On Gyrostatic Devices for the Control of Moving Bodies

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XXV. *On Gyrostatic Devices for the Control of Moving Bodies.*

By JAMES G. GRAY, *D.Sc.*, *F.R.S.E.*, *Lecturer on Physics in the University of Glasgow.*

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IT is the object of the present Paper to describe a number of gyrostatic devices available for the control of moving bodies, such as torpedoes, submarine craft, airships and aeroplanes. These contrivances have suggested as a kind of by-product a variety of gyrostatic bicycles and motor-cars, both two-wheeled and four-wheeled. The stability of the gyrostatic system is, however, in all the cases considered in the present Paper, derived directly or indirectly from the propelling system. Hence these cases do not include solutions of the monorail problem; for they have not true stability when they are at rest or moving in the backward direction. Further, it will be seen that the tandem-wheeled motor-cars to be described, although they may be set to run in a perfectly straight path, will not balance on a single rail. The devices, however, have properties which are not possessed by any of the monorail devices so far evolved, properties which may possibly render them of the greatest value to a nation whose continued existence depends on its ability to retain supremacy on sea, and to obtain the supremacy of the air.

With a view to making clear the action of the devices I shall first show some old experiments and will make some deductions which are not obvious. In Fig. 1 is shown a gyrostat set up in a fork and pedestal mounting. The arrangement is substantially that made use of long ago by Léon Foucault in demonstrating the earth's rotation. The flywheel possesses three freedoms. The fork is capable of rotation, with but little friction, about a vertical axis, and the gyrostat is carried on knife-edges formed in the prongs of the fork, and is thus free to turn in the line joining the knife-edges. The axis of rotation of the flywheel XX′ and the two axes just specified—namely, ZZ′ and YY′—are mutually perpendicular when the axis of the flywheel is horizontal. Under these conditions the instrument is, of course, freely mounted.

The curved rod terminating in an arrow-head shows the direction of spin. The straight rods are intended to represent the angular momentum of the flywheel and the applied couple respectively. With the direction of rotation shown, the

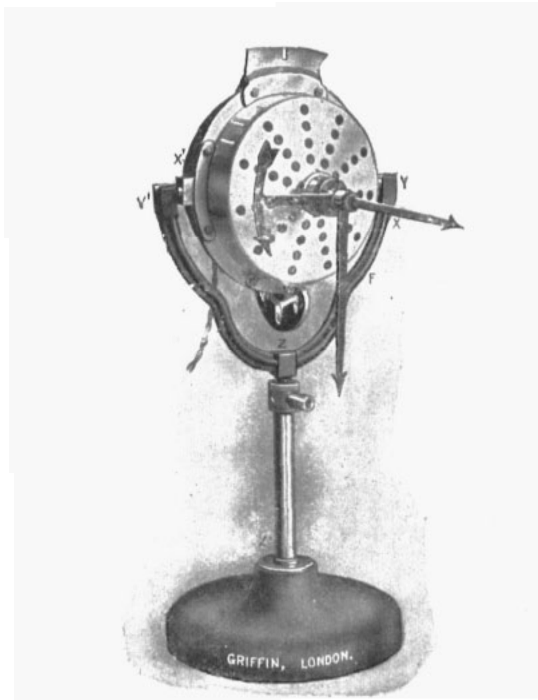

FIG. 1.—GYROSTAT IN "FORK AND PEDESTAL" MOUNTING.

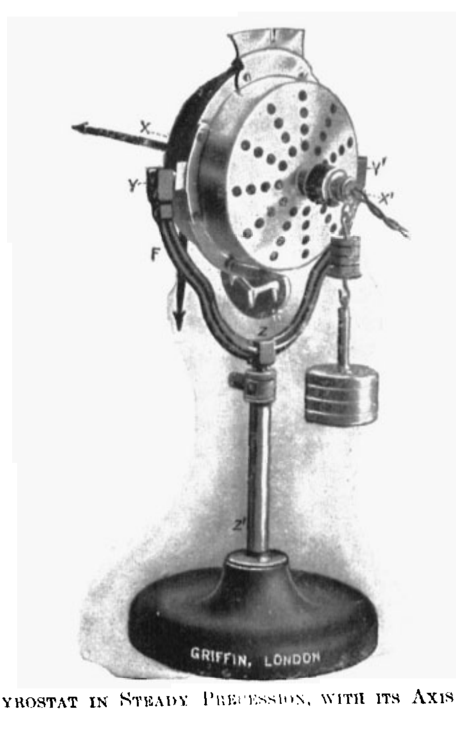

FIG. 2.—GYROSTAT IN STEADY PRECESSION, WITH ITS AXIS HORIZONTAL.

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angular momentum or spin is, according to the usual convention, represented completely by a straight line of proper length, drawn at right angles to the plane of the flywheel, as in the figure. The second straight rod can be moved round in a plane parallel to that of the flywheel; it is held in any position by means of a spring washer. These lines, which represent the "spin" and the applied couple, are called the spin-axis and couple-axis respectively.

The model is available for demonstrating the principal properties of the gyrostat. By its means it is easy to show that if a couple is applied to the gyrostat, so as to cause precessional motion, the motion is such that the spin-axis moves towards the instantaneous position of the couple-axis. This rule always holds. A couple tending to turn the gyrostat about the fork-axis causes precession about the pedestal axis; one tending to cause turning about the pedestal axis causes precession about the fork axis.

In Fig. 2 the gyrostat is shown in steady precession, with the axis of its flywheel horizontal, under the action of a suspended weight. If W is the weight, l the distance of its line of action from the axis of the knife-edges, I the moment of inertia of the flywheel, and ω_1 its angular velocity, the gyrostat and suspended weight turn about the vertical axis with angular velocity ω_2, where

$$Wl = I\omega_1\omega_2.$$

Providing that the vertical axis is frictionless and the spin is maintained constant the weight will be carried round at a constant rate ω_2. In practice, of course, this condition is not fulfilled; there is in general a small oscillation about the steady motion, and, in consequence of friction, there is a gradual descent of the weight with slow variation of ω_2, which (with constant spin) will be an increase or a diminution according as the couple Wl is increased or diminished by the descent. There is a loss of energy on the whole. If the weight descends through a distance d, its loss of potential energy is Wd, and, since for rapid spin ω_2 is small, it is substantially this potential energy that is converted into heat by friction at the vertical axis.

The work done in a given time, T, is $L_1\omega_2T$, where L_1 is the frictional couple. Now the greater the value of ω_1 the smaller is ω_2, and the less is the work done against friction in a given time.

Again, suppose that with the gyrostat in steady precession, with its axis horizontal, a couple of moment L_2 is applied in a horizontal plane in the direction of the precessional motion.

If L_2 is greater than L_1 the effect will be to raise the weight against gravity. The work done by this couple on the weight in time T is $(L_2—L_1)\omega_2T$, and hence the rate of working is proportional to ω_2. This is of great importance from the point of view of the application of the gyrostat as a transmitter of work and as a stabilising agent. For a given value of ω_1, ω_2 is proportional to W, and hence the greater W, the greater is the amount of work done by the net couple $L_2—L_1$ in a given time. If $L_2—L_1$ is small and W great the action is the analogue of the ascent of a heavy weight along an inclined plane of very small slope under the action of a force applied up the plane. Again it will be seen that by making ω_1 very large—that is, by rotating the flywheel at a very high speed—a large weight may be raised through a sensible distance without ω_2T being necessarily great, if L_2-L_1 be made large enough. This point is of importance.

Now let the side weight be removed, and a top weight be added to the frame of the gyrostat, so as to bring the centre of gravity of the system vertically above the line of the fork bearing when the axis of the flywheel is horizontal. When so arranged the gyrostat is unstably mounted in the fork, and if the flywheel is spinning any tendency to tilt will result in precessional motion ; tilting to one side causes precessional motion in one direction, tilting to the opposite side reverses the direction of the precessional motion. Further, if the gyrostat is precessing in one or other direction and a couple is applied to the fork in the direction of the precessional motion the gyrostat tilts on the fork bearing, so as to raise the centre of gravity of the arrangement—that is, so as to annul the tilting couple.

It should be observed that here the gyrostat acts as a transmitter. The couple applied to the fork (which may be called the stabilising couple) is applied in a horizontal plane, the gyrostat and its attachments turn instantaneously in a vertical plane. The precessional motion about the pedestal axis ceases when the centre of gravity of the system is vertically above the line of the fork bearings. If the stabilising couple goes out of existence at the instant at which the precessional motion ceases, and the motion about the horizontal arm be, as it usually is, very slow, the gyrostat is practically left in the upright position.

Precessional motion about the pedestal axis in one or other direction follows on tilting of the gyrostat on the fork bearings. If now a mechanism is devised whereby the fork is forcibly turned in the direction of the precessional motion immediately such precessional motion takes place, and further if the stabilising action ceases at the instant at which the necessity for its existence disappears, it is clear that the gyrostat will be maintained in the upright position.

In Fig. 3 is shown a form of stilt top devised by Prof. H. A. Wilson, and exhibited by him to the Physical Society in 1907. A gyrostat is mounted as shown in a frame, *f*. The gyrostat frame is on cross bearings carried by *f*. When *f* is upright these bearings are in a vertical line. The crank *c*, which is rigidly fixed to the frame of the gyrostat, is attached to one end of a stretched spring *s*, the other end of which is fastened to a point, *p*, in the main frame. If the flywheel of the gyrostat is set spinning and the top placed on a table with the plane of the flywheel and the main frame, *f*, in the same vertical plane, and left to itself, it will balance for a considerable time if the spin is great. Initially *f* is in the same plane as the spring *s*.

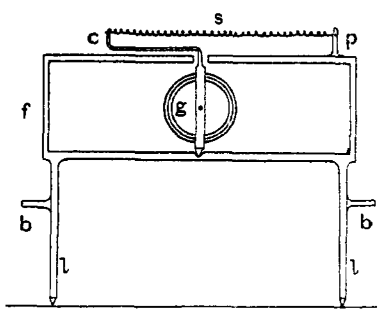

FIG. 3.—STILT TOP.

The stretching force in the latter, therefore, exerts no moment on the gyrostat about the cross bearings which attach it to *f*; but as soon as the gyrostat precesses on the latter bearings the crank gets out of line with the frame, and the spring exerts a moment in the direction of the precessional motion.

The entire top, when vertical, is unstable, without rotation of the gyrostat flywheel, about the line of contact of the feet with the table. Further, in consequence of the stretched spring, the gyrostat is unstably mounted on the frame. Thus the gyrostat is doubly unstable without rotation of its flywheel.

Starting with *f* in a vertical plane containing the crank and spring we may suppose it to tilt over on the table. As a consequence the gyrostat precesses about the cross bearings and the precession is aided by the spring, with the result that the frame erects itself into the vertical. But at the instant at which the frame has attained the vertical the spring is out of line with the frame, and is exerting a moment on the gyrostat. Under the influence of this couple the gyrostat continues to precess about the line of contact of the feet with the table; that is, the main frame passes beyond the vertical position, after which the lateral instability of the entire structure results in the establishment of a couple tending to accelerate this precessional motion. This couple causes precession about the cross-bearing bringing the crank and spring into line with *f*, but when this alignment occurs, the entire top is inclined from the vertical; and so on. The amplitudes of these oscillations continually increase, and finally the top falls over.

Again, suppose that, starting as before with *f* and the crank in one vertical plane, the crank gets out of line with *f*. As a result the spring exerts a moment on the gyrostat, which, in consequence, precesses about the line of contact of the feet of the top with the table. This precessional motion is automatically accelerated and the spring is thrown into line with *f*, which is now inclined from the vertical, and so on.

It will thus be seen that starting with the main frame and the spring contained in one vertical plane the top balances; and if the spin is great the balancing power is very considerable. But there is not true stability. The frame oscillates to and fro on the legs, the gyrostat oscillates to and fro on the bearings which carry it in the frame. If the stability were real the top, if started in an inclined position, would erect itself into the vertical one with the spring in the plane of *f*.

It is interesting to consider this matter from the energy point of view. The entire structure is unstable on the legs, and thus possesses a stock of potential energy. Again, potential energy is stored in the spring. When the frame tilts on the legs and the gyrostat turns on the frame bearings energy is dissipated in friction. Consequently once the frame has become inclined to the vertical, or the crank has got out of line with the frame, the system cannot return of itself to the position of maximum potential energy, that is, to the position in which the frame and crank are in one vertical plane.

In Figs. 4 and 5 are shown two further experiments in which a gyrostat is mounted in such a manner as to possess two instabilities without rotation of its flywheel. In Fig. 4 is shown a new form of stilt top designed by the writer. A gyrostat is

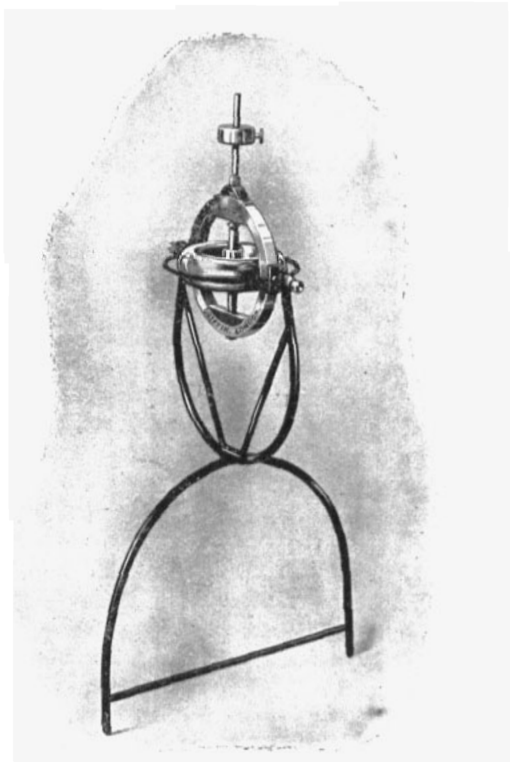

FIG. 4.—FORM OF STILT TOP.

FIG. 5.—GYROSTAT ON GIMBALS.

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carried, with its axis vertical, on two horizontal bearings arranged in a frame terminating in two legs as shown. When the supporting legs and the axis of the gyrostat are vertical, with the weight in the upper position, as shown in the figure, the gyrostat is doubly unstable without rotation. If the flywheel is spun rapidly and the top set up as described, it displays considerable balancing power. But from what has been said it will be evident that this arrangement does not provide an example of true gyrostatic stability. Oscillations about the line of contact of the feet with the ground and about the horizontal bearings quickly grow up.

The top is well adapted to show the necessity for two instabilities without rotation of the flywheel. If the arrangement is set up as shown, but with the weight vertically below the gyrostat, the top exhibits no balancing power.

Fig. 5 shows Lord Kelvin's "gyrostat on gimbals" experiment. The gyrostat is supported on a universal joint, or pair of gimbal rings. When the gyrostat is in the vertical position it clearly possesses two instabilities without rotation, one about each gimbal axis. In performing the experiment the flywheel is rotated rapidly and the arrangement placed on the gimbal rings, with the axis of the gyrostat vertical, and left to itself, when it balances on the ring in contact with the table. The upright position is soon departed from, and is never regained. The axis moves round its initial position, its distance from the latter continually increasing. Energy is continually dissipated at the gimbal axes, which energy is derived from the potential energy possessed by the arrangement by virtue of the peculiar manner in which it is mounted.

Returning now to the top shown in Fig. 3 it will be seen that I have added to Mr. Wilson's arrangement the two projecting pieces, *bb*. So designed it may be set up with these projections engaging on the knife edges arranged in the fork of the apparatus shown in Fig. 1. The arrangement is shown in Fig. 6. The flywheel of the gyrostat is set into rapid rotation and the arrangement mounted on the fork with the frame *f* and the crank in one vertical plane. The fork is grasped in the hand of the experimenter. Now suppose the arrangement to tilt on the fork bearings b_1, b_2. The gyrostat precesses on the bearings that carry it in the frame, and immediately a couple, due to the spring, tending to accelerate the precessional motion, comes into existence. At the same time, the experimenter turns the fork so as to bring the frame into line with the crank.

Providing this operation is properly carried out, the frame is restored to the upright position and the crank is in line with it. The spring has supplied energy to the frame in restoring it to the vertical position, the potential energy lost by the spring has been made good by the experimenter.

Now let a weight, *w*, be attached to one side of the frame. This at once causes precession of the gyrostat and the establishment of a couple due to the spring. The experimenter turns the fork so as to bring the frame into line with the crank. Here energy is being transmitted from the spring to the frame by means of the gyrostat, and at the same time energy is being supplied to the spring by the experimenter. The frame turns on the fork bearings so as to raise the weight against gravity. The precessional motion continues until the centre of gravity of the entire arrangement is vertically above the line of b_1 b_2.

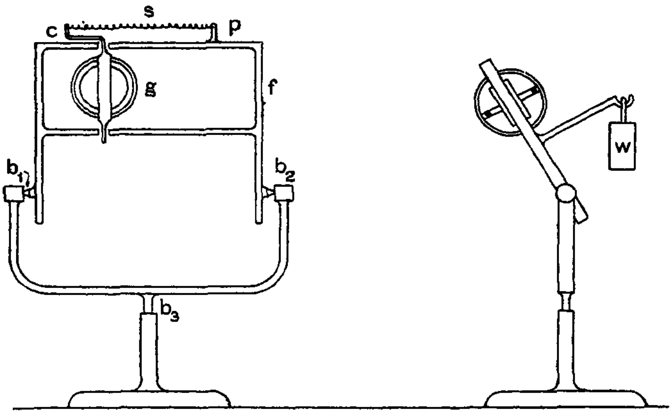

FIG. 6.—STILT TOP SET UP ON FORK AND PEDESTAL MOUNTING.

The spring is now in line with the frame, and consequently its stock of potential energy is precisely that which it possessed at the start of the experiment. The energy required to raise the top against gravity has been supplied by the experimenter.

The action of the top shown in Fig. 7 is identical with that of the one just described. The crank and spring are placed transverse to, instead of in the plane of, the main frame.

Fig. 8 illustrates the applications of the principles just described to the construction of two-wheeled and four-wheeled gyrostatic motor cars. The figure shows a car in which the wheels, of which there are two, run in tandem. The gyrostat *g* is mounted on top and bottom bearings provided in the main frame F. One of the axles which carry the gyrostat is extended and terminates in a bearing for one of the wheels w_1 of the car. The construction is such that this wheel is in the plane of the flywheel of the gryostat. The back wheel of the car is geared up to driving mechanism. The gyrostat is fitted with a crank

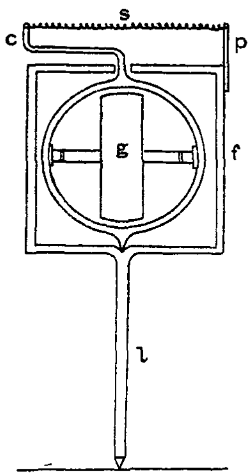

FIG. 7.—STILT TOP.

and spring device as already described. The wheel w_1 and the flywheel of the gyrostat are in the same plane Arrows on the wheels indicate the direction of motion of the device.

Let the flywheel be set into rapid rotation and the car

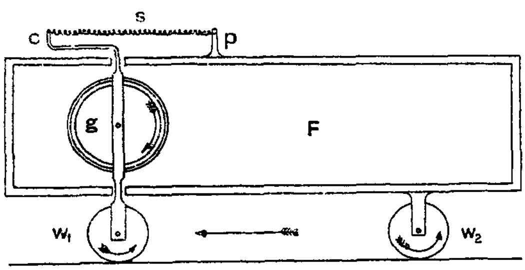

FIG. 8.—TWO-WHEELED MOTOR CAR.

placed on the floor with the main frame, the flywheel ot the gyrostat, the two wheels supporting the device and the crank in one vertical plane. It will be clear from what has been said that, if left to itself, the car will balance on the wheels, but with the accompaniment of gyrostatic oscillations. If it were allowed to remain stationary the device would eventually fall over; but when driven in the forward direction it is completely stable. This stability is obtained in the following way: The gyrostat steers the car, and when precessional motion on the cross bearings takes place this results in the main frame F, to which the end of the spring remote from the crank is attached, being brought into line with the crank. Thus the action is precisely that described above for the stilt top when mounted in the fork bearing. The stability is complete when the car is moving in the forward direction. If a weight is attached to one side the car banks up against the weight so as to bring the centre of gravity directly above the wheels, and thereafter proceeds in a straight line path.

In this device the gyrostat derives the stabilising forces from the spring, and when the stock of potential energy possessed by the spring is drawn upon an equal amount of energy is automatically supplied to it by the propelling system. The gyrostat thus detects a tendency to tilt in either direction, calls upon the spring to supply the necessary correcting forces, and upon the propeller to maintain constant the energy possessed by the spring.

The gyrostatic action of this device is illustrated graphically in Fig. 9. We suppose the car to start perfectly balanced and upright. This condition is shown in (1) of the upper diagram (A) of the figure. The arrow at the back of the car shows the direction of motion, and the curved arrow attached to the gyrostat indicates the direction of rotation of the flywheel. The angular momentum may be completely represented by a straight line drawn out from the flywheel towards the reader. Thus, a_1 is the spin-axis. Now, the car is unstable about the line of contact of the wheels with the table, and hence, after a short interval, a tendency to tilt in one or other direction will assert itself. We suppose that when the car is in the position (2) there exists a tendency of the device to tilt towards the reader. This tilting couple is completely represented, according to the usual convention, by a line a_2 (the couple axis), of proper length drawn as shown in (2) towards the back of the car. The gyrostat precesses, so that a_1 turns towards the instantaneous position of a_2, the crank comes out towards the observer, and a couple tending to turn the gyrostat counterclockwise, as viewed from above, is established. This couple is represented by a_3 in (3) above. The gyrostat now precesses so that a_1 moves towards the instantaneous position of a_3—that is, the car erects itself against gravity; it moves away

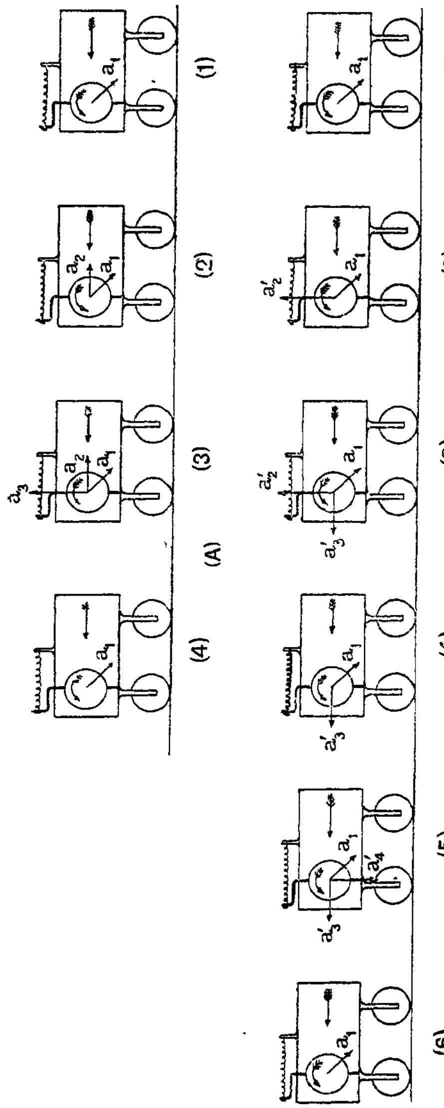

FIG. 9.—ACTION OF TWO-WHEELED GYROSTATIC MOTOR CAR.

A.—March of Vectors following on Tilting of Car towards Reader.

B.—March of Vectors following on Displacement of Spring from Central Position.

from the reader about the line of contact of the wheels with the ground. The tilting couple is thus reduced and finally annulled. Further, in consequence of the fact that the gyrostat is steering the car, which is moving in the forward direction, the want of alignment of the crank and car is being reduced. Thus, a_2 and a_3 tend to diminish together, and the car is finally left as in (4) of the top diagram of the figure.

We may now investigate the annulment of the instability introduced by the crank and spring. This will be understood from the lower diagram (B) of the figure. In (1) the car is shown balanced in the upright position with the crank in line with F. We suppose it to get out of line with the car without there being any tendency of the latter to tilt (this may be due to a jolt). Let the displacement of the crank be towards the reader. The couple brought into existence by the want of alignment is represented by a_2' of (2), and the gyrostat turns so that a_1 moves towards the instantaneous position of a_2'; the car turns over from the upright position (away from the reader), and a couple represented by a_3' of (3) comes into play. The gyrostat now turns on the vertical bearings in the direction which results in a_1 moving towards the instantaneous position of a_3'—that is, in the direction which brings the crank into line with the car. The couple due to want of alignment of the crank and frame disappears, but the car is left inclined to the vertical. This stage is shown in (4). The gyrostat is now precessing on the vertical bearings, and a couple represented by a_4' (5) is introduced. The resulting precessional motion and the forward motion result in a_3' and a_4' going out of existence, as already explained, and the device is left as shown in (6). It is now upright, with the crank and frame F in line.

As we have already seen, the effect of attaching a weight to one side of F is to cause the car to bank up and then to pursue a straight path. The properties of the device are, however, greatly added to by attaching a weight, w, to the frame of the gyrostat, as shown in Fig. 10 (a) and (b). If the gyrostat is spinning in the direction in which the wheels of the car rotate, the weight should be placed as in (a); if the direction is reversed the weight should be as in (b). Consider diagram (a). Let a side weight (Fig. 6) be supposed attached. The car banks up against this weight, with the result that the line of the frame bearings becomes inclined to the vertical. A couple acting against the spring is then applied by. A steady state is now arrived at, in which the couples applied to the gyrostat by the spring and by the weight are equal. The car is not sufficiently banked

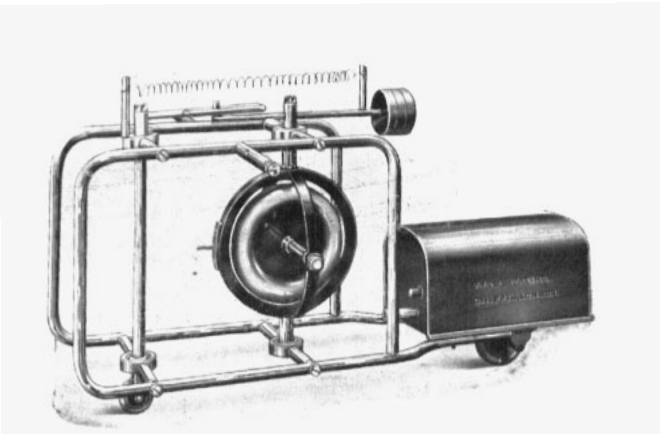

Fig. 11.—Gyrostatic Motor Car.

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up to account entirely for the side weight, and the gyrostat precesses continually. The car moves in a circular path.

When the side weight is removed the device straightens itself out and proceeds in a straight path. Attaching the side weight to the other side of the car causes the latter to move in a circular path in the opposite direction to the former one.

Fig. 11 is a photograph of an actual working model of a two-wheeled car constructed on the above principles. The front wheel is the driven one. The gyrostat is carried on the main frame on vertical bearings. It steers the back wheel through a link attachment. The car is available for demonstrating the action of a monorail car, or the gyrostat can be placed under the control of a weight as just described. It can then be set to move in a curved path in either direction. A much larger model, provided with an electromagnetic steering device

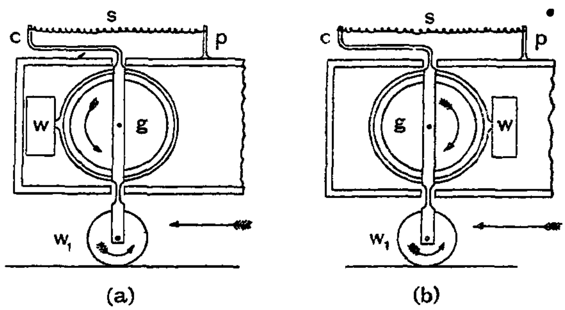

FIG. 10.—GYROSTATIC MOTOR CAR FITTED WITH CONTROLLING WEIGHT.

capable of being actuated by the wireless transmission of electrical action, is in course of construction.

Fig. 12 shows the application of the principle to the steering of a torpedo or dirigible airship. The upper diagram shows a side elevation, and the lower a plan of the arrangement. The gyrostat is mounted, with its axis horizontal, on cross bearings, b_1 b_2, carried by a frame, *f*. This frame is mounted on fore-and-aft bearings, b_3 b_4, attached to the moving body, and the construction is such that the system composed of gyrostat and attachments is laterally unstable on the body. The spring s_1 and the crank *c* render the gyrostat unstable relatively to the frame *f*. The moving body is supposed to be stable of itself. It will thus be seen that the gyrostat possesses two instabilities without rotation of its flywheel. By causing the gyrostat to steer the body these two instabilities without rotation result in complete stability when the flywheel is rotating and the body moving in the forward direction.

In the construction of wheeled vehicles it has been found sufficient to connect up the gyrostat directly to the steering wheel or wheels. In the case where a steering mechanism, such as a rudder or plane, has to be operated forcibly this is not possible. Apparatus for operating a vertical rudder is shown in the lower diagram of Fig. 12. One end of a cord is attached to a point on the frame of the gyrostat. The cord is then passed once or more times round a vertical drum or pulley, d_1, and its free end attached to a point on a drum, D. A second cord is likewise attached at one end to a point on the opposite side of the frame of the gyrostat, passes once or more times round a second pulley or drum, d_2, and is attached to the

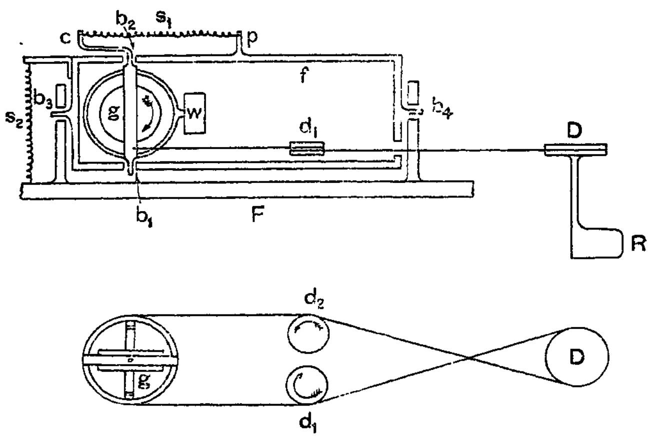

FIG. 12.—DIRIGIBLE TORPEDO, WITH STABILISED GYROSTATIC SYSTEM.

opposite side of the drum D. The two pulleys d_1, d_2, which are of equal diameter, are geared up to a small electric motor; they revolve in opposite directions with the same speed. If the gyrostat precesses one of the cords (say c_1) attached to it becomes taut. A small stretching force in the cord on the gyrostat side of d_1 gives rise to a large stretching force in the cord on the drum side of d_1. If the stretching force on the gyrostat side of d_1 is zero that on the drum side is also zero. It will thus be seen that a small couple applied by the gyrostat results in the application of a very large couple to the drum, and hence to the rudder.

The rudder is so connected up that when the gyrostat precesses the body is steered up parallel to it, that is, so as to maintain the axis of the flywheel transverse to the body.

In the form of torpedo at present in use the gyrostat is freely mounted on gimbal rings. In the absence of a disturbing couple the axis of the gyrostat will retain its direction in space unaltered. Hence when the torpedo deviates in its path a shift occurs between the direction of the axis of the gyrostat and that of the projectile. The apparatus must be made with great precision ; notably the centre of gravity of the gyrostat must coincide exactly with the point of intersection of the gimbal axes. If this condition is not precisely fulfilled the torpedo will travel in a curved path.

The existing type gives very good results over the short distances ; but a gyrostat freely mounted would be useless in a long-distance projectile, even if a motor gyrostat were substituted for the one now employed. This point is not as a rule understood. In a dirigible torpedo, properly so called, the gyrostatic apparatus should be such that the gyrostat is endowed with complete stability. This condition fulfilled, the gyrostat can be caused to bring about turning movements of the torpedo by the application to it of tilting couples.

The device just described is well adapted for use on small dirigible airships. It is easy to contrive apparatus on hydrostatic principles which will cause an airship to ascend to a given height and to remain at that height.

Let, now, the apparatus be supposed mounted on an aeroplane, the bearings b_3 b_4 being fore and aft. The gyrostat is balanced on b_3 b_4 and a lateral tilt of the aeroplane would bring about a shift between it and the gyrostat, which might be utilised to operate the balancing apparatus. The gyrostat, it is to be observed, is maintained automatically in the position in which its axis is horizontal and across the aeroplane. Thus this gyrostatic device, as well as a further one to be described, would appear to be available as a detector and corrector of lateral tilting.

In the device as illustrated the axis of the gyrostat is across the moving body. It is possible to mount the gyrostat, doubly unstable as before, on the body with the axis of its flywheel fore and aft. The frame of the gyrostat is suitably connected up to the steering apparatus in such a manner that the moving body is maintained with its length parallel to the axis of the flywheel. A gyrostat so mounted would appear to be available as a detector and corrector of longitudinal tilting.

In order that a gyrostatic aviator should confer both longitudinal and lateral stability upon an aeroplane it must be mounted with complete stability on the latter with its axis vertical. This would be easy on the principles explained, if it were feasible to steer the aeroplane in a vertical plane. This, of course, is not practicable.

Attention is now directed to Fig. 13, which shows a new form of stilt top. A gyrostat is pivoted within a structure terminating in two stiff legs. When the feet of the top are supported on a table with the plane of the frame vertical the line of the pivots which carry the gyrostat is sloped to the vertical,

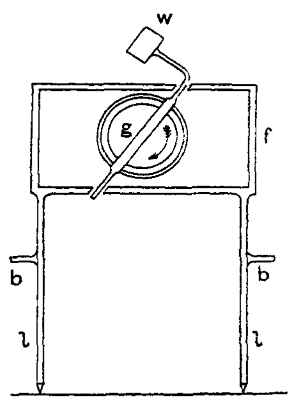

FIG. 13.—STILT TOP.

and with the direction of slope indicated it will be seen that when the plane of the flywheel coincides with that of the frame the weight w is constrained to move, relatively to f, in a circle whose highest point coincides with that occupied by w in the figure. Thus in the position shown the gyrostat, in consequence of the presence of the weight, is unstably mounted on the frame. Further, the frame is unstable about the line of contact of the feet with the table. Thus the gyrostat possesses two instabilities without rotation of its flywheel. If the flywheel is rotated rapidly in either direction and the top placed on a table as described, and left to itself, it will balance on the table. It will be readily seen, however, that the stability is not true stability; gyrostatic oscillations soon grow up.

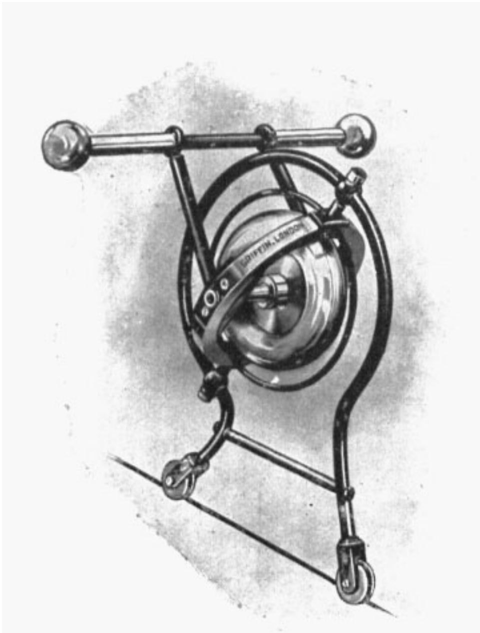

Fig. 14.—Pole-Balancing Top.

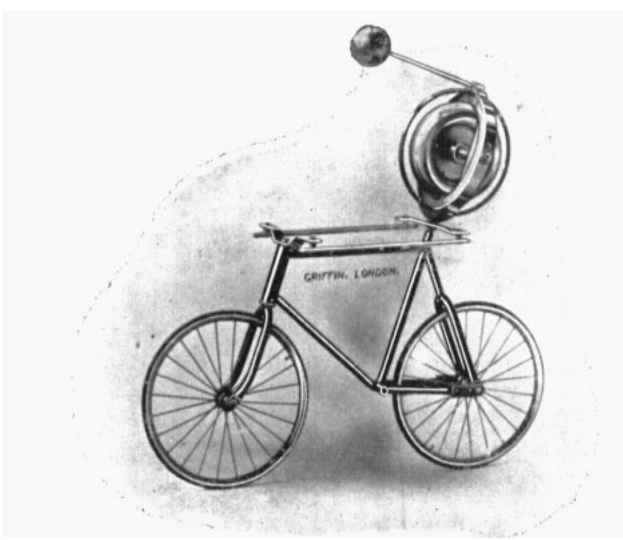

Fig. 15.—Gyrostatic Bicycle.

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Fig. 14 shows a pole-balancing top constructed on this principle. The frame terminates on two wheels adapted to run on a tight or slack wire. Attached to the gyrostat frame are two arms which support a pole weighted at both ends. This pole provides the necessary instability of the gyrostat relative to the frame. The flywheel is rotated clockwise as viewed by an observer from one side with the pole on his left, and the arrangement set up with the frame vertical and the pole horizontal. With this direction of spin the tilting of the frame to one side of the wire causes the pole to be carried over to the other side.

Returning now to the first of the tops just described, let it be spun and set up in the fork and pedestal mounting (after the manner of Fig. 6), with the frame and flywheel in the same vertical plane. As before, the experimenter operates the fork. With the direction of spin indicated in the figure tilting of the frame to one side of the fork causes the weight to be carried over to the other side. Now let a side weight w' be attached to the frame f. The gyrostat precesses on the frame bearings and w is carried (Fig. 13) over to the side of the frame remote from the attached weight; let the fork be turned by hand in the direction in which the gyrostat precesses, so that it follows up the latter. Providing that the fork is not turned too quickly the gyrostat will continue to turn on its bearings. It is to be observed that at any instant the acting tilting couple is the difference of the moments about the fork axis due to the side weight w' and w respectively. The effect of turning the fork is to diminish the moment due to w and the precessional motion is maintained. This action, it will now be shown, has resulted in apparatus of great beauty.

Fig. 15 illustrates a form of gyrostatic bicycle. A gyrostatic bicycle rider is mounted upon a safety-machine. The frame of the gyrostat is attached to the bicycle by means of a sleeved joint, and a pair of arms, carried by the frame of the gyrostat, are attached by means of pivots to the handle-bar of the machine. The construction is such that when the wheels are in one vertical plane the sleeved joint, referred to above, is considerably inclined to the vertical, and this results in the brass ball (*see* the figure) conferring considerable instability upon the gyrostat relatively to the bicycle. The entire machine is, of course, unstable on the wheels. These two instabilities, without rotation of the gyrostat flywheel, are available to annul one another with rotation.

The rider of a bicycle keeps his machine upright by operating his handle-bar. When the machine tilts over to the left the rider instinctively turns the handle-bar to the left, and the forward momentum of the bicycle and rider aided by the gyrostatic action of the wheels (a relatively small factor), results in the erection of the machine. Similarly, if the machine tilts to the right the handle-bar is turned to the right.

The action of this gyrostatic bicycle is entirely different, and much more beautiful. The gyrostat is spun in the direction opposed to that in which the wheels of the cycle rotate when the latter is moving in the forward direction. Tilting of the machine to the right causes the gyrostat to precess, so that the brass ball and the front wheel and the brass ball move over to the left. As described above, energy is supplied from the forward motion, and the precessional motion ceases when the tilting couple is annulled. The stability, when the bicycle is moving in the forward direction, is complete. If brought to rest, following on motion in a straight path, it is left perfectly upright, and it then balances for a considerable time. Gyrostatic oscillations, however, grow up, but on the restarting of the machine these at once disappear. If the bicycle is started in an inclined position it erects itself into the upright position, and thereafter pursues a straight path.

Starting with the bicycle moving forward in the upright position, let a weight be placed on one side of the frame. The machine now proceeds in a circular path, the action being that described for my stilt top when set up in the pedestal mounting. Suppose the weight to be attached to the right-hand side of the frame as seen by an observer viewing the bicycle from behind. The front wheel and the brass ball are carried over to his left. The fact that the gyrostat steers the machine results in the latter turning continually, so as to annul the moment due to the brass weight ; at the same time the precessional motion turns the ball so as to increase its tilting moment. A steady state is soon arrived at, and the bicycle moves in a circular path.

Fig. 16 is a diagrammatic representation of a large motor car constructed on the above principles. It will be seen that the gyrostat stabilises the entire structure and at the same time operates the steering wheel.

The function of the weight W_2 is to apply the necessary tilting couples. W_2 is carried on an arm which is rotated about a vertical axis by means of a small geared electric motor. When completed this car will be capable of being operated by wireless transmission of electrical action.

It should be noticed in the case of this bicycle and the motor car, that, provided the gyrostat is sufficiently powerful, the controlled device cannot possibly upset. The frame is continually following up the gyrostat, which thus cannot lose control.

Fig. 17 shows in side elevation a gyrostatic device adapted for steering a body stable of itself, such as a tricycle, four-wheeled motor-car or torpedo. The gyrostat is mounted on

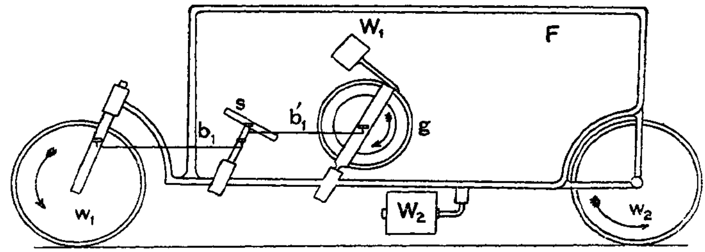

FIG. 16.—GYROSTATIC MOTOR WITH ELECTROMAGNETIC STEERING DEVICE.

bearings b_1b_1 carried by a frame, *f*; it is made azimuthally unstable by sloping the line of these bearings to the vertical, and attaching a weight, *w*, to the frame of the gyrostat. The frame is carried on horizontal bearings b_2b_2 arranged in pillars p_1p_1 attached to the moving body. The frame *f* is rendered laterally unstable on these latter bearings by attaching to it the

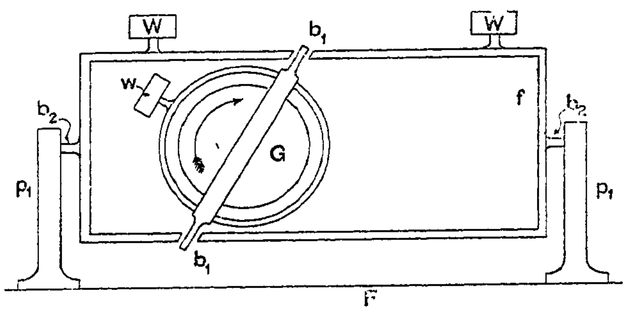

FIG. 17.—GYROSTATIC CONTROL FOR TORPEDO OR AIRSHIP.

weights WW, as shown. The gyrostat clearly possesses two instabilities without rotation of its flywheel. When the gyrostat is suitably connected up to the steering mechanism these two instabilities give rise to complete stability of the gyrostat when the body is in motion. The frame *f* may conveniently carry apparatus for applying tilting couples to the gyrostat.

In arriving at a conclusion as to the merits of the gyrostatic controls that have been described it should be remembered that the action of the gyrostatic system is a function of the angular momentum of the flywheel, of the double instability of the gyrostat, and of the forward momentum of the body. These can be varied to meet particular cases. In general, the greater the speed of the moving body the better is the behaviour of the device. The experiments exhibited show that the contrivances possess great power even when the speed of the controlled body is very small.

It may be pointed out in connection with the applications to the problem of the dirigible torpedo that by arranging that the instabilities of the gyrostat are small its properties are made those of a gyrostat freely mounted. It, however, remains correctly balanced on its mounting so long as the spin is main-

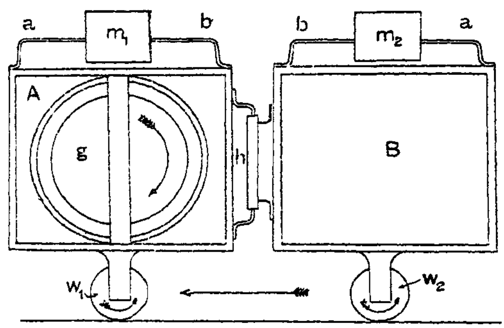

FIG. 18.—GYROSTATIC MOTOR CAR.

tained and the body is in motion. Further, if it is disturbed by any cause (for example, by tilting action to change the direction of motion of the body) it automatically restores itself to the correct position once the disturbance has ceased to exist.

In Fig. 18 is shown a model illustrating a new principle. It takes the form of a two-wheeled motor-car, and has been constructed as an example of a moving body manœuvred by means of a gyrostatic "nose." The model is built up in two parts, a front one, A, and an after and propelling one, B. These are connected together by a vertical hinge, *h*, an arrangement which to most people will appear, on the face of it, absurd. Rigidly attached to the front part, with its axis horizontal, is a gyrostat, *g*. The after part carries the propelling mechanism, which is geared up to the back wheel. When the gyrostat is rotating and the car is in motion there is true stability. If the device is started in the inclined position it erects itself into the upright one. It it is jolted any oscillations which may arise are quickly wiped out.

When the weights m_1 and m_2 shown in the figure are central the action is entirely gyrostatic. The car is, of course, unstable about the line joining the points of contact of the wheels with the ground. Further, the after part is propelling the front part, and thus an instability is introduced through the hinge. These two instabilities without rotation of the flywheel result in complete stability when the car is in motion in the forward direction.

The car is kept upright by the propeller forces. When tilting takes place the gyrostat at once sets about obtaining from the propeller the forces, *and no more,* required to erect the car. The action is shown in detail in A of Fig. 19. The view (1) represents the car when exactly vertical with the two parts in line. The direction of propulsion is indicated by the arrow placed on the after part, and the direction of rotation of the flywheel by the curved arrow. With the direction shown the spin-axis is a straight line, a_1, drawn outwards from the plane of the flywheel towards the reader. View (2) shows the car after a tendency to tilt towards the reader has asserted itself; the tilting couple is represented by a_2. The two parts now get out of line, and the after part exerts on the gyrostat a couple which is represented by a_3. The car now moves up so as to annul the tilting couple. Further, and this is very important, the forward motion of the device tends to bring about a diminution of the want of alignment of the parts. As a result diminution of the tilting couple is accompanied by diminution of the couple applied through the hinge; both couples diminish at about the same rate and finally disappear together. The car is now in the upright position with the two parts in line; its direction of motion has been slightly changed.

Again, suppose the car to be in the upright position with the two parts in line. Let a want of alignment be brought about without there being any tilting couple to account for it (this might be due to a jolt). The gyrostatic action is shown in B of Fig. 19. 1′ shows the car upright with the two parts in line; 2′ shows the device upright, but with the parts out of line; and 3′ shows the car in a tilted position brought about by the want of alignment. The vector a_2' now disappears, leaving a_3', which is accounted for in the manner already explained.

Now, let the gyrostat be rotated in the direction opposed to that in which the wheels of the car rotate, and let the weights

m_1m_2 be put in the positions *aa* of Fig. 18. If tilting takes place the parts turn on the wheels and at the hinge, with the result that the weights *ww* are carried over so as to correct the tilting couple. Further, a stabilising couple is introduced through the hinge. If the weights are placed in the positions *bb* of Fig. 18 the gyrostat should be spun in the direction in which the wheels of the car rotate.

This two-wheeled device is completely stable when being propelled, even though very slowly. When balanced it moves in a perfectly straight path. When the direction of spin is opposite to that in which the wheels of the car rotate the effect of placing a weight to one side—say, to the right, as viewed

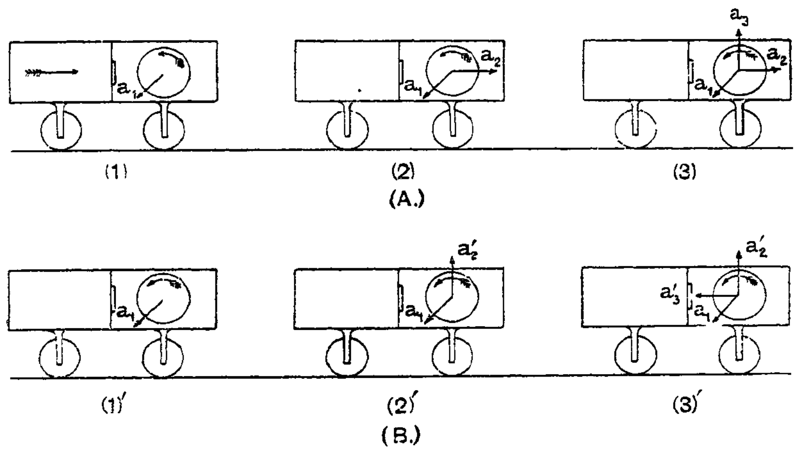

Fig. 19.—Action of Gyrostatic Motor Car.

from behind—is to cause the car to move counter-clockwise in a circular path as viewed from above. Weighting the car to the left causes it to move clockwise in a circular path.

Figs. 20 and 21 show two working models of the device. One of the models, it will be seen, is provided with an electro-magnetic steering device. A very small motor, provided with worm gearing, rotates a weight carried at the end of an arm. When the motor is running the weight is carried round in a horizontal circle. When the arm is in line with the car the latter moves in a straight path ; when it is to one side the car moves in a circular path in one direction ; rotating the weight to the other side of the car and switching off the motor leaves the device moving in a circular path in the opposite direction.

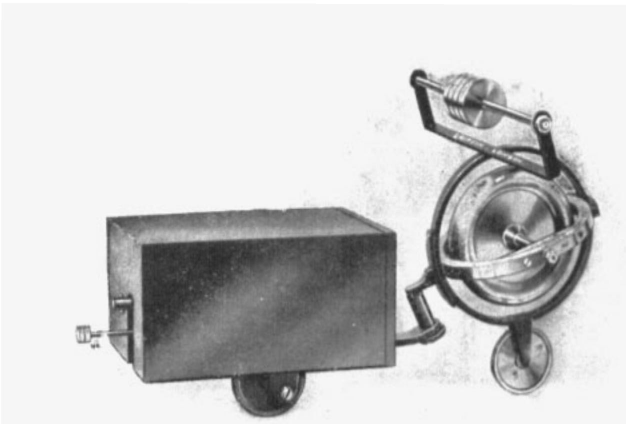

Fig. 20.—Gyrostatic Motor Car.

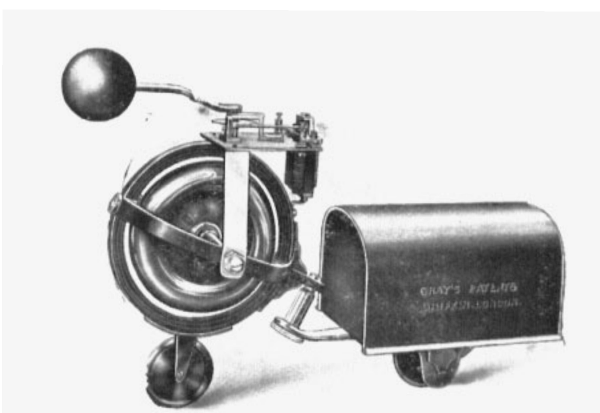

Fig. 21.—Gyrostatic Motor Car with Electromagnetic Steering Device.

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The principles which have just been demonstrated appear of great importance in their applications to airships. As a first example, consider an airship built in two parts, a front one and an after one, connected together by a vertical (or inclined) sleeve. On the front part let there be a gyrostat mounted so as to be laterally unstable without rotation of its flywheel. The after part carries the car, propelling mechanism and power appliances. Provided that the gyrostat is sufficiently powerful, and the construction is properly attended to, this gyrostatic arrangement is one of stability when the airship is in motion. The airship could be manœuvred forcibly in a horizontal plane; the forces required to stabilise the system and to turn the airship against the resistance of the air would be obtained from the propeller system. From the point of view of construction it would simplify matters if the entire airship were made laterally unstable.

Again, let the gyrostat be mounted on gimbal rings at the front of an airship, with its axis fore and aft, and so that the intersection of the gimbal axes passes through the centre of gravity of the gyrostat. Further, let the gyrostat be provided with a system of vanes and springs, so that it is made doubly unstable, without rotation of its flywheel, when the airship is moving in the forward direction. With the flywheel in rapid rotation the gyrostat would be completely stable, and would be of great service in manœuvring the airship in both the vertical and the horizontal directions, the couples bringing about the turning being derived directly from the propelling system, which applies a direct push. To manœuvre the airship couples are directly applied to the gyrostat.

Such gyrostatic airships on a large scale could only be brought to perfection as a result of experiment and trial. Experiments of the nature required are not posssible to a private individual. It may be said, however, that careful calculations have been made relating to the size and power of the motor-gyrostats which would be required, and these could certainly be produced. Such airships are perfectly safe if the gyrostat breaks down. With the propellers reversed and the gyrostat out of action the arrangement is one of stability. In conclusion it may be said that airships on a small scale, capable of being manœuvred by gyrostatic action, could be easily evolved. Such a contrivance could be caused to soar upwards or downwards, or to turn in a horizontal plane in either direction by means of forces derived from a propeller system exercising a direct propulsive force on the system.

ABSTRACT.

The Paper dealt with a number of new contrivances for stabilising, steering and forcibly manœuvring moving bodies, such as torpedoes and airships.

A number of old experiments were first shown. These included the "gyrostat on stilts" and "gyrostat on gimbals" experiments due to Lord Kelvin, the "crossed bifilar" experiment due to Prof. Blackburn, and a stilt top devised by Prof. Harold Wilson. It was shown that the gyrostatic system in each of these experiments, although exhibiting considerable balancing power, was not possessed of real stability. An unstable body rendered truly stable by gyrostatic action must possess the property that if displaced from the mean position it returns to, and comes to rest in, that position. The mean position is that in which the potential energy of the gyrostatic system is a maximum, and if the system is disturbed energy must be supplied to restore it to the mean, or undisturbed, position.

A number of new gyrostatic models were displayed in action. These include two-wheeled and four-wheeled gyrostatic motor cars and bicycles. These all provide examples of gyrostatic systems provided with complete or real stability, and in all the cases shown the stabilising forces are derived from the propelling system.

One of the cars shown runs on two wheels in tandem, and is stabilised by a single gyrostat. This gyrostat is mounted in the car and controls the steering mechanism ; it forms, in fact, a gyrostatic chauffeur. The model illustrated a new form of torpedo and airship control.

A second form of motor car, which also runs on two wheels in tandem, consists of two parts, a front one and an after one. The front part carries a gyrostat, the back part the propelling mechanism, and the two parts are connected together by means of a vertical hinge. The front part is propelled by the back part, and the arrangement is one of complete stability. The entire system may be manœuvred by means of the gyrostat. It was pointed out that by properly fitting an airship with a gyrostatic "nose" it should be possible to manœuvre forcibly the airship by means of forces derived from the propellers.

The bicycles, which are provided with gyrostatic riders, are examples of moving bodies steered by gyrostatic action. The action is quite different from that of an ordinary bicycle. They are not "momentum" instruments.

The devices shown are at once applicable to long-distance torpedoes, both submarine and aerial. The gyrostatic system may be operated by the wireless transmission of electrical action.

At the conclusion of the Paper the author showed a new series of animated gyrostats.

DISCUSSION.

Dr. W. Watson thought the mechanisms shown were of great theoretical importance. He gathered, however, that the author himself thought they were more of theoretical than practical interest. He concluded some time ago that a two-wheeled car would not be of much use, as, although gyrostatic control worked satisfactorily either on a straight path or on a curved path of constant curvature, any attempt to alter the curvature had to be made with great caution. Hence a train built on this system would have to slow up on approaching either the beginning or the end of a bend. With a motor car, where one had to steer immediate courses on account of other traffic, the arrangement would be impracticable. At one time, when some cars had engines laid longitudinally and others transversely, makers of the latter type claimed that gyrostatic action came intc play and tended to prevent skidding. However, unless the gyrostat was free to move relatively to the car, one might as well have a lump of iron in its stead. He had investigated the amount of relative motion which might take place due to give in the springs or mountings, and it was quite insufficient to allow of appreciable gyrostatic action.

Mr. Duddell complimented the author on the collection of beautiful models which he had brought before the Society and the admirable way in which he had explained the principles underlying their action. He asked what speed was attained by the flywheels of the gyrostats.

Mr. R. S. Whipple also expressed his admiration of the models.

Mr. F. J. Whipple asked if the author had worked out the theory of the ordinary bicycle, and if it was his considered opinion that the rider had to perform the actions which he had described in steering. It was his opinion that when travelling rapidly this was not so, and that there was a stabilising effect due to the gyrostatic action of the front wheel. This was particularly noticeable in the way in which the wheel seemed to be pulled back into position if, when riding without the hands, the cyclist encountered a small stone.

Dr. Russell asked concerning the use of the word "gyrostat." He remembered on one occasion when Lord Kelvin was showing some of these experiments to von Helmholtz an accident occurred which resulted in one of the gyroscope wheels passing through Helmholtz's silk hat. After that it was customary to enclose the gyroscope in a brass case, and it was then usually called a gyrostat. He did not quite see why.

The Author, in reply, said that the larger gyrostats could be taken up to a speed of 20,000 revs. per min. in half a minute, and would run for 75 minutes. In steering a bicycle the rider turns the front wheel to the side to which the machine leans, and the forward momentum brings it up to the vertical position. The gyrostatic action helps, but only to a very slight extent. The name "gyrostat" was the one invariably used at Glasgow since Lord Kelvin's time.