Tech Notes

Tunable Toroids

[*While Varicap diodes are the component of choice in VCO designs, at one time at least one company, Vari-L, marketed a line of small magnetically tunable inductors. By varying the current through an internal electromagnet, the inductance could be adjusted over a large range. In* RadCom's *December 2000 and April 2001 Technical Topics columns, Tech Topics Editor Pat Hawker, G3VA revisited the concept of using a variable magnetic field to achieve permeability tuning—along with some possible advantages offered by these implementations. This column has been adapted from those columns.—Peter Bertini, K1ZJH,* QEX *Contributing Editor,* **k1zjh@arrl.org**]

There are several advantages given by permeability tuning, not least the virtually consistent Q throughout the frequency sweep. In the Amateur Radio field, permeability tuning was exploited by Collins Radio in many of their excellent post-war receivers such as the 75A series in the 1950s and their later S-line transceivers. Permeability tuning was also used in several car-radio broadcast receivers made by such firms as Radiomobile in the 1950s, and it was commonly used in television receivers.

The usual technique was mechanical, moving ferrite or powered-iron cores into and out of fixed solenoid inductors, but even then, a few designers took advantage of electrical techniques to change the permeability by magnetic means. Jack Hardcastle suggests that is time to look again at these techniques, both at LF (136 kHz) and HF. He also shows how they can be applied to toroid cores.

from Jack Hardcastle:

The renewed interest in the LF and VLF bands has so far passed me by. Not having acres in which to erect antennas has demotivated me for building equipment for either 73 or 136 kHz. However, I have been intrigued by the particular problems of making tunable circuits at these unfamiliar frequencies. Space considerations rule out the large diameter, multitapped inductors and variometers so beloved by our predecessors. Lack of availability rules out very large capacitors. So, what are the alternatives?

It seems to me that the most fruitful avenue to explore is to use relatively low-impedance circuits and to devise some means of varying the inductance. The obvious way to do this is to use a cylindrical coil of wire and to insert a rod of powered-iron or ferrite—(as in a ferrite-rod antenna). This has indeed been done in the past, notably in the RAF's T1154 transmitter and in the Collins S-line equipment. Both of these use a linear motion to control the tuning cores, a technique that is difficult to emulate without considerable mechanical-engineering resources. I felt, however, that a rotary motion could be more readily implemented, so I made tests using a pair of ferrite E-cores (see Fig 1).

So that the variable inductor could be readily tested, I built it into a Hartley test oscillator (see Fig 2). I found that rotating one E-core through 90° resulted in a frequency change from 157 kHz to 232 kHz. I must confess that I never actually made a mechanical drive to perform this rotation. At its simplest, I can visualize it being comprised of an epicycle slow-motion drive with one of the cores cemented to a rod attached to the drive.

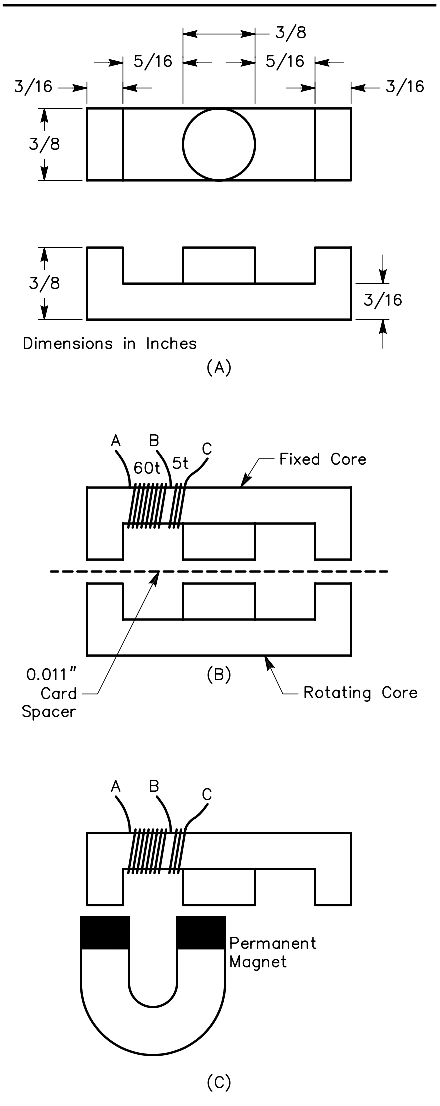

Fig 1—Experiments with a coil wound on an E core. (A) shows front and top views of a bare core. At B, a coil is wound on one half of the core and the second half is rotated (on the axis of the E's center leg). At C, one half of the core is removed and a permanent magnet is brought close to magnetically bias the core.

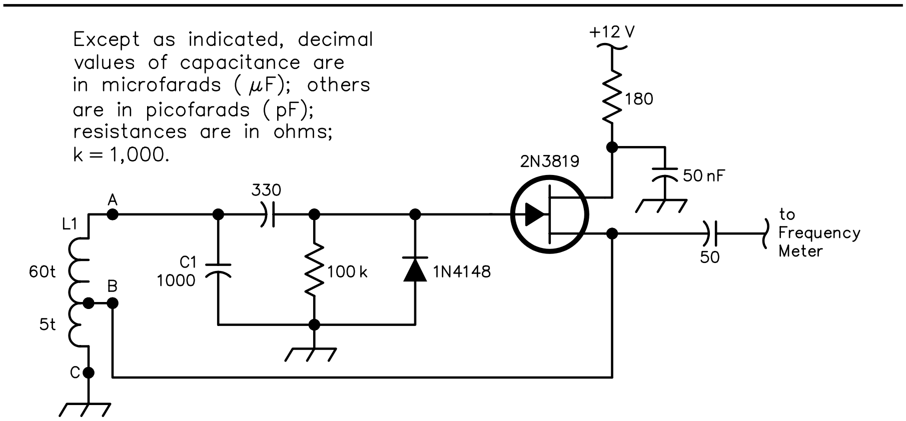

Fig 2—A simple Hartley oscillator used to test inductance variation.

Another, fairly obvious, way of changing to effective permeability of the ferrite cores is to increase the air-gap between them, but there is also a more subtle approach. If an external magnetic field is applied to a ferrite core, it drives the material toward saturation, lowering the permeability as it does so, thereby raising the oscillator frequency.

The use of an external magnetic field to lower the permeability of ferrite cores is a well-documented technique.[1,2,3] The technique was used before semiconductor tuning diodes were available to make 'wobbulators' (or gyrators) and to apply automatic frequency control.

In all these cases, the magnetic field was produced by an electromagnet so that a frequency sweep could be produced. However, for manually tuning a resonant circuit, the same result can be produced using a permanent magnet as shown in Fig 1C. For instance, the above test circuit showed that by bringing a strong horseshoe magnet near one of the E-cores (with one core removed) the frequency could be increased from 232 kHz to 421 kHz.

It is also possible, as noted by M. G. Scroggie, to tune inductors wound on toroids. By applying the magnetic field generated by a relay coil to a coil wound on an FT50-30 ferrite toroid, the oscillator frequency can be swept from 421 kHz to 1 MHz when the relay current was increased from 0 to 117 mA (see Fig 3). In practice, it is not normally required to tune over a very wide range, so the system is not as power-hungry as it appears at first glance.

So, what is the significance of this technique to radio amateurs? It allows resonant circuits to be tuned over a very wide range, particularly at very low frequencies. The bias toward the low-frequency end of the spectrum is a consequence of needing to use materials of lower permeability at higher frequencies. This limits the potential for reducing the effective permeability by whichever means is used.

It provides an alternative to variable capacitance as a means of manual tuning. It provides an al-

[1]Notes appear on page 57.

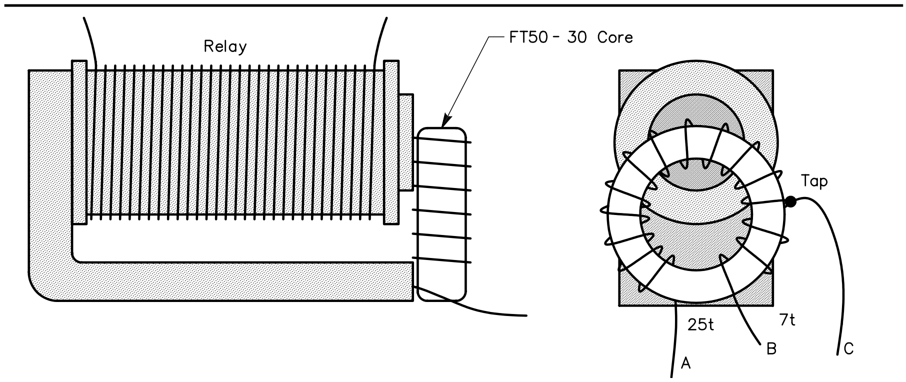

Fig 3—A toroid inductor is positioned near a relay coil so that a dc-generated magnetic field from the relay can affect the permeability of the toroid core.

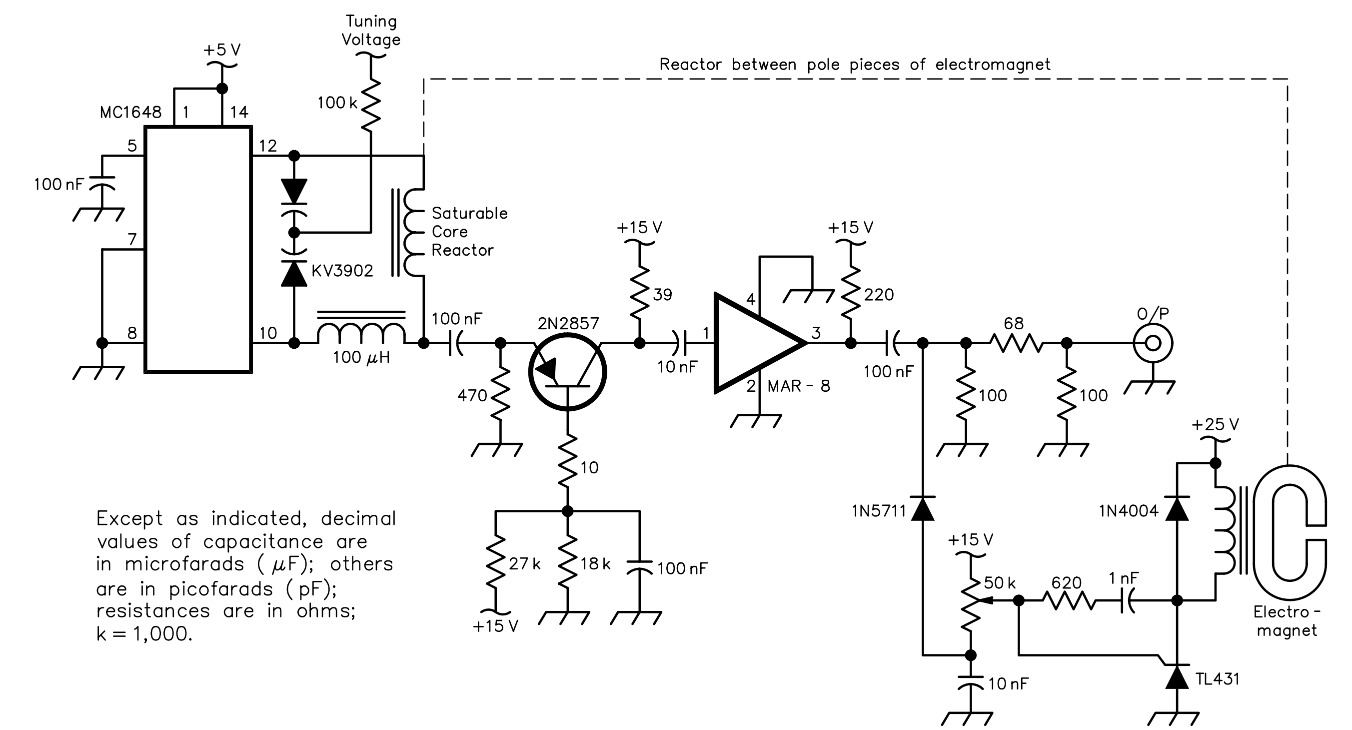

Fig 4—Circuit diagram of the wide-range constant-reactance voltage controlled oscillator (CRVCO) with a permeability-tuned TO-50 toroid-core inductor. Although the *RF Design* article was originally published some years ago, the *2000 Data Digest* books show that versions of all the semiconductor devices were still in production last year. The MC1648D is an 8-pin SO device; the MC1648L and P devices are 14-pin DIP versions.

ternative to varactor diodes as a means of electrical tuning. More speculatively, it may be a means of reducing phase noise in oscillators and synthesizers. Because varactor diodes are also noise sources, any means of eliminating them from a circuit is advantageous to designers. It remains to be seen whether ferrite materials are a significant source of noise, comparable with a varactor.

A WIDE-SPAN TUNED-TOROID VCO

David Mackenzie, GM4HJG, recently stumbled onto an Internet page that provides an interesting example of the practical value of permeability tuning—using an FT50 toroid inductor placed in the field of an electromagnet.

It appears on the Wenzel Web site (**www.wenzel.com/pdffiles/crvco.pdf**) as a reprint of one of the *RF Design* Awards articles as originally published in the magazine, probably in the period from 1985 to 1989. (I searched the contents pages of issues later than 1989 without success).

The article "Constant Reactance Voltage-Controlled Oscillator" (CRVCO) is by Raymond T. Page of Wenzel Associates Inc. It shows how a very-wide-range VCO providing good frequency and amplitude stability over a tuning range of 20 to 150 MHz (7.5:1 span) can be implemented without any complex band switching. These characteristics are much superior to the conventional VCO, which tends to be limited to a frequency span of not more than 3:1 with the loaded Q and resulting circuit stability degraded at the end of the frequency range. By actively holding the inductor's reactance constant in a feedback system that tracks the tuning varactor, high Q and exceptionally constant output power are maintained over the entire frequency span.

It is stressed that this form of CRVCO implementation need not be restricted to high-ratio tuning applications. Designs with smaller-ratio tuning spans can benefit from its inherent stability. The key feature is the use of permeability tuning as suggested by G3JIR, with the toroid mounted between the poles of an electromagnet, in conjunction with an ingenious feedback (AGC) system. The "saturable-core reactor" (tunable toroid) consists of a ferrite FT50 toroid-core inductor sited in the variable magnetic field. As the magnetic flux is increased, the 4C4 core loses permeability without significant changes in Q. A convenient electromagnet is formed from a modified Wabash reed relay (#208-31-1) with a soft iron rod replacing the reed switch and used to direct the saturating magnetic field to the toroid. The coil uses seven turns of #30 AWG wire on a Ferroxcube core (#135TO504C4). This combination requires less than 100 mA to saturate the inductor fully. With a tuning voltage of 1 to 24 V, the CRVCO tunes from 20 to 150 MHz with the output response a barely detectable ±0.04 dBm from end to end.

Jack Hardcastle, G3JIR, comments:

The small size of the photocopied Web diagram (Fig 4) was quite challenging *[I heartily agree!—G3VA]* and for a time I wondered whether the position of the 100-µH inductor was correct, since it appears to be in series with the tuning inductance and the Varicap that form the oscillator tuned circuit. In order to clarify this, I visited the Wenzel Web site and downloaded the circuit for myself. This enabled me to view an enlarged picture so I could see more clearly that my first impression was correct.

On investigating the internal circuit of the MC1648, it became clear that the 100-µH choke was a dc path for biasing the IC. The RF path from the tuning inductor is actually via the 100 nF capacitor, the 2N2857 emitter-base circuit, the 10-Ω resistor and the 100-nF decoupling capacitor. Once I realized this, the rest of the circuit fell into place. It is a most ingenious idea that deserves to be better known. I am not sure whether the MC1648 PLL device is still available *[see caption to the diagram—G3VA]* but the idea could be applied to any discrete component oscillator, and I hope to try this some time in the future. GM4HJQ has certainly turned-up a most innovative application of the magnetically-tuned inductor.

Notice, however, that Raymond Page stressed that the exceptional performance of this CRVCO depends, not only on the tunable toroid, but also on the choice of other components.

From Page's article:

The MC1648 is selected as the VCO because it contains an automatic-gain control that precisely sets the voltages across the tank, allowing the inductor's reactance to be determined by measuring its current. This current is metered by connecting the ground end of the coil to the synthetic ground at the collector of a grounded-base stage. A voltage proportional to the emitter current appears at the collector. This voltage is amplified and detected. The low-impedance collector resistor and MMIC amplifier provide very flat wide-band response.

Once detected, the inductor current results in a dc voltage that is scaled by a 50-kΩ potentiometer before it is applied to the reference pin of a TL431 shunt regulator. In this unique application, the TL431 modulates the current into its cathode in an attempt to keep the reference pin at 2.5 V dc.

As an increasing voltage is applied to the varactors, the VCO frequency begins to rise, which makes the inductor current start to drop. Since this drop in inductor current shows up as a proportionate dip in RF voltage at the detector, the voltage at the reference pin of the TL431 will attempt to increase, causing the cathode to sink more current. This increases the saturation of the toroid and lowers its inductance, bringing the current back to its preset level, thereby satisfying the feedback loop. The compensation network (620-Ω resistor in series with a 1-nF CIF capacitor) assures that the frequency response of the TL431 is slower than the frequency response of the electromagnet for good loop stability.

The combined performance of the grounded-base stage and MMIC stage play a crucial role in just how well the toroid reactance can be regulated. This trans-resistance amplifier is useful to 400-MHz.

G3JIR points out that the Wenzel Web site also contains useful material on such items as "Low-Cost Phase-Noise Measurement" (3 pages), "A Low-Noise Amplifier for Phase-Noise Measurements" (3 pages) and "Phase Noise, Harmonics and Sub-Harmonics" (2 pages).—*G3VA*

Notes

[1]Pressman and Blewett, "300-4000-kHz Electrically Tuned Oscillator," *Proceedings of the IRE*, January 1951, pp 74-77.

[2]M. G. Scroggie, "An unconventional FM receiver," *Wireless World,* October 1957, p 505.

[3]A. E. Ford and J. S. White, "An Insertion Loss Display and Recording Equipment for the Frequency Range 50 kHz to 8 MHz," *Post Office Electrical Engineers Journal,* October 1960, pp 145-50.

Constant Reactance Voltage Controlled Oscillator

By Raymond T. Page
Wenzel Associates, Inc.

A need exists for a very wide range voltage controlled oscillator that exhibits good frequency and amplitude stability over its entire frequency span without complex band switching. Applications include wide pull phase locked loops which incorporate a single continuously tuned VCO, broadband sweep generators with good stability at the high end of the frequency range and network analyzer oscillators with extremely flat output level over frequency.

Traditional wide-range VCOs vary only the capacitance in an oscillating tank. The reactance of this varactor and an inductor increase with frequency since the operating frequency is inversely proportional to the square root of the capacitance. Consequently, these VCOs have been limited to a tuning ratio of about 3 to 1 and the loaded Q and resulting circuit stability become degraded at the end of the frequency range. Some designs have incorporated complex switching circuits to select a more appropriate inductor as the frequency increases. Such circuits do not tune continuously from one end to the other. Varactors combined with saturable core inductors have also been used to obtain better than 3 to 1 tuning ranges, however, these circuits have been found to be hopelessly unstable, noisy and exhibit substantial hysteresis due to core magnetization.

A new approach in VCO design, a Constant Reactance VCO, (CRVCO) can be realized which exhibits the stability of a varactor-only tuned VCO while providing the wide continuous tuning range (7.5 to 1) of a varactor/ saturable core reactor VCO. By actively holding the inductor's reactance constant in a feedback system that tracks the tuning varactor, high Q and exceptionally constant output power are maintained over frequency.

The saturable core reactor consists of a ferrite toroidal inductor placed in the field of an ordinary electro-magnet. As the magnetic flux increases, the 4C4 core loses permeability without significant changes in Q. This CRVCO employs a modified Wabash reed relay(PIN: 208-31-1) with a soft iron rod replacing the switch to direct the saturating magnetic field to the VCO coil, which uses seven turns of 30 gauge wire on a Ferroxcube core (P/N: 135T050-4C4). This combination requires less than 100 mA to fully saturate the inductor.

The MC 1648 is selected as the VCO because it contains an automatic gain control which precisely sets the voltage across the tank, allowing the inductor's reactance to be determined by measuring its current. This current is metered by connecting the ground end of the coil to the synthetic ground at the collector of a grounded base stage. A voltage proportional to the emitter current appears at the collector which is amplified and detected. The low impedance collector resistor and MMIC amplifier provide very flat wide-band response.

Once detected, the inductor current results in a DC voltage which is scaled by a 50 kilo-ohm pot before it is applied to the reference pin of a TL431 shunt regulator. In this unique application the TL431 modulates the current into its cathode in an attempt to keep the reference pin at 2.5 volts DC.

As an increasing voltage is applied to the varactors, the VCO's frequency begins to rise which makes the inductor current start to drop. Since this drop in inductor current shows up as a proportionate drop in RF voltage at the detector, the voltage at the reference pin of the TL431 will attempt to increase causing the cathode to sink more current. More current through the electromagnet increases the saturation of the saturable core reactor which lowers its inductance bringing the current back up to its preset level thereby satisfying the feedback loop. The compensation network consisting of a 620 ohm resistor in series with a 0.001 CIF capacitor assures that the frequency response of the TL431 is slower than the frequency response of the electromagnet for good loop stability.

Performance Data

With a tuning voltage of 1 volt to 24 volts, the CRVCO tunes from 20 MHz to 150 MHz - an incredible 7.5 to 1 tuning ratio! Nearly as impressive is the output flatness, a barely detectable -+ 0.04 dBm from end to end.

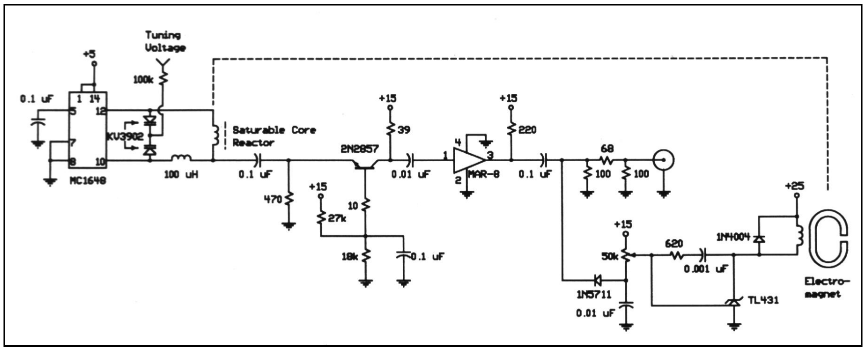

Figure 1. 20 MHz to 150 MHz CRVCO.

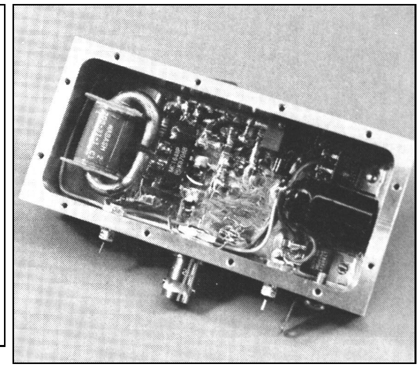
Figure 5. Photograph of CRVCO.

The combined performance of the grounded base stage and MMIC stage play a crucial role in just how well the saturable core reactor's reactance can be regulated. This transresistance amplifier is useful out to 400 MHz.

Summary

This CRVCO implementation need not be restricted to high ratio tuning applications. Smaller ratio designs can still benefit from its inherent stability. Other applications of the tracking saturable core reactor include high Q tracking filters or tanks with a fixed resonant frequency which alter the components' reactances. Insightful applications of this technique should lead to some very promising circuit solutions. RF

Wide-span tunes-toroid VCO

David Mackenzie, GM4HJG, recently stumbled on an Internet page that provides an interesting example of the practical valu of permeability tuning - using a TO-50 toroid inductor placed in the field of an electromagnet- asdescribed by Jack Hardcastl G3JIR, in 'TT' December 2000, pp 63/64. It appears on theWenzel web-site as a reprint of one of the RF Design Awards articles as originally published in the magazine, probably in the period between about 1985-89 (I searched without success th contents pages of issues later than 1989).

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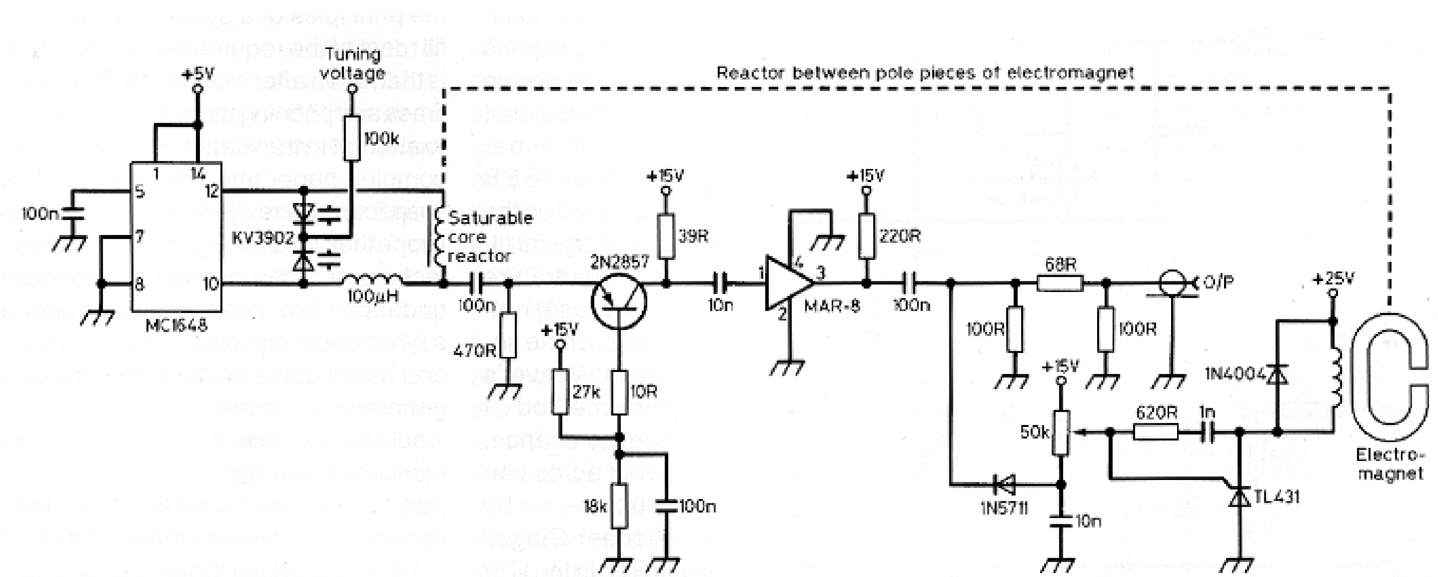

Fig 1 - Circuit diagram of the wide range constant reactance voltage controlled oscillator (CRVCO) with a permeability- tuned TO-50 toroid-core inductor. Although the RF Design article was originally published some years ago, the 2000 Data Digest books show that versions of all the semiconductor devices were still in production last year. The MC1648D is an 8-pin SO device; the MC1648 L and P devices are 14-pin DIP versions.

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GMR points out that the Wenzel web site also contains useful material on such items as 'Low-cost phase noise measurement' (3 pages), 'A low noise amplifier for phase noise measurements' (3 pages), 'Phase noise, harmonics and sub-harmonics' (2 pages).

GM4HJG

Rob's web

More about transductors (Tunable toroids)

'TT', DECEMBER 2000 (pp63/64) noted the advantages of permeability tuning, not least the virtually-constant Q throughout the frequency sweep, quoting a number of practical applications in communications and domestic receivers, etc. It also reported the view of Jack Hardcastle, G3JIR, that it was time to look again at these techniques, both at LF and at HF. More importantly, he showed how they could be applied to toroid-type cores, by varying the strength of an applied magnetic field, either mechanically with a permanent magnet or electrically with the aid of a relay coil. This was followed i 'TT', April 2001 (pp6l/62) by details of a wide range constant reactance voltage-controlled oscillator described by engineer at the American firm of Wenzel Associates using a permeability-tuned T050 inductor with the toroid mounted in the jaws of an electromagnet, much as suggested by G3JIR.

Michael Smallwood, VP8AEM, draws attention to the web site of Applied Microwave & Wireless magazine. He writes: "Th magazine has placed most of its articles online in PDF format at. One interesting article is about using saturable-core inductors (transductors) as mentioned several times in'TT'[see above]. A good feature of this article'The Forgotten Use of Saturable-Core Inductors (Transductors)', by Christopher Trask of ATG Design Services [Technical Editor of QRP Quarterly], is that it includes instructions forwinding transductors. One method is to wind your RF coil through the centre holes of a pot core, turning the pot core into a toroid for the RF winding. This approach was proposed by T A O Gross in 'Revisiting the Cross-Field Inductor', Electronic Design, March 15, 1977: Fig 1 (a).

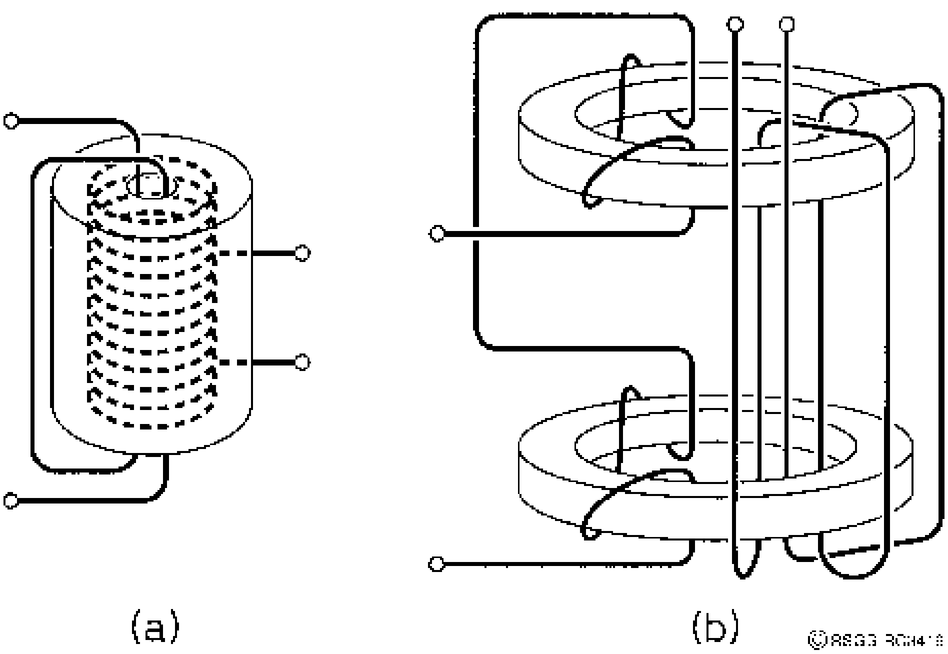

Fig 1: Methods of realising transductors as originally described by T A O Gross in 1977. (a) Pot core (cross-field) transductor as used experimentally by VP8APM. (b) Toroid (parallel field) transductor using a pair of ferrite (or tape-wound) toroids as commonly used in magnetic amplifiers. (Source: Applied Microwave & Wireless)

To quote the AM & W article: "in general, a transductor is composed of three elements: the core material itself, properly chosen for the application at hand; the controlled winding, which is the inductance that we wish to control; and the contro winding, through which we will apply the controlling current.

The controlled and control windings must be constructed on the core material in a way that will prevent them from coupling with each other... Fig 1 (b) illustrates a form known as a parallel-field reactor, commonly found in magnetic amplifiers... Fig 1 (a) illustrates a form referred to as a cross-field inductor, so called because the magnetising field is perpendicular to the signal field in the core material. In this construction, the control winding is placed on a bobbin, or coi former, which is part of a ferrite pot core assembly. This is very convenient, as a large number of turns can be placed on th bobbin... The bobbin is then assembled between two pot core halves of suitable material, and the controlled inductorwinding is formed on the outside of the pot core, through the centre hole normally used for a tuning slug, in effect turning the pot core into a toroid of sorts. This latter form of construction ensures a high degree of isolation between the two windings, and at the same time is easy to reproduce and manufacture."

The article stresses the distinct advantage that transductors offer in terms of linearity, compared with varactors, "a highly desirable feature in the design of communications equipment". It includes test results at 1 MHz of four transductors, one using a Philips P18/11-4C6 pot core with no gap and three using Philips P18/11-3D3 pot cores. Christopher Trask also compares the linearity of varactor-tuned and transductor-tuned bandpass filters, showing that the transductor possess superior linearity properties, especially in terms of second-order distortion over its varactor counterpart (45dBc decrease in second-order products, 5dB increase in the third-order intercept point). To quote: "This feature may well override the disadvantages of cost and physical size when designing critical system functions, such as a remotely-tuned receiver preselector, where harmonic and intermodulation distortion performances are important considerations."

VP8AEM adds: "I built a cross-field transductor using a 300mm diameter by 20 mm high pot core salvaged from a radiotelephone voice-channel filter. I used six turns of hook-up wire through the centre hole and I was able to reduce the inductance from 280 µH to 250 µH by increasing the DC current through what was the original winding from 0 to 100 mA to 170 µH at 200 mA, 155 µH at 300 mA , 115 µH at 400mA and to 90 µH at 500 mA. The inductance of the control winding is 40 mH.

"Another salvaged pot core, in the shape of a 13mm cube, but again with a control winding of 40mH, when wound with four turns of fine hook-up wire went from 105 µH to 50 µH with 100mA of control current, and down to 40 µH when 200 mA was applied. Using two turns for the RF winding, the inductance went from 28 µH at 0 mA to 15 µH at 100 mA and 10.5 µH at 200 mA. This pot core gets too hot with 200 mA flowing through the 34 Ω control winding, and the inductance falls with rising temperature." The heating effect of the control winding suggests that, when this form of integral transductor is used in a critical tuned circuit, some care must be taken to avoid frequency drift, possibly by limiting the control current and hence limiting the range over which the inductance is changed. This would not be a problem with the use of an external electromagnet, as suggested by G3JIR, and in the Wenzel VFO. Incidentally, for control currents, the AMW article misleadingly uses µA in the text but (apparently correctly) mA on the diagrams. Usefully, the author provides 13 published references to the use of magnetic tuning devices between 1938 and 1996 (the original reference is to Wireless World, february 1938 (L de Kramolin).