PCB007 QuietPower columns

Vertical resonances in ceramic capacitors

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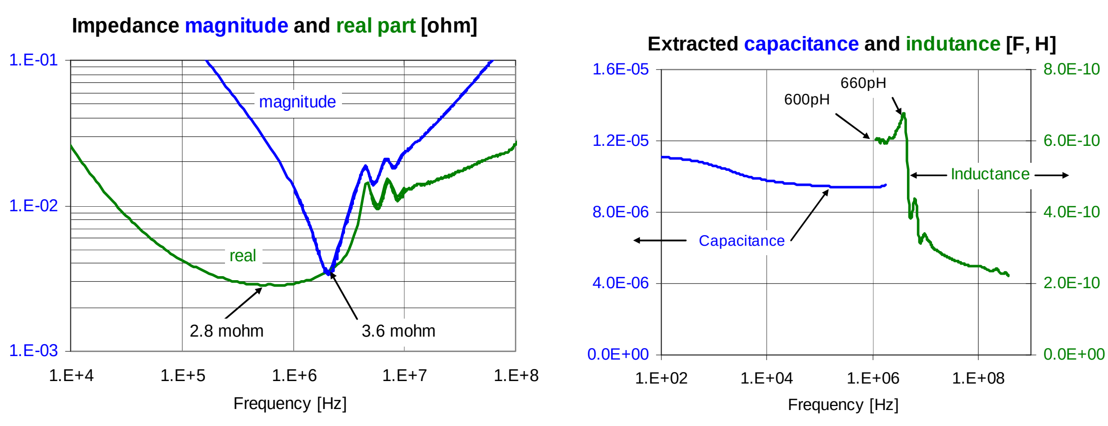
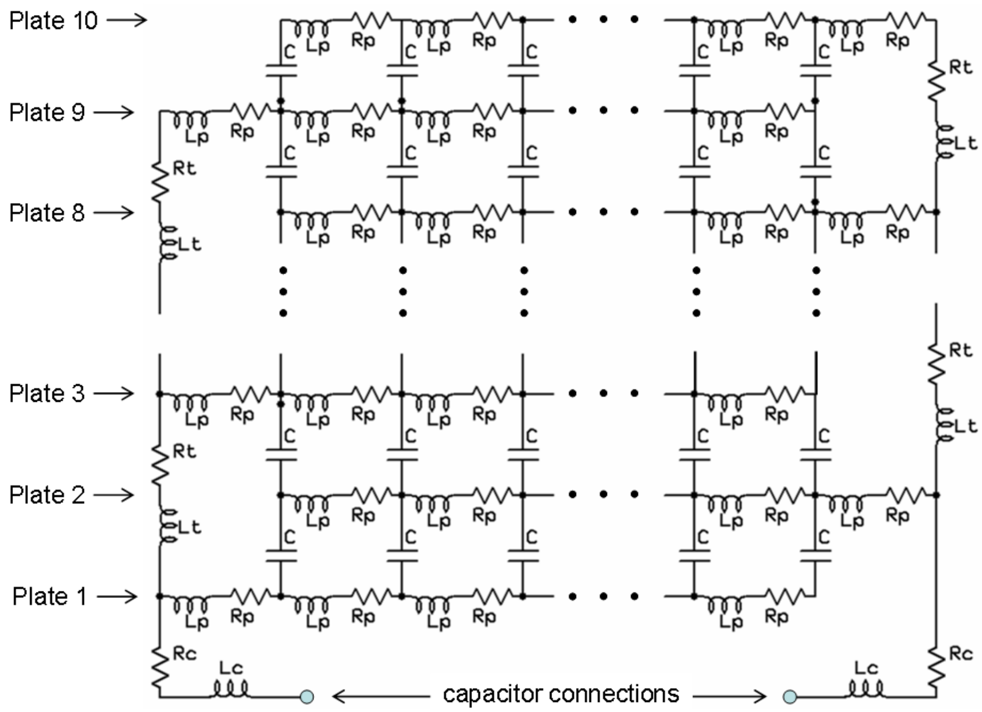
Ceramic capacitors are very popular in power distribution networks (PDN). They are small, cheap and come in a very wide range of available values. Typical ceramic capacitors also have low losses, at least compared to similar-valued electrolytic or tantalum capacitors. Because of their small size, we might think that structural resonances inside the ceramic capacitors do not exist in the frequency range where we usually care for the PDN. The unexpected fact is that the better PDN we try to make, the higher the chances that structural resonances inside ceramic capacitors do show up. This column tells you why and how.

Figure 1 below shows measured data from [1] on a small 0508 reverse-geometry 10 uF capacitor. There are several interesting aspects of these plots that are explained in [1]; here we focus only on one strange-looking detail, the double-hump resonance we see on the impedance magnitude and impedance real part curves somewhere in the 3 to 10 MHz frequency range. The test setup made sure that as much as possible the measurement result represented only the capacitor: the little fixture used for the measurement was separately characterized and showed no resonance in that frequency range. The biggest linear dimension of this capacitor is 80 mils, or 2 mm. The wavelength of 10MHz in free space is 30 meters; this is so much bigger than the linear dimensions of the capacitor that any resonance at such low frequency is really surprising, even if we factor in the high dielectric constant of the ceramic material. To understand what happens, we have to create a detailed electrical model of the capacitor, for instance a two-dimensional bedspring matrix, shown in *Figure 2*.



Measured impedance magnitude of a 10uF 0508 MLCC with the real part of the impedance (on the left), and extracted capacitance and inductance versus frequency (on the right).

Figure 1: *Measured data from [1].*



Partial schematics of the bedspring capacitor model. The model consists of ten capacitor plates, 1 through 10. The lowest capacitor plate, connecting to the PCB, is Plate 1. Plates 1, 3, 5, 7 and 9 are connected to the left terminal. Plates 2, 4, 6, 8 and 10 are connected to the right terminal. Each capacitor plate is divided into ten equal segments (plus an end piece), represented by series RL networks. At each internal plate node, a capacitor represents the dielectrics.

Figure 2: *Bedspring model from [1].*

Ceramic capacitors we use for power distribution bypassing have multiple metal plates interdigitated and embedded in a high dielectric constant ceramic material. As shown in *Figure 3*, the capacitor plates connect alternating to vertical metalized terminals at the two ends of the capacitor body. High-density ceramic capacitors can have hundreds of these capacitors plates. Between adjacent capacitor plates, which are connected to the opposite terminals, there are thin ceramic layers. Many of these sections are connected in parallel by the vertical terminals, conveniently increasing the total capacitance and reducing the inductance as well as the series resistance of the part. Without cross sectioning we don't know how many conductive plates a particular capacitor actually has, but to model the resonances we see in the measured data, it is really irrelevant. The model in *Figure 2* uses a ten-by-ten matrix: ten capacitor plates on each terminal and ten dielectric segments along the plates. L_c and R_c represent connection inductance and resistance between the capacitor's terminals and the observation point: these are the parasitics of the connecting vias and traces. The model, though looks complicated, runs very fast in any SPICE tool in AC simulations. Note that since here we are interested in the capacitor's behavior above the series resonance frequency, dielectric losses are not included in the description.

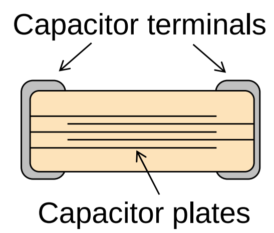


Figure 3: *Internal construction of a multi-layer ceramic capacitor.*

For an illustrating case that creates a series resonance frequency at 10MHz, the simulated impedance results are available in a spreadsheet [2]. The spreadsheet contains the AC sweep SPICE results at 200 frequency points, logarithmically spaced from 1 MHz to 100 MHz, one decade below and above the series resonance. On two 3D charts you can see the current distribution inside the dielectric and in the capacitor plates. On both 3D plots the vertical axis shows current in amperes on a logarithmic scale, the right axis corresponds to vertical location inside the capacitor with the front center corresponding to the bottom of the capacitor, closest to the PCB it is mounted on. The left horizontal axis corresponds to the left-to-right position inside the capacitor body between the two vertical terminals. With a macro you can sweep through the frequency values or you can plug in a specific frequency selector number.

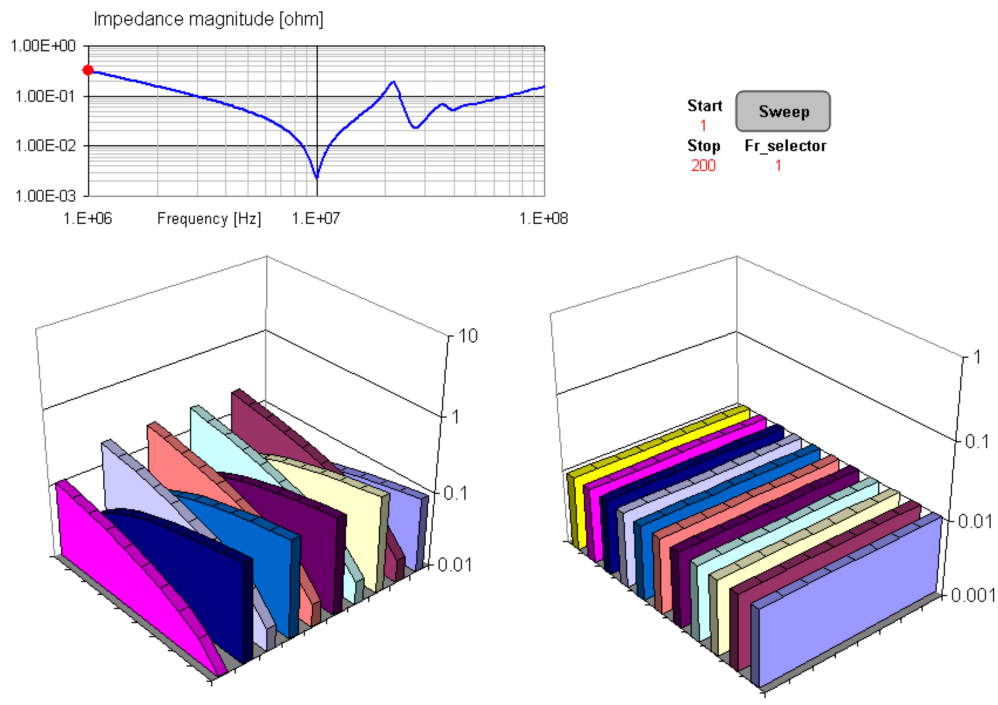


Figure 4: *Impedance magnitude on the top-left chart. The current distribution is shown at 1 MHz in the capacitor plates (lower left 3D chart) and in the dielectrics (lower right 3D chart).*

The current distribution one decade below the series resonance frequency is uniform. This directly shows up in the dielectric current plot being a flat surface. The capacitor plate current shapes look triangular. Since the capacitor plates don't short the opposite terminals, they end in the open dielectric, hence the triangular shape. The equal-height triangular shape in fact corresponds to uniform current sharing among the plates.

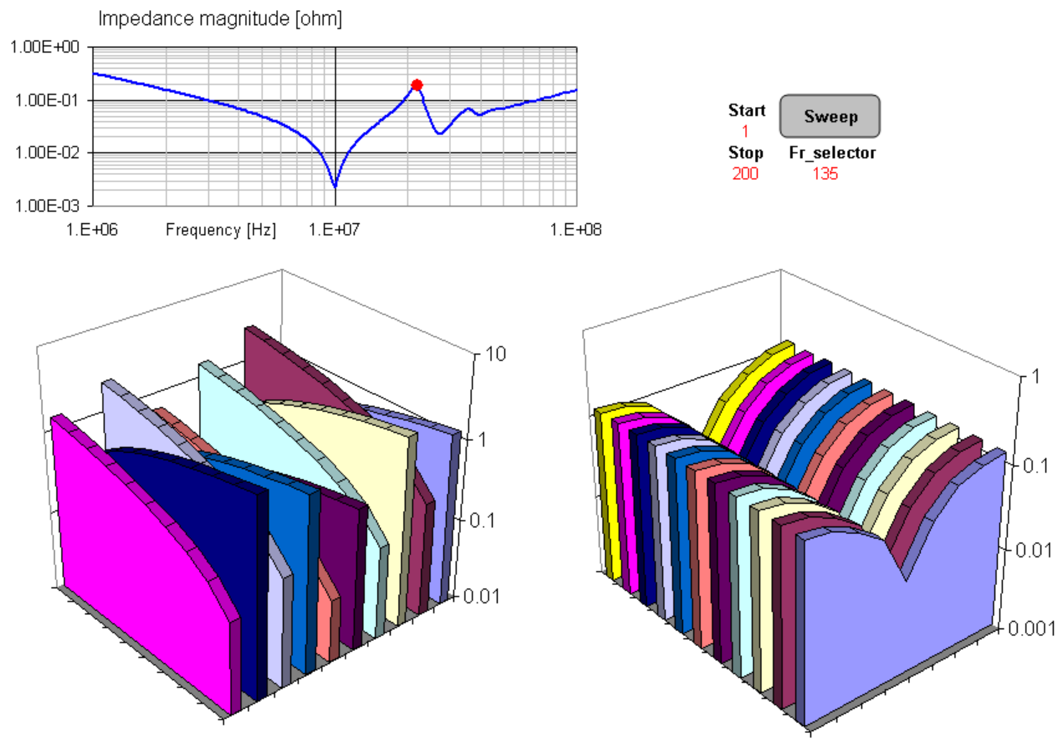


Figure 5: *Impedance magnitude on the top-left chart. The current distribution is shown at 22 MHz in the capacitor plates (lower left 3D chart) and in the dielectrics (lower right 3D chart).*

When we set the frequency selector to the 135th point, which corresponds to 22 MHz, the current distribution plots change significantly. In general, the values in both 3D charts are much higher, already suggesting a resonating scenario. The resonance clearly shows up on the right-hand 3D plot (dielectric current), exhibiting a notch halfway up inside the capacitor body. This comes from a vertical half-wave resonance, also shown as a local peak at 22 MHz on the top left impedance magnitude plot.

If we re-simulate the model with different L_c values, we will see that the structural resonance gets stronger as the ratio of inductances of the vertical terminal versus the external connection increase. With poor connection, when the connection inductance is much higher than the inductance of the capacitor terminals, this resonance is hardly noticeable. Strangely, as we improve the connection of the capacitor by driving L_c down, we also make these structural resonances more pronounced.

As we demonstrated, in spite of their physically small sizes, ceramic capacitors can exhibit structural resonances, too. If you want to read more on the subject, check out the cited references.

References:

[1] "A Black-Box Frequency Dependent Model of Capacitors for Frequency Domain Simulations," DesignCon 2005 East, High-Performance System Design Conference, Worcester, MA, September 19-22, 2005, available at http://www.electrical-integrity.com/Paper_download_files/DCE05East_Black-box-model_SUN-Novak.pdf

[2] http://www.electrical-integrity.com/Paper_download_files/Grid_sweep.xls

[3] "Slow Wave Causal Model for Multi Layer Ceramic Capacitors ," DesignCon2006, Santa Clara, CA, February 6-9, 2006, available at http://www.electrical-integrity.com/Paper_download_files/DC06_Slow-wave-model_SUN_Novak-Blando-Miller.pdf