NEGATIVE MAGNUS EFFECT

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NEGATIVE MAGNUS EFFECT

By Sadatoshi TANEDA

Summary: In certain range of Reynolds number and rotational speed, spheres and cylinders rotating about a cross-flow axis in a uniform stream suffer the lifts which have direction opposite to those in ordinary Magnus effect.

In the present experiment the condition under which the negative Magnus force takes place was clarified for the case of a sphere. And it was found that this remarkable effect can be explained as a transition effect of the boundary layer from laminar to turbulent flow.

The photographs of the actual flow pattern around a rotating sphere was also taken by means of aluminium dust method, and the difference between the two flow-patterns of ordinary Magnus effect and negative Magnus effect was revealed.

1. Introduction and Outline of the Experiments It is well known that the rotating cylinder and sphere placed in a uniform flow of fluid is subjected to the cross-flow force (see Fig. 1), and that this effect can be explained satisfactorily by the ideal fluid theory. The effect is called the Magnus effect.

However, it was shown previously in a paper[1] by Maccoll (1928) that when the ratio of the equatorial speed of the rotating sphere to the flow speed was less than about 0.5, the negative Magnus force was observed. (Maccoll's experiment was made at the Reynolds number of the order of 10^5.) This curious phenomenon has long been a matter of interests to hydrodynamicians. But no detailed experiment has been carried out up to the present.

The purpose of the present experiment is to reveal the detailed conditions under which the negative Magnus forces appear, and to clarify the mechanism of the effect.

If the surface of the sphere is sufficiently smooth and there is no turbulence in the main flow, the lift coefficient C_L is a function only both of Reynolds number R and of V/U, where V is the equatorial speed of the sphere and U is the speed of the main flow.

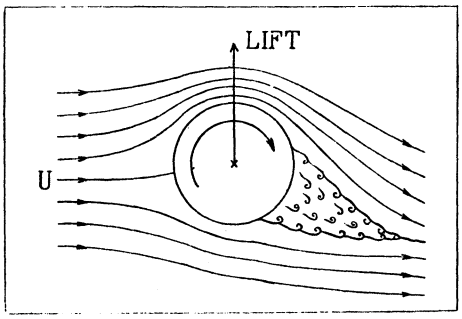


Fig. 1. Ordinary Magnus effect.

First, the region of the negative

lift coefficient was determined in the $R-V/U$ plane. It was found that the effect occurs only at about $R=2.5\times10^5$ and $0<V/U<0.6$. This value of Reynolds number 2.5×10^5 is just the critical Reynolds number at which the transition of the boundary layer from laminar to turbulent flow takes place when the sphere does not rotate. Therefore it would be natural to imagine that this phenomenon has a bearing on the transition of the boundary layer.

Further experiments showed that this really was the case. As the critical Reynolds number depend on the disturbance present in the main flow and also on the roughness of the sphere surface, it was expected that the range of the Reynolds number in which the negative Magnus force takes place would be shifted by the disturbance introduced into the main flow. This effect was actually found experimentally.

Thus it was confirmed that the negative Magnus effect can be explained as a transition effect of the boundary layer from laminar to turbulent flow.

The experimental results mentioned above are also in accordance with what has been predicted in a recent paper[2] by Klahn for the case of a rotating circular cylinder.

2. Apparatus The experiment was carried out in the research water tank of 25 m in length, 2 m in width and 1.5 m in depth at Kobe University of Mercantile Marine. In the middle of both side walls large windows were cut and covered with glass plates.

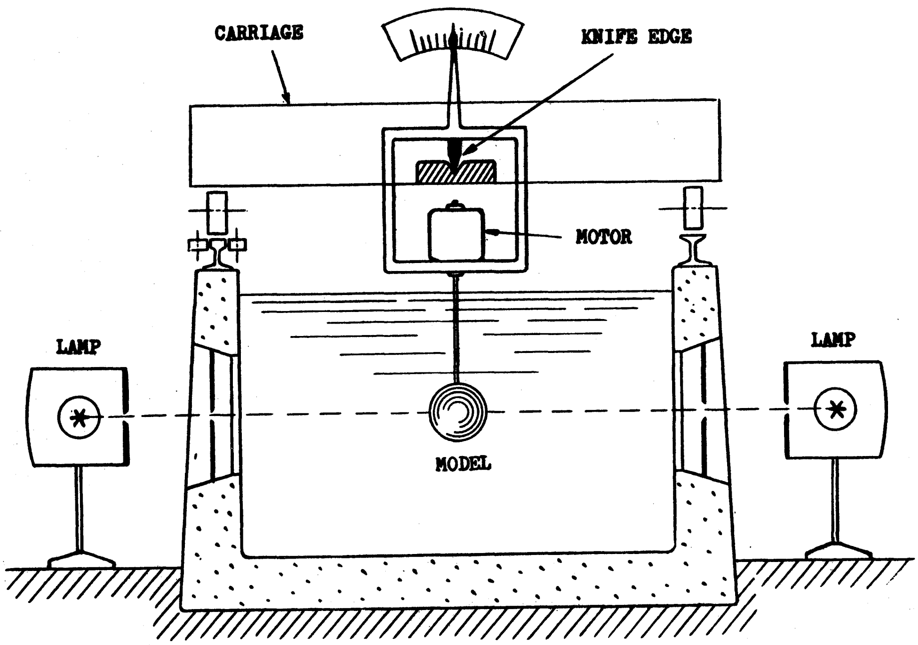


Fig. 2. Schematic diagram of the apparatus.

The carriage, with a rotating device, was moved by a 4 HP D. C. motor on rails mounted above the water tank. Speed of the carriage could be varied smoothly from 20 to 200 cm/s by means of Ward-Leonard system. The general arrangement of the apparatus is illustrated in Fig. 2.

The brass sphere (198 mm in diameter) attached to one end of a long circular cylindrical support (20 mm in diameter and 700 mm in length) was used as the model, and it was rotated uniformly with a 10 Watt A. C. motor.

The rotating sphere device was supported, with knife edges so as to constitute a pendulum, free to swing only in the direction normal to the motion of the carriage. (see Fig. 2) The lift can be measured by reading the inclination of the rotating sphere device.

In order to give an appropriate damping to the movement of the pendulum, an effective oil damper was used.

The grid used to produce a turbulence was 8 cm in mesh length and 0.5 cm in rod diameter.

The photographic arrangement was the same as that used in ultramicroscopy. A sheet of intense light from 1.5 KW incandescent lamps behind a horizontal slit was made to pass through a horizontal plane, containing the center of the sphere on it. The movement of aluminium dust suspended in the water could be photographed from above with a camera fixed to the carriage.

3. Results and Discussion In the first place the region of the negative lift coefficient in the $(R, V/U)$ plane was determined for the case of no disturbance introduced into the main flow. The results are shown in Fig. 3, which reveal the fact that the negative Magnus force appears only in the neighborhood of the Reynolds number of 2.5×10^5 and $V/U < 0.6$. In measuring these forces an interesting phenomenon

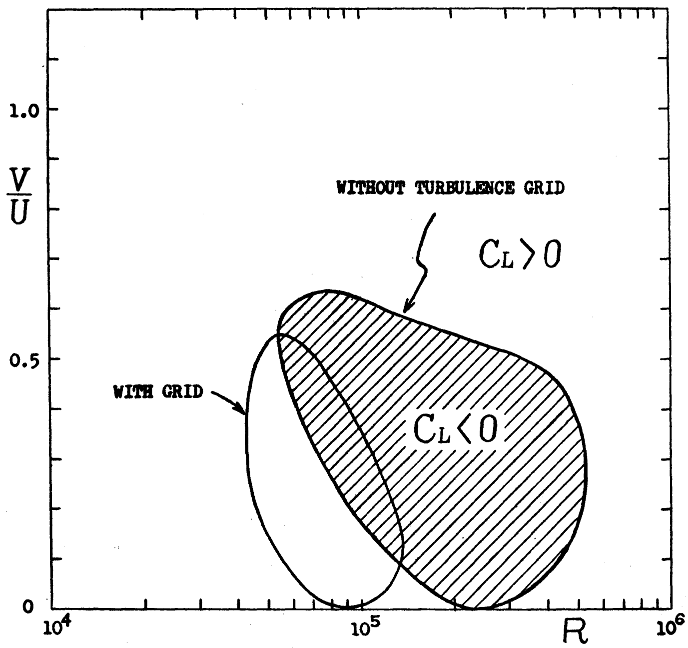


Fig. 3. Region of negative Magnus force in the $(R, V/U)$ plane.

was observed. The negative Magnus force always appeared after the carriage had moved about 10 m. In the beginning of the run the force was always positive, and then it became quite abruptly negative. The reason seems to lie in the fact that the stationary flow around the sphere is completed after some run of the carriage.

In the second place, the experiment was made, designed for the determination of the critical Reynolds number at which the transition of the boundary layer from laminar to turbulent flow occurs. The critical Reynolds number can be determined by detecting the position of separation. When the sphere does not rotate and if the boundary layer is laminar then it separates from the sphere surface at about 83° from the forward stagnation point, while if the boundary layer is turbulent it separates at about 130°. In the present experiment the position of separation was determined by means of the condensed milk method, and the Reynolds number of the transition was found to be approximately 2.5×10^5.

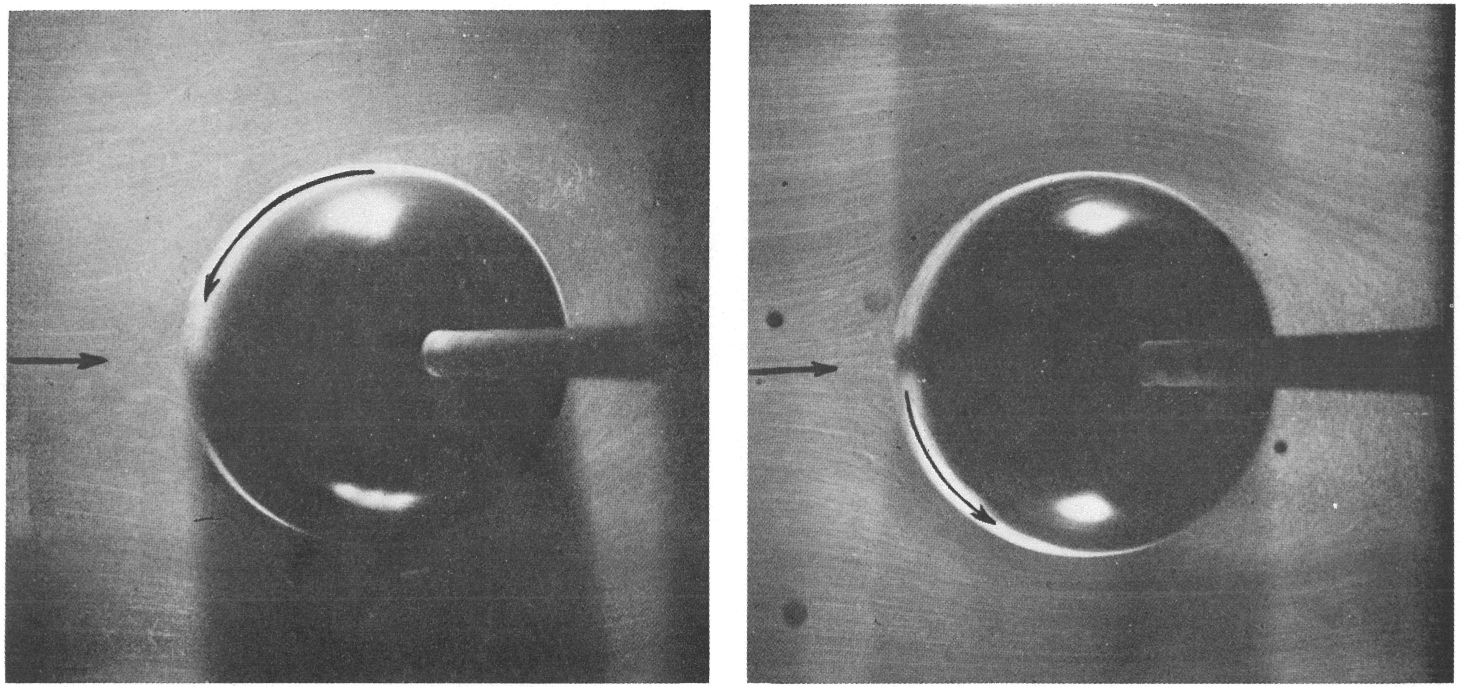
In the third place, the influence of disturbances introduced into the main flow was investigated. The region of the negative lift coefficient was determined with a rotating sphere located 15 cm behind the grid. The results are shown in Fig. 3. As is seen from this figure, the region of the negative lift coefficient shifts to the range of lower Reynolds number of about 8.5×10^4, and moreover it contracts remarkably.

Lastly, the Reynolds number 8.5×10^4 was confirmed experimentally to be just the critical value at which the transition of the boundary layer around a non-rotating sphere takes place in the disturbed flow behind the grid.

The experimental results mentioned above lead us to the following conclusions.

When the sphere does not rotate the flow around the sphere is symmetrical. When the sphere rotate, however, the flow is no longer symmetrical and the transition of the boundary layer occurs at different Reynolds numbers on each of the two sides. As the transition of the boundary layer depends roughly on the relative speed of the flow with respect to the sphere surface, the transition occurs at the Reynolds number (Ud/ν) higher than 2.5×10^5 on the side where the surface moves in the direction of the flow, while on the other side where the surface moves in the opposite direction to the flow, the transition occurs at the Reynolds number lower than 2.5×10^5.

Thus at the Reynolds numbers close to 2.5×10^5, the boundary layer is laminar on one side of the rotating sphere and turbulent on the other side. As the value of V/U is increased, of course, the separation point on the laminar side moves rearward from 83° and that on the turbulent side shifts forward from 130°. For lower values of V/U, however, the separation point on the laminar side remains ahead to the separation point on the turbulent side. This can be actually seen in the photographs obtained by means of aluminium dust method. (see Fig. 4) This is the reason why the negative Magnus force appears.



(a) Ordinary Magnus effect. $R=2.56\times10^4$, $V/U=1.30$

(b) Negative Magnus effect. $R=1.20\times10^5$, $V/U=0.38$

Fig. 4. Photographs showing flow pattern around a rotating sphere moving uniformly in a still water.

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