The methods and problems of ESR measurement

Syfer brand High Q and Ultra Low ESR Capacitor Ranges

Introduction

There are many different types of capacitor with many different parameters; each is suited to a range of applications. As operational frequency requirements increase, electronic systems downsize and power usage becomes more critical the most important parameters are Q, Quality Factor, and ESR, Equivalent Series Resistance.

Measurement and characterisation of MLCC's for these parameters is demanding and with limited standardisation of test methods, comparison of ranges, or competitors, is difficult.

This application note addresses the measurement of ESR in highQ MLCC's, as probably the most requested parameter, considers the test methods in use and explains how Knowles (Syfer) measure the data we publish.

Knowles (Syfer) have two ranges of components, our High Q (Q or MS) range which exhibits a high quality factor and low ESR and our Ultra Low ESR (U) range with an enhanced performance level, which are designed for use in a variety of high frequency applications such as telecommunications PAs, microwave circuitry and RF modules. Non magnetic versions of the High Q (MS) type are also available for use in applications such as MRI tuning; see our application note AN0035 for details.

Q, ESR and Power

Q is the Quality factor; it is the reciprocal function of the dissipation factor, DF, and represents the losses of the capacitor. The higher the Q, the lower the DF and therefore, the lower the loss. ESR is the Equivalent Series Resistance and represents the effective resistance to RF current; it encompasses both the loss properties of the dielectric and electrode.

$$Q = \frac{1}{DF}$$ Q is Quality Factor, DF is Dissipation Factor

$$X_c = \frac{1}{2\pi fC}$$ X_c is Capacitive Reactance in Ohms, f is frequency in Hertz and C is capacitance in Farads

$$R_s = DF.X_c$$ R_s is Equivalent Series Resistance in Ohms, DF is Dissipation Factor and X_c is Capacitive Reactance in Ohms

$$P = I^2R$$ P is Power dissipated in the capacitor in Watts, I is RMS current in Amps and R is R_s in Ohms

Knowing the value of ESR is important because it determines the suitability of the component for use in RF power applications. If the ESR value is too high the self-heating due to $P = I^2R$ losses will be too great and the part will overheat and fail. The ESR also allows one to calculate the maximum current rating for the component.

Worked Example:

A cellular phone base station, operating in the GSM900 band at 940MHz. The RF power is 40W and it is a 50Ω system. The coupling capacitor is a High Q (MS) 47pF 0805 with an ESR of approximately 0.088Ω at 940MHz. Using $P = I^2R$ where R = Z+ESR to find the circuit current gives 0.894A. To find the power dissipated in the capacitor we put this value of current back into $P = I^2R$ where R=ESR which gives 0.0703W or 70mW. It is clear from this that the power dissipated in the capacitor can be simply derived from the ratio of the ESR to the total circuit impedance multiplied by the system power, (ESR/(Z+ESR))xP. For values of ESR significantly lower than the Z value there is a negligible impact on the overall circuit impedance and it can be ignored leaving (ESR/Z)xP.

Using the same calculations for an Ultra Low ESR 0805 47pF, ESR 0.07 at 940MHz the power dissipated in the capacitor is 56mW, a 20% reduction. This allows the system to run cooler or to be run at higher power.

Different dielectric and electrode combinations will exhibit different levels of Q and ESR. At lower frequencies the dielectric material is the dominant factor, metal losses become more important at higher frequencies. X7R materials are utilized at low frequencies and typically have a DF of around 1% to 2%, measured at 1kHz, corresponding to a Q factor of 50 to 100. C0G/NP0 materials have a Q of around 600 to 1000, measured at 1MHz, whilst Syfer High Q & U series capacitors are broadly defined as Q>2000 at 1MHz. Measurement of Q at 1MHz under laboratory conditions can show higher Q values, 10000 or more, but for practical purposes the limit for 100% testing on high speed machines is ~2000.

100% measurement of Q is not practical above 1MHz, Capacitance bridges and LCR meters are not accurate enough and when combined with leads and contacts rapid high frequency measurement is not possible.

It is necessary however to assess the Q and ESR at frequencies nearer to those which the capacitor will encounter during operation, but it is in doing this that we encounter test variance and accuracy issues which cause issues with looking at the data in isolation.

Measurements methods for ESR

1. *Co-axial resonant tube measurement method*

The most accurate method of determining Q and ESR at elevated frequencies (~100MHz to ~1.2GHz), is to use a resonant line coaxial jig. The industry standard tube for doing this was laid down many years ago as the Boonton model 34A, manufactured by the Boonton Electronics Corporation. Designed to be used along with a RF voltmeter and an RF signal generator as seen below.
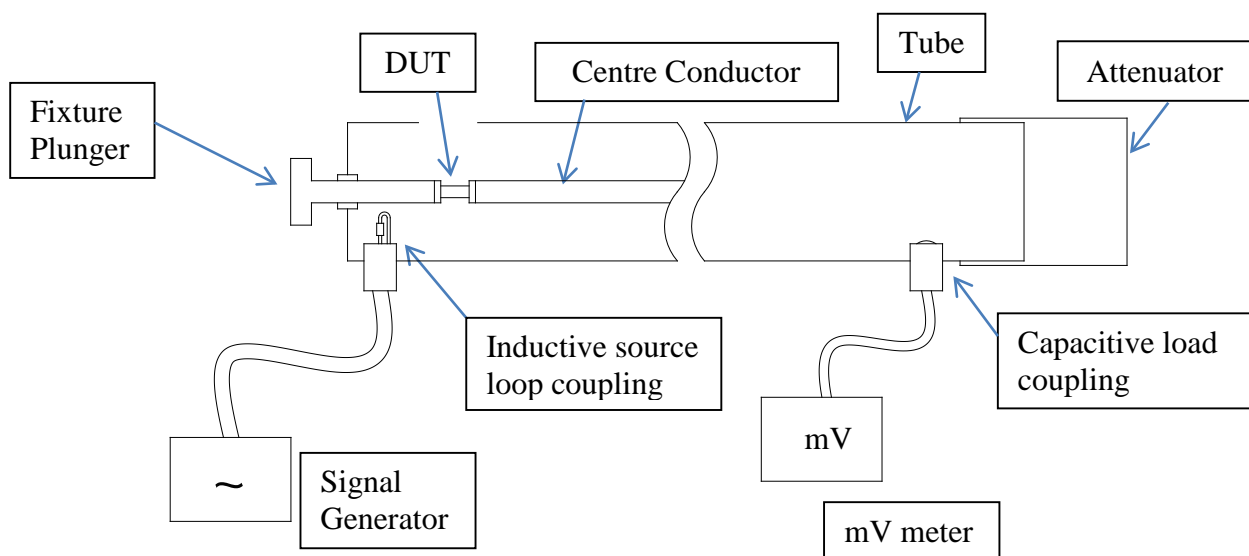

Fig 1. Schematic of resonant tube

The $\frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$ & $\frac{7\lambda}{4}$ resonant frequencies are measured by adjusting the signal generator until the peak reading is recorded on the millivolt meter. For each resonant frequency, the 3dB bandwidth is determined by adjusting the frequency until the millivolt meter reading drops to 50% of the resonant value

The tube is characterised, measuring the $\frac{\lambda}{4}$ & $\frac{3\lambda}{4}$ frequencies and bandwidths in it's open and short mode and the chip introduced between the two conductors, held in place by the shorting plunger. A full set of readings is taken and the ESR & Q can be calculated at the resonant frequencies.

Once you have obtained the 3, 4 or 5 resonant frequencies, a plot is made of ESR vs Frequency and a 'best fit' line is drawn between them, the response curve between resonances assumed to be relatively linear.

Fig 2. Boonton 34A with traditional set-up

The Boonton resonant tube system was developed before the advent of Vector Network Analysers. In practise, these days it is more normal to replace the signal generator and millivolt meter with a VNA.
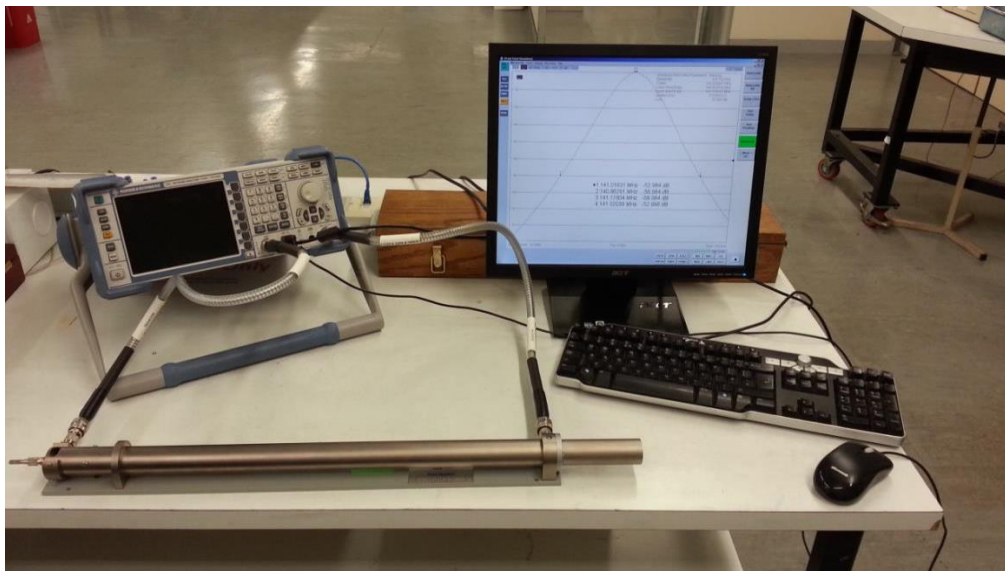

Fig 3. Boonton 34A with VNA set-up

With the resonances visible as a graphical peak the frequency and bandwidth can be easily read off. With modern VNA equipment it is also possible to directly export the results to the calculation program.

The resonant tube method remains the only relatively accurate way of measuring ESR and Q of small MLCC's and this was recognised when the international standard for ESR measurement, EIA-RS-483, was written around this equipment.

There are limitations to this measurement method though. The operating frequency range of the tube is limited by the physical length to ~100MHz to ~1.25GHz. This is reflected in EIA-RS-483 which only covers ESR measurement in that frequency range. It can also be seen in data published by some MLCC manufacturers that quote data to the 1GHz to 1.5GHz maximum frequency.

If response at frequencies outside this range is to be evaluated by resonant tube, it is necessary to manufacture and characterise a new tube. Boonton made the only commercially available tube in the 34A, any other tube will be 'home made' and characterisation / build quality may not be as good as the Boonton.

There are also the problems of resonances within the capacitor to consider. The ESR response of an MLCC is not linear, but peaks at the **P**arallel **R**esonant **F**requencies (PRF's) around which points the capacitor response is erratic. If the resonances of the tube are close to a PRF peak of the MLCC then the measurements need to be ignored, but as the tube does not show the PRF of the MLCC then it takes an experienced operator to identify which measurements must be eliminated from the curve.

As an example, consider the following 0805 47pF MLCC measured using 2 resonant tubes:

- Readings to 1.2Ghz taken using a Boonton 34A
- Reading from 700Mhz to 5GHz taken using a home-made 10cm resonant tube.

Notice the severe change in response between the 2 tubes and elevated readings in the GHz region. In practise this MLCC had a PRF around 2.6GHz with a second level resonance ~5Ghz, rendering the readings taken from the smaller tube irrelevant much beyond the 1.3GHz level seen with the commercial tube.
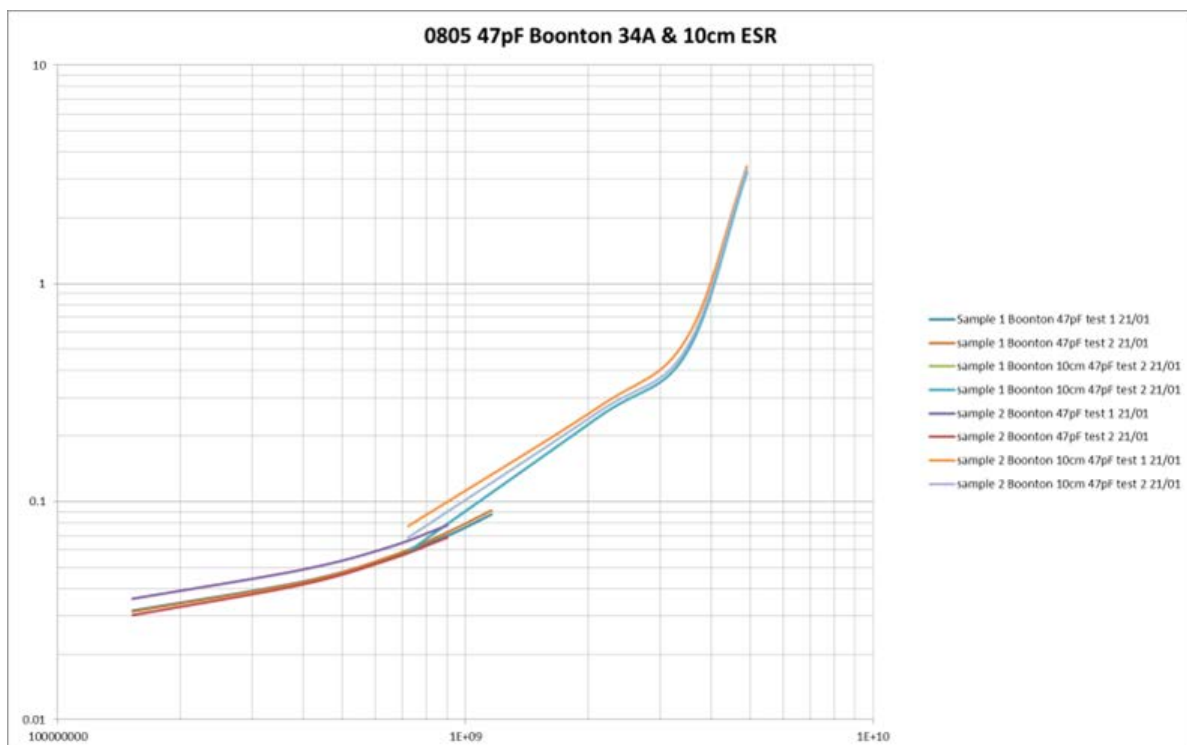

Fig 4. 0805 47pF 'U' series Boonton 34A & 10cm tube results

2. *Swept VNA Impedance Analyser Measurements*

It is clear then we must look at alternatives to measure ESR with a sweep method, taking more measurement points across the frequency range to get a better understanding of the performance of the component.

It is possible to take reasonably accurate readings by soldering parts to boards and measuring the response using a VNA to generate S parameters and reverse modelling to determine the ESR. These methods are not as accurate as the resonant tube, but do have the advantage of producing a swept response highlighting any resonances in the system. The problem with accuracy of swept measurements if used in isolation can be shown later.

There is one piece of equipment on the market (as of Oct 2015) that allows direct measurement of ESR of an MLCC using a swept measurement up to a maximum of 3GHz and this Keysight E4991 is becoming recognised as the new standard method for characterising MLCC's as it is increasingly adopted by the manufacturers and users of these components.
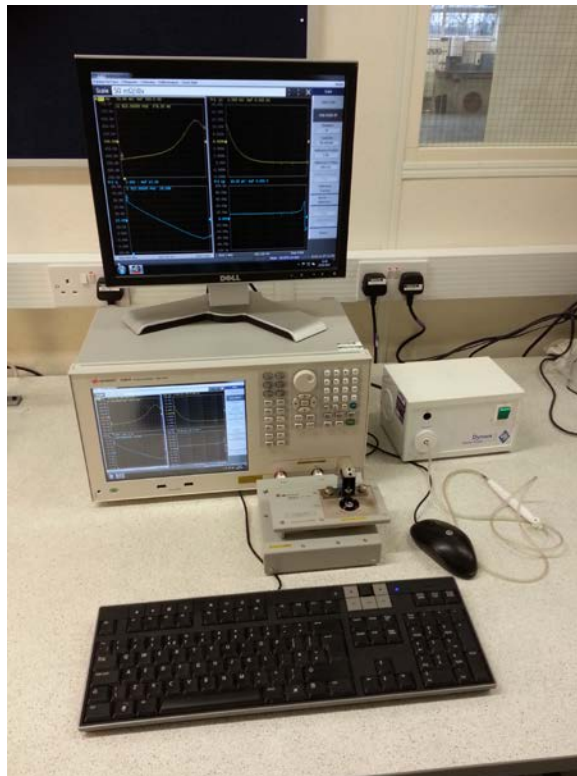

Fig 5. Keysight E4991B with jig 16197A attached

The E4991 is essentially a VNA with a modified front end interface which allows direct measurement of ESR, Q and Z. Various jigs are available to enable measurement of different chip sizes, but again there is a limit that it is important to recognise.

If you analyse the accuracy of this measurement method, as shown in the Keysight documentation, it becomes clear that measurement of the very small ESR figures associated with MLCC's is very difficult. The errors and uncertainties in the measurement are best shown with a demonstration of accuracy based on an 0805 MLCC with the following measured parameters :

Test Frequency: 500MHz
Cs: 51pF
Zx: 6.153 Ohm
Rs: 0.026 Ohm
Q: 250

Applying the accuracy calculation in the Keysight handbook you get the following :

DUT: Cs=51pF, Zx=6.153 ohm, Rs=0.026 ohm D=0.026/6.153=0.00423, freq= 500MHz

Accuracy calculation for E4991A (refer to datasheet P4-P5);
Ea=0.8%
Eb=(Zs/|Zx|+Yox|Zx|)x100 = (263m/6.153 + 55ux6.153)x100 = 4.27%
  Zs=13+0.5xF(MHz) mohm = 13+0.5x500 = 263 mohm
 Yo=5+0.1xF(MHz) uS = 5+0.1x500 = 55 uS
 Zx=6.153 ohm

Cs=(Ea+Eb)xSQRT(1+Dx^2) = (0.8+4.27)xSQRT(1+0.00423^2) = 5.07%
Rs=(Ea+Eb)xSQRT(1+Qx^2) = (0.8+4.27)xSQRT(1+(1/0.00423)^2) = 1200% (**0.026 ohm +-0.312 ohm**)

Note that this does not include the accuracy / uncertainty of the test fixture. Assuming 0805 size MLCC's are tested using Keysight test fixture 16197A, then we must add the calculation for that as well :

Ze=A+(Zs/Zx+YoxZx)x100 = 0.3+(105m/6.153 + 17ux6.153)x100 = 2%
  A=1.2xf(GHz)^2 = 1.2x0.5^2 = 0.3%
  Zs=(30+150xf(GHz)) mohm = (30+150x0.5) = 105 mohm
  Yo=(2+30xf(GHz)) uS = (2+30x0.5) = 17 uS
  Zx=6.153

Res=Ze/Dx = 2/0.00423 = 473% (**0.026ohm +- 0.123ohm**)

The combined accuracy / uncertainty is given from

SQRT(0.312^2+0.123^2) = 0.335 ohm -> **0.026 ohm +-0.335 ohm**

So we can see that the accuracy of this test method is not very suitable, *in isolation,* to producing test figures.

The curves it produces, however, do include the PRF resonances and are much more useful in determining the actual true performance of the component. If we show the measured curve from the E4991 of the same components shown above on the resonant tube, we get the following :
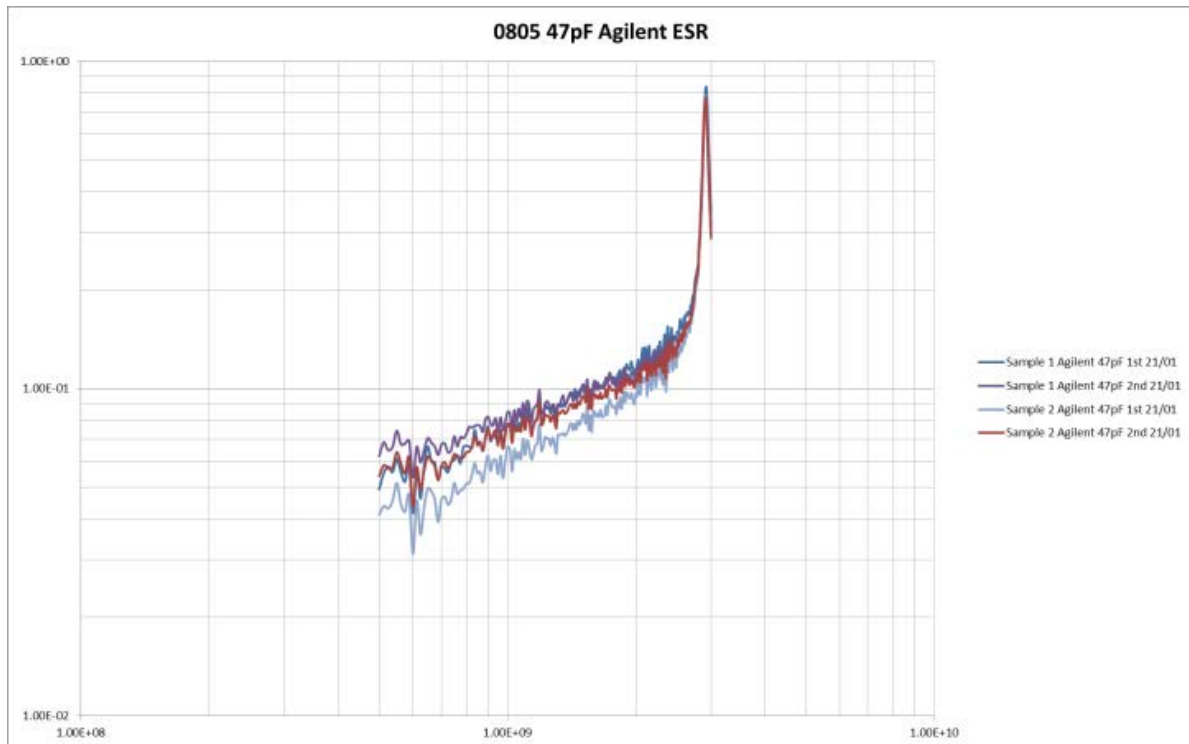
Fig 6. Swept plot 0805 47pF 'U' series

Overlaying the two curves from both pieces of equipment we can see exactly how the resonant tube measurements are being affected by the PRF resonances, and how inaccurate both a resonant tube measurement and a swept measurement can be in isolation.
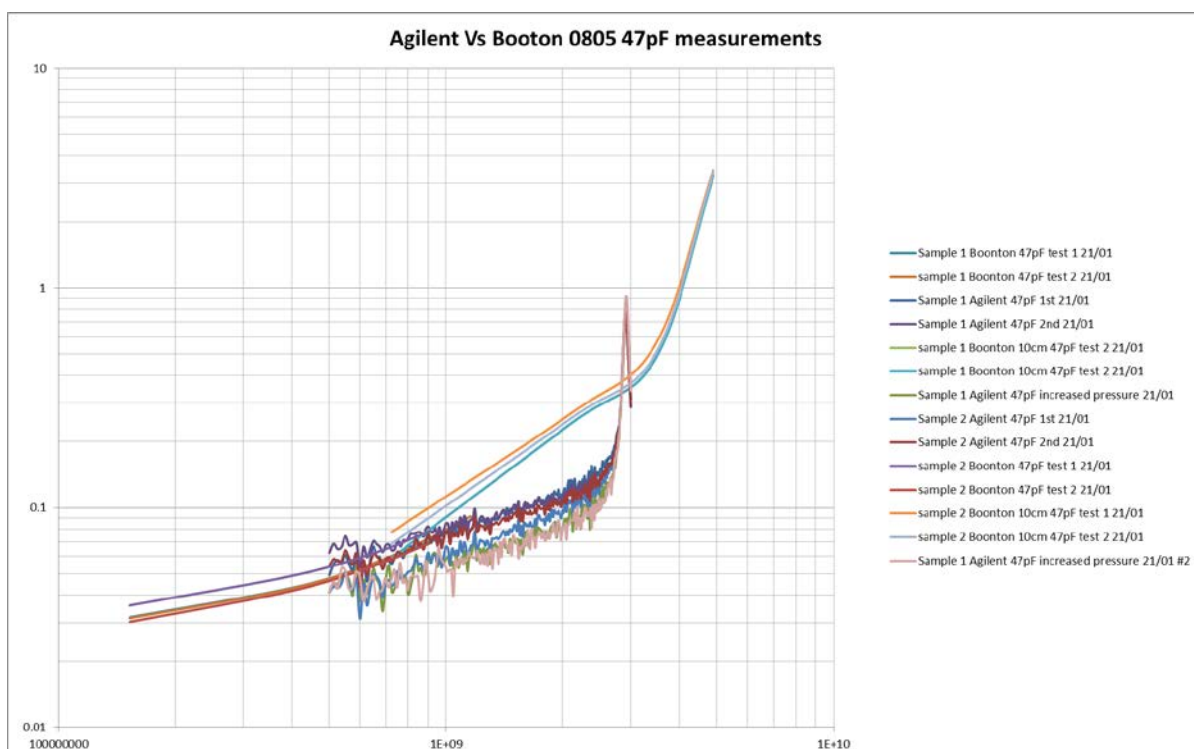

Fig 7. Comparison of swept plot Vs Boonton tube 0805 47pF 'U' series

3.   *Combination of Boonton and swept measurements*

We therefore have a situation where we have two sets of test equipment, both producing results that have accepted inaccuracies. Neither test method can be used in isolation, but combining the two enables us to cross check results and confirm the readings taken are reasonably accurate.

The procedure adopted by Knowles, therefore, is :

1. Measure component using Boonton 34A generally in accordance with EIA-RS-483 to a maximum of 1.2GHz

2. Use the results generated from the Boonton test to verify the set-up of the Keysight E4991 to demonstrate that the calibration is as accurate as possible.

3. Complete the measurements using a swept function on the Keysight.

4. Combine both sets of readings to produce the declared results.

Using this method a set of plots can be generated for ESR, Q & Z.

Example plots (0805 'U' series) are shown below (refer to range datasheet for latest plots)
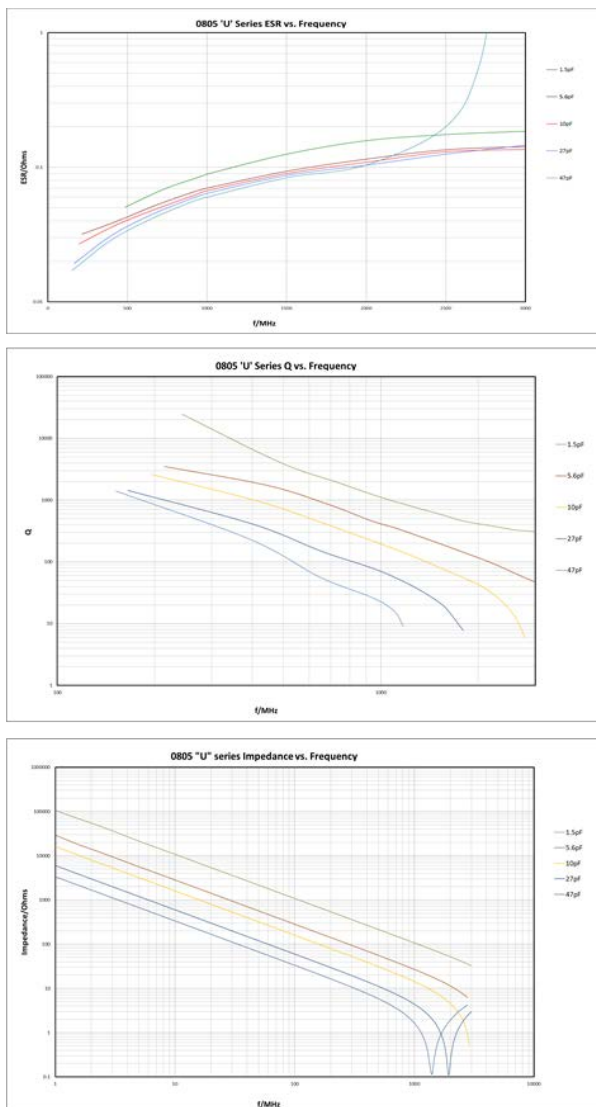

Fig 8. Datasheet curves for 0805 'U' series MLCC's. Readings taken using Boonton 34A & Keysight E4991B analyser with 16197A test fixture

Comparison of test jigs

In defining our test regime, all data on chip sizes 0603 to 1206 is generated on jig type Keysight 16197A, surface mount fixture.

An alternative fixture, type Keysight 16196*, is available and may be used by others for testing. Keysight 16196 is a range of jigs tailored to specific MLCC sizes from size 0603 down. The major difference between the 16196 & 16197 jigs are the connection to the MLCC – 16196 only contacts the end of the chip, whilst 16197 contacts the bottom pad of the termination. Neither are truly representative of an MLCC soldered to a board, but do allow comparison testing between different MLCC's.

It is important to note that it is not unusual to achieve different test results from the same component tested on the 16196 & 16197 jigs. When making comparisons, it is important to only compare results taken on the same type of fixture.
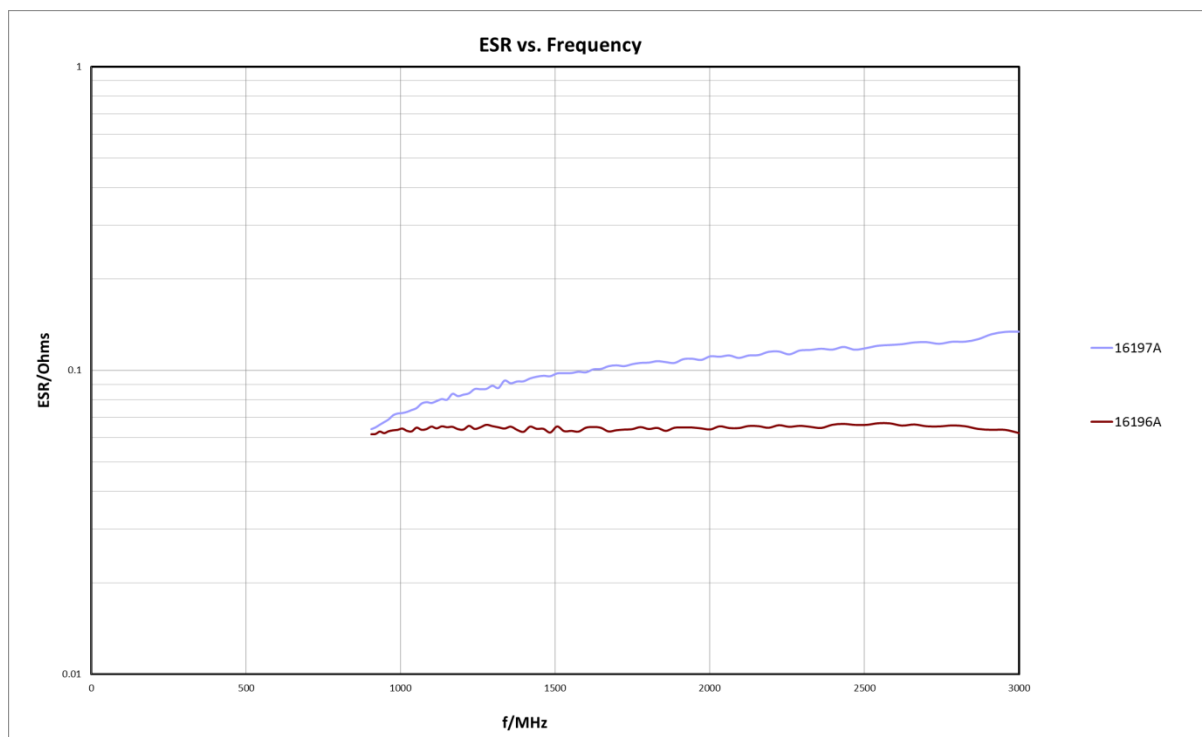
Example :

Fig 9. 0603 18pF 'U' series MLCC measured using Keysight E4991B analyser and different test fixtures

![Knowles logo - DLI·Novacap·Syfer·Voltronics]

Application Note
Reference No: AN0036
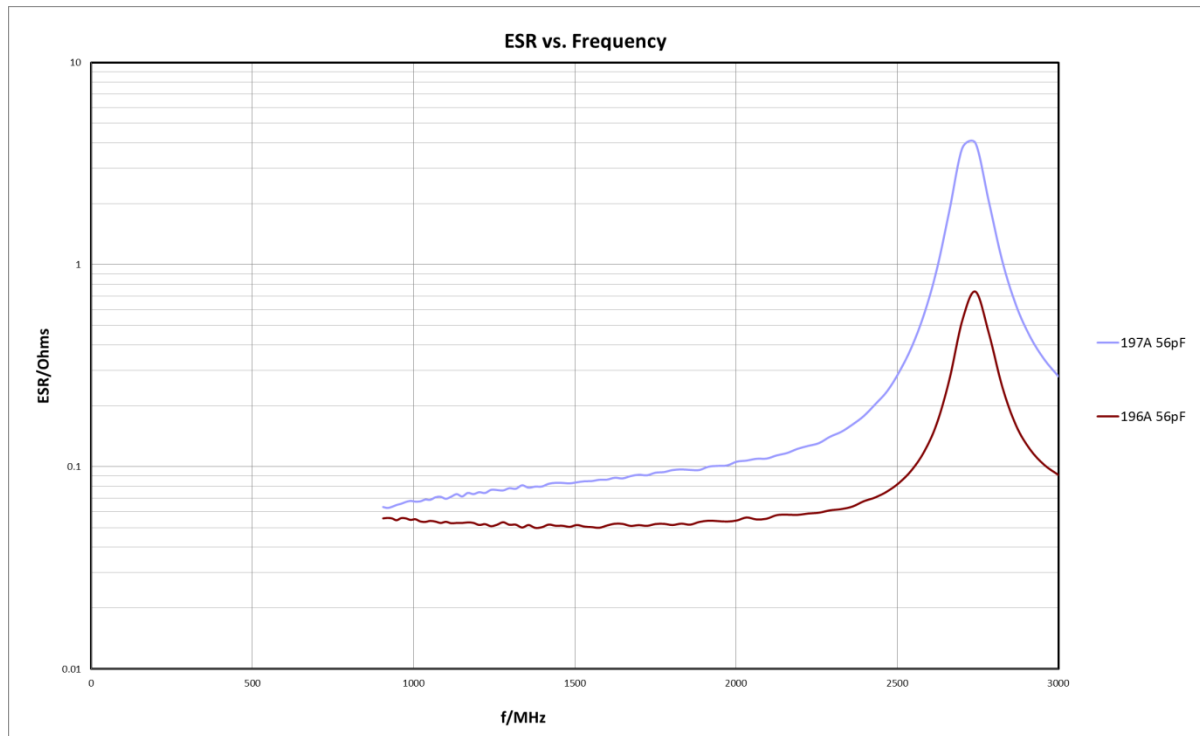ESR Measurements of
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Fig 10. 0603 56pF 'U' series MLCC measured using Keysight E4991B analyser and different test fixtures

Clearly some care must be taken to ensure that comparisons are only made between relevant test results.

Conclusion

ESR and its associated data plots (Q, Z etc) are important considerations for circuit design, but are notoriously hard to measure and equally hard to make comparisons between data supplied from different companies, or to take measurements to verify with data supplied.

The difficulties and accuracy issues associated with its measurement mean that these figures / plots are always given as 'typical' data. MLCC's are defined by the capacitance value and working voltage. Good control of materials and design mean that the performance will be consistent, but actual measured data may vary.

ESR is best considered as a comparative measurement – measurement of components on the same system on the same day with the same compensation set allows a good indication of relative performance. Comparison of data with figures obtained from other sources or tested at other times may not give a true picture of how the parts will perform in circuit.

Even when considering comparison test data, it must be remembered that it is obtained from a component mounted in a test fixture and may not be totally representative of a component soldered into a circuit. Suitability of operation must always be confirmed by evaluation in circuit.
ESR, Q & Z plots are therefore supplied with the aim of giving an indication of the performance of an MLCC over a given frequency range of operation.

CapCad™

Knowles (Syfer) web based CapCad™ capacitor modelling software has been developed to provide customers with an easy to use and readily accessible comparison tool for choosing the best Multilayer Capacitors to suit the customer's needs. CapCad™ includes SPICE models with values that reflect typical performance at the chosen frequencies and temperatures that are of importance to an application. The user also has the ability to plot 2-port Scattering Parameters, Impedance, Q Factor or Equivalent Capacitance over any frequency span from 1MHz to 40GHz while maintaining the ability to adjust the temperature and note how it may affect the performance. CapCad™ also includes a Smith Chart utility and the ability to copy the S-Parameter data in touchstone format (s2p). CapCad™ can be found on the Knowles (Syfer) website under the technical information menu and includes data for the HighQ (MS) range of MLCC's

The graphing links allow the user to produce graphs of various parameters in both horizontal and vertical mounting orientations.

Modelithics

MODELITHICS, INC. provide simulation models for RF, microwave and millimetre-wave devices, offering highly accurate, scalable measurement-based models that integrate seamlessly with popular electronic design automation (EDA) tools.

The 0603 "U" range has been modelled by Modelithics and scaleable models are available as part of their model libraries for Keysight ADS, Keysight GENESYS, and AWR Microwave Office EDA software.

Further information is available on the Modelthics website www.modelithics.com

S parameters for the 0603 are available on both the Modelithics (www.modelithics.com) and Knowles Capacitors website www.knowlescapacitors.com/syfer

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