The Forces which lift Aeroplanes.¹

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THE forces which carry aeroplanes are now subject to intensive experimental and theoretical investigation. In one respect, however, these investigations have led to a surprising result, namely, that the force which makes flying possible belongs to a group of forces discovered long ago, before the period of aviation. Their existence had been predicted mathematically, and these predictions had been verified by experiments.

THE DIRECT GEOMETRIC AND THE INVERSE DYNAMIC ANALOGY BETWEEN HYDRODYNAMIC AND ELECTRO-MAGNETIC FIELDS.

This old theory, and these old experiments, relate to what is called *hydrodynamic actions-at-a-distance*. The period when the doctrine of action-at-a-distance was absolutely predominant lasted, at least on the Continent, until about thirty years ago. The researches which I am about to describe, date from that period. My father, C. A. Bjerknes, could not reconcile himself with this doctrine at the time when he was a student at the University of Christiania, about eighty years ago. Ten years later he had the opportunity of acquainting himself with recent results of research in theoretical hydrodynamics. These had just led to a surprising fact: a spherical body could move through a frictionless fluid without experiencing any resistance. This paradox was in his eyes an important fact in discussing action-at-a-distance. The doctrine of Newtonianists had been that space was empty. They believed that a medium filling it would ultimately stop every motion. But this argument now turned out to be erroneous. The supposition that space was filled with a medium was not contradictory to the first axiom of dynamics, the principle of inertia. This made another idea occur to him: Should not the same medium be able also to propagate actions from body to body, thus giving rise to apparent action-at-a-distance? And would not the answer be found by solving the problem of simultaneous motion of two or more bodies in the fluid—for mathematical simplicity of spherical or cylindrical form?

The conditions under which my father worked were not favourable. But he never gave up his point of view, and twenty-five years later he was in possession of the full solution of the problem, and had verified the results by a series of striking experiments.

The result was that a very remarkable analogy became evident between the field of motion in a fluid and the electric or magnetic field of force: the bodies produced fields of motion of precisely the same geometric structure as static or stationary electric or magnetic fields. Moreover, they exert apparent actions-at-a-distance upon each other, equal to, but—most curiously—opposite to the actions-at-a-distance between the corresponding bodies in the electric or magnetic fields.

GENERAL STATEMENT OF THE ANALOGY.

In one respect, however, my father's theory was special: he had proved this analogy to exist only for bodies of spherical or cylindrical form. By slightly changing the problem, I succeeded some twenty years

ago in giving an absolutely general proof of the analogy. I retained in my theory the idea that the main fluid was homogeneous and incompressible. But for the solid spheres and cylinders I substituted *fluid* bodies of any shape. These bodies may differ from the surrounding fluid in four respects: (1) In density: this gives the body a reaction against acceleration, different from that of the surrounding fluid; (2) in compressibility: the bodies may perform motions of expansion and contraction; (3) the motion considered was allowed to be vortical inside the bodies, while it was always irrotational in the surrounding fluid; (4) external force may act upon the elements of the bodies but not on those of the surrounding fluid.

The advantage of considering the entire system as fluid is that its dynamics are then determined completely by the hydrodynamic equations. Therefore the analogy to the electric or magnetic field may be demonstrated by a simple—in reality very simple—transformation of these equations. The leading idea of this transformation is to consider the actual fluid field of motion as made up by two partial fields: the *impressed field*, which is that produced by external force, including the hydrodynamic actions-at-a-distance; and the *induced or free field*, which is due to fluid pressure, setting aside that part of the pressure which produces the hydrodynamic actions-at-a-distance. The impressed field exists only inside the bodies, while the induced or free field pervades all space, including that inside the bodies, and when added to the impressed field in this inside space, it gives the actual fields of motion of the bodies.

This system can be compared with an electric or magnetic one. Specific volume will then correspond to magnetic permeability or specific inductive capacity; velocity will correspond to magnetic induction or electric displacement. The product of velocity into density, that is, specific momentum, will correspond to magnetic or electric intensity. Impressed field within the fluid bodies will correspond to impressed field in the interior of a permanent magnet or a pyro-electric crystal, and induced hydrodynamical field will correspond to induced magnetic or electric field in external as well as in internal space. Velocity of expansion or of contraction will correspond to magnetic or electric charge, positive or negative; and vorticity, specially defined here to be the curl of induced specific momentum, will correspond to electric current density.

This correspondence between the quantities used for describing the two kinds of fields being agreed upon, the analogy between the two kinds of fields may be stated thus:

At any moment the field of motion of the fluid system is identical in geometrical structure with a certain static or stationary magnetic or electric field; and in this hydrodynamic field there are apparent actions-at-a-distance which, element for element, are equal but opposite to those of the corresponding forces of the magnetic or electric field.

Having obtained this theoretical result we can easily apply it to solid bodies; for the external force which we have introduced is subject to no restriction. We can

¹ From a discourse delivered at the Royal Institution on Friday, May 9.

therefore let this force, or a certain part of it, control the motion of a body in such a way that it moves as if it were rigid, or solidly elastic. This result is attained by imagining reciprocal actions between the particles of the body which have no resultant for the entire body. The only thing to be taken into account will be the impressed fields produced by these reciprocal actions between the particles. But as these fields are characterised by small motions in all possible directions, they will in general give rise only to insignificant reactions with the exterior field.

By substituting solid bodies for the fluid bodies we can obtain experimental demonstrations. But, it may be argued, where solid bodies are moving in a fluid we do not in general observe any striking analogy with the phenomena of the electric or magnetic fields. The reason for this is twofold. First, to recognise the analogy we must divide the field into its impressed and induced parts. The distinction between these two partial fields will not in general be visible to the eye. It must be found by a dynamical analysis. Secondly, the hydrodynamic system is a moving system which is always changing its configuration, and the direction and intensity of motion of its different parts. During each new phase of its motion we must therefore compare it with a new electromagnetic system: this gives a fugitive character to the analogy. But in two cases it must crystallise into a concrete and strikingly visible form: first, when the motion is permanent, and secondly, when it consists of small synchronous oscillations about an invariable average configuration. In both cases we have to compare it with a constant electric or magnetic field. In both cases the induced hydrodynamic field is hidden as a more or less invisible field, while that part of the impressed field which is due to the hydrodynamic actions-at-a-distance produces strikingly visible effects.

This result is, however, obtained in both cases at the expense of a certain reduction of the extent of the analogy. As vortices cannot be oscillatory in a frictionless fluid, they must be zero. In the oscillating case, therefore, the analogy with the electric currents fails. On the other hand, as displacement of the boundary surface would violate the permanence of the motion, all phenomena due to change of volume or of place of the bodies drop out; and we retain only the phenomena depending upon permanent circulation, corresponding to those of electric currents.

THE INSTRUMENTS.

A general auxiliary instrument is a generator for producing vibrating motion. A little electric motor drives a spindle having two eccentrics, each of which works a little pump. Each pump is double-acting and consists simply of cylinder and piston but has no valves. Through the outlet tubes communicating with the ends of the cylinders a few cubic centimetres of air is thus alternately driven out and in, in opposite phases from the two ends of the same cylinder. A cock allows us to regulate the amplitude of that oscillating air current which is conveyed to the main instruments. When a unidirectional air current is desired, a simple valve arrangement may easily be inserted.

A practical peculiarity of the instrument is that the

cylinders, not the pistons, are connected with the eccentrics, and that the pistons react against the motion only by their inertia. This proves useful in connexion with the regulation of the amplitudes. Cylinder and piston are carefully polished but *never* oiled. Another peculiarity of construction is an elaborate symmetry of the moving masses and of their motions, in order to eliminate all vibration of the instrument by compensation.

The alternating air currents from the generator are used to produce two kinds of vibration: first, pulsations, or periodic changes of volume, and secondly, oscillations or periodic changes of place. The pulsating body is a drum having metallic membranes (by their durability preferable to indiarubber membranes) and fixed on the end of a metal tube (Fig. 1, I, II). The membranes are alternately blown out and sucked together by the alternating air current. Loading one membrane of

FIG. 1.—Balance arrangement with pulsators (I, II), oscillator (III), rotating cylinder (X).

such a pulsator, and connecting the other membrane with a spherical shell, which is mounted on a tube and surrounds the pulsator, we get an oscillator (Fig. 1, III): the outer shell and the inner load make opposite oscillations. The desirable case when these become equal amplitudes is attained when the weight of the load equals the sum of the weight of the spherical shell and the half of the mass of water displaced by it. In this event the pulsator will, by the principle of the conservation of the centre of gravity, remain at rest, and the outer shell will oscillate undisturbed both when the projecting tube of the pulsator is taken in the hand and when it is inserted in a rigid clamp. It will not transfer disturbing oscillations to sensitive balances in which it is inserted for the experiments.

Different arrangements can be made for giving such a pulsator or oscillator the degree of mobility required for examining the forces or couples exerted upon them. It is generally convenient to let it float with a buoy. If then the tube conveying the air from the generator is sufficiently flexible, we have at once both translatory and rotatory mobility. To reduce the mobility to a pure translational one, we may give the system of tubes which convey the air from the generator the form of a torsion balance. The weight of this balance is conveniently carried by a floating buoy, swimming in the tank used for the experiments, or in an extra vessel outside it, to reserve the main tank exclusively for the bodies under experiment. We may also do away with the torsion tube of this balance, and let the air go directly from a fixed tube through a loose joint into the balance with really very little loss of air (Fig. 1, IV). This has the advantage that the equilibrium is always indifferent. One of these balance arrangements may be used for demonstrating the attractions, repulsions,

or lateral displacements exerted upon a pulsating or an oscillating body. The latter may be inserted in the balance in two principal ways: for longitudinal mobility, so that its direction of mobility coincides with its axis of oscillations; or for transverse mobility, so that the direction of its mobility is normal to its axis of oscillation. Rotational mobility of an oscillator is obtained either by suspending it by a rubber tube, or by letting the air pass direct into the floating oscillator through a loose joint.

As bodies having no vibrating motion of their own, we use a heavy sphere suspended from a float, a light sphere held under water by a load and suspended from a float, a light and heavy cylinder suspended in the same way.

Finally, for studying the field of motion set up in the fluid we may use a simple arrangement, namely, a light spherical body attached to an elastic wire. This sphere will be set into induced oscillations by the surrounding fluid, and, choosing that period which gives resonance,

we can magnify the minute water oscillations and make them visible. The sphere may also carry a light rod which projects above the surface of the water, and carries a pencil which inscribes its oscillations automatically with ink upon a glass plate placed above the water.

These instruments serve for experiments with vibrating bodies. Permanent motions can be produced by the rotation of cylindrical bodies. By a simple valve arrangement inserted in the tubes conveying the air current from the generator, the alternating current may be changed into a unidirectional one. This current can then be used to drive a turbine attached to a cylinder which is thus set into rotation (Fig. 1, X). To examine the forces exerted upon such a cylinder the latter is placed in the balance just as the pulsator or oscillator was, while another cylinder driven in the same way is mounted on a handle which may be taken in the hand or fixed in a support.

(To be continued.)

Obituary.

SIR WILLIAM BAYLISS, F.R.S.

"BAYLISS'S book is by far his greatest contribution to science—much more important than any of his individual discoveries is his statement of his point of view." These were substantially the words used to me by a very competent critic. At the time I wondered whether or not it were so, and I have often wondered since. Bayliss's investigations into the electric phenomena of the heart¹ and the salivary glands,² into the conditions which govern the cerebral circulation,³ into the muscular movements of the alimentary canal,⁴ into the mechanism of vaso-dilatation,⁵ into the correlation of vaso-motor reflexes;⁶ his establishment of the existence of antidromic fibres in the mammal,⁷ his researches on the application of surface phenomena to physiological action,⁸ and the discovery of secretin⁹—these were his principal discoveries.

When all allowance has been made for the fact that most of this work was carried out in collaboration, it remains an extraordinary tribute to a man's point of view to say that the statement of it transcends such researches. Yet in support of my friend's statement I reflect that in another continent there are "Bayliss Clubs"; these do not exist for the study of the specific subjects enumerated, but for the joint discussion by physiologists and chemists of so much of science as they have in common. The association of Bayliss's name with such societies is a tribute precisely to Bayliss's statement of his point of view. It is not merely that when one asked why the clubs were so called one received the answer, "We discuss the sort of thing which is in Bayliss's book," but that when one comes to think the matter out, one finds it not a little surprising that such societies were not associated with other names; for it cannot be claimed that Bayliss was a pioneer in the investigation of biochemistry.

His interest in the subject—so far as may be gleaned from his published works—dated from about the commencement of this century—before which date the pioneer work in Great Britain had been done. Hardy had launched colloid chemistry in the 'nineties; Hopkins, before the eighteen hundreds were complete, was well forward with that series of isolations which adorn both organic chemistry and physiological science; and Halliburton had done the major portion of his work.

Bayliss's great contribution was that he discussed the whole subject of biochemistry as a continuous whole, thinking out each point *ab initio*, and committing the record to paper, so that what he thought for himself he thought also for others. His method of approaching a subject was one which lent itself admirably to this procedure. The quality of genius differs from individual to individual, probably even more than its quantity. Among scientific men, the genius of some is of the artistic type; though possessing great certainty of touch their inspiration comes they know not whence. To the onlooker it appears almost to be an accident; that it is not so is proved by the fact that it crops out too often in the life of the same person. In others genius is of the mathematical type; with them the premises are grouped in a particular way and to their vision the conclusion flashes out.

Bayliss's genius was not precisely of either type—at least if my own appreciation of it may be trusted. He took nothing for granted, he was not in a hurry, he inquired with meticulous care into every step of an argument; if he found something which was not perfectly clear to him, he spared no pains to discover whether the thread of the argument was really broken or whether he had merely failed to follow it. In the end his mind became clear on the subject; to his own satisfaction he was able to pronounce either that he understood the matter and that it was thus, or that he failed to understand it because the thread, to the best of his judgment, was not continuous.

Such a method is eminently calculated to exclude all forms of obscurantism, and indeed nothing was more

¹ *Journ. of Physiol.* 12. xx, 1891, and 13. lviii, 1891.

² *Journ. of Physiol.* 7. 217, 1886.

³ *Journ. of Physiol.* 18. 334, 1895.

⁴ *Journ. of Physiol.* 24. 99, 1899.

⁵ *Journ. of Physiol.* 16. 10, 1894, and 24. 173, 1901.

⁶ *Journ. of Physiol.* 37. 264, 1908.

⁷ *Journ. of Physiol.* 28. 276, 1902.

⁸ *Proc. Roy. Soc. B.* 84. 229, 1911, and 91. 196, 1920.

⁹ *Journ. of Physiol.* 28. 325, 1902, and 29. 174, 1903.