Variable-slope, low-pass LF filter

Tone controls in audio preamplifiers are regarded by the cognoscenti as outmoded. Reg Williamson disagrees and presents a design for a steep-cut, variable slope filter to remedy deficiencies in some programme sources

Some of the more fascinating aspects of commercial hi-fi are the effects of contrived fashion. Each new fashion, be it oxygen-free copper cables or gold-plated plugs, seems to be dreamed up by a company's promotions department and then aided and abetted by a sycophantic review industry. None of this has anything to do with the aims of high quality sound reproduction and real engineers have little time for such commercially motivated goings-on; happily, there is a remaining handful of companies that eschews such practices.

It is a paradox that, in so-called "high end" amplifiers and preamplifiers, the facilities offered appear to be in inverse proportion to the price; the more inflated the cost, the more minimalist the functions. One might expect the volume control to disappear as soon as some self-appointed guru prescribes it as yet another cause of subjective aberration of minuscule magnitude.

Despite the considerable improvement in the quality of programme sources in the home, there is still the need for "tone controls", although they may now take a somewhat different form. Since 78s and LPs are still popular, and since the transfer of old analogue tapes to CD is sometimes not especially careful, the desirability of access to a steep-cut low-pass filter still remains.

This design arose from a feeling of irritation with the current, irrational, minimalist trend and, while it may form part of a complete preamplifier, it was felt that the steep-cut filter as an independent unit might prove of interest. I make no secret of the fact that it emulates the well-tried and trusted Quad control with its selection of three frequencies and a variable slope; although, as will be seen later, the design approach is somewhat different.

A variable-slope low-pass filter was a feature of a design of mine some 21 years ago[1], but this had only one fixed frequency and was based on a conventional m-derived full π-section filter (**Fig. 1**) with a potentiometer progressively shorting the inductor and shunt capacitor to provide the variable slope. A novel function was that, at the minimum setting of the potentiometer, an integral switch could take the filter out of circuit altogether.

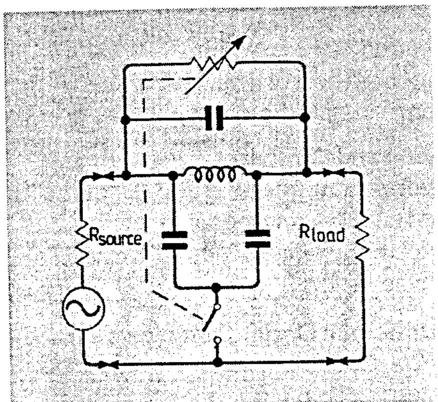


Fig. 1. Variable-slope filter based on an m-derived π-section with the capacitor shorted by a potentiometer.

Gyrators

The new version uses the same approach, but this time a pot-core inductor is not used. Fortunately, modern linear design methods now include an alternative to real inductors, a circuit technique that had just been introduced at the time of my first design. I refer to the gyrator.

It is outside the province of this article to deal in any depth with how a gyrator functions — there are many excellent references[2] — but a little historical background is not without interest. The concept was first mooted by Tellegen in 1948 and I believe he coined the generic noun. In simple terms, it can be shown that, by the use of active devices, one can in a linear circuit interchange the relationship between current and voltage; so in theory, for example, it is possible to make a capacitor behave like an inductor and vice versa.

Figure 2 shows the simplest version I know, and in this series tuned circuit,

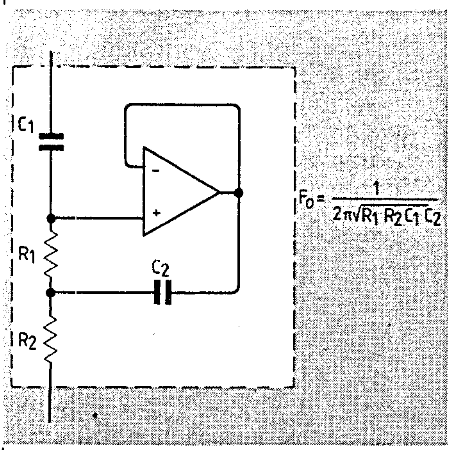


Fig. 2. Elemental gyrator circuit, which emulates an inductor in series with a resistor.

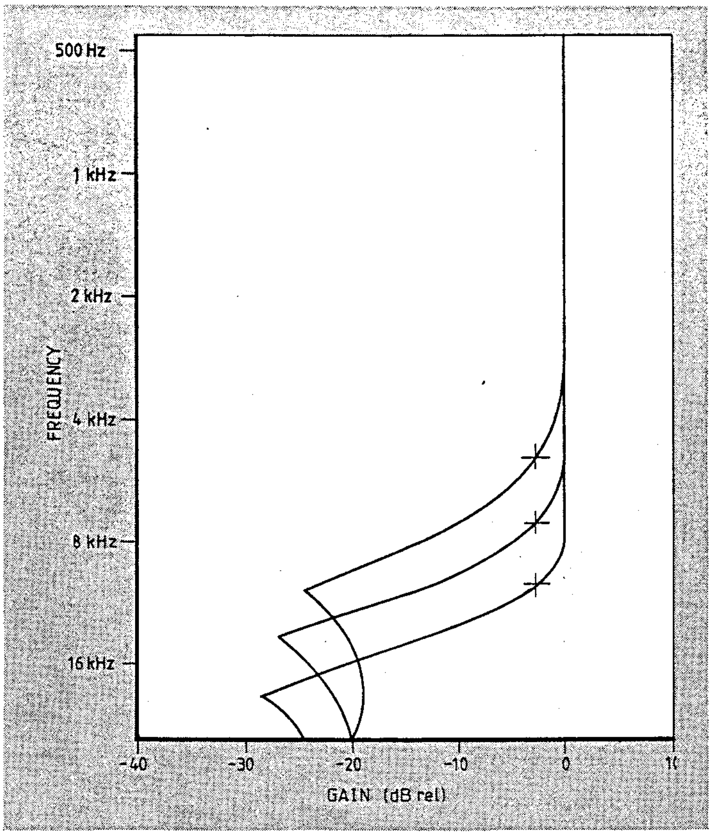


Fig. 5. Manually plotted curve of filter characteristic. Roll-off may be varied from −25dB/octave down to −6dB/octave at half-way setting.

C_2, R_1 and R_2 behave like an inductance in series with resistance; acceptable where a modest Q is required. Riordan proposed a rather more sophisticated version using two op-amps in 1967[3] and two years later Antoniou[4] realised a number of variants, all bearing superficial similarity to the Riordan original with one in particular proving of special interest — the one adopted for this design (**Fig. 3**).

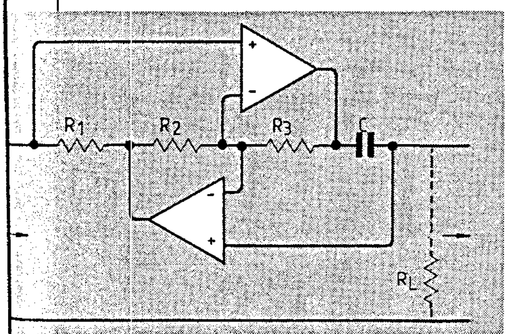


Fig. 3. Gyrator due to Riordan, after Antoniou, which forms the basis for the present design.

Fig. 4. Practical filter with switchable cut-off control. R_1 and R_2 in buffer amplifier control gain.

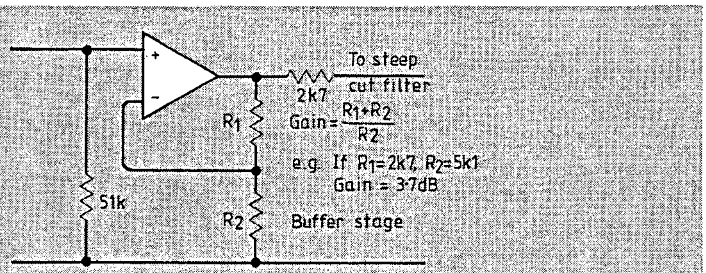
This circuit is a generalised impedance converter and if a resistor is connected from the output to ground, it appears to the input as an inductor

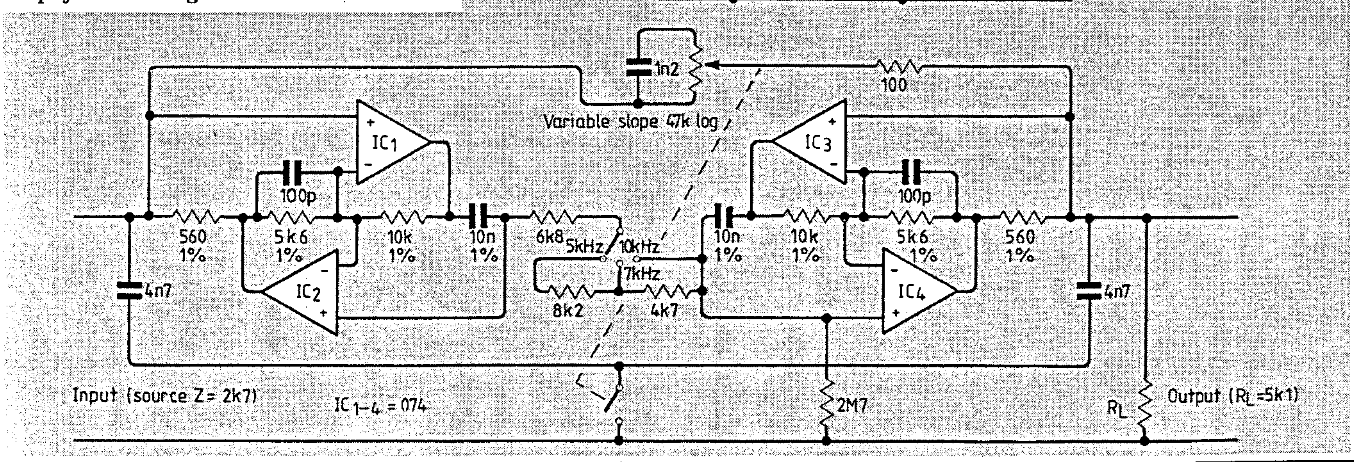
$$L_{eff} = KR_L$$

where $K = CR_1R_3/R_2$. So it can also be seen that if one chooses appropriate values for the capacitive and resistive elements, the scaling factor K can be a comfortable round integer. In the practical design of **Fig. 4** this is equal to

$$L_{eff}(\text{henries}) = R_L(k\Omega)/100$$

A special feature of the Antoniou circuit is that, where the "inductor" is floating above ground, as in the case of a low-pass full-section π configuration, then two can be connected tail-to-tail with resistor (inductor) between them.





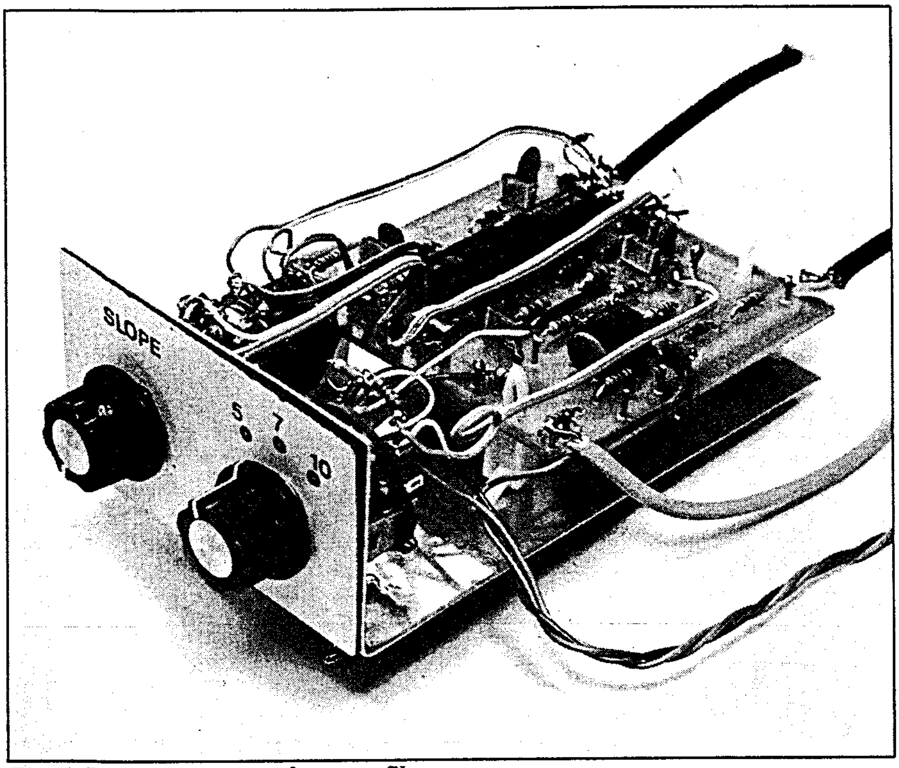


Fig. 6. Prototype steep-cut low-pass filter.

Fast Basic listing for the design of m-derived, half-section high or low-pass filter.

```
  \These programs are to facilitate the design of a m-derived half section
  \parallel high or low pass L-C filter.Designed sections may be cascaded
  \in T or π configuration. Written in Fast Basic by R Williamson 20/1/87.
  CLS:TXTSIZE 13
start:INPUTTAB(12,10)"Do you want High pass or Low Pass? Type HP or LP..:"A$
  CLS
  IF A$="HP" OR A$="hp" THEN GOTO hp
  PRINTTAB(8,0)"This Program will design a low pass half section filter,"
  PRINTTAB(8)"m-derived and which may be cascaded in π configuration."
  PRINTTAB(8)"It is of the parallel type (see associated diagrams)":PRINT
lps:INPUTTAB(8)"Select the frequency of cutoff (Fc in KHz)";Fc
  PRINTTAB(8)"Enter the null frequency (Fn in KHz and which"
  INPUTTAB(8)"should not be <1.25Fc)................      ";Fn
  IF Fn/Fc<1.25 THEN PRINTTAB(8)"Fn is too low. Re-start!":PRINT:GOTO lps
  PRINTTAB(8)"Enter source and load resistances in KΩ"
  INPUTTAB(8)"(which are initially assumed to be equal)..";R
  M=DSQR(1-(Fc/Fn)^2)
  L = M*R/(2*PI*Fc)
  C = M/(2*PI*Fc*R):C=C*1000000
  Cp = (1-M^2)/(M*2*PI*Fc*R):Cp = Cp*1000000 :PRINT
  PRINTTAB(8)"Inductance L is.......               ";L" Henrys"
  PRINTTAB(8)"(if standard gyrator module used"
  PRINTTAB(8)"                        ...then Rz = ";L*100" KΩ)"
  PRINTTAB(8)"Shunt Capacitance C is........   ";C" pF"
  PRINTTAB(8)"Series Capacitance Cp is.......  ";Cp" pF"
  PRINTTAB(8)"Note: m = ";M
  PRINT: PRINTTAB(8)"Assuming cascaded sections in preferred"
  PRINTTAB(8)"π configuration, then....     L = ";2*L" Henrys"
  PRINTTAB(8)"(if standard gyrator module used"
  PRINTTAB(8)"                        ...then Rz = ";L*200" KΩ)"
  PRINTTAB(37)"Cp = ";Cp/2" pF"
  GOTO end
hp:CLS:TXTSIZE 13:PRINT
  PRINTTAB(8,0)"This Program will design a high pass half section filter."
  PRINTTAB(8)"m-derived and which may be cascaded in T configuration."
  PRINTTAB(8)"It is a series type (see associated diagrams)":PRINT
hps:INPUTTAB(8)"Select the frequency of cutoff (Fc in Hz)";Fc
  PRINTTAB(8)"Enter the null frequency (Fn in Hz and which"
  INPUTTAB(8)"should not be >0.8Fc)...............     ";Fn
  IF Fc/Fn<1.25 THEN PRINTTAB(8)"Fn is too high. Re-start!"::GOTO hps
  PRINTTAB(8)"Enter source and load resistance in KΩ"
  INPUTTAB(8)"(which are initially assumed to be equal)..";R:PRINT
  M=DSQR(1-(Fn/Fc)^2)
  L =R*1000/(M*2*PI*Fc)
  C =1000/(M*2*PI*Fc*R)
  Cs=M*1000/((1-M^2)*2*PI*Fc*R)
  PRINTTAB(8)"Inductance L is......               ";L" Henrys"
  PRINTTAB(8)"(if standard gyrator module used"
  PRINTTAB(8)"                      ...then Rz = ";L*100" KΩ)"
  PRINTTAB(8)"Shunt Capacitance C is......    ";C" µF"
  PRINTTAB(8)"Series Capacitance Cs is....    ";Cs" µF"
  PRINTTAB(8)"Note: m = ";M
  PRINT:PRINTTAB(8)"Assuming cascaded sections in preferred"
  PRINTTAB(8)"T configuration, then....   L = ";L/2" Henrys"
  PRINTTAB(8)"(if standard gyrator module used"
  PRINTTAB(8)"                      ...then Rz = ";L*50" KΩ)"
  PRINTTAB(35)"Cs = ";Cs*2" µF"
end:PRINT
  INPUTTAB(8,19)"Type Y for repeat or N to end..."E$
  IF E$="Y" OR E$="y" THEN CLS: GOTO start
  END
```

Filter design

The final step is to decide on the parameters for a conventional m-derived low-pass filter, determine the value of the inductor and, from that, the equivalent resistor. The mathematical procedures are freely available and will not be repeated here. In the design of Fig. 4 there are three resistors, giving three switched frequencies. The null frequency above the nominal turnover point is a little lower than one octave, giving an m factor of ≈0.8.

The circuit was first simulated by a cad program and a few empirical changes were needed in the prototype, not only because only the inductive component is varied, but also because some adjustments were necessary to allow standard values of R and C outside the gyrators. This departure resulted in some shifts to the turnover frequencies which are insignificant.

Attention to DC and AC stability was also needed. To meet the matching needs of the filter and to compensate for its insertion loss of 3.7dB, there is an input buffer, giving an overall gain of 0dB. The gain may be modified by a simple adjustment to the two resistors in the buffer amplifier feedback path. **Figure 5** shows that the asymptotic rate reaches about 25dB/octave and can be infinitely varied down to a first-order rate of 6dB/octave at about the half-way setting.

Interfacing the unit with existng equipment is simple, since the input impedance is high at around 50kΩ and output impedance is low (this must always "see" 5kΩ, so a fixed resistor might be needed across the output when the load is determined). To preserve an adequate s:n ratio, the signal level should be greater than 100mV. The maximum signal level before clipping is 5.3V RMS and THD<0.002%. ■

My thanks to the University of Keele for the use of facilities and to Alan Watling for constructing and initially testing the prototype.

References

1. *Hi-Fi News* March 1969, The Twin Twenty MkII.
2. M.E. Van Valkenburgh *et al*, Analog Filter Design, Chapter 15 (Holt-Saunders International).
3. R.H.S. Riordan, Simulated Inductors using Differential Amplifiers, *Electronics Letters*, vol. 3, 1967.
4. A. Antoniou, Realisation of Gyrators Using Operational Amplifiers and Their Use in RC-Active Network Synthesis, *Proc. IEE*, vol. 116, 1969.