All About Capacitors

The finer points of capacitors and how to select them.

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There is an old joke that a metallurgist is someone who, given a choice of materials, chooses wood... The point, I suppose, being that any specialist who knows the snags inherent in his chosen speciality is likely to be more enthusiastic about the potential use of something else.

This is basically how I feel about capacitors.

For some years I was involved in the manufacture of the polypropylene film used in making capacitors, responsible for the electrical evaluation of our own and competitive films of various types to see how well they would perform. This was quite an interesting project and involved visits to a large number of capacitor manufacturing companies to discuss the use of polypropylene and other films in this particular field. I don't think that this makes me a capacitor specialist, but at least I have had a rather closer acquaintance with this topic than is normal for electronics engineers. I know a lot of the unpublicized problems.

So Say The Hi-Fi Buffs

Quite a lot has been written in recent years in the 'Hi-Fi' and electronics press about the differences in sound quality which can be brought about by changes in the type of the passive components used in the audio system, whether these be resistors, capacitors, connecting cables, mains transformers, printed circuit board materials, solder, or even the screws with which the cases are held together.

With most of these claims technically plausible explanations for the observed effects are usually only remarkable by their absence.

The tests on which they are based are also inevitably subjective in their nature and rely on listening trials which, however extensive, can seldom be conducted on an instantaneous 'A vs B' switch-over comparison. Where any length of time elapses between two alternatives, the memory becomes clouded and expectations begin to colour the observations.

There may be basis for the claims, though I feel that these are often exaggerated or incorrectly interpreted by their discoveries – like the change in sound quality (sometimes even for the better, since it lessens crossover distortion) which happens when an amplifier having a poor stability margin is caused to oscillate at some ultrasonic frequency by the unwise connection of high self-capacitance LS leads. I remain agnostic.

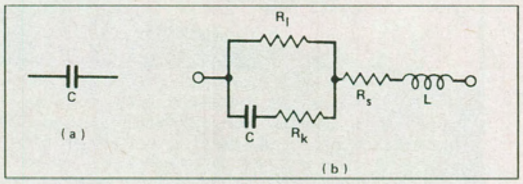

Fig. 1 (a) Circuit symbol (b) Accurate representation of a capacitor

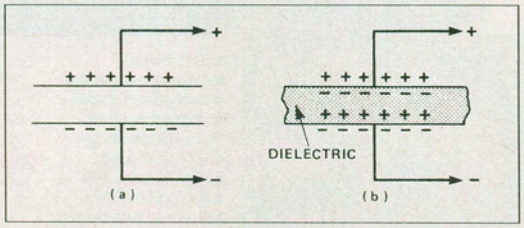

Fig. 2 Physical construction (a) without dielectric (b) with dielectric

Nevertheless, in the case of capacitors and particularly in the case of those used in the feedback loop of an amplifier using negative feedback (NFB), I feel that a good case can be made for care in their choice, since there are effects which are capable of being measured instrumentally as well as being heard.

But there is no blanket answer to the question of which capacitor do I use – it will depend on where you want to use it, what are the particular qualities which are especially needed in that position, how much space you can spare, and how little bothered you are about wasting money.

As for polypropylene (the current favourite of the golden-eared fraternity) the questions I would ask are "what type, how made and by whom, and how used?" So, let us look at some technicalities.

Normally in circuit diagrams the circuit symbol shown in Fig. 1a is used to depict a capacitor, but in reality it is more accurately represented by the drawing of Fig. 1b, where C is the capacitance at some specified frequency, temperature and applied voltage, R(1) is the leakage resistance across the capacitor (which again may be temperature, humidity, frequency and applied voltage dependent), R(k) is the equivalent series resistance due to dielectric loss (again not a constant factor), R1 is the straightforward series resistance due to its method of manufacture, and finally 'L' is the inevitable inductance of the component.

Physical construction

In principle, a capacitor is a pair of conductors in proximity to each other but not in electrical contact, such as a pair of parallel conducting plates in a vacuum (as shown in Fig. 2a). When an electrical potential is applied between these plates, electrons will flow into the negatively connected plate from the negative pole of the applied potential. An equivalent number of electrons will be repelled away from the opposite plate and will flow towards the positive pole of the applied potential. If there is some circuit resistance this will lead to the familiar charging current stage shown in Fig. 3.

If the potential is removed and the wires from the capacitor are shorted together, the same process will happen in reverse, so the wires will probably spark as they touch since there is now no longer any reason for the asymmetry of charge on the plates. The theoretical value of such a capacitor (ignoring the effects of fringe fields at the edge of the plates) is given by the formula:

C = AK/11.315d (pF)

where A is the effective opposed area of the plates, K is the dielectric constant of the material separating the plates (=1 for vacuum or air), and d is the gap separating them – all dimensions being in centimeters.

The practical problems of such a construction are due to the need to prevent the plates from touching and the difficulty of getting any large amount of capacitance.

These can be solved if some insulating material is fitted into the gap, as I have shown in Fig. 2b. If this is thin and has a good electrical strength, the gap d between the plates can be made very small which increases the capacitance for a given effective plate area (see the formula above).

Dielectric For Division

The capacitance will also be increased because the dielectric constant K of the insulating material will be greater than unity. This comes about because all such insulating materials will 'polarize' to some extent, either by the displacement of orbital electron clouds surrounding the atoms of the constituent material, or by the migration of ions, or by the physical reorientation of polar molecules.

This has the effect of producing equal but opposing charges on the surface of the insulator facing the capacitor plates (Fig. 2b) which lessens the effective spacing between the plates.

Unfortunately, the introduction of a dielectric brings the problem of leakage (though this isn't such a problem with modern materials as it was with the old waxed paper insulated "tar babies" of my early years in electronics). The insulation may break down electrically though there are techniques for reducing this hazard. The dielectric constant may not be constant – certainly it will decrease with applied frequency and will also be affected to a lesser extent by temperature and applied voltage.

Finally the dielectric introduces "dielectric loss" which is represented by the term Rk in Fig. 1b. This comes about (understandably)ably because the migrations of electrons or ions or the molecular reorientations (which produce the effect shown in Fig. 2b, and which cause the increase in capacitance) all absorb some energy when they occur, which is every time the applied electrical field is reversed.

The more frequently the polarity of the applied electric field is reversed (the higher the operating frequency) the higher the loss. Materials such as the largely non-polar plastic (polyethylene, polypropylene, PTFE, and polystyrene) don't have very high dielectric constants – which doesn't help very much to make compact high value capacitors. On the other hand very little happens when the field is reversed, so the dielectric loss is very low and the dielectric constant K doesn't alter significantly with frequency (up to the GHz range).

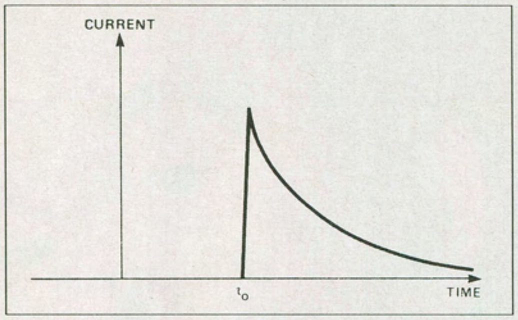

Fig. 3 Typical capacitive charging current pulse

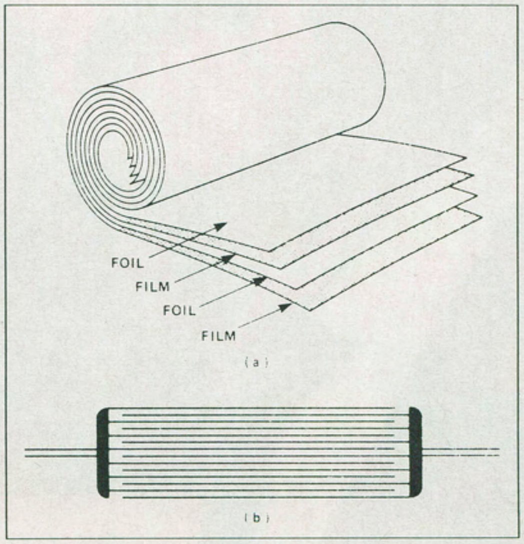

Fig. 4 Foil/film capacitors (a) construction (b) contacts

The thinking of the hi-fi purists is largely coloured by considerations of dielectric loss, and "pp" is reputed to be very low and therefore very good. However, the actual loss factor depends on the purity of the material, on the way in which it is made (including additives included to assist in production and the extrusion temperature). I have listed the major qualities of the most common dielectric materials in Table 1, but as I have indicated these figures can only serve as a guide.

Non-polar Manufacture

Generally, plastic film insulated capacitors are either of the film/foil type, or of the metallized film construction. In the F/F type, two long lengths of aluminum foil (which should be scrupulously clean and of high purity if the loss factor of the capacitor is not to be worsened) are sandwiched between a pair of slightly longer strips of plastics film and the whole thing is wound up in swiss roll form, as shown in Fig. 4a.

Usually the foils are arranged so they extend a bit beyond the edges of the film strips so that electrical end contacts can be made to them as shown in Fig. 4b. Sometimes (as is usually the case with, the small polystyrene capacitors) the foils don't overlap the film but a pair of connecting wires is simply trapped in the spiral while it is being wound.

With larger capacitors it is helpful to make a continuous edge contact since this lessens the spurious inductance value, because of the shorted-turn effect. It also helps keep the electrical resistance of the plates low.

In all film/foil capacitors the electrical strength and consequently the thickness of the film must be great enough to prevent any possibility to electrical breakdown at the rated working voltage. Such capacitors therefore tend to be bulky for a given capacitance value.

In the case the metallized film (MF) types, the problem of possible electrical breakdown is solved by using a very thin metallic conducting layer, vacuum evaporated onto the surface of the film so that it leaves a clear strip along each alter-

Dielectric Material	Dielectric Constant (K)	Breakdown Strength (Volts/mil)	Loss Factor (Tan σ. 60Hz
Polyethylene (High density)	2.3	500-1000	0.0003-0.001
Polypropylene	2.2-2.3	450-650	0.0001-0.0003
Polyester	3.0-3.5	1500-2000	0.001-0.005
Polystyrene	2.5-2.6	500-100	0.0001-0.0002
Polycarbonate	2.97	400-450	0.0001-0.0005
PTFE	2.1	500	<0.0001
Polysulphone	2.82	420	0.008
Mica	5.4	2500	0.0005
Ceramics	30-6000	50-250	0.01-0.4

nate edge. End contacts are then made by spraying a solderable metallic layer onto each end of the sandwich. Such MF capacitors will "self heal" in that if there is a local breakdown of the dielectric, the instantaneous discharge of the stored electrical energy through the puncture will burn off the metallized layer in that region.

Such internal flash-overs cause a gradual worsening of the loss factor because of the accumulation of combustion products in the windings. They also cause a gradual decrease in capacitance. Both of these problems are lessened significantly by not running the capacitor at more than half of its rated working voltage.

The major problem with 'MF' types however is that the metallized layer is so thin and has a significant winding resistance Rs which cannot be distinguished electrically from dielectric loss. On the other hand they are very small in size.

There has recently been an increased availability of stacked foil capacitors, a number of postage stamp sized pieces of film with either metallized layer or foil plates assembled into a small rectangular stack, and then resin encapsulated with projecting radial connection leads as shown in Fig. 5. These have the advantage of low series inductance and compact PCB assembly, but are otherwise similar in characteristics to the spiral wound versions.

Tantalum And Aluminium Electrolytic

In these capacitor types, a large value of capacitance is obtained by chemically growing a very thin insulating oxide film on the surface of an etched metal plate or a pellet of sintered metal powder, with a conducting electrolyte occupying the gap between this and the other plate. This avoids the problem of electrical failure through breakdown of the insulating layer because if there is a puncture in the oxide film it is promptly repaired by local electrolytic action between the exposed metal and the electrolyte.

The snag is that this action is going on all the time, with continuous small pulses of current evened out by the capacitor itself into a fairly smooth current flow. The electrolyte though quite a good conductor is not as good as a layer of metal, which is why the non-polar capacitors always have a lower series resistance value. The other problems are that the value of the series resistance is dependent on voltage, temperature and frequency, as is the capacitance itself.

Also, the polarity of the capacitor must be observed, and if any AC potential is likely to appear across it there must always be a continuous DC bias voltage which is greater than this. This means that electrolytic are not very happily used with zero polarizing potentials.

When tantalum bead (sintered tantalum pellet, resin encapsulated) electrolytic first appeared they were greeted with great enthusiasm since they had a lot of factors in their favour. The tantalum oxide dielectric was electrically and chemically very strong, and it had a much higher dielectric constant than alumina. This meant that a much more acidic electrolyte could be used giving lower

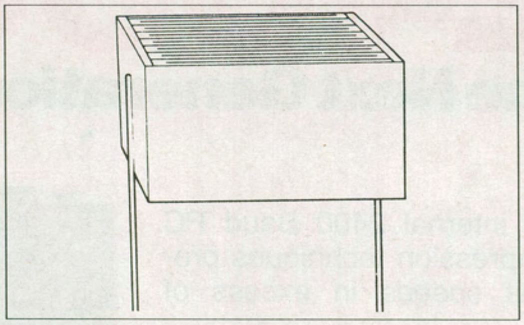

Fig. 5 Stacked foil capacitor

series resistance, and more capacitance could be packed into a small volume.

In addition because of the strength of the oxide layer, the capacitor would even stand small (0.5-1V) reverse potential which permitted use in signal lines. Unfortunately the instantaneous (though small) voltage dependence of conductivity leads to a complex behaviour pattern on transient voltage steps, and this can give a rather dull sound when used as the blocking capacitor in a feedback line.

The increase in the cost of tantalum bead capacitors has stimulated research work on their aluminum equivalents with the result that physically small high-capacitance aluminum types are now available which are much to be preferred in audio use such as DC blocking in signal or feedback lines if high capacitance values are essential (though their quiescent working potentials must be carefully chosen). Even so, non-polar types should always be the first choice, except in routine supply line decoupling duty.

Permanent Polarization

This is the electrostatic equivalent of permanent magnetization and is a snag which is exclusive to the plastics film dielectric types of capacitor. As in steels, the durability of such a permanent polarization is a function of the hardness of the materials. It occurs much more readily in those films which are biaxially stretched during manufacture such as polypropylene or polyester (PETP) since this greatly increases their mechanical strength.

Those films which are made by casting from a lacquer (such as polystyrene, polycarbonate, or polysulphone) or by sintering a powder (such as PTFE) are much more limp physically and much less prone to this defect which can have the effect of building in a permanent series potential within the capacitor dielectric.

Circuit Applications

It is practicable to design audio amplifiers without very many capacitors at all and most IC opamps only have one, used to stabilize the circuit at high frequencies by reducing its HF gain.

In audio circuitry, capacitors will be used as DC blocking elements such as C1 in Fig. 6 to prevent inadvertent DC offsets that occur in early stages of the system from being amplified along with the wanted AC signal and ending up as a very big DC offset at the speaker output terminals.

A similar function is performed by the series capacitor in a negative feedback circuit (C2 in Fig. 6) where A is some kind of gain block (an op amp or equivalent). The gain of this stage at some frequency where the impedance of C2 is low enough to be neglected is (R2 + R3)/R2. However at DC, where the capacitor (if it is a perfect component) is an open circuit, the gain reduces to unity so any DC offset between the (insert plus,minus symbol) in' points of the amplifier will not be made worse by the AC stage gain. The corollary to this is of course that the gain of the stage will decrease as the operating frequency decreases and the impedance of the capacitor increases, so it must be big enough.

A further important function is in the decoupling of the supply lines to the amplifier (C3 and C4 in Fig. 7).

Most amplifier circuitry is designed in the expectation that the plus and minus DC supplies to it will be stable and free of ripple, unwanted signal components or general noise and rubbish. The performance of the amplifier may be impaired — especially in relation to its stability margins, which are very important — if any output signal can find its way back into the signal circuit by way of the supply lines. The easiest way to secure clean smooth supply voltages is in theory to decouple them to a good neutral OV line by way of a very low impedance capacitor.

The final circuit positions where capacitors are needed is in time-constant generation circuitry, in tone controls, frequency response shaping circuitry (such as RIAA), LF and HF filters, and HF loop stabilization functions. Fortunately, in most of these positions the actual capacitance values required are fairly small, so problems of cost or physical bulk are usually minor ones.

Now let us look at these applications and see what characteristics are required.

DC Blocking

Looking at the circuit in Fig. 6, the important needs are that the impedance of C1 at any valuable part of the audio signal bandwidth should be sufficiently low (in comparison with R1 and the input impedance of the gain block A) that the input signal is not attenuated significantly. For the blocking function to be adequately performed, the leakage resistance of the capacitor must also be very high. Fortunately with modern film dielectric capacitors this can usually be taken for granted.

This might not be true in the case of electrolytics, especially if the polarity is inadvertently reversed through careless installation or incorrect interpretation of circuit operating potentials. Generally, in circuitry with hi-fi pretensions it is well to avoid electrolytics in this position and if necessary rearrange the circuitry so that large capacitance values are unnecessary. The impedance presented by the other parasitic elements (inductance and series resistance) is unlikely to be significant, certainly in audio use, in comparison with the combined input impedance of R1 and the gain block.

It could also be argued that for hi-fi circuitry the effective capacitance value of C1 should remain constant (especially as a function of the voltage applied across it) so that it does not introduce subtle waveform distortion effects.

Once again, plastic film dielectric capacitors (the so-called non-polar types) are unlikely to suffer from the defect at typical small signal voltage levels to an extent which is detectable. It might though be a problem with electrolytics.

Feedback Path Capacitors

The other DC blocking function is typified by C2 in Fig. 6. Here the problems are greater since circuit constraints are likely to force the use of a relatively low value of R2, and the LF roll- off frequency (the -3dB point) occurs where the impedance of C2 (1/2nfC) is equal in value to R2.

In the past, C2 would have almost always have been an electrolytic type, aluminum or tantalum, but in current practice it is likely that a non-polar component would be employed to avoid any possible dulling of the sound. The values of R3 and R2 would be increased as much as other circuit demands allowed. The same needs exist here as in the input DC blocking capacitor, but are all greatly magnified because the circuit impedance is usually so much lower so that small changes in series impedance or capacitance value are likely to be much more important.

Supply Line Decoupling

Here the overall need is for the effective impedance to be as low as possible and to remain low over the whole of the frequency spectrum. The preservation of a low decoupling impedance well beyond the limits of the audio range is important for loop stability reasons. Improvements in the purity of the supply lines are usually apparent in the sound quality. Electrolytic capacitors are usual for this and have a relatively high series impedance by comparison with a non-polar type of the same value. Modern practice is to quote the 'equivalent series resistance' (ESR) of electrolytic in the manufacturer's specification (usually for power supply reservoir capacitor applications).

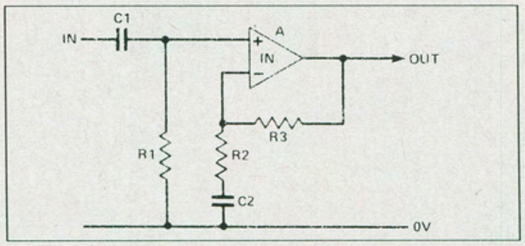

Fig. 6 Capacitors in audio amplification

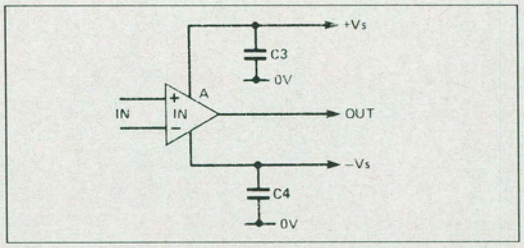

Fig. 7 Capacitors as supply decouplers

A low ESR component is usually a good choice if only because it implies that the manufactures have tried to lessen the inevitable series resistive components by greater care in design or construction. At HF the problem need not be serious, since the main capacitor can always be bypassed by a smaller non-polar type and that if necessary bypassed yet again by a smaller one still.

The reason for the piggyback activity is that the method of construction of large value bipolar units is likely to lead to higher values on inductance and winding resistances. Indeed for RF bypass use (as in the HF stages of FM tuners) small value disc ceramic capacitors are obligatory because of their very low self-inductance. No wound component would ever be adequate here. Unfortunately disc ceramic devices are usually only available at low for audio circuitry. Stacked film bipolar types are a good equivalent for audio circuit use.

At the very low frequency end of the passband no capacitor of any sensible size is ever likely to be entirely adequate, and here an electronically stabilized power supply is by far the best answer, especially since if it does its job effectively it will provide an absolute barrier between the operational circuitry and everything on the power supply side of the hardware. This frees the user from worries about whether he ought to replace his mains transformer with a filing cabinet sized substitute.

Time Constant Components

Here the overriding need is for accuracy in value and for reasonably low levels of stray inductance, since this could have some effect on the characteristics of filters or feedback circuits. However, spurious inductance effects can normally be ignored for modern components used in sensibly designed AF circuitry, and the effects of stray series winding or loss resistances are likely to be swamped by the general circuit impedances.

Choice In Circuit Applications

In general and bearing in mind the manufacturing details discussed last month, my own order of preference in the capacitor world is polystyrene, polycarbonate, polypropylene and polyester. And I prefer film/foil to metallized foil. The most critical application, in my opinion, is as the DC blocking capacitor in an NFB loop, though other DC blocking usages must be scrutinized. Supply line bypass duty requires other qualities and a good quality electrolytic of adequate size and rating bypassed by one or more polyester capacitors of descending values will be quite adequate.

In HF stabilizing or time constant duty, polystyrene is the first choice if available in adequate capacitance values. Otherwise use any close tolerance non-polar types. Above all remember that no single type should always be first choice. ■