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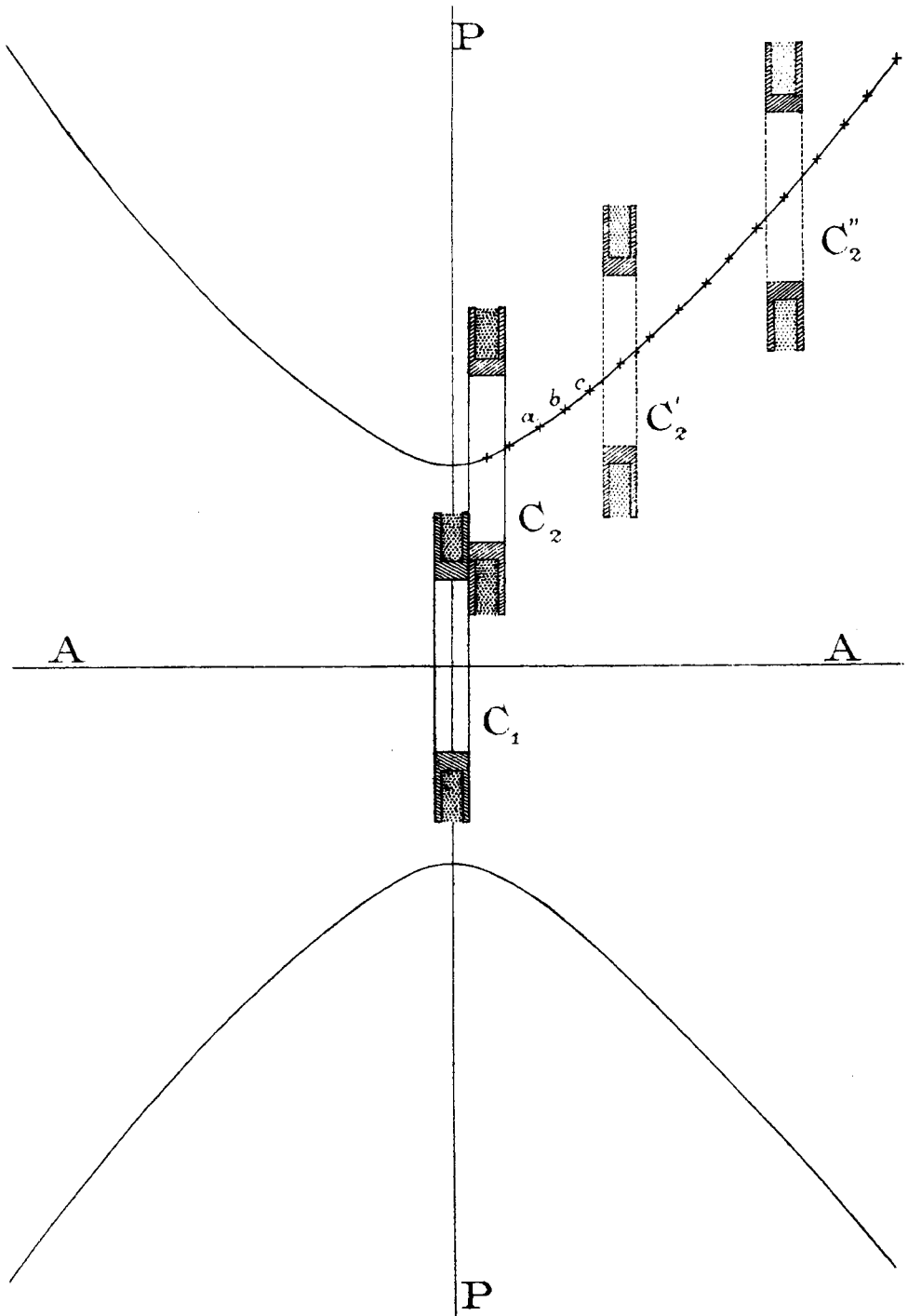
XIX. *On the Conjugate Positions of two Circular Coils of Wire.* By W. GRANT, Assistant in the Physical Laboratory, University College, London*.

[Plate XVII.]

WHILE recently engaged on some experiments on induction, I observed certain circumstances which I had not before noticed, and which seemed deserving of further attention. I was therefore led to inquire a little more closely into these matters; and although the investigation is by no means full or complete, I have obtained one or two results which I thought I might venture to lay before the Physical Society. The apparatus used in these experiments consisted, as at first arranged, of two coils of copper wire, one of which was connected in circuit with a battery of three Leclanché cells, and with a microphone which was actuated by a watch, while the other was connected with a telephone, in order that the induced currents, while passing through it, might render audible the beating of the watch which was used as the source of sound.

A modification of this arrangement was afterwards tried, a Grove's battery of twelve cells being substituted for the Leclanché battery, and a key being used for making and

* Read June 28th, 1879.



breaking the circuit. This was done in order to obtain greater inductive effects between the coils than could be obtained from the variations in the strength of the current which were caused by the action of the microphone. It was found, however, that with a little care in the adjustment of the coils, one cell gave sensibly as great an effect in the telephone as twelve cells; in subsequent experiments, therefore, the Grove's battery was discarded, and that of Leclanché again resorted to.

Now if two similar coils, connected as above described, are arranged with their planes parallel and their axes coincident, it is found that they may be separated to a considerable distance before the sounds which are heard in the telephone on making and breaking the circuit are obliterated. But it is also found that if the planes of the coils are kept parallel, the one in connexion with the telephone (that is, the secondary coil) may be placed in certain positions in the neighbourhood of the primary coil, and even in contact with it, without sounds being heard in the telephone. This happens when the mutual inductive effect between the two coils becomes zero; and when they are so placed as to fulfil this condition, they are said to occupy conjugate positions relatively to each other.

With the first arrangement of apparatus it was possible to place the coils so as to get complete silence in the telephone. With the powerful current from twelve Grove's cells and the key for making and breaking the circuit, however, the silence is not absolute; but in the positions which give a minimum of sound the sound is very faint, being just audible and no more. This faint sound may perhaps be accounted for partly because the different convolutions of wire in the secondary coil experience slightly different inductive effects from the primary one, and partly because it is difficult to adjust the positions of the coils with any great degree of accuracy without having special arrangements for the purpose.

Now it was found that the various conjugate positions in which the secondary coil could be placed in the neighbourhood of the primary one were situated in a path along which it could be moved either towards or away from the primary coil without sounds being heard in the telephone, but that

with a slight deviation from this path to either side the sounds were again heard.

In order to ascertain whether the direction of the currents in the secondary circuit was reversed when the coil was moved from one side of the path to the other, a delicate reflecting galvanometer was substituted for the telephone, and the position of the coil so adjusted that on making and breaking the circuit no deflection of the galvanometer was observed. The coil was now moved slightly away from this position, say, towards the right; and the direction of the deflection of the galvanometer on making contact was noted, that on breaking being, of course, in the opposite direction. The coil was now moved towards the left to the other side of the path, and the direction of the deflections again observed; and it was found that they were now reversed. We may therefore infer that this path (which, if it could be fully traced, would of course constitute a surface of revolution about the axis of the primary coil) divides space into two regions, in one of which the inductive action of the primary coil has the opposite direction to what it has in the other.

This path appeared to be slightly curved; and it seemed as if a part of it might very readily be traced. The part which appeared to be best suited for this purpose was that along which the secondary coil has to pass while being moved away from contact with the primary one parallel to it to a position at some distance from it, as here the inductive effect is greatest, and therefore any deviation of the coil from the proper position in the path is most easily detected. As the coils are further separated, however, the position of the path becomes more difficult to trace, until at last we lose it altogether.

In order, then, to trace a curve which would represent this path, it was necessary to find several points in it whose positions could afterwards be accurately laid down. This was done by fixing the secondary coil in several positions successively and determining the position of a certain point in it with relation to certain fixed objects, by measurements which were afterwards used as abscissæ and ordinates in tracing the curve. These measurements were taken in inches; and their values are given in the annexed Table, where the columns

headed x and y are those of abscissæ and ordinates respectively.

$x.$	$y.$	$x.$	$y.$
0.625	4.0	4.5	7.5
1.0	4.19	5.0	8.12
1.5	4.56	5.5	8.75
2.0	5.0	6.0	9.37
2.5	5.5	6.5	10.0
3.0	5.94	7.0	10.62
3.5	6.44	7.5	11.25
4.0	7.0	8.0	11.87

No special arrangement was used to adjust the parallelism of the coils, and only one measurement was taken for each number; hence the irregularity in the increase of the ordinates. The point whose position was determined in each case was the centre of the plane of the secondary coil; and that is the point which is situated in the curve when silence is maintained in the telephone.

The curve (Pl. XVII.) is that found in this way; and it represents the path which the selected point of the coil has to follow in order that silence may be maintained in the telephone. C_1 and C_2 are sections of the primary and secondary coils respectively; C'_2 and C''_2 represent the secondary coil in two other conjugate positions. The lines A, A and P, P represent the axis and plane of the primary coil. The points a, b, c , &c. are the intersections of the abscissæ and ordinates, and represent the successive positions occupied by the selected point of the secondary coil when the measurements were taken by means of which the curve was traced. As the coils became further separated, however, the position of the curve became less distinct; and so no attempt was made to trace it further.

If, now, we suppose the curve to rotate round the axis of the primary coil, a surface will be generated of which it is a section; and if we observe the conditions necessary for placing the secondary coil in the curve in the proper position for silence, we may place it in any part of the surface with a like result.

The reason why we are enabled to trace a curve in this way will be found by referring to the lines of force due to a circular current. These lines are represented by closed curves surrounding the section of the wire through which the current

flows ; and they are given in Prof. Clerk Maxwell's work 'On Electricity and Magnetism,' vol. ii. pl. 18. If we draw tangents to them parallel to the plane of the circular current, it will be found that the points where they touch are situated in a curve somewhat similar to that which we have found by experiment. The two curves, however, will not be found to coincide exactly, except in the case where the secondary coil does not enclose a space—that is to say, when its diameter is infinitely small. With respect to the curve drawn through the points of contact of the tangents to the lines of force, it will be seen that the direction of all these lines between the curve and the axis of the circular current is away from, and that their direction on the other side of the curve is towards the plane of the circular current: hence on opposite sides of the curve their tendency is to produce currents in opposite directions.

If the curve is now supposed to revolve round the axis of the circular current, all lines of force enclosed by the surface generated will tend to produce currents in one direction, while all lines outside the surface will tend to produce currents in the opposite direction. Therefore, when the secondary coil is so situated with respect to this surface that as many lines of force pass through it in one direction as in the other, the resultant inductive effect on it will be zero; and this will be the case when it occupies any of the conjugate positions*.

It is evident from this, therefore, that we may combine the coils in several ways for the suppression of inductive effects:—first, by placing them close together face to face with their axes coincident, and so arranged that one of them may be moved across the face of the other parallel to their planes till a balance is obtained; secondly, by placing them at some distance apart with their planes parallel and their axes coincident, and so arranged that if their planes are vertical each of them

* In what precedes, the planes of the coils have been always supposed to be parallel to each other; but it evidently follows from the reasoning here indicated that, if any set of parallel tangents be drawn to the lines of force and a curve be traced through the points of contact, an infinitely small coil would experience no inductive effect if it were placed with its centre anywhere in this curve, and with its plane parallel to the given set of tangents.

may be made to rotate round its vertical diameter ; then if they are joined together when their axes are coincident, and combined like parallel rulers, they may be made to rotate together until a balance is obtained. With regard to this combination, it may be observed that the greatest inductive effect occurs when the planes of the coils are at the greatest distance from one another—and that as the planes approach, this effect gradually diminishes, until, when they are still at some distance, it becomes nothing.

Another, and perhaps more convenient, way of combining them is to place them, as in the last case, with their planes parallel and their axes coincident, the distance between them being equal to, or a little greater than, the radius of either coil : then, if their planes are vertical, we may fix one of them in that position ; and if the other is capable of rotating round its vertical diameter, it will be found that when it has rotated through 90° (that is, when the planes of the coils are at right angles) the inductive effects in the secondary circuit have ceased. If the coil is made to rotate through a few degrees to one side of this position, the currents induced in it will be in a certain direction ; and if it is rotated to the other side, their direction will be found to be reversed.

As with either of these combinations we could pass from sound to silence, some experiments were made in order to compare the rate of diminution of the induced currents with the movements of the coils in passing from a maximum to a minimum of inductive effects.

For this purpose the coils were placed with their faces in contact and their axes coincident, the secondary one being joined in circuit with a reflecting galvanometer. In this position five observations were taken and the mean recorded. They were now separated until their planes were an inch apart, and a mean of five observations again taken ; and this process was repeated at intervals of half an inch till the distance between them was increased to five inches.

They were now arranged as in the first combination, their faces being in contact during all the experiments ; and while their axes were coincident, five observations were taken and the mean recorded. One of them was now slid over the other, the faces being still in contact, through a distance of half an

inch and a mean recorded as before ; and this process was repeated at intervals of half an inch till a balance was established.

The second and third combinations were treated in the same manner, the coils being moved by steps of 10° at a time, and readings taken till a balance was obtained ; and as the deflections were small in all cases, they were taken as being proportional to the strength of the currents.

The numbers given in the annexed Table are those found in the way indicated, the mean in each case being that of five experiments.

Axes of coils coincident.		First combination.		Second combination.		Third combination.	
Distance of planes.	Mean.	Distance of axes.	Mean.	Angle.	Mean.	Angle.	Mean.
0.625	88	0	88	0°	8	0°	17
1.0	77	0.5	84	10	7	10	17
1.5	52	1.0	70	20	7	20	17
2.0	38	1.5	57	30	6	30	16
2.5	28	2.0	40.6	40	5	40	16
3.0	22.5	2.5	30.8	50	4	50	15
3.5	17	3.0	20	60	3	60	12
4.0	13.4	3.5	10	65	0	70	9
4.5	10	4.0	0	...	...	80	5
5.0	8	...	...	...	...	85	2
						90	0

Note.—I may state here that I intend to continue this subject, and, when time permits, to trace some of the curves of equal induction.

XX. *On Magneto - Electric Induction.* By FREDERICK GUTHRIE and C. V. BOYS, *Assoc. R. School of Mines.*—Part I.

[Plate XVIII.]

It is well known that the electric currents caused in a conductor by relative motion between that conductor and a magnetic pole are in such a direction as to impose a drag upon such motion. An ideal friction (that is, one without