

LES CLASSIQUES DE LA MÉCANIQUE DES FLUIDES ET DE L'HYDRAULIQUE

SÉRIE PUBLIÉE SOUS LA DIRECTION DE ENZO O. MACAGNO

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Les suggestions concernant les textes à inclure dans cette série seront les bienvenues, spécialement si des indications précises sont données, dans le cas d'articles très longs ou de livres, sur les parties considérées comme les plus importantes.

CLASSICAL WORKS IN FLUID MECHANICS AND HYDRAULICS

A SERIES SELECTED BY ENZO O. MACAGNO

No attempt to correct errors, if they would be detected, will be made, unless they appear as obvious misprints. Each reader will be confronted with the original writing as it was. Translations in this series are intended to be quite literal with purpose of providing an access as direct as possible to the original form of the writing. Suggestions to include material in this series will be most welcome, especially if indications are given of the excerpts that are considered valuable in the case of long papers or books.

LUDWIG PRANDTL

(1875-1953)

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Traduit en anglais par Dwight M. MILLER. Quelques changements dans les termes techniques utilisés dans la traduction ont été effectués avec l'idée de préserver autant que possible le sens original. Nous sommes reconnaissants à la NASA d'avoir permis la publication de la version anglaise.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Technical memorandum No 452

MOTION OF FLUIDS WITH VERY LOW VISCOSITY

by L. PRANDTL.

In classic hydrodynamics the motion of *nonviscous* fluids is chiefly discussed. For the motion of *viscous fluids*, we have the differential equation whose evaluation has been well confirmed by physical observations. As for solutions of this differential equation, we have, aside from unidimensional problems like those given by Lord Rayleigh (*) only the ones in which the inertia of the fluid is disregarded or plays no important role. The bidimensional and tridimensional problems, taking viscosity *and* inertia into account, still await solution. This is probably due to the troublesome properties of the differential equation. In the "Vector Symbolics" of Gibbs (**), this reads

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) + \nabla (V + p) = k \nabla^2 \mathbf{v} \quad (1)$$

in which \mathbf{v} is the velocity; ρ , the density; V , a function of the power; p , pressure; k , viscosity constant. There is also the continuity equation

$$\text{div. } \mathbf{v} = 0$$

for incompressible fluids, which alone will be here considered.

From the differential equation, it is easy to infer that, for sufficiently slow and also slowly changing motions, the factor of ρ , in contrast with the other terms, can be as small as desired, so that the effect of the inertia can here be disregarded with sufficient approximation. Conversely, with sufficiently rapid motion, the quadratic term $\mathbf{v} \cdot \nabla \mathbf{v}$ (change of velocity due to change of location) is large enough to let the viscosity effect $k \nabla^2 \mathbf{v}$ appear quite subordinate. The latter almost always happens in cases of fluid motion occurring in technology. It is therefore logical simply to use here the equation for non-viscous fluids. It is known, however, that the solutions of this equation generally agree very poorly with experience. I will recall only the Dirichlet sphere, which, according to the theory, should move without resistance.

(*) Proceedings London Math. Soc., vol. 11, p. 57, and Papers, vol. I, p. 474.

(**) The symbols \cdot and \times indicate, respectively, dot and cross product. The symbol ∇ represents the Hamiltonian (or Laplacian) vectorial differential operator.

I have now set myself the task to investigate systematically the laws of motion of a fluid *whose viscosity is assumed to be very small*. The viscosity is supposed to be so small that it can be disregarded wherever there are not great velocity differences nor accumulative effects. This plan has proved to be very fruitful, in that, on the one hand, it produces mathematical formulas, which enable a solution of the problems and, on the other hand, the agreement with observations promises to be very satisfactory. To mention one instance now: when, for example, in the steady motion around a sphere, there is a transition from the motion with viscosity to the limit of nonviscosity, then something quite different from the Dirichlet motion is produced. The latter is then only an initial condition, which is soon disturbed by the effect of an ever-so-small viscosity.

I will now take up the individual problems. The force on the unit volume, due to the viscosity, is

$$\mathbf{K} = k \nabla^2 \mathbf{v} \quad (2)$$

If the vorticity is represented by $\mathbf{w} = \frac{1}{2} \text{rot } \mathbf{v}$, then $\mathbf{K} = -2k \text{rot } \mathbf{w}$, according to a well-known vector analytical transformation, taking into consideration that $\text{div } \mathbf{v} = 0$. From this it follows directly that, for $\mathbf{w} = 0$, also $\mathbf{K} = 0$, that is, that however great the viscosity, a vortex-free flow is possible. If, however, this is not obtained in certain cases, it is due to the fact that turbulent fluid from the boundary is injected into the vortex-free flow.

In a periodic or cyclic motion, the effect of viscosity, even when it is very small, can accumulate with time. To attain a steady state, therefore, the work of \mathbf{K} , that is, the line integral $\int \mathbf{K} \circ d\mathbf{s}$ along very streamline with cyclic motions, must be zero for a full cycle.

$$\int^P \mathbf{K} \circ d\mathbf{s} = (V_2 + p_2) - (V_1 + p_1).$$

A general formula for the distribution of the vorticity can be derived from this with the aid of the Helmholtz vortex laws for bidimensional motions which have a flow function ψ (*). With steady flow we obtain (**)

$$-\frac{dw}{d\psi} = \frac{(V_2 + p_2) - (V_1 + p_1)}{2k \int^P \mathbf{v} \circ d\mathbf{s}};$$

With closed streamlines this becomes zero. Hence we obtain the simple result that, within a region of closed streamlines, the vorticity assumes a constant value.

For axially symmetrical motions with the flow in meridian planes, the vorticity for closed streamlines is proportional to the radius $w = cr$. This gives a force $K = 4kc$ in the direction of the axis.

(*) Cf. Encyklopädie der mathem. Wissensch., IV, 14, 7.

(**) According to Helmholtz, the vortex of a particle is permanently proportional to its length in the direction of the vortex axis. Hence we have, with steady plane flow on each streamline ($\psi = \text{const.}$), w constant, consequently $w = f(\psi)$. Herewith

$$\int \mathbf{K} \circ d\mathbf{s} = 2k \int \text{rot } \mathbf{w} \circ d\mathbf{s} = 2kf'(\psi) \int \text{rot } \psi \circ d\mathbf{s} = 2kf'(\psi) \int \mathbf{v} \circ d\mathbf{s}.$$

The most important aspect of the problem is the behavior of the fluid on the surface of the solid body. Sufficient account can be taken of the physical phenomena in the boundary layer between the fluid and the solid body by assuming that the fluid adheres to the surface and that, therefore, the velocity is either zero or equal to the velocity of the body. If, however, the viscosity is very slight and the path of the flow along the surface is not too long, then the velocity will have its normal value in immediate proximity to the surface. In the thin transition layer, the great velocity differences will then produce noticeable effects in spite of the small viscosity constant.

This problem can be handled best by systematic omissions in the general differential equation. If k is taken as small in the second order, then the thickness of the transition layer will be small in the first order, like the normal components of the velocity. The lateral pressure differences can be disregarded, as likewise any curvature of the streamlines. The pressure distribution will be impressed on the transition layer by the free fluid.

For the plane problem which has thus far been discussed, we obtain in the steady condition (X -direction tangential, Y -direction normal, w and v the corresponding velocity components) the differential equation

$$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) + \frac{dp}{dx} = k \frac{\partial^2 u}{\partial y^2}$$

and

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

If, as usual, dp/dx is given throughout, as also the values of u for the initial cross section, then every problem of this kind can be numerically solved, by obtaining the corresponding $\partial u/\partial x$ by differencing u . Thus we can always make progress in the X -direction with the aid of one of the well-known approximation methods (*). One difficulty, however, consists in the various singularities located on the solid surface. The simplest case of the problems here considered is when the water flows along a flat thin plate. Here a reduction of the variables is possible and we can write $u = f(y/\sqrt{x})$. By the numerical solution of the resulting differential equation, we obtain for the drag the formula

$$R = 1.1 \dots b \sqrt{k\rho l u_0^3}$$

(b width, l length of plate, u_0 velocity of undisturbed water upstream from the plate). Figure 1 shows the velocity variation.

The most important practical result of these investigations is that, in certain cases, the *flow separates from the wall* at a point entirely determined by external conditions (Fig. 2). A fluid layer, which is set in rotation by the friction on the wall, is thus forced into the free fluid and, in accomplishing a complete transformation of the flow, plays the same role as the Helmholtz separation layers. A change in the viscosity constants k simply changes the thickness of the vortical

(*) See, e.g., Zeitschr. f. Math. u. Physik, 46, 435, (Kutta).

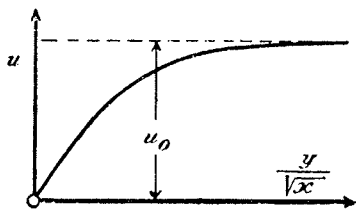


Fig. 1.

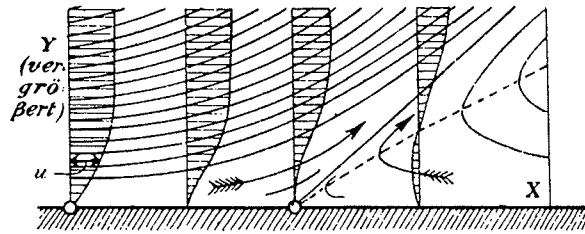


Fig. 2.

layer (proportional to the quantity $\sqrt{kl/\rho u}$), everything else remaining unchanged. It is therefore possible to pass to the limit $k = 0$ and still retain the same flow figure.

As shown by closer consideration, the necessary condition for the separation of the flow is that there should be a pressure increase along the surface in the direction of the flow. The necessary magnitude of this pressure increase in definite cases can be determined only by the numerical solution of the problem which is yet to be undertaken. As a plausible reason for the separation of the flow, it may be stated that, with a pressure increase, the free fluid has its kinetic energy partially converted into potential energy. The transition layers, however, have lost a large part of their kinetic energy and no longer possess enough energy to penetrate the region of higher pressure. They are therefore deflected laterally.

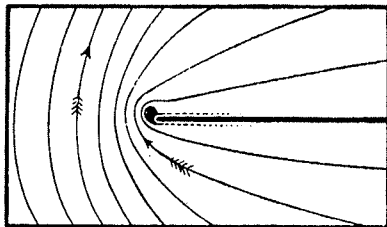


Fig. 3.

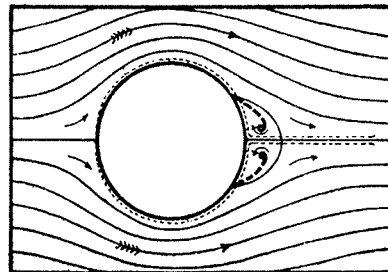


Fig. 5.

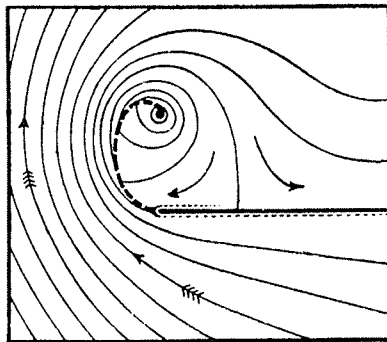


Fig. 4.

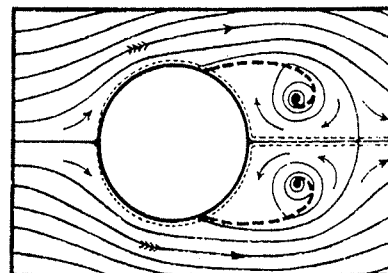


Fig. 6.

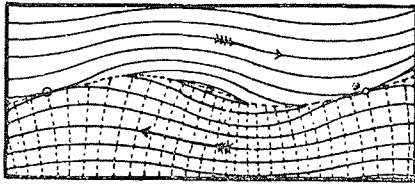


Fig. 7.

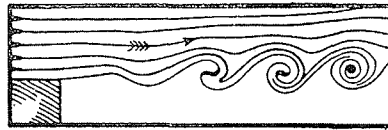


Fig. 9

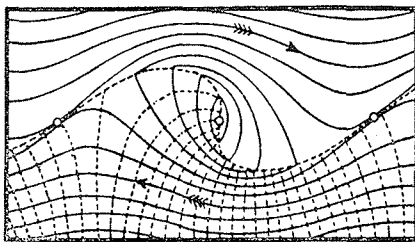


Fig. 8.

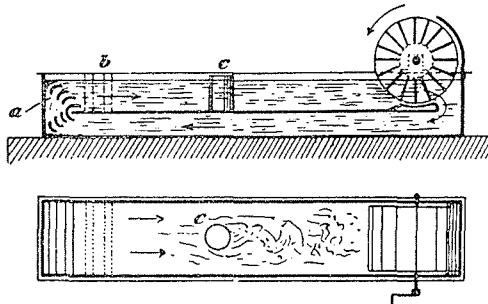


Fig. 10.

According to the preceding, the treatment of a given flow process is resolved into two parts mutually related to one another. On the one hand, we have the *free fluid*, which can be treated as nonviscous and governed by the Helmholtz vortex laws, while, on the other hand, we have the transition layers on the solid boundaries, whose motion is determined by the free fluid, but which, in their turn, impart their characteristic mark to the free flow by the emission of vortical layers.

I have attempted, in a few cases, to illustrate the process more clearly by diagrams of the streamlines, though no claim is made to quantitative accuracy. In so far as the flow is vortex-free, one can, in drawing, take advantage of the circumstance, that the streamlines form a system of orthogonal curves with the lines of constant potential.

Figures 3-4 show, in two stages, the beginning of the flow around a wall projecting into the current. The vortex-free initial flow is rapidly transformed by a spiral separating layer (dashed line). The vortex continually advances, leaving still water behind the finally stationary separated layer.

Figures 5-6 illustrate the analogous process for a cylinder. The fluid layers set into rotational flow by friction are plainly indicated by dashed lines. Here also the separating layers extend to infinity, once the steady flow is attained. All these separating layers are known to be labile. If a slight sinusoidal disturbance is present, motions develop as shown in Figures 7-8. It is clearly seen how separate vortices are developed by the mutual interference of the flows. The vortex layer is rolled up inside these vortices, as shown in Figure 9. The lines of this figure are not streamlines, but such as were obtained by using a dyed liquid.

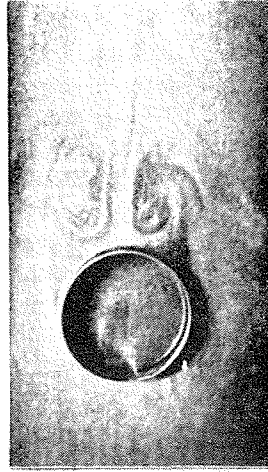
I will now briefly describe experiments which I undertook for comparison with the theory. The experimental apparatus (Fig. 10, in plan and longitudinal views) consists of a tank 1.5 meter long with a false bottom. The water is set



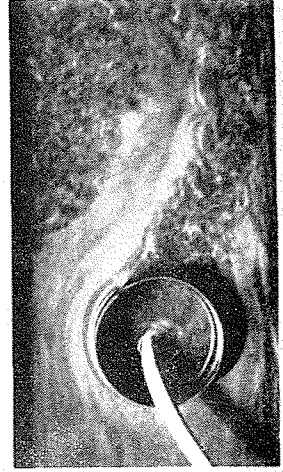
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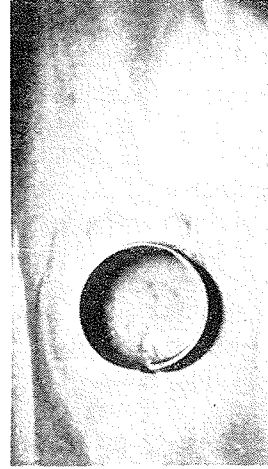
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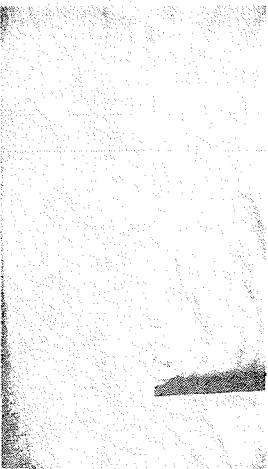
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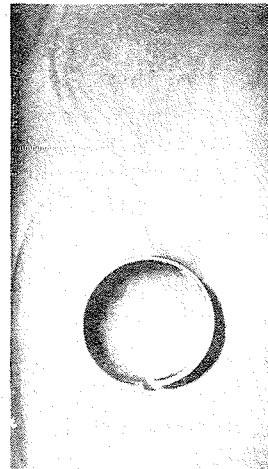
11.



1.



4.



7.



10.

into motion by means of a paddle wheel and, after passing through the deflecting apparatus *a* and four sieves *b*, enters the upper channel comparatively free from eddies, the object to be tested being introduced at *c*. Fine scales of micaceous iron are suspended in the water. These scales indicate the nature of the flow, especially as regards the vortices, by the peculiarities of their reflection due to their orientation.

The accompanying photographs were obtained in this manner, the flow being from left to right. Nos. 1-4 show the flow past a wall projecting into the current. The separating boundary layer, which passes off from the edge, is apparent. In No. 1 it is very small; in No. 2, concealed by strong disturbances; in No. 3, the vortex spreads over the whole picture; in No. 4, the "permanent condition" is shown. A disturbance is also evident above the wall. Since a higher pressure prevails in the corner, due to the stagnation of the water flow, even there the flow separates from the wall after a while. The various striae visible in the "vortex-free" portion of the flow (especially in Nos. 1-2) are due to the fact that, at the inception of the flow, the liquid was not entirely quiet. Nos. 5-6 show the flow around a curved obstacle or, from another viewpoint, through a continuously narrowing and then widening channel. No. 5 was taken shortly after the inception of the flow. One separated layer has developed into a spiral, while the other has elongated and broken up into very regular vortices. On the convex side, near the right end, the beginning of the separation can be seen. No. 6 shows the steady state, in which the flow begins to separate about at the narrowest cross section.

Nos 7-10 show the flow around a cylindrical obstacle. No. 7 shows the beginning of the separation; Nos 8-9, subsequent stages. Between the two vortices there is a line of water which belonged to the transition layer before the beginning of the separation. No. 10 shows the steady-state flow. The wake of eddying water behind the cylinder swings back and forth, whence the momentary unsymmetrical appearance. The cylinder has a slot along one of its generators. If the slot is placed as shown in Nos. 11-12 and water is drawn out through a tube, the transition layer on one side can be eliminated. When the layer is sucked out, its effect, the separation, is eliminated. In No. 11, which corresponds, in point of time, to No. 9, there is only one vortex and the line. In No. 12 (steady-state condition), the flow closely follows the surface of the cylinder till it reaches the slot, although only very little water enters the cylinder. A separation surface has developed instead on the flat wall of the tank (its first indication having appeared in No. 11). Since the velocity must diminish in the widening cross section and the pressure consequently increase (*), we have the conditions for the separation of the flow from the wall, so that even this striking phenomenon is explained by the theory presented.

(*) On each streamline, $\frac{1}{2} \rho v^2 + V + p = \text{const.}$