PICKING CAPACITORS

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*F*rom time to time we hear references to distortion and other nonlinear effects produced by *passive* circuit components, such as capacitors, used in audio circuits. However, only on rare occasion can anything be found in written form which attempts to *quantify* or otherwise document capacitor problems, particularly as they specifically relate to audio. Yet, distortions are produced by a wide variety of basic capacitor types, and in some cases forms of this distortion are rather easily measurable. Why there hasn't been more written on this topic is truly a good question, as in many instances the audible defects produced by capacitors can easily be the Achilles' heel of a given design. If this were not a truism, why else would there be so many audiophile modifications consisting essentially of capacitor upgrades only? The implications of this will be apparent when this article is fully appreciated.

While there has been no detailed overview or discussion of these problems in print, two articles are noteworthy, because they do in fact address this specific topic. In [1], Dave Hadaway gave a summary of relative quality rankings for capacitor types. More recently, John Curl [2] discussed some measured results for two capacitor types. Dick Marsh [3,4,5] has been specific in cautions against certain types, in several *Audio Amateur* letters.

What we hope to do in this article is cover capacitor basics, means of testing for impedance and distortion, and summarize with some selection criteria which will optimize sound quality. We will begin by discussing some simple (but deceiving, really) distortion tests. A summary of key capacitor performance defining terms is given in the sidebar entitled Capacitor Basics.

Capacitor Basics

A brief review of capacitor fundamental relationships is appropriate to a more complete understanding of the applications-oriented discussions of this article.

As can be noted from the physical diagram (Fig. B1), a capacitor consists of two plates or conductors separated by a dielectric or insulator and the whole is capable of storing electrical energy. Capacitance is determined by the area and spacing of the plates (dielectric thickness) and the dielectric constant which is symbolized by K. The K of a given material is a direct measure of its ability to store electrons as compared to air. Note that within a given size, capacitance can only be maximized by increasing K.

Table Bl is a short summary of some of the dielectrics used in audio work. As can be noted, all of the film dielectrics have relatively low Ks, while the remainder, such as aluminum and tantalum oxides, are quite a bit greater. This is the reason why a 10- " F polycarbonate capacitor is so much larger than a 10- ,u F aluminum or tantalum electrolytic for a comparable voltage.

All capacitors can be modeled electrically by the equivalent circuit in Fig. B2. The elements shown here are actually t parasitic, with the exception of C, which is an ideal capacitor. In practice a parallel resistance, RP (sometimes called IR or Insulation Resistance), shunts C, causing leakage. Rp By both temperature and voltage dependent. A series resistance, Rs (also often called ESR, for Equivalent Series Resistance) appears in series with C, limiting the minimum impedance. Rs is composed of plate, lead, and termination resistances primarily. For high-current circuits, Rs can represent a significant power loss, and it is desirably minimized. L represents the net inductance of the winding and leads. C is actually composed of C1 and C2, where C2 and RDA comprise the dielectric absorption model (discussed fully in text).

The losses in capacitors are described by the real and reactive impedances, as shown in the vector diagram triangle, Fig. B3, with the respective impedances as described by equations 2, 3, and 4.

In capacitor specification literature, the angles (theta) and ð are often seen. Both are used to represent losses, which can be described either by the term power factor (PF) or dissipation factor (DF). As equations (5) and (6) indicate, they are trigonometrically related.

An important point to be appreciated is that for very small values of Rs, PF and DF are nearly the same. Note also that both PF and DF can also be expressed in percentage form, as DF (%), as noted in equations (7) and (8).

Capacitor losses are also sometimes expressed in terms of Q or quality factor, a general figure of merit. Q is simply the inverse of DF, as shown in equation (9). The practical expression of this is that low DF capacitors have high Q.

An appreciation for the interrelation of these various capacitor loss elements can be gained by regarding Fig. B4, a hypothetical capacitor impedance vs. frequency curve. At relatively low frequencies, the value of Z observed is equal to XC and follows the inverse relationship of equation (2). At some higher frequency, it reaches a minimum value, due to R5. At this minimum impedance frequency, the capacitor actually acts as a series-resonant circuit, with maximum current limited only by Rs. Note that only if the capacitor were truly ideal would it impedance continue to fall indefinitely with the frequency. On a log-log scale, this is shown as a straight (non-curved) descending line with increasing frequency (shown dotted in Fig. B4). It should also be noted that Rs is both temperature and frequency dependent (although not shown here).

Signal Path Tests For Capacitor Distortion

One of the more frustrating aspects of the distortion problem vis-a-vis capacitors is that they do not always allow direct quantification as they typically operate in the signal path. A good example of this very point will be demonstrated below in the discussion of some THD tests on tantalum capacitors. By these THD results, one might be led to believe that tantalum capacitors. By these THD results, one might be led to believe that tantalum types are adequate when suitably selected. Nevertheless, they still fail to measure up in auditioning and show poor electrical quality when measured by other methods—even though they may appear to be operating in a virtually distortionless fashion by THD tests.

> Two series of THD tests were performed on two types of capacitors, tantalum electrolytics and ceramic discs. These tests seem to be representative, as different capacitors of the same variety produced similar results, and the results here generally correlate with Curl's [2].

Tantalum Capacitor Tests

In the tantalum tests, a circuit was built in the form of a simple high-pass filter, as shown in Fig. 1. The general test circuit used is shown in Fig. 1a, and the details of various capacitor connections are in 1b. The 3-V rms generator and meter is a THD oscillator/analyzer combination. The general goal of this test is to examine the distortion sensitivity of the polar tantalum capacitor in handling bipolar a.c. signals.

> As the different connections of 1b indicate, there are various ways that a polarized capacitor such as this can be connected. The circuit as shown in 1a is a simple a.c.-only circuit with no d.c. polarizing bias applied to the capacitor in test condition A.
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> For such a mode of operation, a tantalum capacitor will generate appreciable distortion when the signal conditions are such that there is appreciable a.c. voltage dropped across it. Or, stated another way, when its reactance becomes appreciable in relation to that of the load (here 680 ohms).
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> For condition A, the capacitor is a single 6.8- uF unit, and its reactance equals 680 ohms at about

35 Hz. To generalize, we will talk in terms of this frequency, which is the corner frequency, fc. As will be seen, it is a key to understanding this particular pattern of distortion behavior.

THD data were taken on this and the remaining connections, as shown in Fig. 2. For condition A, it can be seen that distortion is low at frequencies above about 10 times fc, but rises as fc is approached and nears 1 percent in level below fc when the capacitor sees a large a.c. voltage. From these data, it seems somewhat analogous to regard a polarized tantalum operated thusly as a capacitor shunted by an imperfect diode. The distortion it produces is even order, which is shown in the distortion photos in Fig. 3. Since the device's a.c. characteristic is asymmetrical, it appears that circuit means which tend to minimize the asymmetry also tend to minimize the distortion produced.

As John Curl showed [2], a simple parallel connection of like capacitors, as in B, reduces distortion appreciably. Compared to condition A, condition B reduces the distortion at fc by a factor of 2 to 3 (Fig. 2).

The series back-to-back connection of condition C can reduce the distortion further, if the two capacitors happen to have complementing characteristics. The distortion products for condition C are also shown in Fig. 3 (at fc). However, it appears this particular connection depends strongly on the match of the specific units used. Also, unlike the connection of B, the series connection of C increases the net equivalent series resistance (ESR), which is usually not desirable as discussed later.

If the series connection is so effective, the logical question is, then, does polarizing bias applied to the junction help further? The answer is yes, with increasingly better results with more bias, as shown in conditions D, E, and F. However, even a relatively small bias, such as in D, is very effective, reducing THD at fc to 0.01 percent. This bias level is 5 V or just in excess of the greatest signal peak swing. The distortion for test condition D is shown in Fig. 3 at fc.

What this series of tests seems to say is that one should carefully control the a.c. signal developed across such a polar capacitor to minimize this distortion. If you use a simple single-capacitor connection with no d.c. bias, it appears that a just derating by a factor of about 10 times will minimize the distortion. In other words, if a given capacitor used for coupling is calculated to have an fc of 10 Hz, making it corner at 1 Hz will minimize the distortion produced by this particular mechanism. However, as alluded above, this is not the whole story, as the discussions later will show.

Ceramic Capacitor Tests

In a second series of tests, the distortion produced by a common ceramic disc capacitor was studied. Data in the form of the THD vs. frequency for this test are shown in Fig. 4. The first circuit used is a simple low-pass (LP) filter, with the capacitor under test as the shunt C arm. The values chosen for the test were R = 1K and C = 0.1 uF. A 100-V type was used for the capacitor.

As the LP data show, distortion is produced well below the corner frequency, which in this case is 1800 Hz. The data shown are corrected, so the THD 100 percent set level follows the LP roll-off. Even as such, however, the higher harmonics are attenuated, and this data may be a pessimistic representation. An IM test might show even worse performance for this LP filter. Figure 5 shows the nature of distortion in 5a; as can be noted, it is third harmonic. By contrast, a polyester type inserted into the circuit shows no discernible distortion (5b).

By placing the same ceramic capacitor in an HP filter circuit, the roll-off of harmonics can be circumvented. In this type of use, the voltage across the capacitor is highest at low frequencies. Thus nonlinearities will show up as higher harmonics, which are readily passed by the filter. The data for the HP test show much stronger distortion at the lower frequencies, where the voltage is highest. We are not sure what should be interpreted as the common distortion-producing source in these two tests. One thing seems quite clear, however, and that is the simple fact that you cannot "work around" the distortion problem in ceramics. Our feeling is that they should simply be avoided anywhere near an audio signal path and probably just avoided altogether for audio. For example, some listening tests have indicated that they can produce audible distortion when used as supply bypasses, let alone coupling!

One obvious implication which emerges from the above is that a capacitor is not just a capacitor by any means. Of course, what we've discussed here are only two types of capacitors, and we really ought to make some general recommendations as to desirable types. This leads us more deeply into just what a capacitor is, and how this knowledge relates to audio.

Interpreting Capacitor Performance Data

One of the most important factors needed for a full and effective understanding of capacitor audio application criteria lies in interpreting data. Most of us have probably seer examples of impedance/ frequency curves such as the one hypothesized in Fig. B4. However, considering such curves in the light of real data actually allows us to separate the men from the boys among capacitors - and also shows us which ones to use for audio.

Typical data of this nature for tantalum capacitors are shown in Fig. 6. Regarding this data and recalling the model of a real capacitor (Fig. B2), we see that under d.c. or low frequency conditions, Rs and L are negligible, compared to the C and Rp combination. As the frequency increases, particularly above a few kilohertz, the effects of both Rs and L increase.

In these practical cases shown here (one of which is typical of good-quality Ta units), it can easily be noted that Xc does not follow the ideal capacitor -6 dB-per-octave pattern with increasing frequency.

Further examination shows that as frequency increases, Xc tends to decrease, while X, increases in value. This of course means that the (Xc-Xl)2 term of the Z formula gradually decreases until at some frequency, the term (Xc<-Xl)2 disappears. Then the observed impedance is resistive or Z = Rs. This is the so-called series resonant frequency of the cap, which for tantalum and aluminum electrolytics will generally fall between 10 kHz and 1 MHz. From this, it should be apparent that if a capacitor is operated at a higher frequency than this, it will no longer be a capacitor to the circuit.

Although the discussion thus far has treated only tantalum electrolytics, this pattern of non-ideal Z vs. frequency behavior is actually inherent to all real capacitors to some degree. In the better quality dielectrics, Rs and L are lower and more closely controlled, and this is reflected in lower losses (DF), due to the lower parasitic parameters. This will be more apparent as we present data for other dielectrics.

Aluminum electrolytics show a quite similar broadly resonant frequency, where Z = Rs (or ESR).

Data for a wide range of aluminum electrolytics are summarized in Fig. 7.

As can be noted from these data, the resonant frequency is typically between 10 and 100 kHz. Note, however, that the absolute level of impedance is much lower in the case of aluminum, due to the availability of much larger values. Also, many of the larger electrolytics are designed to handle large ripple currents and thus have very low values for Rs, as can be noted.

If these data are very carefully interpreted, a number of quite useful points can be drawn from it. Generally speaking, for two capacitors of similar value, the one with the higher voltage rating will show lower Rs (and DF, if viewed thusly). This can be seen, for example, between units A and B, as well as units F and G. And, it can also be seen in tantalum units (the two specific cases for comparison in Fig. 6 show this quite well).

One might at this point ask what is the disadvantage of a relatively high Rs (or high DF) in a capacitor used in audio. The answer can be had by regarding the data of Fig. 7 in a different light. Using the capacitors A and B as illustrative examples, their actual effective capacitance values were calculated for various frequencies, using equation 4 to solve for C. The results, plotted in Fig. 8, clearly show the A unit (the higher Rs unit) to exhibit strong changes in capacitance with frequency. The B unit improves the situation relative to A, but still shows substantial capacitance change.

It is not at all hard to imagine how a capacitor whose value actually changes with frequency might distort an audio signal's integrity, particularly with regard to phase.

If we can visualize the complex frequency relationships of music passing through a capacitor (it doesn't really), while Z is simultaneously changing with the complex frequencies of the music, it is possible to appreciate how it can be relatively easy to upset the subtle harmonic/fundamental phase and amplitude relationships. Not only from the capacitance variation standpoint but also from the inductive behavior region. Used as a coupling capacitor, the resulting effects of high DF (L or Rs) are image blurring, and instrument harmonics/overtones are less accurately reproduced, with a general overall veiling of the sound. Use in a feedback path further complicates the matter, because we are using this signal to provide error correction. For example, if we consider the general transfer relationship for an amplifier where the gain = Zf . Zin, it is easy to see that variations in Z with frequency which depart from the ideal will distort the relationship.

When we talk of film capacitor types, we find that the situation of less than ideal behavior regarding impedance vs. frequency is improved greatly. This is simply due to the fact that film dielectrics, such as polystyrene, polypropylene, polycarbonate, and polyester, have much lower dielectric losses. This is reflected in lower DF and Rs, as well as generally much more stable parameters with respect to frequency and temperature.

The impedance vs. frequency characteristics of a number of film-type capacitors are shown in Fig. 9. In general, it can be noted that they all show lower minimum impedances (lower Rs), and sharper dips around resonance. These points underscore the fact that the resistive losses can be much lower, in many cases below 10 milliohms.

Film capacitors also appear inductive above their series resonant frequency, due to inevitable parasitic inductance of the winding and/or leads. However, the inductive effects can be minimized, by suitable winding and termination techniques, which can extend the usefulness of a capacitor to substantially higher frequencies. Useful cues to look for in this regard are specified noninductive winding techniques and extended foil-welded-lead attachments.

Measuring Capacitor Impedance Values

Since the above points are so basic to optimum capacitor selection, it logically follows that most audio experimenters will want to have the capability to measure the various capacitor performance parameters. Since few of us have access to the necessary bridges (and if so, many of them can't measure Rs or DF), it seems necessary to devise a setup to measure these parameters. A setup we find most convenient to these purposes is shown in Fig. 10, and it was actually used to gather all of the data for Fig. 8.

> This setup basically measures impedance (Z) by the voltage divider method, using a sine-wave generator and voltmeter. From the impedance data, C, Rs, L and DF can be derived. Table I and the notes describe the details of the procedure, which is written for either a bench voltmeter or an oscillator-analyzer combination. You should, of course, take appropriate precautions regarding bias voltages, polarity, and so forth. Also, be sure to use shielded leads on the voltmeter and connections direct to the terminals on low Rs units.
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> You will be pleased with how much power this simple little setup gives you in grading capacitors, particularly electrolytics. For example, you can use it to quickly weed out poor-quality units, such as A (a junkbox special). Given a few units of similar value, it is quite easy to select the lowest Rs unit, such as H versus 1.
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> If you use an audio oscillator and meter, you will most probably be limited to upper frequencies below 100 kHz or 200 kHz. However, you can use the same basic technique with a wide-range function generator as a sine-wave source and a high-gain scope as the readout device. This will allow testing of the smaller value film capacitors, which typically are series resonant at appreciably higher frequencies.
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> A somewhat lesser known performance parameter of capacitors called dielectric absorption (DA) is also a major contributor to sonic problems. Actually, in spite of the fact that DA is not generally understood, it may well be more important than DF.
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> This phenomenon is really a reluctance on the part of the capacitor dielectric to give up the electrons that it has stored within itself whenever the capacitor is discharged. Then, when the shorting mechanism is removed, these electrons that remained in the dielectric will, in time, accumulate on an electrode and cause a "recovery voltage" gradient to appear across the capacitor terminals. This has been referred to as a capacitor's "memory" of what was just previously applied. The recovery voltage, divided by the initial charging voltage, and expressed as a percent figure, is called the "percentage dielectric absorption" (% DA).
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> Conversely, there is also a reluctance on the part of the dielectric to accept all of the energy presented to it with a uniformity of speed. These factors may be understood by regarding the capacitor model of Fig. B2. The effect of DA is represented by the capacitor C2, with a series resistance, RDA The total capacitance seen externally is C = C1+C2. Variation of the relative size of C2 and C1, and RDA, represents the equivalent of real capacitors, with varying degrees of DA. (Note that this model suggests that the externally perceived effects of DA might be controllable to some degree by manipulation of the relative impedances controlling charge and discharge of the real capacitance. Experimental evidence discussed later tends to support this contention.)
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> In addition to the "bound" electron phenomenon, a secondary factor in the magnitude of recovery

voltage values is that of "free" electrons in random movement in the dielectric. These free electrons take finite time to move from the dielectric to the electrode, and therefore contribute to this recovery voltage.

Dielectric absorption becomes a critical factor in circuits which are highly dependent upon speed of response. As the a.c. signal goes to zero (as in a short circuit) the trapped or bound electrons within the dielectric do not follow as fast. These electrons take a finite time to move from the dielectric to the electrode. As capacitors are typically used in audio circuitry, we could translate these defects into loss of accuracy in reproducing the fine inner detail of music, as well as the music's dynamic structure.

It is quite illuminating to consider what effect a phenomenon such as DA will have on an a.c. signal consisting largely of transients (such as audio) might have. For example, when an a.c. voltage is applied, there is a tendency for the dielectric absorption phenomenon to oppose this change in polarity.

When music is the a.c. signal, the sonic degradation is one of compression or a restriction of the dynamic range. Also, a loss of detail results, and the sharpness is noticeably dulled. With dielectric types which have high DA, there is a definite "grundge" or hashy distortion added to the signal.

It is quite important to describe the sonic thumbprint that DA contributes to subjective audio. The effects of DF and DA can be perceived differently. DF is primarily a contributor to phase and amplitude modulation DA reduces or compresses dynamic range. This it does by not returning the energy applied all at once. With signal applied to a capacitor with DA present, the amplitude is reduced by the percent DA. When this energy does get returned (later), it is unrelated to the music and sounds like noise or "garbage" being added; the noise floor is also raised. High-frequency and/or transient signals are audibly compressed the most. Signals that look like tail pulses (a lot of transient music information is of this nature) are blunted or blurred in their sound. "Dulling," 8'loss of dynamics," "added garbage or hash," and "an inability to hear further into the music" have been subjective terms used to describe the DA effect in capacitors.

All polardielectrics have relatively high DA; the best examples of this pattern are tantalum and aluminum electrolytics, which can have DAs as high as several percent. There is also a general correlation between dielectric constant and DA, with the high K dielectric types being worst in terms of DA (we would like to thank T. Von Kampen of TRW Capacitors for making this point to us). For example, regarding Table Bl, ceramics and both the Al and Ta oxides have high values for K, and also show correspondingly high values for DA.

Glass and mica dielectrics have intermediate values for K, and also intermediate levels of DA. They are nowhere nearly as bad as ceramics or the Al and Ta oxides, but neither are they as good as the films.

Interestingly, it should be noted that there is also a general correlation between low values for DF and low DA, particularly among the film dielectrics. However, a low DF does not always go hand in hand with a low DA, and the glass and mica dielectrics are good examples of this fact. Both of these dielectrics have excellent properties with regard to DF, and also low capacitive variations with regard to frequency and temperature. Unfortunately, however, these excellent properties (which make these types highly desirable for such applications as resonant circuits and equalizers) are not realized concurrently with low DA. So, these types are therefore not ultimately as desirable for high-performance audio.

The film dielectrics, which are non-polar, are a different story with regard to DA and DF. All types listed in Table Bl have relatively low values (3 or less) for K, and good to excellent performance with regard to DF and DA. Among the film dielectrics there can be found a direct correlation between K and DA, and even the relatively worst film dielectric (polyester) has a DA of less than 1 percent. The best of them, Teflon, has a DA on the order of 0.01 or 0.02 percent, while polypropylene and polystyrene are nearly as good.

Testing Capacitor DA

Measurement of the DA of a capacitor is a rather involved procedure when it is done in accordance with MIL-C-19978D [28]. This standard is widely used and referenced by the capacitor industry, and unless you test a particular type according to the MIL-C-19978D format, you are not likely to get comparable results (even though the relative quality relationship may still hold between different dielectrics).

The procedure outlined in this specification calls for a five minute capacitor charging time, a five-second discharge, then a one-minute open circuit, after which the recovery voltage is read. The percentage of DA is defined as the ratio of recovery to charging voltages, times 100.

It should be understood that this is quite a stringent test, with regard to both the capacitor and the instrumentation. It takes an excellent dielectric to show small recovery voltages after a full charge, a five-second discharge, and a one-minute open circuit. It also takes some special low-current voltmeter techniques to read this voltage without introducing serious errors.

To simulate a MIL-C-19978D type of test, we built the circuit of Fig. 11, which reads the recovered voltage (Vo) via a bench DVM. The capacitor being tested (D.U.T.) is charged to 0.6 V. This level might seem low, but was chosen because it represented a typical peak signal level, particularly for lower level circuits. (A slightly higher charging voltage would make measurements easier and more applicable to higher peak signal voltages, should this be desired.)

A MOSFET input amplifier is used, the CA3160BT. This is done because only a few pA of bias current are allowable in the D.U.T. circuit; if the current were higher the D.U.T. voltage would vary, by being charged by this bias current, and not be distinguishable from the true DA-produced voltage. In the circuit here, the 3160 bias current begins to limit the accuracy of readings below about 0.1 percent DA.

The test procedure is largely self-explanatory. However, the precautions listed in the notes should be followed, and we recommend no deviations from the parts specified if you want comparable results.

Two series of tests were run with this setup, as outlined in Table II. The first test compares four similar value capacitors with different dielectrics to see the differences in DA. As can be noted, both aluminum and tantalum electrolytics are very poor, with tantalum sample being slightly worse than the aluminum. This might be expected from their relative Ks.

The metalized polyester unit is far better than either electrolytic, measuring less than 0.15 percent. This may be quite good for polyester types, as typical specification data available do not always show comparably low figures. The metalized polypropylene unit is extremely good in terms of DA with a measured figure which compares quite well with the manufacturer's data. The polypropylene foil unit is not quite as good, but is still excellent.

For both units 3 and 4 (or any other comparably low percentage DA type) the particular test conditions chosen are very sensitive to millivolt or sub-millivolt errors. This is simply because 0.1 percent of 0.6 V is only 600 u V—a voltage easily lost or obscured without very careful construction and calibration of the setup. Higher charging voltages (say 10 V) would ease this burden considerably, but we do not as yet know that such a test level can always be directly correlated to lower levels.

Test 2 examined a number of higher value aluminum and tantalum electrolytics. Comparison of units 1 and 2 shows that a higher voltage rated unit of the same value will tend to have a lower relative DA. This is an interesting point, as this same consideration for selection criteria is also true with regard to DF. It means that wherever possible, if you must use an electrolytic, use the highest practical voltage rating. This applies to either aluminum or tantalum units. Units like number 1 should be avoided at all costs!

Unit three is a 50- u F non-polar aluminum electrolytic of a type often seen in solid-state audio circuits. As can be noted it has a somewhat lower DA. Apparently, a back-to-back connection tends to reduce the DA of a single unit. For example, unit 4, actually a series pair of two units like number 1, shows less DA than a single. This tends to say that nonpolar units or non-polar connected conventional electrolytics will be better in DA relative to a conventional polar cap. However, this difference is largely academic we feel, since if you want really high-quality sound, you cannot tolerate more than a small fraction of a percent DA. Obviously this rules out all but the best of the film dielectrics. Unit 6 is an example of one of the better quality aluminum electrolytics (see also Fig. 7).

While studying the DA problem in tantalum and aluminum electrolytics, we also bench-tested a large number of : various units in a much simpler, unbuffered test setup. The 0 basic procedure was to charge a cap to S V for 10 seconds 0 discharge it (through a 1K) for 10 seconds, then open circuit it, and read the recovery voltage after 30 seconds. With this technique we could grade the various units into relative DA categories. The best would read less than 5 mV (or 0.1 per cent) for this test, the worst over 20 mV (0.4 percent). Obviously, this simple test does not compare directly with the Fig. 11 test results, but it still can grade units relatively. And we would invariably find that lower DA units would sound better in an audio circuit. However, the clincher is that no electrolytic known to us, aluminum or tantalum, sounds like a wire in even so simple an application as a coupling cap. Once you try some of these tests for yourself in a good audio system, one free of masking, you may begin to abhor capacitors and seek means to eliminate them where at all possible and, indeed, where it is possible this is perhaps the most effective method of eliminating these distortions. However, it is not always practical to eliminate capacitors, therefore ways to minimize their degrading of the signal are valuable and will be discussed.

"Tuning" typically used in audio circuits with quality capacitors

Since we would otherwise be endlessly asked "How can I improve my brand X preamp or power amp using the improved capacitor types recommended in this article?" it seems appropriate to make some comments as to the methods which would be typically used. First, readers should understand that we are not equipped to answer individual requests for consultation in these areas. If you cannot translate our general comments into the specific steps appropriate to modify your particular gear, please ask a more technically knowledgeable friend for some help. One should not attempt these changes without some prior experience in electronics and familiarity with the components used. Please be advised that if you choose to do so, you make such changes at your own risk, which is to say we cannot be responsible for any accidental damage you may incur. You should also be aware that the alteration of some equipment may result in invalidating a warranty and may also influence its potential resale value.

> Since the minimum number of equipment blocks an audio system can be assembled with is two, preamp and power amp, we will discuss these two items as generally used. The basic ideas can be translated to any audio equipment using capacitors, which of course includes everything. Figure B5 shows a block diagram of how a typical solidstate preamp is often-realized. In the phono section of B5A, it can be noted that the signal path contains six capacitors, all of which can potentially degrade the signal's quality. The amplifier circuit is shown generally as a gain block A, which can be an op amp or discrete circuitry, and the comments on optimum capacitor usage apply to any active devices used (even those not yet invented!).
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> C1 is typically used to block d.c. from the cartridge, and is often a small electrolytic in the 1- to 10- uF range. It might better be a film unit such as a 2.2 uF, with a 0.01- uF polystyrene shunt. An interesting point here is that low bias current op-amp inputs (such as FET units like the TL071 or LF356) remove the requirement for C1 altogether, and the amplifier can be directly coupled to the cartridge. This, of course, will not be possible with the classic type of two transistor topology, due to the inherent bias restrictions.
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> C2 is typically a large electrolytic, in the range of 10 to 100 or more, the large value necessary for extended bass response. This function can be optimized by selecting a low ESR type, using a back-to-back connection, and shunting with a film. The complete composite of Fig. 17B is useful.
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> C3 and C4 are the RIAA equalization capacitances and are very critical to fidelity as well as basic frequency response. If the network values are those appropriate for accuracy of the three RIAA time constants (see S. Lipshitz's article "On RIAA i Equalization Networks," Jour. of the Audio Eng. Soc., Vol. 27, No. 6, p. 458, June 1979), C3 and C4 should be realized with film types such as polystyrenes or polypropylenes (best) or at the least, polyesters. It is probably ill-advised to use a ceramic unit for equalization if quality results are to be expected. C5 is a simple output blocking capacitor and can be a composite such as Fig. 17B for best wideband response (or a large-value film type if the input impedance of the next stage is high).
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> The above comments can also be adapted to address tubetype phono sections, such as the Dynaco PAS series. In such cases, cathode bypasses (when used) are analogous to C2 and can be low ESR electrolytics, with film shunts. Interstage coupling caps should be the best-quality films, such as polypropylenes or polystyrenes, of appropriate voltage ratings. The output cap C6 cannot normally be an electrolytic because of d.c. leakage caused by the high bias voltages,

so a composite film type such as several 5- to 10- p F units, shunted by a small polypropylene or polystyrene, is useful. This will be similar to Fig. 17A, but less the electrolytic. Be sure to use an adequate voltage rating and consider surges.

A point worth making is that it may be useful to minimize the grid resistances in tube circuits, while increasing coupling capacitance. This will tend to minimize the DA effects, by loading the capacitor as generally described with 17C. This idea also applies to the output capacitors used with cathode followers as well.

The high level preamp section of Fig B5B is typical of many modern solid-state preamps. C1 and C2 block the d.c. Ievels associated with the active devices used. If electrolytics are used, they should be low ESR types, with film shunts.

Depending upon the actual circuitry employed, C1 or C2 (or both) may even possibly be eliminated. For example, an LF357 op amp is often seen used for this amplification function, in which case its very low bias currents eliminate the need for C1 and C2, that is they can be jumpered out. Any residual offset of the IC used will still be blocked by C3, the output coupling cap. C3 would be selected, as was true for C6 in the phono section (a non-polar composite, such as Fig. 17B) .

Not shown here are tone control functions which, if used, would couple into the feedback path of the amplifier. Comments similar to those on the RIAA equalization capacitors apply to tone control capacitors as well. Since relatively high values will often be employed, polypropylenes will likely be effective here.

Power Amplifiers

In solid-state power amplifiers as are typically used today, the capacitor numbers are reduced due to the more simple function required.

A typical power amp signal path is as shown in Fig. B6. The amplifier circuit itself is direct coupled to the speaker to eliminate a huge blocking capacitor and to simplify biasing. C1 serves as an input coupling capacitor of 1 to 10u F in value, while C2 may be 100 to 1000 p F. Both of these capacitors should be optimized similar to the method described for the preamp. C2 usually must be an electrolytic, but should be an optimized composite type. In some cases, depending upon the value of R2, C1 might possibly be a film (only) unit, but with typical input impedances of 10-50K, it will usually need to be 10" F or more for adequate LF response.

C3 and R5 form an output compensation network for the power devices, and C3 may in some cases be a ceramic disc. An equivalent value film unit is likely to be profitable here as a substitution.

In summarizing these comments, it is perhaps important to underscore the point that capacitors as used in the audio signal path can be optimized mostly independent of the circuit topology or devices used. This is simply to say that while our generalized guidelines have addressed more popular examples of circuit types, good-quality capacitors go well in other circuits also; crossover networks are an example of passive circuits, an equalizer could be a good example of active ones. Both functions have performance basic to capacitors. In making such changes as outlined above, a logical approach is to upgrade all the poorer quality capacitors first, for example the ceramic capacitors if used, and in particular those in the signal path.

Performance Comparison of Various Dielectrics

At this point we are ready to survey the various capacitor dielectrics with regard to their parameters relevant to audio This we will do for all dielectrics mentioned thus far, with the exception of ceramic and the electrolytics, since for the highest-quality audio these dielectrics should not be used if at all possible. Where an electrolytic type is a must because of a time constant or filter criteria, some qualified recommendations can be made for aluminum types which make them quite useful; this will be covered at the end.

> Table 3 is a summary of the various dielectrics most useful for consideration, with typical specifications listed for each major performance parameter (left column). These specs are really ranges, as are typically available from average suppliers, and are not meant to represent a given type or series in specific terms. They are, however, broadly representative of what is generally available. For a given electrical parameter, the dielectric type (or types) which are outstanding are noted by shaded areas.
>
> While Table 3 summarizes comparative data in discrete form, Figs. 12 through 16 illustrate graphically a selection of these different characteristics.
>
> Dissipation factor of the various dielectrics is usually given at 25° C, but there is always some temperature dependence. Figure 12 shows that polyester is the worst of the films in this regard, but the better ones show very flat DF change with temperature.
>
> Insulation resistance (Rp) has not been strongly addressed in this discussion, because it is not often a critical parameter in audio (at least from a distortion point of view). Figure 13 is an excellent summary of how the dielectrics compare for Rp. As can be noted, all show decreases in Rp with increasing temperature.
>
> While DF is an important parameter for capacitors, it is also important that DF remain low for different frequencies. However, in many dielectrics there is substantial frequency dependence exhibited by DF, as shown in Fig. 14. The better dielectrics in this regard are parylene, polystyrene, polypropylene, and Teflon (not shown). A related parameter is capacitance variation with frequency, shown in Fig. 15. Again, parylene, polystyrene, polypropylene, and Teflon (not shown) are best in this regard. These variations are due to the variation in K versus frequency for the different materials.
>
> Film capacitors are generally quite good with regard to capacitance variation with temperature, as is shown by Fig. 16. The better a capacitor in this regard, the more stable a tuned circuit based on it will be when undergoing changes in temperature. Of the films, polyester is the poorest, followed by polycarbonate. The lowest TC is exhibited by polystyrene.
>
> One should view TC minimization with some caution with regard to audio use, as in certain dielectrics optimization techniques which minimize TC raise DA. A good example of this factor is the characteristic "B & C" parylene dielectrics, which have nominally 0 TCs, but a DA several times that of characteristic A parylene, which has a 0.1 percent DA but a TC of -200 ppM/°C. For audio use, the A characteristic would be preferred, since you can't "compensate" for zero DA, whereas for TC you can (where necessary). One should, incidentally, check for a possible compromise in DA for any "0 TC" capacitor; they often occur, and we do not mean to imply the

DA compromise is peculiar to parylene.

The remaining parameters of Table lil are not illustrated by graphical data, but also deserve comment. For example, the available tolerances and range of values can strongly influence the selection of a capacitor, aside from the electrical specs. Generally, very tight tolerances are available in most films, to below 1 percent on special order. The range of values is a difficulty, though, particularly when large sizes are needed.

Most film capacitors are readily available, many off the shelf, in sizes up to 1 " F. Above 1 IJ F they become very hard to obtain, and almost non-existent for some dielectrics, such as polystyrene.

In the larger values, any film capacitor will be quite large, relatively speaking. So, to make use of the excellent electrical properties and ultimate sound quality, we must be prepared to accommodate a largish capacitor when 1 u F or more is needed. A factor which can help minimize the final size is the metalized dielectric. Most film capacitors (except polystyrene) are available in metalized types, as opposed to the foil-wound variety. The metalized dielectric uses a very thin metalized layer for the electrode and thus conserves space. A danger area of metalized caps is the lead attachment, which is tricky. If it is not done adequately, a high (or worse, intermittent) Rs can occur. As a result, metalized caps will usually show somewhat higher levels of DF than a foil unit. However, they can still be of excellent quality, and the best advice here is simply to thoroughly check a given type before use.

The final "parameter" of Table 3 is the relative cost of the various dielectrics. A statement that is unquestionably true here is that you do get what you pay for—the "super dielectric" films will cost you more money for a given value. For example, a small-quantity of price for a 5- p F polypropylene will be on the order of $8.00, whereas a 5-1uF aluminum electrolytic will cost about 20 cents.

This kind of comparison is a sobering one, and the authors would be foolish to think it will not scare many off. However we should not attempt to kid ourselves that "cheaper is better," as it simply is not if you want the best quality. As time progresses and more become aware of the advantages of these excellent capacitors, we hope volume usage will help their price reduction. Where it is inevitable that a cap be used, we should be prepared to pay more for the quality unit necessary. If this seems like a harsh, unrelenting statement, the final summation should give you better perspective for why we feel the true audiophile must be prepared to bite the bullet with regard to capacitors.

Summary

If we have done a good job on this article, a glance at Table III and considerations of the distortion discussions should allow the reader to easily select a good capacitor. For reasons of practicality and other rationalizations, there are the inevitable trade-offs. However, here is the way we see it.

Up to values of about 10,000 pF, polystyrene is the best all around choice, as it has reasonable size and is readily available in many sizes, with tight tolerances available. Above 10,000 pF, and up to 0.1 u F, it still can be used but is much harder to obtain.

Above, 0.1- u F polypropylene (or metalized polypropylene) is the dielectric of choice, as it has nearly the same relative qualities of DF and DA as polystyrene. Tight tolerances are available (but will be special order), and you can get capacitors up to 10 u F or more.

Teflon may well be the best dielectric of all for audio, but is produced in limited volume and is generally not practical. Parylene is an excellent dielectric also, but limited in electrical size (1 uF or less) and not widely available. Polycarbonate is perhaps the next best all-around choice behind these and is generally available in a wide range of values.

Polyester types are the most widely available for all the films and are already widely used in many audio circuits. There is no doubt that this is due to the generally low cost of these capacitors, but convenience and low cost should not be primary selection criteria to a critical audiophile. Polyester capacitors can be readily heard in good systems, with defects similar to those described for tantalum but, of course, reduced in magnitude.

In our opinion, polyester capacitors should be very carefully applied in an audiophile's system, and any system using them in the signal path may potentially benefit by the substitution of (equal value, voltage and tolerance) polypropylenes or polycarbonates. We have done this ourselves on different items of equipment, tube and transistor, with always the same result—a stunning upgrade in sound quality. Further, we have observed others do similar things, either completely independently or at our direction, with the same type of results.

It is not surprising to us that this type of reaction occurs, since one single polyester or electrolytic (or other polar type) can be heard, and a typical update to an old preamp or amp might replace a dozen or more! If you did nothing more than take an old (stock) Dynaco PA5 preamp and change the capacitors to polypropylenes, you can be literally astounded at the results. All of this is available at moderate cost to anyone who can solder, and you need not send your amp off to the specialty audio shop either! (Capacitor sources are listed in the appendices.)

More Specific Recommendations

Beyond the above described substitutions (which are basically of a one-to-one variety), we'd also like to show how to use aluminum electrolytics effectively, so as to minimize their sound degradation.

In Fig. 17 are shown two types of connections which might need to employ higher capacity value, 100 p F or more. The trick is to select a low RS electrolytic, such as one of the two specifically mentioned for CA (see Fig 7 again). Either of them may be considered overkill from a time constant standpoint, as 50 uF may be all that is necessary. But, the high value and voltage listed will minimize RS, and the relatively high voltage also minimizes DA. At the higher frequencies where the electrolytic becomes inductive, the film shunt carries the signal and minimizes the audible degradation.

Figure 17A is used where the capacitor will always see a defined polarity and can thus be correctly polarized. Figure 17B uses two of the specified types to form a low RS, IOW DA non-polar electrolytic. For the film cap CB, use a polypropylene if at all possible; if not, use a polyester. In either case, a smaller polypropylene shunt Cc helps even further. Optionally, an even smaller polypropylene or polystyrene (in addition) in the range 0.01 to 0.1 pF may be useful in some circumstances.

Figure 17C illustrates how the composite capacitors of 17A or 17B would be best applied as a coupling capacitor (d.c. blocking) within an actual circuit typical of such use. The load resistance which the capacitor must feed into is comprised of R, (which may be the input resistance of, say, a power amp) plus the local bleeder resistance, RB The net load resistance will be RB.and R,, added in parallel fashion.

For two reasons, this impedance should be minimized. First, and most obvious, a low impedance is necessary to bleed off any d.c. leakage of the large electrolytics (which can for certain conditions be on the order of 1 p A or more). Selecting a load resistance of 10K or less will, for example, reduce the leakage-induced d.c. offset at the output to 10 mV or less for a leakage of 1 " A.

The second reason is to minimize the audible effects of whatever DA may exist in the capacitors actually used for CA and CB. A low load (and source) resistance presented to a coupling capacitor tends to minimize sonic deterioration.

In a single blind listening test using such various capacitor dielectric types as mica, polyester, tantalum, and polypropylene, it was found that a simple coupling capacitor can degrade sound quality quite strongly if the load impedance is high. In this test R, was 50K and RB was varied from infinity down to 1K, and the source impedance for C was 1K.

A tantalum capacitor (Table II, Test 2, sample 1) feeding the 50K load distorted the sound very strongly, with severe hashy sound and loss of detail. However, the same capacitor under 1K load conditions improved in sound quality appreciably (it did not become transparent, but it did improve). The other dielectrics mentioned followed similar patterns: Poor performance into the higher impedance, improvement in clarity with the lower impedance. However, even the best dielectric on hand in a usable size (5-1JF polypropylenes) sounded much better into a lower impedance load.

Of course, one cannot lower load resistance arbitrarily from this general viewpoint, as low-frequency response will suffer sooner or later. But the evidence of these tests and also the general pattern of bench tests for DA (which show reduced recovery voltage for low R,) indicate that it is worthwhile to lower load resistance (within allowable bounds) to minimize DA effects. This factor can very logically explain points of disagreement on whether or not capacitors really do sound bad, as it tends to say they sound bad (within a given dielectric type) to the degree that the DA is allowed to manifest itself. Minimizing load resistance tends to optimize the circuit in terms of suppressing the DA. General procedural guidelines for "tuning" typical audio circuits with capacitor improvements are described in the sidebar.

Interestingly enough, there is very strong indication to us that in many situations the power supply electrolytics also need the same careful attention as do signal path units. The general rule of selection is the same: Use a low RS unit and bypass it with a film (such as in Fig. 17A). While the degree to which this problem may be apparent is surely related to the circuit topology, it is certainly worth consideration in all instances of amplifier circuits, tubes or transistors.

For those readers unfamiliar with the "sound" of capacitors or this general subject area, much of the above might sound like mad ravings to some degree or another. We'd like to leave some implication of what we feel the magnitude of this problem really is.

After we had gone through all of the above exercises and exorcised our complete system of unnecessary or poor-quality capacitors, the total degree of improvement was greater than any other improvement measure ever employed. With no capacitors (or clean capacitors), you begin to hear the music in a new light, one which is much more like the sound of the real thing. In fact, you will be able to differentiate subtleties you never before even realized existed. Your system

> simply becomes a new system, in terms of resolution and definition. The "solid-state sound" we've all heard discussed may be largely due to lousy electrolytics—which by and large never got used in the signal path in the tube days.

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