ModuLab® mts

Technical note

Impedance analysis techniques

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1. Introduction

The frequency response analyzer developed for the ModuLab MTS materials test system (MFRA 1MHz) utilizes the latest signal processing technology to provide amazing high-speed impedance measurements while maintaining the accuracy, repeatability and resolution of previous generation Solartron frequency response analyzers.

Solartron's reputation for the design and manufacture of top quality AC measurement instrumentation is built upon the performance of its range of frequency response analyzers (FRAs). Solartron started developing instruments in 1948, initially supplying frequency response test instrumentation into critical, high accuracy aerospace applications. Over the years, the company has diversified into many applications areas including battery, fuel cell, materials and electrochemical test, but the basic philosophy for producing high quality, accurate and reliable test instrumentation has always remained the same.

2. Impedance analysis

Impedance analysis is a very popular, non-destructive measurement technique that provides detailed diagnostic information about a wide range of materials - semiconductors, ceramics, polymers, photovoltaics, ferroelectrics, displays, nanomaterials, biomaterials etc.

The technique involves the application of a low level AC waveform to the sample under investigation and measurement of the sample's response to this stimulus. Measurements are taken of the AC voltage across the sample and the AC current through the sample. The impedance is obtained by taking the ratio of AC voltage / AC current. Since a low level stimulus is used, no damage is caused to the sample. Typically a swept frequency sine waveform or multi-sine waveform is used as the stimulus so that the impedance can be evaluated across the frequency range of interest.

3. Impedance measurement techniques

There are many types of AC measurement instruments on the market including voltage sweep capacitance meters, LCR meters, impedance analyzers, sub-sampling FRAs and "soft" FRAs.

3.1 Swept voltage capacitance measurement

The simplest implementation is to apply a voltage sweep to a sample and acquire time domain voltage and current measurements at a high enough rate to be able to calculate the material's low frequency capacitance from the results. This type of system is able to obtain basic low frequency capacitance measurements, but is not able to perform a complete impedance vs. frequency sweep and can therefore introduce large errors in interpretation of the data, especially where a number of relaxation processes are closely related in frequency. This type of system operates over a narrow frequency band and gives little diagnostic information about the sample under test. Usually other quite separate analyzers are required at high frequency in order to complete the impedance analysis of the material, and of course the use of different techniques can produce difficulties in matching two sets of data that are obtained by entirely different techniques.

3.2 LCR meters / impedance analyzers

These instruments are designed to make general purpose measurement of electronic components usually at a number of spot frequencies. These instruments are low cost but usually offer limited performance with few selectable frequencies, poor frequency resolution and limited impedance measurement range. It is not usually possible to measure to low frequency with these instruments - typically the low frequency cut-off is around the 1 kHz mark. Low frequency / high impedance analysis is critical for many types of materials including polymers, semiconductors, dielectrics and ceramics and LCR meters therefore have limited applicability in many of these applications. The same limitation applies to many precision impedance analyzers that are also not able to measure to low frequency and high impedance.

Often these instruments need to be supplemented by the use of swept voltage techniques as in 3.1 in order to perform a complete characterization of the material at high and low frequency (and we have already discussed some of the limitations of the swept voltage technique - matching data from different techniques, difficulty analysing samples that have relaxation processes that are closely related in frequency, limited ability to change voltage ramp rates to obtain a full analysis etc.).

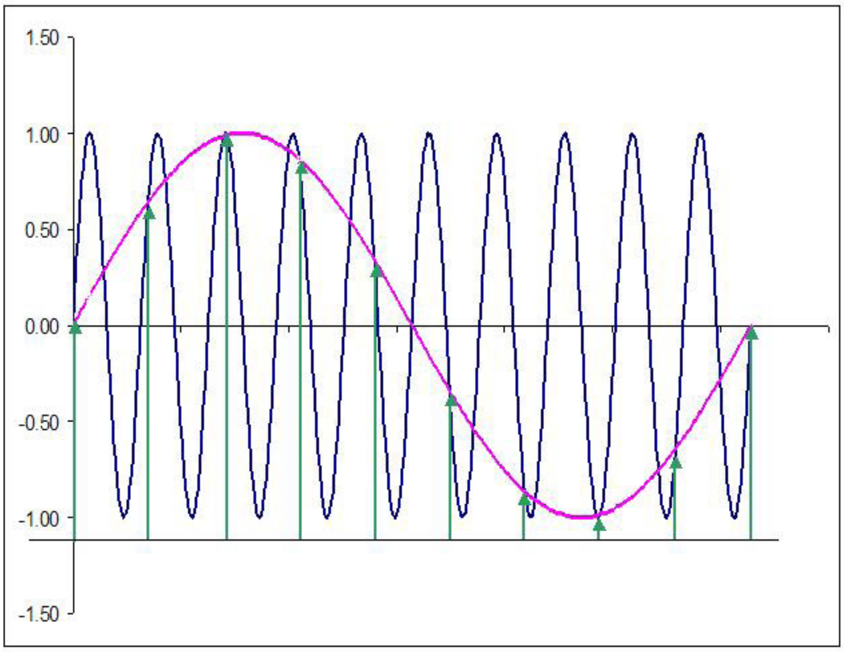

Figure 1: Sub-sampling a sine wave

3.2 Sub-sampling analyzers

Sub-sampling (also known as under-sampling) is a technique that is used to measure at a higher frequency than the actual maximum sample rate of a particular analogue to digital converter (ADC). This is apparent when the specification of the system indicates a maximum measurement frequency of, for example, 1 MHz while the ADCs are actually measuring at a much lower frequency (maybe tens or hundreds of kHz or even less). The Nyquist sampling theorem requires that to be able to uniquely measure a particular signal frequency, the measurement equipment needs to sample the data at least 2 x that frequency. In some cases however, equipment is deliberately designed to sub-sample the data to utilize reduced cost ADCs, processors and memory. This type of system can be compared to watching car wheels on a movie film, the wheels often appear to rotate in the wrong direction due to the frames of the film being captured at a rate which is too slow compared to the speed of rotation of the wheel. This effect is known as “aliasing”.

Figure 1 shows pictorially the effect of sub-sampling a sinusoidal waveform. The higher frequency waveform is the signal that is to be measured (like the wheel of the car in the film analogy). The arrows indicate the points where the sine wave is actually sampled by the measurement system (these are like the individual frames in the movie film) and the lower frequency curve shows the sub-sampled result waveform. It can be clearly seen from the overlaid lower frequency sine wave, that due to sub-sampling, signals at these two frequencies would both give the same measured response from the system, even though they are at entirely different frequencies (this is the principal by which the sub-sampling system works).

However, in practice there are many additional frequencies that also give the same amplitude levels at the points where the data is sampled and would therefore add into the results. In the above case, to illustrate the technique, the samples are taken at just less than the frequency of the sine wave that is to be analyzed. In practice however, samples are usually taken at a frequency that is at least 10 x or even 100 x less than the maximum frequency that is to be analyzed, so a 1 MHz signal may be actually sampled at around 10 kHz. The higher the ratio of measurement frequency to sub-sampling frequency, the more interference and noise is able to add into the results, and the more ambiguity there is about the signal that is being measured, giving reduced repeatability and reliability of results. The components of a sub-sampling system are lower priced but there is a penalty to pay.

In addition, this type of system does not allow much flexibility since it can only measure one frequency (the stimulated frequency) at a time when measuring at a frequency which is higher than the sample frequency of the ADCs. This leads to restrictions over the frequency range where multi-frequency analysis techniques such as multi-sine / Fast Fourier Transform (FFT) and harmonic analysis can be used. Such systems may offer multi-sine / FFT measurement over a quite restricted frequency range (or not at all). We will return to multi-sine / FFT analysis in section 4 of this paper since this is a useful technique when properly applied with a high sample rate measurement system.

3.3 "Soft" FRAs

There is another category of FRA that is used. In this case the measurement system is arranged to sample the data at high frequency, and the sampled data is passed back to the PC where FFT analysis is performed to extract the impedance information. This can be quite time consuming for the PC since it is involved in analysing a great deal of data per measurement frequency. In addition, the fixed sample rate of the ADCs in the materials analyzer means that there are often very large gaps between available analysis frequencies (particularly seen at the middle to high frequency end of the analysis), which limits the use of the equipment for detailed research. This type of system often uses sub-sampling techniques resulting in the problems identified in section 3.2.

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4. The new concept for impedance measurement

As we have seen, the measurement systems discussed in the previous section all suffer from limitations. The latest measurement technology from Solartron removes these limitations and provides single sine, harmonic and multi-sine / FFT analysis over the entire frequency range of the instrumentation. This provides massive advantages in terms of measurement frequency range, speed of analysis and in the consistency of the results.

The ModuLab FRA uses high performance digital signal processing technology to provide high accuracy impedance measurements. The analogue to digital converters (ADCs) and digital to analogue converters (DACs) in the FRA provide sample measurements at 40 MHz, which means that when the highest frequency of the system (1 MHz) is being analyzed, the ADCs are actually 40 x over-sampling the data. Since the measurements are over-sampled (as opposed to being sub-sampled), it is possible to use any of the impedance techniques, single sine analysis, harmonic analysis or multi-sine / FFT analysis, over the full frequency range of the equipment. This provides accuracy, consistency and flexibility that cannot be achieved by other system.

4.1 Single sine correlation impedance analysis

Single sine correlation is widely used by researchers throughout the world for the accurate impedance characterization of a wide range of materials, for example polymers, ceramics, semiconductors, photovoltaics, display technologies and nanomaterials. Other techniques have been tried for impedance analysis but none give such good rejection of noise, interference and distortion. The ModuLab MTS FRAs take this a stage further and provide amazing high-speed performance while maintaining the accuracy, repeatability and resolution of previous analyzers.

4.2 Multi-sine / FFT impedance analysis

The high sample rates that are utilized by the ModuLab FRAs permit multi-sine / FFT analysis to be performed over the entire frequency range of the system, from 10 μHz to 1 MHz. This is a unique feature of Solartron equipment, unlike other analyzers on the market, there are no restrictions where certain techniques can only be used over a particular range of frequency or cannot be applied at all.

The main advantage of multi-sine / FFT analysis is the speed of measurement. Whereas single sine correlation requires a separate measurement at each frequency, (hence the total time taken for the complete analysis is the sum of the individual measurement times), the multi-sine / FFT technique allows multiple frequencies to be analyzed at the same time. The multi-sine / FFT technique can therefore save a lot of time particularly when measuring at low frequency. By comparison, a multi-sine / FFT analysis from 1 mHz to 1 MHz can be performed in less than one quarter of the time taken for an equivalent single sine analysis, which is particularly beneficial for impedance measurements on systems that might be changing with time (for example quick set adhesives).

4.2.1 Choice of stimulus / analysis frequencies

The multi-sine / FFT technique makes use of waveform generation and Fast Fourier Transform analysis (FFT) techniques. The FFT is a mathematical algorithm that is used to convert time domain data (voltage and current samples collected over a period of time) into the frequency domain (analyzing the frequency content of the signal and presenting impedance vs. frequency result data).

The starting point of this technique is to be able to generate a smooth waveform that contains a number of sine waves at different frequencies that have been added together to produce a composite waveform. Figure 2 shows the result of adding just three sine waves (three frequencies) each starting with the same zero phase offset (i.e. the three individual sine waves each start at the zero amplitude point in the sine wave). The generated waveform contains three frequencies, (the fundamental plus two harmonic frequencies – 1 x, 3 x, 5 x the fundamental frequency). If this waveform were applied to a cell, it would be possible to measure the impedance of the cell at these three frequencies. This particular measurement would be over a quite restricted frequency range due to using only three closely spaced frequencies (for example 10 Hz, 30 Hz and 50 Hz), usually many more frequencies are required and over a much wider frequency range, but this simple waveform shows some of the principles of the technique.

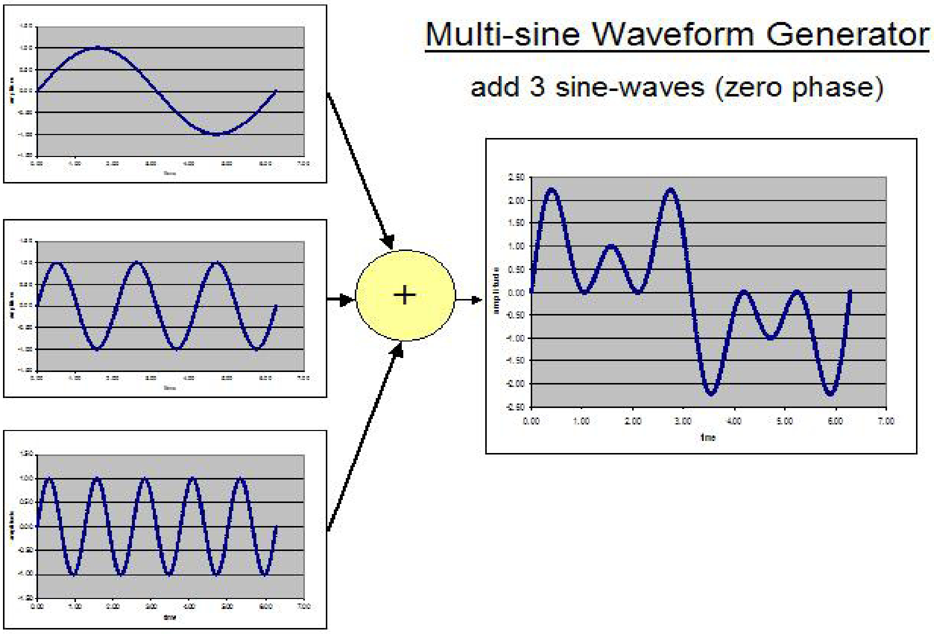

Figure 2: Three harmonically related sine waves with ZERO phase added together

One problem is that the generated waveform in figure 2 has quite large peaks which may cause problems for many materials since this might start to excite non-linear response from the sample. Ideally the peak values need to be minimized so that any non-linear response from the sample is minimized.

The problem with non-linearities in the sample is that this is usually seen as harmonic distortion which could cause harmonics of the lower frequencies to interfere with measurements at other frequencies. By measuring some of the frequencies that were not stimulated, it would be possible to identify how much distortion the material is producing and make some decisions about whether the amplitude of the applied signal is appropriate (we will return to this idea later). In any case, non-linearity in the measurement needs to be avoided since in the presence of non-linearity, impedance measurements are simply not valid.

By randomizing the phase of the three sine waves (the three waveforms start at non-zero amplitude levels and are now even moving in different directions), a quite different, more random waveform may be produced such as that shown in figure 3. By selecting different random phase values, an infinite variety of waveforms can be produced, some of which look more random in character or have larger peaks or are simply smoother. By suitable phase optimization the peaks on the waveform may be much reduced compared to the original waveform.

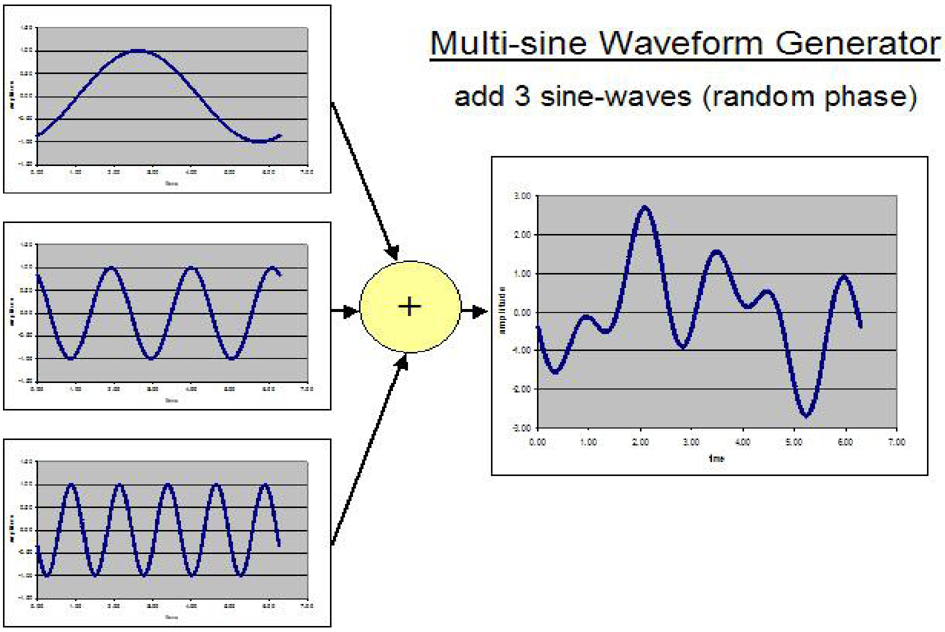

Figure 3: Three harmonically related sine waves with RANDOM phase added together

The ModuLab MTS FRAs provide complete flexibility and allow the user to select all frequencies if required (though this would give more than one thousand frequencies in the final waveform and would result in very low signal amplitude at each frequency and therefore much noisier results). It is much better in practice to reduce the number of frequencies in the waveform and therefore have a higher signal level at each frequency. In addition, it is usually preferable to use a list of frequencies that are close to being logarithmically spaced since impedance results, when viewed on a logarithmic frequency axis graph, would then appear evenly spaced. The default frequency list provided by the system of thirty-one frequencies logarithmically spread over three frequency decades takes all of these considerations into account and is therefore a good starting point which may be customized if required. This usually provides a smooth impedance curve with minimal noise on the results.

4.2.2. Choice of AC level and non-linearity checks

It may be beneficial to use slightly higher AC level for multi-sine / FFT analysis, since due to the number of frequencies being stimulated by the multi-sine waveform, there is less signal level at each frequency which may tend to give noisier impedance results. However, increasing the signal level should be done with great care making sure that the cell is not being over-driven and is not operating in a non-linear regime.

One way of checking for non-linearity in the results is to apply the multi-sine waveform at the required amplitude and instead of capturing only the stimulated frequencies, capture all frequencies by selecting the “measure non-stimulated frequencies” mode of operation in the ModuLab MTS software. In this case all frequencies are measured. The results may then be exported into Excel to allow the non-stimulated frequencies to be examined. If the non-stimulated frequencies are relatively low level compared to the stimulated frequencies then the cell is operating in a linear mode, but if the non-stimulated frequencies are of significant level compared to the stimulated frequencies, then the cell is behaving in a non-linear mode and the stimulus level should be reduced. This is a very useful diagnostic test for signal non-linearity. Harmonic analysis is also used in distortion applications providing information about non-linearities in materials as they approach breakdown voltage.

The ModuLab MTS FRAs allow the user to select any list of frequencies in the measurement range, but best results are usually obtained by selecting frequencies where harmonics of one frequency interfere as little as possible with other frequencies that have been selected. The ModuLab MTS system assists the user, by providing a default frequency list that may be used if required. By selecting a number of frequencies (for example the default frequency list) it is possible to produce a waveform that looks very much like random noise but in fact still contains only the frequencies that were selected. By optimizing the phases it is possible to produce a waveform that has reasonably low peak amplitude (see figure 4).

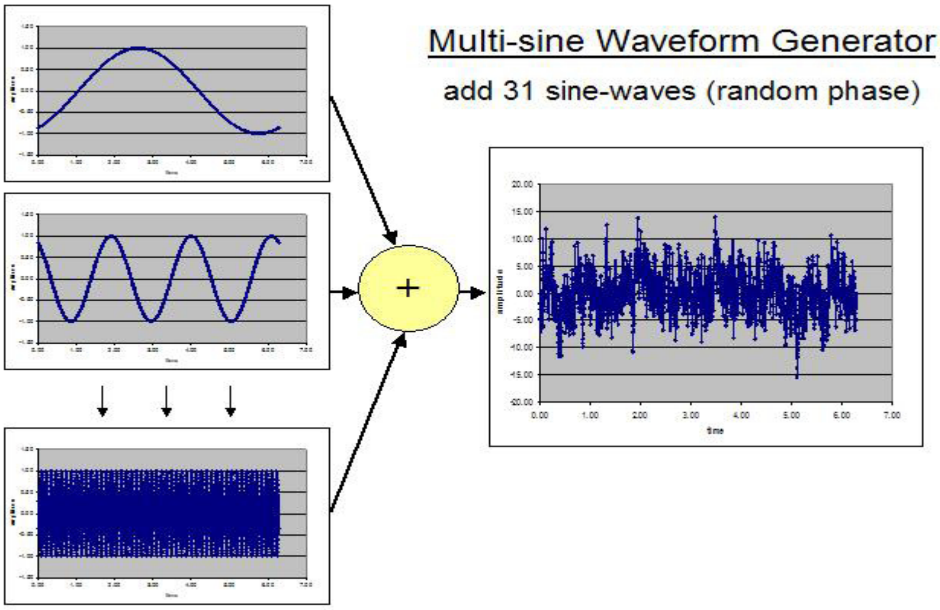

Figure 4: Thirty-one harmonically related sine waves with RANDOM phase added together

4.3 Other important requirements for impedance measurement systems

4.3.1 Smooth continuous applied AC waveform

Whether using single sine or multi-sine / FFT modes of operation, It is important to have a smooth continuous AC waveform applied to the sample. At low frequency, the ModuLab MTS FRAs generate waveforms with over 200,000 points per cycle of the waveform ensuring that the sample sees a pure AC waveform. At high frequencies, the waveforms are produced at least 40 x the maximum measurement frequency and analogue filtering is applied so that these waveforms are also very smooth and pure.

4.3.2 DC bias rejection

ModuLab MTS FRAs have their own built-in automatic bias rejection facilities that remove DC from the signals to be measured (the signal from the materials interface current to voltage converter representing the AC current through the cell and the buffered voltage signal that represents the AC voltage across the cell). This is especially important if attempting to measure the impedance of a material while it is under high DC voltage / current load conditions. Once the DC bias has been rejected, the FRA can measure on a more sensitive range, reducing result noise and improving accuracy.

4.3.3 Multi-channel capability

In the race to develop improved new materials, the ability to test more samples in parallel is becoming ever more important. In addition, measurements taken at the same time offer the possibility to test samples in exactly the same environmental conditions. The MTS system is able to be used in single channel and multi-channel configurations.

4.3.4 Frequency resolution

The ModuLab MTS FRAs have very high frequency resolution due to the use of a purpose designed 26 bit frequency synthesizer. This gives the ability to zoom into any frequency range to obtain detailed results almost without limit. This is ideal for tests on crystals and piezoelectrics investigating resonance behaviour of the materials.

4.3.5 Bandwidth

It is worth remembering that the frequency bandwidth of any impedance measurement system is only as good as its most limited component. Often manufacturers specifications quote the bandwidth of only one element of the system (quite often this is the voltage measurement part of the system, which is usually the component with the widest bandwidth). This can give the false impression that the whole system has wide bandwidth. Another way that specifications are sometimes presented is to only quote impedance accuracy at particular impedance levels (which happen to be the best impedance levels for that system). It is important to investigate the capabilities of the test system for the particular impedance levels that are to be measured (for example, it may be <1 mΩ for some materials or > TΩ for others).

Another type of impedance specification to watch out for is one that indicates a constant accuracy for all impedance levels and frequencies being measured, this is very unlikely since in all cases electronic amplifiers operate best in the middle of their range and operate less well at very high frequency or at the bottom of their amplitude range (which occurs at extremely high or low impedance levels). Solartron products always give a detailed accuracy specification to allow assessment of whether the equipment is suitable for particular measurements.

5.0 Summary

There are very many materials that require impedance analysis down to 1 mHz or even lower frequency. In addition these materials are often found to be extremely high impedance at low frequency and therefore require very sensitive measurement equipment. It is important to choose a system that is able to expand its capabilities in order to be able to meet the challenges of testing these very demanding materials (from insulators to superconductors). The modularity of the ModuLab MTS is a key capability that enables it to be used for testing a very wide range of materials. The FRA developed for the MTS is flexible and accurate and is particularly suited to fast low frequency analysis, making use of its multi-sine / Fast Fourier Transform techniques. Harmonic analysis is available for those interested in investigating non-linearity in materials, possibly as the material approaches dielectric breakdown. These techniques are of course in addition to the widely referenced stability and repeatability of Solartron's swept frequency single sine analysis (a technique for which Solartron has gained a worldwide reputation for high quality impedance results). The new ModuLab MTS system from Solartron, is a major step forward in testing technology which will lead to further development of new and improved materials.

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