May 5, 1953 D. A. YOUNG 2,637,761

MOVING-COIL ELECTRICAL INSTRUMENT

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Fig. 1.

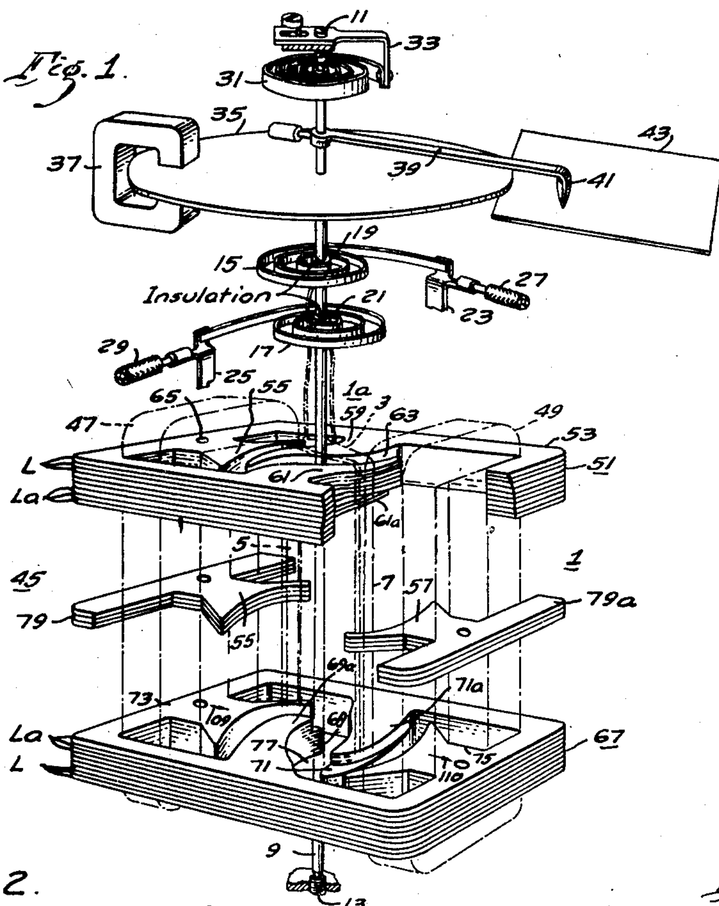


Fig. 2.

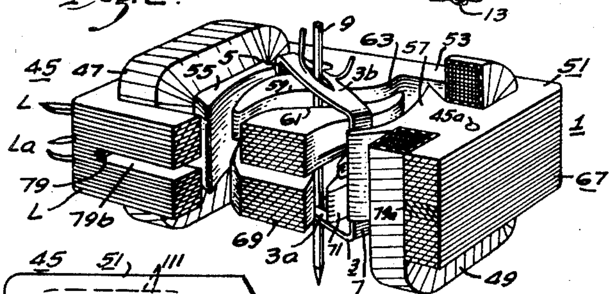
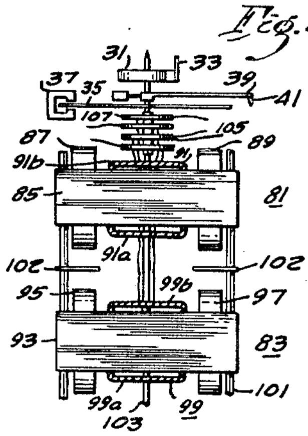


Fig. 4.



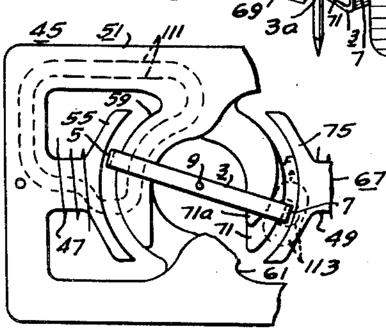


Fig. 3.

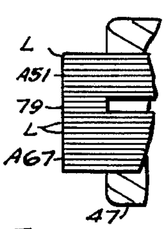


Fig. 5a.

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MOVING-COIL ELECTRICAL INSTRUMENT

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Fig. 6.

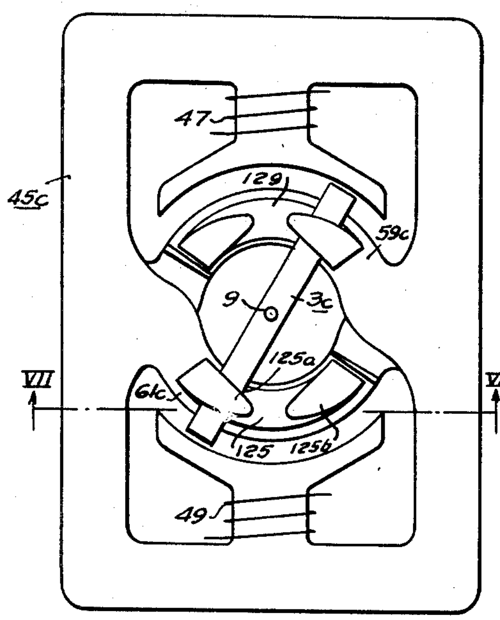


Fig. 8.

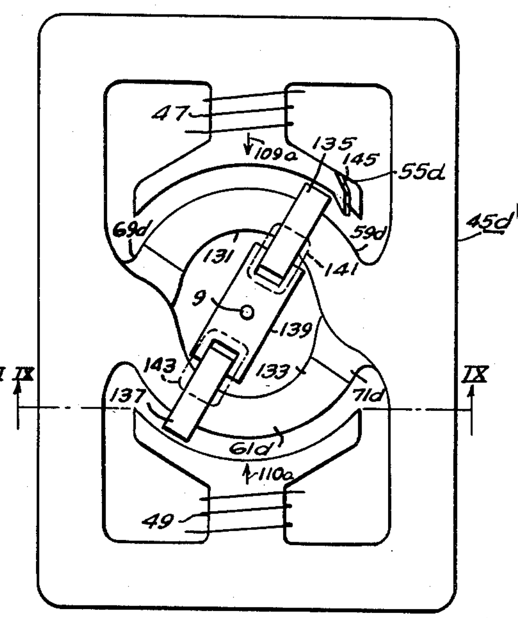


Fig. 7.

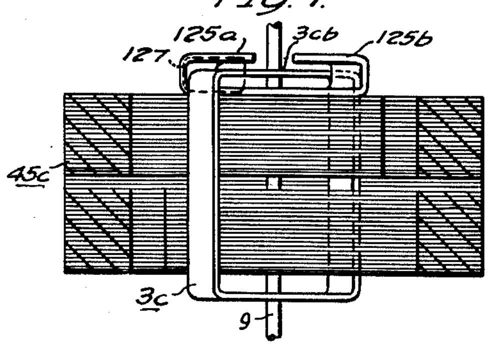
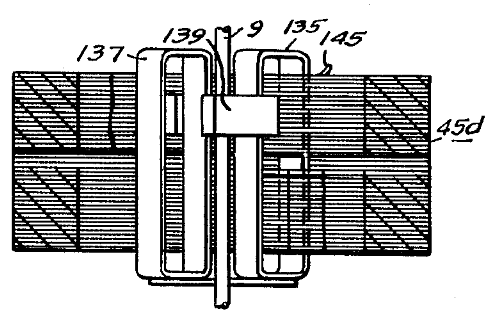


Fig. 9.



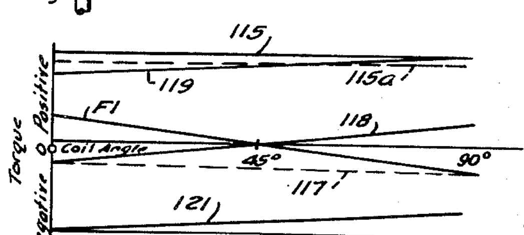


Fig. 5.

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MOVING-COIL ELECTRICAL INSTRUMENT

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Fig. 10.

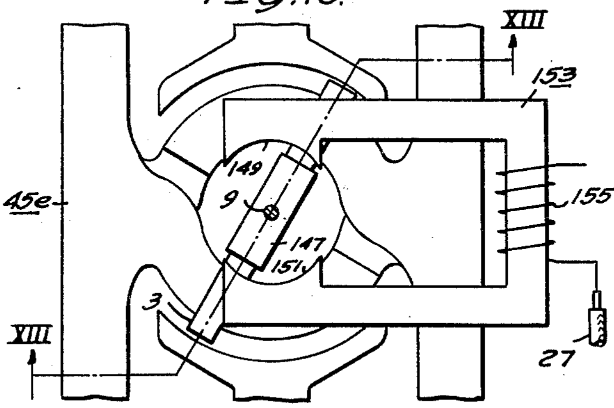
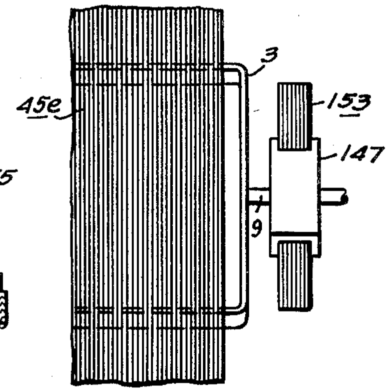


Fig. 11.



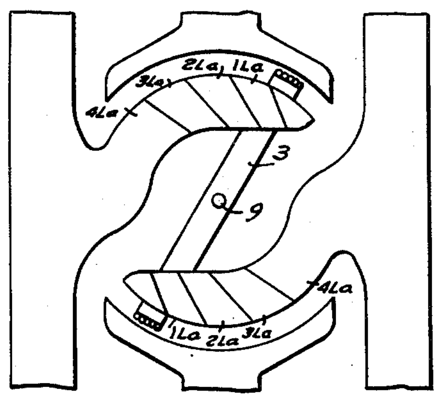


Fig. 13.

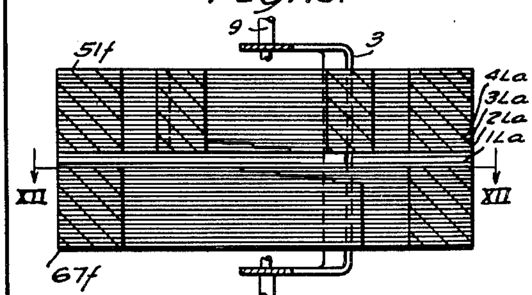
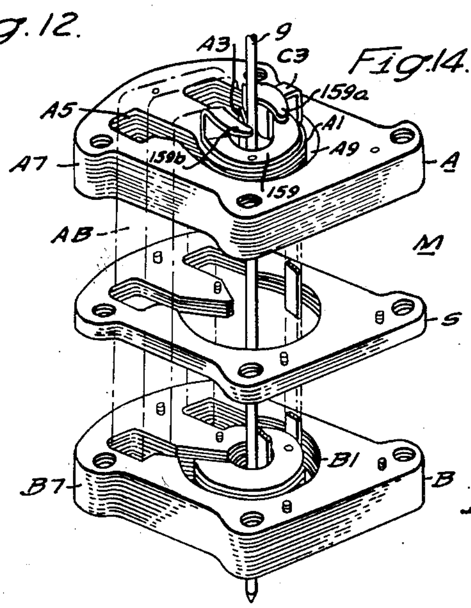


Fig. 12.

Fig. 14.



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Patented May 5, 1953

2,637,761

UNITED STATES PATENT OFFICE

2,637,761

MOVING-COIL ELECTRICAL INSTRUMENT

Douglass A. Young, East Orange, N. J., assignor to Westinghouse Electric Corporation, East Pittsburgh, Pa., a corporation of Pennsylvania

Application January 30, 1948, Serial No. 5,404

28 Claims. (Cl. 171—95)

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This invention relates to moving-coil electrical instruments and it has particular relation to moving-coil electrical measuring instruments having ferromagnetic structures defining air gaps for the associated moving coils.

Moving coil instruments are employed in various fields, such as for measuring and relaying. The advantages of ferromagnetic structures for moving-coil instruments, particularly those of the electrodynamometer type, long have been recognized. The deterrents to adoption of such magnetic structures have been lack of accessibility and lack of accuracy. Ferromagnetic structures are structures constructed from a material, usually containing iron, which has a magnetic permeability substantially greater than that of a vacuum.

Recently moving-coil instruments of the electrodynamometer type have become available which include ferromagnetic structures defining air gaps for the associated moving coils, wherein accuracy is obtained without sacrifice of accessibility. Examples of such instruments will be found in the Young et al. application, Serial No. 500,896, filed September 2, 1943, now Patent 2,438,027, and the Lunas application, Serial No. 570,028, filed December 27, 1944, now Patent 2,508,410.

In the aforesaid patent applications, a moving-coil is associated with a ferromagnetic structure which is divided into two spaced sections. These sections have passages permitting removal of the associated moving coil without disturbing the magnetic structure in any way. Each of the magnetic sections produces a solenoid force acting on the moving coil in response to energization of the moving coil alone, but the solenoid forces of the two sections are oppositely directed. Consequently, errors due to the solenoid forces are to a substantial extent eliminated.

Instruments of the type discussed above also appear to be subject to a force responsive to energization of the moving coil which urges the moving coil towards a position intermediate the ends of the path of travel of the coil, usually a midscale position. This force is smaller than the previously-mentioned solenoid forces, and for some applications of instruments, may be neglected. However, it does introduce an error and the magnitude of the error is dependent on the energization of the moving coil. This force appears to be due to magnetic flux produced by the moving coil, which circulates around a side of the moving coil located in the air gap of the associated magnetic structure, crossing and re-

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crossing the air gap. It will be referred to herein as a force F.

In accordance with the invention, a moving-coil instrument having a magnetic structure defining an air gap for the moving coil is designed to develop an auxiliary force or torque which compensates for the aforesaid force F. In a preferred embodiment of the invention, if two opposed solenoid torques are available as in the instruments previously disclosed in the aforesaid patent applications, these opposed torques are proportioned to compensate for the force F. Alternatively an auxiliary mechanism may be provided for developing the desired compensating force.

The invention further contemplates an improvement in scale distribution of a moving coil instrument having a laminated magnetic structure defining an air gap for the coil, wherein laminations are bent for the purpose of changing scale distribution.

It is, therefore, an object of the invention to provide an accurate moving-coil instrument having a ferro-magnetic structure defining one or more air gaps for the moving coil.

It is a further object of the invention to provide a moving-coil instrument having a magnetic structure developing torques in response to the energization of the moving coil, urging the moving coil towards an intermediate position in its path of travel with means for compensating for such torques.

It is a still further object of the invention to provide an improved method for controlling the scale distribution of a measuring instrument employing a laminated magnetic structure.

Other objects of the invention will be apparent from the following description taken in conjunction with the accompanying drawings, in which:

Figure 1 is an exploded view in perspective with parts broken away of an electrical measuring instrument embodying the invention;

Fig. 2 is a view in perspective with parts broken away showing the instrument of Fig. 1 in assembled condition;

Fig. 3 is a view in top plan with parts broken away of the instrument shown in Figs. 1 and 2;

Fig. 4 is a view in side elevation of a two-element electrical measuring instrument;

Fig. 5 is a graphical representation of the solenoid forces or torques developed by the instrument of Fig. 1;

Fig. 5*a* is a view in side elevation with portions broken away of a modification of the instrument shown in Figs. 1 and 2;

Fig. 6 is a view in plan of an instrument embodying a modified form of invention;

Fig. 7 is a sectional view taken along the line VII—VII of Fig. 6;

Fig. 8 is a plan view showing a further modification embodying the invention;

Fig. 9 is a sectional view taken on line IX—IX of Fig. 8;

Fig. 10 is a view in plan with parts broken away of a further embodiment of the invention;

Fig. 11 is a view in side elevation of the structure shown in Fig. 10;

Fig. 12 is a view in plan taken on the line XII—XII of Fig. 13 showing a still further modification of the invention;

Fig. 13 is a view in section taken on the line XIII—XIII of Fig. 12; and

Fig. 14 is an exploded view in perspective with parts broken away showing a still further embodiment of the invention.

Referring to the drawing, Fig. 1 shows an electrodynamometer instrument which includes a stator assembly **1** and a rotor assembly *1a*.

The rotor assembly comprises a shaft **9** which is mounted for rotation by suitable bearing screws **11**, **13** which are part of the stator assembly. The shaft **9** supports a coil **3** having coil sides **5** and **7** parallel to the shaft, but spaced radially therefrom. A pair of spiral, flexible, electroconductive strips **15**, **17** have their inner ends secured to insulating bushings **19**, **21** which are carried by the shaft. The outer ends of the strips are connected to lugs **23**, **25** for the purpose of establishing connections between the movable coil **3** and an external circuit through conductors **27**, **29**. The terminals of the coil **3** are connected to the inner ends of the spiral strips **15**, **17**, respectively. For damping purposes, the shaft **9** carrier an electroconductive disk which is mounted for rotation between the poles of a permanent magnet **37**. A control spring **31** has its inner end connected to the shaft **9**, and its outer end connected to a lever **33** adjustably secured to the stator assembly. The control spring biases the rotor assembly towards a predetermined angular position. Indicating means such as an arm **39** is attached to the shaft. This arm carries a pen **41** across the surface of a chart **43**. The chart may be advanced continuously relative to the pen **41** in a manner well understood in the art.

The stator assembly **1** includes a magnetic structure **45** which establishes magnetic paths for the magnetic fluxes produced by currents flowing in the coil **3** and in fixed windings **47** and **49** which are associated with the magnetic structure. The magnetic structure **45** includes a magnetic section **51** having a substantially continuous magnetic body or rim portion **53** which substantially surrounds the shaft **9** and the coil **3**. A pair of pole pieces **55** and **57** (Fig. 2) project from opposite interior surfaces of the rim portion **53** to provide arcuate pole faces adjacent the paths of travel of the coil sides **5** and **7**. In addition the magnetic section **51** has a pair of cantilever arms or magnetic cores **59** and **61** which project from opposite interior faces of the rim portion **53** and which pass through the coil **3** on opposite sides of the shaft **9**. These magnetic cores **59** and **61** are spaced in a direction transverse to the shaft **9** by a distance sufficient to permit passage of the movable coil **3** therebetween. Furthermore, the magnetic cores **59** and **61** have arcuate surfaces spaced from the pole pieces **55** and **57** to provide a pair of arcuate air gaps within which the coil sides **5** and **7** are disposed for movement. It will be noted that the magnetic cores **59** and **61** provide a substantially cylindrical magnetic core which is attached on opposite sides to the rim portion **53** and which has the passage **63** extending therethrough. Since the passage **63** communicates with the air gaps in which the coil sides **5** and **7** are positioned, the coil **3** may be rotated in a counterclockwise direction (as viewed looking at the rotor assembly from the control spring end) to bring the coil into alignment with the passage **63**. The coil then may be moved in a direction parallel to the shaft **9** through the passage **63**.

The magnetic section **51** may be formed of any suitable soft magnetic material having a magnetic permeability substantially greater than that of a vacuum. Such materials are termed ferromagnetic or generally magnetic materials, an example being silicon iron. Preferably, a material having low hysteresis loss is employed. The magnetic section **51** may be formed of a solid piece of soft iron. However, it is preferable to form the magnetic section **51** of a plurality of laminations L as shown in Figs. 1 and 2, particularly if the instrument is designed for measuring alternating-current quantities. The laminations may be provided with suitable openings **65** through which rivets may be passed for the purpose of securing the laminations together. If the magnetic section is formed of laminations, the desired contour of each lamination may be accurately formed by a punching operation.

By inspection of Figs. 1 and 2, it will be noted that a separate magnetic path is provided for each of the coil sides **5** and **7**. The magnetic path for the coil side **5** includes the pole piece **55** and the magnetic core **59** together with the air gap therebetween. The winding **47**, when energized, directs magnetic flux through this magnetic path to provide a magnetic field for the coil side **5**. In a similar manner, the magnetic path for the coil side **7** includes the magnetic core **61** and the pole piece **57** together with the air gap therebetween. When the winding **49** is energized, magnetic flux is directed through the associated magnetic path to establish a magnetic field for the coil side **7**.

Although the magnetic section **51** alone may be employed, an improvement in performance may be obtained by adding thereto an additional magnetic section **67**. The reason for this additional magnetic section may be understood by considering the solenoid action of the magnetic section **51** when employed alone. The magnetic section **51** is asymmetric with respect to the path of travel of the movable coil **3**. When the coil **3** is in its extreme counterclockwise position (looking at the rotor assembly from the control spring end thereof) the magnetic reluctance of the magnetic path offered to magnetic flux produced by current flowing through the coil **3** is a maximum. Conversely, when the coil **3** is adjacent its extreme clockwise position the magnetic reluctance offered to magnetic flux produced by current flowing in the coil **3** is a minimum. Consequently, when the coil **3** is energized and the windings **47** and **49** are deenergized, the coil **3** tends to take a position wherein the magnetic reluctance of the associated magnetic path is a minimum. This may be termed a solenoid action and the force applied to the coil **3** by the solenoid action urges the coil in a clockwise direction. In some cases, as when the energization of the fixed windings is constant, it is possible to calibrate the instrument to read correctly despite the presence of this solenoid action. However, this solenoid action is substantially compensated by the provision of the additional magnetic section **67**. The compensation permits more correct indication by the instrument for substantially all applications thereof.

The magnetic section **67** is similar in construction to the magnetic section **51** but is reversed with respect to the magnetic section **51** about a line transverse to the shaft **9**. The magnetic section **67** has a pair of magnetic cores **69** and **71** which extend through the coil **3** on opposite sides of the shaft **9**. In addition, the magnetic section **67** has a pair of pole pieces **73** and **75** which are positioned respectively in the windings **47** and **49**. It will be observed that the magnetic cores **69** and **71** are spaced to provide a passage **77** therebetween which corresponds to the passage **63** of the magnetic section **51**.

Since the magnetic section **67** is reversed with respect to the magnetic section **51**, the force due to solenoid action which is applied thereby to the coil **3** is opposed to the force developed by the solenoid action of the magnetic section **51**. Consequently, the resultant magnetic structure is substantially free of errors resulting from such solenoid action. The magnetic cores **59**, **61**, **69** and **71** all pass through the coil **3** to form a resultant magnetic core therefor which is substantially symmetric with respect to the path of movement of the coil **3**.

By inspection of Fig. 1, it will be observed that the passages **63** and **77** are displaced angularly about the shaft **9** with respect to each other. Consequently, the coil **3** cannot be removed from the magnetic structure **45** by a simple movement thereof in the direction of the shaft **9**. To permit removal of the coil from the magnetic structure the magnetic sections **51** and **67** are spaced from each other along the shaft **9** by a distance sufficient to permit movement of a side of the coil **3** therebetween. The desired spacing may be provided by any suitable spacer formed of either magnetic or nonmagnetic material. In the embodiment illustrated in Figs. 1 and 2, the spacer is divided into two parts **79** and **79*a***. Each of the parts is in the form of a plurality of magnetic laminations which are similar in construction to the adjacent parts of the laminations of the magnetic section **51**. In order to facilitate inspection of the space between the magnetic sections **51** and **67** after assembly thereof, the parts **79** and **79*a*** are located at a substantial distance from each other to provide an opening **79*b*** (Fig. 2) in the magnetic structure **45**. The space between the magnetic sections is clearly visible through this opening. Consequently, when the magnetic sections **51** and **67** are assembled with the spacer therebetween as shown in Fig. 2, a space is provided between the pair of magnetic cores **59** and **61** and the pair of cores **69** and **71**. This space is sufficient to permit movement of a side of the coil **3** therebetween.

It is believed that the operations required to assemble and disassemble the instrument illustrated in Figs. 1 and 2 are apparent from the foregoing discussion. To facilitate a further description of such operations, reference will be made to a leading side **3*a*** of the coil **3** (the lower side of the coil **3** as viewed in Figs. 1 and 2), and a trailing side **3*b*** (the upper side of the coil as viewed in Figs. 1 and 2). It will be understood that the magnetic structure **45** comprising the laminations of the magnetic sections **51** and **67** and the laminations of the spacer is first completely assembled as shown in Fig. 2 wherein a rivet **45*a*** is disclosed for uniting the laminations to each other. Also the rotor assembly **1*a*** is completely assembled, the complete assembly including the shaft **9**, the coil **3**, the conductor strips **15** and **17**, the disk **35**, the arm **39** and the control spring **31**. The rotor assembly then is placed above the magnetic structure **45** (as viewed in Figs. 1 and 2) with the leading side **3*a*** of the coil aligned with the passage **63** of the magnetic section **51**. The rotor assembly including the coil **3** is then lowered in a direction parallel to the axis **9** to pass the leading side **3*a*** completely through the passage **63**. The leading side **3*a*** of the coil now is positioned between the pair of magnetic cores **59** and **61** and the pair of cores **69** and **71**.

To complete the insertion of the coil **3** into operative position, the rotor assembly including the coil next is rotated in a clockwise direction (looking at the rotor assembly from the control-spring end thereof) to bring the leading side **3*a*** of the coil into alignment with the passage **77** of the magnetic section **67**. During such rotation of the coil **3** the leading side **3*a*** moves between the magnetic sections **51** and **67**. After the leading side **3*a*** has been brought into alignment with the passage **77**, the rotor assembly is lowered in a direction parallel to the shaft **9** to pass the leading side **3*a*** completely through the passage **77**. The coil now is positioned to embrace the complete resultant magnetic core formed by the magnetic cores **59**, **61**, **69** and **71**. The bearing screw **11** and the support therefor are next placed in position, and the bearing screws **11** and **13** are adjusted to mount the rotor assembly for rotation with respect to the magnetic structure. The outer ends of the conductor strips **15** and **17** are soldered to the lugs **23** and **25** and the permanent magnet **37** is positioned as shown in Fig. 1. To complete the installation of the rotor assembly, the outer end of the control spring **31** is soldered or otherwise secured to the lever **33**. By following a reverse procedure the rotor assembly **1*a*** may be removed from the magnetic structure **45** without disturbing the magnetic structure in any way.

From the foregoing discussion, it is clear that the magnetic structure **45** is formed of a plurality of unitary laminations each of which has integral pole pieces and magnetic cores. Because of this construction the magnetic structure may be provided with accurate air gaps, and the accuracy of the air gaps is not disturbed by assembly or disassembly of the instrument.

In certain applications a two-element electrodynamic instrument is required. Such an instrument may be constructed in the manner illustrated in Fig. 4. Referring to Fig. 4, a two-element electrodynamic instrument is disclosed which includes the two elements **81** and **83**. The element **81** comprises a magnetic structure **85** which is similar in construction to the magnetic structure **45** of Figs. 1 and 2. It will be observed that the magnetic structure **85** has associated therewith a pair of fixed windings **87** and **89** which correspond to the fixed windings **47** and **49** of Figs. 1 and 2. In addition, the magnetic structure **85** has disposed therein a movable coil **91** which corresponds to the movable coil **3** of Figs. 1 and 2. The element **83** is similar in construction to the element **81** and includes a magnetic structure **93**, fixed windings **95** and **97** and a movable coil **99**. The magnetic structures **85** and

93 are mounted on suitable supporting posts 101 and are spaced from each other sufficiently to permit rotation of one of the movable coils therebetween. In certain cases it may be desirable to place magnetic shields 102 between the fixed windings 87 and 95 and between the fixed windings 89 and 97 to prevent magnetic interference between the windings on opposite sides of the shields.

The movable coils 91 and 99 are secured to a common shaft 103 for rotation therewith. This shaft carries a pair of conductor strips 105 for connecting the terminals of the movable coil 99 to an external circuit and a pair of conductor strips 107 for connecting the terminals of the movable coil 91 to an external circuit. These conductor strips correspond to the conductor strips 15 and 17 of Fig. 1. In addition, the disk 35, the arm 39 (which may support an indicating pointer or a recording pen), and the control spring 31 are secured to the shaft 103 with the disk 35 positioned for movement between the poles of the permanent magnet 37. As well understood in the art, each of the elements 81 and 83 may be energized from a separate pair of conductors of a three-wire circuit or from a separate phase of a polyphase circuit.

Since the principles employed in the construction of the instrument illustrated in Figs. 1 and 2 are also employed for the instrument of Fig. 4, it follows that the rotor assembly in Fig. 4 may be introduced into operative position with respect to the magnetic structures 85 and 93 or may be removed therefrom without disturbing the magnetic structures in any way. For example, in constructing the instrument, the magnetic structures 85 and 93 are completed and are secured to the supporting posts 101. For convenience in discussing the assembly of the instrument, the coil 99 will be referred to as having a leading side 99*a* and a trailing side 99*b*. The coil 91 will be referred to as having a leading side 91*a* and a trailing side 91*b*. This corresponds to the notation employed for the coil 3 of Figs. 1 and 2. The rotor assembly of Fig. 4 is first completely assembled. This rotor assembly includes the shaft 103, the coils 91 and 99, the conductor strips 105 and 107, the disk 35, the pen arm 39 and the control spring 31. The rotor assembly then is placed above the magnetic structure 85 as viewed in Fig. 4 with the leading side 99*a* of the coil 99 positioned above the adjacent passage in the magnetic structure 85. The rotor assembly then is dropped in a direction parallel to the shaft 103 rotated and again dropped to position the coil 99 for embracing the magnetic cores of the magnetic structure 85. This procedure is exactly similar to that employed for dropping the coil 3 of Figs. 1 and 2 through the passages 63 and 77 to embrace the associated magnetic cores.

The coil 99 then is passed completely through the magnetic structure 85 by rotating the coil until its trailing side 99*b* is in position to drop through the adjacent passage in the magnetic structure 85. After the trailing side has passed through the adjacent passage, the coil 99 is rotated to pass the trailing side 99*b* between the magnetic sections of the magnetic structure 85 until the trailing side 99*b* is positioned to drop through the lower passage in the magnetic structure. The coil 99 now is lowered to a position between the magnetic structures 85 and 93.

The operation of passing a coil completely through its magnetic structure may be understood more fully by a further consideration of Figs. 1 and 2. Assuming that the coil 3 is in the position illustrated in Figs. 1 and 2 and that it is desired to drop the coil completely through its associated structure 45, the coil is rotated until its trailing side 3*b* is adjacent the passage 63 in the magnetic section 51. The coil now is lowered until the trailing side 3*b* is positoned between the magnetc sections 51 and 67. By suitably rotating the coil 3 in a clockwise direction (looking at the rotor assembly from the control spring end thereof) the trailing side 3*b* is moved through the magnetic sections 51 and 67 to a position wherein the trailing side is in alignment with the passage 77 in the magnetic section 67. The trailing side 3*b* now may be dropped through the passage 77 to complete the passage of the coil 3 through its associated magnetic structure 45. The operation of passing the coil 99 of Fig. 4 completely through the magnetic structure 85 is similar to that discussed for the coil 3 of Figs. 1 and 2.

With the coil 99 positioned between the magnetic structures 85 and 93 of Fig. 3, the rotor assembly is rotated to bring the leading side 99*a* of the coil 99 into alignment with the adjacent passage of the magnetic structure 93. The coil 99 next is dropped, rotated and again dropped in the manner previously discussed with reference to the coil 3 of Figs. 1 and 2 until the coil 99 is in position to embrace the magnetic cores of the associated magnetic structure 93. Since the magnetic structures 85 and 93 are similar, the movement of the roil 99 from a position between the magnetic structures 85 and 93 to a position wherein the coil 99 embraces the magnetic cores of the magnetic structure 93 also moves the coil 91 from a position above the magnetic structure 85 to a position wherein the coil 91 embraces the magnetic cores of the associated magnetic structure 85. Consequently, both of the coils 91 and 99 are in their operative positions with respect to their associated magnetic structures. With the rotor assembly of Fig. 4 in this position, the bearings associated with the shaft 103 may be adjusted and the outer ends of the conductor strips 105 and 107 may be connected as discussed with reference to Figs. 1 and 2. In addition, the outer end of the control spring 31 may be connected to its associated lever 33 and the permanent magnet 37 may be moved to operative position with respect to the disk 35. The instrument of Fig. 4 now is in completely assembled condition. By following a reverse precedure, the rotor assembly of Fig. 4 may be removed completely from the magnetic structures 85 and 93 without disturbing the magnetic structures in any way.

Referring again to Figs. 1 and 2, the windings 47 and 49 are connected in series and are so energized that if direct current is passed therethrough, magnetic flux flows through the pole pieces in the directions illustrated by the arrows 109 and 110 of Fig. 1. If the windings are energized by alternating current, the arrows 109 and 110 represent instantaneous directions of magnetic flux flow. In order to provide a magnetically astatic construction, the energization of one of the windings may be reversed and the moving coil 3 may be replaced by a pair of moving coils as hereinafter pointed out. Such astatic construction also is discussed in the aforesaid Lunas patent application.

If the magnetic sections 51 and 67 were constructed entirely of the magnetic laminations L, the instruments illustrated in Figs. 1, 2, 3 and 4 would be exactly similar to instruments illustrated and described in the aforesaid Lunas patent application. The reversely related sections 51 and 67 eliminate to a substantial extent the solenoid forces resulting from energization of the moving coil alone. However, a force exists which tends to move the moving coil towards a midscale position. It will be helpful to review briefly the present understanding of the theory underlying the force acting on the moving coil.

Referring to Fig. 3, it will be noted that when the windings 47 and 49 are deenergized and the moving coil 3 is energized, magnetic flux is produced which passes through the coil 3 and crosses the air gap between the magnetic core 59 and the pole piece 55. This magnetic flux is illustrated in Fig. 3 by dotted lines 111. It will be understood that magnetic flux crosses each of the air gaps of the sections in substantially the same manner.

The magnetic flux represented by the dotted lines 111 produces a solenoid force which urges the moving coil 3 in a clockwise direction as viewed in Fig. 3. However, since the solenoid forces developed by the two magnetic sections 51 and 67 are in opposition, such solenoid forces substantially cancel.

Current passing through the moving coil 3 also produces magnetic flux which follows a path represented in Fig. 3 by dotted lines 113. It will be noted that this path extends from the magnetic core 71 to the pole piece 75 across the air gap therebetween and recrosses the air gap to return to the magnetic core. This magnetic flux urges the moving coil 3 towards a position wherein the magnetic reluctance offered to the magnetic flux is a minimum. For the structure of Fig. 3, the moving coil 3 is urged towards a midscale position. Since the magnetic flux represented by the dotted lines 113 crosses the air gap twice, the magnetic reluctance of the path through which the magnetic flux flows is large compared to the magnetic reluctance of the path followed by the magnetic flux represented by the dotted lines 111. As previously pointed out, the force developed by the magnetic flux represented by the dotted lines 113 will be termed a force F. For some applications, the error introduced by the force F may be neglected. However, it is desirable that this source of error be eliminated insofar as possible. It will be understood that magnetic flux similar to that represented by the dotted lines 113 is present in each of the air gaps of the magnetic sections 51 and 67.

The problem may be considered further with reference to Fig. 5, wherein ordinates represent torque applied to the moving coil 3 of Fig. 3 and abscissae represent the angle of displacement of the moving coil 3 from its zero position which is assumed to be the counterclockwise end of the path of travel of the moving coil in Fig. 3. The force F developed by a predetermined current flowing through the moving coil 3 is represented in Fig. 5 by a curve F1 which has a positive value acting in a clockwise direction when the coil 3 occupies its extreme counterclockwise position and which has a negative value acting in a counterclockwise direction when the coil occupies its extreme clockwise position. It is assumed in Fig. 5 that the coil 3 is capable of movement through an angle of 90°. The curve F1 also shows that in the midscale position of the coil 3 (45°), no force F is applied to the moving coil.

If all laminations of the magnetic sections 51 and 67 are similar to the previously described laminations L, the previously mentioned solenoid forces developed by the magnetic sections 51 and 67, when the coil 3 is energized by the predetermined current, may be assumed to be represented in Fig. 5 by curves 115 and 116. These solenoid forces are assumed to be uniform, oppositely directed and equal in magnitude throughout the angular movement of the coil. Consequently, these solenoid forces fully compensate each other. If the forces represented by the curves F1, 115 and 116 alone act on the moving coil 3, the moving coil seeks a midscale position (45° in Fig. 5).

If the solenoid forces are deliberately unbalanced, the coil may be made to seek other scale positions. For example, let it be assumed that the magnetic section 51 has laminations removed and the magnetic section 67 has magnetic sections added to produce solenoid forces represented by the dotted curves 115*a* and 116*a* of Fig. 5. These curves have a constant difference throughout the angular path of the coil 3 which is represented by the dotted curve 117.

The force represented by the curve 117 is equal in magnitude and opposite in direction to the force represented by the curve F1 only when the coil 3 occupies its zero or extreme counterclockwise position. Consequently, when the coil 3 is in its zero position, it would be free of any error resulting from the application of the three forces represented by the curves F1, 115*a* and 116*a*. However, when the coil 3 is adjacent its extreme clockwise position (90° in Fig. 5), the error introduced by the three forces would be larger as a result of the unbalance represented by the curves 115*a* and 116*a*. By selection of the numbers of laminations in the magnetic sections 51 and 67 to provide the required amount and direction of unbalance represented by the curve 117, the force F1 may be compensated at any one angular position of the moving coil 3. For example, the compensated position may correspond to the position of the moving coil when the coil occupies its zero position, whether the instrument is a left-zero, a right-zero or a center-zero instrument.

A structure providing an unbalance force similar to that represented by the curve 117 is illustrated in Fig. 5*a*. The magnetic sections A51 and A67 of Fig. 5*a* correspond respectively to the sections 51 and 67 of Figs. 1 and 2, and are constructed entirely of the laminations L. Otherwise, the instrument is similar to that illustrated in Figs. 1 and 2. By inspection of Fig. 5*a* it will be noted that the magnetic section A67 has a larger number of laminations than the number employed for the magnetic section A51 to produce the unbalance force represented by the curve 117. If the magnetic section A51 were to have a larger number of laminations than the number employed for the magnetic section A67, the unbalance curve 117 therefor would be located above the coil-angle axis of Fig. 5. The magnitude of the force represented by the curve 117 depends on the difference in the thickness of the magnetic sections or in the numbers of laminations employed for the magnetic sections.

In order to compensate for the force F, a compensating force or torque represented by the curve 118 is required. The force represented by the curve 118 may be obtained by suitable shaping of the magnetic cores 59, 61, 69 and 71. Conveniently, such shaping may be obtained by suitable punching of one or more of the laminations L. In the embodiment of Figs. 1, 2 and 3, certain of the laminations L*a* are modified to produce the desired force. By inspection of the magnetic section 67 of Fig. 1, it will be observed that each of the laminations L*a* is similar to each of the laminations L, except for the shaping of the magnetic cores. The laminations La provide magnetic cores 69a and 71a which are tapered somewhat more than the magnetic cores 69 and 71 of the laminations L. It will be understood that the magnetic section 51 is exactly similar to the magnetic section 67, except for the reversal thereof about a line transverse to the shaft 9.

The effect of the tapering of the magnetic cores is to vary the solenoid force developed by each of the magnetic sections 51 and 67 as a function of the angular position of the moving coil 3 about its axis of rotation. For example, the curve 119 in Fig. 5 may represent the solenoid force developed by the magnetic section 51, whereas the curve 121 may represent the solenoid force developed by the magnetic section 67. The sum of the two curves 119 and 121 is represented by the curve 118. Consequently, by suitable shaping of the magnetic cores, a compensating force represented by the curve 118 of Fig. 5 may be obtained which substantially compensates for the force represented by the curve F1. The forces represented in Fig. 5 are for a predetermined current flowing through the coil 3. Inasmuch as all of these forces vary in magnitude in accordance with variations in magnitude of the coil current, the compensation is effective for all energizations of the coil.

Although the outer laminations (those adjacent the coil sides 3a and 3b) of the sections 51 and 67 may be tapered, the location of the tapered laminations La adjacent the coil sides 3a and 3b may make the operation of the instruments sensitive to exact axial positioning of the coil 3. For this reason, the laminations La preferably are placed interiorly of the resultant magnetic structure, such as adjacent the spacers 79 and 79a.

Referring to Figs. 1 and 3, it will be observed that the magnetic cores 69a and 71a provide air gaps which increase in length adjacent the coil 3 as the coil moves in a clockwise direction. The tapering of the magnetic cores associated with the laminations La does not appreciably affect the resultant effective distribution of magnetic flux in the air gaps as a result of energization of the windings 47 and 49. This follows from the fact that the magnetic sections are reversed with respect to each other. Since the magnetic cores associated with the magnetic sections 51 and 67 taper in opposite directions, the resultant effective air gap length remains substantially constant throughout the path of travel of the moving coil.

The instrument of Fig. 6 employs a magnetic structure 45c which is similar to the magnetic structure 45 of Fig. 1, except that all of the laminations in the structure 45c are substantially the same as the laminations L of Fig. 1. Compensation for the force F is obtained in Fig. 6 by a magnetic strip 125 which may be constructed of iron. This strip is secured to a magnetic core 61c which corresponds to the core 61 of Fig. 1. The magnetic strip 125 has its ends 125a and 125b bent to form a pocket at each end of the strip. The instrument of Fig. 6 also employs a moving coil 3c which corresponds to the moving coil 3 of Fig. 1. By inspection of Figs. 6 and 7, it will be observed that the upper coil side 3cb of the coil 3c is positioned for movement through the pockets formed by the magnetic strip 125. When the coil side 3cb is disposed in one of the pockets, such as that formed by the end 125a, a path is established for magnetic flux produced by current flowing through the coil. This path is indicated in Fig. 7 by a dotted line 127. This magnetic flux produces a solenoid force which tends to urge the coil side 3cb farther into the pocket. Similarly, when the coil side 3cb is located in the pocket formed by the end 125b of the magnetic strip, current flowing through the moving coil produces a force urging the moving coil farther into the last-named pocket. Consequently, by properly shaping the ends 125a and 125b, the force exerted thereby on the moving coil 3c may be proportioned to compensate for the force F developed by current flowing through the coil.

One or more of the magnetic strips 125 may be employed as desired. In Fig. 6, a second magnetic strip 129 is secured to the magnetic core 59c which corresponds to the magnetic core 59 of Fig. 1. The magnetic strip 129 may be exactly similar in construction to the strip 125.

The ends 125a and 125b are spaced by a distance sufficient to permit passage of the moving coil therebetween. The moving coil has a length sufficient to permit it to be raised sufficiently to clear the ends of the magnetic strip. This permits removal of the moving coil from the associated magnetic structure in the manner discussed with reference to Figs. 1 and 2.

In the embodiment of Fig. 8, a magnetic structure 45d is employed which is similar to the magnetic structure 45c, except for the shaping of the associated magnetic cores. The magnetic structure 45d has magnetic cores 59d and 61d which correspond to the magnetic cores 59c and 61c of Fig. 6. However, the inner faces of these magnetic cores have noncylindrical configurations to provide pole faces 131 and 133, respectively.

In Fig. 8, the single coil 3 of Fig. 1 is replaced by two coils 135 and 137 which may be connected in series to serve in place of the coil 3. The coil 135 links the magnetic cores 59d and 69d which correspond to the magnetic cores 59 and 69 of Fig. 1. The coil 137 links the magnetic cores 61d and 71d which correspond to the cores 61 and 71 of Fig. 1. The provision of the double-coil structure illustrated in Fig. 8 is discussed in the aforesaid Lunas patent application.

If a magnetically astatic instrument is desired, the windings 47 and 49 may be connected to direct magnetic flux respectively in accordance with the arrows 109a and 110a. For alternating current energization, the arrows represent instantaneous directions. The coils 135 and 137 may be energized with proper polarities to apply cumulative torques to the associated shaft 9.

The shaft 9 also has secured thereto a magnetic armature 139 which has slotted ends for receiving respectively the inner coil sides of the coils 135 and 137. Consequently, when the coils are energized, magnetic flux is produced which follows paths represented by the dotted lines 141 and 143 in Fig. 8.

The pole faces 131 and 133 are so shaped that the gaps between the pole faces and the associated armature 139 are a maximum when the coil assembly is in its midscale position; and are a minimum when the coil assembly is at either of its end positions. Consequently, when the coil assembly is displaced from its midscale position, the armature 139 acts as the armature of an attraction mechanism to urge the coil assembly away from the midscale position. By proper shaping of the pole pieces 131 and 133 and by proper dimensioning of the armature 139, the forces developed by the armature may be proportioned to compensate for the resultant force F developed by current flowing through the coils 135 and 137.

Scale distribution may be controlled to a substantial extent by bending one or more of the laminations employed in the various magnetic structures. For example, in Fig. 8, the magnetic structure 45*d* includes a pole piece 55*d* which corresponds to the pole piece 55 of Fig. 1. If the sensitivity of the instrument is too great when the coil assembly is adjacent its extreme clockwise position as viewed in Fig. 8, the sensitivity may be decreased by bending a portion 145 of one or more of the laminations adjacent the right-hand end of the pole piece 55*d*. Consequently, by bending any portion of the laminations away from their effective positions, the sensitivity of the instrument may be decreased as desired.

Fig. 10 shows a magnetic structure 45*e* which is similar to the magnetic structure 45*c* of Fig. 6. The rotor assembly associated with the magnetic structure 45*e* may be similar to that illustrated in Fig. 1, except for the addition of a magnetic armature 147. This magnetic armature rotates between the pole faces 149 and 151 of an electromagnet 153 which has an energizing winding 155 connected in series with the coil 3. The pole faces 149 and 151 are shaped to provide air gaps between the ends of the armature 147 and the pole faces which are a maximum when the coil 3 is in its midscale position and a minimum when the coil 3 is at either of its end positions. Consequently, the armature 147 and the electromagnet 153 comprise an attraction mechanism which operates in substantially the same manner as the armature 139 and associated parts of Fig. 8. By proper shaping of the pole faces 149 and 151, by proper dimensioning of the armature 147, and by proper energization of the electromagnet 153, the force developed by the armature 147 may be proportioned to compensate for the force F resulting from current flowing in the coil 3.

In Fig. 1, certain of the laminations L*a* had their magnetic cores tapered to increase the lengths of the associated air gaps. The tapering of the magnetic cores also may be effected by cutting off the tips of certain of the laminations as illustrated in Figs. 12 and 13. Although the number of laminations to be cut may vary, it will be assumed that four laminations, 1L*a*, 2L*a*, 3L*a* and 4L*a* are to be cut in each of the sections 51*f* and 67*f*. These sections correspond to the sections 51 and 67 of Fig. 1. The laminations 1L*a*, 2L*a*, 3L*a* and 4L*a* correspond to the laminations L*a* of Fig. 1. By inspection of Fig. 12, it will be observed that the laminations 1L*a*, 2L*a*, 3L*a* and 4L*a* have their core ends cut off by increasing increments. The effect of such cutting is to taper the resulting magnetic core and to taper the effective width of the air gap. Since the instrument of Figs. 12 and 13 operates in substantially the same manner described with reference to Figs. 1, 2 and 3, further discussion thereof is believed to be unnecessary.

Any of the foregoing embodiments may be incorporated in a "circular scale" instrument wherein a moving coil has only one side disposed in the air gap of an associated magnetic structure. As a specific example, a circular scale instrument is illustrated in Fig. 14 and is provided with compensation similar in substance to that discussed with reference to Figs. 6 and 7. In Fig. 14, a moving coil C3 is secured to the shaft 9. Except for the coil C3, the rotor assembly may be similar to that illustrated in Fig. 1, and mounts the coil C3 for rotation with respect to a magnetic structure M. The magnetic structure M includes a magnetic portion A having an annular magnetic core A1. This annular magnetic core is proportioned to pass through the coil C3 and has a channel A3 extending radially from the interior to the exterior of the annular core for the purpose of permitting passage of a side of the coil C3 therethrough. The annular core A1 has a magnetic member A5 projecting therefrom adjacent the channel A3 to connect the annular core A1 to an outer magnetic element A7. The annular core A1 and the magnetic element A7 have adjacent surfaces which are spaced to define an annular air gap A9 within which a side of the coil C3 is positioned for rotation. This annular air gap may be of sufficient length to permit angular rotation of the coil C3 about the axis of the shaft 9 for an angular distance of the order of 250°. It will be observed that the annular core A1 and the magnetic member A5 are substantially in the form of a hook wherein the annular core A1 is the hook section and the magnetic member A5 is the shank section. A fixed winding AB surrounds the magnetic member A5 and when energized produces a magnetic field in the annular air gap A9.

Because of the channel A3, the annular core A1 for the coil C3 is asymmetric with respect to the path of travel of the coil. Such asymmetry is undesirable because of the solenoid action resulting from current flowing through the coil C3. This may be understood by assuming that the coil AB is deenergized and that a current flows in the coil C3. Under these conditions, no torque should be applied to the shaft 9 by the coil C3. However, because of the asymmetry of the annular magnetic core, the coil C3 tends to move to a position wherein the reluctance of the magnetic path associated therewith is a minimum.

In order to eliminate substantially this solenoid action, the magnetic structure M includes a second magnetic portion B which is similar to the magnetic portion A, but which is reversed with respect to the magnetic portion A about an axis perpendicular to the shaft 9 and parallel to the magnetic member A5. Since the magnetic portions A and B are similar in construction, parts of the magnetic portion B will be designated by the reference character B followed by the numeral applied to the corresponding part of the magnetic portion A.

By inspection of Fig. 14, it will be observed that the asymmetries of the magnetic portions A and B with respect to the path of travel of the coil C3 are such as to produce a resultant magnetic structure which is substantially symmetric with respect to the path of travel of the coil. This is accomplished by positioning the channels A3 and B3 adjacent opposite ends of the path of travel of the coil 93. As a result of this construction, torque resulting from solenoid action is to a substantial extent eliminated.

In order to permit the insertion of a preformed coil into embracing relationship with the annular magnetic cores A1 and B1, the magnetic portions A and B are spaced axially along the shaft 9 in any suitable manner for a distance sufficient to permit passage of a side of the coil C3 therebetween. The spacer is a magnetic or non-magnetic structure S which, if desired, may be similar to the magnetic portion A except for the omission of the annular magnetic core A1. Although the magnetic portions A and B and the spacer S may be formed of magnetically-soft iron or steel of solid section, preferably they are laminated, as illustrated in Fig. 14.

With the construction of the circular scale instrument as thus far described, a force F is produced which urges the coil towards an intermediate or midscale position. By increasing the number of laminations in one of the magnetic portions A or B and decreasing the number of laminations in the other of the magnetic portions, the position towards which the coil is urged by the force F may be moved in either direction and to a desired extent away from the midscale position. The principles involved have been discussed above with reference to Fig. 5a.

For complete compensation of the force F, the magnetic cores A1 and B1 may be tapered in opposite directions in conformance with the principles discussed with reference to Figs. 1, 2 and 3 or with reference to Figs. 12 and 13. As still further examples, the auxiliary mechanisms of Figs. 6 to 11 may be employed in accordance with the discussions thereof. The compensation illustrated in Fig. 14 is based on that shown in Figs. 6 and 7.

The magnetic section A has secured thereto a magnetic strip 159 having ends 159a and 159b bent to form pockets in the manner discussed with reference to the strip 125 of Figs. 6 and 7. Except for the increased range of angular movement of the coil C3, the strip 159 operates in the same manner as the strip 125 of Fig. 6 to compensate for the force F. It will be understood that the coil C3 of Fig. 14 is long enough to be lifted between the ends of the strip 159 to clear the strip preparatory to removal of the coil from its associated magnetic structure.

Although the invention has been described with reference to certain specific embodiments thereof, numerous modifications are possible, and it is desired to cover all modifications falling within the spirit and scope of the invention.

I claim as my invention:

1. In an electrical instrument, a stator structure, a rotor assembly including a coil, means mounting the rotor assembly for rotating the coil relative to the stator structure through a predetermined path, means responsive to energization of said coil alone for developing solenoid torques urging the coil relative to the stator structure towards an intermediate position in said path, and compensating means for producing torques acting between the rotor assembly and the stator structure for urging the coil away from the intermediate position in a direction determined by the position of the coil relative to the intermediate position to compensate for said first-named torques.

2. An electrical instrument as defined in claim 1 wherein said coil and said last-named means are connected for energization from a common source of energy.

3. In an electrical instrument, a magnetic structure having an air gap, a rotor structure comprising an armature assembly, said armature assembly including a coil having a coil side disposed in said air gap, means mounting the rotor structure for rotation relative to the magnetic structure to move the coil side through the air gap in a predetermined path, said coil when energized developing a solenoid torque relative to the magnetic structure which urges the coil towards an intermediate position in said path from any other position in said path, said magnetic structure including an auxiliary air gap, the armature assembly including an armature portion disposed for movement through said auxiliary air gap, one of said structures comprising means for establishing a magnetic field in the last-named air gap, said last-named air gap being shaped to provide a torque directed and proportioned to urge the coil away from the intermediate position to compensate for the first-named torque, and means for establishing a magnetic field in said first-named air gap.

4. In an electrical instrument, a coil, a magnetic structure having an air gap, means mounting the coil with a coil side in the air gap for movement relative to the magnetic structure, said magnetic structure comprising a first magnetic portion defining a path for magnetic flux produced by electrical current flowing through said coil, said magnetic portion providing a first substantial solenoid force in response to said current acting between said magnetic portion and said coil, the solenoid force increasing as said coil moves in the direction of the force, a second magnetic portion defining a path for magnetic flux produced by current flowing through said coil, said second magnetic portion providing a second substantial magnetic solenoid force in response to current in said coil acting between said second magnetic portion and said coil, the second solenoid force increasing as said coil moves in the direction of the second solenoid force, and means mounting said magnetic portions to direct said forces in opposition to each other, said increases in the solenoid forces in response to movement of the coil being proportioned to compensate for the force resulting from magnetic flux crossing and recrossing the first-named air gap produced by current flowing through the coil which urges the coil towards an intermediate position in its path of travel.

5. An instrument as defined in claim 4 in combination with means for establishing a magnetic field in said air gap, whereby the movement of the coil in response to reaction of current flowing therethrough with said magnetic field is substantially independent of said forces.

6. In an electrical instrument, a pair of similar magnetic structures, each of said magnetic structures comprising a hook-shaped magnetic core having a hook section and a shank section projecting from the hook section, each of said magnetic structures also comprising a magnetic member surrounding, but spaced from, a substantial portion of the associated hook section to form therewith an arcuate air gap, said hook section, shank section and magnetic member defining a magnetic path for directing magnetic flux through the associated air gap, means mounting the magnetic cores with their hook sections extending around a common axis, one of the magnetic structures being reversed relative to the other of the magnetic structures about a line perpendicular to said axis, a coil having a coil side disposed in the air gaps, means mounting the coil for rotation relative to the magnetic structure about said axis, each of said hook sections being shaped to provide a solenoid force in response to current flowing through the coil which varies as the coil moves from a position adjacent the associated shank section to a position displaced therefrom, the oppositely directed solenoid forces of the two structures having a resultant proportioned to compensate for the force produced by

magnetic flux produced by current flowing in the coil which magnetic flux does not flow through the shank sections.

7. In an electrical instrument, a magnetic structure having an arcuate air gap, said magnetic structure comprising a plurality of laminations of magnetic material, certain of said laminations having pole faces adjacent said air gaps which differ in configuration from other of said magnetic laminations to produce a resultant air gap having desired characteristics, a second magnetic structure similar to the first-named magnetic structure but reversed relative thereto about a line perpendicular to the axis of the air gaps, a coil having a coil side disposed in said air gaps, and means mounting the coil for rotation relative to the magnetic structures.

8. In an electrical instrument, a pair of substantially similar magnetic structures having air gaps substantially concentric about an axis and aligned to produce a resultant air gap; each of said magnetic structures comprising a plurality of laminations of magnetic material certain of the laminations having pole faces defining a portion of the resultant air gap having a length which varies as a function of the angle about said axis; said magnetic structures being reversed relative to each other about a line transverse to said axis, a coil having a coil side disposed in said resultant air gap, and means mounting the coil for rotation relative to the magnetic structure, said variations in air gap length being proportioned to compensate forces acting on said coil as a result of current flowing through the coil.

9. An electrical instrument as defined in claim 8, certain of the laminations of each of said magnetic structures having an air gap of uniform length throughout the path of travel of said coil side.

10. An electrical instrument as defined in claim 8, said magnetic structures being spaced along said axis by a distance sufficient to permit rotation of a side of said coil therebetween, and means for establishing a magnetic field in said resultant air gap.

11. In an electrical instrument; a pair of substantially similar magnetic structures having air gaps substantially concentric about an axis and aligned to produce a resultant air gap; each of said magnetic structures comprising a plurality of laminations of magnetic material certain of the laminations having pole faces defining a portion of the resultant air gap having a dimension at angular positions about said axis which differs from the corresponding dimension of other of said laminations; said magnetic structures being reversed relative to each other about a line transverse to said axis, a coil having a coil side disposed in said resultant air gap, and means mounting the coil for rotation relative to the magnetic structure, said variations in air gap dimension being proportioned to compensate forces acting on said coil as a result of current flowing through the coil.

12. In an electrical instrument; a pair of substantially similar magnetic structures; each of said magnetic structures comprising a plurality of magnetic laminations having two pairs of inner and outer pole pieces defining two air gaps spaced angularly about an axis; means mounting said magnetic structures reversed relative to each other about a line transverse to the axis with the air gaps of the two magnetic structures in alignment, coil means having a separate coil side disposed in each pair of aligned air gaps, means mounting the coil means for rotation about the axis, the inner pole pieces of the magnetic structures being spaced to provide a passage through which the coil means may be introduced into operative position and removed from the magnetic structures without disturbing the magnetic structures, each of said inner pole pieces having a configuration providing a varying solenoid force acting between the magnetic structure and the coil means in response to current flowing through the coil means which varies as said coil means moves over the last-named inner pole piece, the inner pole pieces of the magnetic structures having opposed solenoid forces proportioned to produce zero resultant force acting on the coil means in response to current flowing through the coil means for all positions of the coil means in the normal path of rotation of the coil means.

13. In an electrical instrument as defined in claim 12, means for producing a magnetic field in said air gaps, the configuration of said inner pole pieces being determined by different shaping of a plurality of the laminations forming each of the inner pole pieces.

14. In an electrical instrument, a stator assembly, a coil, and means mounting the coil for rotation relative to the stator assembly about an axis, said stator assembly including a pair of magnetic core members projecting through said coil, said magnetic core members being spaced axially of said axis and having uniform ends adjacent the radial sides of said coil, pole piece members cooperating with the cores to define air gaps for the coil, at least part of the members having dimensions adjacent the coil which vary in size with the angular position of said coil, the variation in dimensions being produced by variations in the members intermediate said ends to modify the torque acting between the coil and the stator when the instrument is energized, whereby the response of said instrument is substantially independent of the axial adjustment of the coil along said axis.

15. An instrument as defined in claim 14 wherein said magnetic cores comprise magnetic laminations, and the magnetic laminations adjacent the space between the cores are smaller than laminations displaced from said space to produce said variation in dimension.

16. In an electrical instrument; a stator magnetic structure including a magnetic core arcuate about an axis, said magnetic core having an outer pole face and an inner pole face, and a pole piece spaced from said outer pole face to define therewith an air gap; a rotor assembly including a coil having a first coil side disposed in said air gap, said coil having a second coil side intermediate said inner pole face and the axis, means mounting the coil for rotation about said axis relative to the magnetic structure, said magnetic core when current flows through the coil alone coacting with the coil to develop solenoid forces urging the coil towards an intermediate position in its path of travel, and a U-shaped magnetic element surrounding said second coil side and movable with the coil, said magnetic element having its tips adjacent the inner pole face to form with the magnetic core a path for magnetic flux produced by current flowing in the coil, said inner pole face being shaped to produce torques acting between the magnetic element and the magnetic core to urge said magnetic element away from the intermediate position in a direc-

tion determined by the position of the coil relative to the intermediate position to compensate for the solenoid forces when the coil is displaced from the intermediate position.

17. The method of calibrating a moving coil instrument having a laminated magnetic structure providing pole pieces defining an air gap for a side of the moving coil which comprises bending in one of the pole pieces a portion of a lamination relative to an adjacent lamination of the magnetic structure adjacent the air gap to modify the distribution of magnetic flux in the air gap.

18. In an electrical instrument, a pair of magnetic structures each having an air gap, a coil having a coil side disposed in said air gaps, means mounting the coil for movement relative to the magnetic structures, said magnetic structures establishing magnetic paths for magnetic flux produced by current flowing in the coil proportioned for developing forces in response to current flowing through the coil which, if equal, urge the coil towards an intermediate position in its path of movement, said magnetic structures being proportioned to produce unequal solenoid forces acting on the coil in response to current flowing through the coil, and means mounting the magnetic structures to direct said solenoid forces in opposition for urging said coil away from said interminate position towards a predetermined position.

19. In an electrical instrument, a stator structure, a coil, means mounting the coil for rotation relative to the stator structure, said stator structure comprising a pair of magnetic structures each having inner and outer pole pieces spaced to define an arcuate air gap for reception of a coil side of the coil, each of the magnetic structures producing a solenoid force responsive to current flowing through the coil for urging the coil towards an end of the path of travel of the coil, means mounting the magnetic structures reversely relative to each other for directing said solenoid forces in opposite directions, said magnetic structures providing unequal magnetic paths for magnetic flux produced by current flowing in the coil to make said oppositely directed solenoid forces unequal in magnitude, whereby the resultant of said solenoid forces urges said coil towards a predetermined position.

20. An instrument as defined in claim 19 in combination with winding means effective when energized for establishing magnetic fields in the air gaps, said magnetic structures being constructed of similar magnetic laminations, one of said magnetic structures having a larger number of said laminations than the number employed for the other of the magnetic structure.

21. An electrodynamic instrument comprising a winding, a soft magnetic structure having an air gap through which is directed magnetic flux produced by current flowing in the winding, a coil, means mounting the coil with a portion of the coil in the air gap for movement therethrough in accordance with the reaction between current flowing in the coil and magnetic flux in the air gap produced by current flowing in the winding, said magnetic structure being responsive to energization of the coil alone to produce a solenoid force urging the coil towards a predetermined intermediate position in the path of travel of the coil, and compensating means energized in accordance with the current flowing in the coil for urging the coil away from the intermediate position in a direction dependent on the position of the coil relative to the intermediate position to compensate for the solenoid force.

22. An electrodynamic instrument as defined in claim 21 wherein the compensating means provides an air gap configuration for said coil which varies for different positions of the coil portion therein.

23. An electrodynamic instrument as defined in claim 21 wherein the magnetic structure comprises a pair of hook-shaped magnetic cores passing in opposite directions through the coil, and pole piece means spaced from the magnetic cores to define an arcuate air gap within which said portion of the coil is mounted for rotation.

24. An electrodynamic instrument as defined in claim 23 wherein the compensating means includes configurations of the magnetic structure by which the air gaps between the magnetic cores and the pole piece means vary in opposite directions as the angular position of the coil portion in the air gaps changes.

25. In an electrical instrument; a pair of substantially similar magnetic structures; each of said magnetic structures comprising two pairs of inner and outer pole pieces defining two air gaps spaced angularly about an axis; means mounting said magnetic structures reversed relative to each other about a line transverse to the axis with the air gaps of the two magnetic structures in alignment, coil means having a separate coil side disposed in each pair of aligned air gaps, means mounting the coil means for rotation about the axis, the inner pole pieces of the magnetic structures being spaced to provide a passage through which the coil means may be introduced into operative position and removed from the magnetic structures without disturbing the magnetic structures, each of said inner pole pieces having a configuration providing a varying solenoid force acting between the magnetic structure and the coil means in response to current flowing through the coil means which varies as said coil means moves over the last-named inner pole piece, the inner pole pieces of the magnetic structures having opposed solenoid forces proportioned to produce zero resultant force acting on the coil means in response to current flowing through the coil means for all positions of the coil means in the normal path of rotation of the coil means.

26. In an electrical instrument, a stator assembly, a coil, means mounting the coil for rotation about an axis relative to the stator assembly, said stator assembly including a magnetic core unit positioned within the coil and a magnetic pole-piece unit spaced from the magnetic core unit to define an air gap for a portion of the coil, one of the units having dimensions which vary with the angular position of the coil relative thereto for the purpose of varying the response of the instrument to various energizations thereof, said variations in dimensions being located intermediate the axial ends of the last-named unit, said axial ends being substantially uniform adjacent the path of travel of the coil for all angular positions of the coil to make the response of the instrument substantially independent of the axial adjustment of the coil along the axis.

27. In an electrical instrument, a coil, a magnetic structure having an air gap, means mounting the coil with a coil side in the air gap for movement relative to the magnetic structure, said magnetic structure defining a magnetic path for magnetic flux produced by current flowing in the coil which produces a solenoid force acting between the coil and the magnetic structure, compensating means energized in accordance with current flowing in the coil for producing a second

force acting in opposition to said solenoid force between the magnetic structure and the coil and proportioned to compensate fully for the solenoid force in all positions of the coil side in its path of movement relative to the magnetic structure, said compensating means comprising a second magnetic structure having an air gap for receiving said coil side, said second magnetic structure defining a magnetic path for magnetic flux produced by current flowing in the coil which produces a solenoid force acting between the coil and the magnetic structure in opposition to the first-named solenoid force, and means associated with the magnetic structures for directing magnetic flux through said air gaps to establish magnetic fields in the air gaps, said air gaps tapering in opposite directions corresponding to the two directions of movement of the coil relative to the magnetic structures by amounts proportioned to make the two solenoid forces equal in magnitude for all operating positions of the coil in the air gaps.

28. In an electrical instrument, a magnetic structure having an air gap, a coil having a side disposed in said air gap, means mounting said coil for rotation relative to said magnetic structure, said magnetic structure and the coil developing solenoid torques which urge said coil towards an intermediate position in its path of travel, and means compensating said torque, said last-named means comprising an auxiliary magnetic structure establishing a path for magnetic flux produced by current flowing in the coil, said auxiliary magnetic structure developing torques which act in opposition to said first-named torques, said auxiliary magnetic structure comprising a magnetic element extending through the coil, the magnetic element having a separate pocket at each end of the path of travel of a coil side to provide an auxiliary air gap for receiving said last-named coil side on each side of said intermediate position, whereby said magnetic element cooperates with the coil when current flows through the coil, and when said coil is displaced from the intermediate position, to urge the coil away from said intermediate position.

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