

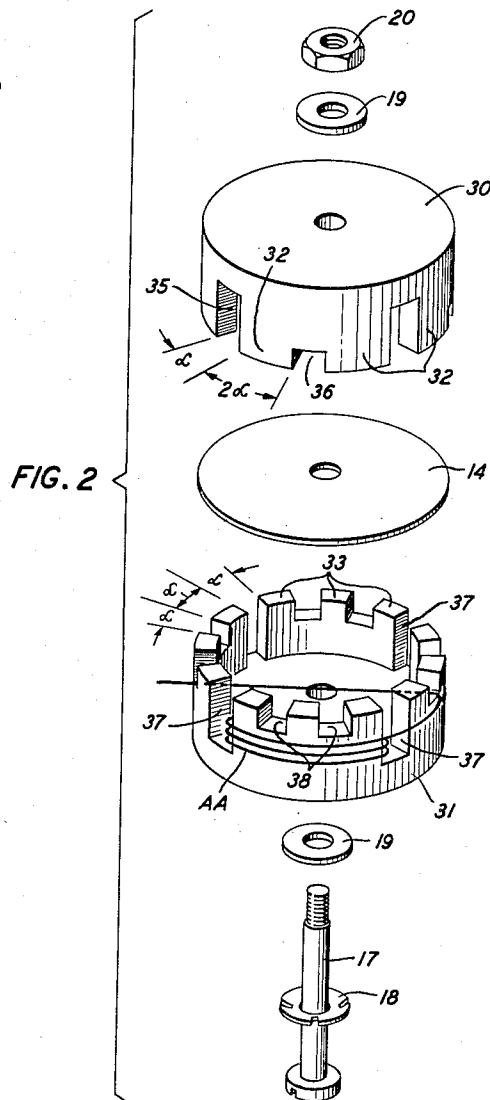
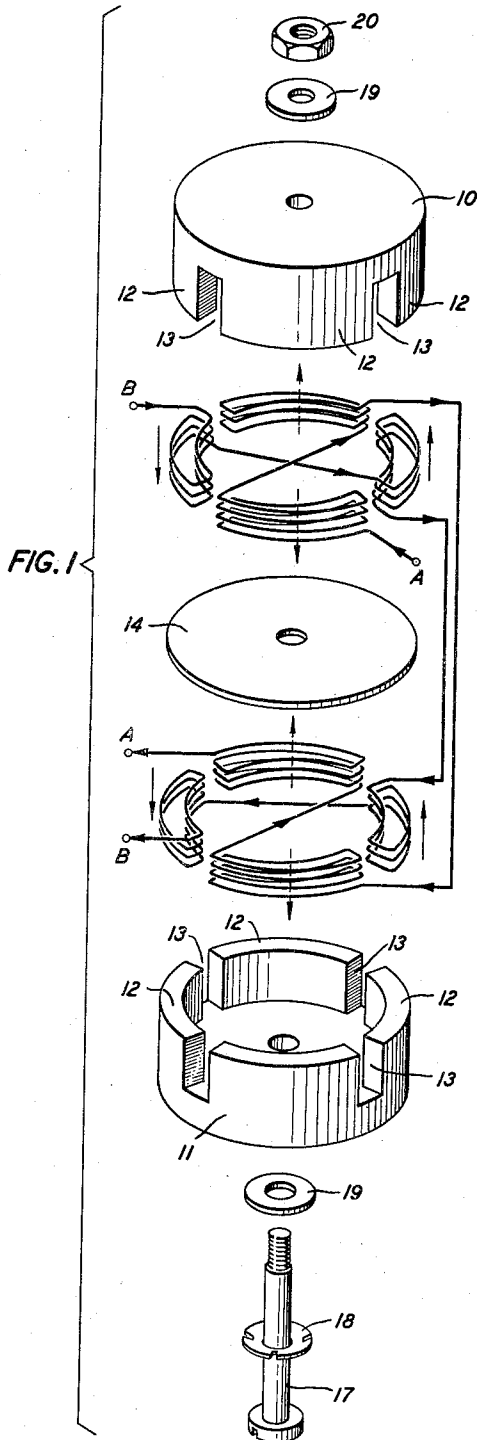
June 10, 1958

R. S. DUNCAN
ADJUSTABLE INDUCTOR

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3 Sheets-Sheet 1



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3 Sheets-Sheet 2

FIG. 3

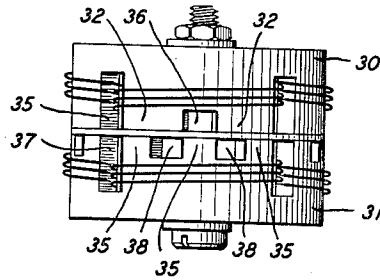
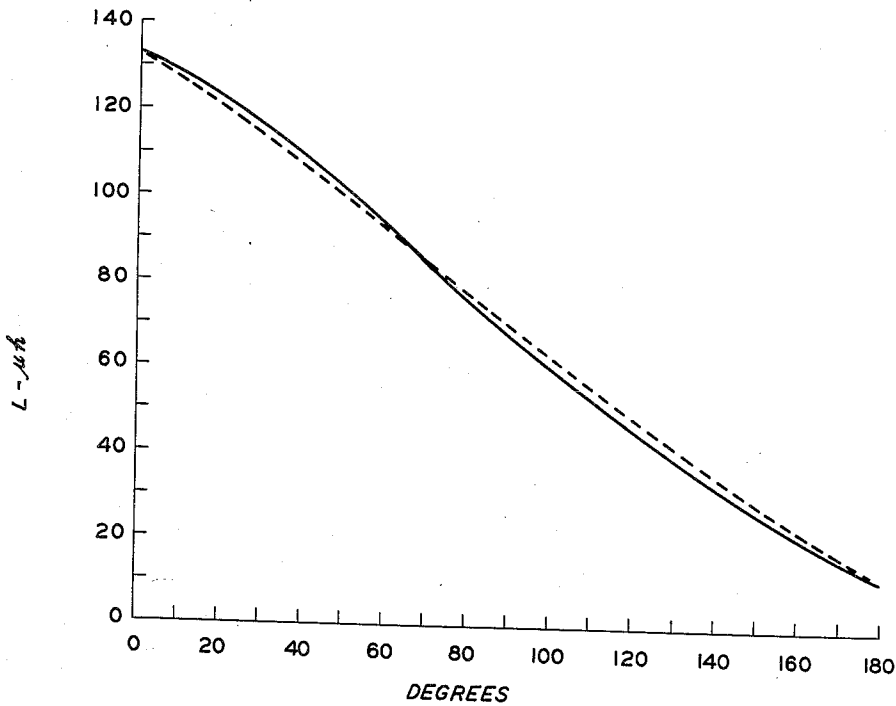


FIG. 4



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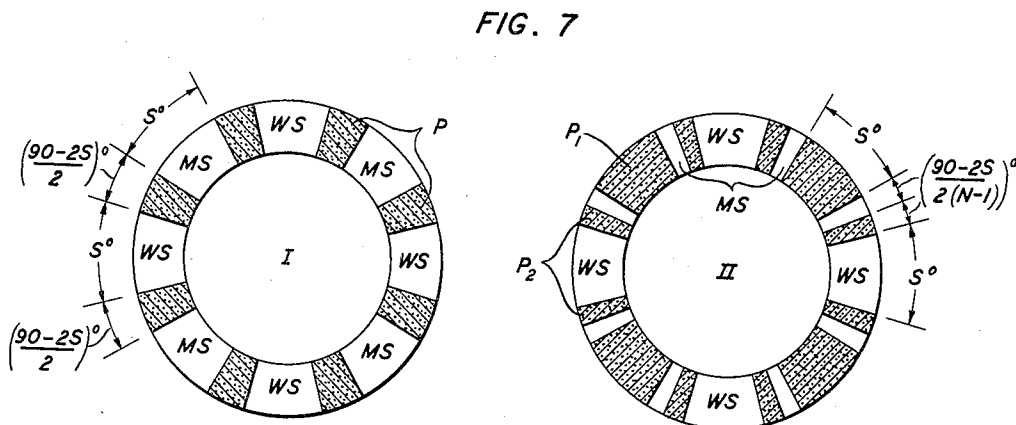
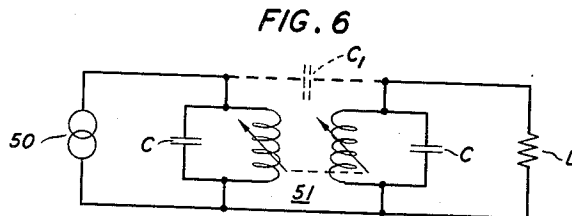
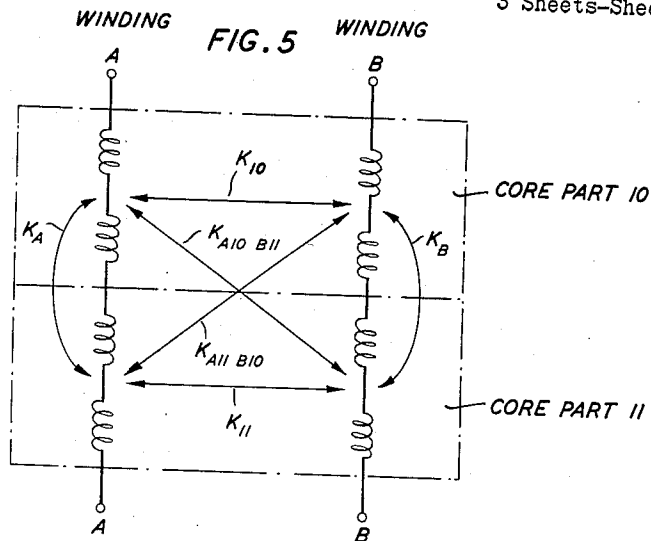
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3 Sheets-Sheet 3



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ADJUSTABLE INDUCTOR

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14 Claims. (Cl. 336—120)

This invention relates to inductive devices and more particularly to mechanically ganged multiple adjustable inductors.

In recent years improved inductor design and higher magnetic core permeabilities have fostered a change in tuned circuits from capacitive adjustment by means of variable air condensers to that of permeability tuning units employing adjustable inductors. In such applications as superheterodyne receiving circuits where it is desirable to tune the oscillator and radio frequency unit simultaneously, formerly the rotor shafts of a pair of air condensers were coupled together to form a ganged unit; more recently it has been the practice to join a pair of cylindrical inductor core members by means of a yoke which is translatable to move the cores in and out of individual windings. Ganged permeability tuning units of this type have low cost and offer reasonably adequate tuning accuracy, but several difficulties are encountered. The core members are usually cantilevered within the coil form in a manner allowing them to be withdrawn axially. The assembly is somewhat fragile, subject to shock and vibration and requires sufficient room for the core members in their outermost position along with the volume required for the winding assembly. Furthermore, the tuning adjustment is made by an axial movement or translation rather than rotational motion which is more desirable. Various mechanisms have been employed to improve the inductance versus core movement characteristics and to allow the translatory movement of the core to be controlled by a rotatable knob. The mechanisms, of course, add to the size and cost of the tuning unit.

In view of these limitations encountered in the past, it is a general object of this invention to improve adjustable inductive devices.

More specific objects of this invention are to facilitate the manufacture of high Q permeability tuning units of small size and low cost; to obtain such units of small size in which the mechanical coupling between multiple windings is complete while the electromagnetic coupling is a minimum; and to obtain a permeability tuning unit having a substantially linear inductance change characteristic with respect to mechanical adjustment.

A further object of this invention is to realize such a tuning unit in which a uniform inductance adjustment is obtained directly by rotational motion.

These objects are accomplished in accordance with this invention, in which one embodiment comprises a pair of aligned cup-shaped core parts of ferromagnetic material defining an enclosed shell and mounted for rotation relative to each other about their common axis. Each core part includes diametrical slots which define a plurality of distinct arcuate pole segments, for example four in number. A series of turns of insulated wire is wound about each of the arcuate pole segments and interconnected with the turns on the opposite pole segments to form a plurality of distinct windings. The windings each remain in fixed relationship to a mounting core part, and simultaneous inductance adjustment of the plurality

2

of windings is obtained by rotational movement of the core parts.

In another embodiment of this invention the pole segments of the core parts mounting the windings include additional slots defining subpoles having a prescribed area whereby linearity of inductance adjustment characteristic is insured.

One feature of this invention resides in the mounting of a plurality of magnetically decoupled sets of windings in close physical relationship symmetrically and effectively perpendicular upon a single set of magnetic core parts for rotational inductance adjustment.

Another feature of this invention lies in the area relationship of the core part pole segments of the individual core parts whereby deviations from a linear inductance characteristic of the individual windings caused by variations of core area in contact are eliminated.

In accordance with another feature of this invention adjacent windings are overlapped to further linearize the inductance characteristics without any increase in coupling between the windings.

These and other features of this invention may be more clearly understood from the following detailed description and by reference to the drawing in which:

Fig. 1 is an exploded view of an inductor in accordance with this invention with the windings shown in schematic form;

Fig. 2 is an exploded view of the magnetic core assembly of another embodiment of this invention with a portion of one winding shown in place;

Fig. 3 is an elevational view of another embodiment employing the winding of Fig. 1 and the core elements of Fig. 2;

Fig. 4 is a graphical representation of the inductance-adjustment characteristic of a device of the type shown in Fig. 2;

Fig. 5 is a schematic representation of the device of Figs. 1, 2, and 3;

Fig. 6 is a schematic diagram of a continuously tunable band pass filter incorporating an inductor of this invention; and

Fig. 7 is an elevational view of the general form of core parts according to this invention showing the subpole and slot arrangement.

Referring now to Fig. 1, the multiple winding inductor comprises a pair of cup-shaped core parts 10 and 11 of ferromagnetic material, for example manganese-zinc ferrite. The walls of core parts 10 and 11 are divided into a plurality of pole segments 12 by diametrical slots 13. In this embodiment the number of pole segments is four, but this number may be increased in multiples of two within the physical limits of the core part dimensions and area required for the windings. Mounted upon each segment 12 is a winding, for example, comprising turns of enameled or otherwise insulated wire, giving a total of eight individual sets of turns connected together seriatim in groups of four, giving windings AA and BB which are electrically independent of each other. Flexible leads contained within the assembled core are advantageously employed to join the sets of turns of each winding. In each of the windings AA and BB two sets of turns encompass opposite pole segments 12 of core part 10 and two sets about opposite pole segments 12 of the core part 11. The core parts 10 and 11 with windings AA and BB mounted thereon are assembled with an air gap spacer 14, for example, a paper disc 0.009 inch in thickness, between the end surfaces of the pole segments 12. A nonmagnetic bolt 17 mounting a spring washer 18 and a pair of conventional washers 19 and secured by nut 20 holds the core part winding assembly together while allowing freedom of rotation of one core part relative to the other. The presence or absence of the

air gap spacer 14 and its thickness depends upon the particular mean value and range of inductance sought and is not an element of this invention.

As the windings AA and BB are shown in Fig. 1, the core part pole segments and their associated windings are arranged in the maximum inductance position, i. e., where all of the portions of the windings AA are in series aiding relationship. With current flowing into the upper A terminal, magnetic flux is induced in the direction of the dotted arrows. Windings BB likewise are arranged in series aiding relationship with the core parts in the position shown. With current flowing into the upper B terminal magnetic flux is induced in the pole segments in the direction of the solid arrows.

When the core parts are rotated 180° relative to each other, pole segments carrying the AA windings will again be in juxtaposition, but the windings will be in series opposing relationship resulting in a minimum inductance. The same is true of the windings BB. Intermediate inductance values will be obtained with the core parts 10 and 11 positioned intermediate the 0° and 180° positions. Throughout the range of adjustment the change in inductance varies substantially linearly with respect to angular changes in the orientation of the core parts. This advantageous characteristic is obtained because the only variable in the electromagnetic circuit is the cross sectional area of the most restricted portion of the magnetic flux path, that is, the area of the faces of the pole segments in juxtaposition electromagnetically coupled to a single winding. The length of the magnetic flux paths indicated in Fig. 1 by the dotted and solid arrows, respectively, associated with each of windings AA and BB is constant and equal. Similarly, the electromagnetic coupling between each pole segment and its respective set of turns is fixed, and the total number of effective turns of both windings AA and BB is constant in every position of core part orientation. Variations in magnetic flux path length, electromagnetic coupling of the turns to the magnetic core, and the number of turns have been employed to produce variations in the inductance in the past, but the variation generally is exceedingly non-linear. This is apparent from an analysis of the equation for the inductance of a magnetic core inductor:

$$L = \frac{KN^2 A \mu}{l}$$

where

L = the inductance

K = a constant

N = the number of turns

A = the cross sectional area of the most restricted portion of the magnetic core in the flux path

μ = magnetic core permeability

l = the mean length of flux path through the magnetic core.

The inductance varies directly with the constant K , the core permeability, the number of winding turns squared, and the minimum cross sectional core area; and it varies inversely with the length l of the flux path. The permeability μ and constant K are normally not adjustable. Any uniform adjustment of the number of turns or the length l will give an undesirable logarithmic change in inductance. An adjustment varying the cross sectional area A uniformly effects a uniform variation in inductance. Such is obtained in inductors according to this invention.

One basic feature of the arrangement of the multiple windings on the magnetic core is that the windings are symmetrically mounted on the core parts, and the magnetic flux induced in the core by the windings passes through common portions of the magnetic circuit at right angles resulting in a minimum of cross coupling. Symmetry and perpendicularity facilitate analysis of the inductor design and also are instrumental in obtaining advantages of maximum mechanical and minimum elec-

trical coupling of the independent windings in a high Q inductive device.

In order to comprehend the aspects of this invention by which the inductance adjustment of this inductor is accomplished, an analysis of the electromagnetic coupling between segments of the windings is desirable. The effects of coupling between the windings in intermediate positions or in any position will be understood by reference to Fig. 5, wherein the inductive device of Fig. 1 is shown in schematic form.

For simplicity, the two physically separate series of turns of each winding on opposite pole segments of each core part may be considered as one, since they are very closely coupled through the body of the core part. With regard to the electromagnetic coupling, K , of the windings A and B there are three distinct effects. They are defined as:

K_{10} and K_{11} , the coupling between the windings upon the same core part;

$K-A$ and $K-B$, the intended or productive coupling between the turns of winding A or B of one core part with the turns of the same winding upon the other core part; and

$K-A_{10}-B_{11}$ and $K-B_{10}-A_{11}$, the cross coupling between the A winding of one core part and the B winding of the other core part.

Considering first the direct coupling K_{10} and K_{11} between windings upon the same core part, it is found that the magnetic fluxes induced by these windings are mutually perpendicular. Since the flux concentration within the core parts is advantageously in the linear portion of the (B-H) characteristic, the coupling of these mutually perpendicular fluxes is substantially zero and K_{10} and K_{11} may both be considered as equal to zero. Since both windings are on the same core part in fixed relation to each other, relative angular changes of the two core parts cannot affect this coupling factor, so K_{10} and K_{11} equal zero regardless of the orientation of the core parts.

Considering next the coupling $K-A$ and $K-B$, as one core is rotated relative to the other, the values of $K-A$ and $K-B$ will vary simultaneously from maximum positive through zero at $\theta=90^\circ$ to maximum negative as θ , the angle of core part orientation, varies from 0° in the series aiding position to 180° in the series opposing position. This result is obtained since the coupling $K-A$ and $K-B$ depends upon the cross sectional area of the pole segments encompassed by each respective winding and in juxtaposition. When the rim or wall thickness of the core parts is uniform, the area in juxtaposition of each core part encompassed by winding AA or BB varies directly with the angular displacement of the core parts.

The equation expressed above for the inductance of a magnetic core inductor

$$L = \frac{KN^2 A \mu}{l}$$

since N , μ , and l remain constants, may be reduced to $L=K'A$. The area A , as has been mentioned above, is a direct function of the angle of core part displacement θ between 0 and 180° or π radians, so the equation becomes $L=K''\theta$. In one particular device incorporating this invention employing manganese-zinc ferrite core parts and eight turns of four enameled wires, measured values indicate that K'' equals 38.2 microhenry/radian. The cross coupling between windings AA and BB, identified above as $K-A_{10}-B_{11}$ and $K-B_{10}-A_{11}$, varied with angular orientation of the core parts from a minimum of 0.1 percent to a maximum of 1.5 percent, which is well within allowable cross coupling limits for multiple winding inductive devices.

It has been found by extensive tests that the variation of inductance is substantially linear with changes of the angle θ . Some nonlinearity was noticeable near the angles 0° and 180° . Of course, in most applications a slight

5

amount of nonlinearity is of little or no consequence. It has been determined that this nonlinearity was due to a slight nonuniform change in area of the juxtaposed pole segments due to the necessary winding slots. The nonlinearity could be reduced by a reduction in the width of the winding slots within limits, but according to another feature of this invention the undesired nonuniform change in area may be eliminated without the necessity of narrowing the winding slots. The inductive device of Fig. 2 demonstrates this feature. The difference between the device of Fig. 2 and that of Fig. 1 lies in the configuration of the pole segments. Core part 30 includes winding slots 35 similar to core part 10, but the pole segments are divided each into a pair of subpoles 32 by a minor slot 36 of lesser depth than the winding slot 35. The core part 31 includes four pole segments, each of which includes three subpoles 33 separated by slots 38 of lesser depth than the winding slots 37. A pair of windings similar to AA and BB of Fig. 1 are normally mounted upon the pole segments. Illustrative of another feature of this invention is the winding area shown on core part 31, wherein a portion of the turns about a single pole segment also encompass the nearest subpole of adjacent pole segments. A more complete description and explanation of this winding appears hereinafter.

Certain of the features of the inductive device of Fig. 2 are identical with those of Fig. 1 and are so identified. They include the spacer 14, bolt 17, spring washer 18, conventional washers 19, and nut 20. Fig. 3 shows the assembled device of Fig. 2 in elevation whereby the relative size of the subpoles 32 and 33 of core parts 30 and 31 may be compared. In the particular embodiment of Figs. 2 and 3 employing four pole segments on each core part the angle α , here 15° , formed the basis for determining the size of the winding slots 35 and 37, minor slots 36 and 38, pole segments, and subpoles. All the slots subtend an angle of 1α or 15° . The pole segments subtended an angle of 5α , or 75° , while the subpoles 32 of core part 30 are 2α each in angular width, and the subpoles 33 of core part 31 are equal to 1α in angular width. The result of such angular width or area relationship is that there is no change of area of the core parts in juxtaposition due to the presence of any slots. For example, as shown in Fig. 3 the windings AA are in the maximum series aiding position since the pole segments are aligned and the flux paths which pass through the outermost subpoles are indicated. In all positions the areas of opposite pole segments in juxtaposition have an angular width of 2α , and since there are four pole segments on the core parts illustrative device, the total juxtaposed area is 8α . Only the area of the pole segments in the magnetic flux path encompassed by each individual winding varies with angular displacement of the core parts. That change in area A takes place uniformly and directly with angular displacement.

The design of inductors according to this invention is by no means limited to this particular angular division of the core part rims where 15° forms the basic angular width and any value of α may be used which (1) provides winding slots between each quadrant of both core parts, (2) insures a constant total rim area in contact at all angular positions, and (3) offers juxtaposed rim area coupled to each independent winding which varies uniformly and directly with core part orientation. These three requisites are met when the rims of the core parts appear as shown in Fig. 7. Core part I includes four winding slots WS and four auxiliary or minor slots MS alternating at 45° spacing around the rim. Each slot is S° wide where S equals any value between 0° and 45° . Between each winding and minor slot is a subpole P which is

$$\left(\frac{90-2S}{2}\right)^\circ$$

6

wide. Core part II includes, similar to core part I, winding slots WS which are S° in width and arranged at 90° intervals around the rim. Symmetrically placed between each winding slot WS of core part II are auxiliary subpoles P_1 , which are S° wide, spaced 90° apart with centers 45° from the centers of the nearest winding slots WS. Between each auxiliary subpole P_1 and its adjacent winding slot WS are alternate subpoles P_2 and minor slots MS each of which has an angular width of

$$\left(\frac{90-2S}{2(n-1)}\right)^\circ$$

where n is the number of subpoles in each repeating cycle of subpoles and slots of core part II which in this embodiment is a quadrant. n may be any odd integer except 1. Examples of particularly valuable core part parameters are tabulated below.

Core I

Winding Slot Width (S°)	Minor Slot Width (S°)	Subpole Width $\left(\frac{90-2S}{2}\right)^\circ$
5 15 30	5 15 30	40 30 15

Core II

[With $n=3$]

Winding Slot Width (S°)	Minor Slot Width $\left(\frac{90-2S}{2(n-1)}\right)^\circ$	Subpole P_1 Width (S°)	Subpole P_2 Width $\left(\frac{90-2S}{2(n-1)}\right)^\circ$
5 15 30	20 15 7.5	5 15 30	20 15 7.5

The configuration of the pole segments, as shown in Figs. 2 and 3, and the correlation between the angular width of the subpoles and slots of the core parts eliminates any nonlinearity due to changes in total pole segment area in juxtaposition with rotation of the core parts. A residual nonlinearity in characteristic was encountered at the centermost position of adjustment, i. e., $\theta=90^\circ$, which, it was determined, was occasioned by the existence of the finite areas of the periphery of the core parts not encompassed by either winding AA or BB. The areas are those of the major or winding slots. By partially distributing the windings, this residual nonlinearity is avoided without any increase in cross coupling between the independent windings. The distributed windings are mounted in series aiding relation to the pole segments that they completely encompass and in series opposing relationship to those on the adjacent subpoles, so that neither the symmetry nor the perpendicularity of the magnetic flux paths associated with the individual windings are changed. An inductance versus mechanical adjustment characteristic, as shown in Fig. 4 as the solid and dotted lines, identified as L_{AA} and L_{BB} , respectively, is thereby obtained. The manner of winding distribution is indicated in Fig. 2. There three turns of winding AA are shown about one pole segment, and one turn also encompasses the adjacent subpoles of other segments. When completed, the particular inductor shown includes eight turns about each pole segment, and two of which, or 25 percent, also encompass the adjacent subpoles.

The most apparent application of multiple winding inductors of this invention is in loosely coupled double-ganged tuning circuits for radio receivers as a double-tuned adjustable frequency interstage network, as a selective antenna coupling network, or in a superheterodyne circuit as a ganged oscillator and radio frequency tuning unit. In each of these applications the multiple in-

ductor most probably replaces a pair of variable air capacitors as the adjustable element with a substantial saving in space.

Another useful application for this device is as the adjustable element in a tunable band pass filter. A schematic diagram of such a filter is shown in Fig. 6. The circuit comprises a generator 50 connected to supply a multifrequency signal to a load L, for example, a 4500-ohm resistor. Interposed between the generator 50 and load L is filter 51 comprising an inductor of this invention, each winding of which is connected in parallel with a capacitor C of capacity in the order of 600 micro-microfarads. The interwinding capacity C_1 of the inductor, which is in the order of 62 micromicrofarads and substantially constant, is shown in dotted lines joining the halves of the filter section. Employing an inductor having characteristics as shown in Fig. 4, a filter is obtained in which the pass band midfrequency is continuously adjustable from approximately 400 to 1800 kilocycles, with a uniform midband loss. The uniformity of midband loss, which is a highly desirable characteristic of adjustable band pass filters, results from the constant electromagnetic and capacitive coupling of the multiple inductor which is an inherent quality of devices of this invention. In other filter applications where impedance transformation is sought between the signal source and load the windings of the inductor need not be balanced in number of turns. Where the inductor employs either identical or different windings the advantageous low cross coupling is maintained resultant upon the symmetry and perpendicularity of the electromagnetic coupling between the winding and the magnetic core in inductors of this invention.

It is to be understood that the above-described arrangements are merely illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An inductive device comprising a pair of cup-shaped core parts of ferromagnetic material, said core parts including walls having rim portions, said core parts being aligned with rim portions in juxtaposition, the walls of each of said core parts including two pairs of radial slots defining four distinct pole segments, a first winding seriatly wound about a pair of opposite pole segments of one of said core parts and then seriatly about a pair of opposite pole segments of the other of said core parts, a second winding seriatly wound about a second pair of opposite pole segments of one of said core parts and seriatly about a second pair of opposite pole segments of the other of said core parts, and means for rotating one core part relative to the other core part about their common axis to adjust the inductance of each of said windings simultaneously.

2. A multiple winding adjustable inductive device comprising a pair of cup-shaped core parts of ferromagnetic material including annular rim portions in juxtaposition, said annular rim portions being divided into a plurality of pairs of distinct pole segments by a series of radial slots, a first winding seriatly wound about a pair of opposite pole segments of one of said core parts and then seriatly about a pair of opposite pole segments of the other of said core parts, a second winding seriatly wound about a second pair of opposite pole segments of one of said core parts and then seriatly about a second pair of opposite pole segments of the other of said core parts, and means mounting one of said core parts for rotation relative to the other of said core parts about an axis coextensive with the axis of said rim portions.

3. A multiple winding adjustable inductive device in accordance with claim 2 wherein said pole segments are arranged in circular array having an axis coextensive with the axis of rotation of the core parts.

4. A multiple winding adjustable inductive device com-

prising a pair of ferromagnetic core parts including distinct pole portions in juxtaposition, said core parts defining a plurality of closed magnetic flux paths each passing through juxtaposed pole portions of said core parts, a series of turns of insulated wire wound about each of said pole segments in electromagnetic coupling relation to each of said magnetic flux paths, opposite pairs of said sets of turns on one of said core parts being seriatly connected together and to opposite pairs of sets of turns on the other of said core parts to form a plurality of electrically independent windings, and means for rotating said core parts relative to each other to vary the area of pole portions in juxtaposition simultaneously.

5. A multiple winding adjustable inductive device in accordance with claim 4 wherein said core parts define a pair of substantially closed, mutually perpendicular magnetic circuits through the pole segments.

6. A multiple winding adjustable inductive device in accordance with claim 4 wherein the sets of turns comprising the multiple windings are arranged symmetrically upon the pole segments with respect to the axis of rotation of the core parts and to each other.

7. A multiple winding adjustable inductive device comprising a magnetic core including a pair of cup-shaped core parts having rim portions in juxtaposition and wall portions divided into a plurality of pole segments by radial slots, said pole segments on each core part being four in number and arranged in circular array, a series of turns of insulated wire wound about each of said pole segments, opposite pairs of said sets of turns on one said core part being seriatly connected together and to opposite pairs of sets of turns on the other of said core parts to form a pair of electrically independent windings, and means mounting said core parts and sets of turns for rotation relative to each other about a common axis to vary the inductance of said windings simultaneously.

8. A multiple winding adjustable inductive device comprising a magnetic core including a pair of core parts including a plurality of pole segments arranged in circular array, the pole segments of one of said core parts being aligned and in juxtaposition with the pole segments of the other of said core parts, each of said pole segments being divided into at least two subpoles, a series of turns of insulated wire wound about each of said pole segments, opposite pairs of said sets of turns on one of said core parts being seriatly connected together and to opposite pairs of sets of turns of the other of said core parts to form a pair of electrically independent windings, a portion of each of the sets of turns of one of said core parts encompassing in addition to a pole segment a subpole of each of the adjacent pole segments, and means mounting said core parts and sets of turns for rotation relative to each other about a common axis to vary the inductance of said windings simultaneously.

9. A multiple winding adjustable inductive device comprising a magnetic core including a pair of core parts each including a plurality of pole segments arranged in circular array and separated by winding slots spaced 90° apart, a series of turns of insulated wire in electromagnetic coupling relationship to each of said pole segments, opposite pairs of said sets of turns on one of said core parts being seriatly connected together and to opposite pairs of sets of turns of the other of said core parts to form a pair of electrically independent windings, and means mounting said core parts and sets of turns for rotation relative to each other about a common axis, the pole segments of said core parts including subpoles of width correlated so that the area of subpoles in juxtaposition encompassed by each winding varies uniformly with the extent of rotation of said core parts.

10. A multiple winding adjustable inductive device in accordance with claim 9 wherein the total area of all of said subpoles in juxtaposition is constant at all degrees of core part orientation.

11. A multiple winding adjustable inductive device in accordance with claim 9 wherein a portion of each of said sets of turns on one of said core parts is positioned in electromagnetic coupling relationship with adjacent subpoles as well as with a pole segment.

12. A multiple winding adjustable inductive device comprising a magnetic core including a first cup-shaped core part and a second cup-shaped core apart, said core parts positioned with rim portions in juxtaposition, said first core part including a plurality of winding slots equally spaced around the periphery of said rim portion and dividing said rim portion into distinct pole segments, said first core part also including a plurality of minor slots equal in angular width to the winding slots dividing said pole segments into a plurality of subpoles, said second core part including winding slots corresponding to the winding slots of said first core part dividing the rim portion into a plurality of pole segments, said second core part also including a subpole equal in angular width to said winding slots and positioned midway between adjacent winding slots and including in alternating order between said subpoles and winding slots, minor slots and auxiliary subpoles, the angular width of said minor slots and of said auxiliary subpoles being equal to

degrees where n equals the total number of subpoles on said second core part in each repeating cycle of subpoles and slots and where S equals the angular width of said winding slots, a series of turns of insulated wire in electromagnetic coupling relationship to said pole segments of both said core parts, and means mounting said core parts for rotation relative to each other about a common axis.

13. A multiple winding adjustable inductive device in accordance with claim 12 wherein a portion of each of said sets of turns is wound symmetrically about an adjacent auxiliary subpole of said second core part.

14. A multiple winding adjustable inductive device in accordance with claim 12 wherein in the order of 25 percent of each of said sets of turns encompass both a pole segment and adjacent auxiliary subpoles.

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