Tuning Receivers and Transmitters

This month we consider how radio receivers are able to select just one of the hundreds of radio transmitters on the air, rejecting all others. The simplest method for this purpose uses a "tuned circuit", consisting of inductance and capacitance.

by BRYAN MAHER

An "inductor" is a component designed to exploit the electrical property *inductance*. For radio use an inductor usually takes the form of a coil of wire, possibly with an iron ferrite core. If our interest is in low frequencies we would use a coil of perhaps hundreds of turns (see Fig.1), but for very high frequency use a tuning coil may have only a few turns.

Inductance

The property of inductance is a natural effect possessed by every piece of wire, and the effect is enhanced when a wire is wound into a coil. Any current flowing in the coil creates a magnetic field in and about the coil. Whenever the current in the coil changes, in value or direction, the associated changing magnetic field generates a voltage in the coil. During that time the coil is acting as a generator.

The amount of voltage so generated by the coil is proportional to the *rate* at which the current changes, while its polarity depends on the direction of change of current.

When we attempt to change the value or direction of current in the coil, the inductive effect will cause the generation of a voltage in such a direction as to try to *prevent* such a change. Because of this, any voltage suddenly applied to a coil will produce a current which rises at a comparatively low rate.

Constant steady currents, no matter how large, produce no inductive effects of this type.

The basic unit of inductance is the "Henry", so named to honour Joseph Henry (USA 1797-1878) whose inventive work was not recognised during his lifetime. The abbreviation for the unit is "H".

As the Henry is a fairly large unit, for tuned circuit work we usually use millihenries (mH) or microhenries (uH). (Remember that the prefix *milli-* means one thousandth of the basic unit, while *micro-* means one millionth.)

Capacitance

A "capacitor" is a component in which we exploit the electrical property of *capacitance*. Such a component consists of two or more parallel plates or surfaces of conducting material, separated by air, vacuum or a solid insulating material.

The space or material between the conductive plates or surfaces is known as the "dielectric". Connection wires or terminals connect the conductive plates or surfaces to the other components of your circuit. Fig.2 shows a small variable capacitor, using air as the dielectric.

Capacitance is a natural effect exhibited between every pair of separated conductors. If a changing voltage exists between the two, this change in voltage causes a current to flow. The amount of current which flows is proportional to the *rate* at which the voltage changes, while its direction depends on the direction of change of the voltage. A steady voltage produces no capacitance current.

Fig.1: The tuning coil shown in the centre of this picture is wound on a ferrite rod, which significantly enhances its inductance.

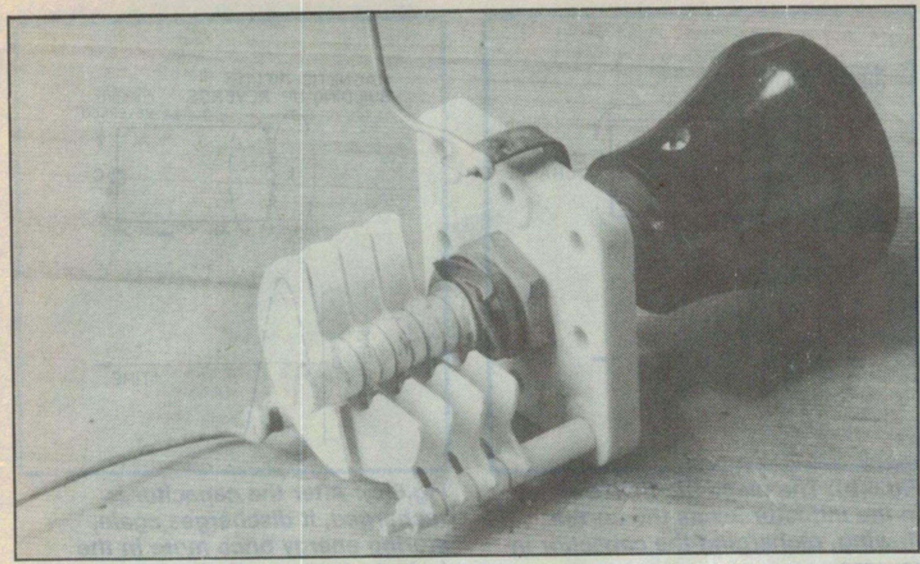

Fig.2: This small variable capacitor is adjustable between 3 and 13pF, and is intended for tuning in the range 10 – 50MHz.

The basic unit of capacitance is the "Farad", to honour Michael Faraday (England, 1791-1867) who invented the electric generator and motor. The abbreviation for the basic unit is "F". But because one farad is a very big quantity of capacitance, we commonly use the million-times smaller *microfarad* (uF), or the thousand-times smaller again *nanofarad* (nF). For capacitors used in tuned circuits we go even smaller and use the *picofarad* (pF), representing one million-millionth of a farad.

As the frequencies used by radio and TV are quite high, all radio frequency *voltages* are continually changing at quite a fast rate, so the capacitance currents flowing are important. Similarly as the radio frequency *currents* are always changing quite quickly, inductive effects also play a big part in circuit operation.

Unwanted resistance

Unfortunately *resistance* is another electrical property which pervades almost everything. Certainly all ordinary coils of wire designed to be used as inductors also have some resistance. Even the plates and connections of capacitors have some resistance. Part of the tuned-circuit maker's art is to produce components having the minimum possible value of resistance.

Techniques that can be used for this include winding the coil from relatively thick wire, and plating the surface of both the coil and the capacitor plates with a particularly good conductor such as silver or gold.

L-C interaction

A capacitor can be "charged" with electric charge by connecting it across any voltage source, for example a battery, as in Fig.3. Here C represents the capacitance of the capacitor, connected to a battery which will quickly charge it.

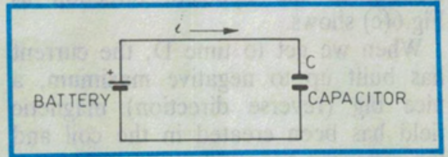

Fig.3: Connecting a battery across a capacitor C causes a current i to flow, to "charge" the capacitor.

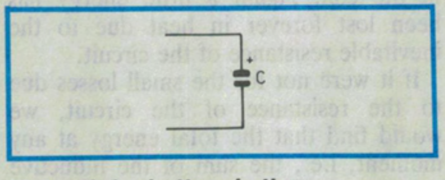

Fig.4: If the battery is then disconnected, the capacitor will hold the charge for some time until it leaks away.

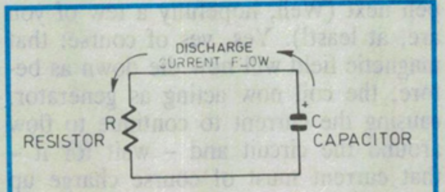

Fig.5: But a resistor will discharge the capacitor much faster, wasting the stored energy as heat dissipated in the resistor.

Once charged, we could remove the battery, leaving the capacitor in the fully charged state (Fig.4). The charge would stay on the capacitor for some time if we left it like this, slowly leaking away. If we connect a resistor across the capacitor as Fig.5 a current will flow, discharging the capacitor and dissipating all the charge by turning the energy into heat in the resistor.

"That's not very clever", you probably are objecting "What's the good of that?". Quite right you are, of course, it's no use at all! But let's now throw that resistor away and do something else rather startling.

If while the capacitor is well charged, we were to connect an inductance across it as in Fig.6(a), things are very, very different. A chain of events would follow that would please the most expectant soul. We depict what happens in the next few microseconds in the sequence of little "snapshots" represented by Figs.6(a)-(e).

In Fig.6(a) charge begins flowing out of the capacitor at time A, passing a current through the inductance – which sets up a magnetic field in the inductance. In the figure we show a little diagram showing how the current starts from zero at time A, rising to a maximum at time B, perhaps in a microsecond or less.

By time B the current has built up to a maximum. The capacitor has lost all its charge, and all of its electric-field energy has been transferred into magnetic energy stored in the magnetic field of the inductor. We now have the condition in Fig.6(b).

The completely discharged capacitor C is just sitting there, connected in parallel with the inductor L, which has a nice big current flowing in it. This produces a strong magnetic field entwining its turns.

But life never stands still. That magnetic field is proportional to the current flowing, and now with the capacitor discharged there is nothing to keep that current flowing. So the current decreases down to zero, at time C. But that's not all that happens!

The falling current means a change in magnetic field in a downward direction, so this decreasing current must induce a voltage in the turns of the inductor, with opposite polarity as shown in Fig.6(b). The inductor during this time has become a generator of voltage.

The voltage generated by the inductor keeps the current going around the circuit in the same direction as previously, as in Fig.6(b). But the current's value decreases all the while, from time B to time C.

There's still more to come, though. At time B there was no charge left in the capacitor, yet the inductor forced the current to continue flowing. Whence did this current flow?? It must be that from time B to time C the current is re-

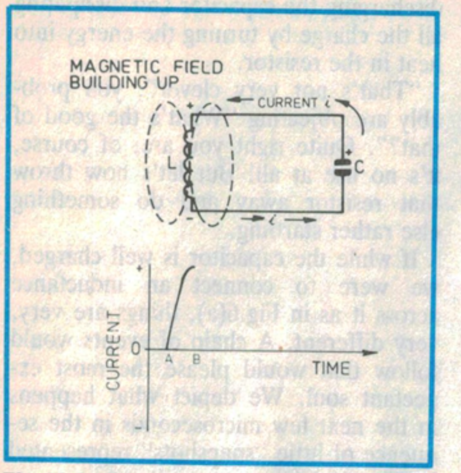

Fig.6(a): If an inductor L is connected across a charged capacitor, the discharge current first rises relatively slowly.

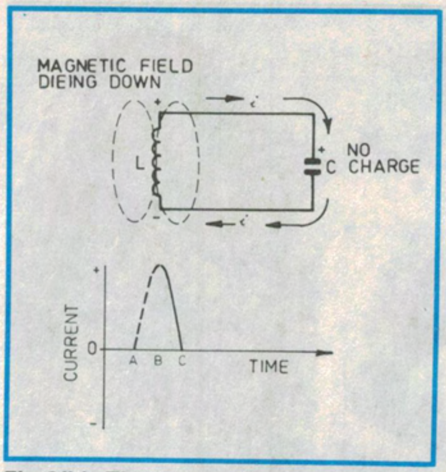

Fig.6(b): The magnetic field built up in the inductor keeps the current flowing, recharging the capacitor in reverse.

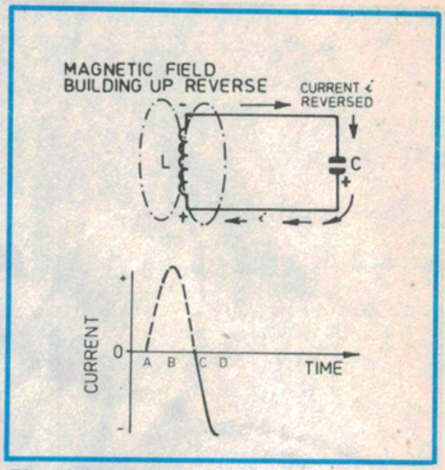

Fig.6(c): After the capacitor is recharged, it discharges again, storing energy once more in the inductor's magnetic field.

charging the capacitor. And because our diagram shows the current flowing "into the bottom" of the capacitor, that current must be charging the capacitor in the opposite direction to the original – i.e., negative at the bottom, as in Fig.6(b).

During this time B to C the current is decreasing and the energy in the magnetic field is decreasing, but the charge on the capacitor is building up (in the opposite direction) and the energy stored in the capacitor is increasing. So the energy is transferring from the inductor back into the capacitor.

Sadly some energy is also being lost (turned to heat) in the inevitable resistance of the circuit.

By the time the current finally decreases to zero at time C, no energy is left in the inductor. But the capacitor now has all the remaining electrical energy, because it is now well charged, up to a voltage a little less that the original full charge. (A little less because of those resistive losses). The only other difference from when we started is that the capacitor voltage is now opposite in polarity.

Now, gentle reader, what do you expect will happen next? The situation is as Fig.6(c). At time C we again have a coil with no current and no magnetic field, in parallel with a well charged capacitor.

First prize to the reader who said that the whole process recommences again, i.e., the capacitor drives a current into the coil, such current building up from zero value until some maximum is reached at time D. Because of the reversed polarity of the charge on the capacitor this new current is negative, flowing in the opposite direction as Fig.6(c) shows.

When we get to time D, the current has built up to negative maximum, a nice big (reverse direction) magnetic field has been created in the coil and the capacitor has used up all its charge, as depicted in Fig.6(d). The energy has swapped again from electric field energy in the capacitor to magnetic field energy in the coil. Again a little energy has been lost forever in heat due to the inevitable resistance of the circuit.

If it were not for the small losses due to the resistance of the circuit, we would find that the total energy at any moment, i.e., the sum of the inductive energy plus the capacitive energy, is a constant.

All over the country readers are clamoring to cry out just what will happen next (Well, hopefully a few of you are, at least!). Yes, yes of course: that magnetic field will now die down as before, the coil now acting as generator, causing the current to continue to flow around the circuit and – wait for it – that current must of course charge up the capacitor yet again!

Notice the direction of charge building up on the capacitor. By the time the magnetic field completely dies down the current has decreased to zero, and we are at time E as in Fig.6(e). All the energy we have left is back in the form of an electric field in the capacitor, with no energy in the coil and the capacitor voltage as shown, positive at the top. Clearly the capacitor is anxious to go again.

Do you have a feeling of *deja vu*? Yes, we have been here before. The whole description that you, most gallant reader, have just ploughed through is about to repeat all over again, with current rising from zero value at time E to start the second cycle, reaching the second (slightly reduced) positive peak at time F. From there it will continue on as before, so let's not say any more. Like an old movie, the rerun will be the same again only a bit less dramatic.

Subsequent maximum charge, voltage and current values encountered will be less again, as the small amount of resistance in the circuit inexorably gnaws away at the energy stored in this tuned circuit.

And just what have we achieved? Basically we have generated an *alternating current*, using a coil and an initially charged capacitor. Admittedly the alternating current is slowly running down, like a pendulum clock that needs winding up, but it's certainly there.

Could we find a way to continually "wind it up" by injecting small charges of electricity to make up for the losses incurred by the circuit resistance? If so, our alternating voltage and current would repeatedly return to the same maximum values every cycle, time after time.

Readers overcome by enthusiasm will immediately see the above description of the generation of an alternating current in a coil/charged capacitor circuit as a parallel to last month's description of the generation of alternating current in a power station alternator. Indeed they are both the same kind of alternating current, and both have a sine waveform. But this month, because we have no moving parts to limit speed, our frequency may be thousands, millions or billions of Hertz.

Now let's pose some questions, as yet unanswered:

(1) Why do we keep calling this coil-

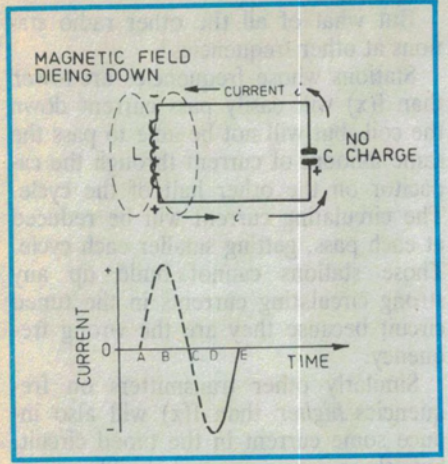

Fig.6(d): Again the inductor keeps the discharge current flowing, recharging the capacitor with the original polarity.

and-capacitor combination a *tuned circuit*?

(2) At what rate do all these goings-on go on?

(3) How long does it all *keep* going on?

As any good politician would, we answer the last question first. The process repeats many times over, but decreasing in voltage and current amplitude all the time because of the resistance (unfortunately) present in the circuit.

In answer to question (2), the time taken for each of these complete cycles of events, "from one deja vu to the next", is constant for any one pair of coil-and-capacitor. This time does not "stretch out" as the system runs down.

We call the time for each complete cycle of current (or voltage) values one *period*, defined as the time taken from one positive peak to the next.

More exactly, one period is the time taken, measured from any convenient point on the current waveform diagrams (Fig.6) to the next occurrence of that same current value, where the graph is going the same direction. The period may be measured in seconds or less, for example:

1.0 millisecond = 10^{-3} second
1.0 microsecond = 10^{-6} second
1.0 nanosecond = 10^{-9} second
1.0 picosecond = 10^{-12} second

Frequency in Hertz

We could also answer question (2) by saying that the rate or *frequency* of these happenings is simply the number of times the whole process repeats in one second.

The unit of frequency was once upon a time simply called "cycles per second" but nowadays the unit is called the

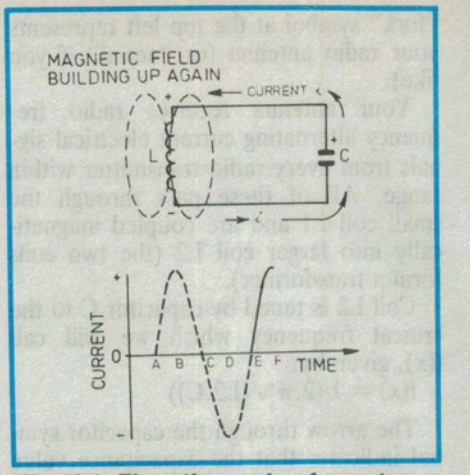

Fig.6(e): Then the cycle of events tends to repeat all over again, with energy oscillating between the capacitor and inductor.

Hertz (abbreviation Hz), to honour Heinrich Rudolph Hertz (Germany, 1857-1894) – the first man to experiment with electromagnetic radiation. If one complete cycle of current values, say from point B in Fig.6 (where the current is at maximum positive value) to the next occurrence of maximum positive current value, occurs *n* times per second then the frequency of that tuned circuit is *n* Hz.

In radio and TV we often measure frequencies in kilohertz, megahertz, gigahertz, etc. These multiples were defined in the first of these articles, you may remember.

Now let's see if we can find the answer to question (1): Why is a coil-and-capacitor combination called a *tuned circuit*?

The answer to this will emerge if we consider what determines the frequency of the alternating current that we've been generating. It turns out that this is set by the coil and capacitor values themselves. But how?

In the following we make a simplifying assumption. This is that the resistance in our circuit is so small (compared to the inductance and capacitance) that we can forget about the degrading effects of resistance.

If we make this assumption, this means that the total energy in the circuit will truly be always a constant.

Finding the frequency

It has been found by experiment that if a sine waveform alternating current of frequency f is passed through an inductor of inductance L Henries, as in Fig.7, then an alternating voltage drop occurs across the inductor. The value of this alternating voltage drop is found to be:

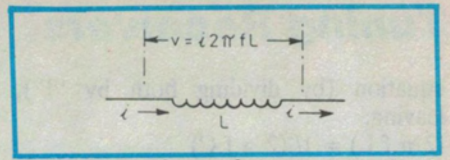

Fig.7: The voltage drop across an inductor is proportional to frequency and inductance.

Voltage across inductor = $(i.2.\pi.f.L)$

Where i = the current flowing
π = 3.1416 (ie the number of radians in a circle)
f = the frequency in Hz, and
L = the inductance in Henries

Furthermore it is also found by experiment that if an alternating current is passing thru a capacitor, an AC voltage drop occurs across the capacitor as in

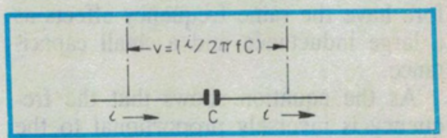

Fig.8: Conversely, a capacitor's voltage drop is inversely proportional to frequency and capacitance.

Fig.8, and the value of this voltage drop is given by:

Voltage across capacitor = $(i/(2.\pi.f.C))$

where i = the current flowing
π = 3.1416
f = the frequency in Hertz,
and C = the capacitance in Farads

But as Fig.9 insists, in our tuned circuit the same alternating voltage exists

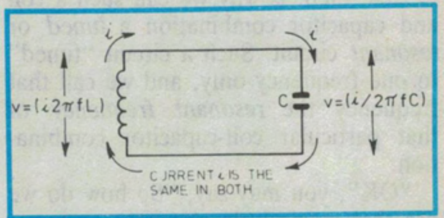

Fig.9: When a capacitor and inductor are connected together, their currents and voltage drops must be the same. This fact allows us to find an equation for their natural oscillation frequency.

across both coil and capacitor because they are both in parallel. So:

Voltage across inductor = Voltage across capacitor.

i.e.,

$(i.2.\pi.f.L) = (i/(2.\pi.f.C))$

And as Fig.9 also shows, the current i is the same in both coil and capacitor, since they're also in series. Therefore we can cancel "i" from both sides of the equation (by dividing both by "i"), leaving:

$$(2.\pi.f.L) = 1/.(2.\pi.f.C)$$

By cross multiplying this we get:

$$f = 1/(4.\pi^2.f.L.C)$$

then cross multiplying again:

$$f^2 = 1(4.\pi^2.L.C)$$

Finally, taking the square root of both sides: $f = 1/(2.\pi\sqrt{(L.C)})$

So we see that it is the value of inductance L of the coil, and the value of capacitance C which together decide the frequency.

More exactly the frequency is a function of the *LC product*. A small inductance and large capacitance can therefore have the same frequency effects as a large inductance and a small capacitance.

As the equation shows that the frequency is inversely proportional to the square root of the LC product, so broadly speaking small component values work at high frequencies, and large components operate at low frequencies.

But for any one value of inductance and capacitance there can be only one frequency at which the actions described above can take place. The energy-swapping and constant total energy features of the circuit will only hold for that one critical frequency, f as given above.

A tuned circuit

This, then, is why we call such a coil and capacitor combination a *tuned* or *resonant* circuit. Such a circuit "tuned" to one frequency only, and we call that frequency the *resonant frequency* of that particular coil-capacitor combination.

"OK", you may say, "So how do we use that magic little circuit to tune our radio receiver so that it receives just the one radio transmitter? We know there are thousands of stations out there!"

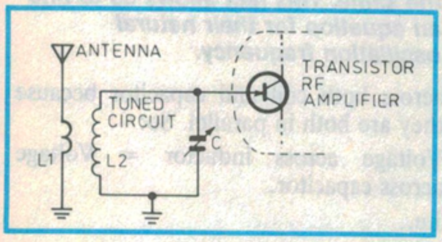

Fig.10: In a radio set the L-C tuned circuit selects just one RF signal, rejecting all others.

Fig.10 shows in abbreviated form the first part of a radio receiver. The little "fork" symbol at the top left represents your radio antenna (or "aerial" if you like).

Your antenna receives radio frequency alternating current electrical signals from every radio transmitter within range. All of these pass through the small coil L1 and are coupled magnetically into larger coil L2 (the two coils form a transformer).

Coil L2 is tuned by capacitor C to the critical frequency which we will call f(x), given by:

$$f(x) = 1/(2.\pi\sqrt{(L2.C)})$$

The arrow through the capacitor symbol indicates that the capacitance value C can be varied, perhaps by rotation of one set of blades, as in the capacitor of Fig.2. But for the moment we will consider the capacitor fixed at the one value C.

To the right of the tuned circuit in Fig.10 is a connection to the first amplifying transistor of the radio receiver. At the moment we are only interested in the tuned circuit part of the business, L2 and C.

Down the antenna line comes a great mixture of received radio frequency (RF) currents, at different frequencies and at various levels of power. All are coupled into L2 and C, and will "attempt" to produce the energy-swapping routine we've looked at above – involving the exchange of energy between magnetic field and capacitor charge. But we now know that this energy-swapping can only be done at the one critical frequency f(x), the resonant frequency set by the value of L and C.

Should one of the received radio transmitters happen to be transmitting at frequency f(x), then we are in luck.

Yes, the radio station signals at that frequency will supply the power which the tuned circuit loses by its circuit resistance. The current induced by that radio station in the antenna and coupled into the tuned circuit, will be rising and falling in its sinewave pattern at exactly the correct rate to excite the circulating RF currents in the tuned circuit. Backwards and forwards in the tuned circuit those currents will go, energy first in the inductance, then in the capacitance. And this will repeat as long as the circuit is excited by that radio station at the resonant frequency f(x).

Such nice large circulating RF currents have a comparatively large voltage drop across the circuit – RF voltage which is passed on to the receiver amplifier stages, to be further amplified (and processed) until large enough to operate your loudspeaker.

But what of all the other radio stations at other frequencies?

Stations whose frequencies are *lower* than f(x) will easily pass current down the coil, but will not be able to pass the same amount of current through the capacitor on the other half of the cycle. The circulating current will be reduced at each pass, getting smaller each cycle. Those stations cannot build up any strong circulating currents in the tuned circuit because they are the wrong frequency.

Similarly other transmitters on frequencies *higher* than f(x) will also induce some current in the tuned circuit, but these again cannot build up to strong circulating currents, for while they easily pass current down the capacitor branch, they cannot pass enough current through the coil. They cannot effectively swap energy between coil and capacitor, therefore the tuned circuit does not respond well to them either.

In other words, our tuned circuit of resonant frequency f(x) responds well only to the one station which is transmitting on the same frequency f(x). All other stations are received at much reduced response, as depicted in Fig.11.

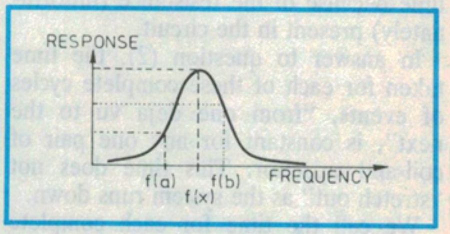

Fig.11: Response of a tuned circuit to three different frequencies, including its resonant frequency f(x).

Our radio thus plays music and other program material from that one station, rejecting all others.

Changing stations

Should we want to listen to a different station, we could mechanically change the setting of our variable tuning capacitor C to a different capacitance value. Then our tuned circuit would have a different resonant frequency, so it would respond preferentially to some other transmitter.

Alternatively by varying the position of a ferrite iron core inside our coil L2, it can be made to have different values of inductance, again changing the tuned circuit resonant frequency.

There are also other methods used for tuning, so our story of radio transmission and reception will continue next time. 'Til then, bye.