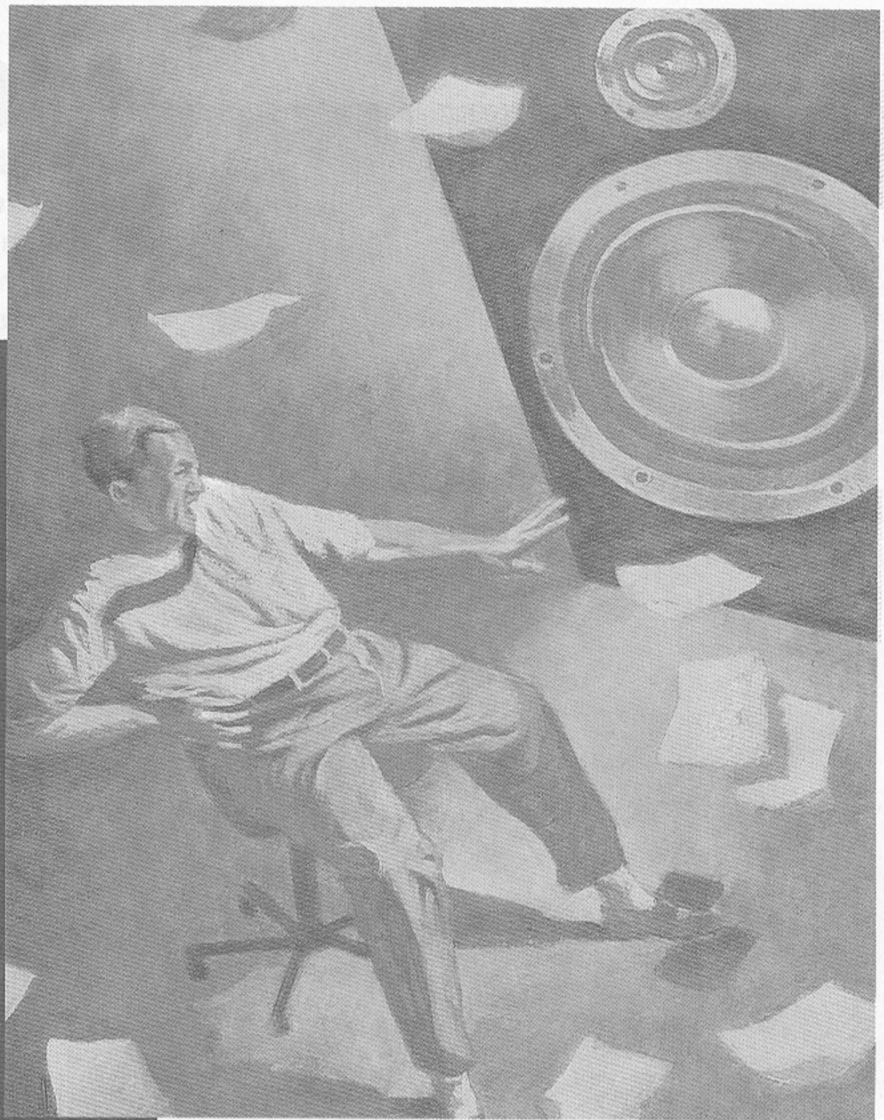


Connecting a speaker to an amplifier isn't just a matter of linking a piece of wire. There are reactances, impedances and phase to consider – all conspiring to upset stability. Ivor Brown shows how to avoid trouble.

Between amplifier and speaker

In audio systems, there is usually more than just a length of cable between the power amplifier circuit and the loudspeaker; additional components are there because the amplifier designer has no control over the load that the amplifier will have to feed. They are intended to isolate load variations from the amplifier circuit so that it operates as intended for all reasonable loads.

Usually, a series resistor-capacitor network is across the amplifier's output terminals and an inductor of a few microhenries goes between the output of the circuit and the live speaker terminal. The *RC* network provides an effective low-impedance load at high frequencies where, for example, an electromagnetic loudspeaker will have an impedance much larger than its nominal value. The inductor removes the effects of significant capacitive loads on the amplifier, such as may be encountered with long leads. The amplifier 'looks into' the inductor, whose impedance rises with frequency and buffers the capacitance loading at these frequencies. It sounds very simple, but analysis reveals that the circuit's operation is rather complex.

Why are amplifiers sensitive to reactive loads? Most employ some negative feedback to linearise their behaviour, the stability of the feedback loop being all-important. To ensure adequate stability margins for a multi-stage amplifier with a resistive load is difficult enough, but to do it for unspecified reactive loads is virtually impossible. An inductive load may cause the open-loop gain of the amplifier to rise at high frequencies and prevent satisfactory stability margins being obtained. A capacitive load will introduce additional phase lag into the forward gain path and this may also lead to unsatisfactory stability margins.

Negative feedback has had a bad press over the last few years, some designers making a feature of using as little as possible. There is nothing wrong with the technique in itself, but its use without appreciating and avoiding its limitations can – and does – cause problems[1]. Most importantly, open-loop bandwidth of the amplifier must cover the whole audio frequency range. Outside these frequencies the gain must be rolled-off in a controlled manner to ensure satisfactory gain and phase stability margins; behaviour made difficult to achieve by unspecified reactive loads. Since most designs employ dc-coupled feedback loops, serious stability problems are normally confined to high frequencies above 10kHz, extending to around 1MHz[2,3].

Series inductor

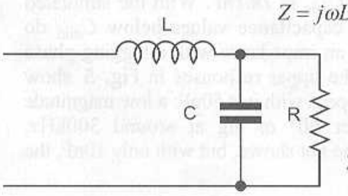
To start, assume a load consisting of a resistive loudspeaker plus some shunt capacitance. Inductor L, shunt capacitance C and the load resistor R form the damped resonant circuit of **Fig. 1**. In practice, the capacitance is mainly due to the speaker cable, but a well designed amplifier should be stable with appreciably larger values than those expected from this source. This implies that the design has good stability margins and component tolerances between samples are unlikely to be a problem. Also, although having an amplifier remote from the speaker is not a good idea, it may be operated in this way and must not be unstable even with very long cables.

Equations in the diagram describe the impedance of the network. When the imaginary parts in the numerator and denominator of the right hand impedance expression are equal, it is resistive. The equation for the zero-phase frequency, zpf, shows it is real only for capacitance above a minimum value (C_{min}); with C_{min} in circuit, zpf tends to zero, the significance of zpf being that, below it, the impedance of the network is capacitive and, in spite of the inductor, will capacitively load the system. Above it, the impedance is inductive with leading phase.

Figure 2 is zpf shown plotted against capacitance for two values of inductor and a 8Ω resistor; also shown is the frequency calculated from the LC product. With large values of capacitance, circuit Q is high and the two frequencies are virtually identical. As the capacitance is reduced towards the minimum value, Q is lowered and zpf differs appreciably from the LC frequency. The larger inductor lowers the zpf for a given value of C and hence the frequency range where the amplifier experiences capacitive loading.

With a larger load resistor, C_{min} is lower and the curves are shifted upwards and to the left.

"Negative feedback has had a bad press over the last few years, some designers making a feature of using as little as possible. There is nothing wrong with the technique in itself, but its use without appreciating and avoiding its limitations can – and does – cause problems."



$$Z = j\omega L + \frac{R}{1+j\omega CR} = R\left(1-\omega^2 LC\right)\left[\frac{1+j\left(\omega L/R\left(1-\omega^2 LC\right)\right)}{\left(1+j\omega CR\right)}\right]$$

$$Z \text{ is resistive when } \omega CR = \frac{\omega L}{R\left(1-\omega^2 LC\right)}$$

$$\text{Zero-phase frequency } f = \frac{1}{2\pi}\sqrt{\left(1-\frac{L}{CR^2}\right)\left(\frac{1}{LC}\right)}$$

$$C_{min} = \frac{L}{R^2}. \text{ Below this value, ZPF is imaginary.}$$

Fig. 1. Impedance and frequency for zero phase of the deceptively simple circuit with series L, cable capacitance and resistive speaker load. Above and below zero-phase frequency, impedance is inductive and capacitive respectively.

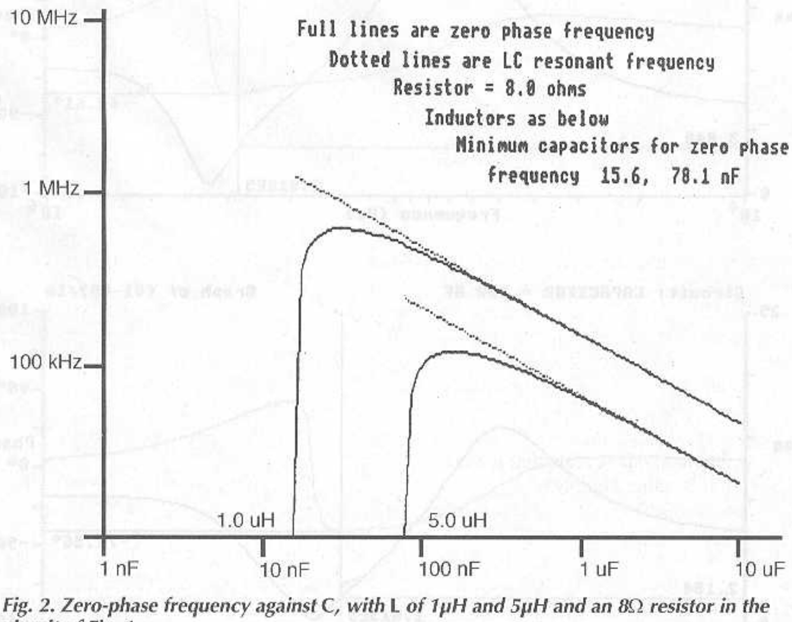


Fig. 2. Zero-phase frequency against C, with L of 1μH and 5μH and an 8Ω resistor in the circuit of Fig. 1.

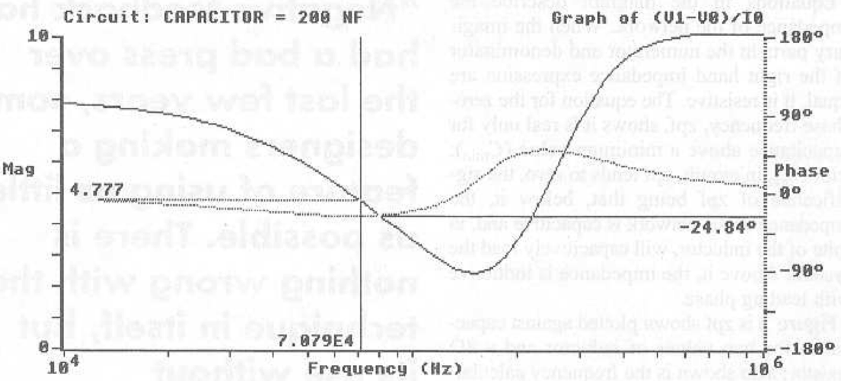
The zpf curve follows the LC line to lower values of C and reaches higher frequencies, as expected because circuit Q is increased. Before proceeding, the series RC network must be added across the input, 10Ω and 100nF being typical values. In the introduction I suggested that its purpose was to prevent the inductive speaker presenting a high impedance load at high frequencies, but now a physical inductance is connected to the amplifier output.

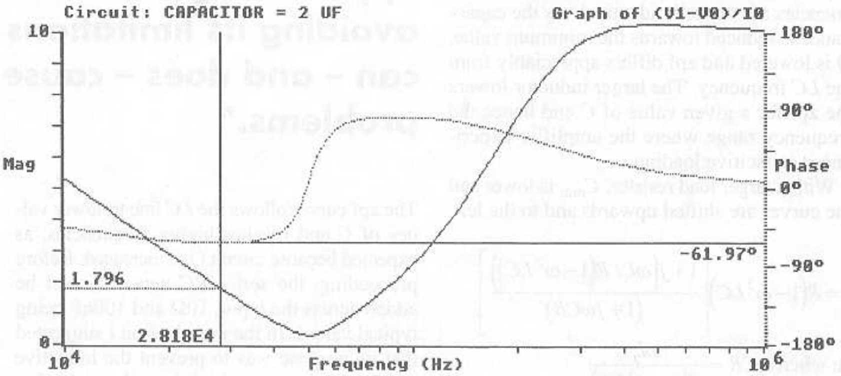
Figure 3 shows the circuit as so far described and two simulated responses of its input impedance for shunt capacitances of 200nF and 2μF, showing the lower zpf and the larger maximum phase lag occurring at a lower frequency for the larger C. The input RC network increases the maximum phase lag slightly but, more importantly, reduces the magnitude at higher frequencies. Without the network, the phase would tend towards +90°.

Connecting a load of 8Ω and 2.2μF in parallel is a common test to assess stability margins. It will almost certainly cause a square-wave output to ring severely on the transitions, but the ringing should die away quickly, indicating that the amplifier has adequate margins. Most of the ringing may be due to the transmission characteristic of the LCR circuit with the waveform at the input side of the inductor looking much better. In this case the additional phase lag at relatively low frequencies is not causing a problem.

However, with an appreciably lower capacitor, more representative of cable capacitance, things may not be so good. Maximum phase lag is less, but it occurs at higher frequencies; active devices in the amplifier are also causing appreciable lags and the circuit may not be able to tolerate the additional loading.

When looking at the loading impedance, one must consider both magnitude and phase. A large magnitude with phase tending to –90° represents a small capacitor which may have little effect. A small magnitude with a smaller





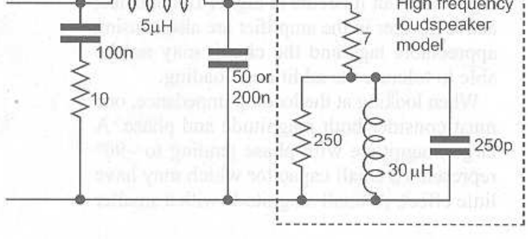
phase angle may take an appreciably greater quadrature current component.

Practical loudspeaker loads

At audio frequencies, the impedance of loudspeakers varies widely from the nominal resistive value; however, in the context of this article, it is the impedance above 10kHz that is important. Measurements have been made on a number of 8Ω, two-unit systems and the results suggest that the impedance curves for such systems are not too dissimilar: the magnitude rises gradually from about the nominal value at 10kHz to above 100Ω at 1MHz.

Figure 4 is a reasonable model with typical component values shown. There is no point in

Fig. 4. Three-component circuit of Fig. 2, with a speaker instead of an 8Ω resistor. Both magnitude and phase swings are much worse, even though magnitude scale is now 25Ω. Performance curves are shown on the right.



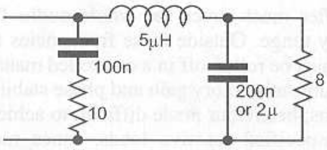


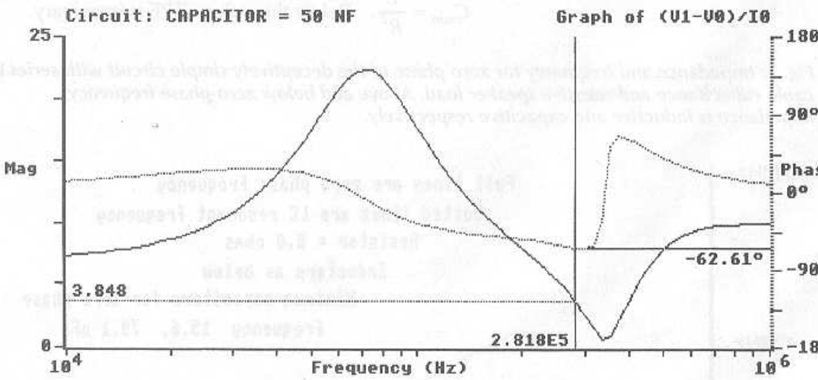
Fig. 3. Additional CR across input of circuit in Fig. 1 reduces impedance magnitude swing at high frequencies. Performance curves are shown on the left.

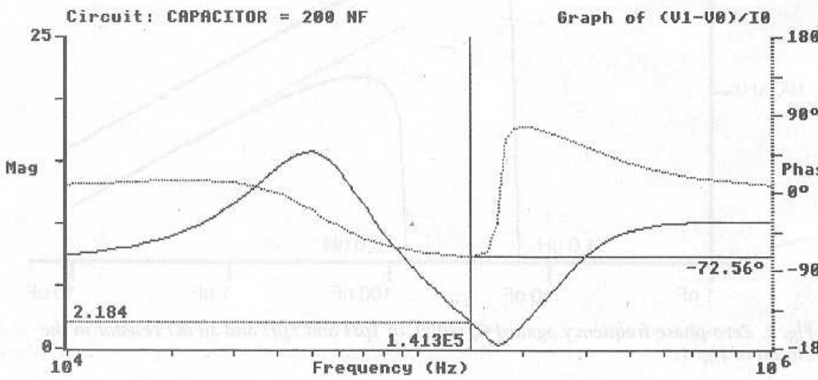
seeking great accuracy unless an amplifier is being designed for use with one specific speaker system; hardly a practical proposition.

Input impedance responses in Fig. 4 show the result of using the three-component compensation circuit with the 8Ω load replaced by the loudspeaker model. Note the wide variation in magnitude with the scales going up to 25Ω as opposed to 10Ω in Fig. 3.

Comparison of the 200nF responses in Figs 3 and 4 reveals how much the loudspeaker model has changed matters for the worse. Maximum phase lag is much greater than before and it occurs at a higher frequency; the magnitude at maximum phase lag is considerably reduced; just the effects we have been trying to avoid!

Figure 1 shows that, for 8Ω and 5μH, the value of C_{min} is 78.1nF. With the simulated speaker, capacitance values below C_{min} do result in an impedance with a lagging phase angle. The upper responses in **Fig. 5** show what happens with just 50nF: a low magnitude with over 60° of lag at around 300kHz. Curves are not shown, but with only 10nF, the





lag approaches 45° over the range 100kHz-700kHz.

Inductive speaker impedance is again causing a problem and second series *RC* network must be added to ground from the load side of the inductor. Considering the other impedances in the circuit and the likely low output impedance of the amplifier, values of 10Ω and 500nF form a negligible shunt across the speaker at audio frequencies, and largely overcome the problem. Figure 5 is the complete circuit and simulated input-impedance plots for three shunt capacitor values, two the same as in Fig. 4; the reduced magnitude variation, on a 0 to 10Ω scale, and the smaller lag angles are clearly shown. Responses for the larger capacitors are not very different from those shown in Fig. 3.

Investigation of the five-component isolation circuit with the loudspeaker model replaced by a 8Ω resistor gives responses that are also not very different from those in Fig. 3. There is only a small phase lag for capacitors less than C_{min}. With larger values, the magnitude and phase at the maximum-phase-lag frequency are within 20% and 10° respectively, although this condition does occur at a slightly lower frequency. To make the test more stringent, a larger load resistor could be used to increase the lag angle somewhat.

A point that needs watching is the dissipation in the 10Ω resistor of the second *RC* network. A sinusoidal output of 100W at 1kHz into a 8Ω load will give less than 100mW in the 10Ω resistor but, at 10kHz, the power increases to about 8W. Under normal use with music signals, this will present no problem, but if high-frequency, high-power testing is attempted, a suitably rated resistor must be used. Similar considerations apply to the first *RC* network, but the smaller capacitor reduces the 10kHz dissipation to less than half a watt.

Conclusions

High-frequency impedance of real loudspeakers makes the three-component load isolation circuit with shunt *CR* and series *L* perform relatively ineffectively.

Connecting a second *CR* network in series across the output terminals to the speaker largely compensates for the speaker impedance, the resulting five-component isolation circuit presenting a more easily driven load to the amplifier. When loaded by a loudspeaker, it performs in a similar manner to the three-component circuit with a resistive load. Provided a range of capacitors are used with the five-component circuit, testing with a load resistor and capacitor in parallel is meaningful. It provides a loading not too far removed from what may be encountered in practice.

This article is intended as a general discussion of the effects of loading on amplifiers. Computer analysis and simulation cannot be performed in general terms, so component values have had to be introduced to illustrate the points discussed. I do not suggest that they are suitable for general application and it is left for designers to evaluate the component values most suited to their particular amplifier. ■

References

1. I J A Brown. Feedback and fets in audio power amplifiers. *Electronics and Wireless World*, vol. 95, No 1636, February 1989.
2. Savant, Roden and Carpenter. *Electronic Design, Circuits and Systems.* Benjamin/Cummings 1991.
3. Schilling and Belove. *Electronic Circuits, Discrete and Integrated*, 3rd ed. McGraw-Hill 1989.

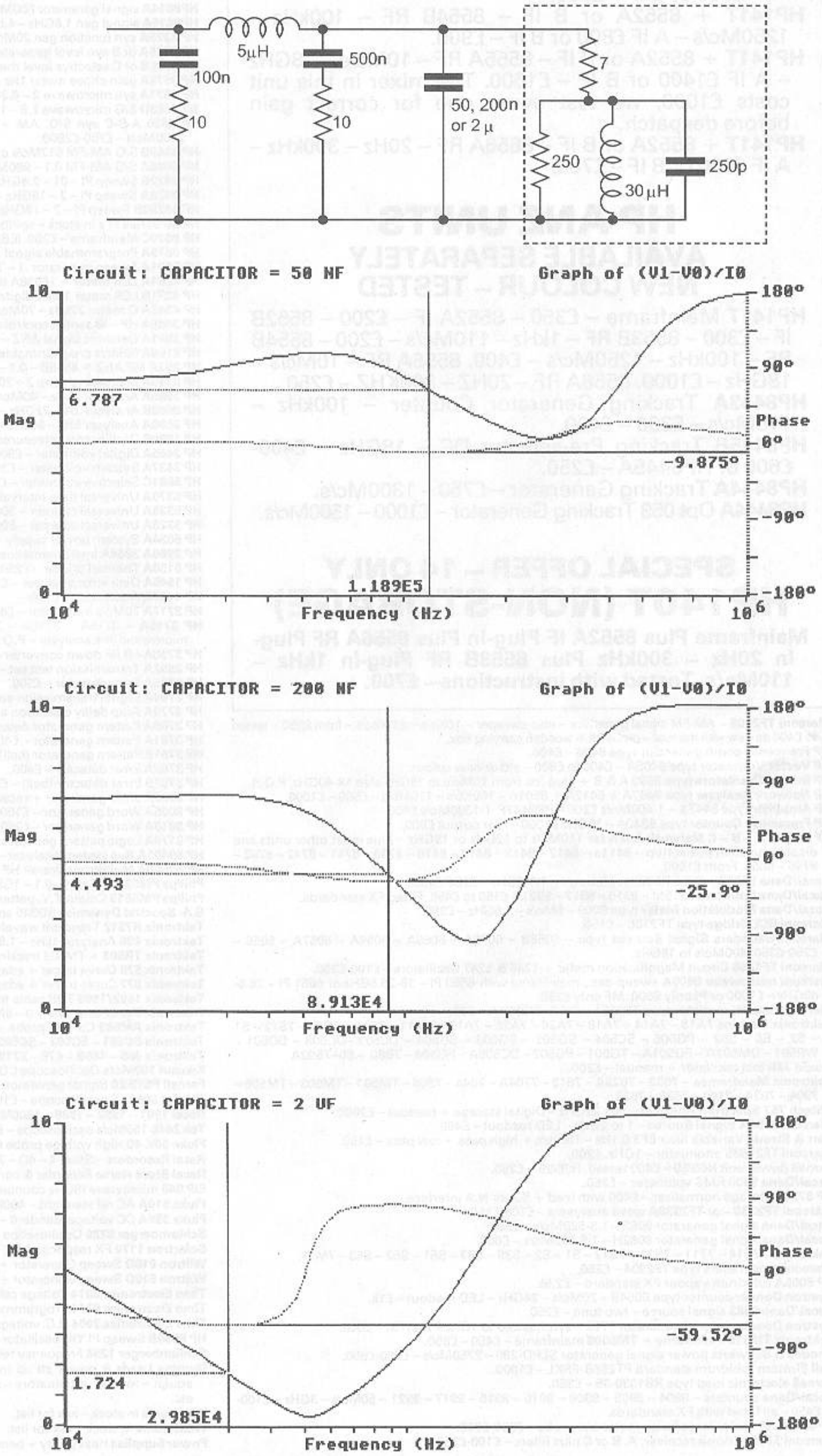


Fig. 5. Second RC after the L solves the problem and this is the complete circuit. Magnitude scales on graphs are back to 10Ω.