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THE CURSE OF THE SUPERHETERODYNE
and how to hex it

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The merit of the superheterodyne is that it provides the convenience of amplifying at a fixed frequency. This is a big advantage from the standpoints of constant gain and constant selectivity. Additionally, since the I.F. frequency is generally lower than the band covered, stable gain is more easily achieved and greater selectivity can be obtained with the same operating Q's. Finally, with all signals converted to a single frequency, it is possible to employ, when necessary, very sophisticated circuitry that would be quite impossible to implement otherwise. Some examples of this are crystal and mechanical filters, Q multipliers, synchronous detectors with "I" and "Q" channels, phase locked loops, etc.

The superheterodyne, however, is anything but an unmitigated blessing. In the process of providing the desired result, it has in effect become a comb filter, responding not only to the desired signal but to a multitude of spurious ones as well. The basic nature of the frequency conversion process requires that a non-linear device be present to accomplish it. This takes the form of the usual mixer. The mixer is normally biased near cut-off and the applied oscillator voltage causes the current in the mixer output to flow in class "C" pulses rather than sine waves. The result, of course, is an output current rich in harmonics of the oscillator frequency. In addition, undesired signals present at the mixer that are strong enough to experience significant non-linearity also produce harmonics. It is then possible for harmonics of strong undesired signals to beat with the harmonics of the desired oscillator frequency and some combinations will produce the 455 kc I.F. These are called spurious responses.

Another "spurious signal" that does not depend on harmonic production is the image response. This is merely the mirror image of the signal. Both signals produce a 455 kc I.F. frequency; the desired signal because it is 455 kc lower in frequency than the oscillator and the image because it is 455 kc higher. The image frequency is therefore 910 kc higher than the signal. If the receiver is detuned slightly, so the oscillator frequency moves, say, in a direction to decrease the I.F. frequency produced by the desired signal; a little thought will make it clear that the I.F. frequency due to the image will then increase. This is why, when tuning through a signal with image interference, a beat note of varying pitch will be produced. Beat notes will also be produced when spurious responses caused by harmonic combinations are present. In this case, the tuning of the beat through the audible range will become sharper depending on the order of the harmonics involved.

Another form of superheterodyne interference should be mentioned in passing and this is generally referred to as 910 tweet or 1365 tweet, corresponding to the 2nd and 3rd harmonics of the 455 kc I.F. In the strong signal case, these are produced in the mixer but more generally it is a weak signal phenomenon and the culprit is, then, the signal detector. Since this is also a non-linear device, harmonics of the I.F. frequency are produced and if any stray coupling exists between the diode circuitry and the receiver input, signals at these two frequencies will be applied to the input and beat with any desired signals that may arrive. Again, the mechanism involved produces a variable beat during the tuning process. Additionally, if the I.F. feedback is intense, the receiver will become unstable at these two frequencies.

Cross modulation and intermodulation are not exclusively superheterodyne phenomena so will not be considered in this paper.

Since the exact mechanism of spurious response production is frequently misunderstood, perhaps a few specific examples involving fictitious situations may be helpful:

Listener #1 in Schenectady, N.Y. has a strong local, WGY, on 810 kc. He finds reception difficulties because of this station with WOR in N.Y.C. on 710 kc; WSB, Atlanta, on 750; WABC, N.Y.C. on 770; and WKBW, Buffalo, on 1520. Let's take a look at this: When tuned to WOR (710), his oscillator frequency is 455 kc higher or 1165 kc. The second harmonic of WGY is 2 x 810 or 1620 kc and this beats with the oscillator frequency of 1165 to produce a difference frequency of 455 kc. The others-

WSB-750. f(osc) = 750 + 455 = 1205. 8 times 810 = 6480.
5 times 1205 = 6025. 6480 - 6025 = 455.

WABC-770. f(osc) = 770 + 455 = 1225. 5 times 1225 = 6125.
7 times 810 = 5670. 6125 - 5670 = 455.

WKBW-1520. f(osc) = 1520 + 455 = 1975. 3 times 810 = 2430.
2430 - 1975 = 455.

A second listener lives in Fort Wayne, Indiana, and he has a strong local, WOWO, on 1190 kc. This interferes with KXOK, St. Louis, on 630; WHAS, Louisville, on 840; WAVE, Louisville, on 970; KMBZ, Kansas City, on 980; WCSI, Columbus, on 1010; KMOX, St. Louis, on 1120; WHUT, Anderson, on 1470; and KXEL, Waterloo, Iowa, on 1540:

KXOK-630. f_o = 1085. 7 x 1085 = 7595. 6 x 1190 = 7140. 7595 - 7140 = 455.
WHAS-840. f_o = 1295. 8 x 1190 = 9520. 7 x 1295 = 9065. 9520 - 9065 = 455.
WAVE-970 f_o = 1425. 7 x 1425 = 9975. 8 x 1190 = 9520. 9975 - 9520 = 455.
KMBZ-980 f_o = 1435. 4 x 1190 = 4760. 3 x 1435 = 4305. 4760 - 4305 = 455.
WCSI-1010. f_o = 1465. 9 x 1190 = 10710. 7 x 1465 = 10255. 10710 - 10255 = 455.
KMOX-1120. f_o = 1575. 7 x 1190 = 8330. 5 x 1575 = 7875. 8330 - 7875 = 455.
WHUT-1470. f_o = 1925. 2 x 1190 = 2380. 2380-1925 = 455.
KXEL-1540. f_o = 1995. 5 x 1995 = 9975. 8 x 1190 = 9520. 9975 - 9520 = 455.

Finally, a DXer in Santa Monica, California, has to contend with KDAY on 1580 kc. This interferes with WMAQ, Chicago, on 670; WSB, Atlanta, on 750; KBIF, Fresno, on 900; WCFL, Chicago on 1000; KPAY, Chico, on 1060; KEZY, Anaheim, on 1190; KSRO, Santa Rosa, on 1350; and KBBQ, Burbank, on 1500.

WMAQ-670. f_o = 1125. simple image. 1580 - 1125 = 455.
WSB-750. f_o = 1205. 3 x 1205 = 3615. 2 x 1580 = 3160. 3615 - 3160 = 455.
KBIF-900. f_o = 1355. 5 x 1355 = 6775. 4 x 1580 = 6320. 6775 - 6320 = 455.
WCFL-1000. f_o = 1455. 9 x 1455 = 13095. 8 x 1580 = 12640. 13095 - 12640 = 455.
KPAY-1060. f_o = 1515. 7 x 1515 = 10605. 7 x 1580 = 11060. 11060 - 10605 = 455.
KEZY-1190. f_o = 1645. 7 x 1645 = 11515. 7 x 1580 = 11060. 11515 - 11060 = 455.
KSRO-1350. f_o = 1805. 6 x 1580 = 9480. 5 x 1805 = 9025. 9480 - 9025 = 455.
KBBQ-1500. f_o = 1955. 4 x 1580 = 6320. 3 x 1955 = 5865. 6320 - 5865 = 455.

Now, in order to get into all this trouble, these guys must have had pretty lousy receivers. Actually, the fictitious easterner had a $175 transistor all-wave portable with 6 spread bands, 2 police bands, aircraft, FM, and a broadcast band - such as it was!

The midwesterner used an expensive communications receiver that had seemingly endless spread bands along with BFO, crystal filters, "Q"-multiplier, noise limiter, and including facilities for handling DSB, SSB, CW, and RTTY. It also had a broadcast band but it was added, begrudgingly, at the insistence of the marketing people who thought they should have their fair share of this market also.

And, finally, the Californian was the owner of a high-priced, digitized job with broadband input that displayed his frequency for him accurate to 6 places but he blew his bankroll on the set and cannot afford the preselector that they now tell him is necessary if he wants to hear much of anything.

In the context of the broadcast band DXer, all these sets are bad - but not cheap! If the superheterodyne's problems cannot be solved by spending big money for available products, let us examine what has to be done. Obviously, if we retain the superheterodyne, a mixer is required and this means oscillator harmonics are inevitable. The solution, then, is to prevent all undesired signals from reaching the mixer to combine with these harmonics and this may require essentially duplicating normal superheterodyne selectivity in the form of tuned R.F. preselection. Should this prove necessary, was the superheterodyne a bad deal from the start?

Since the early 1930's, the superheterodyne has been the standard circuit for radio reception virtually unchallenged to the present time. There are three reasons why the TRF or "straight" circuit could not compete.

A. The TRF set is too broad at the high frequency end of the band. This is easily explained. The nature of coils is that their "Q" tends to remain constant over a given tuning range. "Q" equals the operating frequency divided by the 3db bandwidth ("Q" equals f/BW). Consequently, as the frequency increases, the bandwidth will also increase because "Q" remains constant. Since it is difficult to obtain higher operating "Q" 's than 100, the single stage bandwidth (SBW) at 1600 kc equals 1600/100 = 16 kc. For cascaded synchronously tuned single circuits, the overall bandwidth is related (approx.) to the single stage bandwidth, where N is the number of stages, as follows: BW = SBW ÷ 1.2 x square root of N. Accordingly, for 3 stages, BW = 16 ÷ 1.2 x square root of 3 = 7.7 kc. It is necessary to remember that this is only the 3db bandwidth; the 6db bandwidth would be even broader. It further assumes that the stages remain perfectly

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aligned, a ludicrous assumption in view of the drift propensities of the usual mica trimmers that represent a significant portion of the total circuit capacitance at the higher frequencies. Incongruously, at the lower frequencies, alignment is more likely to be preserved since the much more stable capacitance of the air dielectric main section predominates. Additionally, perfect initial alignment can be expected only at the alignment frequency which might be 1500 kc. A good air gang is tracked to 1%. This means that at other frequencies than 1500 kc, the capacitance may be off the curve as much as 1% or the frequency may be off as much as ½%. This amounts to a possible misalignment of 8 kc at 1600 kc and 7 kc at 1400 kc. With these possibilities for a staggered alignment, instead of a synchronous one, it is quite obvious that a "straight" set, as conventially constructed, is ill equipped to cope with the broadcast band radio spectrum from a selectivity standpoint.

B. The gain of a TRF stage is normally not constant over the tuning range. Constant gain is a necessity if several stages are cascaded or the situation rapidly gets out of hand. For instance, if the gain of a single stage varies 3 to 1, the gain of 3 stages would vary 27 to 1, 4 stages 81 to 1, etc. The reason for this variation is the impedance of the tuned circuit. This is equal to QX. As noted above, the "Q" remains substantially constant. The reactance, however, varies linearly with frequency. For the usual case, where the capacitance is varied to provide the tuning, it is convenient to look at the fixed element - the inductance. Since the inductive and capacitative reactances are equal at resonance, we do have this option. The reactance of an inductance increases linearly with frequency (X_L = 2 pi f L), so the impedance and gain increase in this manner also.

C. Basic overall stability problems limit the maximum sensitivity that can be utilized. The screen grid tube minimized the feedback problems experienced with interelectrode capacitance. However, the straight set had a basic problem with the tuning gang. This brought the individual tuned circuits in close proximity with considerable capacitance coupling between the leads going to the gang and between the stator sections themselves. In addition, considerable common coupling between circuits was introduced by the common rotor assembly of the gang shaft, wipers, ballbearings, etc. Since the gain per stage was normally 20 to 30 db, the problem of keeping a high performance design of this type stable was considerable. Toward the end of the TRF era, extremely elaborate shielding was used with each stage individually confined in a separate shield box. Unfortunately, this resulted in a very expensive receiver and it could not compete economically with the superheterodyne.

The electronic environment has changed so significantly since the 1930's, however, that another look at the straight set is in order. Of particular importance in this respect are the transistor and varactor. Let us look at these briefly.

The transistor is really a fantastic device that has a mutual conductance (G_m) of 40,000 micromhos at 1 milliampere, compared with a tube (or FET) which has a mutual conductance of only 4000 micromhos at <u>10</u> milliamperes. Since the gain of an amplifying stage is equal to $G_m Z$, where Z is the load impedance, it is obvious that the transistor can supply a given gain with a much lower load impedance than can a tube or FET. Accordingly, resistance coupled stages with flat gain over the broadcast band are feasible and make it possible to separate the amplification and selectivity functions. By locating the selectivity first, using just enough stage gain to preserve the signal-to-noise ratio (1.5 for example), and then adding the required amplification in the form of an untuned broadband amplifier, provides the ideal arrangement from the standpoints of low spurious responses, cross modulation, etc. In other words, strong nearby signals are attenuated more than they are amplified as they proceed through the amplifier, thus confining the major non-linearity to the first stage. A broadband amplifier as noted above is not feasible with tubes or FETs. These require 10 times the load resistance to provide the stage gain compared with that required by a transistor. In the practical case, the load resistor then becomes so large that the various shunt capacitances become a significant part of the effective load and introduce a serious gain slope that is inversely related to frequency.

Now let us take a preliminary look at the varactor. This is a reverse-biased diode which has the property of changing its capacitance as the reverse bias is varied. They are typically the size of an ordinary glass signal diode and the abrupt junction variety have been around for a number of years. The possible capacitance variation with this construction is typically 3 to 1 with a 1 to 10 volt bias change. Since a 9 to 1 capacitance variation is necessary to cover the broadcast band, a varactor variation of about twice this or, say, 20 to 1 would be necessary because of the stray minimum capacitance that exists in the trimmer, coil, leads, etc. By using a hyper-abrupt fabricating process, this required capacitance variation can be obtained with a 1 to 10 volt bias variation.

Varactor diodes suitable for tuning the broadcast band are manufactured by Motorola, ITT (Intermetal), Matushita, Siemens, and others. As a matter of fact, Matushita (Panasonic) has had two radio models on the market for several years with the broadcast band tuned by varactors. As we shall presently observe, the hyper-abrupt junction varactor offers interesting possibilities for making a practical TRF or "straight" receiver.

It was previously noted that a TRF receiver consisting of several tuned stages has a basic stability problem due to the common condenser gang. By employing varactors instead: (1) the long gang leads are eliminated; (2) the stator capacitative cross-couplings are eliminated; (3) the coupling problems in the common shaft are eliminated and; (4) the tremendous reduction in size eliminates any possibility of significant radiation resistance being present which did exist with the large stator plate assemblies of the condenser gang. Further, by using very low stage gain between the tuned circuits and obtaining the major amplification with a resistance coupled sub-amp not only are the spurious response and cross-modulation problems improved but a completely stable basic amplification system is provided.

With the stability problem solved, let us examine the problem of providing constant bandwidth over the tuning range. By a simple transposition of the basic "Q" relation given previously, we have, BW = f/Q. Obviously, then, to obtain constant bandwidth, the Q should vary linearly with frequency. Since our maximum Q is 100, this should apply at the high frequency end of the band and provision should be made to have it reduce linearly as the frequency decreases. This is not really difficult.

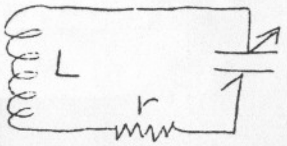


FIG. 1

Consider the circuit of Figure 1. If r represents the total circuit resistance, Q would equal X/r. Since, as noted previously, the capacitative reactance and inductive reactance are equal at resonance, we will exercise our option and select the fixed one to consider as a matter of convenience. As we know, X_L = 2 pi f l, so the reactance of the coil will increase linearly with the frequency and r will remain constant, so Q will also increase linearly with frequency which is the condition we desire.

When we try out this circuit and measure its performance we find that the bandwidth no longer varies 3 to 1 over the band as it did previously, but it is not constant, either. The reason for this is that r does not represent the entire circuit resistance. There are dielectric, magnetic and leakage losses that are effectively in parallel with the tuned circuit and these have an effect on the bandwidth variation which opposes the relation we desire. If this is not clear, a shunt resistor has the greatest loading effect at the frequency where the tuned circuit impedance is highest and this is at the high frequency end of the band since Z = QX.

It is not difficult to correct for this, empirically, with the circuit of Figure 2. Suppose we pick a value of C having a reactance equal to r at 540 kc. We then increase r to give the same Q as before at this frequency. At the high end of the band, however, the reactance of C is so much lower than r that the effect of r in lowering the Q is negligible. By cut-and-try, using this technique, it is no problem to find values of r and C that provide a constant bandwidth over the entire BC band.

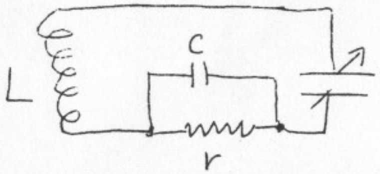


FIG. 2

Perhaps it would be nice to report that having made the bandwidth constant the stage gain would oblige by becoming constant also. No such luck, however. Stage gain, you will recall, is equal to G_mZ where Z is the output load. This load is a tapped down replica of the tuned circuit impedance. The tuned circuit impedance is QX. If we examine this in the light of our bandwidth equalling process, we see that Q now increases linearly with frequency and so does X with the result that the gain instead of varying 3 to 1 over the band now varies 9 to 1. Thanks, however, to the varactor we can linearize the gain very simply with the circuit of Figure 3.

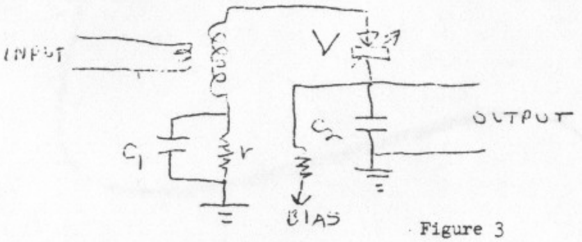
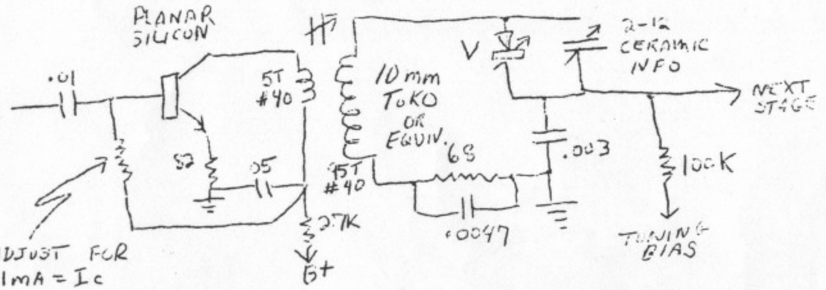


Figure 3

Varactor, V, and capacitor, C2, form a voltage divider network to provide the matching function to the succeeding base and since the tuned circuit impedance is much higher than the input impedance of the transistor, the value of C2 is much larger than the maximum capacitance of the varactor. Since V varies effectively 9 to 1 in order to tune the band, the attenuation produced by this divider will vary 9 to 1 also; being greatest at the high frequency end where the varactor capacitance is smallest. It will be remembered that the equal bandwidth circuitry produced a 9 to 1 variation also with the gain variation exactly the reverse of that produced by the varactor divider. The net result is constant stage gain. We have now achieved equal bandwidth and equal gain and thus have removed the basic limitations to a successful TRF design.

Figure 4 shows a complete single stage amplifier exclusive of components required for tracking a multiplicity of stages.

FIG. 4



This laboratory has constructed and tracked a six stage amplifier in this fashion followed by the necessary sub-amp amplification with selectivity performance at all broadcast band frequencies at least equal to the best superheterodyne available for general use by the public. The 6 db bandwidth, however, is limited by the 100 maximum circuit Q to a minimum of 5 to 6 kc which, though ideal for general use, will not meet the requirements for DX use where single sideband reception at one edge of a narrow passband is sometimes necessary to receive foreign stations only a few kilocycles removed from a local station. The adjacent channel attenuation of 30 db, not including the loop selectivity, is also not enough for serious DXing but equals or exceeds conventional superheterodyne performance. The attenuation 20 kc removed exceeds 60 db and the response to channels further removed is nil. Using a similar pre-selector as a head-end for a superheterodyne designed to provide the sophisticated additional performance required for DXing would combine the necessary advanced features that can only be provided at a fixed frequency with a complete freedom from spurious responses possible only with a straight tuned R.F.

This laboratory is currently in the process of designing and developing a receiver for broadcast band DXing and this work on a multi-stage varactor tuned straight receiver was part of the work to determine if such a sophisticated design would be practical for the head-end of the superheterodyne under development.

Early writers and investigators were intrigued by the possibility of cross modulation in these devices, particularly at the low frequency end of the band where the varactor bias voltage is low. Circuits were often shown with back-to-back varactor connection to minimize the effect. More recently, however, quantitative information is at hand and the situation is as follows: This information is supplied by ITT for their BA163 varactor. The worst voltages for cross modulation are 1 and 4 volts. At these points a .35 volt rms signal, 100% modulated, will produce 1% cross modulation on a weaker signal. To put this in perspective, consider, for instance, a varactor tuned loop and that the loop is directly connected to a tube amplifier. Now .35 volts rms is .49 volts half-peak or .98 volts peak-to-peak, unmodulated. When 100% modulated, the maximum peak-to-peak voltage would be twice this or 1.96 volts. Now a tube is normally biased at 1 volt to place the operating point in the center of the linear part of the input characteristic, so a 2 volt peak-to-peak signal would begin to draw grid current on positive excursions and with negative peaks begin to drive into the conjestion type nonlinearity that occurs at the higher bias voltages. It is obvious, therefore, that the tube would cross-modulate at virtually the same time that the varactor does and at <u>all</u> frequencies, not just the ones corresponding to a 1 volt and 4 volt bias. We have concluded, therefore, and experienced circuit designers in this area have confirmed our conclusion that cross-modulation is not a basic problem in the use of these devices.

The varactor's big problem and the one that has received a lot of effort in this laboratory is tracking. It is necessary to remember that an air gang is a mechanical assembly, where close tolerances can be held on all the pieces making up the final assembly. Even with such precision, however, the final product will not meet the 1% tolerance on tracking. A final operation is to manually "wing" the outside plates of each section to provide the necessary tracking accuracy. This requires a high level of skill on the part of the operator performing the task.

The varactor, by comparison, is constructed from a number of complicated diffusions that are necessary to provide the large capacitance variation required. Individual units, in the context of the required accuracy vary significantly not only in the slope but curve shape as well. Since no opportunity to improve matters by pruning the finished product exists, a grouping technique is necessary. Most if not all vendors intend to do this by computer but, to date, programming difficulties remain. This laboratory has succeeded in obtaining perfect tracking of a 6 varactor TRF preselector but the process is tedious. It involves (1) trimming the high frequency end, (2) varying the inductance to obtain a track to 1400 kc, (3) varying the maximum voltage applied to the varactor to track to 1000 kc, (4) varying the minimum voltage to track to 700 kc and, 5) pad the circuit to track the low end. Since all these adjustments are interdependent, each time one is varied, the complete sequence must be repeated.

By initially selecting reasonably close units before the above process is started, perfect tracking is obtained. The labor involved, however, militates against the procedure being practical at this time in a mass produced receiver. On a semi- custom-built basis it is completely feasible and, of course, a broadcast receiver designed especially for DX reception would be a low production product by necessity anyway. Such a set cannot be cheap but neither are available communication receivers cheap and they have only rudimentary preselection.

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An interesting additional feature appears possible by utilizing the scan possibilities provided by the varactor preselector. If we provide a switch to change from an operating to a standby position, and it switches the varactors from the tuning potentiometer to a sawtooth scan voltage having a frequency of about one scan every 5 seconds, it is possible to electronically sample the activity of the entire band. If this information is detected and integrated by a large diode load capacitor to a time constant of about 1 minute, we will have an effective propagation activity index. This information can be presented as a second scale on the "S" meter and will show rather small deflection during daytime and, of course, much larger deflections at night depending on propagation conditions. It is then a simple matter to add a control that can be preset to sound an alarm whenever reception conditions exceed a pre-determined level. This will prevent wasting time listening when conditions are poor and at the same time avoid the possibility of missing any exceptionally good reception periods. If the latter occurs in the middle of the night, the theory is that the operator, after turning off the alarm, will switch to the operating condition and proceed to log all sorts of new stations. This, of course, assumes that he has more resolve than this writer when a warm bed becons. It should be restated that this is in the nature of an armchair idea - conceived but ungestated and unborn. The writer would be interested in hearing from members having any opinion, one way or the other, as to whether such a device would prove useful and what form it should take, if different from the above.

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