The Sound of Capacitors - Capacitor Linearity **Expanded**

Many people believe there is a distinct sound to different types of capacitors. This article covers this topic by examining the linearity (or deviations from linearity) associated with different capacitor types. I've expanded this report and slightly re-arranged it to keep the load times reasonable.

Background

A capacitor is an energy storage device. The capacitance value is related to the size of the device plates, the spacing between them and the dielectric material of the media between the plates. In the simplest media (air or vacuum), the dielectric constant is unity. You can increase the value of the capacitance by inserting some material (such as paper, various plastics, mica, oxides etc) between the capacitor plates. Most material has a dielectric constant greater than unity, thus increasing the capacitance. However, there is a price to pay: this material may be nonlinear.

Most people are familiar with magnetic materials non-linearities. The familiar B-H curve describes this non-linearity. (The slope of the line is related to the inductance). Electrostatic materials have a similar property: the D-E curve. The slope of this curve is related to the capacitance value.

Obtaining the D-E curve

Again, using the more familiar "magnetic" analogy, you can obtain a B-H curve (well, actually a PSI vs I curve) by noting the E-M relationship:

$$E = L\, dI/dt.$$

If you sample the current flowing in an inductive circuit (x axis), and integrate the voltage across the inductor (y axis) this gives you a curve proportional to the B-H curve.

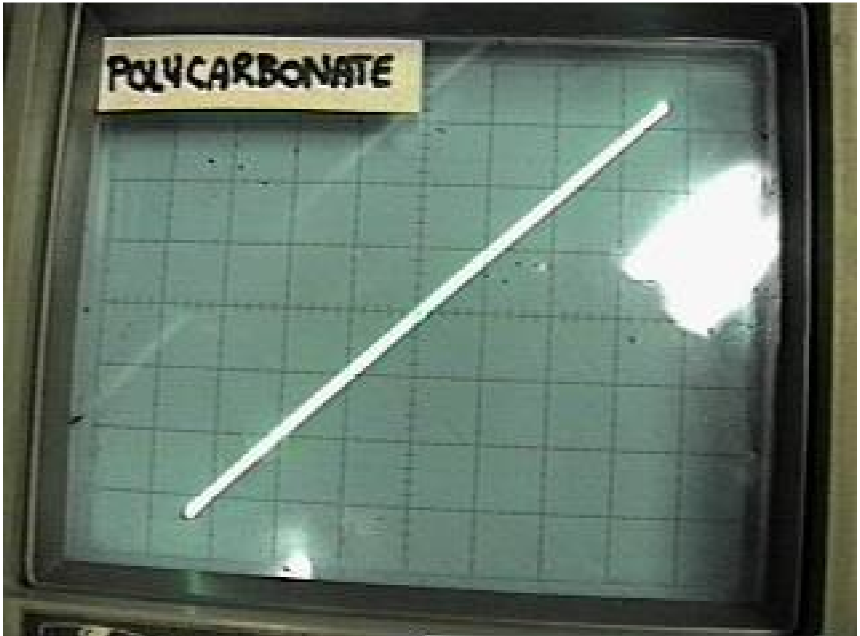
For a capacitor, the operative equation is:

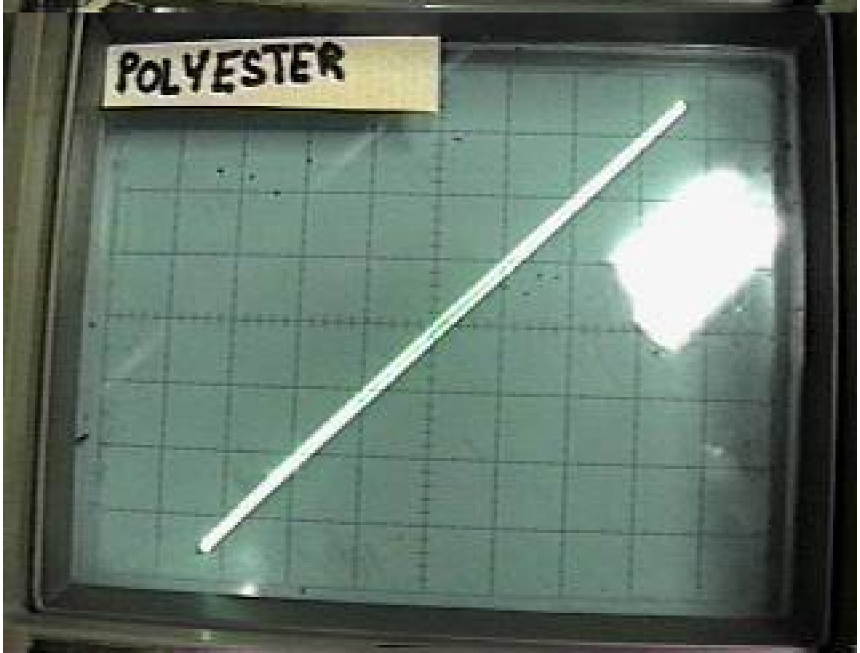
$$I = C\, dV/dt$$

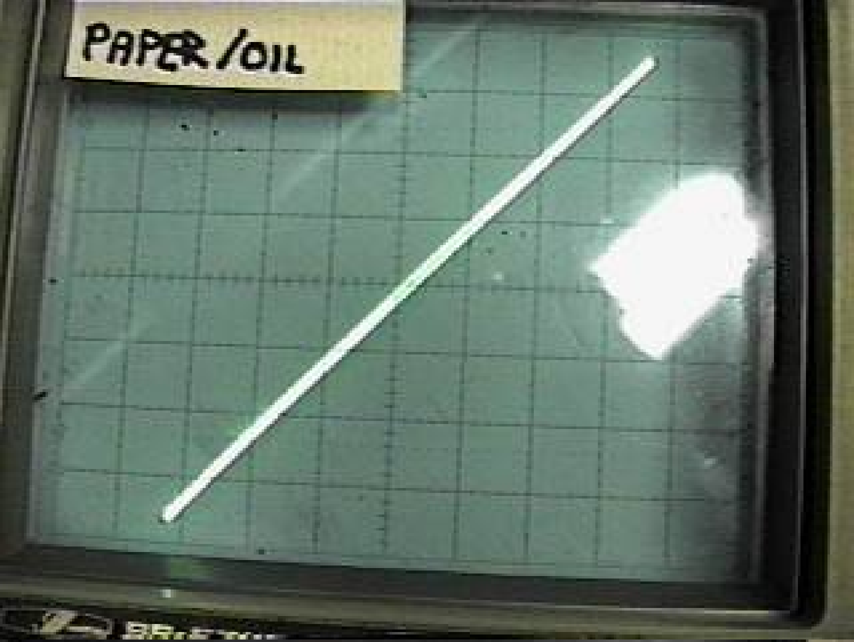
Thus, if you sample the voltage, and integrate the current, you get a curve that is proportional to the D-E curve of the part. Amazingly enough, real valued parts have a CURVE, not a straight line. They may also exhibit hysteresis, much as an inductor or transformer may. This introduces subtle forms of distortion and non-linearities, which can cause a loss of precision in musical reproduction. Note that there are also other mechanisms that can alter the sound, but this report concentrates only on the non-linearity introduced by the D-E curve.

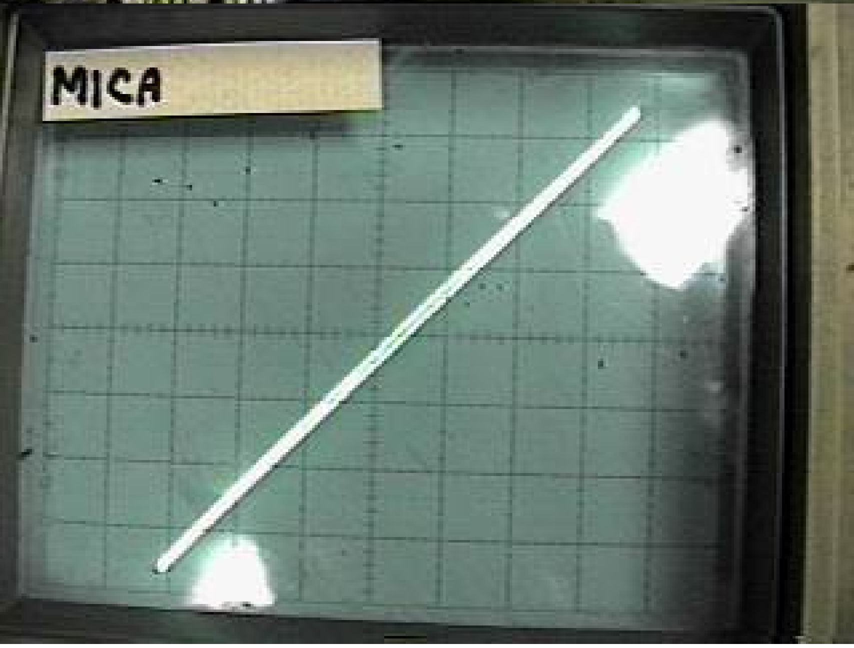
Results

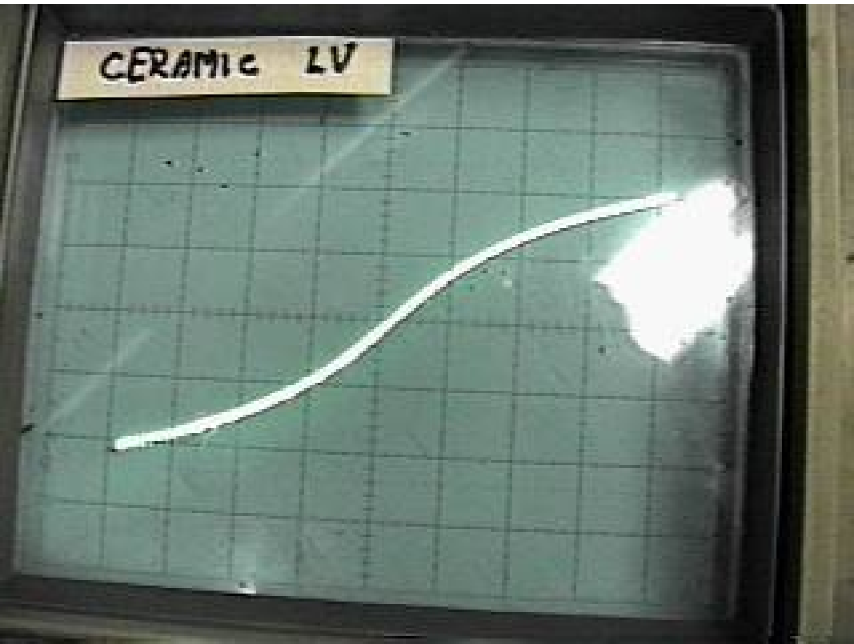
I measured several different types of parts, and captured the results (simply by training a camera at the scope). The value of each of the capacitors was constant, 0.1uF. The signal level was held constant at about 70 volts RMS at 600 Hz across the capacitors. (for about 26mA signal current). This is probably more than you would normally expect, and serves to show the results better. A number of capacitor types were used in this experiment. The first series of curves show paper and oil, polycarbonate film, polyester film, polystyrene film, polypropylene, 100 v olt and 1000 volt ceramic and silver mica. Here's the results:

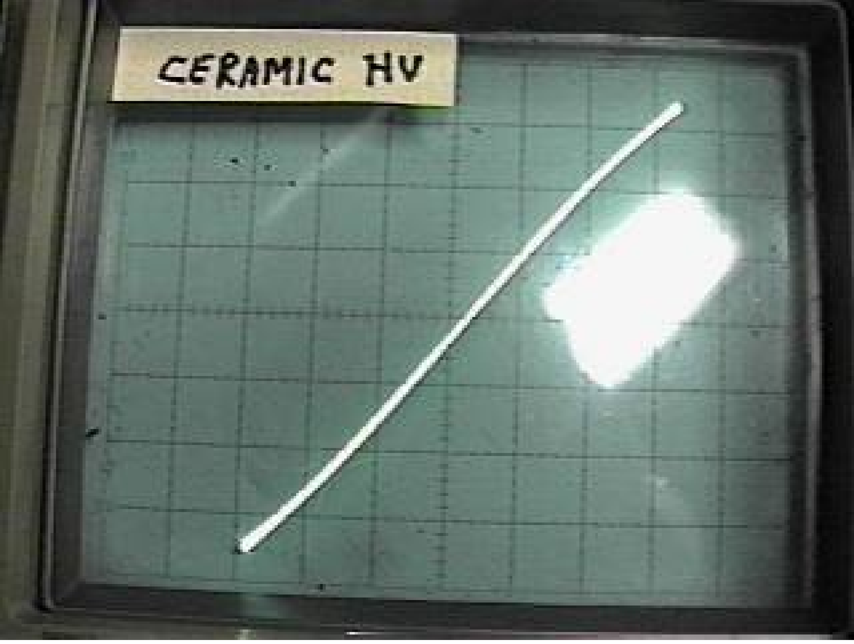


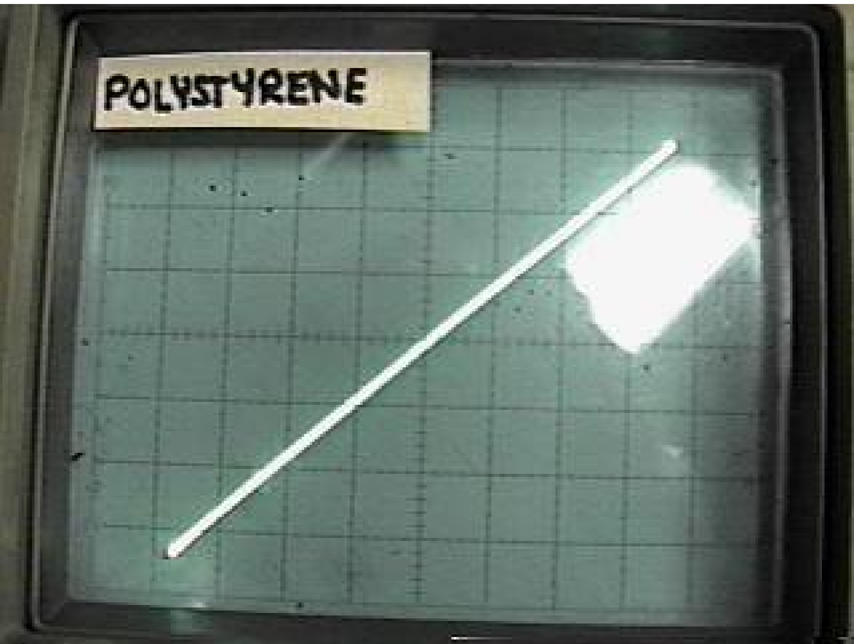


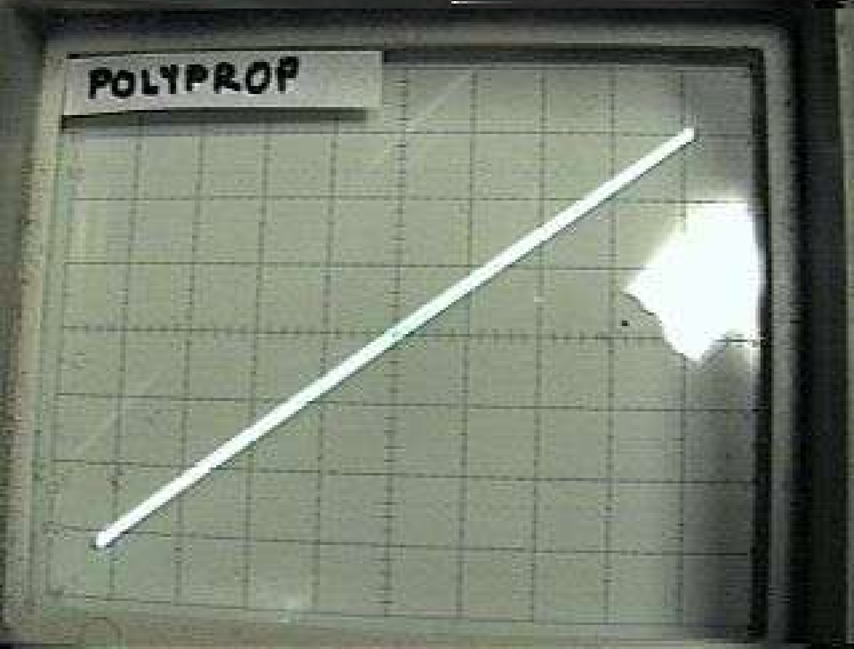

PAPER/OIL


MICA


CERAMIC LV


CERAMIC HV


POLYSTYRENE


POLYPROP

I've expanded and put into their own section the electrolytics curves. This section now shows the effects of DC bias voltage change on the capacitor curves of electrolytics as well. To see this data, click here.

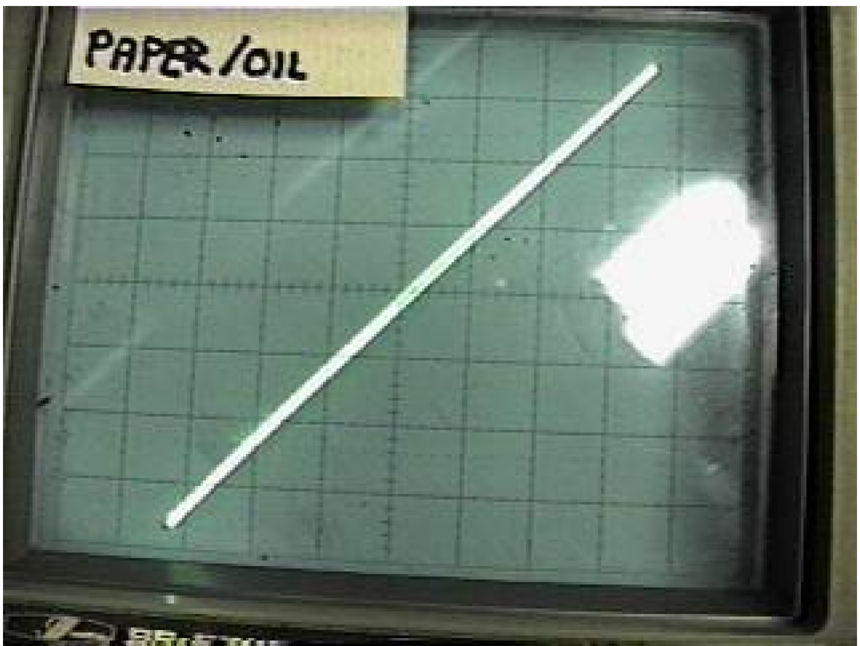
The other very non-linear type, the ceramic capacitor, also "deserves" some additional information. I've added yet another type, the ubiquitous "logic bypass capacitor" monolythic as well as some curves showing the effects of operation at different frequencies. To see this data, click here.

Discussion

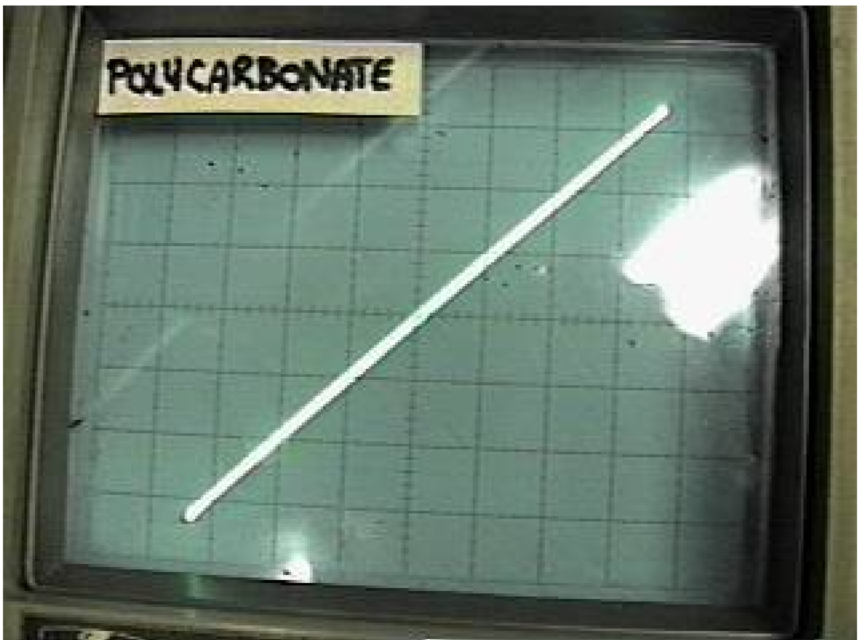
Notice the non-linearities associated with the electrolytics (mostly in the form of hysteresis, although tantalum is particularly bad). Properly biasing these parts removes the hysteresis, but still leaves a "curved" characteristic.

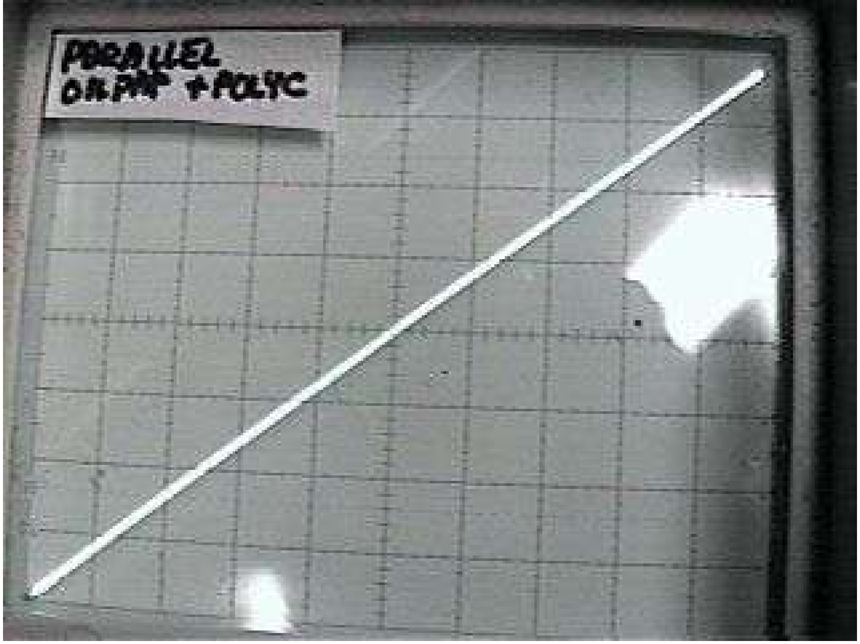
Also, notice the very apparent non-linearities associated with the ceramics. All of these are bad enough to be acoustically displeasing. The characteristics also change quite radically with frequency. It's been pointed out that sometimes, these characteristics can be used to advantage to add "crunch" to guitar amps. Because of the effect of voltage, it ought to be possible to fine tune the sound by using different voltage rated parts (assuming they are rated high enough for your amp.)

The paper in oil is extremely clean, best of the group. That may be one reason why some people prefer the sound of the paper capacitors. Although not recorded, oil capacitors in general appear to be very linear. These caps also appear to have relatively stable characteristics with change in frequency. Here's the original set of oil/paper along side the same capacitor but with the frequency changed to 100 Hz.



The polycarbonate is interesting. If you look carefully, you will notice a slight curvature that is reminiscent of a SE triode amp. Some people may prefer this sound. Also, you can alter the characteristics by series or parallel connection of different capacitor types. Here's a parallel combination of polycarbonate and paper-oil compared against the polycarbonate alone:





I know it's hard to tell, but the slight bending has been reduced by this combination.

The mica shows a very slight hysteresis effect. The polyester also shows a slight hysteresis. The polystyrene appears to be intermediate between the oil and paper and the polycarbonate. It's almost as good as the oil and paper. If you look very carefully at the polypropylene curves, you should be able to notice a very slight curvature. This type appears to be similar to the linearity shown by the polystyrene, but it too has its own "signature".

What sounds the best? That's up to you. I had been asked to evaluate some new manufacture paper capacitors, and they sounded so good, I just had to find out why. This article is the result.

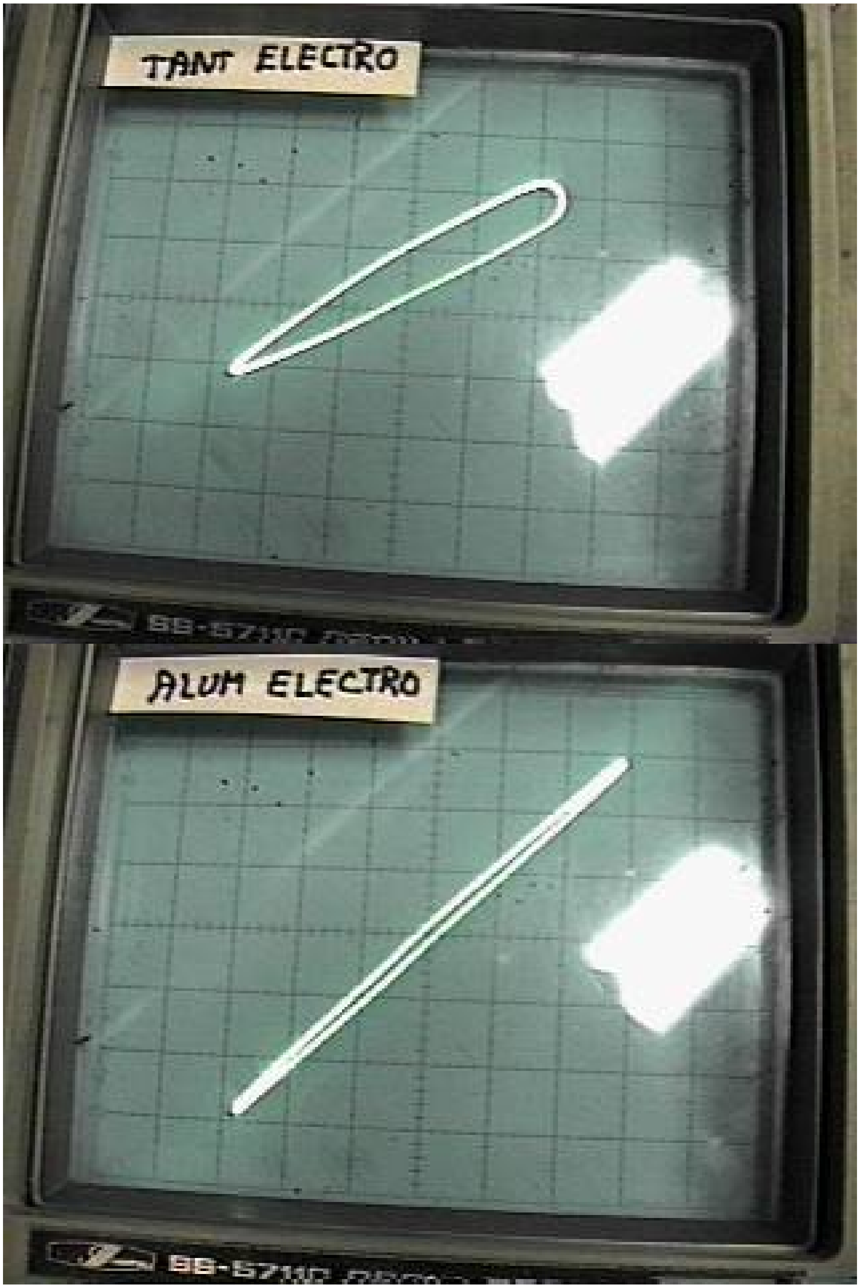
Technical Note

The "current monitor" resistor used for all curves was 100 ohms. The "integrator" was passive, using a 100k and 0.047, 0.1, or 0.47 uF capacitors depending on the frequency and level. The "X" input to the scope was fed with an additional series capacitor and adjusted for exactly "90 degrees" phase shift (typically ran 0.01u into the 10 meg scope probe resistance) to reduce systemic errors. The generator is absolutely isolated, being the secondary of a transformer capable of 300 volts into 1k from 15Hz to 1kHz. The bias voltage was added "in series" with this from an HP regulated and isolated supply. The junction of the current monitor resistor and the capacitor under test serves as the scope and system "reference" point.

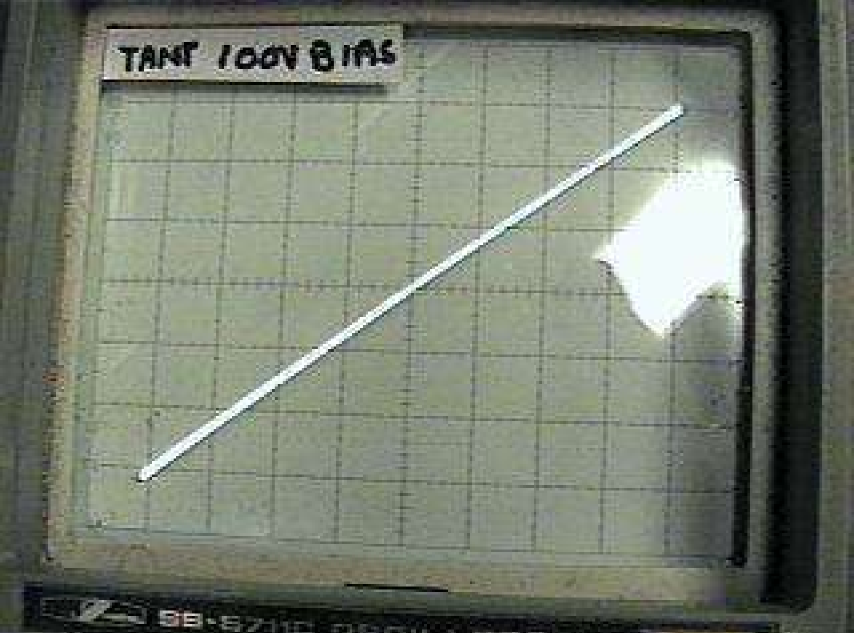
Steve

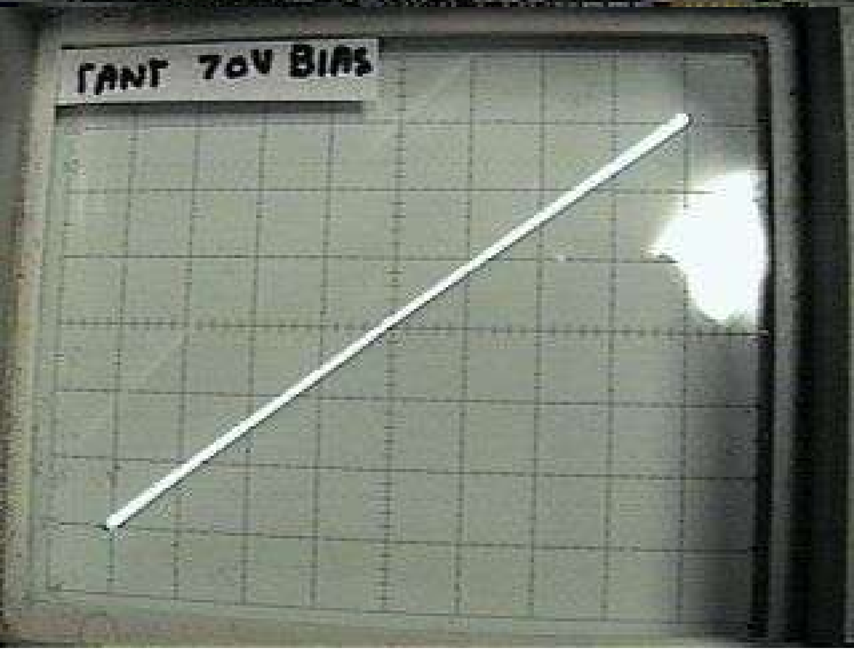
The Sound of Capacitors - Electrolytics

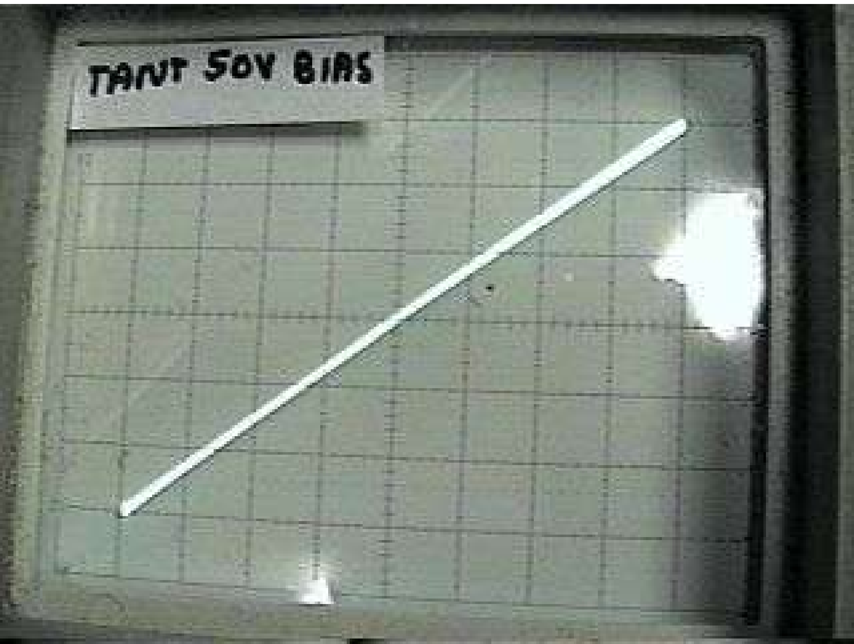
Electrolytic capacitors are not known for their linearity. In the initial article, I presented two curves, one a Tant, and one an Aluminum electrolytic. These were so called "non polarized" devices, and they displayed a lot of hysteresis. Here's the curves:

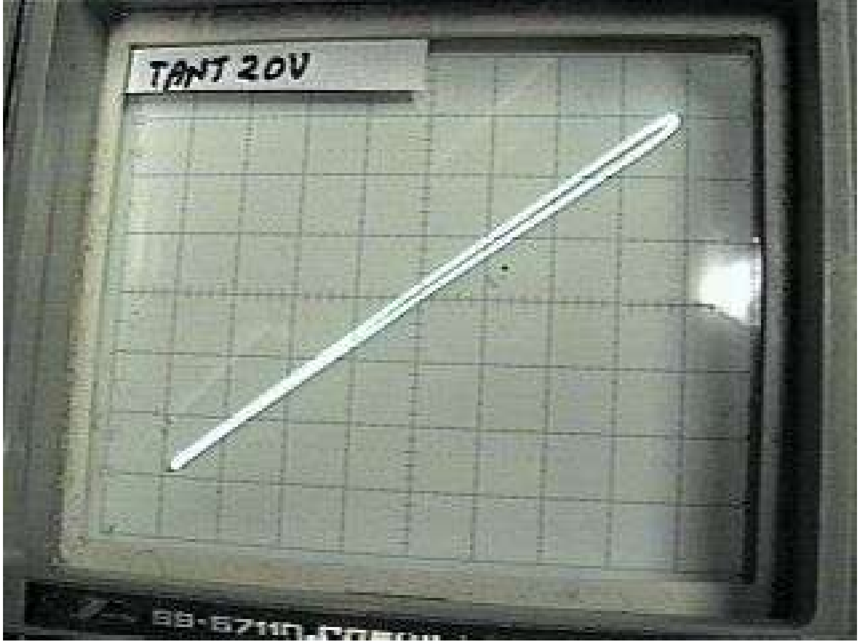


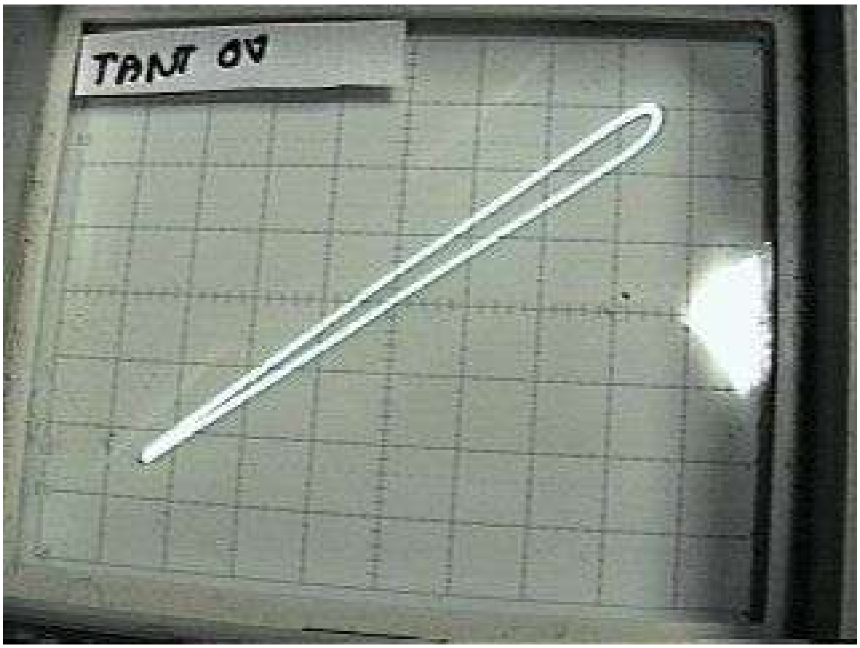
Neither of these are particularly grand. In discussions with several folks, it was pointed out that these devices really want to be polarized with a DC bias, so I thought I'd run a few curves as a function of DC bias. The part(s) chosen were polarized tantalum capacitors, 5 - 0.47uF 35 volt parts in series (175 volt capability) [Note: I originally reported these as 25V parts to some folks off line; they're indeed 35 volt parts.] Here's the results:


TANT 100V BIAS


TANT 70V BIAS


TANT 50V BIAS





There are a couple of items to note:

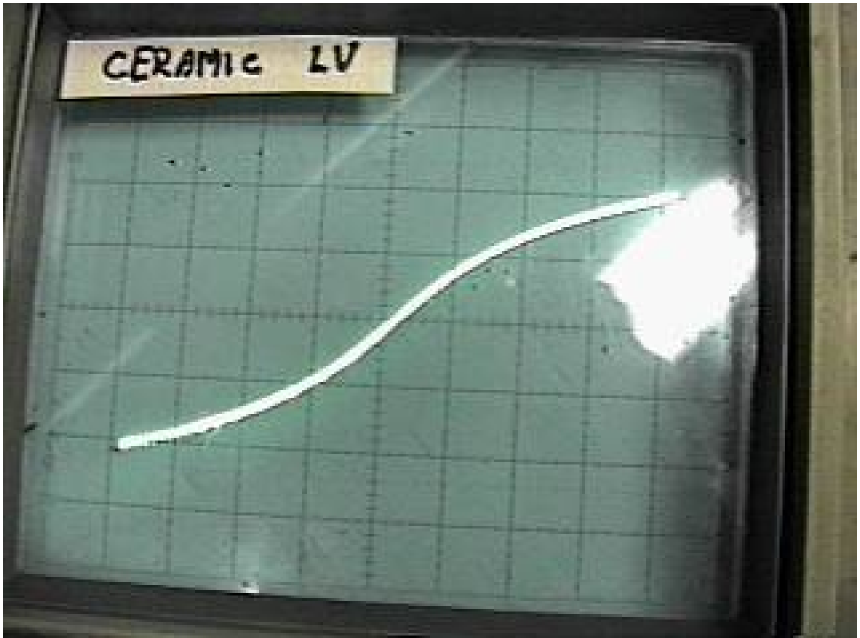
- The so-called non-polarized parts with no bias look dangerously like the polarized parts with bias. That probably tells you "worth" of the non-polarized parts. Don't depend on that characteristic.
- With relatively healthy biasing (100 volts) the hysteresis has disappeared. If you look carefull though, you can note that the characteristics is curved, indicating non-linear operation. Appar the hysteresis was "hiding" the otherwise non-linear character of these parts.

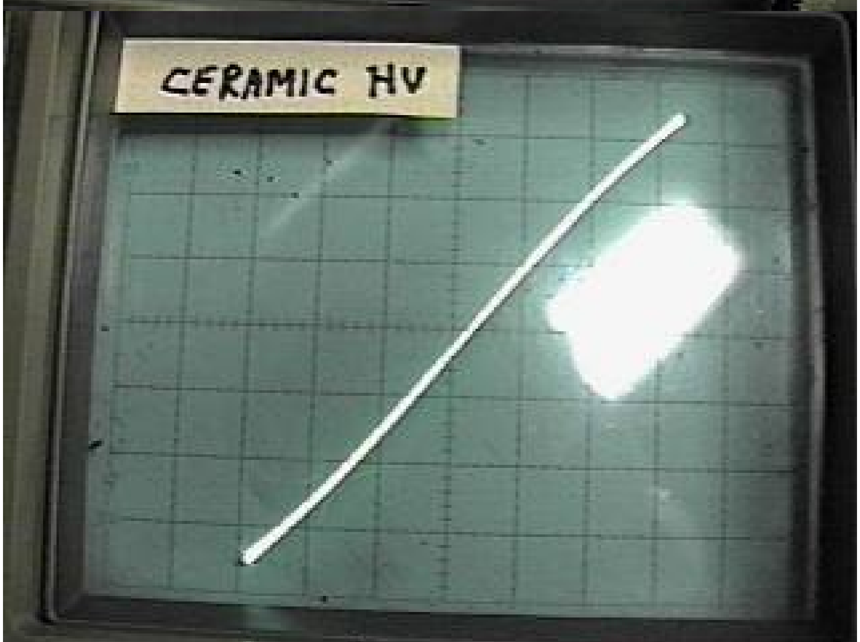
For high quality audio, these parts are probably best avoided.

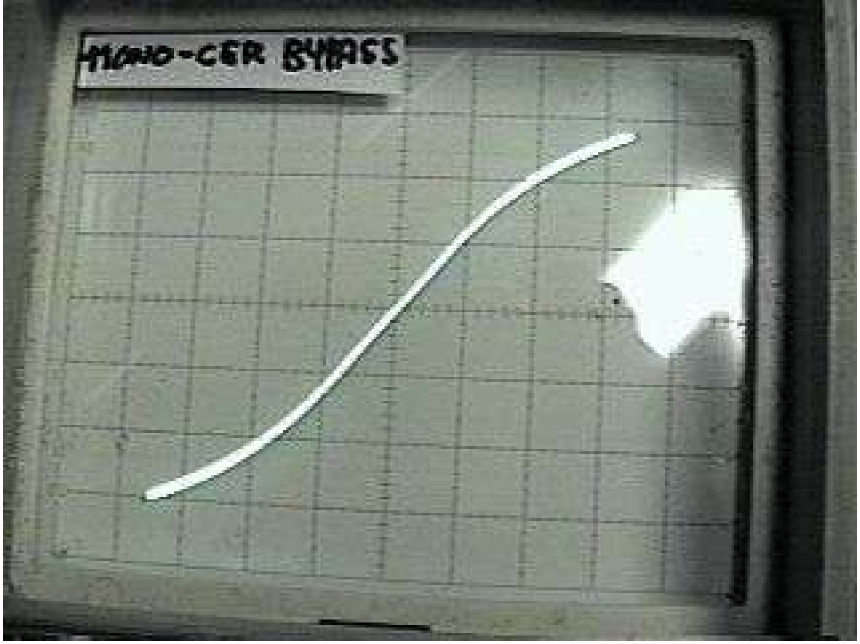
Steve

The Sound of Capacitors - Ceramics

I reported two types of ceramic capacitors, one a 100 volt Z5U part, one a 1000V Z5U. To this I will add one additional part: the ubiquitous monolythic "digital logic" bypass capacitor. Here's the results:

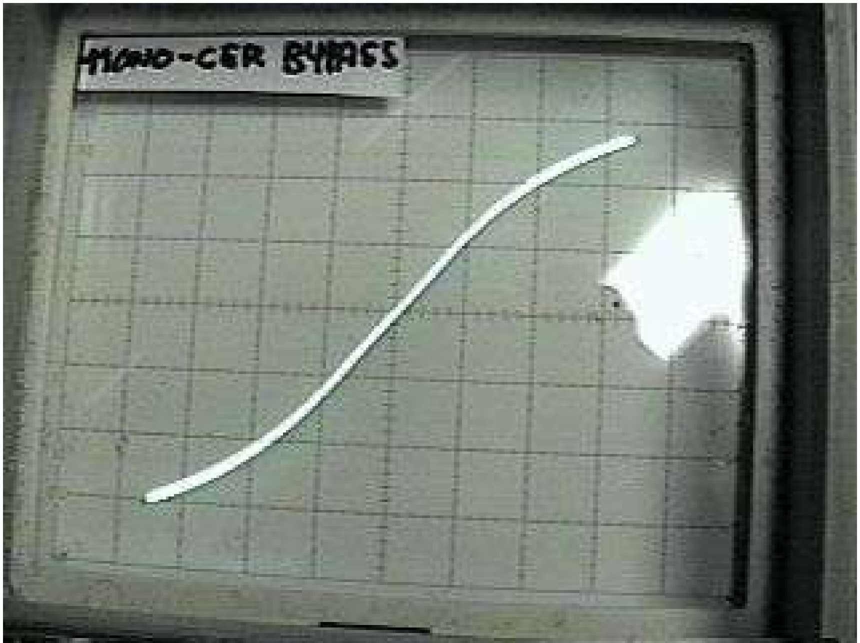


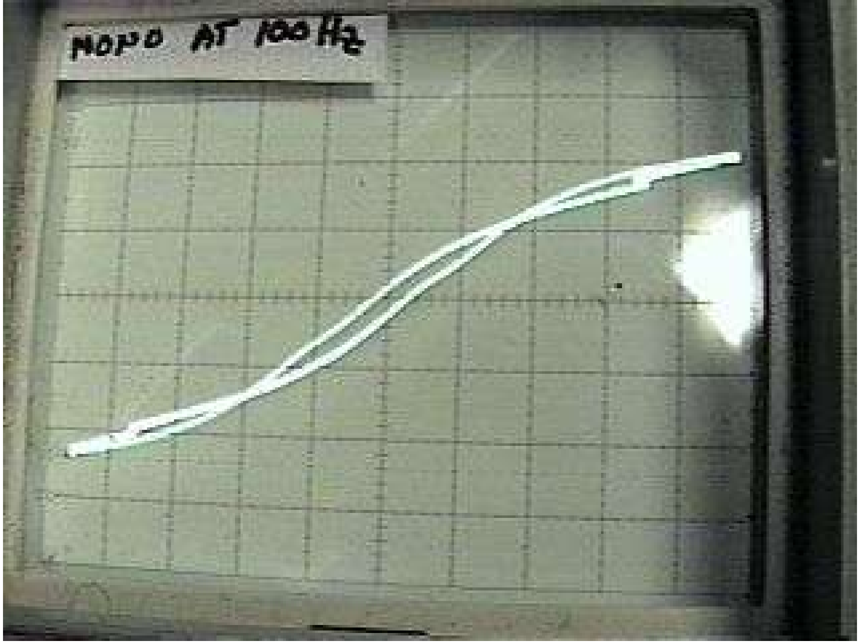




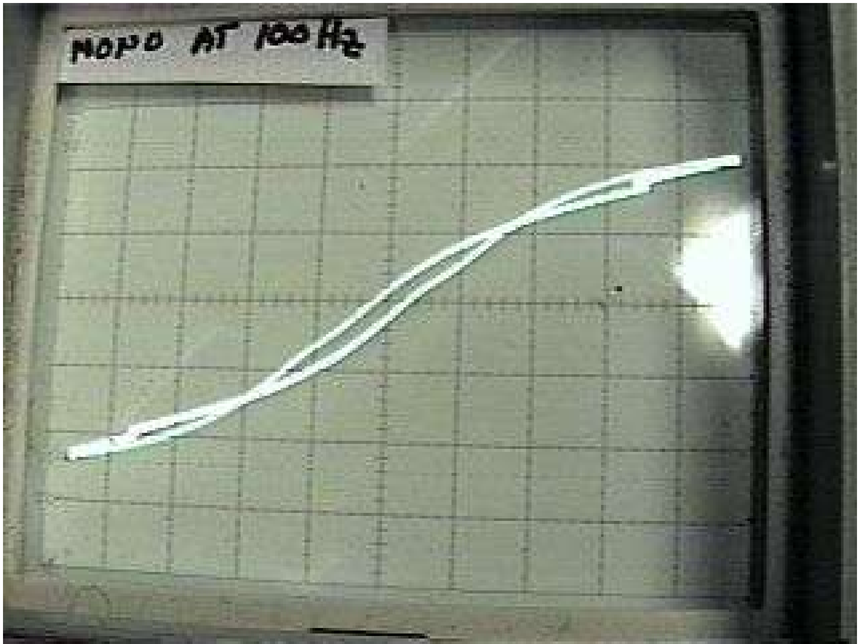
Notice that in the last picture, in addition to the non-linearities at the ends, theres another "kink" around the zero crossing point, adding yet another delightful characteristic to the sound!

In fact, there's yet a worse characteristic to these type of capacitors: their characteristics change considerably with frequency. Here's the data at 600 Hz and at 100 Hz:





Notice that there's hysteresis, "saturation" and odd kinks present in the curve. Just to prove there is no systemic setup problem, here's the characteristic of the mono at 100 Hz, and an oil-paper also at 100 volts:



Nope: it's the ceramic doing that!

Steve