WORKING WITH OP~AMPS

Part 4

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Filtering is the act of separating what is wanted from what is unwanted. In electronics this usually means some form of separation on the basis of signal frequency. In the simplest case, signals are divided into two 'bands' known as 'low frequencies' and 'high frequencies', separated quite arbirarily by the 'cut-off' frequency. The fact that capacitive reactance depends upon frequency is often used to obtain such separation. This idea leads to simple filters of the 'inverted-L' type, known as 'low-pass' and 'high-pass' filters; these, together with their characteristics, are shown in Figure 1.

The characteristics of these simple filters show that, soon after the cut-off frequency is reached, the filter cuts off with a constant slope which is never greater than -6dB/octave (i.e. -20dB/ decade). This is a basic limitation where a high degree of separation is required. Also, there is no gain at all, even at the wanted frequencies. These filters are said to be 'passive'. By using the op-amp with its high gain and differential inputs, filters can be designed to have real gain and high degrees of rejection of the unwanted frequencies: these are known as 'active filters'.

The Op-amp as an Active Filter

To see how the op-amp can be used as the basis for an active filter, consider a now familiar circuit, the inverter. This is shown in Figure 2, where the circuit is drawn twice (a) and (b), each case illustrating how either the input component or the feedback component can be represented by a 'block' which could contain literally anything. For example, if these components are a resistor R1 and another resistor R2 respectively, the circuit is then just an inverting amplifier with a gain of R2/R1, this gain being quite independent of frequency, at least within the limitations of the op-amp itself. But, if either block contains frequency-conscious components, then the situation will be entirely different. The gain of the amplifier will vary with frequency and in such a way that it is under the designer's control by his choice of network components, either at the input or in the feedback path or both. Thus, a number of different configurations for active filters are possible, based on this idea.

The Twin-tee Selective Amplifier

One example of a frequency-conscious network is the twin-tee filter. This has the characteristic that at a particular frequency, given by $f=1/(2\pi RC)$, its impedance is very high. If the impedance of the network is called Z2 and it is used in the feedback path, then it will give a gain of Z2/R1 (if the input circuit is a simple resistor of value R1); this gain will be a maximum at the frequency quoted above. The circuit is obviously selective and in fact behaves rather like a high-Q resonant circuit, but at low frequencies instead of radio frequencies. The frequency that it selects depends upon the values of R and C used in the twin-tee network. A

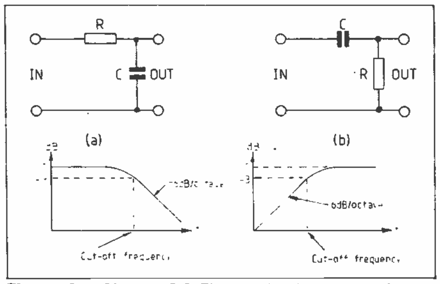

Figure 1. Simple RC Filters: (a) Low-pass filter (b) High-pass filter.

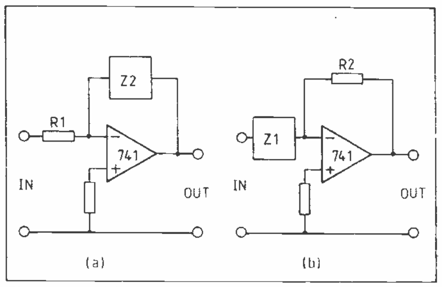

Figure 2. The Basic Idea of an Active Filter.

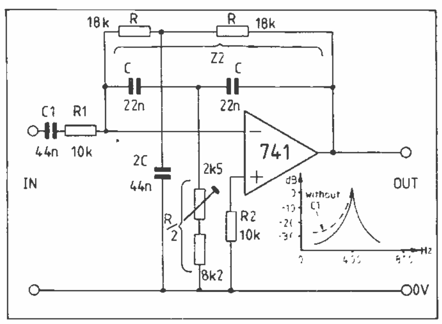

Figure 3. A 400hz Twin-tee Selective Amplifier.

selective amplifier of this type is shown in Figure 3, together with a sketch of relative output (in dB) as a function of frequency, for a design frequency of 400 Hz. To use the amplifier at some other frequency, it is only necessary to assign new values to R and C (giving new values to R/2 and 2C at the same time of course). The R/2 branch should contain a pre-set part since the circuit selectivity is best when the resistance of this branch is actually slightly less than the nominal value of R/2 calculated. The selectivity can be improved further by adding a little 'bass-cut'. This is provided by the series input capacitor C1, a value equal to 2C being about right. Using 22nF for C, 2C becomes 44nF; this value can be realised by wiring two 22nF capacitors in parallel or, alternatively, opting for the nearest preferred value of 47nF. The latter choice may well be close enough.

The Twin-tee Rejector

Instead of selecting a frequency at the expense of all others, the opposite course of action may be taken. The circuit is then made to reject just one frequency and to pass all others (ideally anyway). The obvious way of doing this is to place the twin-tee network in the input of the op-amp, calling its impedance Z1 now, which will give a very low value of gain, R2/Z1, the feedback network being a simple resistor R2. This gain is a minimum at a frequency given by the formula already quoted, as is fairly obvious. A possible circuit is shown in Figure 4, additional components being provided so that the gain 'off the centre frequency' is defined by R2/R1 (giving unity gain in this case) as well as giving some degree of control over the shape of the rejection curve. For example, increasing the value of R2 increases the gain away from the centre frequency but does so at the expense of the sharpness of the curve. At the centre frequency, the situation is more complex because then R3 comes into play as well; it also has some effect on the sharpness of cut-off but, if its value is made too large, use of RV to obtain maximum rejection of the centre frequency is more difficult. It is a point worth experimenting with. For the values given in Figure 4 and a design frequency of 400 Hz, a sketch of the characteristic with RV adjusted as well as possible is also shown.

For both of these twin-tee filters, note that the sharpness of cut-off is considerably greater than that of the simple filters mentioned earlier.

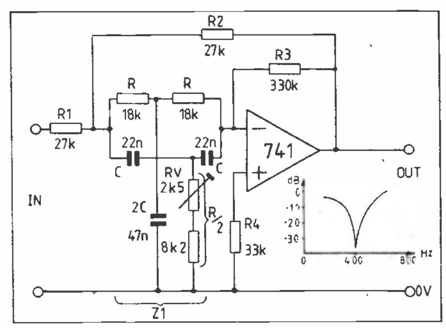

Figure 4. A 400Hz Twin-tee Rejector Amplifier.

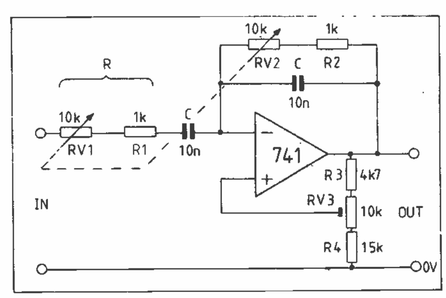

Figure 5. A Tuned Acceptor Amplifier (Wien Network).

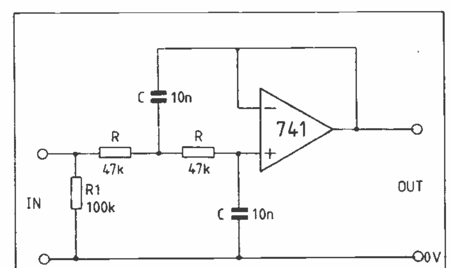

Figure 6. Second-order Low-pass Filter.

The Wien Acceptor Amplifier

An acceptor amplifier is a useful circuit in that it allows analysis of a complex signal i.e. one containing a number of harmonics, which can then be separated into its constituent parts and each measured individually. An obvious example of this is the measurement of harmonic distortion in audio signals. If the fundamental frequency

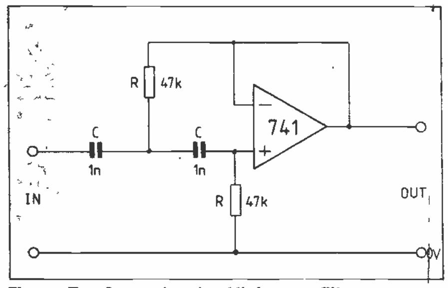

Figure 7. Second-order High-pass Filter.

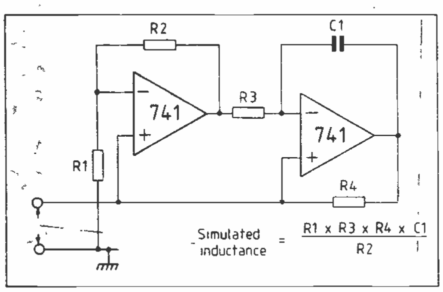

Figure 8. The Gyrator Circuit.

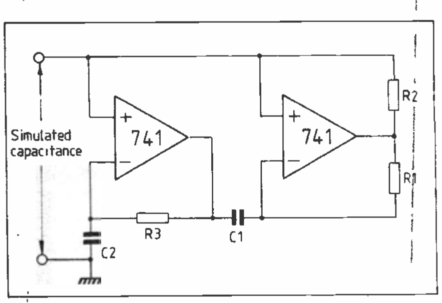

Figure 9. The FDNR (Frequency-Dependent Negative-Resistance) Circuit.

and harmonics of a distorted signal are selected separately by a filter, each can be measured by an electronic voltmeter to give information about the percentage of the various components in the signal. Obviously, such a filter must be variable and the twin-tee is not particularly useful in this application because of the need to vary three components at once. For this reason, the Wien network is a better proposition and a selective amplifier based on this approach is shown in Figure 5.

The circuit uses positive feedback from the output to the non-inverting input, and negative feedback from the output to the inverting input. The amount of positive feedback can be controlled by RV3 and is independent of frequency. On the other hand, the negative feedback is provided by the Wien network and therefore depends upon frequency. If RV3 is adjusted correctly, both types of feedback cancel out at one particular frequency, given by $f=1/(2\pi RC)$, and the gain of the circuit is very high. At all frequencies above and below this value the negative feedback predominates and the gain is low. With the values of R and C given in Figure 5 the circuit can be tuned to accept any frequency in the range 1.6-12.5kHz. Switching values of C would allow several ranges to be covered.

Low-pass and High-pass Filters

Both the circuits of Figure 6 and Figure 7 are known as 'second order' filters because they double up on the use of the previously mentioned inverted-L filter sections. As a result, the ultimate cut-off slope is 12dB/octave instead of being only 6dB/octave. The circuits are arranged to give unity gain over the passband but substantial attenuation outside the passband.

The filter elements for Figure 6 and Figure 7 are R and C and, for the single inverted-L section, the cut-off frequency (-3dB) is obtained when $R=1/(2\pi fC)$ which, by transposition, means that the cut-off frequency $f=1/(2\pi RC)$. However, the use of two identical sections means that the attenuation is actually -6dB at this frequency so that the true -3dB frequency is rather different than give by the above formula for a single section.

For example, in Figure 6, the cut-off frequency for a single section works out at 339Hz but the actual value obtained for the second order circuit is nearer 200Hz.

Similarly for the circuit of Figure 7 while the cut-off frequency for a single section works out at 3.386kHz, the actual cut-off frequency for the second order circuit was found to be about 5kHz.

An Alternative Approach

So far each active filter presented has consisted of a well-known passive filter used in conjunction with an op-amp, the filter type being quite clearly identifiable e.g. as in the Wien circuit.

Now a completely different approach will be demonstrated which shows even more

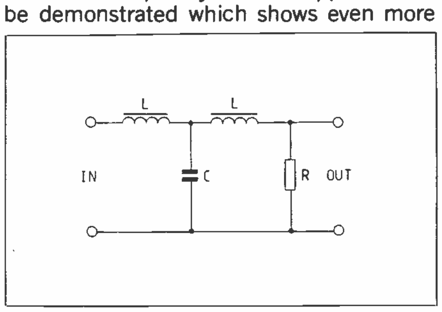

Figure 10. A Low-pass Passive RLC Filter.

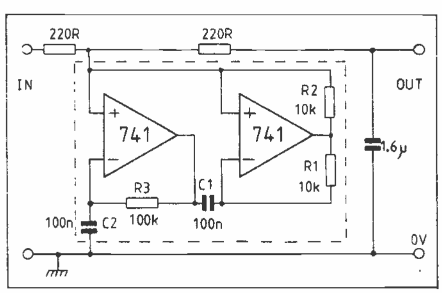

Figure 11. Design for a FDNR-based Low-pass Active Filter.

clearly the clever tricks that can be played with the aid of op-amps.

The starting point is the idea that inductors and capacitors can be 'simulated' by any circuit that produces a 'lagging' or 'leading' phase angle between applied voltage and the resulting current respectively. To illustrate the first case, Figure 8 shows how two op-amps can be connected to produce a 'gyrator' circuit or simulated inductor. This apparent inductor appears between the terminals shown and the major advantage is that a costly, heavy and bulky component is replaced by a handful of small, cheap ones; also the inductance value is readily changed. Thus, any real filter that contains an inductor could contain a gyrator circuit instead. However, inductors in LCR filters are often in series with the signal and the gyrator simulates an inductor which has one terminal earthed, a slight disadvantage.

This limitation of the gyrator is overcome by the circuit arrangement of Figure 9, which is known as the 'frequency-dependent negative-resistance' circuit or just FDNR for short. This circuit simulates a capacitor but, and here is the clever bit, when a passive filter normally comprised of L, C and R is synthesised by a circuit arrangement based on the FDNR, not only is C replaced by the FDNR but R is replaced by a capacitor C' and L is replaced by a resistor R', the following relations being used to find the component values in the synthesised circuit.

New capacitance C' (Farads) = 1/R (R in ohms)

New resistance R' (Ohms) = L (L in Henries)

Note that the final synthesised circuit contains no inductors, just resistance, capacitance and FDNRs.

The component values for the FDNR circuit to replace a given value of capacitance C are obtained from the relation,

C = (R1 x R3 x C1 x C2)/R2

(capacitance values in Farads, resistance values in Ohms).

What this implies is that it is possible to design any conventional filter based on R, L and C and then translate the required passive values into those for the FDNR circuit, using the relations given above. To conclude, an example of a design using this approach will now be given.

Low-pass FDNR Filter

Figure 10 shows a T-filter using high value series inductors. Such components are inconvenient because of cost, weight, size, etc., and the use of an FDNR-based filter allows them to be eliminated. Suppose that the filter is to cut off at 500Hz, the values of the passive components being found from the following two simple formulae.

(1) Cut-off frequency = $1/(\pi\sqrt{2LC})$

(2) R =$\sqrt{2L/C}$

As a starting point, let L be equal to some arbitrary value and then evaluate C for the cut-off frequency of 500Hz; if C turns out to have a ridiculous value then choose another value of L and try again. Suppose L is 200H, then the formula (1) gives a value of C of about 1nF, a perfectly reasonable value. Now R can be evaluated from formula (2) and is found to be 632k.

Thus, for the passive circuit, the values are L = 200H; C = 1nF and R = 632k. These are the values that must now be transformed into the values for the synthesised circuit.

Thus, for the FDNR-based circuit, C' = 1/(632 x 10^3), = 1.6uF; R' = 200 ohms and the values for the FDNR circuit are related by the expression

C = 1 x 10^9 = (R1 x R3 x C1 x C2)/R2

Again an initial choice has to be made. Suppose that a guess is made at reasonable values for the numerator e.g. R1 = 10k; R3 = 100k; C1 = C2 = 100nF, this leaves R2 as the only unknown and by substituting these values into the expression just given and transposing it, R2 is found to be 10k, which is perfectly reasonable. It is obvious that a certain amount of judgement and/or experience is invaluable in this sort of design. The complete circuit is shown in Figure 11.

This example has been presented to illustrate the unique nature of this type of active filter design. The same type of approach can be applied to other circuits employing passive components.