CAPACITORS IN AF CIRCUITS

by H. Baggott

It is well know that coupling capacitors in hi-fi audio circuits can adversely affect the tone quality of the circuits. Unfortunately, there are frequently good reasons that make their use unavoidable. But how do you decide which type to use in a high-quality amplifier? There are so many different types and makes on the market that this is not an easy decision. This article is intended to help in choosing a suitable capacitor.

CONVENTIONAL capacitors are made of two thin metal foils separated by a thin insulator or *dielectric*, such as mica or a man-made fibre. This sandwich is rolled or folded into a compact size and covered with an insulating coating. A wire terminal is attached to each foil. To increase the capacitance, the dielectric should be as thin as possible. This can only be done at the expense of limiting the maximum voltage that can be applied before the insulator ruptures because of the intense electric field. Another important factor is the resistivity of the dielectric. Thin, large-area shapes increase the *leakage* resistance between the foils and thus degrade the capacitor.

In ceramic and plastic-film capacitors, the metal-film plates are deposited directly on to the dielectric. Plastic dielectrics have very high resistivity so that the leakage resistance is very small.

Electrolytic capacitors are made of an oxidized metal foil in a conducting paste (dry) or solution (wet). The thin oxide film is the dielectric between the metal foil and the paste or solution. Since the film is very thin, the capacitance is large. The metal foil is normally made of aluminium or tantalum.

The capacitance, C, of a capacitor is determined by the dimensions of the foils and the thickness and relative permittivity, ε_r, of the insulator:

$$C=\varepsilon_r A/d \times 8.85 \times 10^{-12} \quad [\text{farad}],$$

where A is the surface area of the foils in m^2 and d is the distance between the foils in m. The ε_r of polyester is about 3, while that of tantalum oxide is around 11.

The thickness and type of material of the dielectric determine the breakdown voltage of the capacitor: therefore, a high-voltage type is larger than a low-voltage one.

A capacitor is a non-linear electrical component, which makes it very useful in a number of applications. Its specific characteristic is the frequency-dependent reactance, X_C, which, for an ideal capacitor, is

$$X_C=1/2\pi fC \quad [\Omega].$$

This would appear to indicate that the reactance characteristic of a capacitor is a constantly dropping curve (on a logarithmic scale). This is, of course, not so, because the reactance would then really become 0 Ω.

This is not the only non-ideal aspect of a capacitor. Apart from internal resistance (which is, of course, unwanted), a capacitor also has self-inductance, the magnitude of which is determined by its construction, the manner in which the terminals are connected to the foils and the length and shape of the terminals.

Furthermore, no dielectric is a perfect insulator; therefore, leakage currents will occur and these play an increasing role as the voltage across the capacitor becomes higher.

Figure 1 shows the equivalent circuit of a practical capacitor: C is the real capacitance and this is shunted by the insulating resistance, R_p of the dielectric. In series with that combination is a resistance, R_s, which represents the minimum transfer resistance of the capacitor from one terminal to the other. In

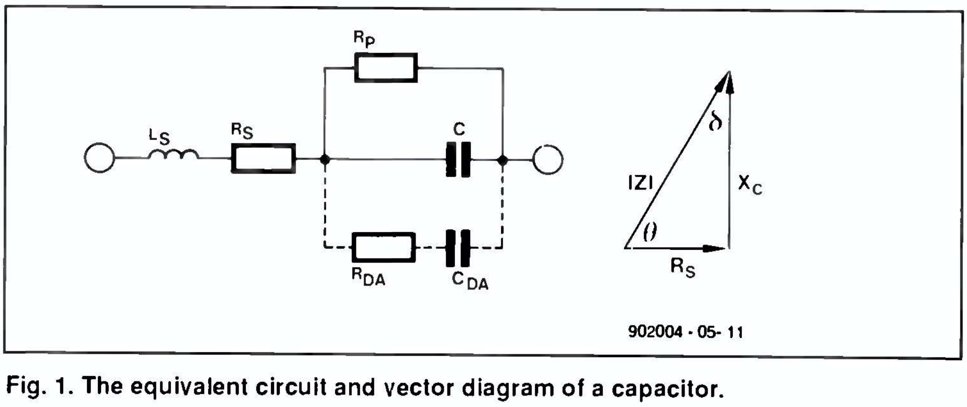


Fig. 1. The equivalent circuit and vector diagram of a capacitor.

series with that network is the self-inductance, L_S, of the capacitor. Furthermore, in parallel with C and R_P is a series network consisting of R_{DA} and C_{DA}, which represents the dielectric absorption of the capacitor. This is a less well-known property of capacitors. The dielectric absorption, DA, is a charge displacement phenomenon in the dielectric that causes a sort of memory lapse (a delayed transfer of acquired energy). Very few manufacturers quote the DA in their datasheets. This phenomenon, which affects the sound quality of the circuit in which the capacitor is used, will be reverted to later on in the article.

The impedance vs frequency characteristic, obtained from measurements on a 2.2 µF capacitor, is shown in Fig. 2. Up to about 200 kHz, the capacitor behaves almost ideally: the impedance diminishes linearly. At around 900 kHz, resonance is brought about by C and L_S (see Fig. 1). The minimum impedance at that point is virtually equal to R_S. At frequencies above 2 MHz, the capacitor behaves as a pure inductance (L_S).

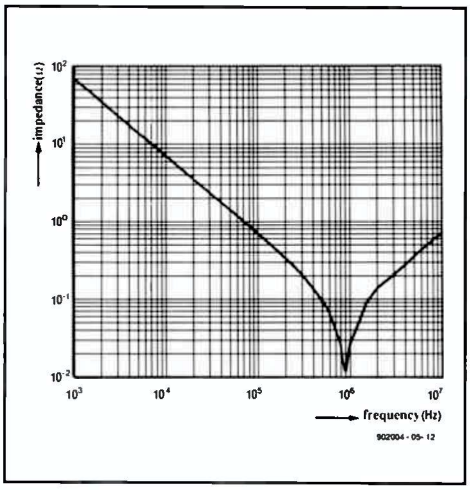


Fig. 2. Impedance vs frequency characteristic of a metal-plated polypropylene (MKP) filmcapacitor.

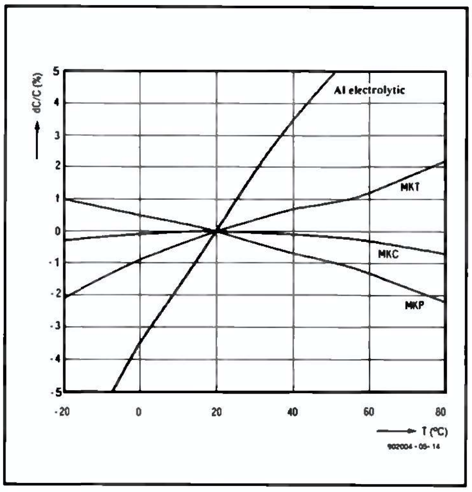


Fig. 3. Temperature-dependent behaviour of four different kinds of capacitor.

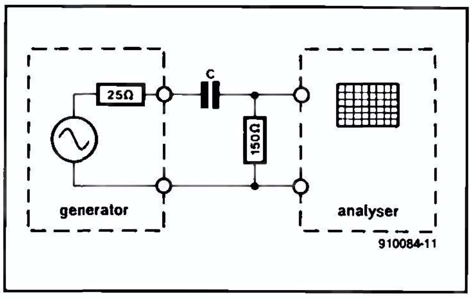


Fig. 4. Setup for measuring the harmonic distortion of various capacitors.

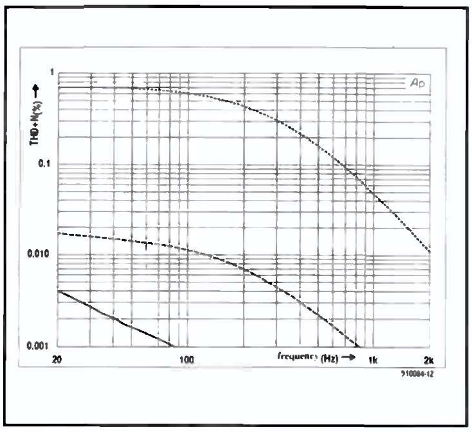


Fig. 5. Harmonic distortion vs frequency curves for tantalum (top), electrolytic and MKT (bottom) capacitors.

Specifications

Parameters to look for in manufacturers's specifications and data sheets are given below.

- The *dissipation factor*, $\cot\theta$ or $\tan\delta$, indicates the losses caused by R_S, and should thus have a low value (θ is the phase angle; δ is the loss angle). A low value is particularly important if the capacitor is to be used in a cross-over filter. Note that $\tan\delta$ is frequency-dependent and is approximately equal to $2\pi fCR_S$. Some manufacturers give the value of R_S separately for large-value electrolytic capacitors.
- Only a few manufacturers give the value of the *dielectric absorption* (DA) and then only in the case of film capacitors. Here again, the lower this value, the better the capacitor. The DA of electrolytic capacitors is so large that it is never quoted.
- The *insulation resistance*, R_P, is normally of the order of hundreds of megohms and seldom plays a role in audio applications.
- The dissipation may be indicated by the *power factor*, which is equal to the ratio R_S/Z ($=\sin\delta$).
- The *temperature behaviour* is usually given for a certain dielectric—see Fig. 3.
- The *capacitance* and associated *tolerance* of most capacitors, but not HF types, is normally given at a frequency of 1 kHz.
- The *working voltage* must, of course, be higher than the maximum voltage that will occur across the capacitor. Note that the manufacturer may state this as a direct voltage or as an alternating voltage.

What kind of capacitor?

Since this article deals with capacitors for audio applications, we will restrict us to the kinds of capacitor that are available in relatively high values: ceramic and mica capacitors are, therefore, not considered. That leaves film, electrolytic and paper capacitors.

Paper capacitors are hardly seen these days, although they are found in some equipment from the Soviet Union. Their quality is in general very good.

Of the film capacitors, *polyester* (Mylar™) types form the largest and least expensive group. Their quality is fairly good and their dimensions are reasonable.

Polycarbonate (MKC) capacitors have slightly better properties than polyester types. They are the right choice for circuits where good temperature behaviour is important.

Polypropylene (MKP) types are better still, but are generally rather larger than the previous two types.

Polystyrene (MKS or Styroflex™) capacitors are definitely the best for use in audio circuits, but they are fairly large and generally not available in values above 0.5 µF.

Electrolytic capacitors are decidedly inferior to film capacitors. Their tolerance is fairly large and this makes them unsuitable for use in filters.

A special version of the traditional wet electrolytic capacitor is the *bipolar* type that is used primarily in cross-over filters, although they can be useful in other audio circuits.

Finally, *tantalum* capacitors are not really suitable for processing audio signals, because, owing to their construction, they exhibit semiconductor effects.

Measurement results

A large number of measurements on a variety of capacitors from different manufacturers showed the following results.

The measured value of capacitance deviated from the stated value by not more than 2% in the case of *polypropylene* capacitors; not more than 4% in most of the tested *polyterephthalate* (MKT) types; and up to 20% in the case of *electrolytic* capacitors.

The measured *dissipation factor*, $\tan\delta$, of all tested capacitors was low.

The *third harmonic distortion* (THD) of capacitors used in a high-pass filter with a load resistance of 100 Ω, measured at 250 Hz, was <0.001% for all film types, and varied between 0.011% and 0.025% with electrolytic types.

The *dielectric absorption*, DA, was measured by charging the capacitors for 5 minutes at a direct voltage of 1.5 V, then short-circuiting them for 3 seconds and finally measuring the residual voltage with a voltmeter with 50 MΩ input impedance. This deviates somewhat from the MIL-C-19978-D test, but it is felt to give a better insight into the relation between C_{DA} and R_{DA}. The DA for all MKP types was 0.01% or smaller; varied between 0.05% and 0.11% with MKT types; and varied between 0.63% and 3.3% with electrolytic types.

It is clear from these measurements that differences between capacitors with the same dielectric are small. This has, no doubt, a lot to do with the fact that capacitor manufacturers buy the foil from a small number of producers. The tests threw up a few bad results even with the more expensive types. In other words, even when you buy an expensive capacitor, you have a (very) small chance of getting a rogue.

The poor DA figures of electrolytic capacitors are probably the reason that these components often adversely affect the sound quality of audio circuits, which is not at all evident from their THD figures. Note that the DA and the THD have no direct relationship.

The self-inductance of the capacitors tested was negligibly small: <50 nH in the case of 2.2 µF capacitors. Modern production methods appear to result in minimal self-inductance: most of this is formed by the terminals (length and shape).

As an aside: when procuring the many capacitors for the tests, it was found that the larger values are normally stocked by loudspeaker DIY dealers, but not by many general electronics retailers.

In the audio circuit

Where quality is paramount, leave out anything from the signal path that is not strictly necessary is good advice. But, be careful, because poor components in the feedback loop of an opamp or power amplifier do, of course, also adversely affect the quality of the signal. Furthermore, the power supply also plays a role: it is advisable to shunt its large electrolytic capacitors with film types of not less than 0.47–1.0 µF to improve the circuit's performance at higher frequencies.

Figure 4 shows an interesting setup for investigating the kinds of irregularity capacitors produce. It is a high-pass filter with

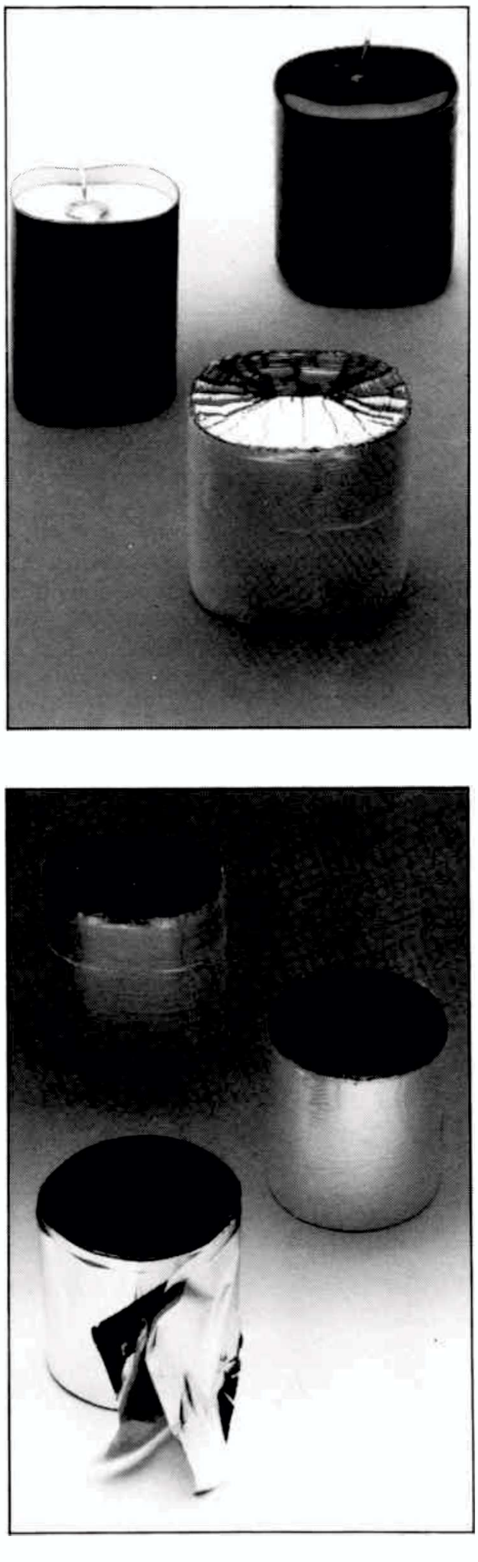


Fig. 9. Capacitors are made of two thin metal foils separated by a thin insulator or dielectric, such as mica or a man-made fibre. In plastic-film capacitors, the metal plates are deposited directly on to the dielectric. This 'sandwich' is rolled or folded into a compact size and covered with an insulating coating. An axial wire lead is attached to each foil. Shown here are the various production stages of a metal-plated polyterephtalate film (MKT) capacitor.
Electrolytic capacitors are made of an oxidized metal (usually aluminium or tantalum) foil in a conducting paste ('dry electrolytic') or solution ('wet electrolytic'). The thin oxide film is the dielectric between the metal foil and the solution or paste. Since that film is very thin, the capacitance is large: values from 1 µF to 10 000 µF are available. The largest values can only be used in circuits where the applied voltage is low to avoid breakdown of the dielectric.

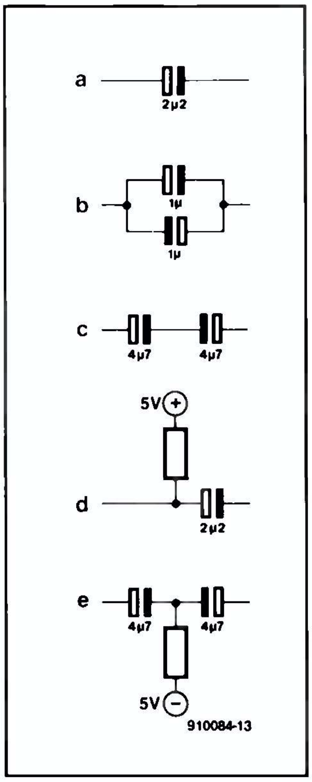


Fig. 6. Possible configurations of electrolytic capacitors.

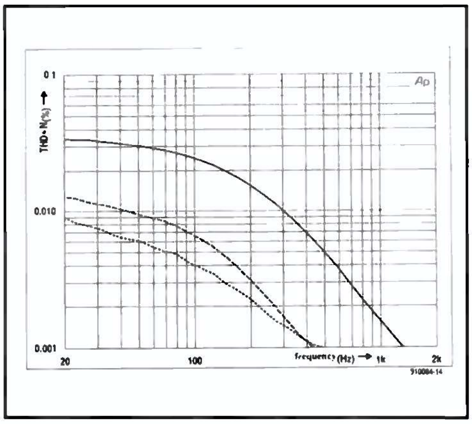


Fig. 7. Harmonic distortion vs frequency characteristics of configurations in Fig. 6a (top); 6b, and 6c (bottom).

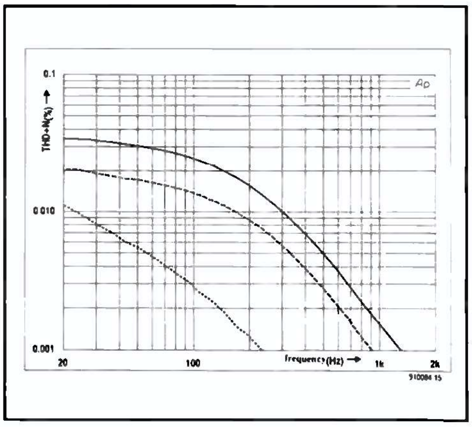


Fig. 8. Harmonic distortion vs frequency characteristics of configurations in Fig. 6a (top); 6d, and 6e (bottom).

cut-off frequency at around 400 Hz. A relatively low load is used to better show up any deficiencies (high loads improve the distortion factor). A frequency of a few hundred hertz is necessary to show how the capacitor behaves below the cut-off point.

Figure 5 shows the harmonic distortion of three types of capacitor: MKT, wet electrolytic and tantalum. The tantalum is poor, the electrolytic is reasonable and the MKT produces virtually no distortion (ignore its distortion at very low frequencies because that is caused by the measurement setup).

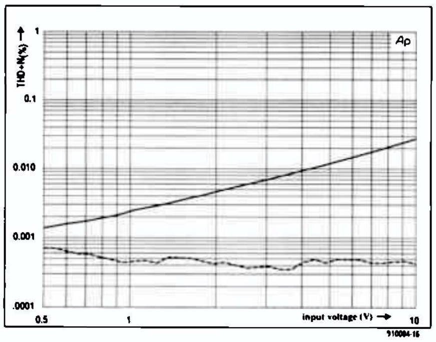


Fig. 10. Distortion vs applied voltage characteristic of an electrolytic capacitor(top) and a metal-plated polypropylene type; the test frequency was 500 Hz.

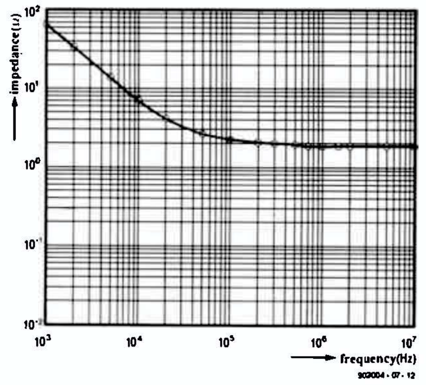


Fig. 11. Impedance vs frequency characteristic of an electrolytic capacitor shows that above 10 kHz the component does no longer behave like a capacitor.

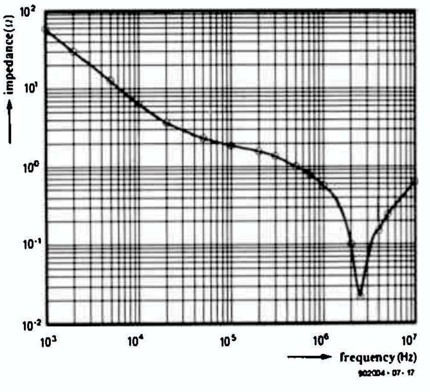


Fig. 12. The impedance vs frequency characteristic of an electrolytic capacitor shunted by a film type is still far from ideal.

It appears, therefore, that the distortion increases below the cut-off point of the *RC* combination, that is, when the voltage across the capacitor increases: the same condition that a coupling capacitor experiences. It could be concluded that it would be advantageous to give the coupling capacitor a much larger value than necessary, that is, to choose a cut-off point of 1 Hz instead of 10 Hz. In principle, the area of distortion would then also be shifted downwards and largely fall outside the audio range. A measurement with a 100 μF capacitor in the setup of Fig. 4 showed that the distortion did, indeed, shift down relative to that with a 2.2 μF capacitor, but it also showed that the distortion characteristic became much steeper upwards. In other words, large-value electrolytic capacitors produce a relatively much larger distortion than smaller ones.

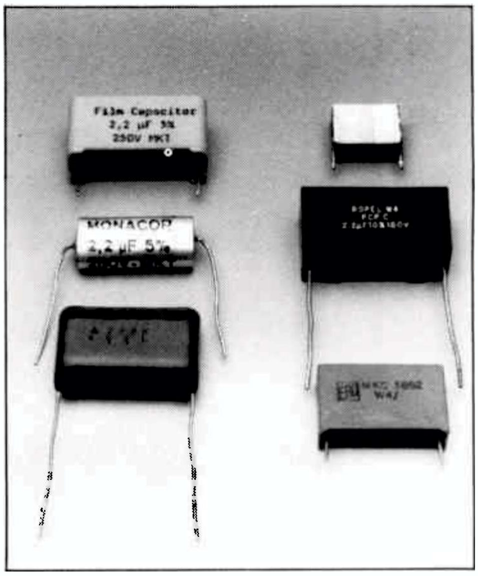
It is undoubtedly best to use MKP or MKT types for coupling capacitors. Unfortunately, that is not always possible owing to non-availability or lack of space, and electrolytic types must then be used. To find out how to keep the distortion caused by these components as low as possible, measurements were carried out on several configurations of electrolytic capacitors as shown in Fig. 6; the resulting distortions are shown in Fig. 7 and Fig. 8. The level of the input signal was 2 V r.m.s.

The distortion of a single electrolytic capacitor (Fig. 6 a) is fairly high as seen in Fig. 7. The distortion of an anti-parallel network (Fig. 6b) is much smaller, but this configuration can handle alternating voltages of a few volts only; moreover, the direct voltage across it must be virtually zero. The series network (Fig. 6c) is better still; it behaves, in principle, as a bipolar electrolytic capacitor.

In a practical circuit, there will be a direct potential across the coupling capacitor, which can have beneficial results. For instance, with a direct voltage of 5 V across a single electrolytic capacitor (Fig. 6d), the distortion, as shown in Fig. 8, is noticeably smaller. If the same voltage is applied to a series combination (Fig. 6e), a small improvement in distortion compared with that of the setup in Fig. 6c results. This is easily realized with the aid of a resistor of, say, 100 kΩ, to the negative supply line.

Figure 10 shows the distortion measured on an electrolytic capacitor and an MKP type at a frequency of 500 Hz and input signals of 0.5–10 V r.m.s. It is clear that the distortion caused by the electrolytic type is voltage-dependent. When, therefore, large signal levels (as in valve amplifiers) are processed, the quality of the coupling capacitor is even more important than with small signals.

In these tests, only harmonic distortion was measured. In the case of electrolytic capacitors, this is caused primarily by odd harmonics, which are particularly offensive to the human ear. There are, however, other types of distortion, such as that caused by DA. This causes irregularities in the dynamic behaviour of a capacitor and also muffles the sound at low frequencies. Figure 11 shows the impedance characteristic of a typical 2.2 μF electrolytic capacitor, which, compared with the curve of Fig. 2, is poor. At 20 kHz, the curve is already well away from the ideal line, while above that frequency, the impedance sticks at 2 Ω. In preamplifiers, this does not matter all that much, because the terminating impedances there are of the order of a some thousands of ohms. In low-impedance circuits, however, it does. To retain the proper functioning at higher frequencies, the electrolytic capacitor is often shunted by a film type. This is, however, effective only if the value of the film capacitor is not too small compared with that of the electrolytic type. Figure 12 shows what happens when a 2.2 μF electrolytic capacitor is shunted by a 0.22 μF MKT type: the characteristic improves but only at fairly high frequencies. For good results, the value of the film capacitor must be not less than one third of that of the electrolytic type.



The shunting has no effect on the DA, because the worst component in the parallel network determines the DA. Only when the values of the film capacitor and the electrolytic capacitor are about the same is the DA of the combination reduced to about half that of the electrolytic capacitor.

Figure 12 also shows that shunting the electrolytic capacitors in a power supply with film types makes real sense. The electrolytic capacitors alone hardly decouple the supply lines at higher frequencies, whereas the film capacitors ensure that signals up to a few MHz are suppressed effectively so that they cannot cause interference in the audio circuits. ■

AUDIO/VIDEO SWITCHING UNIT

As more and more audiovisual equipment is cheerfully stacked up in your living room, connecting it all is bound to become a problem sooner or later. What do we want? A number of audio and video signals have to switched between different equipment: for instance, we want the pictures produced by the hi-fi video recorder to be visible on two TV sets at the same time, while the recorder should still allow us to choose between recording TV sound or a signal from 'the stereo'. All this is possible with the electronic switch discussed here, which can be given as many inputs as you think necessary.

by T. Giffard

GONE are the days when every home had one TV set and one radio, and many of you will have grown accustomed to the presence of a stereo set, a video recorder, several TV sets, a camcorders, a portable CD player, or a DAT recorder in the living room and elsewhere in the home. Unfortunately, linking all this wonderful equipment is never easy, since low-frequency (audio) as well as high-frequency (video) signals have to be switched and routed without losses and cross-talk. Apparently, a kind of 'switchbox' is in order.

The audio/video switching unit described in this article has the function of a versatile signal router that allows two or more devices to be connected to a single video input on a TV set or a video monitor. This feature is particularly useful with older TV sets.

Switching and routeing video signals is not as easy as audio signals because the signal bandwidth is much greater (approx. 6 MHz instead of 20 kHz). Since an ordinary rotary switch is not suitable for this function, Philips Components have developed an integrated circuit capable of switching two (stereo) audio and two video signals simultaneously, and electronically. Fig. 1 shows the block diagram of this IC, the TDA8440,