active loudspeaker-crossover filters (1)

Few things can so hold the attention of the serious audiophile as do loudspeakers. This applies with particular strength to those whose fingers always have the experimenter's itch — so that they cannot or will not without reserve accept somebody else's idea of a loudspeaker system. This can lead to the expenditure of considerable sums, if only on wooden panels, and it will sometimes also lead to frayed tempers at home . . .

One of the ways of sinking cash into an existing system is to replace the 'passive' separating ('crossover') filters by 'active' types. This of course involves the provision of a separate power amplifier for every driver in the system.

This article on Active Crossover Filters (ACF's) will describe a universal filter circuit, capable of producing a vast number of filter characteristics.

High-quality loudspeaker systems are invariably designed on the basis of 'divide and rule' principles. The incoming audio spectrum is split up into two, three or even four sub-spectra, each of which is then passed to a loudspeaker specially designed for that particular frequency range. The changeover from one loudspeaker to the next higher in frequency range is accomplished by a complementary filter-pair whose roll-off response-flanks 'cross over' each other at a point some decibels below the 'full power' level. The filter-pairs are therefore called *'crossover filters'*.

A loudspeaker system that uses such filters is usually called a *'multiway'* system.

When the filter sections are inserted between the single power amplifier and the individual 'drivers' (i.e. loudspeakers proper), the system is said to have a *passive* filter. Figure 1 illustrates a typical three-way system. The low-to-midrange crossover frequency is f_1 and the midrange-to-high crossover occurs at f_2. The representatives of the animal kingdom shown have had their typical calls 'borrowed' to provide a classification of the drivers into the categories low-range (woofer) midrange (squawker) and high-range (tweeter).

The big idea behind the multiway approach is the fact that an optimally-designed 'woofer' is — for basic design reasons — a sub-optimal loudspeaker at higher frequencies. This does not mean that a 'new' design method may not someday produce a first-class full-range driver; it simply hasn't been done yet. The problems to be faced are quite formidable — and a computer is only useful to quickly do the sums that a human being already *knows how* to do.

A multiway system is necessarily more complicated and more expensive to produce than a single-driver system. That is a clear disadvantage. There is however a second objection to the multiway approach — a more fundamental objection: how does one tackle the fact that frequencies near the crossover point are radiated by *both* drivers? The two radiating diaphragms cannot be at the same position in space — although they often can be spaced quite closely — so that 'interferences' between the two radiated waves can cause irregularities in the response characteristics and in the *radiation pattern* of the system.

'Dividing' is one thing; 'ruling' is quite another . . .

Most of the interference effects can be avoided when the two frequency-adjacent drivers are mounted concentrically — one within the other. This is usually no problem, since an optimal tweeter can be made smaller than a woofer. The past has known designs — many of them still very popular — in which a tweeter of one kind or another has been built into a woofer (or, more accurately, a woofer-midrange) cone-loudspeaker. The crossover can be mechanical in nature (as in the 'good old' Philips 9710M), or a more advanced twin-driver-plus-electrical-crossover system can be employed (as in the famous Tannoy Monitor Gold and certain Goodmans and Isophon units).

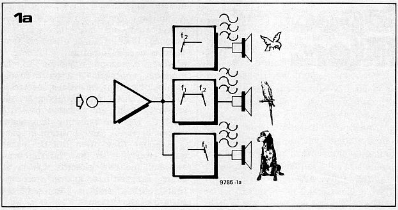
Passive or active?

Having decided that a good loudspeaker system, at the present state of the art, is going to need at least one crossover filter, we have to decide whether this filter should be a 'passive' or 'active' design. (For our purposes, an 'active' filters is one in which the inductors have been eliminated by the application of capacitors and *amplifiers*).

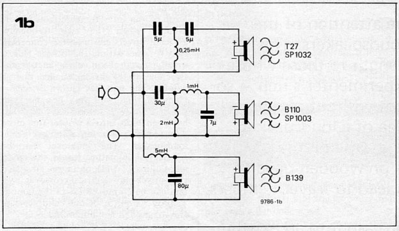
Figure 1a illustrates a typical passive-filter three-way system. The passive filter is built up with inductors, capacitors and any matching networks that may be necessary (e.g. to reduce the drive to a too-sensitive tweeter). Figure 1b illustrates the bare bones of a three-way passive filter.

One difficulty is immediately apparent. The woofer section requires an inductor in series with the driver voice-coil. The considerable inductance involved means that there will be power loss in the copper-resistance of a many-turn air-cored coil, or else that there will be distortion due to the non-linearity of a low-loss coil that has a ferromagnetic core. Neither of these effects should however be viewed out of proportion: the often-cited effect of the series-resistance on the woofer's electrical damping is completely swamped by the effect that the voice-coil resistance has — and one can design iron-core inductors with a level of distortion that is insignificant compared to that of the actual driver.

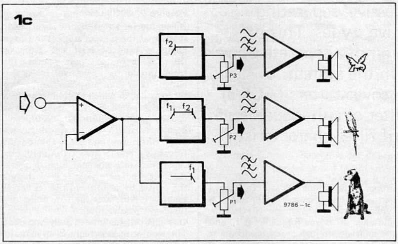
1a



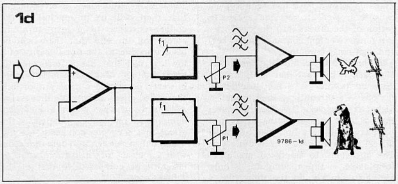
1b



1c



1d



Another source of difficulties is more awkward to eliminate. Normal electrical wave-filters assume a pure-resistance load-termination. When you connect a *loudspeaker* to such a filter the final characteristic may not be quite what you intended – it may even be wildly off. The trick of connecting an RC network across the speaker terminals to compensate the high-frequency rise in impedance (due to the coil's inductance) certainly works and should be better known; but the fun really begins when the speaker impedance contains significant components 'reflected' from the mechanical 'circuit'. That usually happens in the neighbourhood of the driver's fundamental resonance; it can be a very expensive nuisance in the case of midrange and tweeter units that have a resonance (as is usual) at or just below their high-pass crossover frequency.

Now, a well-designed commercial 'passive filter system' will invariably work very well – but that success is due to a combination of design experience and available facilities beyond the reach of the 'do it yourself' audiophile.

Although it would be possible to say a great deal more about passive filter arrangements and matching networks, this article is supposed to be about *active* arrangements. Having implied, above, that the amateur is better off tackling his problem with an active system, we must now try to explain how.

Active Crossover Filters

Figure 1c shows the block diagram of a three-way active ('electronic') crossover filter. It is immediately clear that each of the loudspeakers requires its own power amplifier. This need not be so expensive as one might think, since the *total* power required (and hence the amount of mains transformer, reservoir capacitor and heat sink) is not increased by subdividing the amplifier. As a rule, the woofer will need the most powerful amplifier (perhaps 50 . . . 70% of the total), with the midrange unit handling perhaps two-thirds of the remainder. Much will obviously depend on the individual drivers used. When drivers are obtainable with varying rated impedances, the power distribution over the output stages can be achieved by using a single supply voltage together with a low-impedance woofer (say 4 ohm), a mid-range unit of higher

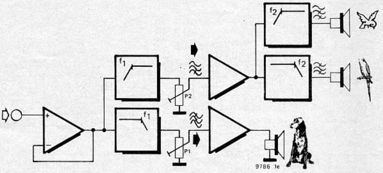
Figure 1a. Block diagram of a three-way system with passive crossover filter.

Figure 1b. As an example: the KEF type DN 12 SP 1004 three-way passive filter.

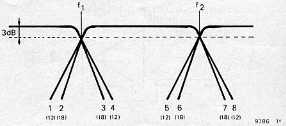
Figure 1c. Block diagram of an active-filter three-way system.

Figure 1d. An active-filter two-way system.

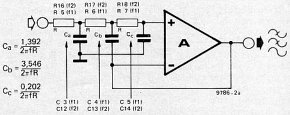
1e



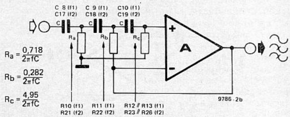
1f



2a



2b



impedance (say 8 ohm) and a tweeter of still higher impedance (15 ohm).

A major advantage of the active-filter approach is the ease with which sensitivity differences between the drivers can be eliminated. In figure 1c this is accomplished by adjustment of the presets P1, P2 and P3. Figure 1d gives a simpler two-way circuit, suitable for use with smaller diameter woofers that are also well-behaved throughout the mid-frequency range. Still another possibility is shown in figure 1e, a 'hybrid' three-way system. In this case the woofer to midrange crossover is done with an active filter and two power amplifiers; the frequency ranges for the midrange and tweeter drivers are however separated by a passive filter set.

What are the other advantages of the active filter approach?

- the design is far more flexible; a change of crossover frequency or drive level can be quickly and conveniently achieved by changing one or two R's and C's or adjusting a preset potentiometer.
- there is no complication in the filter design caused by the awkward termination (the loudspeaker impedance).
- it is relatively simple to produce complicated filter characteristics whenever this is thought desirable or necessary.
- since the power amplifiers will usually be installed in the loudspeaker cabinet, the individual drivers can be protected from overload by suitable choice of the power rating of the amplifier concerned.

The filter circuits

Figure 1f shows a set of filter characteristics, as would be required for a three-way system. The frequencies f1 and f2 are the '−3 dB' points, at which the response curves of a complementary filter-pair actually 'cross over' each other. Half of the power at a crossover frequency is transmitted through each filter of the pair. For a three-way system f_1 will frequently lie between 300 and 600 Hz (sometimes as low as 100 Hz, or as high as 800 Hz). The other crossover will then usually be found between 2 kHz and 8 kHz − typically near to 5 kHz. The single crossover in a two-way system is usually between 1 kHz and 3 kHz (typically around 2 kHz).

The slope of the various filters well into their respective 'stop-bands' is a multiple of 6 dB/octave (i.e. 20 dB/decade). The figure 1f curves are drawn for 12 dB/octave (1,4,5,8) and for 18 dB/octave (2,3,6,7). If we assume that either slope may be used for each of the four filters, then there are sixteen possibilities for a three-way filter. It is not always desirable to make the filters of a crossover-pair with the same slope − a so-called *asymmetrical crossover* may be needed when the response of one of the loudspeakers is not flat through the crossover point. Table 1 lists the possibilities.

The last four alternatives apply to two-way systems. We will refer in this article to the single crossover as f_1.

An electric wave-filter is characterised not only by the 'ultimate slope' of the rolloff curve, well into the 'stop band' but also by the 'sharpness of transition' between the pass-band and the stop-band. A number of Famous Names are associated with a classification of filters into categories with increasing sharpness (once again: note the distinction between *sharpness* and *steepness*).

Almost all loudspeaker crossover filters are of the *Butterworth* 'maximally flat amplitude' type. We will therefore illustrate the workings of the practical circuits by Butterworth responses. When the 'pass-band' is defined as the frequency range up to the −3 dB point (low-pass) or from the −3 dB point upwards (high-pass), then Butterworth gives the lowest possible 'pass-band attenuation' that can be obtained without allowing 'ripples'.

The figures 2, 3 and 4 give the design information for Butterworth low-pass filters ('a' figures) and Butterworth high-pass filters ('b' figures), for ultimate slopes of 18 dB/octave (figure 2), 12 dB/octave (figure 3) and 6 dB/octave (figure 4). The two sets of component numbers refer to the two different crossovers. We will come back to this when referring to the parts list.

The active element in the circuits of figures 2, 3 and 4 is a voltage follower. The best known AC voltage follower is the so-called 'emitter follower'. Since a voltage gain of unity can only be closely approximated by an amplifier with extremely high current gain, the total circuit diagram of figure 5 shows 'super emitter followers' using two transistors each. The derivation of the component values always assumes the use of an ideal voltage follower; any attempt to 'make allowances' is fraught with great uncertainties – and the assumption that a one-transistor follower is ideal is just too optimistic!

This is not the place to go into the

Figure 1e. A hybrid active/passive three-way system.

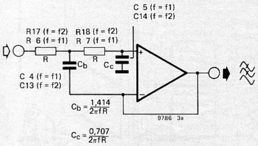
Figure 1f. A few frequency-response plots, with slopes of 12 and 18 dB/octave and one or two crossovers, as an aid to interpretation of table 1.

Figure 2. Circuit diagram and values for a Butterworth low-pass (a) and high-pass (b) 18 dB/octave filter.

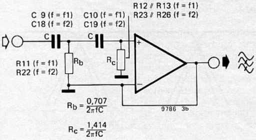
Figure 3. Circuit diagram and values for a Butterworth low-pass (a) and high-pass (b) 12 dB/octave filter.

Figure 4. Circuit diagram and values for a low-pass (a) and high-pass (b) 6 dB/octave filter.

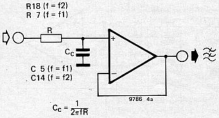
3a



3b



4a



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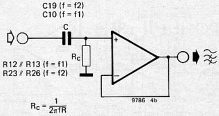
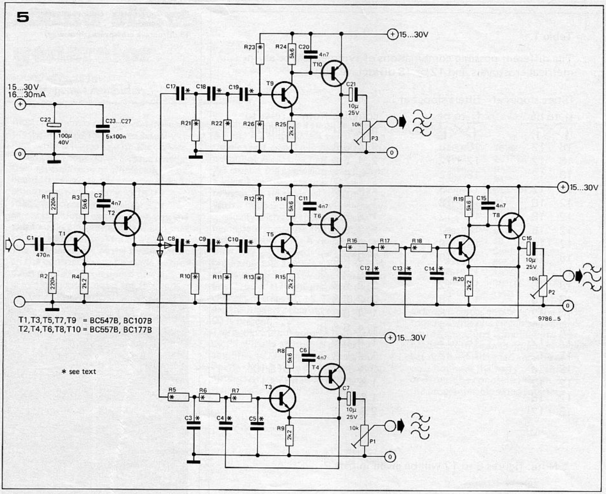


5



details of the derivation of design formulae.

One practical consequence of the derivations must however be noted here. That is the fact that it is not always possible to design filters in which all the frequency-determining R's and C's have convenient values. We have chosen circuits with either three equal C's (high pass) or three equal R's (low-pass), the other components hopefully coming fairly close to standard E12 values. Filters with low 'Q' values (such as Butterworth) will, fortunately, not immediately go haywire when some of the components are a few percent out. That is not to say that a fusspot with access to 1% R's and C's should not indulge a craving for 'precision' . . .

So much for the general aspects of active crossover filter design. It is now time to try working out a specification.

One way to tackle this problem is to use a check-list.

- Active filters only (figure 1c or 1d) or hybrid (1e)?
- Three-way or two-way?
- Which speakers?
- How steep the filters?
- Which amplifiers?

Do not try to find complete 'paper' answers to these questions. A great deal will depend on one's individual taste and on whatever happens to be available. Note that the idea was to find something to *play* with!

There is one fundamental guideline, however. *Loudspeaker are meant to be used for listening to music, not the other way round.* If it sounds right, then never mind what it looks like on paper. Assuming that one's musical taste is reasonable, any discrepancy between the theory and the actual result will usually be due to an oversight or incompleteness in the theory.

It will simplify this story if we introduce two further 'boundary conditions'. Let us assume that (1) we are going to do the job properly – no skimping on parts – and (2) that the reader already knows how to design his enclosure.

The question that should be tackled first is the choice of the loudspeaker to be used. This usually will involve a dig into the manufacturer's literature – or at least a good look into a distributor's catalogue. Unless one knows precisely what one wants, it is a good idea to select a combination recommended by the manufacturer, replacing only the inevitable passive filter by circuits covered in this article. Information on how to construct special woofer enclosures, such as folded horns or 'transmission line' types, can often be found in the literature.

The basic choice between two-way and three-way systems is not inevitably one of cost,with three-way always better if you can afford it. On the contrary, some of the best-sounding systems around use a woofer-midrange unit plus a tweeter. These woofer-midrange units do however tend to need rather more than a simple closed-cabinet if they are to do a really good job at the deep-bass end.

The frequencies and ultimate slopes of the crossover filters can be taken, at least as a starting point, from the parameters of the passive filter recommended by the speaker manufacturer. If one is combining speakers from various sources, then some experiment may be necessary (great fun!). There are one or two guidelines here, more 'don'ts' than 'do's'. In the first place, beware of the 'power handling capacity' ratings of tweeters. It is in the nature of things that their smaller coil systems cannot handle the massive amounts of input power that will not damage woofers. The temptation to suppliers is to quote a high power rating for a tweeter *in combination with a specified high-pass filter*. The 'power density' of normal music spectra certainly becomes significantly lower as the frequency increases; but this no longer applies when the amplifier is driven into distortion (accidentally or on purpose).

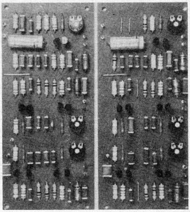
Table 1.

The different possible combinations of symmetrical or asymmetrical crossovers and 12 or 18 dB/octave slopes

filters slopes at f_1 to be		filters slopes at f_2 to be		combine from figure 1f	refer to figures
18	12	18	18	2, 4, 6 & 7	
18	12	12	12	2, 4, 5 & 8	
18	12	18	12	2, 4, 6 & 8	
18	12	12	18	2, 4, 5 & 7	
12	18	18	18	1, 3, 6 & 7	
12	18	12	12	1, 3, 5 & 8	
12	18	18	12	1, 3, 6 & 8	
12	18	12	18	1, 3, 5 & 7	
18	18	18	18	2, 3, 6 & 7	5 & 6*
18	18	12	12	2, 3, 5 & 8	
18	18	18	12	2, 3, 6 & 8	
18	18	12	18	2, 3, 5 & 7	
12	12	18	18	1, 4, 6 & 7	
12	12	12	12	1, 4, 5 & 8	7* & 8*
12	12	18	12	1, 4, 6 & 8	
12	12	12	18	1, 4, 5 & 7	
18	18	–		2 & 3	9*&10*
12	12	–		1 & 4	11*&12*
12	18	–		1 & 3	
18	12	–		2 & 4	

* Note: figures 6 to 12 will be given in part 2.

Figure 5. Complete circuit diagram of an active filter set for two symmetrical 18 dB/octave crossovers (three-way).



Put another way: (1) the high-pass filter associated with a certain tweeter will invariably have a 'protection' function as well as its effect on the response and (2) don't try to get a quart out of a pint pot!

The other guideline worth mentioning concerns the fact that a given loudspeaker invariably will have a frequency response extending far higher than the recommended crossover low pass cutoff. The response in the non-recommended range is however usually ragged or 'peaky' due to the cone (or other diaphragm) 'breaking up' into patterns of flexural resonance. This effect will impair the transient response. When a high-pass rolloff is recommended, quite apart from the input power consideration given above, there may be a mechanical limitation on the obtainable sound output in the non-recommended range. This would apply in particular to dome-type tweeters and squawkers.

The filter slope of 6 dB per octave is rarely used, although there is considerable evidence that a slow woofer-midrange rolloff combined with a steeper tweeter slope can give excellent results. It is included here for completeness sake, since 'asymmetrical' crossover filter design really requires access to acoustical measurement facilities.

The amplifiers

We come now to one of the great sources of endless discussion. How may watts need one provide for each loudspeaker? There are many ways of looking at this question, depending on the kind of music you have in mind for instance, or depending on which 'trade-off' you prefer.

We have already noted that the (continuous) dissipation of which a typical tweeter is capable will be less than that of a mid-range and significantly less than that of a woofer. That is simply a question of the physical size of the respective 'motors'. It would seem obvious that the continuous-power ratings of the associated amplifiers should reflect this fact. All one can hope to achieve with some 'reserve watts' is an increased risk of sometime needing a 'reserve speaker'. There is a bit more to it than this; but let us break off at this point.

Every loudspeaker has a certain 'instantaneous' power rating, referring to how much driving force it will handle (quite apart from the dissipation involved) before some moving part hits an end-stop. Since, at a given sound level, the diaphragm amplitude will be greatest at low frequency, the actual useful instantaneous rating will depend on the choice of (high-pass) crossover frequency. This seems to indicate that the amplifier's 'music power' rating, together with the choice of crossover frequency, should be matched to the (higher) instantaneous rating of the individual speaker. This applies literally to the midrange and to the tweeter; for the woofer something similar applies – but now with the 'box' design setting the high-pass cutoff frequency.

Having taken a look at the *limiting* amounts of power that an amplifier should not be *able to exceed*, we still have no answer to the real question: how much do we need? The answer is, for *normal domestic listening*, 'surprisingly little'. Simply read off from the manufacturer's literature low much input will produce about 96 dB SPL ('sound pressure level) at 1 metre from the loudspeaker (usually specified for free-field-room measurement). It will usually prove that 10 or 20 Watts already offers a very comfortable safety margin!

So much for the design considerations. Next month we will give circuits and printed circuit boards for 6-, 12- and 18 dB/octave filters for use in both 2- and 3- way systems. ⧓