HISTORY OF TUNING

K R Thrower

United Kingdom

SUMMARY

The paper summarises many of the important developments that have taken place in the tuning of radio apparatus, starting with the early work of Oliver Lodge and Guigliemo Marconi. Over the years improvements have been made both to tuning capacitors and tuning coils. Amongst these were the development of air-spaced, vane-type capacitors and of magnetic cored materials for tuning coils, notably iron-dust and ferrites. Of special note was the introduction of variable capacitance semiconductor diodes, which made tuning possible by voltage control. The final part of the paper discusses a common method for the tuning of wide-band radio transmitters.

LODGE AND MARCONI

The early radio transmitters and receivers produced by Marconi up to about 1900 were untuned. The transmitted signal was produced by a spark discharge from an induction coil. The waveform was highly damped, consisting of three or so cycles of oscillation. As a result the transmitted signal occupied a very wide band. Without tuning it was impossible for the receiver to separate one spark transmission from another.

The principle of tuning goes back to the work of Oliver Lodge. In 1889 he demonstrated his syntonic jars experiment at the Royal Society in London and this was published in *Nature* in the following year (1). A diagram of the experiment is shown in Figure 1. The tuned circuits of the transmitting and receiving parts consist of Leyden jar capacitors and a single inductive loop of 3ft diameter, the two being separated by a distance of 6ft. An induction coil in the one circuit was made to produce a spark discharge. The radio frequency energy from this was received in the second circuit, the frequency of which could be tuned to that of the first circuit by adjusting the position of the slider. When correctly tuned a small spark was produced in the 'overflow path' (a tiny spark gap on the outside of the Leyden jar).

Lodge realised that, because of the low-losses in the transmitting circuit, it would be a feeble radiator of energy. 'In fact I doubt whether it will visibly act as a radiator beyond ¼λ at which true radiation of broken-off energy occurs.' To achieve efficient radiation he showed that the Leyden jar capacitor had to be opened up in space.

'By separating the coats of the jar as far as possible we get a typical Hertz radiator whose dielectric extends out into the room, and thus radiates powerfully. In consequence of its radiation of energy, its vibrations are rapidly damped, and it only gives some three or four good swings' (i.e. oscillations).

The next important step made by Lodge was shortly after Marconi had demonstrated wireless telegraphy over a distance of a few miles. In August 1897, Lodge applied for the first tuning patent (2). In this patent he described several different receiver and transmitter circuits, some examples of which are shown in Figure 2. In each of these the tuned circuit is formed by an inductor and the antenna capacitance. In a further patent, also taken out in 1897, Lodge replaced the cone-shaped radiating elements with flat plates, one of which could be set in the ground. At the receiver he utilised an r.f. transformer with primary and secondary taps for optimum tuning (see Figure 2d).

Starting in 1898, Marconi introduced important improvements to his wireless telegraph equipment. By a process of trial and error he independently developed a transformer for coupling to the antenna (he called this transformer a jigger). Initially the prime purpose of the transformer was to provide a voltage drive to the coherer rather than a current drive.

'The effect of electrical oscillation on the imperfect contact' (i.e. coherer) 'seems to increase very greatly with their e.m.f. and not with their quantity' (i.e. current). 'The object of this invention is to increase the e.m.f. of the received oscillations by transforming up their e.m.f. at the expense of the quantity. This greatly increases the distance over which....it is possible to transmit and receive messages.'

Marconi's principal contribution to tuning was encapsulated in his famous 'four sevens' patent of 1900 (3). This was a combination of his work with jiggers, antenna matching and tuning. A circuit of the receiver is shown in Figure 3. An adjustable inductor is used in the antenna feed; the transformer is tuned on both the primary and secondary windings and there are further variable inductors in series with the split secondary windings. The two iron-cored chokes are provided to block r.f. from the relay or telegraph instrument, R. The main tuning is by the two capacitors, h and h'. These variable capacitors were constructed from two metallic tubes separated by a dielectric and sliding telescopically on each other.

In summary, the concept of tuning was first envisaged by Lodge in 1897 and demonstrated at the Royal Society. With the advent of wireless telegraphy, first Lodge and then Marconi (from 1897–1900) developed practical means for coupling the antenna to the transmitter and receiver and providing means for tuning these to specific wavelengths. It must be stressed, however, that the purity of the transmitters oscillations was poor; consequently, in spite of the tuning, considerable energy was spread over a wide frequency band.

EARLY VARIABLE INDUCTORS

For the early radio equipment, variable inductance was usually provided either by having a range of plug-in coils or by a series of taps along the inductor, selected by a suitable switch.

One form of truly variable inductance was the variometer. The first of these to be produced would appear to be the Ayrton-Perry variable self-inductance standard described by Lord Rayleigh in 1886 (4). The first application of a variometer to wireless equipment was covered in a patent of Rosenthal and the Amalgamated Radio-Telegraph Co. in 1907 (5).

Basically the variometer consists of two mutually coupled coils, one fixed and the other movable. In a typical configuration the movable coil is mounted on a central shaft within the fixed coil. When the coils are in line so that the turns are in the same sense the overall inductance will be enhanced. When the coil is rotated through 180 degrees the inductance will tend to cancel. The exact amount of inductance variation will, of course, depend upon the coupling coefficient, k. If the two coils have inductances of L_1 and L_2 it follows that the maximum and minimum inductances will be given by:

$$L = L_1 + L_2 \pm 2k\sqrt{L_1 L_2} \qquad (1)$$

If the two coils have the same inductance, L, then:

$$L = 2L\,(1 \pm k) \qquad (2)$$

For an open type of variometer k is typically 0.5 which gives a total inductance range of 3:1 (corresponding to a frequency range of 1.73:1). If the outer coil totally encloses the inner coil the value of k will be about 0.8, which gives and inductance range of 9:1 and a corresponding frequency range of 3:1.

The main limitation of the variometer is the low value of Q at its minimum inductance setting. This problem was recognised by Rosenthal in his 1907 patent. To minimise the problem, a principal claim was to include a series of fixed inductors which could be switched in series with the variometer.

VARIABLE CAPACITORS

The second element of a tuned circuit is the series or parallel connected variable capacitor. Initially these frequently took the form of a concentric structure with an inner metal tube that could be slid telescopically. An early form of variable capacitor, in which semi-circular plates could be rotated within a set of fixed plates, was patented by Pletts and the Marconi's Wireless Telegraph Co. in 1906 (6). This type of construction, much improved over the succeeding years, became the most common type of variable capacitor, and is still used to this day.

For low-value, pre-set capacitors a common type of construction was two plates separated by a dielectric material, such as mica or ceramic. The separation between the plates was adjusted by a screw.

For capacitors with semi-circular vanes the variation of capacitance over the majority of the range is directly proportional to the angle of rotation. If stray capacitance is ignored, then the variation of frequency is proportional to the inverse square of the rotation angle. It was several years before the vanes were shaped to give either linear wavelength or linear frequency against rotation. See Griffiths (7,8) and Figure 4.

MARCONI MULTIPLE TUNER

An important improvement in tuning was made in 1907 when C S Franklin of the Marconi's Wireless Telegraph Co. patented the Marconi Multiple Tuner (9). A simplified circuit of the tuner is shown in Figure 5. It consists of two switched inductors, three variable capacitors, and a pair of transformers with variable coupling between the primary and secondary windings. The adjustments are made as follows:

1. The capacitor, g, and the two switched inductors, b and c, are adjusted for maximum signal level.
2. The two capacitors, l and n, are then also adjusted for maximum signal level.
3. Coils, h and k, which are mounted on a common shaft, are rotated within c and m until the signal strength is reduced sufficiently to minimise interference.
4. If necessary, steps 1 to 3 are repeated.

The Marconi Multiple Tuner is an early example of a band-pass filter and was much used with Marconi radio equipment for many years.

LATER BAND-PASS FILTERS

The majority of early broadcast receivers had quite poor selectivity, often using just a single tuned circuit. When the screened grid valve was introduced in 1927, selectivity was improved by utilising two tuned circuits. Initially separate tuning capacitors were used, then some form of mechanical coupling was introduced and, finally, by about 1929 ganged capacitors, controlled on a common shaft, came into general use.

Even with the additional tuned circuit, selectivity remained poor and some manufacturers of radio receivers resorted to band-pass tuning (see Figure 6). This type of tuning was quite popular, particularly with the more expensive 'quality sets'. The eventual solution to the selectivity problem came with the general introduction of the superheterodyne receiver from about 1932. (This type of receiver originally appeared in the mid-1920s but they were very expensive. Improvements in performance and a significant reduction in manufacturing costs came about with the mass production of multi-electrode valves in the early 1930s.) The variable band-pass filter is, of course, widely used today in professional radio equipment to prevent blocking and cross modulation from strong unwanted signals close in frequency to a relatively weak, wanted signal.

IRON DUST-CORED AND FERRITE-CORED INDUCTORS

Almost without exception r.f. coils up to the early 1930s were air-cored. As a result they were quite large, typically about 50 to 75 mm diameter. In order to limit stray coupling the coils were often screened by metal cans. A reasonable spacing was required between the can and the coil, otherwise the Q factor was reduced significantly. Ideally the screen diameter should be greater than 1.6 times the coil diameter. In later years smaller diameter coils were produced for receiver applications as a result of improved winding methods.

Because of the skin effect litz (litzendraht) wire was developed for r.f. coils. This is a multi-strand wire (5, 7, 9, or 15 being typical), each strand being insulated with enamel and silk coverings. The optimum frequency range for this type of wire is 0.3 to 3MHz.

Air-spaced coils continue to be used for v.h.f. and u.h.f. equipment and for the tuning coils of high-power transmitters. For most other applications, however, air-spacing has been superseded by cores constructed from magnetic materials. Two classes of such materials have been developed: iron-dust and ferrites.

It took many years before a satisfactory process was developed for the manufacture of iron-dust cores. The first types to appear commercially in Britain were developed by the German Hans Vogt. The magnetic material was known as *ferrocart* and it was formed into a torroid. Initial details of the material was described by Vogt in 1932 (10), and a more detailed, technical description a few months later by Sneider (11). Within a short time the cores were being sold commercially by the Colvern company. An immediate application for this type of core was in the i.f. transformers of superheterodyne receivers.

Over the years improved processes were developed and iron-dust cores became used for virtually all the tuning coils in radio receivers. Typically, the relative permeability of the material was about 10 to 12; furthermore, by forming the core with a screw thread, it was possible to provide a means for adjusting the coil to the required inductance. A significant benefit was a reduction in the size of the coils and a much smaller relative spacing between the coil and its screening can. A further application of adjustable, iron-dust cores was for permeability tuning in push-button receivers, which became quite popular in the late 1930s. For more details on this type of core, see Langford-Smith (12).

A further improvement came with the development of ferrite materials. The eddy current losses in a magnetic core material increases as the square of the frequency. Ferrite materials have the benefit of having very high resistivities and hence very low eddy current losses. Ferrite materials were first produced by Hilpert in Germany in 1909 (13). The first practical materials, however, were developed by Snoek who worked for the Philips company in Holland (14,15,16). Starting in 1943, he carried out extensive research with substances of the type XF_eO_4, where X was a divalent metallic ion such as manganese or nickel. The specific resistivities of the materials were between 10^7 and 10^{12} times that of iron and hence the eddy current losses were negligible.

The first ferrite cores, known as *ferroxcube*, became available commercially in the mid-1950s. Since that time they have effectively replaced iron-dust cores and their useful frequency range has been extended well into the v.h.f. bands. Two classes of ferrite materials are now in common usage for r.f. applications: manganese-zinc (MnZn) and nickel-zinc (NiZn). The first of these is used for frequencies up to about 2MHz and has relative permeability values in the range 300 to 10,000 The second type is used for frequencies up to about 300MHz and has relative permeability values in the range 10 to 2000. As a general rule the higher frequency ferrites in either class have lower values of relative permeability.

VARACTOR DIODE

Mechanically controlled variable capacitors continued to be used, unchallenged, until the mid-1950s. By this time, semiconductor diodes and transistors began to replace thermionic valves for low-power applications and it became apparent that one feature of these devices could lend itself to electronic tuning: the capacitance that exists across the junction of these semiconductor devices depends on the reverse voltage applied, decreasing as the voltage is increased. For most requirements this capacitance is undesirable because it limits the high frequency performance of the devices. In 1955, however, Giacoletto and O'Connel (17) described a new class of germanium junction diodes specifically designed for tuning applications. The capacitance of a specific device described in their paper varied inversely with the square root of the bias voltage up to −16 volts from 160pF to 25pF.

These capacitors are now known as *varactors*. Various types have been produced having different laws for the voltage/capacitance. For example, an abrupt junction type has an almost linear relationship between the voltage and capacitance.

The local oscillator frequency of modern communications equipment is almost invariably controlled by varactor diodes. The more sophisticated of these equipments utilise frequency synthesisers: varactor diodes, in conjunction with microprocessors and other integrated circuits, enable small frequency steps to be generated and their settings stored in memory devices. In addition, the front-end tuning of the radio receivers can also controlled by varactor diodes, with the tuning frequency 'ganged' to that of the frequency synthesiser. Apart from local control, varactor diode tuning has made possible the remote control of the radio equipment.

AUTOMATIC FREQUENCY CONTROL

The superheterodyne receiver provides excellent selectivity but, because of this, there is the possibility of mis-tuning, either by operator error or by frequency drift of the local oscillator. The problem can be particularly serious with pre-set tuning and increases with frequency. Automatic frequency control (a.f.c.) provides a solution to the problem.

An entirely electronic means for achieving a.f.c. was described by Travis in 1935 (18) and by Foster and Seeley in 1937 (19). The principle was to apply the i.f. signal to a frequency discriminator, which produced an output voltage proportional to the frequency offset. This voltage was then applied to a variable reactance valve, connected across the tuned circuit of the local oscillator.

One form of reactance valve circuit is shown in simplified form in Figure 7. This is known as a quadrature circuit, with a capacitor connected from anode to grid and a resistance from grid to cathode. Providing that $R >> 1/\omega C$, the anode current and anode voltage differ in phase by almost 90° and hence the impedance between anode and cathode will be almost entirely reactive.

The value of the capacitance is proportional to the mutual conductance, g_m, which, in turn, is controlled by the voltage fed back from the frequency discriminator to the grid of the valve.

AFC is commonly used in modern f.m. receivers, but the variable reactance device is now a varactor diode.

TRANSMITTER TUNING

In many respects the tuning of radio transmitters is very similar to that of receivers. The high voltages involved and the need of matching the power output stage to the antenna, however, introduces special problems. Ferrite cores can only be used for low-power stages but for higher powers an open torroid is generally essential. The power levels are too high for varactor diodes. Consequently, special vacuum dielectric variable capacitors have been produced. These typically consist of concentric cylinders, one of which is mounted on a sliding shaft. Flexible bellows allow for axial movement. The whole assembly is usually mounted in a glass or ceramic envelope.

Figure 8 shows a simplified circuit of a high-power output stage for a 10kW h.f. transmitter covering the band 2–30 MHz. There are four adjustable components: a pair of vacuum capacitors, C_2 and C_3, the main tuning inductor, L_2, and the loading coil, L_3. One motor controls the capacitors and tuning coil and a separate motor controls L_3. In order to facilitate tuning, approximate settings are stored for these variable components. Final tuning is achieved at reduced power using a quadrature detector connected between the anode and grid of the output valve. The loading coil is adjusted for minimum VSWR.

In order to ensure low losses in the coils these are made from copper strip, silver plated and wound on an open former; the unused portion of the windings are shorted out and two shorting contacts are used to overcome unwanted resonances.

For some transmitters, particularly where higher speed tuning is required, the continually variable inductors and capacitors are replaced by banks of fixed items, which are then switched by vacuum relays.

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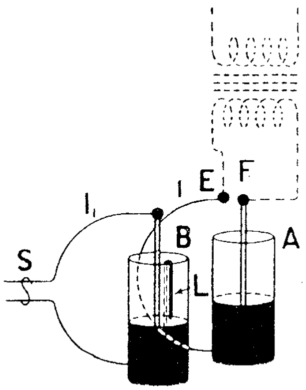
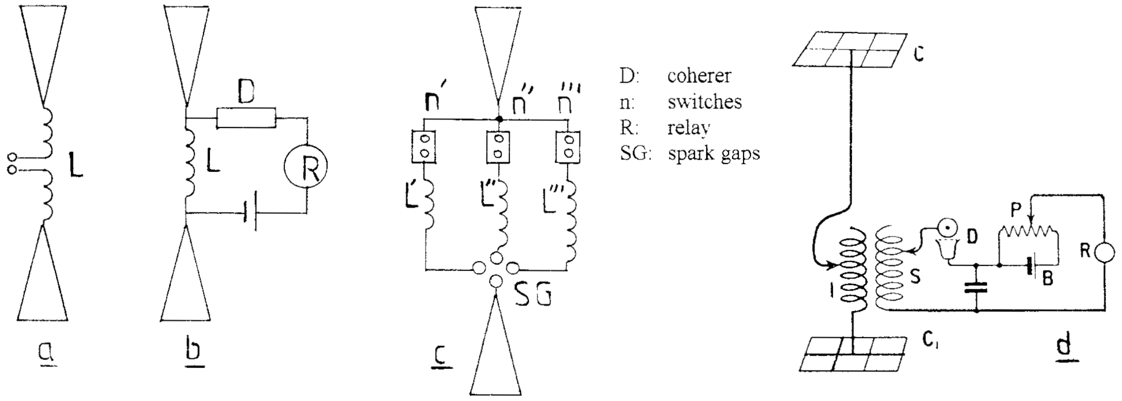


A,B: Leyden jars
E,F: Spark gap
I,I₁: Inductive loops
L: 'Overflow path'
S: Shorting link

Figure 1: Lodge's syntonic jars (1889).



D: coherer
n: switches
R: relay
SG: spark gaps

Figure 2: Early tuning circuits of Lodge. (a) Transmitter with spark gap. (b) Single-frequency receiver. (c). Receiver with switched tuning. (d) Receiver with coupling transformer and plates for the antenna and earth.

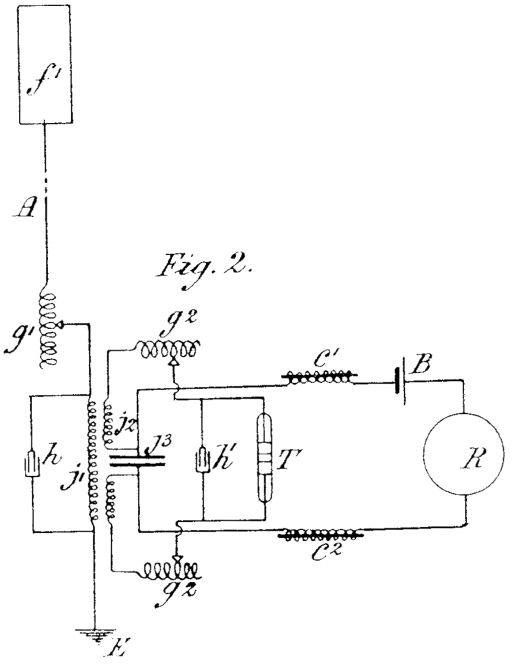


Figure 3: Marconi tuning system (1900).

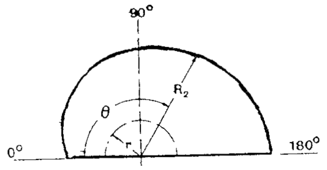


Figure 4a: Plate design for constant wavelength change.

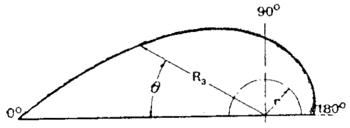


Figure 4b: Plate design for constant frequency change.

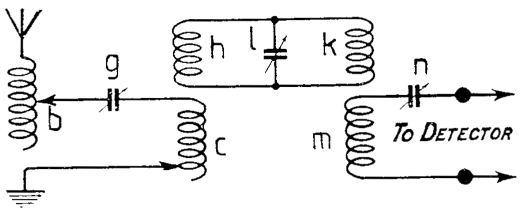


Figure 5: Marconi multiple tuner (1907).

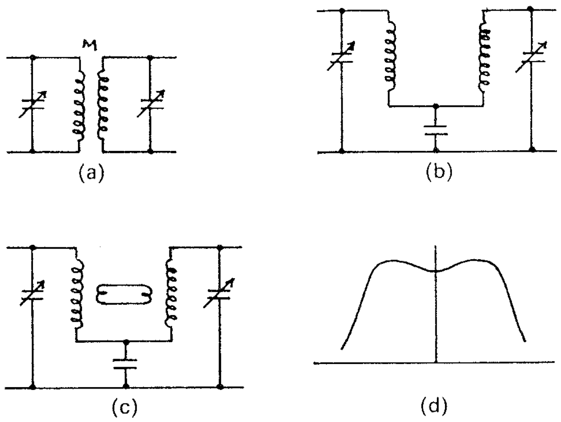
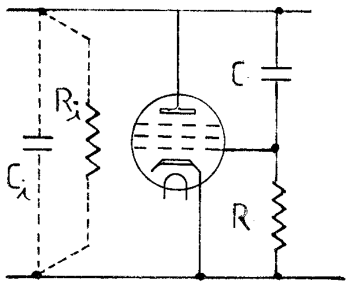


Figure 6: (a) Mutual inductance coupling. (b) Series capacitance coupling. (c) Combined mutual inductance and series capacitance coupling. (d) Band pass fitter frequency response.



This simplified circuit shows one arrangement for a reactance valve. The approximate values of input capacitance and resistance are given by:

$C_i \cong g_m CR$

$R_i \cong 1/g_m(\omega CR)^2$

Figure 7: Reactance valve circuit.

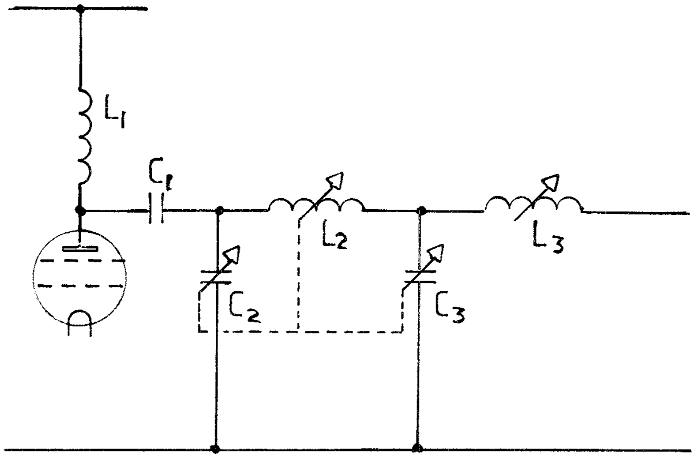


Figure 8: Simplified output circuit of a 10kW h.f. transmitter.