

# CAPACITY FOR THOUGHT

*The capacitor is a much used but often misunderstood component. John Linsley Hood turns your doubts to dust with a two-part look at all things capacitive*

**T**here 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 I know a lot of the unpublished problems.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 fixing screws with which the cases are held together.

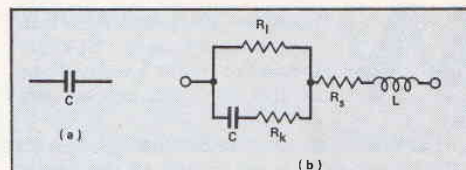
With most of these claims technically plausible explanations for the observed effects are usually only remarkable by their absence.

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.

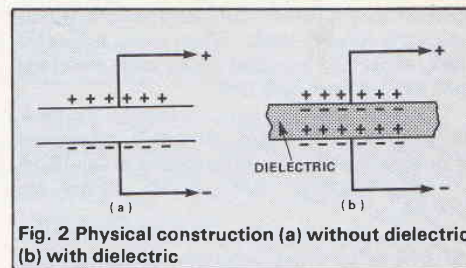
There may be basis for the claims, though I feel that these are often exaggerated or incorrectly interpreted by their discoverers — like the change in sound quality (sometimes even for the better, since it lessens 'crossover' distortion) which happens when an amplifier having a poor stability margin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

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



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



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

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<sub>l</sub>' is the leakage resistance across the capacitor (which again may be temperature, humidity, frequency and applied voltage dependent), 'R<sub>k</sub>' is the equivalent series resistance due to dielectric loss (again not a constant factor), 'R<sub>s</sub>' 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.

CAPACITORS

The theoretical value of such a capacitor (ignoring the effects of fringe fields at the edges of the plates) is given by the formula:

$$C = AK/11.315d \text{ (pF)}$$

where A is the effective opposed area of the plates, K is the dielectric constant of the material separating the plates ( $\approx 1$  for vacuum or air), and d is the gap separating them — all dimensions being in centimetres.

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 'polarise' 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 ' $R_k$ ' in Fig. 1b. This comes about (understandably) 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 plastics (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).

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

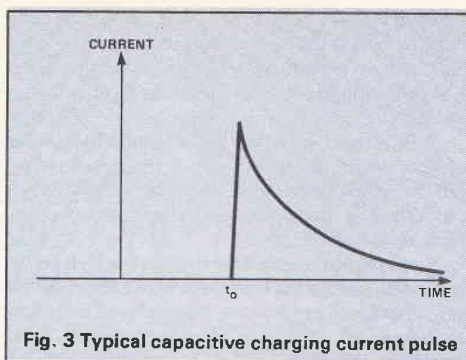


Fig. 3 Typical capacitive charging current pulse

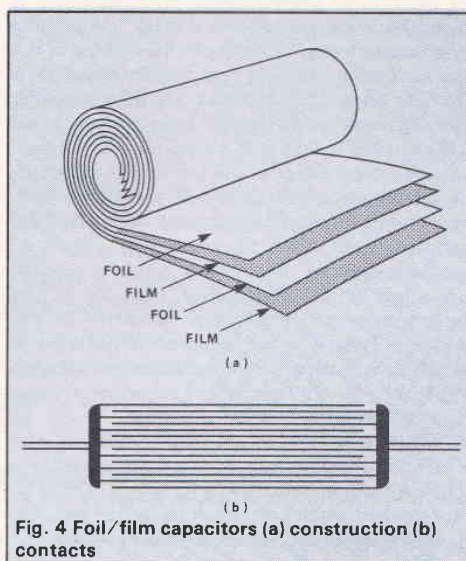


Fig. 4 Foil/film capacitors (a) construction (b) contacts

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, plastics film insulated capacitors are either of the film/foil type, or of the metallised film construction. In the 'F/F' type, two long lengths of aluminium 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

Dielectric Material	Dielectric Constant (K)	Breakdown Strength (Volts/mil)	Loss Factor (Tan $\delta$ , 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

Table 1 Characteristics of some common dielectric materials



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 of electrical breakdown at the rated working voltage. Such capacitors therefore tend to be bulky for a given capacitance value.

In the case of the metallised 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 alternate 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 metallised 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 metallised layer is so thin and has a significant winding resistance  $R_s$  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 metallised 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 Electrolytics

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.

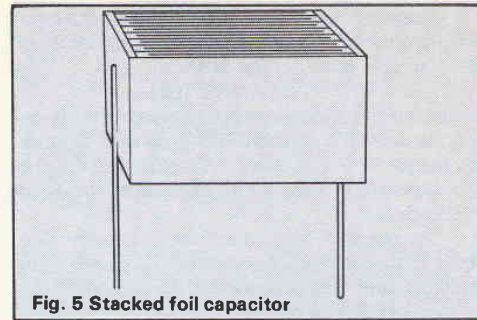


Fig. 5 Stacked foil capacitor

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 electrolytics are not very happily used with zero polarising potentials.

When 'tantalum bead' (sintered tantalum pellet, resin encapsulated) electrolytics 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 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 a 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 aluminium equivalents with the result that physically small high-capacitance aluminium 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 Polarisation

This is the electrostatic equivalent of permanent magnetisation and is a snag which is exclusive to the plastics film dielectric types of capacitor.

As in steels, the durability of such a permanent polarisation is a function of the hardness of the material. 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

Next month I shall look in detail at the specific requirements of audio circuits and how best to fulfil them.

**ETI**