Basics of Radio Transmission & Reception - 6

Superheterodyne Receivers

This month we meet the superheterodyne receiver, which can have exceptionally high sensitivity and sharp selectivity – essential requirements for the reception of distant radio stations.

by BRYAN MAHER

The TRF receivers we considered last month were simple, basic but limited in performance. They lack *sensitivity*, and hence do not have enough gain to 'pull in' distant stations. Also TRF receivers have insufficient *selectivity*, so they have trouble separating the many strong local stations in a large city.

To overcome these deficiencies, in 1918 Major Edwin H. Armstrong invented a radical new idea, the *superheterodyne* receiver. The word 'heterodyning' means the act of beating two different frequencies together, working to obtain a third frequency as in Fig.1. (hetero = different; dyne = work).

TRF deficiencies

To see why we would bother to increase the complication of radio receivers, compared to the relatively simple TRF receiver discussed last month, it appears that the greatest shortcomings of the TRF receiver stem from two facts. In TRF receivers:

1. When tuned to a station the TRF receiver circuits are all tuned to the same frequency.
2. The frequency to which they are all tuned must be continuously variable.

Tuning many circuits to the one frequency runs the risk that accidental coupling via the power supply lines or stray capacitance can couple output radio frequency (RF) signal back to the sensitive input of the tuned stages or to the antenna, causing instability.

In an unstable condition a receiver screams, whistles its head off and is quite useless.

The design of continuously variable circuits initially required large ganged variable capacitors, as we saw last month. These have such massive metal components that stray capacitive coupling from one section to another is a natural, though unwanted consequence.

Because of this effect the variable tuned circuits cannot be designed to have very high gain, nor can too many stages be used, or unstable oscillatory conditions will inevitably occur.

Thus sensitive high gain TRF receivers are an impossibility. The lack of selectivity of TRF receivers stems both from the above limit on the number of tuned stages and also from another rather subtle effect – the change in bandwidth of a tuned circuit as we tune it across its variable frequency range.

Recall that earlier in this series we defined the *quality factor* 'Q' of a tuned circuit as:

$$Q = (2Pi\ f\ L)/R$$

where Pi is 3.1416; f is the frequency in Hz to which the circuit is tuned; L is the inductance of the tuned coil in henries; and R is a quantity in ohms representing all losses of the tuned circuit.

Despite this definition it is found in practice that the Q of a tuned circuit hardly changes at all as we tune it across its frequency range.

The reason for this unexpected state of affairs is that while the inductance L remains mostly constant, as the frequency is increased we find that the circuit losses R also increase. This is because R is much more that the simple DC resistance of the coil.

R represents a conglomerate effect summarising all the tuned circuit power losses, which includes dielectric shunt resistive losses of the capacitors and all the insulating materials; these power losses increase at higher frequencies. R also includes the series resistance of the coil, wiring and capacitors; these resistances increase at higher frequencies.

Skin effect

This increase in series resistance is called the *skin effect*, as at high frequencies currents are pushed out of the centre of the conductor by their magnetic field, and are forced to flow only near the surface of the conductor. With less effective cross sectional area the conductor appears to have higher resistance to high frequency currents.

So the losses symbolized by R increase roughly in proportion to frequency, with the result that Q remains almost unchanged as we tune across the dial.

But we also said earlier that Q relates the bandwidth 'delta f' of a circuit to its tuned frequency:

$$Q = f/(\text{delta } f)$$

as Fig.2 shows. (The Greek symbol delta is used to mean 'a small change in a value').

But as Q does not change when the

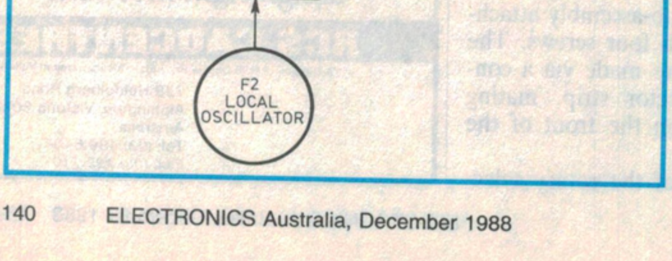

Fig.1: The basic idea of heterodyning. A local oscillator at frequency F2 beats with the input frequency, producing sum and difference signals.

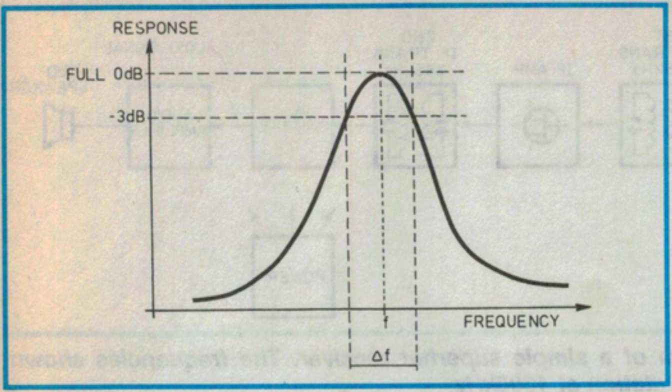

Fig.2: A reminder about the response of a tuned circuit. The higher the Q, the narrower the curve.

TABLE 1: Superhet frequencies		
Station and mixer tuning f1 (kHz)	Local Osc f2 (kHz)	IF = (f2-f1) (kHz)
500	955	455
750	1205	455
1000	1455	455
1200	1655	455
1350	1805	455
1500	1955	455

Table 1: How the local oscillator 'tracks' the signal, to produce a constant IF.

tuned frequency f is increased, it must be that the bandwidth (delta f) also increases. This is why it is impossible to design narrow bandwidth variable-tuned circuits for high frequencies. The bandwidth is different when tuned to different stations. For a broadcast band (500 to 1500kHz) TRF receiver the bandwidth typically increases by a factor of three across the dial.

Enter the superhet

To conquer these deficiencies, which are inherent in all TRF receivers, Major Armstrong proposed a radical new idea, the superheterodyne or 'supersonic heterodyne' receiver as shown in the block diagram of Fig.3.

The antenna feeds signals at chosen station frequency f1 to a non-linear 'mixer' RF amplifier stage. Also fed into the mixer are RF signals at a different frequency f2, from a 'local oscillator' (LO). The local oscillator signals are large enough in amplitude to drive the mixer into the necessary non-linear mode of operation.

Four output frequencies are possible from the mixer stage. These are f1, f2, (f1+f2) and (f1-f2).

Following the mixer is an *intermediate frequency* or 'IF' amplifier stage, fixed-tuned to frequency (f1-f2) and rejecting the other three frequencies f1, f2 and (f1+f2).

Both the mixer and local oscillator are variable tuned, but ganged and designed in such a way that as they are tuned across their frequency range, the *difference* in frequency (f1-f2) remains constant. This has the effect that whichever RF signal may be tuned is converted into a fixed and lower-frequency IF signal, which carries the same modulation as the original received RF signal.

The whole idea of superheterodynes is that, as the intermediate frequency amplifier stages are tuned to a fixed frequency, the IF tuned circuits can be made small, compact, with both coil and fixed tuning capacitor within one metal shield can. This completely shielded construction allows a number of intermediate amplifier tuned stages to be used.

Although all IF stages are tuned to the one frequency, stage gain can be made quite high without instability, by the complete shielding and isolation of each IF tuned circuit.

The intermediate frequency tuned circuits are called IF transformers. These can use mica dielectric tuning capacitors, or fixed capacitors with adjustable ferrite 'cores' in the transformers to perform the tuning. Either way, they can be quite small.

Sharper tuning

The design and construction of these small compact IF transformers achieves a higher Q, sharper tuning and narrower bandwidth than can be realized with variable-tuned circuits such as are used in the mixer stage. Therefore with this superheterodyne arrangement, most of the receiver's selectivity is attributable to the fixed-tuned IF stages.

But as the IF is a constant frequency, the bandwidth does not change much as we tune across the frequency range. As many IF stages can safely be used, quite narrow bandwidth (i.e., high selectivity) can be achieved.

Choice of IF

Once set up, the idea is that the intermediate frequency is a constant.

To avoid any problems of station transmissions interfering with the IF signals, a number of standard IF frequencies have been agreed by manufacturers and governments and few if any radio transmitting stations are allowed on these chosen frequencies. A receiver designer chooses one of these standards for his IF frequency.

The frequencies 175kHz, 455kHz, 3.3MHz, 9.0MHz, 10.7MHz and 45.75MHz are regarded as reserved frequencies for IF use. Most AM broadcast receivers use 455kHz for their IF.

In general the lower the intermediate frequency chosen for a receiver, the greater the selectivity, i.e., the narrower the overall receiver bandwidth.

Though the superheterodyne principle immediately disposes of the low sensitivity and selectivity problems inherent in all TRF receivers, it can bring some new difficulties of its own. But whoa – one thing at a time!

Firstly Fig.3 shows the frequencies used to tune a station on 1000kHz. The mixer input circuit is tuned to the station frequency on 1000kHz, while the local oscillator (or LO) is tuned to 1455kHz. The heterodyning or 'beat' effect yields a difference of (1455-1000) = 455kHz, which becomes the intermedi-

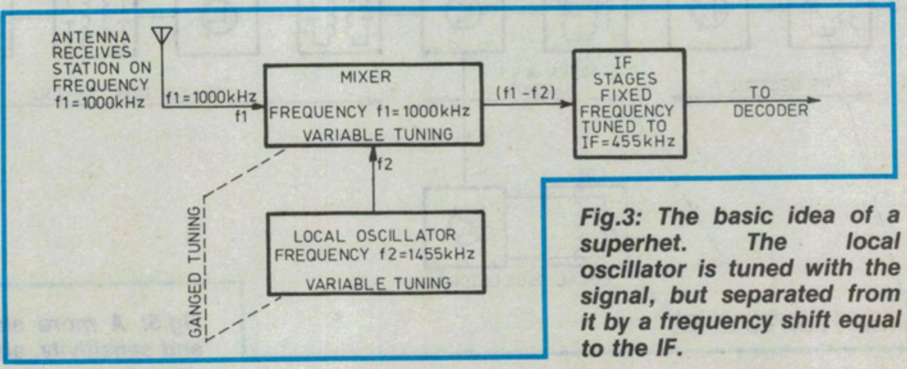

Fig.3: The basic idea of a superhet. The local oscillator is tuned with the signal, but separated from it by a frequency shift equal to the IF.

ate frequency or IF.

A range of frequencies used as the receiver is tuned over the broadcast band would be as shown in Table 1. Notice that while f1 changes over 3:1 range, f2 changes over a lesser range (1955/955kHz = 2.05:1).

Padding & trimming

Before you retort 'So what?', consider that the mixer tuning and local oscillator tuning are both operated by the one tuning dial drive mechanism and knob. The common arrangement is a two-gang tuning capacitor, with one section for the mixer RF tuning and the other for the local oscillator.

But as f1 and f2 must change over a different range, some tricks of circuit design must be used. One method is to use a *padder* capacitor in series with the oscillator tuning capacitor, to shorten its tuning range.

To bring all of the tuned circuits into alignment, small semi-variable capacitors in parallel with the mixer and local oscillator tuning capacitors are 'trimmed' to bring the IF frequency to the required figure – e.g., 455kHz.

Further separate trimming capacitors or *trimmers* may be used to bring all IF tuned transformers to exactly the same frequency. Alternatively adjustable screw-type ferrite cores may be used, as mentioned earlier.

Once this 'lining up' procedure is done, all padding and trimming adjustments are sealed and not moved again.

Any subsequent repairs to the circuit or replacement or components may require re-adjustment of padders and trimmers. For this reason the sealing compounds used are semi-permanent materials, rather than permanent paints or glues.

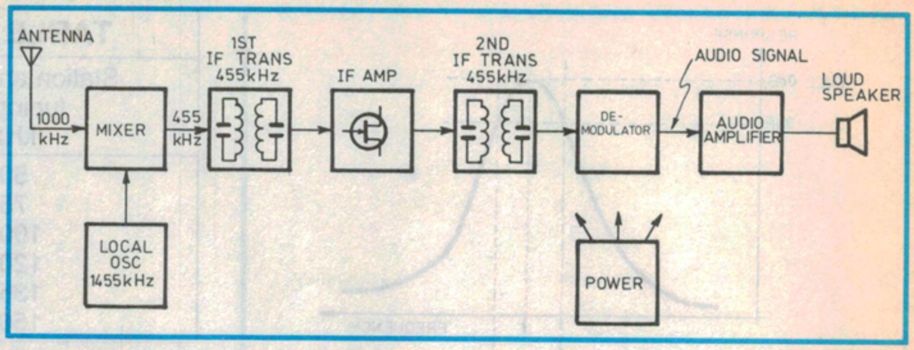

Fig.4: Block diagram of a simple superhet receiver. The frequencies shown are when tuned to a station at 1000kHz.

The basic superhet

Radio receivers intended for city and suburban reception (where station field strength is high) do not need much sensitivity, but still require adequate selectivity because there may be many stations to be separated.

For this very common application a receiver can be implemented using one IF stage, involving one IF amplifier transistor and two tuned IF transformers. Preceding this would be a mixer stage tuned to the station, and of course the local oscillator as in Fig.4.

Such a lineup of stages would be an economy receiver, satisfactory for 'local' reception only, where many powerful stations are located within 50km or so and the owner has no wish for long distance reception.

Radio receivers of this basic superheterodyne type sell for a range of prices from $10 upwards, and millions have been manufactured and sold as most Australians are city or suburban dwellers. Many have also been home-constructed over the years by readers of *Electronics Australia* using designs published in this magazine, and often from the associated kits.

Greater complexity

Away from the cities there are many different applications where people live at distances of 100 to 250 kilometres from their nearest 'local' station. Radio receivers for such use need more sensitivity than can be achieved using the basic superhet of Fig.4.

Also there are listeners who wish for reception of some of the more powerful AM stations on frequencies in the 3.0MHz to 30MHz range, and national transmitters like Radio Australia, Voice of America, Deuschland Speigel, the BBC and so on.

For such receivers better selectivity is mandatory, because the extra sensitivity will pull in many stations from far and near, some of which will be very close in frequency, stretching the receiver's ability to separate them.

These receivers are more complex,

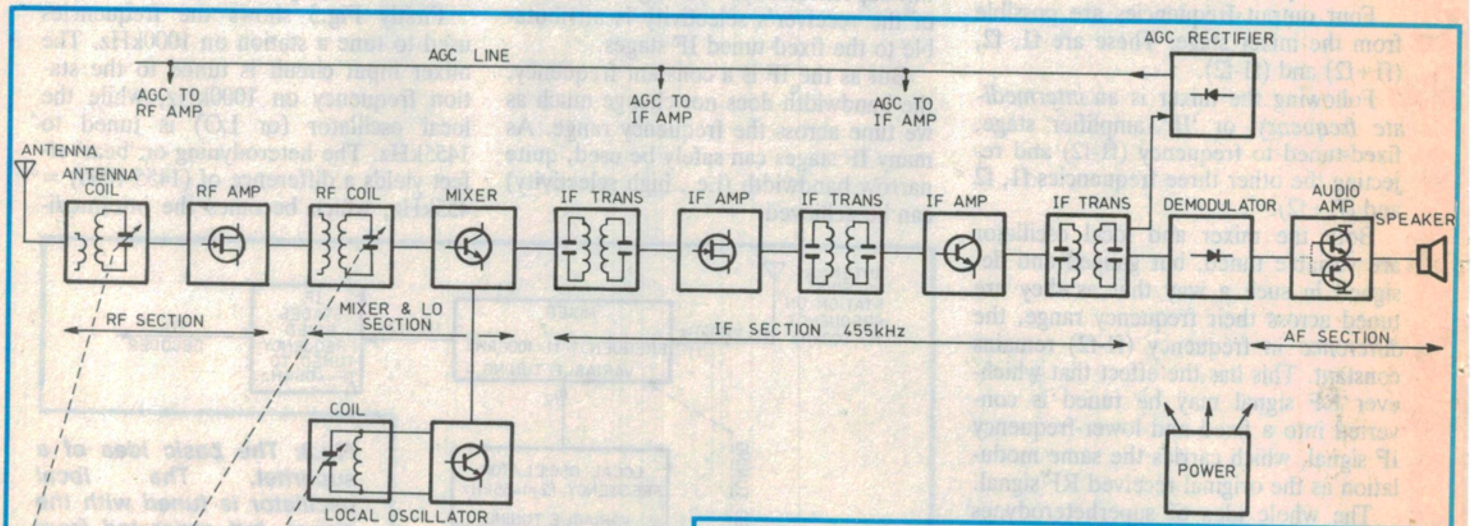

Fig.5: A more elaborate superhet with higher selectivity and sensitivity, also fitted with AGC.

using two or three IF amplifier stages involving three or four IF transformers, as sketched in the block diagram Fig.5.

Such multi-band receivers incorporate some sort of band-switching (or 'wave-change switch' to use a very old name), so that two or more sets of tuning coils can be switched, one set for the medium-wave broadcast band and the other(s) for the HF or 'short-wave' band(s). Some of the more expensive receivers have three or four sets of coils to cover the various bands.

In each case the high gain and sharp selectivity of the intermediate amplifier stages plays an essential role in the reception, the receiver responding to the very weak signal and successfully separating the many stations.

Optional RF stage

For a number of reasons, a high-performance superhet receiver may also include a tuned radio frequency amplifier stage ahead of the mixer, as shown in Fig.5. Such an RF amplifier must of course be variable-tuned, its tuning ganged with the mixer and local oscillator tuning, all being operated by the common tuning dial. If tuned by variable capacitance a three-gang variable tuning capacitor would be required.

One reason for including an RF stage in a high-performance receiver is to allow *automatic gain control* (AGC) of the RF signal ahead of the mixer, to prevent overloading on very strong signals. A second reason applies to long-distance reception, for a mixer circuit is usually less noisy when fed with a fairly strong RF signal.

There is a third important reason favouring the inclusion of an RF stage (and occasionally two RF stages) ahead of the mixer, but that reason is a topic for a whole future episode in this series.

Many designs

Literally hundreds of variations of the basic superheterodyne principle have been designed and built world-wide in the seventy years since Major Armstrong's day.

Superheterodyne receivers are the most successful and widely used type of radio and television receivers, with frequency ranges covering most of the spectrum from VLF all the way up to UHF.

Quite a number of different types for various applications in domestic, hi-fi and amateur service have been featured in this magazine, both under its present name *Electronics Australia*, and its previous names *Radio, TV and Hobbies*, *Radio and Hobbies*, and earlier still *Wireless Weekly*.

Demodulation

As indicated in Figs.4 and 5, in all these AM receivers the output of the last IF transformer feeds the AM demodulator or *detector*, where the audio component (i.e., the music and speech) is extracted from the modulated carrier. Many types of demodulator are possible, the simplest and most common being the diode detector as described in detail in the previous episode.

Following the demodulator the audio signal passes through the volume control, then on to the audio amplifier stages.

Audio amplifier

The audio amplifier stages of radio receivers come in all shapes and sizes, and in a wide range of power capabilities. You will find some radio receivers whose audio stages are simple, cheap and capable of only mediocre audio response. Then there are radios whose audio stages are excellent designs, producing music quality truly classed as hi-fi.

The power output capability of contempory designs in audio amplifier stages for radios cover a wide range. You'll find anything from about 100 milliwatts output for driving headphones, all the way up to 100 watts of hi-fi stereo music intended to drive multiple loudspeakers in lounge rooms or in automobiles.

Just one of the hundreds of possible designs for a suitable audio section is shown in Fig.6. This circuit raises the audio signal level to an amplitude and power sufficient to drive a loudspeaker or perhaps a pair of earphones. Of course we will want a volume control too.

The first stage in Fig.6 is often called the audio 'voltage' amplifier, preceded by the volume control. The second stage is the audio 'power' amplifier, suitable for driving a loudspeaker. In this case it can do so to moderate volume, and with not exactly 'hi-fi' quality – more like 'medium-fi'.

The volume control is usually placed ahead of the audio amplifier, so that the audio stages will not be overloaded on strong signals.

Fig.6 uses a so-called *logarithmic* volume control (to avoid any abrupt control action) followed by a LM741 op-amp as a voltage amplifier with a voltage gain of 6, after which comes an LH0021CK power amplifier whose voltage gain is also set at 6. Thus a 400 millivolt audio signal from the volume control will give full power output of +/-14.4 volts peak (on light loads) or +/-11 volts at output currents up to 1.0 amp.

The safe output power into a loudspeaker load is limited by the type of heatsink to which the LH0021CK is attached. With an effective heatsink, output power up to 8 watts into an 8 ohm loudspeaker is quite easily obtained.

More information on audio voltage and power amplifiers in general is contained in my book 'Op Amps Explained', available by mail order from *Electronics Australia*.

Power supplies

Naturally power supplies for all the sections of the radio circuits shown must be provided. Either one (or more) batteries or a mains transformer and rectifier and filter would be used.

A power transformer stepping down the 240 volt mains to a suitable low voltage around 15 volts, a bridge rectifier and a few large electrolytic capacitors may constitute the simplest possible mains power supply.

To obtain improved results and reduce mains hum sometimes the power supply voltages are held steady (despite mains voltage fluctuations) by the simple application of voltage regulators, either zener diodes or integrated circuit feedback voltage regulators.

More information on power supplies and voltage regulators will also be found in my book 'Op Amps Explained'.

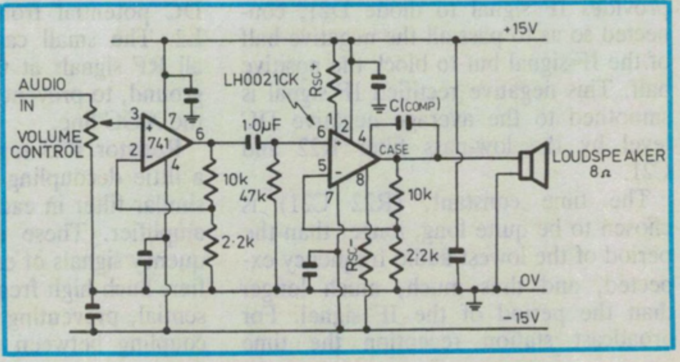

Fig.6: One of the many possible configurations for the audio amplifier section of a receiver.

Superhet receivers

Improvements

That completes the essential parts of a superheterodyne radio receiver for the reception of amplitude modulated (AM) signals. A superhet design may be quite simple, or it may include one or more embellishments to improve the performance, compensating for the shortcomings of atmospheric radio transmission.

The limitations of transmission reveal that in many locations the signal received from the station does not remain constant in amplitude, rather it fades up and down at both very low rates (i.e., stronger at night time) and also high rates (i.e., fluttering signal strength).

Both slow and fast changes in signal strength are caused by the nature of the atmospheric propagation of electromagnetic radiation, especially over long distances.

Automatic gain control

The first improvement we make to our basic radio receiver is to add *automatic gain control*, or AGC circuits. In earlier years this was called 'automatic volume control' or AVC.

Recall that the carrier signal in the frequency domain picture (refer to Fig.7(b) last month) gives us no speech, music nor any information except the fact that the station is transmitting. However we can deduce from the carrier the station frequency, and the signal strength as received at our location. When the signal fades up and down, it is the received RF amplitude of both carrier and sidebands which is changing.

Automatic gain control circuits make use of the IF signal at the output from the final intermediate amplifier. The AGC circuits most commonly used rectify this IF signal to obtain only the negative half of the modulated IF signal, and smooth it out to obtain the average (negative) DC component, using a circuit such as Fig.7.

A second small secondary winding L21 on the final tuned IF transformer provides IF signal to diode D21, connected so as to pass all the negative half of the IF signal but to block the positive half. This negative rectified IF signal is smoothed to the average negative DC level by the low-pass filter R22 and C21.

The time constant, (R22 C21) is chosen to be quite long, longer than the period of the lowest audio frequency expected, and thus much, much longer than the period of the IF signal. For broadcast station reception the time constant (i.e., the RC product R22.C21) is usually made longer than 30 milliseconds.

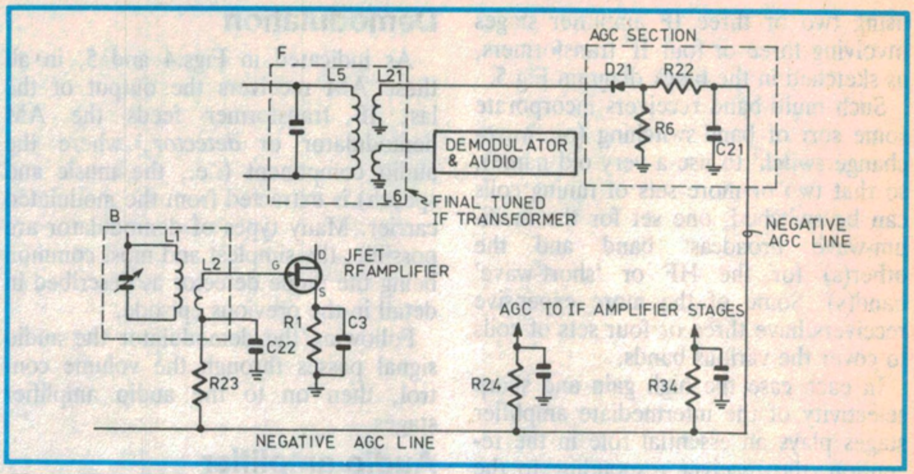

Fig.7: The AGC circuitry of a typical superhet receiver using semiconductor devices.

The output from the filter R22/C21 is a smoothed negative DC voltage, called the AGC line voltage, directly proportional to the average amplitude of the RF signal strength. We will now use this negative DC voltage to control the gain of all the IF amplifiers in the receiver, and perhaps the RF stage (if one is present).

The idea is that the stronger the RF signal, the greater the negative AVC line voltage, which we will use to reduce the gain of the intermediate amplifier stages and RF stage on strong signals. Then vice-versa on weak signals, the AGC line DC voltage will be less, allowing the gain of those stages to rise.

By this automatic control we hope to achieve constant amplitude output, even if the received signal strength varies.

Fig.7 shows the AGC rectifier and filter D21, R22, C21 and the AGC line going to RF and IF stages. Some detail is shown of the RF stage and its AGC connections. Similar AGC connections are made to all IF stages, but note that the mixer stage is not usually AGC controlled.

The gate of the RF amplifier JFET transistor is fed by radio frequency signals from L2, and also fed a negative DC potential from the AGC line via L2. The small capacitor C22 bypasses all RF signals at the low side of L2 to ground, to prevent RF signals flowing in the AGC line.

Resistor R23 together with C22 form a little decoupling filter, and there is a similar filter in each other controlled IF amplifier. These isolate the high frequency signals of each IF and RF amplifier. Such high frequency isolation is essential, preventing any RF or IF cross-coupling between stages via the AGC line (which could lead to high frequency instability).

Superhet bandwidth

The passband of the overall superheterodyne receiver is essentially the passband of the intermediate amplifier section, even if an RF stage is used. This is because the IF transformers can be designed and manufactured to have higher Q value than is possible for the variable frequency tuned circuits of the RF and mixer stages.

Also IF transformers for radio receivers are designed to have 'loose-coupled' tuned primaries and secondaries (i.e., the coupling factor is below critical coupling).

Because of these two characteristics of IF transformers, the IF stages can be more sharply tuned than any variable-tuned RF stages.

The use of many IF stages narrows the bandwidth still further, and while this is desirable for separating stations, the bandwidth may be too narrow to receive all the high notes and high harmonics in the broadcast music.

Superhet versus TRF

Therefore a few hi-fi enthusiasts still prefer TRF receivers with their broader tuning, for reception of high quality local broadcasts. Although popular some years ago, this preference for TRF has faded today as better results can be had receiving hi-fi music from the FM stations. FM receivers will be discussed in a later episode.

While the TRF receiver is only useful for short-to-medium distance reception, for long distance reception the superheterodyne type receiver is essential as only superhets can achieve sufficient sensitivity and narrow selectivity.

The superhet receivers outlined in this

(Continued on page 137)

Superhet receivers

Continued from page 144

chapter are eminently successful in their chosen field as stated. However for the reception of weak distant transmitters such as amateur stations over distances of thousands of kilometres, or (over shorter range) CB broadcasts, mobile transmitters or any of the myriad low-power transmitters that are part of our present day business and professional life, still more advanced superheterodyne receivers are necessary.

The highest class of superheterodynes are called 'communications receivers', having many advanced features, more controls and sometimes radically different types of intermediate stages.

Such special receivers are capable of extremely narrow bandwidth, so that stations very close in frequency can be successfully separated and received. Also sophisticated AGC and 'noise blanking' circuits may be used, and sometimes automatic digital computer-controlled tuning and logging are featured.