The Mariner's Compass.

MORE than 300 years ago William Barlow, writing of the compasses of his day, said that, though the compass needle was "the most admirable and useful instrument of the whole world," yet nothing was more "bungerly and absurdly contrived." How little advance was made in the succeeding two centuries can be gathered from Peter Barlow's remark to the Lords of the Admiralty in 1820 that "the compasses in the British Navy were mere lumber, and ought to be destroyed." It was Barlow himself who made the first notable improvements in compasses during the nineteenth century, and his work was the prelude to the important investigations of Airy, Archibald Smith, Kelvin, and others. The practice of "swinging ship"—that is, turning a ship slowly round and noting the deviations of the compass in different positions by taken bearings—was introduced in 1810 by Matthew Flinders, who also invented the use of the "Flinders bar," a rod of soft iron placed near the compass to correct for changes in the magnetism of the ship due to the vertical component of the earth's magnetism.

The gradual increase in the employment of wrought-iron fittings in wooden ships; the use of iron cables instead of hempen; the placing aboard of ponderous iron boilers and engines; and, lastly, the construction of the vessel itself of iron, each in its turn added difficulties to the problems involved. Barlow, in his attempts in 1819 to find a remedy for the large deviation due to the extending use of iron in ships, made the first experimental investigation of the phenomena of induced magnetism. From his inquiry he was able to give a simple means of correcting ships' compasses by fixing soft iron discs in suitable places near the compass, and he afterwards introduced a type of compass having four or five parallel straight strips of magnetised steel fixed under a card, which remained the standard pattern until Kelvin brought out his famous patent in 1876.

The mathematical investigations of Poisson and of Airy about 1838 led to the introduction of methods of correction by the use of permanent magnets, and also of the well-known soft iron spheres. Many of Airy's experiments were made in the iron vessel *Rainbow* off the old Woolwich Dockyard.

The story of Kelvin's share in the improvement of the compass has often been told. Asked in 1871, by his friend Norman Macleod, to write an article for the newly founded magazine, *Good Words*, Kelvin chose as a topic the mariner's compass. The first part of his article appeared in 1874, and the second not until five years later. "When I tried," he said, "to write on the mariner's compass, I found I did not know nearly enough about it. So I had to learn my subject. I *have* been learning it these five years." The Admiralty standard compass, adopted in 1842, and in use when Kelvin took up the matter, had a card 7½ in. in diameter, and under it four needles, each of which was a long, straight bar of flat clock spring placed on edge. The card and the needles weighed about 1600 grains, and had a period of vibration of 19 sec. So considerable was the friction that the binnacle was often kicked by the sailors to make the card move. Kelvin's "gossamer structure" of eight small needles weighed about 170 grains, and had a period of about 40 sec. The cold reception Kelvin received from the then Hydrographer to the Navy, and Airy's remark on the compass, "It won't do," remind one of the reply made to Berthon in 1835: "The screw was a pretty toy which never would and never could propel a ship."

The ultimate adoption of the Kelvin compass was largely due to Lord Fisher, who had one on board the *Inflexible* at the bombardment of Alexandria in 1882. Torpedo craft, however, continued to be supplied with a form of compass in which the whole card floats in liquid, and improvements made in this type led to its being adopted as the standard compass about 1906. Since this has come the invention of, first, the Anschutz, then the Sperry, and, now, the Brown gyro-compasses, the introduction of which has taken place during the last ten years. As remarked by Mr. S. G. Brown in the Royal Institution discourse reproduced below, the gyro-compass is a necessity in a submarine, while in larger vessels it has the great advantages that it can be placed below the water-line more or less immune from gunfire, and lends itself to utilisation with fire-control apparatus and the torpedo director.

All the work on compasses for the Navy is to-day carried out at the new Admiralty compass observatory at Ditton Park, near Slough, where the work of the five departments—the gyro-compass branch, magnetic compass branch, optical branch, experimental branch, and air compass branch—is superintended by the director, Capt. F. O. Creagh-Osborne.

The Gyrostatic Compass.

BY S. G. BROWN, F.R.S.[1]

THE subject of this lecture is the gyrostatic compass, often called the gyro-compass. An engineer of my acquaintance was asked if he understood what a gyro-compass was, and he replied, "Of course I do; it is a magnetic compass mounted upon a gyroscope." Now the gyro-compass has nothing to do with magnetism or the magnetic compass. The

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[1] Discourse delivered at the Royal Institution on Friday, January 30.

only thing that these two instruments have in common is the property of pointing north and south. I am anxious that this should be clearly understood, because in a recent lecture I gave at Bournemouth on this very subject one of the audience asked me after the lecture how the gyro-compass was shielded from outside magnetic influence. I pointed out, as I had endeavoured to do during the lecture, that the gyro-compass had nothing to do with magnetism, and, therefore, did not require shielding. The magnetic compass and the gyro-compass are, in fact, two absolutely different instruments operated by entirely different laws, although they are for the same purpose.

As many people do not understand why a gyro-compass is needed when the magnetic compass is already available, it is worth while to describe briefly the magnetic or mariner's compass before attempting to explain the gyro-compass. The mariner's compass consists of a magnetic needle, or of several magnetic needles fixed side by side, and balanced upon a sharp point. A card divided into thirty-two (points of the compass) is attached to the needle, and swings round with it, so that the point marked N on the card always points to the north.

The earth, as we know, is a magnet, but not a very powerful one, and it has been calculated that if it were wholly of iron it would have an intensity of magnetism 17,000 times greater than it has. All the same, the magnetism is sufficiently strong to give a good directive action to a pivoted needle. The magnetic poles of the earth are not coincident with the geographical poles, but are situated some distance away. The north magnetic pole was discovered by Sir J. C. Ross to be situated in latitude 70° 5′ N. and longitude 96° 46′ W. in Boothia Felix, just within the Arctic Circle some 1000 miles away from the actual pole.

With this displacement of the magnetic poles we have an irregular distribution of the magnetism over the surface of the earth; and thus the magnetic needle does not point truly north and south at many parts of the earth's surface. In London, for instance, it points at an angle of 16° W. of the true north. This angle is called the deviation or variation of the needle. To enable ships to steer by the compass, magnetic charts have been prepared and the deviation at different places accurately measured. These magnetic charts have to be checked and altered from time to time, as the deviation slowly varies from year to year. Thus in London in 1659 the needle pointed true north, while in 1820 there was an extreme westerly variation of 24½°. Since then it has been slowly coming back to something like 16° at the present time.

On a wooden ship the accuracy of a good modern magnetic compass leaves little to be desired, but on an iron ship the case is quite different. The magnetic field of the earth tends to be weakened in the lengthwise direction of the iron ship, because a portion of the magnetism enters the ship, while across the ship the field is stronger; and as it is essential that the magnetism in which the needle lies should be uniform in strength in whatever direction the ship may happen to point, it is important that this stronger field should be reduced by some method of magnetic shielding. This is accomplished by fixing a pair of iron globes athwart the ship on the two sides of the compass. The effect of the iron of the ship and the corrections that have to be made to the compass is to reduce the directive force of the earth's magnetism, and thus the compass is rendered slow and sluggish in its action. This is particularly the case on board a battleship. In the interior of a submarine the force is still further reduced, so much so as to render the magnetic compass useless for this class of vessel.

It is quite possible on an iron ship to correct the errors of a compass, but as the ship itself may be a magnet, and its strength a variable quantity, it is important that the navigator should test the readings of his compass at every available opportunity, and particularly at the commencement of each voyage. The ship's magnetism may quickly change through the hammering action of the waves, through the heating action of the sun on one side of the vessel, or through an earth on any of the electric wires that may be running near the compass; all these things together add to the anxiety of the captain, as he is never quite certain how far the compass is correct in its readings.

The swings of the modern compass are damped by immersing the needles and card in a liquid such as alcohol, but as this fluid is attached to the ship and turns with it, swinging the ship in any direction carries the liquid round and reacts on the needle and card, so that the compass has a tendency to be carried round with the vessel. This lag in the instrument renders it difficult to hold a ship dead on her course, and the path, as a consequence, is sinuous, and may oscillate, even in a calm sea, as much as 7° each side of the correct heading. As a ship has usually to steam entirely by the readings of the compass, any error is serious. For instance, if there is an error of 3°, and the ship is steaming at sixteen knots, she will move one English mile off her course every hour. It is obvious how necessary it is to have absolutely correct readings.

Lord Kelvin was the first seriously to study the errors of the magnetic compass. He started in 1871, and in 1876 produced his well-known instrument. Although it was a great advance on any compass in the British Navy, he had the greatest difficulty to get it adopted; finally, in 1879 he proposed to place an instrument at the disposal of the Admiralty at his own expense. This offer was accepted. In spite of this, it was only through the acquaintance of influential naval officers, particularly of Capt. (now Lord) Fisher, that the compass was ever adopted. In 1889, eighteen years after the commencement of his experiments, and long after it was in common use in commercial ships, he received official notification that his 10-in. compass was to be adopted in future as the standard of the Navy. It is fortunate that we have an alternative method of securing a north-seeking property in the gyro-compass, an instrument of much greater accuracy than the magnetic and with none of its errors; for if deviations do occur they are known deviations, and can therefore be allowed for.

Evans and Smith, in 1861, were the first to discover how important it was to mount the needles on the card so that the moments of inertia of the moving system should be the same about all directions—that is to say that the system should be in dynamic balance, otherwise the rolling of the ship would cause deviations in the reading. I have lately discovered that another deviation may be brought about, not by an oscillation in one direction, but by the card being set wobbling; the needles and card would then have a force applied trying to carry the moving system round in the direction of the wobble.

I have a magnetic compass here to demonstrate this. It consists of a heavy brass disc mounted on a vertical frictionless spindle. The needles are fixed to the disc, and the whole movable system is carried on a pendulous mounting, as in the gyro-compass. The disc and needles are in correct static and dynamic balance. Swinging the pendulum in any one direction produces no deviation, but by making it swing in a circular conical path, thus giving a wobble to the plate, a serious deviation is caused in the reading of the compass. The error is permanently maintained against the earth's attraction so long as the circular motion of the pendulum persists. When the compass is carried round in a horizontal circular path without wobble, the plate still goes round, or tries to go round, with a circular movement. This should be of interest to mathematicians.

Before leaving the instrument I will set it spinning so as to demonstrate the frictionlessness of the vertical axis. It is rotating now entirely by means of the energy of the motion of the plate, and I think you will find at the end of the lecture that it is still revolving, but, of course, not so fast as at present.

The magnetic compass is a simple piece of apparatus, but it is complicated in its readings and corrections, and points to the magnetic north. The gyro-compass is a complicated instrument, but simple in its readings, and it points to the true north.

Before proceeding to describe the gyro-compass I wish to direct attention to the equipment here displayed. A gyro-compass is in full operation, and at the present moment is recording its movement upon a travelling strip of paper. About half an hour before the lecture started the compass was deflected from the north position, and it has since been left to itself. The record shows that it is engaged in swinging back again to the north, recording a curve upon the paper strip, and this record can be followed during the whole of the lecture.

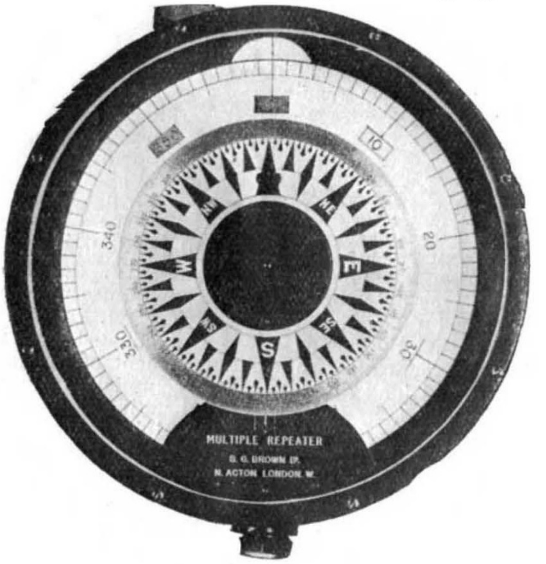

FIG. 1.

The compass is working two repeaters, which truly copy the reading of the master compass. Of course, any number of repeaters could be used on board ship if it were necessary. The steering repeater (Fig. 1) has a card that revolves four times to one of the master, and the divisions are, therefore, very much enlarged. The other is a correction repeater; it moves backwards and forwards very slightly, and this motion we term the "hunt." In the steering repeater the "hunt" has been cut out by providing the mechanism within the case with a requisite amount of slackness.

About sixty-eight years ago Foucault did what was thought a wonderful thing at the time; he gave a lecture-room proof that the earth was rotating on its axis—he looked through a microscope at a gyrostat. He could not get a frictionless, free, vertical axis, so that the experiment could not last for long. I shall be able to show you a piece of apparatus which carries out Foucault's idea in a perfect way, and will be visible to this audience.

A gyrostat consists of an accurately balanced spinning wheel, mounted with as little friction as possible, and in such a way that the axis of the wheel may point in any direction in space. Mere translation in space has no action on the instrument; carrying it about, for instance, does not alter the direction of the axis. On the other hand, the gyrostat is acted upon by any force that tends to tilt the axis or to give the axis a new direction in space.

The wheel (Fig. 2) spins round its axis; call the direction of this *oa*. If we impress a force upon the wheel tending to tilt or rotate it round another axis *ob*, then the rule is that the spinning wheel will "precess" or move in such a direction as to try to make the two axes *oa* and *ob* coincide, and the direction of spin of the wheel to coincide with the new direction of rotation that we are trying to produce by the applied force.

An electric circuit has similar mathematical laws to those of the gyrostat, and may be used as an illustration. The circuit here used (Fig. 3) consists of an outer fixed coil and a central suspended coil. A strong direct current indicated by *a* is kept flowing in the central coil; this corresponds to the spin of the wheel. If a direct current indicated by *b* is sent round the outer coil, then the central coil will move in such a direction as to make not only the axes of the magnetic fields of the two coils, but also the direction of the two currents, coincide. In fact, the coils will move, or try to move, in such a way as to make the self-induction of the whole circuit a maximum.

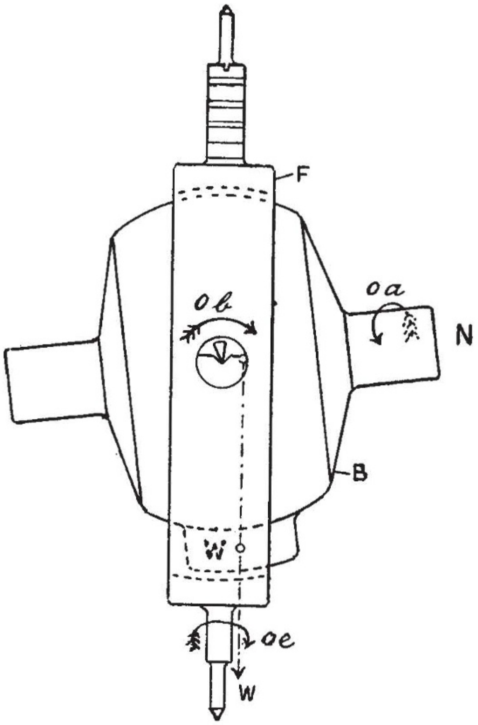

FIG. 2.

This is very much like the gyrostat, or, in fact, any piece of mechanism which under impressed forces tends to move so as to make the whole moment of momentum a maximum. Suppose, therefore, a gyrostat has its axis *oa* fixed parallel to the earth's surface, but free to turn in "azimuth," as it is called, upon a frictionless vertical spindle; the earth will act upon such an instrument, and it would be a gyro-compass.

The earth as it rotates is continually tilting the axis of the wheel in space; the wheel will therefore turn so as to set its axis of rotation as nearly as possible parallel to the axis of the earth. It is only when the two axes coincide that the wheel is free of any further tilting action—that is, when it is pointing true north; deviate the axis, however slightly, from this position of rest, and the action of the earth comes in again to precess the wheel back again to the north.

Here is a simple form of gyrostat with three degrees of freedom. If I hold it in my hand and revolve on my axis, this does not move the wheel, which still keeps pointing to the same part of the room. On the other hand, if I restrain or clamp one of its degrees of freedom so that I am able to tilt the axis of the wheel during my revolution, the wheel is caused to precess and to set its axis parallel to the axis on which I am revolving. Reversing the rotation, the wheel also reverses.

This is what takes place with the gyrostat on the earth's surface provided it is frictionlessly mounted. Such an instrument is before you, and I will try to demonstrate by its means the rotation of the earth. A wheel is rotating inside this case at 15,000 revolutions per minute. The case is constrained to move about this vertical frictionless axis. Mere motion of translation has no effect in changing the direction of the axis of the wheel, but if this room rotates the axis of the wheel tends to set itself parallel to the axis about which the room is rotating.

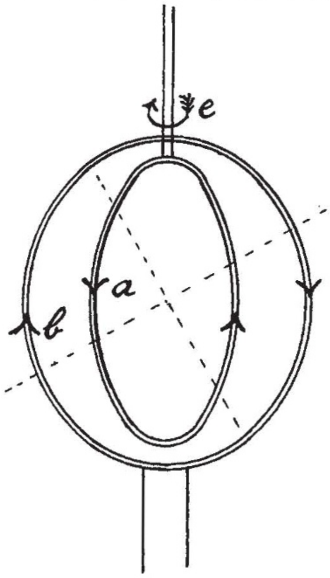

FIG. 3.

We all believe that this room is rotating about the axis of the earth; if so, the axis of the wheel must set itself parallel to the axis of the earth, but it must be kept horizontal, and, therefore, it will point north and south. Here it is pointing in an east-and-west direction; it is held by a string. I will now burn the string, and it will find for us the true north. Observe that it is really the true north direction, whereas that magnet points to the magnetic north. I set it away from the north, but on the other side, and repeat the experiment.

Such a simple form of gyro-compass could not be of any use on a moving ship, because the rolls of the ship would react too violently on the spinning wheel and cause considerable deviations in the readings of the compass. The use of a gyro-compass on land is very limited, and its great value at the present time is on board ship. The spinning wheel is acted upon by forces which tilt the axis. Now, a rolling and pitching ship is about the worst place to put a gyrostat to act as a compass, because the ship's movements all tend to tilt the axis.

The problem, therefore, is to make the compass insensible to the movements of the ship and respond only to the slow angular rotation of the earth. To indicate the severity of the ship's movements, I may recall a recent trip of this gyro-compass on board a fast destroyer. During a severe gale the ship was recorded to roll more than 50° of total angle. Many of the crew were forced to lie on the decks, the lockers emptied their contents, and even some of the oil-lamps suspended from the ceiling were unseated by the pitching of the vessel; yet the gyro-compass maintained its accuracy, and allowed the ship to be steered safely into harbour, to which she had to run for safety. In all this whirlwind of movement the gyro-compass heard, and only responded to, the still, small voice of the earth's rotation.

For use on board ship the compass must be mounted on a pendulum in gymbal rings, and its period of oscillation is lengthened to something like $85'$, which is usual in practice, so that the rolls, which are of the order of 7 to 15 seconds' period, shall have but small effect on the compass. In this case the rotation of the earth does not act directly upon the gyro-wheel, but by means of the force of gravity through the pendulous weight. Unfortunately, this form of mounting introduces troubles of its own.

Suppose we study our simple gyrostat and see what happens when we attach a weight to the end of the horizontal spindle; this will give us some idea of what occurs when the force of gravity is acting through the pendulum trying to tilt the gyro-wheel.

We know from our law that the wheel will precess under the tilting action, but the new direction of rotation that we are trying to produce by means of the weight, unlike that produced by the earth, which is always in one direction, is in this case continually carried round by the precessing wheel, and the precession is, therefore, permanently maintained. We also find that if we hurry the precession the spindle rises, lifting the weight; while, on the other hand, if we delay the precession, the spindle drops and the weight falls. The rate of precession is proportional to the weight. Halving the weight, for instance, halves the rate at which the wheel rotates round the vertical support.

Coming back again to our pendulous-mounted gyro-compass (Fig. 2); suppose the spindle is pointing west and is horizontal, then the earth as it rotates will leave the wheel pointing in this one direction in space, but the weight will try to follow the earth's rotation, and will start precessing the gyro towards the north. The rate at which the wheel comes to the north depends upon the weight W attached to the casing. All the time the wheel is coming to the north the earth is adding to the rate of the precession, and the spindle is, as a consequence, tilted, and deflecting the weight at the north position. Under these conditions the effect of the weight is to continue the precession, and the gyro-wheel will swing through the north position, and continue to move until the effect of the earth arrests and reverses the motion.

The compass will therefore continue to swing through the north position with constant amplitude backwards and forwards, undamped. To render the compass of use, some method of damping the swing must be introduced so that the compass may finally settle on the north. This damping can be carried out by means of friction, preferably fluid friction, between the vertical spindle and its support; but, although this will damp the swings, it is inadmissible because the movements of the ship would react through the friction and cause errors in the reading.

Anschutz, in his early form of compass, by use of an air blast, gets rid of this connection with the ship. The air blast was arranged to oppose the movement in azimuth when the wheel tilted, and thus he obtained an effective method of damping. The strength of the air blast, which varies proportionally to the tilt, should be nothing when the compass is at rest on the north—that is, when the tilt is nothing—and this would be true with the compass on the equator.

In other latitudes, however, the compass rests at the north with a tilt still remaining. It does not come back to the horizontal position because the axis of the wheel is trying to set itself parallel to that of the earth. This leaves a residual air blast continuously acting, producing a permanent twist in azimuth and a constant error. It is, therefore, preferable to damp the swings of the compass by acting upon the tilt rather than upon its movement in azimuth, because in this case there will be no latitude error. The tilt is a maximum at the middle of each swing—that is, when it is moving through the north position—and it is the return of the weight to its truly vertical position that is responsible for the continuation of the oscillation; we therefore require some method of neutralising the action of the weight, not before, but after, the compass has reached the north. This I accomplish in the Brown gyro-compass by automatically moving a liquid from one bottle to another, and in such a direction as to counterbalance the weight, precessing the gyro-wheel, and I delay its action by means of a valve or constriction in the tube joining the two bottles.

The force with which the compass seeks the north is proportional to the product of the rotation (one revolution in twenty-four hours) and the spin of the wheel. The faster we can spin the wheel, the more do we obtain directive force. It is for this reason that the wheel is rotated at its maximum speed and strength consistent with the rise of temperature.

Taking the Brown gyro-compass as an example, the wheel, which is 4 in. in diameter and $4\frac{1}{4}$ lb. in weight, runs at 15,000 revolutions per minute. The maximum directive force of the earth on this wheel—that is, when the spindle is pointing east to west—is only the weight of 30 grains, with a leverage of 1 in. This small force is continually diminishing in value as the axis approaches the north direction, and vanishes absolutely in that position. If the compass was deflected, say, 1° from the north, then the force of restoration is only $\frac{1}{2}$ grain at a leverage of 1 in. It will therefore be seen how important it is to eliminate as completely as possible any friction on the vertical axis that would tend to oppose the directive action of the earth.

There are three forms of gyro-compass now in use: the Anschutz (German), the Sperry (American), and the Brown (British). In the Anschutz the vertical axis is supported by a bath of mercury, and in the Sperry by a suspended wire, the twist, if any, being taken out by a follow-up motor through an electric contact, which switches on the current to the motor; while the Brown is operated by a hydraulic system of support. The lower end of the vertical spindle acts as a ram and stands upon a column of oil. The oil is under great pressure, some 500 lb. per square inch, and is kept pumping up and down, and thus raising and lowering the vertical axis continually some 180 times every minute.

The continual movement of the spindle results in a practically frictionless vertical support, so that the total moving part, some $7\frac{1}{2}$ lb. in weight, can be carried round in azimuth by the smallest force, due to the earth's rotation; in fact, so small is the friction that the compass, if deflected, will always come back again to its true north position, certainly within one-tenth of a degree. I think I am safe in saying that it is the most perfect frictionless support yet given to the vertical spindle of any gyro-compass, or, indeed, of any machine.

In an earlier part of this lecture it was stated that the period of oscillation given to a gyro-compass is of the order of $85'$. I will now try to explain why this is so. The earth has no angular movement from south to north, but has one from west to east, due to the daily revolution on its axis. A ship, however, sailing to the north at, say, twenty knots an hour introduces an angular movement in that direction because it is moving over the curved surface of the ocean, and would complete a revolution of the globe in forty-five days.

If there were a gyro-compass on the ship the instrument would be sensible of these angular movements, set itself so as to make a compromise between them, and, as a consequence, point, not to the true north, but one or more degrees west of the actual pole. This division is termed the "north steaming error." Knowing the latitude, the speed of the ship, and its direction towards the north and south, the extent of the error can be accurately calculated, and speed-correction tables have been prepared so that this error can be determined for any latitude, speed, and heading of the ship, and can be allowed for.

Automatic means have also been devised to make these necessary corrections in the reading of the compass. For instance, my special form of repeater has been designed so that the card can be set eccentric, and, when once set, the correction will be automatically applied without any further reference to the tables.

When a ship is in harbour a gyro-compass on board points due north, but when the ship starts steaming to the north the compass begins an oscillation so as to bring the axis of the wheel into the new resting position to include the north steaming error in the reading. Getting up speed will, however, have another effect on the compass. We know that the gyro-wheel is acted upon by a pendulous weight. As the ship changes its speed the acceleration will act upon the pendulous weight and cause an oscillation to be started. This oscillation is termed the "ballistic deflection."

The permanent north steaming error and the transitory error due to the ballistic deflection are in the same direction, and mathematicians have calculated that with an undamped gyro-compass, if the time of its oscillation is set to $85'$ in any particular latitude, the ballistic deflection can be made exactly the same as the deflection due to the north steaming error; this being so, the compass should move into its new resting-place without further oscillation. This would be true if, as before indicated, the compass were undamped in its swings, but the mathematicians have overlooked the fact that all gyro-compasses are damped, and the ballistic deflection must, therefore, include a term due to the damping.

This damping term up to the present has been neglected, but in practice it is found that when a ship is steaming and turning to alter its course the compass does not come dead-beat to its new position, but has an oscillation started which is common to all existing gyro-compasses. The extent of this oscillation may be termed the "damping error." On a merchant ship the damping error is of little moment, but on a war vessel which is manœuvring it may be serious, as it may swing the compass off its correct reading by several degrees.

(To be continued.)