Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: O O Ivanov *et al* 2017 *J. Phys.: Conf. Ser.* **894** 012036

IOP Conf. Series: Journal of Physics: Conf. Series **894** (2017) 012036 doi:10.1088/1742-6596/894/1/012036

The influence of compliant coatings on skin friction in the turbulent boundary layer

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Abstract. The results of an experimental study of the effect of single-layer monolithic compliant coatings on friction in a turbulent boundary layer are presented. The techniques of manufacturing the coating and measuring their properties are described. A special test model (a section of a wing section of an infinite span) to be used in experiment was designed. The model has four replaceable plates: the solid (metal) plates and panels with compliant coatings 4,6,8,and 10 mm thick can be installed. The direct measurements of the total drag of the model and the local skin friction obtained by the Clauser chart method showed consistent results: drag increased up to 6.5% and 4%, respectively. The relationship between the results and theoretical predictions is discussed.

1. Introduction

The problem of drag reduction of bodies moving in fluids is one of the most important and practically significant in aerohydrodynamics. The use of compliant coatings in liquids is one of the most promising ways to reduce friction, turbulent noise, and to delay the laminar-turbulent transition passively (without additional energy supply).

The idea of drag reduction by compliant coatings was first proposed and studied by M.O. Kramer [1–4]. He obtained experimentally a significant reduction in resistance when using special coatings on a towed body similar to the skin of a dolphin. Followers observed both positive and negative results in the sense of the drag reduction with the Kramer-type or self-made coatings. Details of the studies on compliant coatings can be found in the thorough reviews [5,6,7]. In a large number of experiments, where "soft" coatings (with a porous or gel-like filler covered by a thin film) were used, the λ-shaped folds increased the drag. However, it is difficult to compare and generalize the results as in the majority of the studies the properties of coatings were not measured either at all, or carefully.

A certain success was achieved in experiments with a compliant surface to delay of the laminar-turbulent transition [8] that was also verified theoretically.

For practical use, stiff monolithic coatings are the most promising. The study [9] of such coatings conducted at speed of 10–20 m/s with at owed model in an open reservoir showed a drag reduction up to 20%. An attempt to repeat these results in laboratory conditions was undertaken in a cavitation tunnel of the University of Newcastle at speeds of 1-7 m/s [10]. In these experiments, the coatings of study [9] were used. The drag reduction up to 7% was obtained, as well as a decrease of the level of pressure pulsations at the wall, the longitudinal velocity pulsations, and the turbulence intensity.

The recent appearance of reliable technique for measuring the dynamic viscoelastic properties of coatings over a wide range of frequencies [11, 12], stimulates new studies of compliant coatings. Now it is possible to attribute quantitatively the properties of the coating with its effectiveness in drag reduction or the laminar-turbulent transition delay.

2. Experimental Setup

The experiments were conducted in the water tunnel of Institute of Mechanics, Lomonosov Moscow State University. The operating speed range was 5–16 m/s, the level of turbulence of water tunnel was ~0.2%, the static pressure was maintained at the same level during all runs. For the study, a special model with four replaceable plates (Fig. 1) was designed. The model has a shape of section of an infinite-span symmetric wing. The length of the model is 1190 mm, width is 100 mm, height is 117 mm. Test plates have dimensions of 300 x 20 x 117 mm (LxWxH). The model was installed in a two-dimensional test section of water tunnel with dimensions of 2000 x 1000 x 120 mm. The geometry of the model was optimized by numerical simulations in ANSYS CFX to minimize the pressure gradient along the test plates of the model. The velocity field distribution along the model for the operating speed 20m/s is shown in Fig. 2.

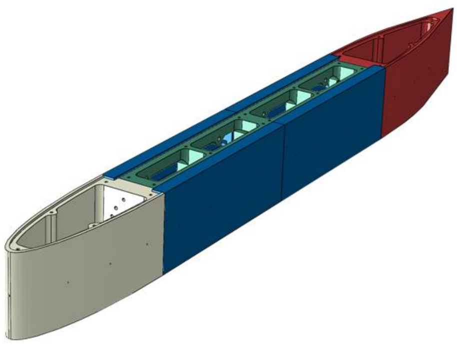

Figure 1. The test model. The leading section is grey, test panels are blue, the trailing section is red.

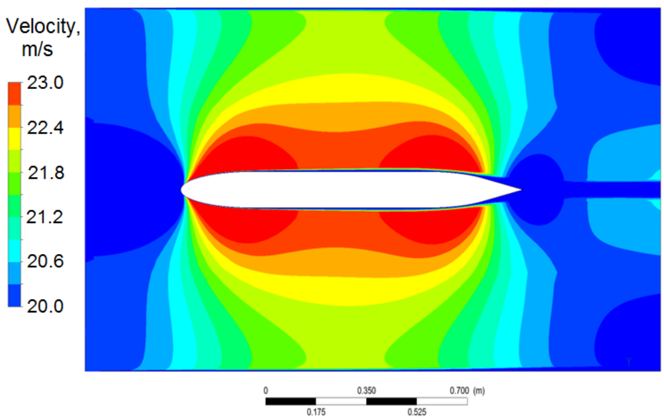

Figure 2. The velocity distribution around the test model at 20 m/s.

The measurements were conducted in two stages. In the first stage, the total drag of the model was measured using one-component drag balance. To determine the contribution of friction force over the test plates into the total drag, a numerical simulation of the flow, including settling chamber, nozzle, operating section, and a part of diffuser was conducted, and this contribution was found to be nearly 20%for the velocities of 5–25 m/s. Therefore, a change in the skin friction on the plates of 5% will result in about 1% corresponding change in the total drag.

In the second stage, the longitudinal mean velocity profiles of the turbulent boundary layer over second test plate were measured by laser Doppler anemometer (LDA). From these profiles, the local skin friction coefficients were determined using the modified Clauser method [13]. The tripping wire with a diameter of 1 mm was mounted on the leading section of the model at the distance of 29 mm from the leading edge to obtain downstream a fully developed turbulent boundary layer. Measurements were conducted at the positions x = 629, 729, 829 mm downstream of the leading edge.

IOP Conf. Series: Journal of Physics: Conf. Series **894** (2017) 012036 doi:10.1088/1742-6596/894/1/012036

3. Coating manufacturing and measurement of their properties.

Viscoelastic coatings were produced from silicone rubber Mold Max 10 (Smooth-On firm), by polymerizing at room temperature and normal pressure with added catalyst. Before mixing the components, it was degassed during 2 hours in an extruder with the under pressure of –0.85 atm. The resulting mixture was then mixed during 10 minutes in a low-speed mixer to exclude appearance of gas bubbles. Two compliant coatings and samples for measuring the viscoelastic properties were produced simultaneously of the mixture. A special mould (Fig. 3) was used to manufacture compliant coatings and to avoid air bubble formation during mixture pouring and shrinkage.

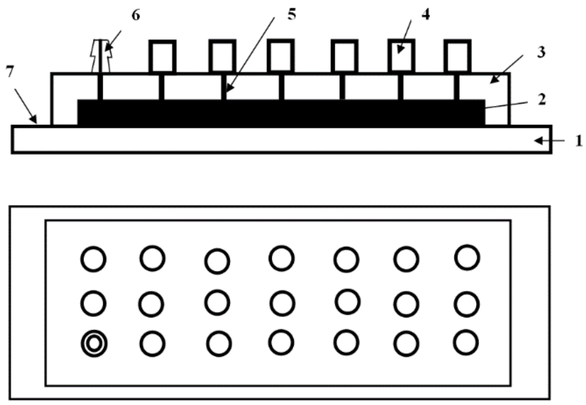

Figure 3. The scheme of the mould for coating manufacturing: flat base (1), compliant layer (2), test plate body (3), anti-shrinkage channels (4) and cylinders (5), fitting (6), film (7).

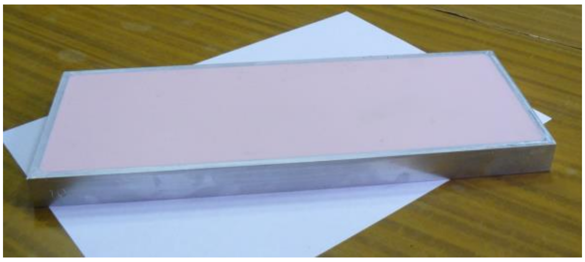

Figure 4. The test plate with compliant layer.

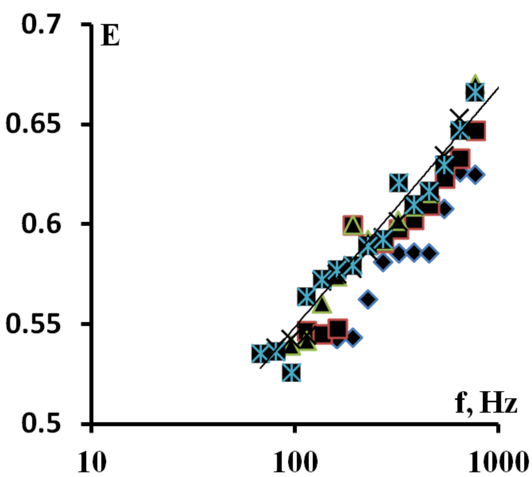

Figure 5. Relation between dynamic modulus of elasticity of Mold Max 10 and load frequency.

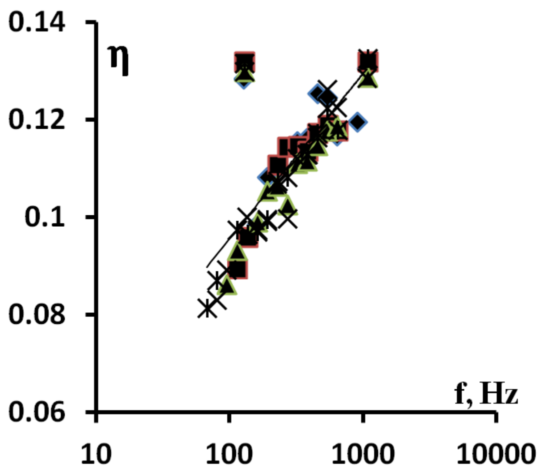

Figure 6. Relation between loss tangent of viscoelastic material and load frequency.

The method for measuring viscoelastic properties of the coatings is described in detail in [12,13]. After the measurements, the following dependencies the dynamic modulus of elasticity and the loss tangent versus oscillation frequency of deformation were obtained (see also Figs. 5 and 6). The dynamic modulus of elasticity (MPa) $E = 0.0521\, ln(f) + 0.3087$, the loss tangent $\eta = 0.017\, ln(f) + 0.0141$.

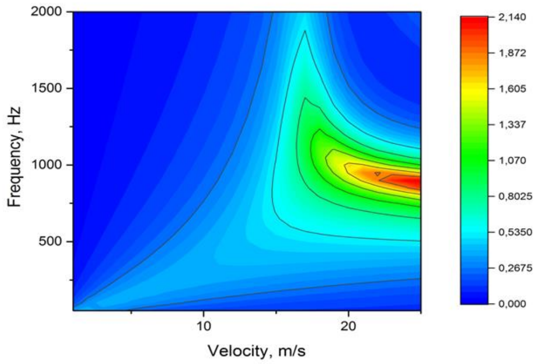

Figure 7. Non-dimensional normal component of compliance vs. pressure fluctuation frequency and flow velocity (8 mm coating).

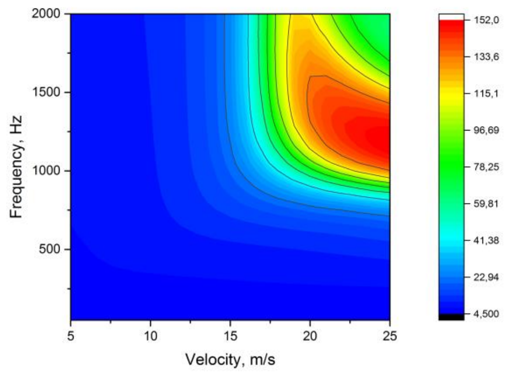

Figure 8. Variation of the phase angle (in degrees) of compliance versus pressure fluctuation frequency and flow velocity (8 mm coating).

4. Prediction of drag reduction

The response of the compliant coating to an actual level of external pressure was theoretically investigated in [14]. The amplitude of deformation of the surface of “stiff” compliant coatings is less than the thickness of the viscous sublayer [14] so that the coating always remains hydraulically smooth. However, in a region of coating–flow interaction frequencies (in the vicinity of the resonance frequency of the coating), the velocity of its surface motion is comparable with the turbulent velocity fluctuations near the wall.

For the current coatings, the complex compliance (the ratio of the strain deformation of a coating surface to the applied pressure) and the phase angle on the stream velocity and the pulsation frequency were obtained as functions of flow velocity and pressure fluctuation frequency. A compliant coating will effectively interact with coherent structures of turbulent flow only at those speeds and frequencies where its compliance is maximum. In all other regions of parameters, it will only slightly differ from the solid wall. Analyzing Figs. 6 and 7, two scenarios of interaction can be distinguished:

– broadband, when the flow velocity coincides with the elongated crest, and the compliance does not reach a maximum, passing along the low-speed slope of the peak (flow velocity 10–20 m/s);
– resonant, at higher frequencies (flow velocity >20 m/s).

5. Results and discussion

5.1. Measurements of the total drag

In the experiments conducted 5–6 months after the viscoelastic coatings manufacturing, the total drag of the model was measured. Experiments with metal and coated plates conducted at the speeds of 7–15 m/s, the Reynolds number based on the model length is equal to $(7.3-15.7)\times 10^6$. The coefficients of total drag $C_x = F / \rho V_\infty^2 S$ (*S* is the area of the midsection of the model) vs. the speed of incoming flow are compared for the solid wall (empty squares) and the compliant coating (filled markers) in Fig. 8.

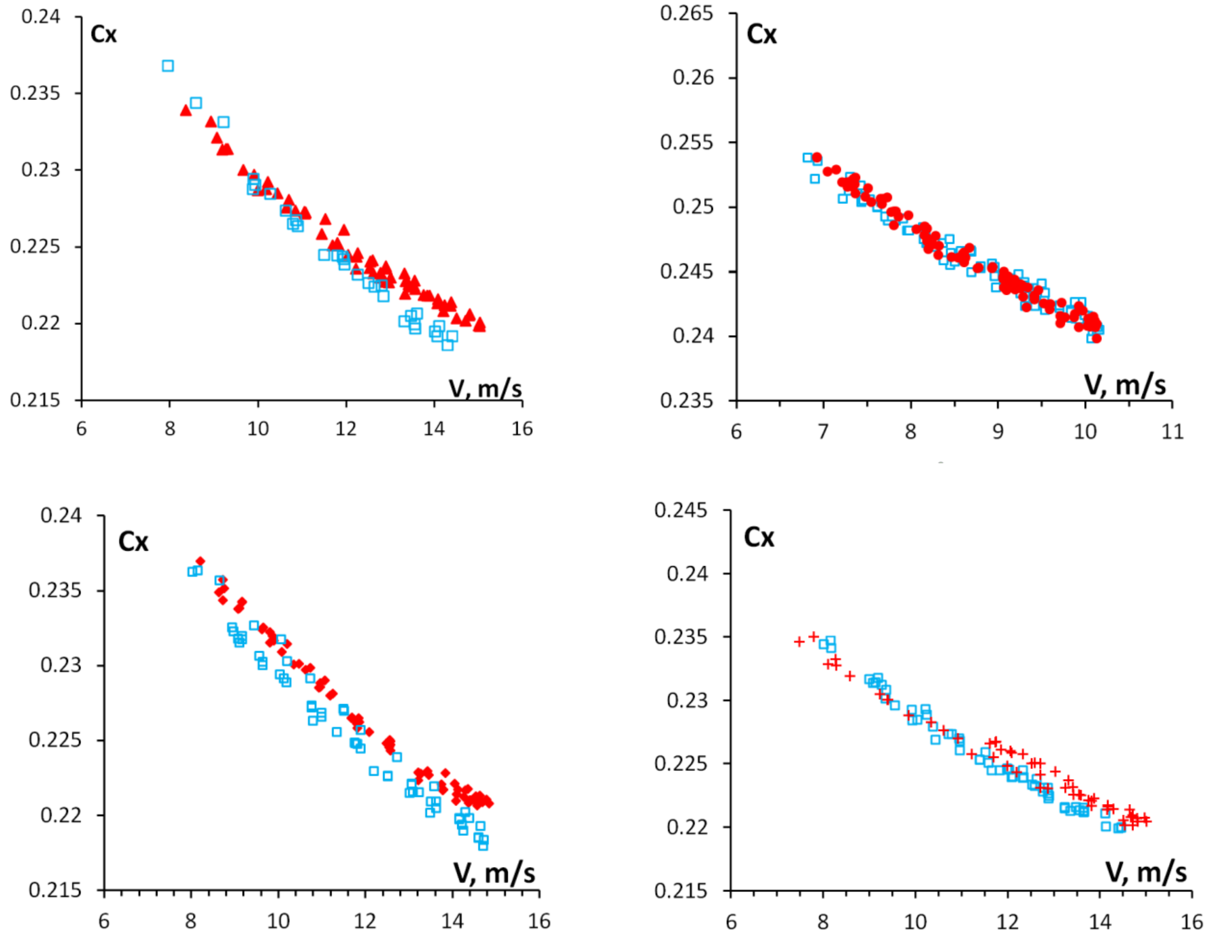

Figure 9. Total drag coefficient versus flow velocity. From top left to bottom right:4 mm (triangles), 6 mm (circles), 8 mm (diamonds), 10 mm (crosses).

The compliant coatings increase the total drag coefficient at the end of the operating speed range. On average, the difference between the coefficients for the solid wall and coatings is 0.001–0.0025, which in relative terms is 0.4–1.3%. In terms of the change in friction, drag over coatings increases up to 2–6.5%. For the 6-mm coating, the model was installed at a small angle of attack, so that the absolute values of C_x are greater than those for other thicknesses.

5.2. Local skin friction measurements

The second stage was conducted 12–15 months after the manufacture of the coatings. To find the local friction, the modified Clauser chart method [13] was used; namely, the error between the Musker profile [16] and the experimental points was minimized (Fig. 9).

The local skin friction coefficients vs. momentum thickness Reynolds number $Re_2 = V_\infty \theta / \nu$ are shown in Fig.10. The lower solid line corresponds to relation $\Sigma_x = 0.0256 \cdot Re_2^{-0.25}$ [15], the upper solid line is $\sum_x = 0.0131 \cdot Re_2^{-1/6}$ [15]. As seen, in this series of tests the coatings also increase the drag up to 4%.

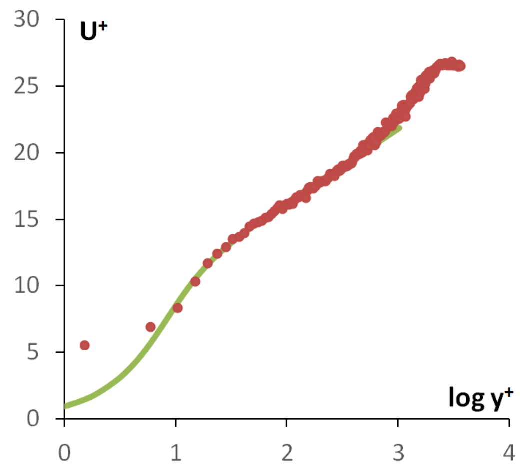

Figure 10. The example of turbulent boundary layer velocity profile in law of the wall scale. Solid line is the Musker profile [16].

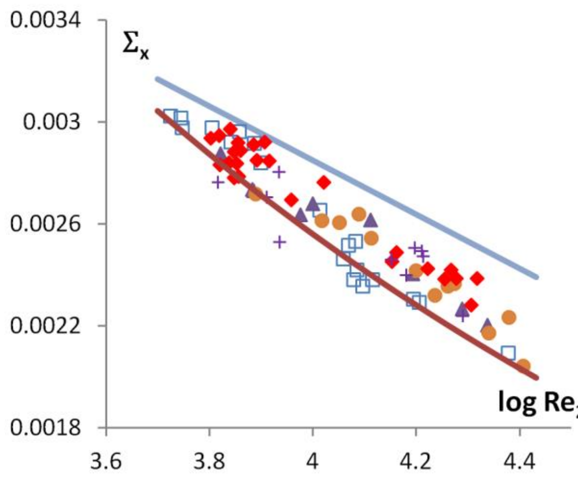

Figure 11. Local skin friction coefficient vs. the momentum thickness Reynolds number. The upper and lower lines are the empirical relations [15].

Note that the results of measurements at the first and second stages are in satisfactory agreement with each other. The theory predicts the maximum interaction region after 15 m/s (17.5 m/sis the peak of the wide-frequency-band interaction). The total drag coefficients of the model with coatings start to differ from those for metal plates at a speed of ~12 m/s, which also indicates the consistency of the theory and experiment, and the predictive capabilities of this theory.

The disadvantage of the theory [12, 14] is that it can show the region of most intensive interaction between the boundary layer and compliant coating, but cannot answer whether it will yield the drag reduction or drag increase. This is also seen from the results of the present study. Given that there is no reliable theory predicting drag reduction in turbulent flow, experimental methods are still the only (besides DNS) way to study compliant coatings. From this point of view, results of the present research can be considered as the contribution into the database of coating properties and their effect.

6. Conclusions

The results of the laboratory measurements of single-layer coating effect on skin friction in turbulent boundary layer are presented. Two stages of direct and indirect measurements are conducted, and the drag increase up to 6.5% and 4% for two stages, respectively, is obtained. Results are compared with theoretical prediction, and satisfactory agreement is obtained.

References

[1] Kramer M O 1957 *J. Aeronaut. Sci.* **24** 459-60
[2] Kramer M O 1960 *J. Am. Soc. Navel Engrs.* **72** 25-34
[3] Kramer M O 1961 *J. Am. Soc. Navel Engrs.* **73** 103-7
[4] Kramer M O 1962 *J. Am. Soc. Navel Engrs.* **74** 341-8
[5] Bushnell D M, Hefner J N and Ash R L 1977 *Phys. Fluids* **20** S31-S48
[6] Gad-el-Hak M, Blackwelder R F and Rilly J J 1984 *J. Fluid Mech.* **140** 257-80
[7] Gad-el-Hak M 1996 *Appl. Mech. Rev.* **49** S147-60
[8] Carpenter P W 1990 *Viscous drag reduction in boundary layers* Progress in Astronautics and Aeronautics (AIAA) **123** 79-113
[9] Kulik V M, Poguda I S and Semenov B N 1991 *Recent Developments in Turbulence Management* ed Choi K-S (Dordrecht: Kluwer) pp 263-89

[10] Choi K S, Yang X, Clayton B R, Glover E J, Atlar M, Semenov B N and Kulik V M 1997 *Proc. Royal Soc.* A **453** 2229-40
[11] Kulik V M, Semenov B N, Boiko A V, Seoudi B, Chun H H and Lee I 2009 *Exp. Mechanics* **49** 417-25
[12] Kulik V M, Semenov B N, Boiko A V, Seoudi B, Chun H H and Lee I 2010 *Int. J. of Solids and Structures* **45** 374-82
[13] Rodríguez-López E, Bruce P J and Buxton O R 2015 *Exp. Fluids* **56** 68
[14] Kulik V M 2012 *Int. J. Heet Fluid Flow* **33** 232-41
[15] Schlichting H, Gersten K, Krause E and Oertel H 1960 *Boundary-Layer Theory* (New York: McGraw-Hill)
[16] Musker A 1979 *AIAA J* **17** 655-7