An Adjustable Audio Filter System for the Receiver - Part 1

The audio response is shaped as required using Switched Capacitor Filters

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Front panel view of the original receiver filter unit. Not shown are frequency calibration scales added with the modifications , Part 2

Introduction

A circuit is presented which provides frequency response adjustment of the audio signal fed from the receiver into the loud speaker. Low frequency and high frequency cut off can be individually set over the speech range by adjustable high and low pass filters respectively. An additional adjustable notch filter allows an unwanted carrier beat note to be rejected from the audio pass band. The high and low pass filters can also be switched to track so that they provide a narrow bandpass at any centre frequency in the speech range thus providing a suitable response for CW or other narrow band modes.

Response is controlled by three switched capacitor filters coupled from three clocks, the frequencies of which determine the setting of cut off frequencies and the notch frequency. The clock frequencies (and hence the filter characteristics) are manually set by three panel mounted potentiometers.

The unit input is Plugged into the receiver (or transceiver) headphone jack (thus disconnecting the internal speaker). A power amplifier at the output of the unit feeds the processed signal to an external speaker. Internal DC power supplies are fitted so that the unit can be powered from the 240 V AC mains.

Filter Nomenclature

As this article is essentially about filters, a few paragraphs introducing the terminology used in filters might be useful for some readers. Filters are used to restrict the band of frequencies which pass through them. Lowpass filters restrict frequencies above a defined cut off point. Highpass filters restrict frequencies below a defined cut off point. Bandpass filters restrict frequencies outside defined band limits and can be made up by combining highpass and lowpass pairs. The cutoff frequency of a filter is normally defined as the point at which the signal level falls by 3 dB (or 0.707) of the nominal level within the passband. Another type of filter is a band reject (or notch) filter which accepts all frequencies except those in a defined (and usually narrow) band.

Some important filter characteristics are the steepness of the response curve slope in the transition from passband to stopband and the general stopband attenuation. Other important characteristics are the consistency of level within the passband (referred to as passband ripple) and linearity of phase response (important in some types of signal such as video). Particular characteristics are well defined by filter designs such as the Bessel, Butterworth, Chebyshev and Elliptic. The choice of these depends on which of the characteristics are most important. For example, the Butterworth might be chosen for low ripple in the passband. On the other hand, the Chebychev has a steeper slope from the cut off point and greater out of band rejection but at the expense of some ripple in the passband.

Filters are classified as passive or active, the latter made up around amplifier elements. Classical passive filters such as the Butterworth and Chebychev are made up with series and shunt elements of capacitive and inductive reactance. Figure 1 shows typical lowpass filters which can be either Butterworth or Chebychev depending on the actual reactive values chosen. As shown in the diagram, the filter can be either unbalanced or balanced to suit the circuit to which it is attached. When the filter is balanced the values of inductance are shared between the two balanced legs.

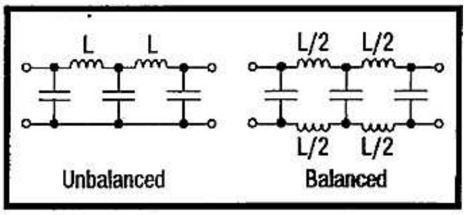


Figure 1 - Typical passive lowpass filters.

Selection of the reactive elements is also determined by the source resistance feeding the filter and the load resistance at its output. When the source resistance is equal to the load resistance, the filter is defined as symmetrical. When these are unequal, the filter is defined as asymmetrical.

Apart from the type of filter (eg Butterworth, Chebychev, etc) the slope and out of band attenuation are dependent on the number of reactive elements in the filter and this number is often called the filter order. For a Butterworth filter, the slope is 6 dB per octave multiplied by the filter order (NB. An octave is an increase to twice the frequency). For a Chebychev filter, the slope is much steeper. In deciding on a filter design, the filter order for a given filter type is chosen to achieve the desired out of band performance.

At low frequencies, and in particular at audio frequencies, the values of inductance required for passive filters necessitate the use of large and expensive inductor components. For low frequencies, most designers prefer to use active filters with operational amplifiers around which characteristics such as the Butterworth and Chebychev can be configured with resistive and capacitive elements. Active filters are used at frequencies up to around 100 kHz. Above this, circuit stability can be a problem.

Switched Capacitor Filters

In general, filters are not adjustable because their frequency determining elements are fixed. One filter which is often made adjustable is the State Variable filter. This has a second order Butterworth characteristic with the feature that lowpass, highpass, bandpass and notch outputs can each be taken out from selected points in the circuit. There are two resistors in the circuit which are of equal value and which determine the cut off frequency. To make this frequency adjustable, these resistors are replaced with a two gang potentiometer.

If a given voltage is applied to a resistance, a current flows as determined by the value of resistance in accordance with Ohm's Law. This can be seen to be simulated by charging and discharging a capacitor from the same voltage at a rate such that the average current is equal to that which flows through the resistor. By varying the switching frequency of charge and discharge so that the average current is varied, the associated circuitry is made to think that it is seeing a resistance varied. The switched capacitor filter is based on the State Variable filter except that the controlled variable resistance is replaced by the switched capacitor controlled from a clock operating at frequencies many times the cut off frequency of the filter. When the clock frequency is varied, the average current into the capacitor is varied making the circuit appear as though a resistance in the circuit were being varied. Hence adjustment of cut off frequency is achieved by varying the clock frequency.

The switched capacitor filters used in our filter unit are the National types MF6 and MF10. The MF6 is configured as a 6th order Butterworth lowpass circuit with its own internal clock operating at 50 times the cut off frequency. It also has two spare operational amplifiers on board the package which have been put to good use in our own filter unit. To operate the package, an external resistor and capacitor are required to set the clock frequency and then it is only a matter of connecting input, output and DC power (plus and minus 5 V).

Setting up the MF10 is not quite so simple. It is equivalent to two MF5 second order units, separate, but fitted in the one package so that a combined unit of 4th order can be achieved. It is a universal filter in that, by varying the values of external resistors and the external connections, it can be configured as highpass, lowpass, bandpass, or notch, with different characteristics such as Bessel, Butterworth, or Chebychev. To work out the desired circuit arrangement, one has to. carefully study all the published application notes. The MF10 requires an external clock source at a frequency selectable either 50 or 100 times the cut off frequency. In our application, two MF10 packages are used, each driven from a 555 package operating as a clock at 50 times the frequency.

Circuit Description

Figure 2 shows the filter system in block form.

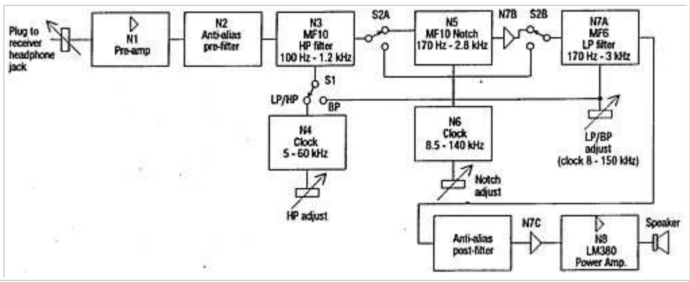


Figure 2 - Audio filter unit - Block diagram.

Detail of the complete circuit is shown in figure 3. Input level from the receiver is assumed to be that which would appear across the receiver loudspeaker voice coil. Preamplifier N1 has a voltage gain of 5. This allows some margin for input level adjustment using potentiometer RV1 and sets the signal to a more comfortable level for the switched capacitor filters. As discussed further on, there is a signal to noise ratio problem if they are operated at too low a level.

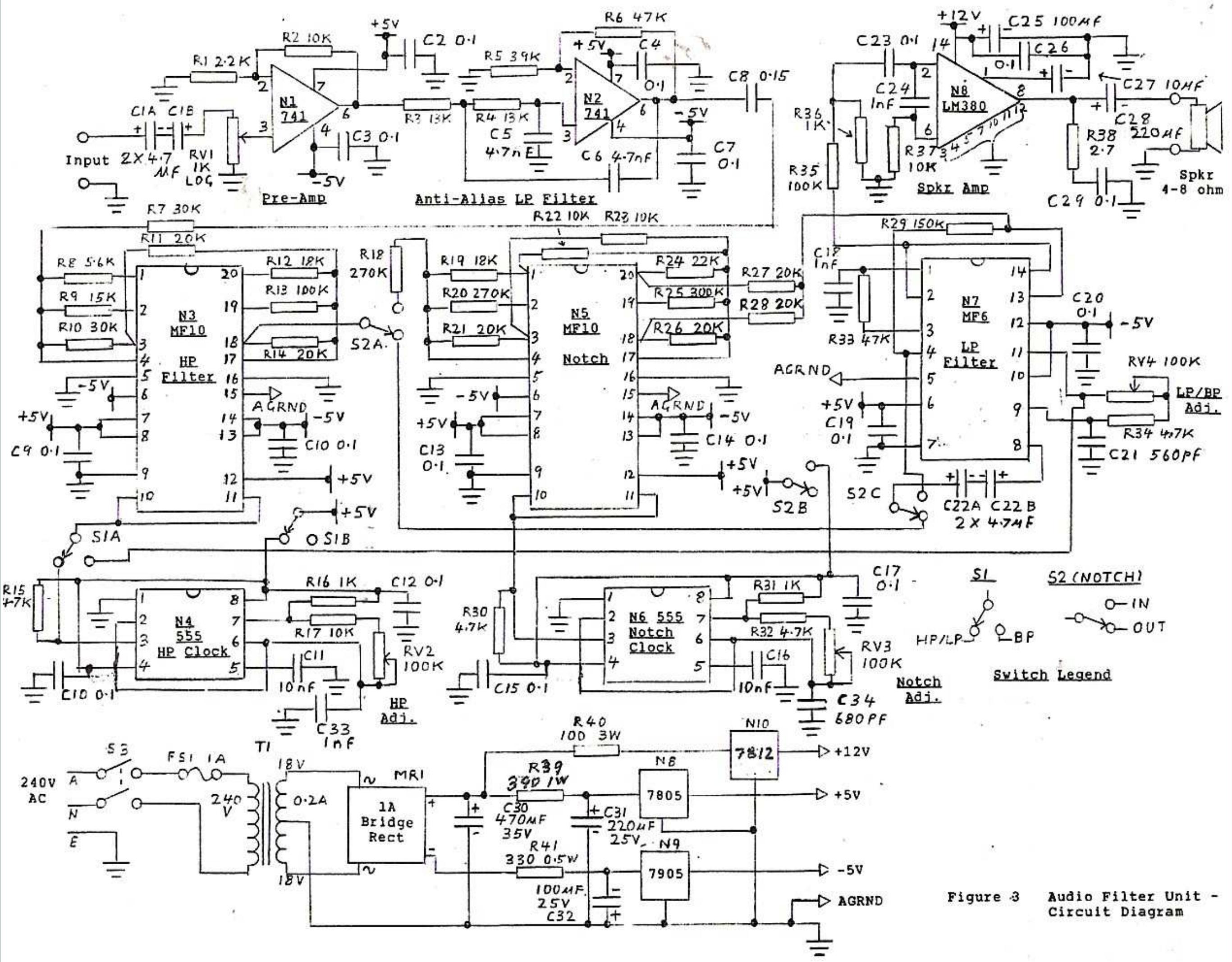


Figure 3 Audio Filter Unit - Circuit Diagram

Figure 3 - Circuit Diagram

Signal components fed into the inputs of the switched capacitor filters near clock frequency cause spurious signals at the filter outputs. These components must be stopped from reaching the filter inputs and this is mainly achieved by band limiting in the IF stage of the receiver and by limits in the audio response of the receiver. As a further precaution, stage N2 is configured as a second order Butterworth low pass filter with its cut off frequency just above 3 kHz which is the upper frequency limit of the complete unit. This is referred to as an anti-alias pre-filter. Operational amplifiers N1 and N2 are type uA741. Type uA747 combines two 741s in one package and alternatively this could have been used. However, there are many components around N2 forming the filter and the separate packages relieve the component congestion.

The first controlled filter in the chain is N3 (type MF10) which is configured as a 4th order Chebychev highpass stage. The Chebychev characteristic was chosen as its 4th order cut off slope is a close complement to the 6th order Butterworth slope of the associated lowpass fitter N7 (type MF6). This choice was made accepting that there would be a few dB of passband ripple hardly noticeable to the ear. Operating as an individual highpass element, the filter is fed with a clock signal from N4 (type 555) which is adjustable using potentiometer RV2 over a frequency range of 5.6 to 60 kHz . Dividing by 50, this provides a highpass cut off adjustment range of 112 to 1200 Hz.

With the Notch circuit switched out, the highpass output is directly coupled into the input of lowpass filter N7 (type MF6). The internal clock of N7 is adjustable using potentiometer RV4 over the frequency range of 8.5 to 150 kHz. Dividing by 50, this provides a lowpass cut off adjustment range of 170 to 3000 Hz.

Operation of switch SW1 to the BP (bandpass) position disconnects highpass filter N3 from clock N4 and reconnects it to the output of the lowpass filter clock in N7. This allows the highpass cut off frequency of N3 to track the lowpass cut off frequency of N7 as adjusted by RV4. A narrow bandpass is formed which can be set by RV4 over the centre frequency range of 17 to 3000 Hz. At 1000 Hz centre frequency, the 3 dB bandwidth is around 200 Hz.

Filter N5 (type MF10) is configured as a 4th order Butterworth notch. In this configuration, an additional external operational amplifier is needed and use is made of one of the spare amplifiers in the N7 (MF6) package (refer N7B in figure 2). The filter is fed with clock signal from N6 (type 555) which is adjustable over the frequency range of 8.5 to 140 kHz using potentiometer RV3. Dividing by 50, this provides adjustment to move the notch over the frequency range of 170 to 2000 Hz. With the notch set for 1000 Hz centre frequency, the notch width for 3 dB down is approximately 100 Hz. At the notch centre frequency, its attenuation has been measured to be near 35 dB.

The output of the filter system, taken from the output of lowpass filter N7, contains components at clock frequency which are easily removed by a simple RC anti-alias filter. This filter is formed by the two components R33 and C18 which are interfaced by the second spare operational amplifier in N7 (shown as N7C in figure 2).

If use of headphones were only required, the output of N7C could be coupled directly into the headphones. To operate a loudspeaker, a power amplifier is needed and for this purpose an LM380 (device N8) has been utilised. The LM380 package has quite high voltage gain, too much for our particular application. To correct for this, the input of the LM380 is fed via attenuation network R35-R36. The LM380 was selected because it happened to be on hand. Any other audio power amplifier such as the LM386 would substitute. To heat sink the LM380, it was fitted on a 60 mm square piece of copper plated circuit board with heat sink pins 3, 4, 5,10,11, 12 soldered to the copper.

Power Supply

Recommended power rails for the switched capacitor filters are +5 V and -5 V relative to ground or +10 V relative to ground. The former split 5V rail arrangement simplifies coupling between packages and this has been adopted to feed both the filters and associated operational amplifiers. The +5 V rail is also used to feed the 555 clocks which then deliver a nominal 5V square wave output which is compatible with the clock signal specification for the switched capacitor filters. The load current on the +5 V rail is 31 mA and on the -5 V rail is 21 mA.

The LM380 power amplifier operates in class AB with large variation of load current with signal level change. To prevent interaction with filter circuitry, it is desirable to use a separate power rail for the power amplifier and a 12 V rail is derived for this purpose. The quiescent load current for the LM380 is around 7 mA. This swings to around 70 mA with normal signal and to 100 mA for power amplifier overload condition.

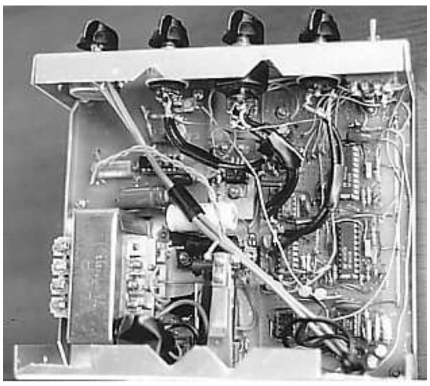
The power supply circuitry is included in figure 3. This utilises straightforward rectifier and voltage regulator circuitry requiring no further explanation.

Clock Noise

The clock frequency is normally well above the speech frequency range and running one or more filters from a single clock (as for the bandpass switch setting) creates no noise problems. However, more than one clock running at different frequencies (when in the LP/HP or Notch switch settings) can produce beat frequencies which may fall in the speech range. In the unit constructed, such noise was measured as less than 50 dB below the overload signal level of the filter system. To achieve the best signal to noise ratio, the gain of pre-amp N1 and the attenuation in R35-R36 are arranged so that, for a comfortable speaker level, the filter system operates just below overload level.

On the unit constructed, the 555 clocks were mounted on the same card and close to the switched capacitor filters. Tests indicated that some of the clock beat noise was induced directly from the 555 packages. The earth and +5 V rails to the 555 packages were isolated from the remainder of the system but a better result might have been achieved had the clocks been mounted on a separate card with improved supply decoupling. Another precaution taken has been to turn off clocks which are not needed for the particular mode of operation. Referring to figure 3, it can be seen that mode switches S1 and S2 incorporate contacts which, when appropriate, disconnect 5V from their associated 555 clock. Each of the switched capacitor filters has a separate analogue ground (marked AGRND) separate from their digital ground. These are taken via a separate common rail to the ground point, desirably with other analogue returns such as those associated with pre-amp N1 and anti-alias filter N2.

The clock beat noise is normally well masked by the signal level but, if the signal is turned off, the noise at low level is apparent to the ear for certain settings of filter adjustment.



The experimental filter unit with the cover removed.

RF Pick-Up

The whole filter system involves a multitude of high gain amplifiers which, in the presence of a high intensity RF field, are likely to pickup and rectify the RF signal. With the constructed unit turned on and the home transmitter operated, RF feedback was apparent even with the filter input disconnected from the transceiver headphone socket. Insertion of RF chokes and bypass capacitors at various points in the filter system failed to eliminate the feedback. It seems that, for operation in conjunction with a transceiver, the filter system must be disabled by relay switching when transmitting. A muting relay has not been included in figure 3 but it must be considered as an addition possibly needed.

Operation

Adjustment of the filter settings enables the bandwidth to be set at the minimum required to interpret the received signal whilst eliminating noise existent on unwanted sections of the audio band. On speech it is really a compromise on what seems best. A narrower speech band reduces the noise but it also reduces the speech intelligibility, particularly when the higher frequencies are cut too far. Cutting the low frequencies makes the voice sound thin but this seems to affect the intelligibility to a lesser extent. For narrow bandwidth signals of only a few hundred hertz (such as CW and RTTY), it is simpler to use the bandpass mode where the lowpass and highpass filters track in a narrow band state.

The notch is very sharp and the adjustment potentiometer must be moved very carefully to settle it on an unwanted carrier signal. It is very easy to move too fast and miss picking up the cancelling which occurs when passing across the signal. Some potentiometers have sloppy bearings which produce backlash and this makes setting the notch difficult. Several different potentiometers were tried out in the unit constructed before a satisfactory one was found. At one stage a 10 turn potentiometer was used and this made fine adjustment much easier. However, winding the knob around and around many times searching for the cancellation became a little tedious.

Cancelling out an unwanted CW signal can be a little tricky. It is very easy to pass the notch through the CW signal frequency in a key up period between Morse characters and miss detecting the cancellation. Whilst the notch handles stable carrier signals and CW signals it is too narrow to cancel out wider bandwidth frequency shift signals such as packet. A further improvement to the system might be an adjustable bandwidth notch which could be set to reject a wider band signal. Refer to modifications Part 2.

Switching in the notch on speech to remove a nuisance carrier beat tone has no detrimental effect on the speech quality. The tiny section of the speech band which is sliced out is not apparent to the ear.

The unit as constructed has been assembled on an experimental basis using components which were on hand. No work has been done to locate a recent source of supply of the National MF6 and MF10 packages or other makes of switched capacitor filter. The other ICs and regulator packages used are readily available.

The unit as assembled works quite well. There could be room for improvement in reducing further the level of clock sourced noise by fitting the clocks on a separate card away from the filters and carefully decoupling the rails. Simple anti-alias filters between each of the switched capacitor filters might help further. However, these were tried out on the assembled unit and, as no noise reduction was noticeable, they were not included in the final circuit. As suggested earlier in the text, an adjustable width notch would be a useful addition worthy of further thought.(This has been done and modifications are described in Part 2).

Complete Unit Specification

Lowpass Cut off - 170 to 3000 Hz adjustable
Slope - 6th order Butterworth

Highpass Cut off - 112 to 1200 Hz adjustable
Slope - 4th order Chebychev

Bandpass Centre frequency - 170 to 3000 Hz adjustable
3 dB bandwidth - 200 Hz

Notch Centre frequency - 170 to 2850 Hz adjustable
Width at 3 dB down - 100 Hz (measured at 1 kHz)
Attenuation at centre frequency - 35 dB

Maximum frequency range for 3 dB down - 170 to 3000 Hz

Input Resistance - 1000 ohms

Recommended load impedance - 4 to 8 ohms

Maximum output power - 400 mW into 4 ohms (Limited by overload level of filters.
Power can be increased if needed by reducing R35)

Maximum voltage gain (input to output) - 10

Noise level below maximum power output - 50 dB

Power supply - 240 VAC 30 mA

On to Additional modifications - Part 2.

Part 2 - The VK5BR Audio Filter Modifications to Include an Adjustable Rejection Band.

by Lloyd Butler VK5BR

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Introduction

In the March 1995 issue of Amateur Radio, I described an adjustable audio filter system which can be added to the receiver(Part 1). One feature of the system is a rejection notch which has a 3 dB band rejection width of about 100 Hz. This is fine to reject an interfering carrier or CW signal. However, I pointed out in the text that some means to increase the width of the rejection band width might be a useful addition to reject wider bandwidth interfering signals.

The 100 Hz rejection notch remains unchanged, but I have added a simple modification to enable the high pass (HP) and low pass (LP) filter sections to be set up for a variable width rejection band. This is an alternative to their normal function of setting the limits of the pass band. The modification is simple in that it is achieved by the addition of one switch and one resistor and changing the value of one other resistor.

HP and LP Filters In Parallel

To understand how the system works, refer to figures 1 and 2. To achieve the bandpass characteristic of figure 1, the signal is first fed through the HP filter which sets the low frequency cut-off and then through the LP filter which sets the high frequency cut-off. Observe that the HP cut-off is lower than the LP cut off.

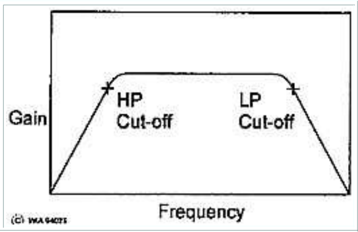

Figure 1 - Normal sequential operation of HP and LP filters with cutoff frequencies set for a wide bandpass.

To achieve the band reject characteristic of figure 2, the two filters are connected in parallel with inputs both connected to the input signal and outputs combined after filtering. Observe that, for this operation, the HP cut-off is now set to a higher frequency than the LP cut-off.

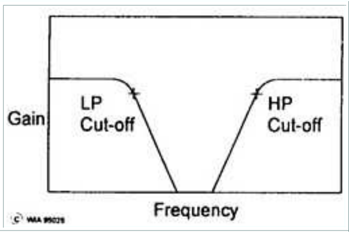

Figure 2 - Parallel connection of HP and LP filters with cut-off frequencies set for a wide band rejection.

The block diagram for the whole system, as published in the previous article, is repeated in figure 3 but with the additional switch S4 to enable the filters to be switched from their normal sequential connection to the parallel connection. Detail of the circuit changes is given in figure 4. Resistor R33 and capacitor C18 form the original post anti-alias filter. Addition of resistor R42 to this circuit enables it to be also used as a mixer to combine the output of the LP filter via R33 with the output of the HP filter via R42.

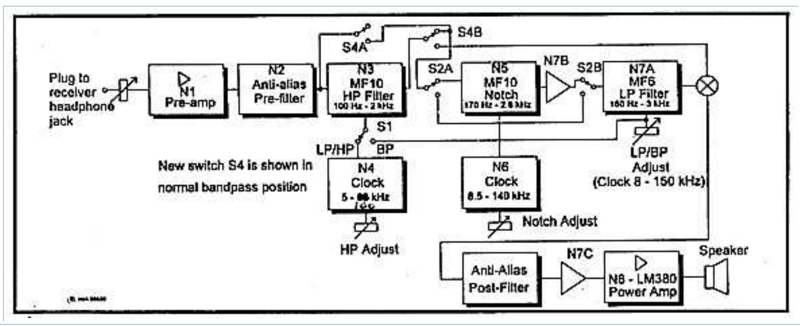

Figure 3 - Block diagram of the Audio Filter Unit with the addition of switch S4.

The maximum setting of the cut-off frequency in the HP filter was originally 1.2 kHz. This has been altered to 2 kHz so that the upper frequency roll over of the rejection trough could be extended a little higher. Resistor R17 in the HP Clock circuit has been changed from 10 k to 4.7 k ohms to achieve this alteration.

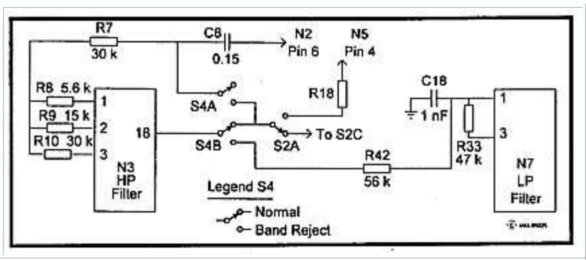

Figure 4 - Changes to the original circuit to include the Band Reject function.

Delete the link between N3-18 and S2A.
Add Switch 54 (DPDT) and Resistor R42 (56 k).
Also replace R17 (10 k), not shown, with R17 (4.7 k).

Operation

To operate in the discussed band reject mode, switch S1 is set to the HP/LP position, notch switch S2 is left off, and the new switch S4 is set to the band reject position. The LP adjust potentiometer is set for a cutoff at the low frequency side of the rejected band and the HP adjust potentiometer is set for a cut-off at the high frequency side of the rejected band. It is desirable to have a frequency calibration on the adjustment controls otherwise it is difficult to know exactly what one is doing. Pointer knobs are coupled to each of the three filter adjustment controls in the filter box. As originally assembled, no calibration to indicate the setting of the pointers was provided. A back plate of paper is now glued to the box and this is marked to show the approximate frequency cut-off indicated by the pointing of each of the three knobs.

It is not intended that a condition be set up whereby the LP cut-off is set higher than the HP cut-off (as in bandpass operation). This crosses over the two pass bands of the two filters causing what might initially appear to be an all-pass condition. Actually, it is not quite all-pass, as the phase of the output from one filter does not track with the other and, when the outputs are combined, troughs occur in the frequency response curve due to signal cancellation. The problem does not occur when the parallel filters are set up for wide band rejection as there is no frequency at which both filters together provide an appreciable output.

For all other modes of operation, such as wide bandpass, narrow bandpass, and notch (as described in my previous article), switch S4 is returned to the normal position.

Some Observations

It is interesting to observe the effects on speech intelligibility when part of the middle of the speech frequency band is taken out. Inserting the 100 Hz bandwidth notch has no effect and you can't detect that it has been switched in. Taking out a large slice of the band alters the speech quality, as one would expect. However, I have observed that, if the rejected band is between around 500 Hz to 1.5 kHz, quite good intelligibility and tonal balance is retained. Loss of intelligibility and change of tonal balance seems to really occur when frequencies are cut below 500 Hz or above 1.5 kHz. It seems that if speech is troubled by interference concentrated within the frequency range of 500 to 1500 Hz, the interference can be reduced, without loss of intelligibility, by rejecting this part of the band.

Another consideration is a speech signal received in the presence of broadband noise which spreads right across the audio spectrum. The level of noise can be reduced by restricting the audio bandwidth up to a point, but intelligibility is reduced when low frequencies are cut above 200 Hz or high frequencies are cut below 2.5 kHz. As an alternative, one might consider cutting between 500 and 1500 Hz and I have tried this on a number of noisy signals. Whilst the effect is not dramatic, it can give a few dB of signal to noise improvement whilst still retaining reasonable intelligibility and tonal balance.

On a slightly different subject, there are various ways of processing speech into a transmitter to improve the effective speech power. Speech clipping and speech compression are two well used techniques. I now wonder whether a reduction of frequency components in the 500 to 1500 Hz range would also be worthwhile. This would allow an increase in power of frequency components which are more critical in determining intelligibility and tonal balance. This gets away from the subject in hand concerning filtering of received audio but it is an interesting idea leading from the band reject tests on received speech.

Conclusion

A simple modification has been added to the audio filter described in a previous issue of Amateur Radio. Switching in parallel operation of the HP and LP filters allows them to be used in an adjustable band reject mode.

Some tests using the band reject mode seem to indicate that a band of frequencies in the range of 500 to 1500 Hz can be taken out of a speech signal whilst still retaining a reasonable intelligibility and tonal balance. This is a characteristic of speech which can be useful in improving intelligibility in the presence of an interfering signal or noise in this part of the audio spectrum.

Addendum

I refer to my observation that speech frequencies in the 150 to 1500 Hz range can be cut out without any noticeable reduction in speech quality. I now know that in the December 1977 issue of QST, Dr R.W.Harris and J.C.Gorski described a method of narrow band method of voice transmission by not transmitting frequencies in the 600 to 1500 Hz range. By moving the 1500 to 2400 Hz speech frequencies down into this region and restoring them on receiving, a total bandwidth of only 1500 Hz was needed. I reviewed this idea in an article in "Amateur Radio", January 1999 and headed "Narrow Band Voice Transmission".

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