THE SKIN-FRICTION DRAG ON FLAT-PLATES COATED WITH FLEXIBLE MATERIAL

TANEDA, Sadatoshi
Research Institute for Applied Mechanics, Kyushu University

HONJI, Hiroyuki
Research Institute for Applied Mechanics, Kyushu University

https://doi.org/10.5109/7165080

出版情報：Reports of Research Institute for Applied Mechanics. 15 (49), pp.1-15, 1967. 九州大学応用力学研究所
バージョン：
権利関係：

Reports of Research Institute for Applied Mechanics
Vol. XV, No. 49, 1967

THE SKIN-FRICTION DRAG ON FLAT-PLATES COATED WITH FLEXIBLE MATERIAL

Sadatoshi TANEDA and Hiroyuki HONJI

The effect of a flexible layer on the boundary layer stabilization was investigated by measuring the skin-friction drag on flat-plates with flexible surface at the Reynolds number range from 6×10^5 to 1×10^7. Experiments were carried out by towing the test-plates in a 80 m water tank. Porous synthetic rubber was used as flexible material for the coating of the test-plates. It was found that the drag on the flexible surface plates is approximately equal to the drag on the rigid reference plates.

1. Introduction

It can be considered that the flexible surface of under-water bodies influences the turbulence of the boundary layer and consequently changes the magnitude of skin friction drag acting on the bodies. In this paper the results of experimental investigations on these influences are reported, and preliminary discussions on the results are given.

Original contributions to this problem was recently made by Krämer[1]. He reported that the bodies coated with a specially designed rubber with oil-filled interspaces have a considerably smaller skin-friction drag than smooth rigid bodies of the same shape. The possibilities of practical applications and the theoretical interests in the problem have aroused many investigations in various places. On the theoretical side, Benjamin[2], Landahl[3] and others tried to analyze the effects of the flexible boundary on the basis of the linearized stability theory. However, the experimental results obtained by Krämer were not sufficiently explained. For a better understanding of the problem, it seems that the extensive and detailed experimental investigation is necessary.

The models tested by Krämer in his experiments had a three dimensionality. If there really exist the effects of flexible walls, the simpler shape of the model will rather facilitate the analysis of experimental results. According to this consideration flat-plates with the flexible surface were tested in the present experiments.

2. Experimental arrangements and the models tested.

In order to investigate the influence of flexible coatings on the transition from laminar to turbulent flow (EXP. 1) and on the fully developed turbulent boundary layer (EXP. 2), two series of experiments were carried out. The models tested in EXP. 1 and EXP. 2 are the flat-plates coated with the porous synthetic rubber which is commercially available. The experiments were carried out in the 80 m×8 m×3 m water tank at the Tsuyazaki Laboratory for Sea Disaster of Research Institute for Applied Mechanics. It was possible to vary the towing speed of the carrier continuously up to a maximum of 3 m/s.

The mechanical properties of flexible material are generally classified into various kinds of the deformation such as elastic, plastic and viscous flow deformation. The influence of these deformations of the flexible layer on the turbulence of the boundary layer becomes to be essential in the present problem. The pressure vs elastic deformation curve for the porous rubber used in this experiments is shown in Figure 1. The measurement of the deformation was made under

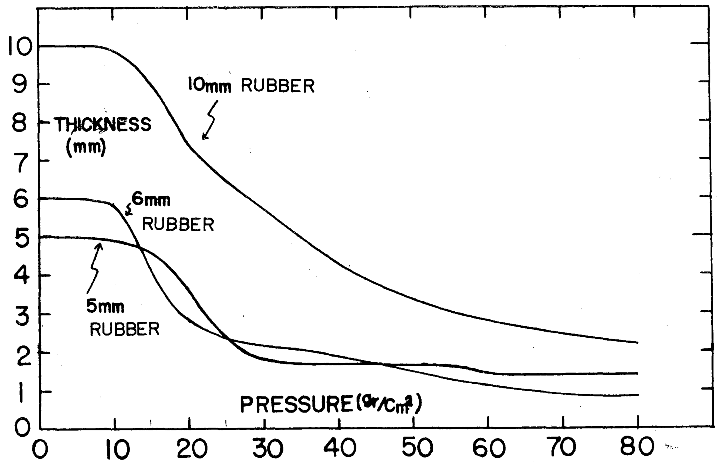

Fig. 1. Pressure vs deformation curve for various porous rubbers.

the condition that the rubber plate was not covered with vinyl sheet. It will be seen from this curve that the elastic deformation of the porous rubber obeys Hooke's law only in the low pressure range. When the pressure exceeds about 10 g/cm², the shape of the curve becomes very complicated. In the experiment, however, as the pressure acting on the rubber is considered to be small, only the straight portion of the curve may be concerned in the present problem.

In the models of the first test series (EXP. 1), the porous rubbers both soaked with water and dried were used for the flexible coating of the test-plates. The flexible medium of the former models was therefore the porous rubber and water, and that of the latter models was the porous rubber and air. In the experiment of the second test series (EXP. 2), only the rubber soaked with water was used.

i) Apparatus and method in EXP. 1.

Skin-friction coefficients were measured directly by the use of a spring balance

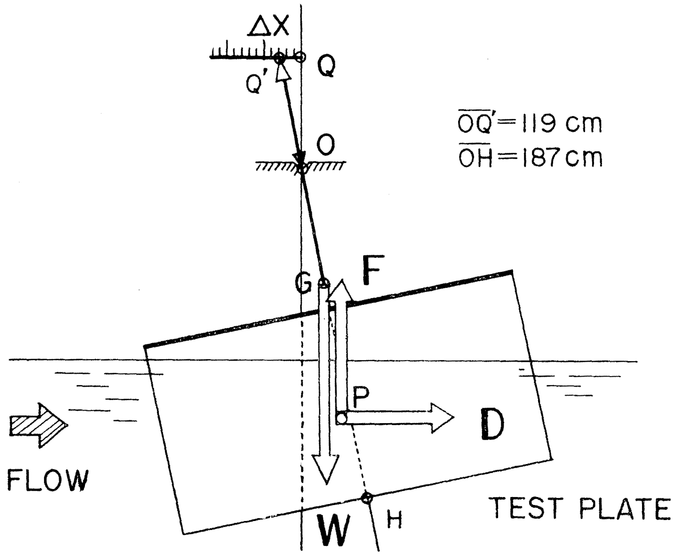

Fig. 2. Diagram for the measurement of skin-friction drag in EXP. 1.

system. The schematic diagram of the method of measurements in EXP. 1 is shown in Figure 2. A test-plate was fixed to a support, which was hung in the water tank as a pendulum by means of points and cups. The force W is the total weight of the support and the test-plate. The forces F and D are the buoyacy and the skin-friction drag on the under-water part of the system respectively. The point G is the point of action of the force F, and the point Q the position of a indicator of Δx.

On the approximation that the angle of inclination is sufficiently small, namely the point P is on the extension line of $\overline{OG}$, the skin-friction drag is expressed as

$$D=\{\overline{OG}\cdot W-\overline{OP}\cdot F)/\overline{OP}\cdot\overline{OQ}\}\,\Delta x\,. \tag{1}$$

The forces W, F and geometrical quantities $\overline{OG}$, $\overline{OP}$, and $\overline{OQ}$ are easily determined by the direct measurements. The angle of inclination was kept within 5° in the measurements.

The shape of the support was like that of a cross, and both ends of a horizontally spanned crossbar were supported by the two distant points. The system was set up so that the direction of the horizontal crossbar might be exactly rectangular to the direction of the flow. Photo. 1 and Photo. 2 show the apparatus and the test-plate in towing respectively. A lathe-center of an apex angle of 60° was used as the points. K. S. metal plates with a conic hole of 5 mm in depth were used as cups. This points and cups had enough strength to bear the total weight of about 50 kg of the system. As seen in Photo. 1, the test-plate

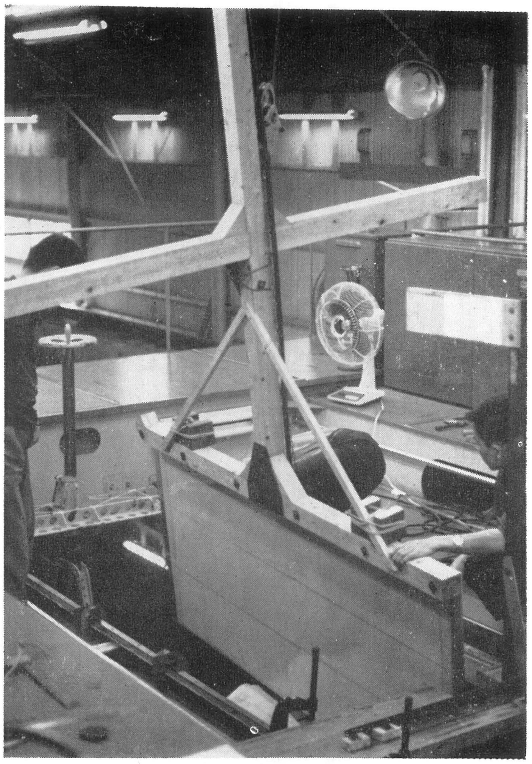

Photo 1. Experimental apparatus in EXP. 1.

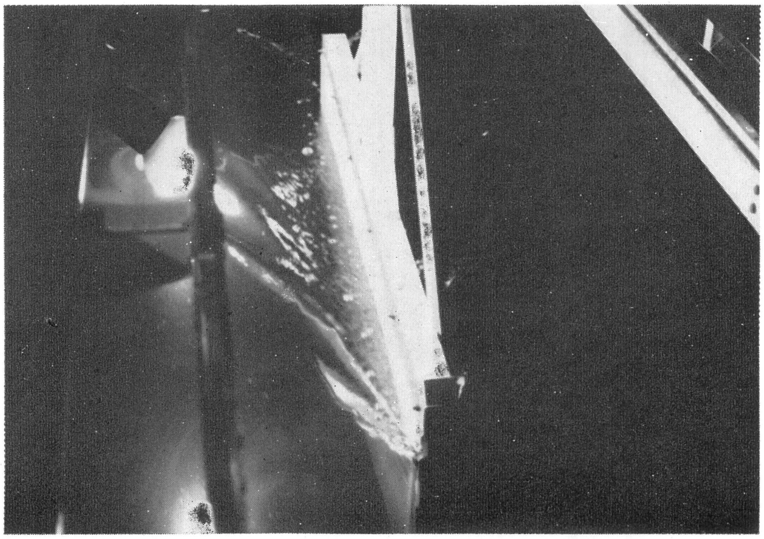

Photo 2. A test-plate in towing in EXP. 1.

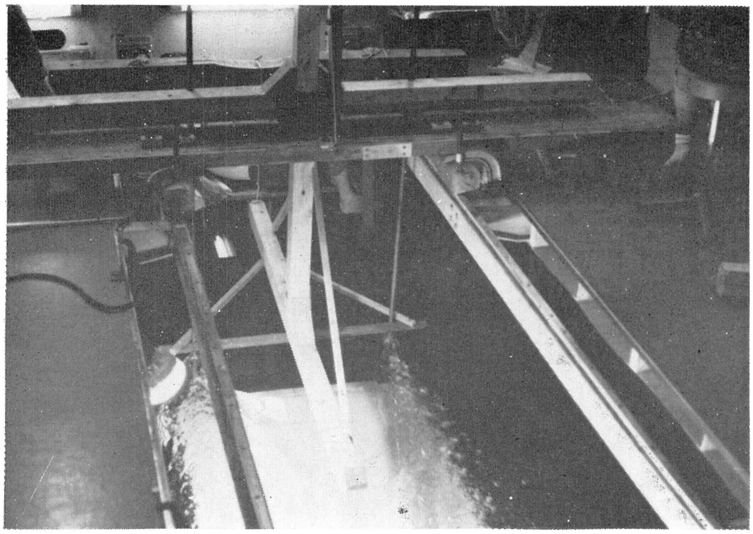

Photo 3. Experimental apparatus in EXP. 2.

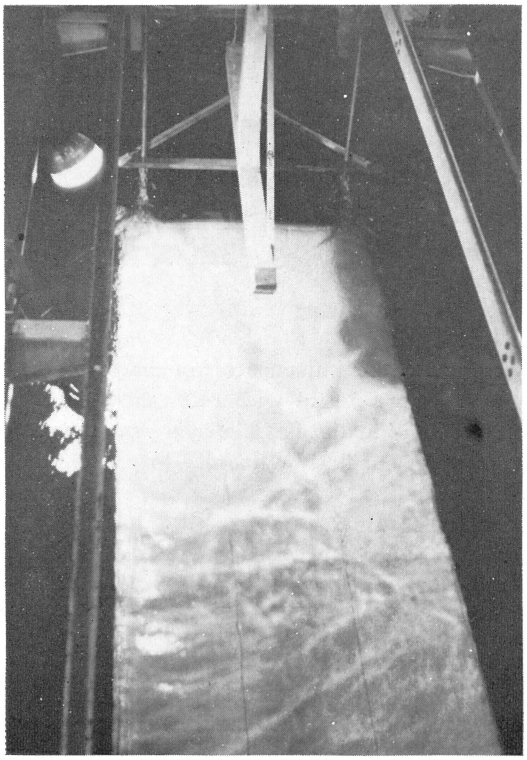

Photo 4. A test-plate in towing in EXP. 2.

was fixed to the another crossbar parallel to the flow so as to be towed without sway. On the other hand, the investigation of turbulence of the boundary layer along the flexible surface were made using a hot-wire anemometer. However, the report on this investigation is not made in this paper.

ii) Construction of the models tested in EXP. 1.

Figure 3 shows the schematic arrangement of the flexible coating of the test-plates. The test-plates were constructed by coating with the flexible synthetic rubber on the surface of the rigid 6 mm × 1 m × 2 m duralmine plates. In order

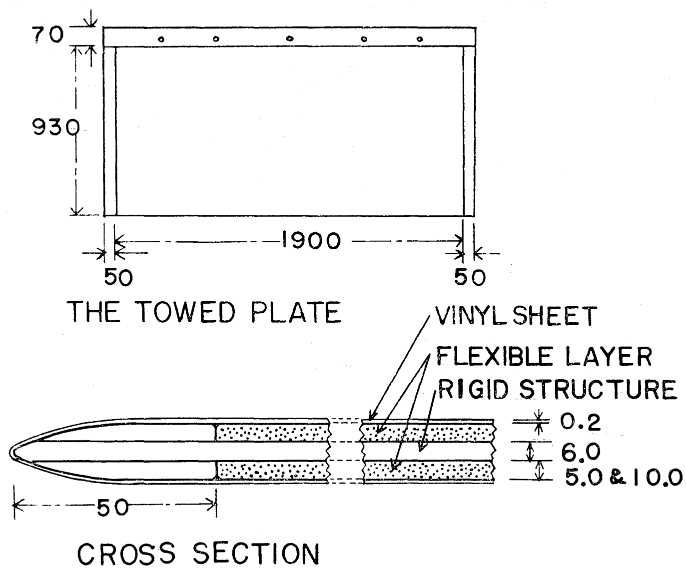

Fig. 3. Construction of the models in EXP. 1.

to eliminate the influence of roughness of the surface, the test-plates except the model *E* were covered with a thin vinyl sheet of a thickness of 0.2 mm. The water confined within the flexible layer was therefore prohibited to be exchanged with the water of the flow. In order to prevent the separation, edges of the testplates were streamlined to sharp edges by fitting the specially designed metal strip as is shown in Figure 3.

In EXP. 1, the following five kinds of model were tested.

Model A: The rigid reference model made of a duralmine plate 6 mm thick, 1 m wide and 2 m long.

Model B: The duralmine plate coated on its walls with the rubber of 5 mm thickness.

Model C: The duralmine plate coated with the rubber of 6 mm thickness.

Model D: The duralmine plate coated with the rubber of 10 mm thickness.

Model E: The duralmine plate coated with the rubber of 6 mm thickness, and both ends of this plate are remained bluff to examine the influence of difference of the shape of models on the skin-friction drag.

Each model has the same square measure of 1 m×2 m. The models B, C and D were covered with the thin vinyl sheet. The models A and E were tested in two cases; when the models were covered with the thin vinyl sheet, and when they were not covered with the vinyl sheet. The synthetic rubber of the models B and D had the same stiffness. The rubber used for the models C and E was a little softer than that of the models B and D. These models were constructed to examine the influence of thickness of the flexible layer as well as its stiffness on the skin friction.

iii) Apparatus and method in EXP. 2.

The method of measurements in EXP. 2 is shown in Figure 4. Although the principle of measurements is the same as that in EXP. 1, the apparatus was partly

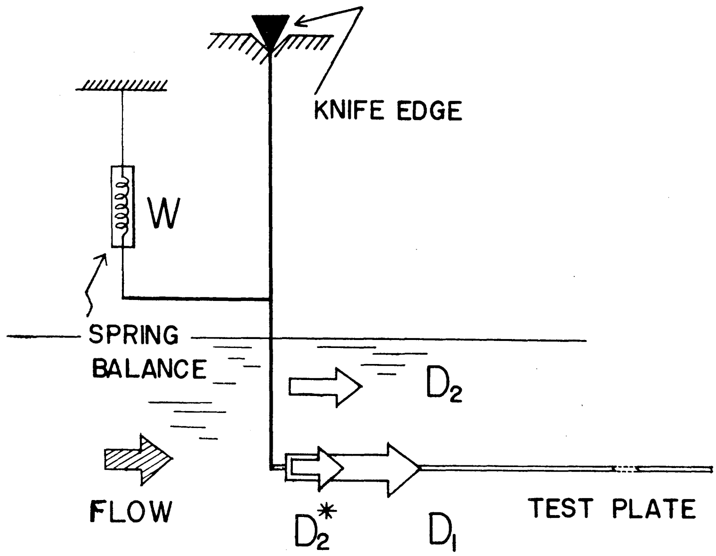

Fig. 4. Diagram for the measurement of skin-friction drag in EXP. 2.

improved so as to use a spring balance (scale of 0.2 kg and full scale of 20 kg). The improvement was made for the following two reasons. First, the length of the test-plates constructed for EXP. 2 was so long (4 m) that the apparatus in EXP. 1 could not be used as it was. Secondly, it was needed to damp the excess force which was caused by the initial acceleration of a towing carriage.

The test-plate was held at the forward edge by two vertical legs 32 cm below the water surface, and allowed to stream out horizontally under the action of the water forces. In Figure 4, the forces D_1 and D_2 are the skin friction acting on the test-plate and the drag on the underwater part of the legs respectively. D_2^* is the converted value of D_2 on the assumpiton that the point of action of D_2 agrees with that of D_1. The value of D_2^* can be easily calculated with D_2 and geometrical dimentions of the support. For convenience, the total friction drag D is introduced as

$$D=D_1+D_2^*. \tag{2}$$

Between D above defined and W, the virtual reading of the spring balance, there exists the relation of

$$D=f(W). \tag{3}$$

The form of f is uniquely determined by the calibration for the actual apparatus. The calibration was made in such a way that the spring balance was read when the towing carriage was brought to rest and the known force was applied to the system. Photo. 3 shows the apparatus used in EXP. 2, and Photo. 4 one of the test-plates in towing. Towing speeds employed in EXP. 2 were varied from 50 cm/s up to 250 cm/s.

iv) Construction of the models tested in EXP. 2.

The structure of the models tested in EXP. 2 is shown in Figure 5. To obtain high Reynolds numbers where the boundary layer is fully turbulent, the test-plates need at least the longitudinal length of 4 m in the present towing speed.

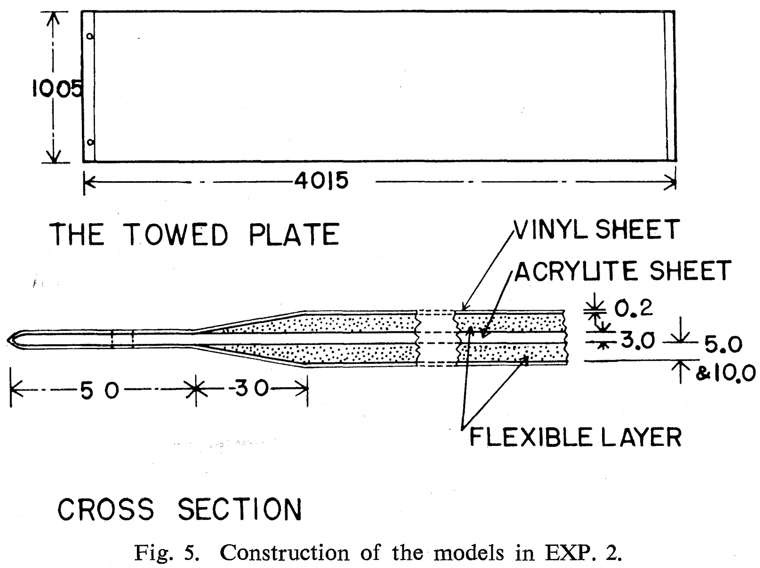

Fig. 5. Construction of the models in EXP. 2.

The maximum Reynolds number obtained by this length of the test-plates was 1×10^7. The rigid reference test-plate used in EXP. 2 was an acrylite plate 3 mm thick, 1 m wide and 4 m long.

The synthetic porous rubber which was used for the model B and D in EXP. 1 was used again as the flexible material. In order to eliminate the influence of roughness of the surface, each test-plate was covered with the vinyl sheet of a thickness of 0.2 mm. In EXP. 2, the following two flexible surface models were tested in addition to the rigid reference model of the single acrylite plate.

Model A: The acrylite plate coated with the synthetic porous rubber of 5 mm thickness. The plate was covered with the thin vinyl sheet.

Model B: The acrylite plate coated with the synthetic porous rubber of 10 mm thickness. The plate was covered with the thin vinyl sheet.

All the coating rubber of test-plates in EXP. 2 was completely soaked with water.

It was impossible to carry out the exact measurements of skin friction when the coating rubber was not soaked with water because of the following two reasons. 1) As the mean specific gravity of the test-plates was much smaller than 1, the rear of the test-plate rose near or above the water surface and the test-plate could not be kept parallel to the flow. 2) The air remained within the porous rubber transfered to the rear of the test-plate and consequently the plate was complicatedly deformed. The drag other than the pure skin friction was therefore fairly increased.

3. Results in EXP. 1.

The drag coefficient C_D is expressed as

$$C_D=D/\rho U^2S, \tag{4}$$

where U is the towing velocity, S the area of one side of the test-plate, and ρ the density of water. In calculation of the Reynolds number, the length of the test-plate is taken as the representative length. Figure 6 shows the drag coefficients of various models in EXP. 1 as a function of Reynolds number for the case that the coating rubber was not soaked with water. The upper curve refers to Schlichting's formula

$$C_D=0.455/(\log_{10}R)^{2.58}, \tag{5}$$

which is valid for fully developed turbulent boundary layer flow. The lower straight line refers to Blasius' formula

$$C_D=1.328\sqrt{R}, \tag{6}$$

which is valid for fully laminar boundary layer flow. Although the drag coefficients obtained experimentally at the Reynolds number range of flow transition

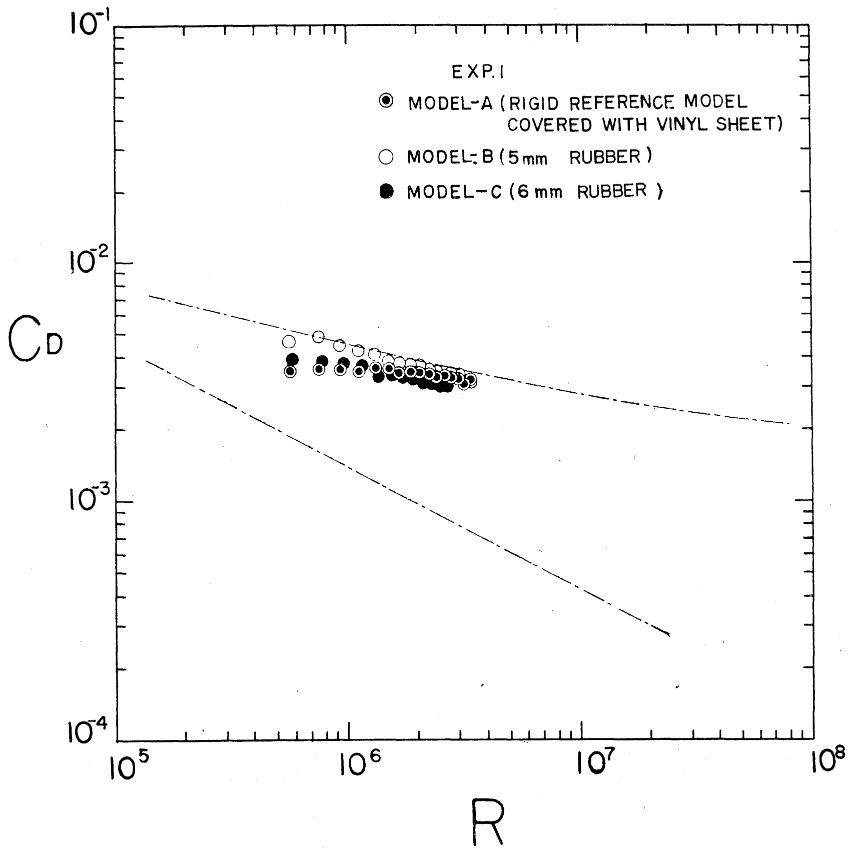

Fig. 6. Drag coefficient as a function of Reynolds number for the models in EXP. 1. for the case that porous rubber coatings were not soaked with water.

are liable to be very irregular, comparatively systematic values were obtained in the present experiment. The drag coefficient of the rigid reference model which was covered with the vinyl sheet is also given in Figure 6.

Some difficulties happened during the experiment. When the coating rubber was not soaked with water, the experiment was troublesome in the following reasons. First, the coating rubber was deformed owing to a change of the static pressure in depth. In fact, the pressure of about 80 kg/cm² acted on the lower part of the surface of the test-plate. It can be thought that the area of the surface which actually behaved as the effective flexible boundary would have been only the upper part of the plate. Therefore the area of the effective flexible surface can be estimated at about 10 percent of the full area of the plate from Figure 1. Second, the air within the coating seemed to influence the elastic behavior of the flexible layer. It was therefore difficult to evaluate the elastic constants of the flexible layer. For these reasons, the experimental results in the

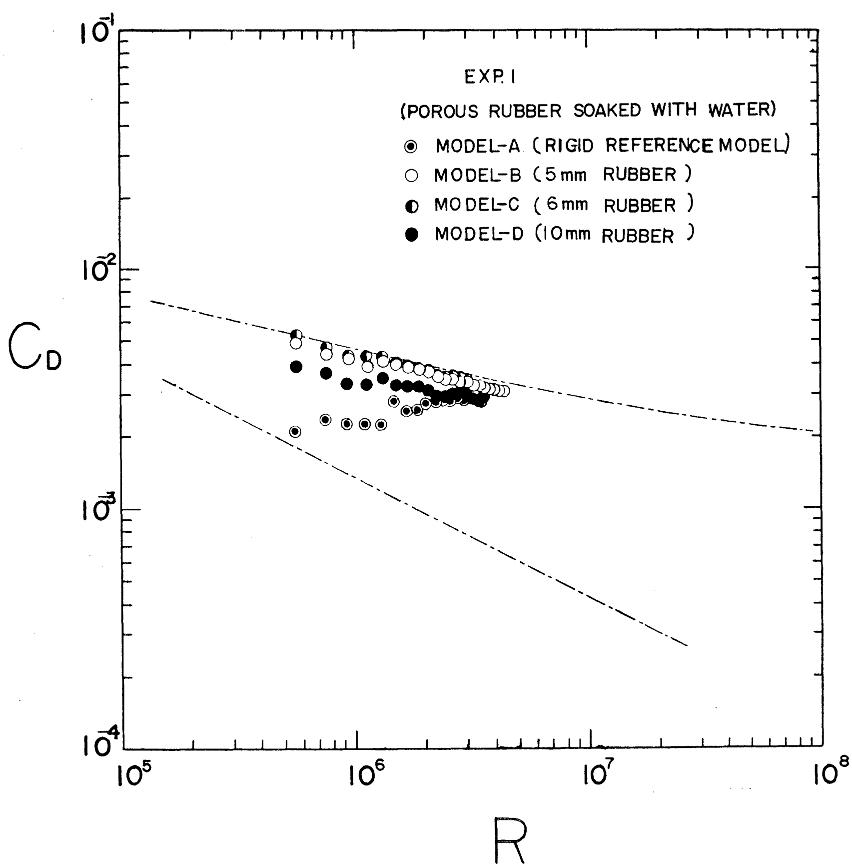

Fig. 7. Drag coefficient as a function of Reynolds number for the models in EXP. 1 for the case that porous rubber coatings were soaked with water.

present case are not available for the investigation of the effects of flexibility.

Figure 7 shows the experimental result for the test-plates whose coating rubber was soaked with water. The rigid reference model A was not covered with the vinyl sheet in this case. The drag coefficient is larger for the model A which was covered with the vinyl sheet than for the same model which was not covered. This means that the small wrinkles of the vinyl sheet promoted the flow transition. It is evident from Figure 7 that the drag coefficient for the model *D* which was coated with the thickest rubber of 10 mm thickness is comparatively small. It is interesting that the drag for the model *C* which was coated with the softest rubber is largest. In any case, the drags for the models with the flexible surface are always larger than those for the rigid reference model.

In order to investigate the influence of the shape of edges and the roughness of the surface on the skin-friction drag, the measurements were made with the

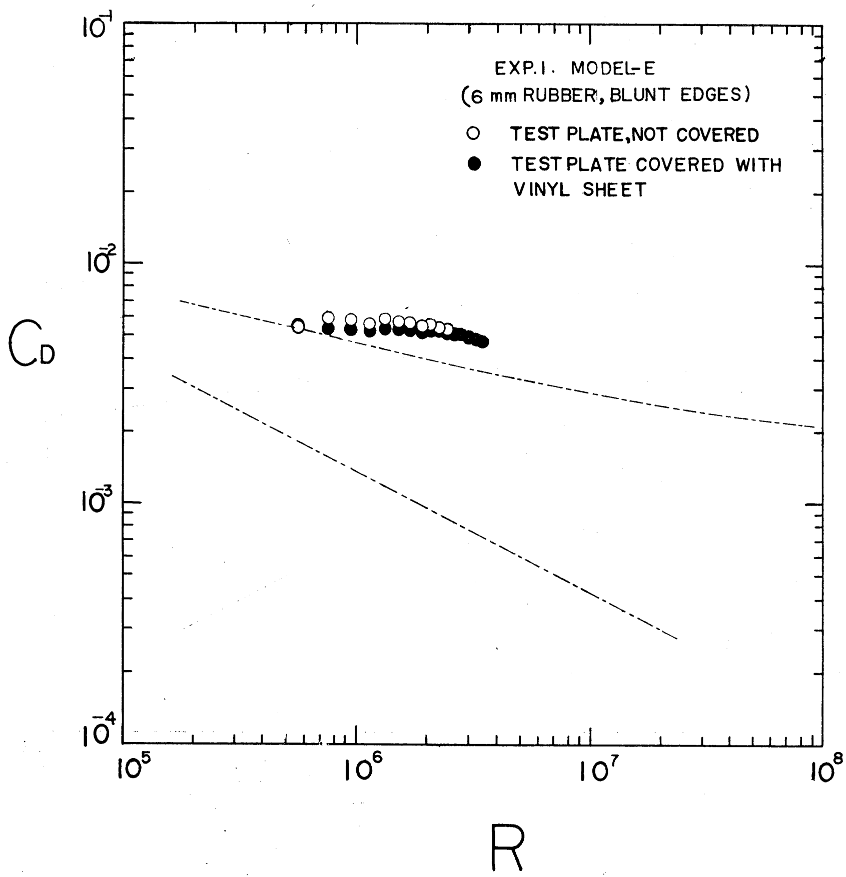

Fig. 8. Drag coefficient as a function of Reynolds number for the blunt edges model E.

specially designed test-plate named model E. This model had the same structure as that of the model C, but the both edges of the plate had a bluff section. The result for the model E is shown in Figure 8. The measurement was carried out in two cases, both when the test-plate was covered with the vinyl sheet, and when it was not covered with the vinyl sheet. In the former case all the coating rubber was soaked with water. At a Reynolds number of 6×10^5 the flow is already turbulent.

4. Results in EXP. 2.

The result of the measurements for the three kinds of the model is shown in Figure 9. The drag coefficient C_D is expressed as

$$C_D = D_1/\rho U^2 S. \tag{7}$$

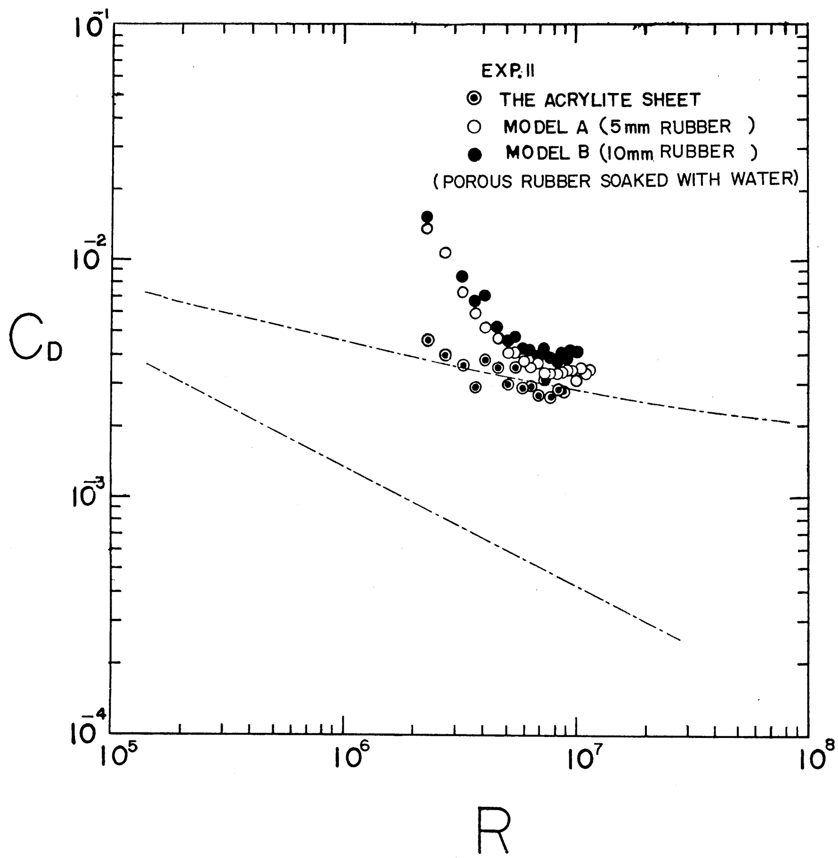

Fig. 9. Drag coefficient as a function of Reynolds number for the models in EXP. 2.

Reynolds numbers are between 2×10^6 and 1×10^7. In EXP. 2 the coating rubber was soaked with water in all cases. It can be seen from Figure 9 that the models with the flexible surface have the larger drag coefficient than the rigid reference model. However, contrary to the result in EXP. 1, the model B with the coating rubber of a thickness of 10 mm has the larger drag coefficient than the model A with the rubber of a thickness of 5 mm. The reason is not evident.

At the Reynolds number range between about 2×10^6 and 4×10^6, the drag was measured both in EXP. 1 and in EXP. 2. However, there exists a large discrepancy between both especially in the lower Reynolds number range. The source of this discrepancy appears to lie in the imperfectness of EXP. 2 at the lower Reynolds number range. In fact, the test-plate was deformed largely by the large buoyancy acting on the plate in the case of EXP. 2 at these Reynolds number range. The drag coefficient for the acrylite-plate which was not deformed well agreed with that for the ordinary flat-plate nearly all over the experimental values. From above considerations, the drag coefficients in EXP. 2 are not well reliable at Reynolds numbers below 6×10^6. However, the drag coefficients at Reynolds numbers of about 8×10^6 are sufficiently reliable because the test-plate could be kept exactly parallel to the flow. As is seen in Figure 9, the test-plates with flexible walls have always the larger skin-friction drag than the rigid reference plate.

5. Conclusion

The flexible surface plates have always the larger skin-friction drag than the rigid surface plates both at the flow transition range and also at the range where the boundary layer is fully turbulent. Thus the evidence that the reduction of skin friction is achieved by the flexible coating of the walls is not found in the experiments. However, it can not be concluded immediately from these experiments that the skin friction is increased by the flexible coating, since the shape of the flexible surface models and the rigid reference models was not exactly identical. In order to exclude the influence of the difference of shape of models on the skin-friction drag, another experiment using models of the exactly same shape is now in preparation.

With respect to the vinyl sheet used to eliminate the effects of roughness, there exists the following complicated problem. The shearing force as well as the pressure on the flexible surface seems to play an important role in the present problem. However, the vinyl sheet used in the present experiments was not well sensitive to the shearing force. For the direct interaction between the flexible coatings and the boundary layer, model-plates must be coated by such a material that is well sensitive to the shearing force and has fairly smooth surface by itself without any covering. In the experiments, only one kind of rubber was adopted as flexible material. Other kinds of flexible material, for example such as damping-oil, the ordinary rubber were not tested. In Krämer's investigation, the special rubber coating with many inter-spaces filled with silicon oil was used as the flexible wall, and its flexibility seems to belong to somewhat a different type from that of the synthetic porous rubber used in the present work. Although there are many technical difficulties in making a model coated with the flexible layer of liquid material, such a model seems to be the most promissing one which can reduce the skin-friction drag effectively. Such a model will be tested in the further experiment.

It should be the most essential question whether the flexibility delays the transition from laminar to turbulent boundary layer, or reduces the turbulence intensity of the fully developed turbulent boundary layer. Further projects will be focused to reveal this point of the problem.

The authors wish to express their gratitude to Prof. Michinori Kurihara, Prof. Jun'ichi Okabe and Prof. Fukuzo Tasai of Research Institute for Applied Mechanics and Prof. Hikoji Yamada of Kyoto University. for valuable discussions of the problem. Tanks are also due to Mr. Hajime Amamoto, Mr. Koji Ishii, Miss

Hitomi Yanase, Mr. Akimasa Tashiro and the staff of the Tsuyazaki Laboratory for Sea Disaster for their helpful collaboration through the experiments.

References

(1) Krämer, M. O.: J. Amer. Soc. Nav. Engrs. 72 (1960) 25.
(2) Benjamin, T. B.: J. Fluid Mech. 9 (1960) 513.
(3) Landahl, M. T.: J. Fluid Mech. 13 (1962) 609.

(Received May 19. 1967)