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Friday, May 20th, 1859.

Colonel the Hon. JAMES LINDSAY in the Chair.

ON ROTATORY MOTION APPLIED TO OBTAIN STABILITY FOR ASTRONOMICAL OBSERVATIONS AT SEA.

By the Rev. BADEN POWELL, M.A. F.R.S., &c. Savilian Professor of Geometry
in the University of Oxford.

ABSTRACT.

THE subject of rotatory motion is one of large extent when considered in reference to the principles of theoretical mechanics, and is connected with some of the most abstruse theories of analytical dynamics. Yet some of its simpler properties, laws, and results admit of direct experimental demonstration, and such elementary ideas of the subject as can be thus communicated are fortunately quite sufficient for the full comprehension and elucidation of some of the most important and valuable practical applications of the principle.

The object of the present Lecture is restricted to the explanation of one or two of such applications which are interesting, and promise to be of considerable practical importance to nautical astronomy in supplying the means for attaining that much-desired object, a stable support applicable to the purposes of astronomical observations on board ship.

In order to render the description of such inventions intelligible, it will be necessary first to advert to one or two theoretical points involved in the nature of the constructions.

The principle of "the composition of rotatory motion" is one of fundamental importance for the explanation of nearly all phenomena of the kind we are considering. It is susceptible of very simple and elementary illustration. If we merely consider the familiar case of composition of rectilinear motions, a body moving by a force which would alone carry it through a given space in a given time, acted upon also by another force, which in the same time alone would carry it through a space in a direction transverse to the former, will, under both, in the same time, describe a space which is the diagonal of the parallelogram of which the two former are the sides.

In like manner, if a body be rotating about an axis, a point in its circumference describes in a small interval of time a small arc, which may be regarded as rectilinear; if a force act on it which in the same time would cause it to rotate in another direction, or to describe a small arc transverse to the first direction, it will, under both, describe the diagonal of the small parallelogram.

In order that the small arc of the circumference may take this new position, it is merely necessary that the axis should take a new direction,

or the plane of rotation of the whole body should shift into a new position, without any change in its inclination to a given fixed plane.

This is the actual case of the earth's rotation as affected by the attractive force of the sun and moon tending to pull down the protuberant equatorial matter of the terrestrial spheroid into the fixed plane of the ecliptic or earth's orbit, giving rise to that slow shifting of the direction of the earth's axis, which carries with it the equinoctial points or intersections of the equator with the ecliptic, without the smallest change in the inclination of the one to the other, and which is the explanation of the well-known phenomenon, the precession of equinoxes.

Hence, in the general case of compounded rotatory motions the resulting effect of this kind is called a "precessional motion." Of this we have many practical instances, especially in the constructions about to be described.

It is also necessary to explain the term "axes of rotation." If any body of whatever form be forcibly struck, it will acquire, besides the general motion of translation, a *rotatory motion*, unless the stroke happen to be directed exactly through its centre of gravity. There is always some one line passing through it, about which it will for the moment be rotating as an axis; but in general this direction will be perpetually changing, until the rotation at length becomes permanently settled about some line related to the figure of the whole mass, which is termed one of its "principal axes." It can be demonstrated that every body has at least three such axes, and in regular figures their position can be determined.

The principle termed "the constancy of the plane of rotation" is evinced in this, that a heavy body rotating about its principal axis shows a powerful tendency to continue its rotation about that axis, in the plane in which it was originally impressed, so much so as to offer a very forcible resistance to any attempt to give it while rotating any inclination out of that plane. This is most conspicuously displayed when the rotating body is mounted on gimbals, so as to be free to turn in any direction.

To occasion this tendency there is, besides the mere inertia, the law of permanent rotation about a principal axis, and the composition of rotations, from which any small tendency to change of direction would not show itself directly, being compounded with the original rotatory force.

These, and a variety of other analogous and related phenomena, are conveniently exhibited by the small apparatus now generally known under the name of the "Gyroscope," originally devised by Bohnenberger, and described by him in 1816, and since largely improved upon by various other mechanists, until it has received its most complete form from the improvements of Professor Wheatstone, in 1854. While for more specific purposes it has received a different construction in the beautiful adaptation of M. Foucault, in 1854: the idea of which was, however, suggested by Mr. Sang of Edinburgh so long ago as 1836.

These preliminary considerations will prepare the way for the elucidation of that remarkable practical application of the principle of rotatory stability which is the specific object of the present Lecture, the means of affording a stable platform for astronomical observations on board ship, exempt from the motion of the vessel.

It is true that for some of the most ordinary, and at the same time most important, operations of nautical astronomy, this stability, owing to the happy invention of Hadley, is not needed.

But there are other classes of observations which it is highly desirable, if not necessary, to make at sea, for which this principle of stability is absolutely essential. Nay, even for the ordinary purpose of measuring altitudes, there are continually occurring cases when the sea-horizon cannot be discerned, while the sun or star is clearly seen above. Hence some means of obtaining an artificial horizontal level becomes of great importance, but unattainable by those means so easily practised on land, by reason of the motion of the ship. Hence, with only this limited, but important, object in view, various plans have been devised; and of these one of the most hopeful was derived from the principle of rotatory stability. The commonest observation showed how easily such stability (in a general sense) was acquired by the mere spinning of a top: and, though many other considerations were really involved, not at first fully apprehended, yet the general idea seems to have presented itself more than a century ago to the inventive mind of Mr. Serson; at least, as far as seems at present known, this is the earliest attempt of the kind on record. The invention consisted essentially in a circular plane reflector through the centre of which an axis passed, the lower part of which terminated in a steel point resting in a hemispherical cup of agate: on the upper a string could be wound by which it was spun; as the support moved with the ship the point shifted its position in the cup, always tending to the lowest point, and thus a nearly horizontal rotation was attained. A brass rim round the reflector descended so low as to bring the centre of gravity of the whole nearly into coincidence with the point of support. If this coincidence had been exact, the instrument would have been more perfect, theoretically, than some since made.

An account of the instrument will be found in Brewster's *Cyclopædia*, art. Sextant, with a figure. A shorter account is given in Rees's *Cyclopædia*, art. Horizontal Speculum.

The inventor went on board the *Victory* in 1744 to try the plan. In this ship (of 110 guns and 1100 men) he was unfortunately lost, when it was totally wrecked by striking on a reef off Alderney in the night.

In the *Phil. Trans.* 1751-2, there is a paper by Mr. James Short, who speaks of the invention as well known. He also states that this top when spun took "the true horizontal plane," and was not disturbed by any motion or inclination given to the box in which it is placed; and thus "may be proper to be used aboard ship" for taking altitudes.

Mr. Short's object was to try whether (as had been suggested) the air had any share in causing this horizontality. He therefore tried spinning it *in vacuo*; and observed that, while in air it kept up 36 minutes, *in vacuo* it continued spinning for 2 hours 16 minutes, "preserving a perfect horizontality for three quarters of an hour."

Owing to whatever cause, however, the invention of Serson seems to have fallen not only into disuse but into oblivion. Some plans on exactly the same principle have been proposed more recently, apparently without any knowledge on the part of their inventors of Serson's priority. But it does not appear that any material improvement in the performance has been attained.

Another invention, that of Mr. Weir, some years later, differed from Serson's only in making the centre of gravity fall below the point of support. This, as we shall presently see, was an error.

Apparently without any knowledge of what Weir or Serson had done, a machine of exactly the same kind was independently devised and constructed by the late Mr. Troughton in 1820. It consists in causing a disc, truly balanced on a fixed pivot, to spin round with great velocity, so as to keep up its motion during the time required for an observation, known by the name of "Troughton's top." The disc carries a plane reflector on its upper surface; and, being a cylinder hollowed out at its lower end, and the point of support within, the centre of gravity is thrown below, so that it is in stable equilibrium when at rest. The velocity is communicated by a separate train of wheels, from which it can be instantly detached. Thus set going it would acquire a momentum which would keep it steadily rotating uninfluenced by the motion of the ship. Such at least was the expectation formed from the acknowledged "stability of rotation."

It may be proper here to observe, that, simple as this idea was, the practical application of it involved several instances of those mechanical resources which its inventor could so readily supply. One of these (of importance in all similar instruments) is the means of obviating the unavoidable inequalities of density in different parts of the most accurately cast metallic disc, as well as defects in accuracy of form, which affect the perfect equilibrium. These were remedied by plugs, or small pieces of metal, screwed more or less deeply into holes made for them at opposite parts of the circumference, three vertically and three horizontally placed, by which, in successive trials, a complete compensation was effected.

The method was, however, practically found to fail. But the cause of failure was by no means understood at the time, nor indeed till some years afterwards, when it has been satisfactorily traced to another mechanical principle. The pivot partakes in the irregular motion of the ship. When the disc is not revolving, this motion is in turn communicated to the disc; and the centre of gravity being below—the very circumstance which gives it stability on land—causes it to acquire an oscillatory movement. When in rotation, this does not show itself directly, but is compounded with the rotation, and causes a precessional motion, which is fatal to its use as a horizontal reflector, as at once appears from considering the principles of rotation at first laid down.

At the same time there were, no doubt, cases under peculiarly favourable circumstances when this plan might be resorted to. So much, however, was the want felt of a method which could be generally relied on, that several other schemes, not dependent on rotation, were successively proposed by naval officers and men of science for obtaining an artificial horizon at sea.

Of such inventions (including those of the late Admiral Beechy, of a glass floating on mercury, of Mr. Fallows by a vessel of mercury suspended from the sextant, and others,) it would be hazardous to speak without reference to actual experience; but it is believed that, though several such plans have been recommended by professional authority, and may be occasionally available under particular circumstances, yet most of

them have been found in some way inconvenient or inefficient for general use; and the cause of failure might in several instances be traced to mechanical principles now better understood than formerly, especially where the principle of suspension is involved, as just explained.

Thus the thoughts of inventors were again turned to the fertile principle of rotation, and, on reconsidering more attentively the causes of failure of the top of Troughton, as arising from the pendulous oscillation, it became evident that to remedy this difficulty we might cause the centre of gravity of the disc to coincide with the point of support, as would be readily done by suspending the revolving disc with its axis and pivots in rings constructed as gymbals, in the manner of the gyroscope of Bohnenberger already alluded to, and thus this cause of irregularity would be avoided.

Having thus the principle of a stable plane secured, still it would remain to bring it to the true horizontal direction, or at least to have the means of determining that direction or the deviation from it.

To this object accordingly Professor C. P. Smyth's attention was directed. Several modifications of the spirit-level had been suggested for this object; but the sound principle of its application was soon seen to be attainable by a simple combination of mechanical and optical means, whence Professor C. P. Smyth was at length led to a very simple, complete, portable, and efficient construction.

As this construction itself is of an optical nature, and not connected with rotation, it would be foreign to the present object to describe it in detail; but we may just mention that it consists essentially in the bubble of a spirit-level reflected from a diagonal mirror above it, seen through a collimating lens, so adjusted that in one inclination the apparent position of the bubble coincides accurately with the true horizontal direction, whence it is easily demonstrated that in every other inclination, within certain small limits, the apparent place of the bubble will deviate from its former place by the same angle as that by which the base is inclined, or will in all positions give the true horizontal direction, the level-tube being bent into a small arc of a circle, whose radius is equal to the principal focal length of the lens.*

Such an instrument being supported on the perfectly balanced rotating disc, into which we have supposed Troughton's top converted, the observer will be thus furnished with a direct view of the true horizontal point with which the image of the sun or star can be brought into coincidence in the usual way with the sextant.

But for other classes of observations on board ship, which involve the direct use of the telescope, especially where one of considerable power is requisite, the condition of invariable stability is yet more necessary, though hitherto unattained.

One of the most important instances of such observations are those of the eclipses of Jupiter's satellites, which it is well known afford so ready, easy, and accurate a method of obtaining the longitude, but hitherto found inapplicable at sea from want of the means of mounting a telescope so as to be free from the motion of the ship.

* This contrivance has been fully described in the Notices of the Royal Astronomical Society, vol. xviii. p. 65, Jan. 1853; it was also exhibited at the Paris Exposition in 1855, and described in a printed notice.

Attempts, however, to attain this object have not been wanting. Indeed the suggestion seemed obvious of some means of this kind, arising out of methods commonly practised on board ship, for giving a kind of stability required for the ordinary purposes of life, such as suspending a table on slings, by which it is, in a certain sense, rendered comparatively steady, so that articles keep their places on it; for example, a glass of water placed on it does not spill.

This effect, however, when more carefully considered, is seen to be only one of the same kind as the common experiment of whirling a vessel of water over the head without spilling; the surface of the water keeps perpendicular to the string, not parallel to the horizon.

When we consider the case as to its mechanical conditions, it readily becomes apparent that a body thus suspended is like a plumb line, when the point of support is itself set in motion it acquires a part of that motion, and from a plumb becomes a pendulum; and it oscillates more irregularly and violently from the accumulation of motions impressed upon it continually by every fresh motion of the ship. The case is the same as that just considered in Troughton's top, but here distinctly displaying itself without any concealment from compounding with other motions.

The invention, which formerly obtained considerable celebrity, called Nairne's or Irwin's "Marine Chair," for carrying the observer and his telescope, was simply an application of this principle. It was tried on board ship, especially in a voyage to the West Indies, by the late Dr. Maskelyne; and, though somewhat prematurely rewarded by the then government, was found not to answer, though no one seemed fully aware of the cause of its failure till Sir J. Herschel (in the "Admiralty Manual") pointed out the principle just stated, and showed that this free suspension must tend to increase and perpetuate disturbances rather than destroy them.

In these cases the centre of gravity is below; this is what constitutes the table or chair a pendulum. If it were suspended in gimbals, so that the centre of gravity should be at the point of suspension, the tendency to oscillate from this cause would be overcome; but still any slight cause might disturb the level; there would be no principle of permanent stability, or tendency to restore the equilibrium when lost.

Yet that, under occasional and very favourable circumstances, this, or any like plan, might be found available, it would be difficult positively to deny. It has, in fact, been alleged that observations have sometimes been effected in this way; but we must suppose that it can only have been in the hands of peculiarly skilful observers, and that the case is quite exceptional.

We have noticed the causes of failure in several apparently promising suggestions for attaining the desired stability; we have also hinted generally at the channel through which a better expectation appears to be opened. To produce this desired stability for a plane or stand on which the telescope is to be rested, we must have recourse to the free revolving disc accurately balanced within gimbals on its centre of gravity. But in following out the details of such a construction there are many points to be attended to. In the first place, agreeably to what was before observed, it will be evident that the equability of density in the mass requires to be carefully secured, and the balancing must be perfected by means of the

adjustable plugs before mentioned, both in the disc and in the gymbal frames; the pivots of the gymbals must be of perfect workmanship, to turn with the least possible friction, yet without looseness or displacement; an immense rotatory velocity must be communicated to the disc by machinery, of which its suspension must be quite independent, so that the moving power can be instantaneously withdrawn. All these conditions are fulfilled in the form of the machine which, after repeated trials, has been adopted by Professor Smyth, exhibited by him at the Paris Exhibition in 1855, and successfully tried by him on board Mr. Stephenson's yacht *Titania*, on his voyage to Teneriffe in 1856.*

The machine is in fact simply a gyroscope, but of a form peculiarly modified to suit the special purpose for which it is intended.

To explain the principle of its action, we must consider the general conditions of the case.

In the first instance, it may be necessary to bear in mind that a telescope pointed to a star may undergo a motion of translation to any extent, and in any direction, provided it retain strict parallelism to its original position, that is, remain pointed to exactly the same altitude and azimuth, and it will retain the object in its field just as if it were absolutely fixed. This (it is obvious to any one acquainted with astronomy) is simply the result of the absence of parallax in the heavenly bodies within the limits of these observations, and applies even to distant terrestrial objects. Thus, if we imagine a ship going in a perfectly straight course on a perfectly level sea, or even if its motion on the waves were confined to one straight direction up and down, this parallelism might be retained; but this, it need hardly be said, is not the actual case, even if the course be perfectly straight, so that the motion of the telescope, in this respect, is perfectly of a parallel kind, yet still the pitching and rolling take place by angular motions, in planes respectively parallel and perpendicular to the length of the ship. The slightest angular motion is destructive to the parallelism of the telescope. It is against this, therefore, that it is our object to guard.

Now to explain the manner in which this result may be obtained, we have merely to recur to the general mechanical principles already laid down; and from these it will be at once understood that, in the construction of the gyroscope or revolver suspended in gymbals, the grand principle of fixity of the plane of free rotation is that which enables the revolving disc to retain parallelism to its original plane, however the external frame or pivots supporting the whole be moved. From this principle the revolving disc resists all angular change of position in directions perpendicular to its plane, but it offers no resistance to any motion in that plane. Thus, if set spinning horizontally, it will resist all angular motion impressed in a vertical plane, either by the pitching of the ship in the direction of its length, or its rolling in the direction of its breadth; but it will not resist lateral motion in a horizontal plane, such as any shifting of the ship's head towards the points of the compass.

* See a paper "On the Angular Disturbances of Ships, &c." by Prof. C. P. Smyth, F.R.S. Trans. of Royal Scottish Society of Arts, vol. iv. part 4, 1857; also Astron. Society Notices, vol. xvii. p. 36. A full notice of the whole subject will also be found in the American Annual of Scientific Discovery for 1859, by D. A. Wells.

In fact, Professor Smyth's original and simpler construction was nothing more than a single balanced revolver thus mounted.

Thus a free revolving disc in gimbals, externally turning on pivots horizontally resting on supports fixed to the deck, will suffice to preserve the telescope from all deviation due to pitching and rolling; the addition of another disc, freely revolving in a vertical plane, whose external pivots turn vertically in a frame attached to the top of the former internal frame, the upper pivot projecting through it, and carrying a small platform for the telescope, and the whole, of course, balanced below, will preserve the telescope from any lateral deviations of the ship; and the combination of the two will give a plane retaining its parallelism against all three causes of disturbance. But under favourable circumstances this last cause of disturbance is but small; so that this addition may be often of little importance.

The invariable platform of this revolving apparatus may then equally be applied to support either a telescope, or the artificial horizon before mentioned, whether simply or in conjunction with the sextant, or reflecting circle.

To render the construction more intelligible the annexed figure is inserted, in which it will be at once seen how the conditions first mentioned are fulfilled.

The lower part of the stand is fixed firmly to the deck; on the first pair of pivots pp the circular rim r swings: this, by the second pivots qq , carries the frame ss , in which turns the vertical axis aa of the heavy balanced disc d . The upper part of ss terminates in a similar but smaller frame $s's'$, in which, in like manner, the ring $r'r'$ turns on vertical pivots $p'p'$. In this ring, by the second pivots $q'q'$, is suspended an inner ring $r''r''$, which carries the disc d' by an horizontal axis a' .

The axis $p'p'$ goes through the upper part of the frame, and to this is attached the support on which may be fixed either the telescope, as represented, or an artificial horizon.

In such a construction we have supposed the observer to stand or sit on the deck of the ship, himself exposed to the motion from which his telescope is exempt; and in this manner were Professor Smyth's trials of the machine on board the yacht actually made; and, from the large amount of motion to which so small a vessel was liable, it may be concluded that a severe test of the capabilities of the method was afforded. The trial appears, however, to have been perfectly satisfactory; but, doubtless, the use of the telescope under such conditions would require considerable skill and practice on the part of the observer, both of a nautical and of an astronomical kind.

The great difficulty being thus got over, it may, perhaps, be thought better not to embarrass ourselves with mere refinements of construction to meet objects which, though of much convenience and value, are not equally essential.

Yet it is evident that, for nice observations, it would be a great advantage to any observer, however skilled, to possess the means of partaking himself in the stability given to his instrument. It may thus not be without interest to devote a few further remarks to the possibility of securing an object of such evident convenience.

Now it is obvious from the nature of the construction that in theory, at least, by a mere enlargement of the scale of the machine, the same stand which carries the telescope might be made to carry the observer also, which would be a material convenience for any nice observations. But a practical difficulty arises: the essential condition is the preservation of perfect equilibrium about the centre of motion. Now if this were secured by proper compensation for the observer in one position, the slightest change of position on his part would vitiate that arrangement.

The observer, instead of being an extraneous source of disturbance to the supports, and thus incapable of producing any impression on the balanced and revolving system, now becomes a part of it, and thus impresses upon it a fresh motion, arising from every slight change of posture, which alters the exact position of the centre of gravity of the whole. This effect, however, would not manifest itself directly, but, being compounded with the rotation, would show itself in a precessional motion, fatal to the stability of the direction of the telescope.

But even the difficulties thus arising may be shown to be capable of being obviated by a mere extension of the same principles as those already appealed to. And though this form of the construction has not been as yet been practically tried—as indeed, its merely secondary importance has hardly seemed to render necessary—yet Professor Smyth has clearly explained the conditions of the case, and fully described a construction by which the evils are obviated.

In fact, the remark above made points to what would take place in a single revolver. If we merely suppose two such revolvers, having their pivots at right angles in a common exterior frame, but both rotating in the horizontal plane, so that one be corrected for pitching, the other for rolling, then any slight disturbance of the equilibrium of the whole would

be resisted by one of the revolvers, according as it might tend to turn the frame about the line of the exterior or of the interior pivots of the entire frames. The resisting revolver would show the disturbing force compounded with its rotation, and giving a tendency to precessional motion, which, when the speed was great and the disturbance small, would be long before it was completed, and thus, for the time, preserve the stability.

Thus, as Professor Smyth observes, "If any want of balance is produced on the frame, it is not immediately altered thereby, the first effect being only to make the appropriate wheel turn on its gymbal pivots. If, too, the wheel is heavy and the speed great, this precessional turning will be so slow that there will be time for an attendant to press in the opposite direction on the general frame, and correct the effect of the observer's want of balance, before the plane of rotation coincides with the direction of the disturbing force, when the virtue of resistance ceases."

To strengthen the effect, and at the same time to give a more convenient balance to the whole, the two discs respectively are reinforced each by a corresponding revolver at the other end of the same diameter of the frame, and similarly mounted in the inner general frame.

Thus all angular disturbance in vertical planes being got rid of, it only remains, on the principle before described, to add a fifth revolver in the middle, in a vertical plane, to counteract angular horizontal motion. The inner general frame supports a vertical frame, which carries this last revolver. Thus we have the construction of "the compound precessional free revolver stand," as the inventor designates it.

It is hardly necessary to add that, in all forms of the apparatus, the motion is communicated by a separate train of wheels, exactly on the same general principle as before described. But, to complete the whole, Professor Smyth has carefully investigated the best form of a train of wheels for communicating the rotatory motion; and has also considered the question of the best moving power to be used—which he finds, after many trials, to be that of water—which is best brought to bear by a peculiarly beautiful and simple form of the turbine.*

* This is fully described and figured in the paper before referred to.