March 14, 1961 D. T. GEISER 2,975,384

TOROIDAL INDUCTOR COMBINATIONS

Filed Sept. 24, 1954 3 Sheets-Sheet 1

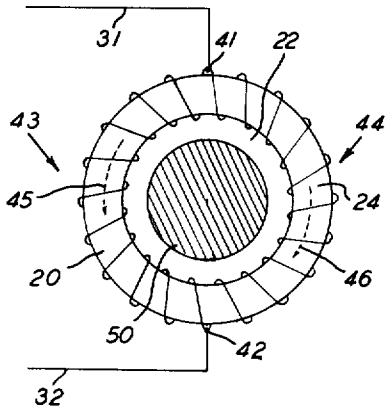



FIG. 1

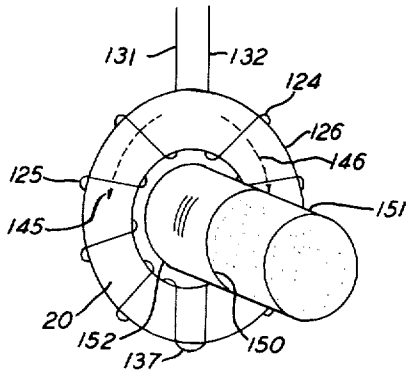



FIG. 2

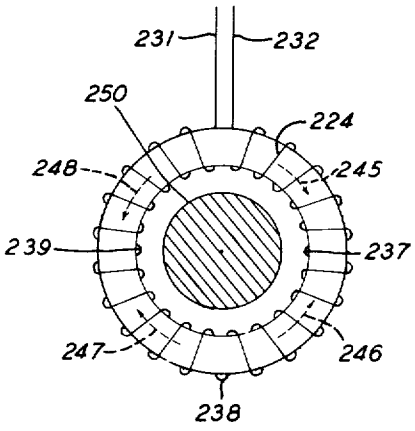



FIG. 3

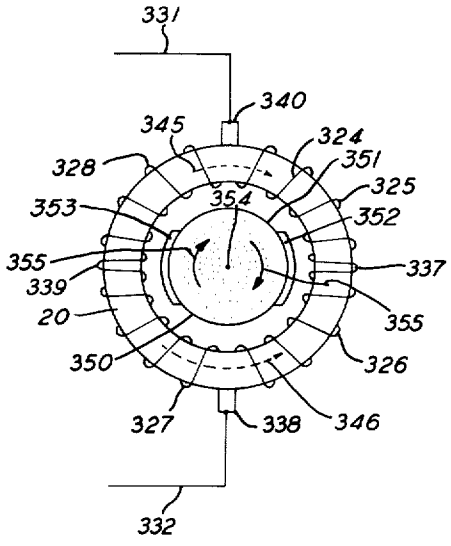



FIG. 4

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TOROIDAL INDUCTOR COMBINATIONS

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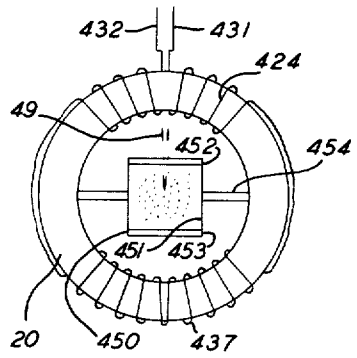



FIG. 5

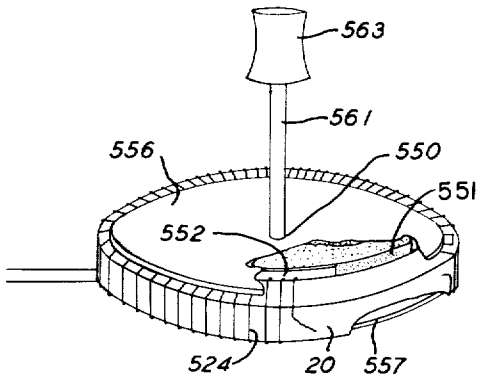



FIG. 6

FIG. 8

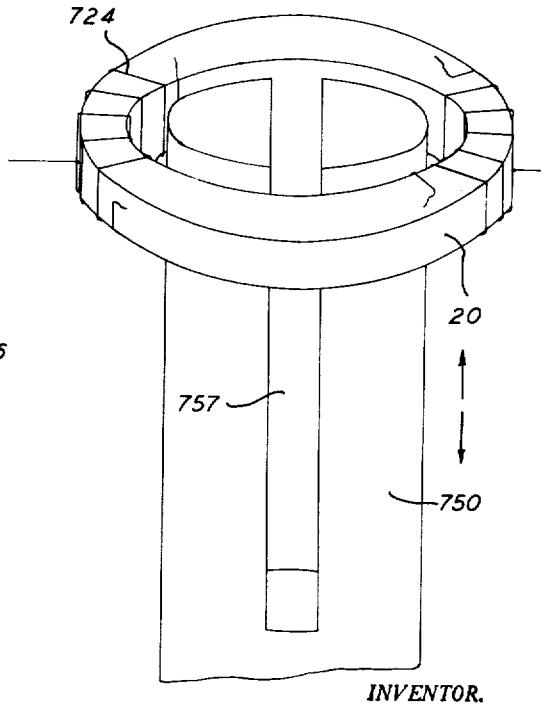
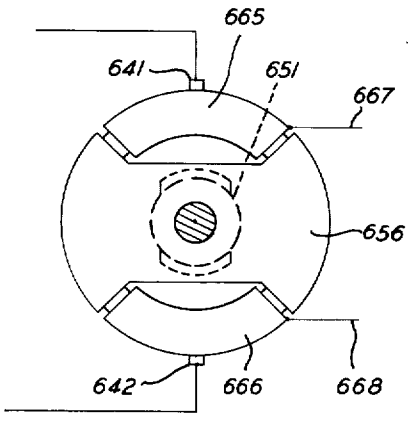



FIG. 7




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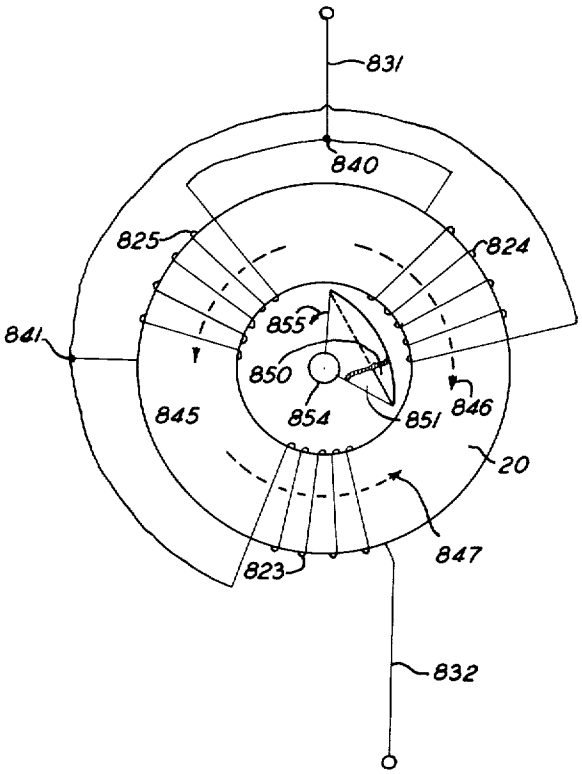



FIG. 9

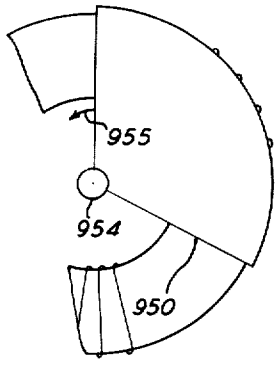



FIG. 10

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2,975,384

# TOROIDAL INDUCTOR COMBINATIONS

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4 Claims. (Cl. 336—77)

The present invention relates to toroidal inductors, that is electrical inductors having windings that are looped around a magnetic core of toroidal or endless form.

Among the objects of the present invention are the provision of novel arrangements of the above forms of inductor by which they are readily tuned.

The above as well as additional objects of the present invention will be more clearly understood from the following description of several of its exemplifications, reference being made to the accompanying drawings in which:

Figs. 1 to 10 inclusive are somewhat diagrammatic showings of the essential details of different embodiments of the present invention.

It has been found that a toroidal inductor can be readily tuned by arranging for its windings to generate separate and opposing sets of magnetic flux, and adjustably positioning a flux-controlling member within or adjacent the opening in the toroid. The windings can be arranged as an even number of groups with the radial orientation of the turns in one group being opposite to that of another. Alternatively, the windings can have turns all of the same radial orientation with leads connected to opposed portions.

Fig. 1, for example, shows the latter type of construction, in which there is a doughnut-shaped magnetic core **20** having a central opening **22** and around which is looped a plurality of turns of conductive wire **24**. The wire can be insulated as by the conventional enamel, although such insulation would not be needed where the core **20** has a sufficiently high electrical resistivity, as when it is made of a ferrite. The turns themselves are shown in Fig. 1 as uniformly distributed around the inductor core with two terminal leads **31**, **32** connected respectively to opposite portions **41**, **42** of the winding. The current flowing between points **41**, **42** will branch through the windings connecting these points on opposed sections of the core, as indicated at **43**, **44**. Although all the turns of the windings have the same radial orientation with respect to the core, the branched current will generate in each section **43**, **44** a magnetic flux which is directed generally parallel between the terminal connections **41**, **42**. Such flux is represented by the dash line arrows **45**, **46**.

At the respective terminal connections these separate sets of flux **45**, **46** will oppose each other, and the flux paths will be completed through the air gap in and adjacent to the center of the core. A flux-controlling member **50**, such as a high permeability slug, or a non-magnetic highly conductive slug, will accordingly increase or decrease the effective permeability of the core and correspondingly change the inductance appearing between the leads **31**, **32**. These slugs can be arranged for adjustable insertion in the opening as by mounting them within a cardboard or resin tube extending axially through the opening of the toroid and cemented to it. The tube can be fitted with a mounting bracket or clip and the slug



provided with a threaded extension threadedly engaged in the bracket or clip and slotted for rotation by a screw driver.

The core **20** can be made of any magnetic material having a permeability of at least about 2 or higher. Pressed, powdered iron bonded together by a resin or the like, makes a very suitable type of core. For the higher frequencies, ferrites such as those of the type described in U.S. Patents Nos. 2,579,978, 2,452,530 and 2,452,529 are particularly suitable. The core can also be made of spirally wound foil or wire with the turns of the spiral winding prevented from short circuiting against each other by insulation. For lower frequencies laminations of ring-shaped sheets can merely be stacked up and bonded or clamped together. The number of turns of the winding is determined by the magnitude of the desired inductance. For frequencies of the order of 2 megacycles or higher, not more than about 20 or 30 turns will be generally needed, depending on the core material and inductance desired.

Fig. 2 shows an embodiment of the invention in which the winding is provided in the form of different sections, the radial orientation of the turns in one section being opposed to that of the other. A core **20**, which may be the same as the core of the construction of Fig. 1, is here provided with windings **124** that reverse in direction. Leads **131**, **132** are connected to the windings which are in turn divided into separate sections **125**, **126** with the direction of the winding reversing between them, as indicated at **137**. A flux-controlling member **150** is shown in this embodiment as divided into two portions, one of which, **151**, is a high permeability magnetic material and the other, **152**, is a non-magnetic highly conductive material such as brass or copper.

By reason of the reversed direction of winding, the flux generated in the core of Fig. 2 will be divided into two opposing sets **145**, **146** in a manner similar to that shown in connection with Fig. 1. If desired, however, four sets of flux can be provided in the construction of Fig. 2 by merely reversing the direction of winding at three places, preferably symmetrically located around the core. In fact, the reversals can be increased a number to provide any number of pairs of opposing sets of flux.

Correspondingly the construction of Fig. 1 can also be provided with additional pairs of opposing sets of flux by merely suitably locating additional taps on the winding **24** and appropriately connecting the taps to the leads **31**, **32**. In addition, a slug of the type shown at **150** in Fig. 2 can be used in the construction of Fig. 1, and conversely the simple type described in connection with Fig. 1 can be used in the construction of Fig. 2.

Fig. 3 shows one type of inductor in which two pairs of opposed sets of flux are provided in accordance with the present invention. This construction is similar to that of Fig. 2 except that the windings **224** reverse direction three times, as indicated at **237**, **238** and **239**. As a result, currents supplied from leads **231**, **232** generate sets of flux, as represented by the dash line arrows **245**, **246**, **247** and **248**. Adjacent sets of flux oppose each other and a flux-controlling insert **250** accordingly provides good inductance variation.

Fig. 4 shows a still further embodiment of the invention in which the number of sets of flux is only half as large as the number of winding reversals. Core **20** is here illustrated as having windings **324** that include three reversals **337**, **338** and **339**, as in the construction of Fig. 3, along with an interconnection of the windings in the form of a fourth reversal **340**. However, terminal leads **331**, **332** are connected at two opposite reversals **340**, **338**. Accordingly, although the windings can be considered as divided into four sections **325**, **326**, **327** and

328. The current between leads 331, 332 will generate only one pair of opposed sets of flux 345, 346.

Fig. 4 also shows a modified form of flux-controlling member 350. This member is shown as a cylinder 351 of high permeability material such as ferrite or bonded powdered iron, with electrically conductive foil segments 352, 353 fixed in place on opposite sides of the cylinder's periphery. The cylindrical assembly is mounted for rotation around its cylindrical axis 354, as indicated by arrows 355. In the rotary position shown in Fig. 4, the conductive layers 352, 353 are interposed between the magnetic cylinder 351 and the core zones (at reversals 337, 339) in which the flux sets 345, 346 are in opposition. In this adjustment the magnetic member 351 will be effectively shielded from most of the leakage flux and the inductor will have minimum inductance. Rotation of the member 350 by 90° around axis 354 will bring the conductive strata 352, 353 away from such interposition and permit the high permeability insert 351 to have its full effect. The inductor will accordingly show maximum inductance in this adjustment.

The flux-controlling insert 350 of Fig. 4 can also be used in the construction of Figs. 1, 2 or 3 and the simpler inserts can take the place of the assembly 350 in the construction of Fig. 4, if desired.

Instead of having the assembly 350 rotatable around an axis parallel to that of the axis of toroid 20, it can be arranged to rotate around an axis perpendicular to the toroid axis and also perpendicular to the principal flux leakage direction.

Fig. 5 shows a flux-controlling arrangement 450 of the last-mentioned type in a somewhat modified form of winding assembly. The core 20 is here illustrated as the single reversal type similar to that shown in Fig. 2. The windings 424 are, however, not uniformly distributed but are crowded together adjacent the zones of flux opposition. These zones are respectively at the leads 431, 432 on one side, and at the reversal 437 on the other side of the core. Between these crowded sections few turns need be provided, and in fact these sections can be interconnected by straight lengths of conductor, if desired. Such a winding arrangement makes a significant improvement in the inductance changes that can be accomplished.

It is also very advantageous, if maximum inductance is to be obtained, to closely space the winding sections that produce the opposing sets of flux. Best results are obtained if the radial angle covered by the space between the opposing sections, as measured around the toroid, is less than 10°. This radial angle is represented by the dash lines 49 in Fig. 5.

The flux-controlling member 450 in this construction is similar to that of Fig. 4 except that member 450 is in the form of a cube rather than a cylinder. The body 451 of the cube is of highly permeable material with the conductive layers 452, 453 attached or plated on opposed faces of the tube. By pivoting the cube on a pin 454 that projects through it and engages against the inner faces of the toroid, the conductive layers 452, 453 are arranged for the desired adjustment. In the position shown these layers are interposed between the core 20 and the portions of the body 451 where the leakage flux enters and leaves. By a ¼ turn around pin 454 the layers 452, 453 are brought to a position substantially parallel with the toroid plane and on opposite sides of the toroid.

Fig. 6 illustrates a still further embodiment of the invention in which the inductance controlling member is somewhat more elaborate. Here the core 20 and the windings 525 may be of any of the types described above and the inductance controlling member 550 includes a rotatable conductor carrying high permeability block 551 as in the construction of Fig. 4. Across both faces of the toroid there are positioned discs 556, 557 of high conductive material such as copper. In Fig. 6 a portion of disc 556 is broken away to show the block 551 as well as one of the conductive layers 552 that the block carries. For rotation of the block, there is shown a shaft 561 which may carry a knob 563 by which it can be more readily manipulated.

In this construction the disc 556, 557 can either be mounted on a shaft 561 for rotation with the block 551, or the disc can be fixed in place so that the block, in rotating, moves around only with its own coatings such as that indicated at 552. A 90° rotation of the block will in this embodiment provide an inductance change as high as 5 to 1. It should be noted that where the windings 524 provide only two opposed sets of flux, only two opposed conductive coatings are needed on block 551. However, where a greater number of opposed sets of flux are provided, as in the type of winding shown in Fig. 3, a corresponding increase in a number of conductive coatings 552, each coating being suitably reduced in segmental size, will enable greater control of inductance.

Inasmuch as the flux leakage external to the core 20 takes place principally between the flux opposition zones, the discs 556, 557 can be cut away from other portions of the core without significantly detracting from their operation. Furthermore, only one disc can be used and the other face of the core left exposed if the maximum inductance changes are not desired. Where the cut-away discs are used and are arranged to be rotated with the block 551, it is preferred that the cut-away locations correspond in radial position to the location of the conductive layers 552.

Fig. 7 shows yet another modification of the invention. The flux-controlling member in this construction is the combination of a conductive layer-carrying block 651 with a cut-away disc 656. The two are arranged to rotate together with the disc slightly spaced from the face of the toroid. In addition, however, this toroid face also carries a pair of fixed plates 665, 666 which can be directly secured to the toroid against its windings. The plates 665, 666 can be used as capacitive members which cooperate in "butterfly capacitor" fashion with the cut-away disc 656. To this end leads 667, 668 are connected to the discs and between these leads there will be a change of capacitance correlated to the change in inductance in the windings around the core. With the windings in the form shown in the construction of Fig. 1, the flux opposition zones are at the lead connections 641, 642 and when the flux-controlling assembly is in the illustrated position, there will be a minimum inductance and minimum capacitance. A 90° rotation, however, will simultaneously provide maximum inductance and maximum capacitance. If it is desirable to have the least stray capacitance between the winding leads and the capacitor plates 665, 666, the winding can be in the form shown in Fig. 4, where the flux opposition zones are 90° away from the terminal leads.

It is sometimes desirable, when using an electrically conductive type of flux-controlling member, to minimize the capacitive effects introduced by the presence of the conductance member.

Fig. 8 shows another phase of the present invention wherein such capacitive effects are reduced. Here the core 20 and windings 724 can be of any of the types described above. The flux-controlling member 750 is, however, in bifurcated form shown in Fig. 8 as an elongated cylindrical rod having a slot 757 cut in one end. The slot has a depth equal to ¼ the wave-length of the signals supplied to windings 724. When the rod 750 is introduced into the inductance-decreasing position, as shown in Fig. 8, the capacitance between the terminals of the winding shows an appreciably smaller increase than where a solid rod is used. It appears that the rod has the desired flux-controlling effects, yet acts as a quarter wave transmission line with the ends of the bifurcation effectively open circuited and showing very little bridging capacitance.

In the construction of Fig. 8, the effective depth of

slot **757** can be adjusted by merely inserting the rod **750** to a greater depth within the toroid **20**. In addition, the reduction of capacitance can also be adjusted by rotating rod **750** around its cylindrical axis. With the flux opposition zones on opposite sides of the rod, maximum capacitance reduction is obtained when these zones are lined up with the slot with the coil of Fig. 4. The capacitance will be at a minimum with the coil of Fig. 1 when the slot is displaced 90° from the flux opposition zones.

More complex winding configurations such as those shown in Fig. 9, may be used to advantage. Windings **824** and **825**, connected in parallel between junctions **840, 841**, generate opposing fluxes **846, 845**, while winding **823** generates flux **847** aiding flux **845**. Depending on the position of rotating magnetic shunt **850**, the fluxes are redirected through shunt **850** to partially or fully aid or oppose each other, resulting in a variation of inductance presented to leads **831, 832**. A shaft **854** and plates **851** may be used to hold the shunt **850**, and may be constructed of plastic or other structural material that does not have any significant electrical effect, yet permits rotation essentially around the axis of the toroid.

Alternately, the shunt may lie adjacent to a face of the toroid rather than an inner or outer circumference. This type is shown at **950** in Fig. 10. The construction of this figure can be otherwise identical with that of Fig. 9.

The toroids used in constructions of the present invention can have any type of cross-section, either circular, elliptical, square, rectangular, polygonal, etc. In addition, the toroids themselves can present an endless path that need not be circular but can be oval or even angular. In fact, somewhat better inductance control is made possible where the endless path is flattened in such a way as to bring the flux opposition zones somewhat closer to each other than any other diametrical air gap in the center of the toroid.

The degree of variation obtainable may be increased by forming the core with protuberances at the flux opposition zones, or distributed generally around the core. These protuberances can extend outwardly as far as the windings or even further. In this way the air gap between the core and the flux-controlling member can be reduced to the minimum required for mechanical clearance. This modification makes a substantial increase in the inductance range that can be provided. The protuberances may be placed on any surface of the core, as for example in the case of a toroid they may be on the inner circumference, outer circumference, any part of the faces connecting these two circumferences, or on any combination of the above locations.

The diametrical air gap, considering the endless path as circular, need not be very large. A gap of about ⅓ of an inch has been used very satisfactorily. However, an improved Q is obtained with larger gaps on the order of ½ inch or more. With such larger gaps, magnetic material having relatively higher loss characteristics are satisfactorily used. The cross-sectional area of the core is selected for the particular flux density desired if the flux-controlling member is permeable material.

An electrically conductive layer of the flux-controlling assembly, as in the constructions of Figs. 5 and 6 for example, need not be more than 10 or 20 mils thick, particularly for signal frequencies of about 2 megacycles or higher. To permit as much magnetic material as possible in the space provided by the toroid, the conductive layers could be recessed into the magnetic block **351** and can advantageously be even less than 10 mils thick as by using silver foil.

Instead of using simple wiring as illustrated above, the windings may be in bifilar form, the resulting assembly being useful as a transformer. Coupling coefficients of .9 and higher can be obtained in this way for frequencies of 20 to 50 megacycles.

A typical example of the present invention is that of Fig. 6 with the winding of the type shown in Fig. 5. A toroidal ferrite core having a permeability of 25 and with rectangular cross-section measuring 1.05 inches, 0.52 inch, and 0.25 inch at the outer diameter, inner diameter, and thickness respectively, was wound with four windings, each having three turns of #33 gage copper wire insulated with heavy enamel. The turns were connected as shown in Fig. 5, the separation of opposing windings being 0.20 and 0.17 inch respectively at the outer circumference and 0.25 and 0.23 inch respectively at the inner circumference. The flux-controlling member was composed of a cylinder of ferrite of a permeability of 95 and having an 0.5 inch diameter, on which was laid two 60° segments of 0.001 inch thick silver foil. The foils were held in position with a single wrap of resin tape, resulting in a maximum diameter of 0.505 inch. The shield discs were constructed of 1/16 inch thick aluminum and had a diameter 50% larger than that of the toroid. An inductance variation of 3.87:1 was obtained with this configuration.

As many apparently different embodiments of this invention may be made without departing from the spirit and scope hereof, it is to be understood that the invention is not limited to the specific embodiments hereof except as defined in the appended claims.

What is claimed is:

1. A tunable inductor device comprising a toroid having a permeability greater than two, said toroid provided with a continuous winding, the two ends of said winding forming the two terminals of the device, said winding arranged in an even number of groups in which the radial orientation of adjacent groups is opposed and said groups are in series with said terminals so as to provide adjacent sets of flux that oppose each other, and a longitudinally adjustable slug of a flux controlling material positioned within the toroid opening to permit varying the inductance of said device.

2. The invention of claim 1 in which the oppositely oriented groups are closely juxtaposed around the core, the spacing between them being no more than about 10 degrees.

3. The invention of claim 1 in which the flux-controlling material includes two portions, one having a permeability greater than 1 and a specific resistivity of at least about 1000 microhm-centimeters, and the other being non-magnetic and having a specific resistivity of less than 20 microhm-centimeters.

4. The invention of claim 3 in which the magnetic portion and the non-magnetic portion of the flux-controlling material are positioned for alternative insertion in the core opening.

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