Considerations for a High Performance Capacitor

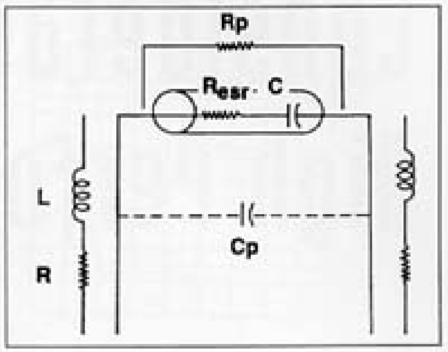
by Richard Marsh

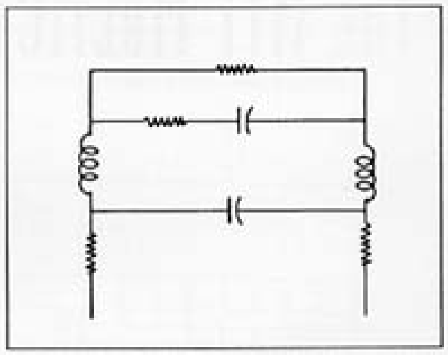
Capacitors in Real-World Applications

The capacitor is one of the primary building blocks of electronic circuits. The basic structure consists of a dielectric material sandwiched between two electrodes or plates.

The impedance of an ideal capacitor is given as Z = Xc = 1/2 (pi)fC and, if graphed, would result in a straight line that gets ever closer to zero as frequency (f) increases. However, no circuit component is ideal, i.e., purely resistive or purely reactive. All circuit components exhibit a combination of complex impedance elements: Inductors show unwanted capacitance and hysteresis effects. Resistors display unwanted inductance characteristics. Capacitors have unwanted inductance, resistance, and dielectric absorption. Different materials and manufacturing techniques produce varying amounts of these unwanted parasitics that affect a component's performance. All components, even those constructed of the finest materials and procedures, exhibit some of these artifacts and therefore should be modeled as complex impedances. (See Figures 1 A & 1 B.)

In addition to capacitance (C), two other parameters, dissipation factor (DF) and equivalent series resistance (ESR) are generally measured to reflect the presence of parasitics. Thus a much more realistic representation of a capacitor is shown in Figures 2A & 2B.





This paper will define several capacitor-based parasitics and explore their relationships and effects upon a capacitor's performance. Dielectric absorption will not be discussed in any depth here: those wanting technical details should refer to Richard Marsh's previous groundbreaking work. (See the bibliography.) Briefly, dielectric absorption has been revealed as a major source of distortion in audio circuits. Film dielectric type capacitors, particularly polystyrene, have very low dielectric absorption and for this reason are preferred in audio circuits.

Basic Considerations: DF, Q, and ESR

Dissipation Factor (DF), Quality Factor (Q), and Equivalent Series Resistance (ESR) are important parameters of high performance capacitors. Their role in low-impedance or high-current circuits such as power supplies, high-current amplifiers, and filters, is especially significant.

DF, Q, and ESR all represent heat-producing losses within the capacitor. Minimizing these losses, thus reducing heat, promotes greater stability, lower distortion, and lower mean-time-before-failure (MTBF).

Dissipation Factor (DF)

DF and "loss tangent" are largely equivalent terms describing capacitor dielectric losses. DF refers specifically to losses encountered at low frequencies, typically 120 Hz to 1 KHz. At high frequencies, capacitor dielectric losses are described in terms of loss tangent (tan ð). The higher the loss tangent, the greater the capacitor's equivalent series resistance (ESR) to signal power. In addition, the poorer its Quality Factor (low Q), the greater its loss (heating) and the worse its noise characteristics.

When a capacitor is used as a series element in a signal path, its forward transfer coefficient is measured as a function of the dielectric phase angle, (theta). This angle is the difference in phase between the applied sinusoidal voltage and its current component. In an ideal capacitor, (theta) equals 90°. In low-loss capacitors, it is very close to 90º. (See Figure 3)

For small and moderate capacitor values, losses within the capacitor occur primarily in the dielectric, the medium for the energy transfer and storage. The dielectric loss angle, ð, is the difference between (theta) and 90º and is generally noted as tan o. The name "loss tangent" simply indicates that tan ð goes to zero as the losses go to zero. Note that the dielectric's DF is also the tangent of the dielectric loss angle. These terms are used interchangeably in the literature.

Figures 1A& B: A capacitor (C) with parasitic elements & equivalent electrical circuit. A true value excludes the effects of the parasitics. In the real world, true values are of academic interest only. The effective value includes the influences of the component's parasitics.

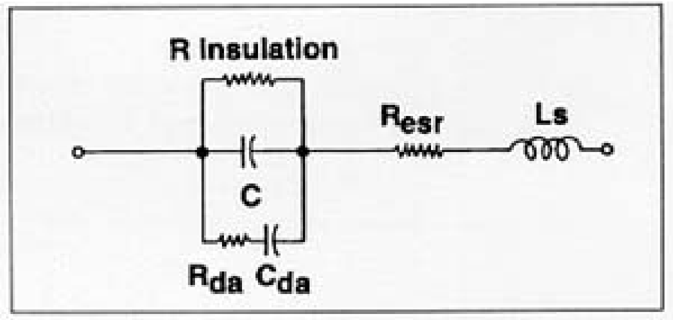


Figure 2A: A film capacitor model showing Dielectric Absorption ($R_{da} + C_{da}$). The total instantaneous charge on a capacitor may be expressed as Q = V C(Tt) + Qa (VTt), where C is the measured capacitance, V the applied electrode potential, Qa the absorbed charge not directly contributing to electrode potential, T the temperature, and t the time.

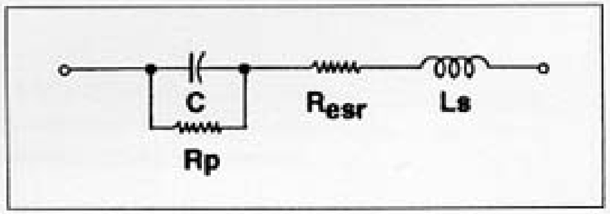


Figure 2B: In this model, $Rp = R_{insulation}$ and $R_{da} + C_{da}$ are shown lumped together. The mathematical expression is: Z =

$$\text{esr} + \frac{Rp}{1+\omega^2Rp^2C^2} + j\,\frac{\omega L - \omega^2Rp^2\,C + \omega^2Rp^2LC^2}{1 + \omega^2Rp^2\,C^2}$$

Quality Factor (Q)

Quality Factor (Q) is the ratio of the energy stored to that dissipated per cycle. For a reactive component, this is defined:

$Q = Xc/ R_{esr}$ = tan (theta)

In one aspect, Q is a figure of merit in that it defines a circuit component's ability to store energy compared to the energy it wastes. The rate of heat conversion is generally in proportion to the power and frequency of the applied energy. Energy entering the dielectric, however, is attenuated at a rate proportional to the frequency of the electric field and the loss tangent of the material. Thus, if a capacitor stores 1000 joules of energy and dissipates only 2 joules in the process, it has a Q of 500. The energy stored in a capacitor (joules. watt-sec) = 1/2 $C(V^{2)}$.

Equivalent Series Resistance (ESR)

Equivalent series resistance (ESR) is responsible for the energy dissipated as heat and is directly proportional to the DF. A capacitor should be depicted as an ESR in series with an ideal capacitance (C). ESR is determined by:
ESR = (Xc/Q = Xc (tan ð), with Q = 1/DF.
From this, we can see that "lossy" capacitors and those that present large amounts of Xc will be highly resistive to the signal power.

Circuit designs employing low Q capacitors usually produce large quantities of unwanted heat because tan ð and DF (or 1/Q) typically increase in a non-linear fashion with rising frequency and temperature. With some capacitors, this effect is enhanced by the naturally occurring decreased capacitance at high frequencies. High currents also produce increase heat, which in turn again increases the ESR and DF.

Even with substantial changes in current flow, high Q (low DF) capacitors will not exhibit the value shifts common to equivalent components exhibiting high DF, ESR, and other parasitics. Low ESR reduces the unwanted heating effects that degrade capacitors. This is an important goal in designing these components for high -current, high-performance applications, such as power supplies and high-current filter networks.

As Figure 4 shows, the significance of loss-contributing factors depends to some degree on the value of the capacitor.

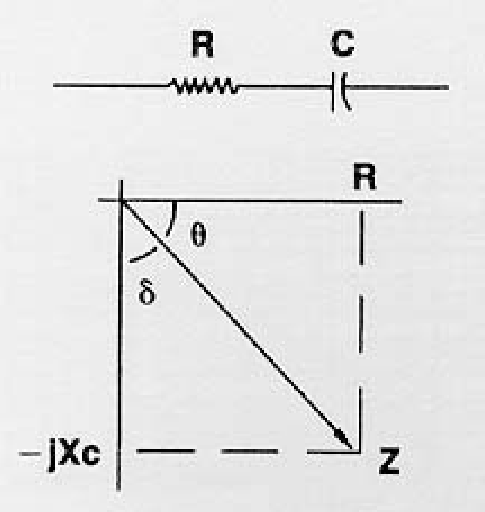
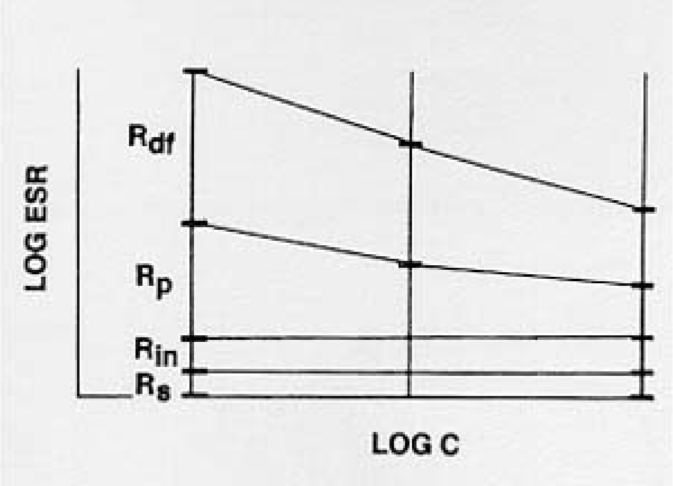


Figure 3: This shows capacitive vector represented in the impedance plane. In an ideal capacitor, (theta) = 90° and tan ð = 0 (for R = 0).



As capacitance increases, different factors have more influence on the capacitor's total ESR.

Physical Considerations

Other factors contribute additional losses: the bulk metal of leads; methods of lead attachment; capacitor plate material; and general construction. Particularly with larger capacitance values, these factors become a significant percentage of the total loss as their contribution to ESR increases.

There are three types of losses in a film capacitor: metal losses (R_s); leakage or insulation losses at DC or low frequencies (R_{in}); and dielectric losses (R_{da}). Leaving out extensive derivation, the following formula shows how these three losses are related to a capacitor's ESR:

$ESR = Rs + 1/R_{in}(2(pi)\ f\ C)^2 + DF/2(pi)\ f\ C$

Metal losses include all the losses in the capacitor's leads, termination junctions, and capacitor plates. As shown in the equation above, the insulation resistance (R_{in}) leakage losses prevail (second term), particularly at low frequencies. Then, as frequency increases, dielectric losses (third term), and then metal losses (first term) become prominent.

Metalized film capacitors utilizing thin conductors or plates have a distinct size advantage over other types - they can be very small. Formed by a vacuum-deposition process that laminates a film substrate with a thin aluminum coating measured in Angstroms, these capacitors are used where small signal levels (low currents/high impedances) and small physical size are primary factors. They are generally inappropriate for large signal AC applications.

The film-and-foil capacitor has much thicker plates (foil) than those made of metalized film; these plates result in lower losses. The thicker foil also helps carry away heat build-up; this means longer life, greater reliability, and minimal effect upon the capacitor's dielectric or DF. film-and-foil construction capacitors may be used in both small and large signal applications, but the higher performance (and higher price) may be unnecessary in some small-signal applications.

Plate resistance increases with its length and so does the capacitor's value. A larger diameter plate can be used to compensate for a shorter length. This short length/large diameter construction further reduces ESR because of the reduced plate resistance and enlarged contact area between the plate and lead and also avoids the inductance increase typically found in long length/small diameter plate construction.

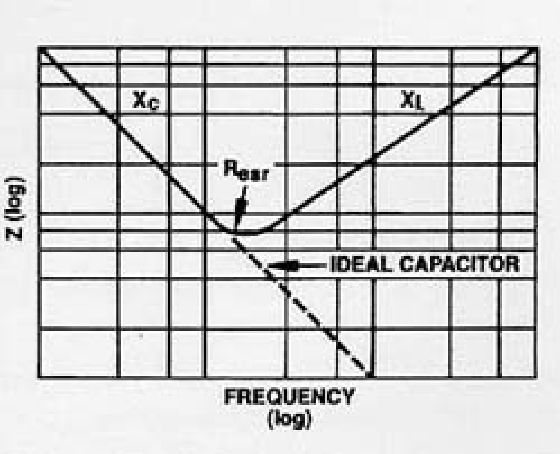


Figure 5: Typical capacitor impedance vs. frequency.

The junction between leads and the capacitor's plate(s) also influences ESR, usually for the worse. in addition to the size and shape of the leads (mentioned above), the following considerations are important: the method of attachment (welding or soldering); the size and shape of the capacitor; and the size of the sprayed metal droplet used to short all the plates together. Long-term reliability and ESR stability also depend on the use of metals that do not form electrolysis action, such as that resulting from the direct contact of aluminum and copper.

For low capacitance values, the inherent dissipation factor of the dielectric material contributes most significantly to ESR. As capacitance value increases, plate resistance, lead resistance, and endcoating resistance become, in turn, the dominant factors affecting total ESR. Careful selection and control of these factors results in uniformly stable and low ESR.

Impedance, Inductance, and Resonant Frequency

An ideal capacitor's reactance decreases as frequency increases, as shown by the formula: Xc = 1/(2(pi) f C). Of course, impedance (Z) also varies with frequency, owing to the ESR and inductance (L) of the capacitor, as shown in Figure 5.

The point of minimum impedance (ESR) marks the frequency at which L and C form a series-resonant circuit, where the inductive reactance equals the capacitive reactance. Above this resonant frequency, the capacitor functions as an inductor. For many applications, the capacitor's series resonant frequency will be a circuit's useful upper frequency limit, especially where the phase angle of the capacitor is expected to maintain a 90-degree (tan ð = 0) or near 90-degree voltage/current relationship. This is a common assumption in filter network design.

The length of the capacitor and its construction determine the capacitor's self-inductance and thus its resonant frequency. The lead length to the capacitor's external circuit load influences the incircuit performance, usually in a quite different manner from that which was calculated based upon ideal (that is, no inductance) conditions. Figure 6 shows the effect of lead length increased from 3/8'/ to 3", a typical length when you add the circuitboard trace length or circuit wiring to the capacitor's lead length. Note that the useful upper frequency limit has gone from 490 KHz to about 290 KHz. the reduction is about 33 KHz per inch for this particular capacitor! for a dielectric loss angle of 10 degrees (tan ð = .176) in the audio pass-band (a common occurrence with larger capacitor values, inductance, and ESR), there is an even more pronounced effect. here the corresponding frequencies for 1/4" and 3" lead lengths are 260KHz and 141KHz (figure 6).

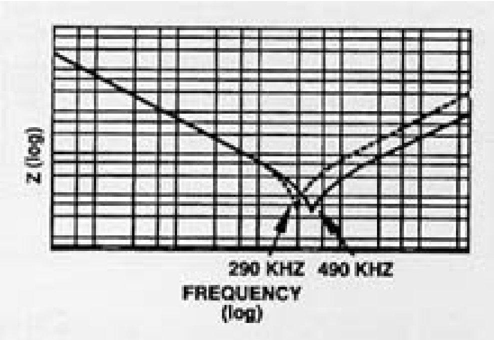


Figure 6: Lead length aiters a capacitor's range of operating frequency. Here a 2 uf capacitor's self-nesonance decreases from 490 kHz to 290 kHz when its leads are lengthened from 3/8 inch to 3 inches. In other words, the capacitor's usable operating range is reduced by almost half.

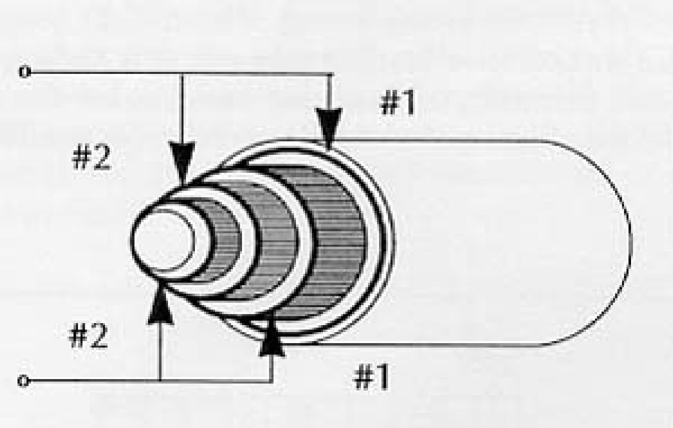


Figure 7: A cross sectional drawing showing the coax al construction of an MultiCap. For simplicity's sake, only tow of the 10 sections are included.

The MultiCap

Advantages & Disadvantages

The MultiCap™ reduces typical capacitor loss factors with a new and patented design that winds capacitors coaxially, one upon the other, in a single unit. See Figure 7.) Since each coaxial capacitor section is in parallel, the inductance of the overall capacitor is reduced by the number of sections used. In fact, inductance characteristics never exceed those of a piece of lead wire the same length as the capacitor's body! Although there is no theoretical limit to the number of sections, practical manufacturing considerations make a ten-section design the optimal choice. Measured ESR values are 5 to 10 times lower than conventional designs, sometimes approaching only a few hundred micro-ohms (11uf), with typical figures well under .001 ohm. This remarkable performance results in part from the fact that the MultiCap uses a plate length vs diameter ratio as close to 1:1 as possible over the entire range of values.

In addition to its unique configuration, the MultiCap uses the finest materials. Its film materials exhibit the lowest Dielectric Absorption among capacitors in use today. The use of fine materials throughout also reduce DF and ESR to extremely low levels for the maximum in signal resolution.

The DF of the MultiCap is typically .00003 to .0003, compared to some equivalent conventional values of .12 or higher. Thus the MultiCap has substantial advantages, particularly in high-current applications where losses can be significant. Solving the equation: Power Loss (watts) = 2(pi) c(V^2) (DF) for a 200 uf/50V capacitor with a typical DF of .12 at 120 Hz, for example, shows a heat loss in excess of .37 watts! An equivalent MultiCap would produce less than 44 micro-watts of unwanted heat under identical operating conditions.

The MultiCap also solves the problems of multiple resonances encountered when a circuit's high-frequency impedance is lowered by externally paralleling a large conventionally wound capacitor with smaller ones. This is a trial and error, hit or miss design process, resulting in a complex combination of series and parallel resonances. These can be minimized and often eliminated by the MultiCap's coaxial multi-section design.

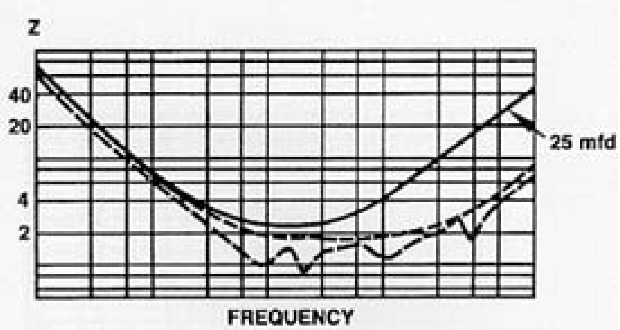


Figure 8: Family of impedance curves obtained when paralelling different values of film capacitors across a 25Suf electrolytic. Note that larger values of film capacitors have greater effects on impedance.

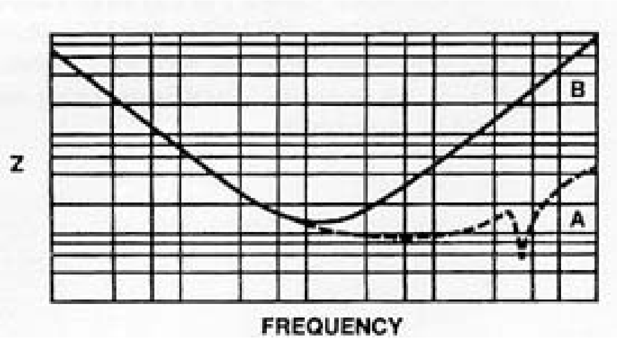


Figure 9: Excessive lead lengths not only reduce the resonant frequency of paralleled caps (A), but can also nullify the effects of the added parallel capacitor (B).

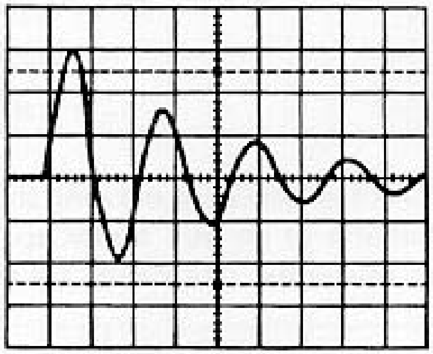


Figure 10: This shows the effect of adding L and ESR to a capacitor. An oscillation or "ringing" results when a capacitor is excited at

or near its resonant frequency. The rate of the oscillation's decay depends on losses (ESR and DF) in the capacitor. The oscillation's perior or frequency depends on the inductance (L) that makes up the series resonant circuit with the capacitrance (C); where

$$F_r= 1 / [2(pi) (square root)LC]$$

Without careful Xc and phase vs frequency measurements of a particular capacitor, one is at a loss as to what capacitor type, brand, and value to parallel it with. Figure 8 shows the out-of-circuit impedance of one brand of a 25 Rf electrolytic capacitor paralleled with smaller values of various brands. Note that larger values of film capacitors have greater effects on impedance.

This same capacitor is shown in Figure 9, which shows that excessive lead lengths not only reduce the resonant frequency of paralleled capacitors, but can also nullify the effects of the added parallel capacitor entirely.

Another aspect of paralleling is shown in Figure 10, where the circuit's resonant frequency causes ringing of an applied signal. Iower in-circuit resonant frequencies increase the possibility that signal components will modulate with the resonant artifact. A MultiCap, which provides the performance of paralleled small values in a single unit, can save valuable development time through the reduction of trial and error paralleling. In some cases, the MultiCap will save space as well.

The MultiCap in Q, DF

A quick review of the formulas for Q, DF, and self-resonant frequency shows how easily a high-performance capacitor can be degraded. Very short termination paths are needed at each terminal to prevent degradation: Just a few milli-ohms of ESR or nano-henries of inductance will reduce a Q of thousands to hundreds of ohms.

Substituting different brands of conventional capacitors in existing circuits is also problematic, particularly when those circuits have been specifically designed with one particular brand exhibiting non-ideal characteristics. Another brand's idiosyncrasies may have undesired results. See Figure 11. For highest performance, a circuit should be designed with the most nearly ideal components available. These components allow more stable signal processing with finer detail and resolution .

Of course, circuit layout and wiring methods can also create stray parasitics that dominate a high-performance capacitor's own parasitic contributions. See Figure 12. Actual execution of an equalizer or filter circuit model, for example, sometimes falls short of expectation. This usually occurs because the model did not include the effects of the component's parasitic elements and the stray parasitics that result from the layout and wiring of the circuit. Again, optimizing the

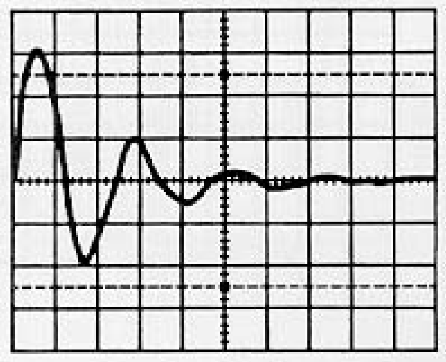


Figure 11: This distorted, damped waveform is caused by the interaction of the parasitic networks of a 2uf capacitor paralleled with an external .22uf capacitor.

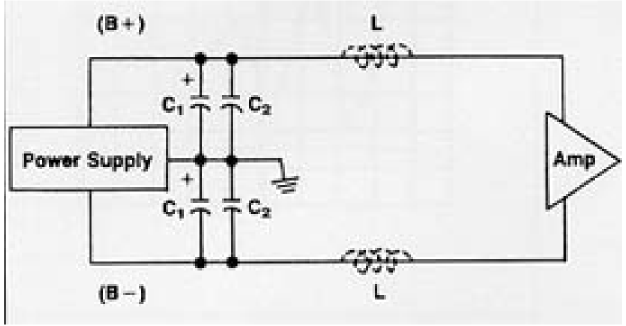


Figure 12: Typically, power-supply electrolytics (C1) are bypassed with film caps (C2) at the location of C1. C1 is usually remote from the amplifier. Therefore the intended benefit (lower Z at high frequencies) of C2 is nullified by the distributed wiring inductance (L) as indicated in Figure 9.

complete design with the more ideal capacitor will produce the best results. (See Figure 13).

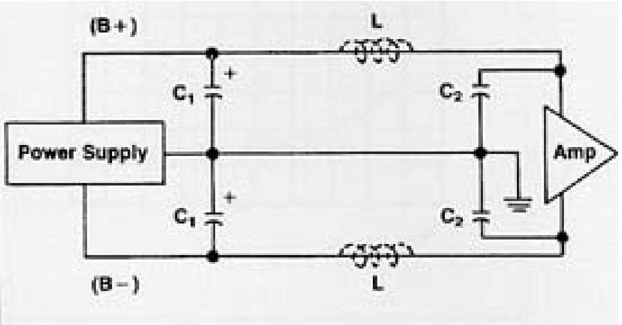


Figure 13: The benefits of C2 are better maintained whe the film bypass capacitors are located as close as possible to the amplifier circuit. The slower, low frequency ca (C1) may be located further away because of l's reduce influence at lower frequencies.

In Summary

To sum up, the advantages of the MultiCap can be seen in the following diagrams, where its real-world performance characteristics can be compared with conventional high-quality designs. (Figure 1 4A -C)

As we can see, only the MultiCap exhibits proper impulse response in both amplitude and time domains. The other - distorted - waveforms are unfortunately typical of the improper behavior found in many circuit applications.

When MultiCaps are substituted in circuits originally using other brands, many of the qualities explained above will reveal themselves with no other circuit changes. However, when circuits are designed to take full advantage of the lower losses of these more ideal capacitors, an even higher level of performance will result.

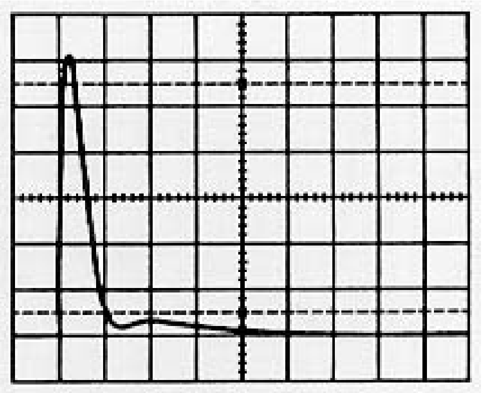


Figure 14A: Tightly controlled impulse response of the MultiCap.

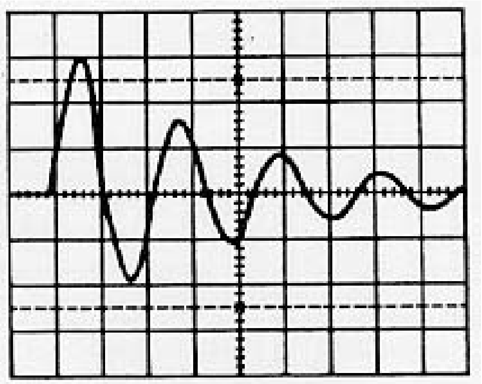


Figure 14B: Uncontrolled impulse response ("ringing") of conventional "audiophile grade"

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film capacitor.

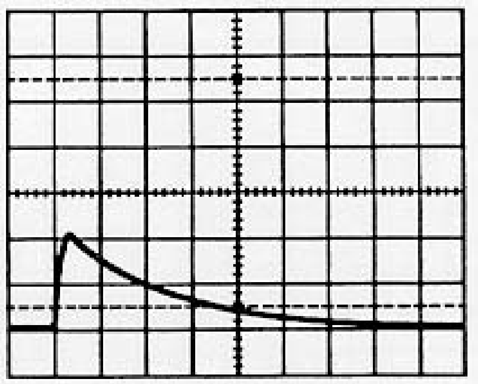

Figure 14C: typically compressed, time-smeared impulse response of bi-polar electrolytic capacitor in many speaker crossover netsworks.

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