temporal factor. This variant is actual for use of hot-wire anemometry to measure velocity in the sublayer. For the condition $2.95 < C_t/(U^{1.8}H) < 8.9$, hence the coating thickness should be enlarged.

EXPERIMENTAL SETUP

The experiments were performed in a closed type wind tunnel of Aerospace Department of Pusan National University. The tunnel test section is 2 m long with 0.7×0.7 m^2 cross section. A flat plate was mounted vertically in the central part of the test section. The plate is 80 mm thick, consists of 4 parts as shown in Fig. 4.

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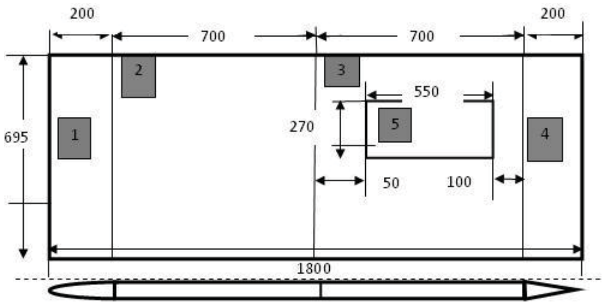

Fig. 4: Flat plate insert; 1 : leading edge, 2 & 3 : interchangeable parts, 4 : trailing edge flap, 5 : insert mounted on a strain-gage balance.

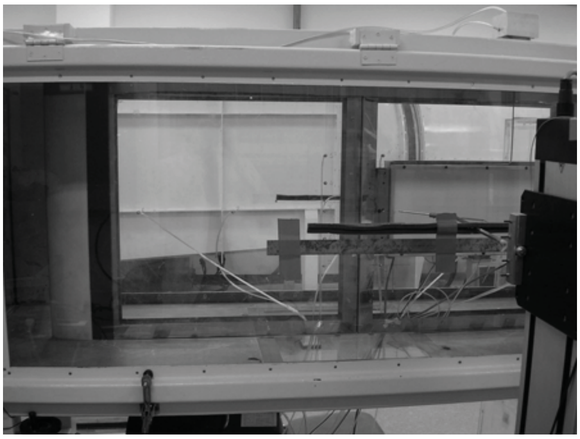

Fig. 5: Photograph of the experimental facility.

The leading edge is elliptic with the axis ratio 3:1. The trailing edge flap could be elevated to adjust pressure gradient at the leading edge and along the plate. The first and the second square sections are interchangeable. A strain-gage balance was placed inside the second section, which was served to mount the insert with the compliant coating. Either a compliant coating or a metal insert with polished surface was flush mounted with the plate surface with 0.2 to 0.5 mm clearance at the insert perimeter.

In the vicinity of the coating upstream and downstream of it sensors of pressure pulsations Endevco 8507C-1 with outer diameter 2 mm were mounted. A three-component vibration sensor Endevco 35A was mounted on a metal frame of the strain-gage balance. The sensor components were aligned with the Cartesian axes: x along the flow, y normal to the plate, and z normal to (x,y)-plane. This sensor was connected to a four channel deltatron conditioning amplifier (Brüel & Kjær Type 2693A). Static pressure distribution was measured by a multiple-tube inclined differential manometer. Mean and fluctuating streamwise velocity components were obtained with Dantec constant-temperature hot-wire anemometer using standard miniature I-type probe. The probe was calibrated against a Pitot-static tube in free stream.

All signals were digitized by NI PCI-6035E A/D converter and logged into hard disc. A PC controlled standard Dantec Dynamics traversing mechanism which allowed positioning of the hot-wire with 0.05 mm accuracy. The setup is shown in Fig. 5.

The measurements of the boundary layer characteristics over the compliant surface were performed mostly in 5 downstream positions at velocities 8, 15 and 24 m/s and in some cases at 60 m/s. The turbulence trip was installed by attaching a sand paper strip (45mm×690mm) downstream the leading edge. Changing the trailing edge flap was used to provide zero pressure drops just upstream and downstream the insert.

EXPERIMENTAL RESULTS

Figure 6 shows that, with both, the standard and weak coatings, the drag reduction increased slightly while it decreased with strong coating by 4% at flow speed from 20 to 40 m/s.

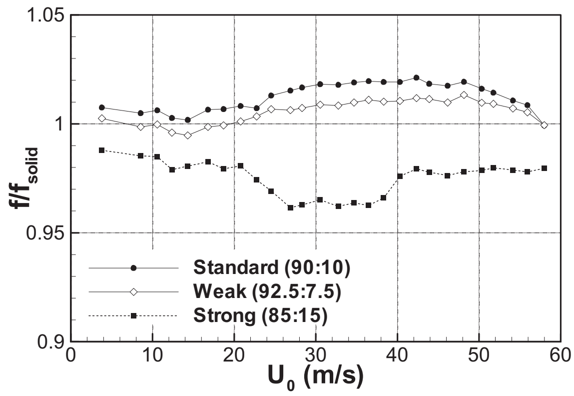

Fig. 6: The drag reduction efficiency with respect to freestream velocity.

Figure 7 shows the development of velocity profiles over the “strong” coating in respect to that at the solid wall. It is seen that the profiles at the solid wall are almost self-similar. However, certain changes of the logarithmic part of the profiles over the compliant coating at U=25 m/s indicate modifications of the local skin friction. In this case pronounced changes can also be observed in the viscous sublayer (more exactly at y+<100). Meanwhile, at U=8 m/s the profiles measured at all four surfaces under study (i.e. three compliant and one solid walls) are self-similar that indicate that the observed variations at U=25 m/s cannot be attributed to an experimental error.

CONCLUSIONS

Three compositions of a silicon rubber (Silastic S-2/Catalyst) compliant coatings (90:10, 87.5:12.5 and 92.5:7.5) were tested in a wind tunnel by placing them on a flat plate mounted in the test section. The skin friction drag were measured by using Strain balances which were mounted in the trailing part of the plate over removable insertions. To determine the viscoelastic properties and calculations, two series of measurements of samples manufactured from the same mixture and at same time are performed. The development of velocity profiles measured at all four surfaces under study are self-similar. The strong compliant coating achieved 5% drag reduction within a velocity range 20~40 m/s while standard and weak coatings increased drag reduction.

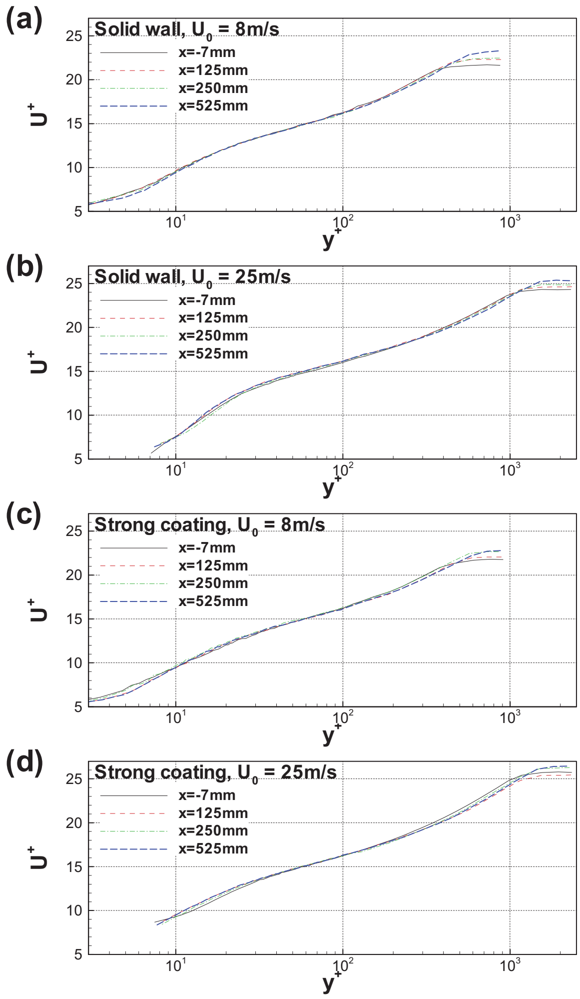

Fig. 7: Non-dimensional velocity profiles for the solid wall (a, b) and for "strong" coating (c, d). U = 8 m/s (a, c), U = 25 m/s (b, d).

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