Electrochemical Impedance Spectroscopy
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Lecture – 10
Windowing

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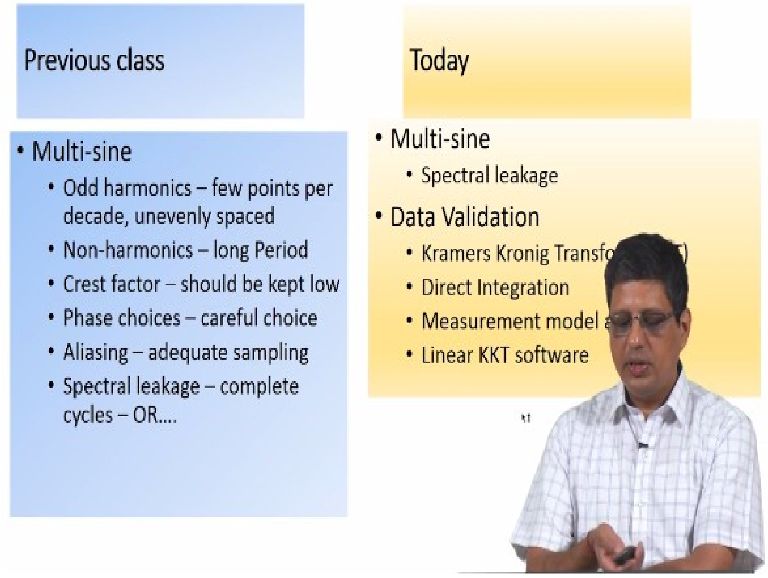

Earlier we discussed that you can use odd harmonics or you can use non-harmonics as inputs for creating the multi-sine. If you use odd harmonics you will have few points per decade which are not evenly spaced. If we use non-harmonics you will get longer period. In either case, you have to make sure that the amplitude of the multi-sine peak amplitude is not very high. It is given by a factor called crest factor. Crest factor has to be low. If it is very high, electrochemical system will give nonlinear response and usually the analysis assumes that the response is linear. Now we can reduce the crest factor by using combination of phase values for each input wave, but you have to be careful in choosing them. For example, Schroeder phase is supposed to give low crest factor for odd harmonic but you will have to use full set of odd harmonics and not with just 1, 3, 9 or any limited set of odd harmonics. Sometime people use random phase, sometimes zero phase, which is easy to use and you can also optimize using numerical methods and get the phase values. But each one comes with its own disadvantage and one has to be aware of them.

We also saw an example where if we do not sample it fast enough, if we sample it at low sampling rate you may get misleading results. Once you get poor sampling data then subsequent process cannot recover that information. You can use Fourier transform, or any data massaging, but you will not be able to recognise that actually data comes from a different sinusoidal wave and if we use logarithmic spaced frequencies which means non-harmonics, we combine some of them, we know that if we combine and get a complete wave it will take long time. If we truncate it we will get into another type of problem called spectral leakage. I want to discuss an example of spectral leakage and one way of handling that problem. Next, we will move to data validation. There are multiple ways of doing the data validation and go through the examples there.

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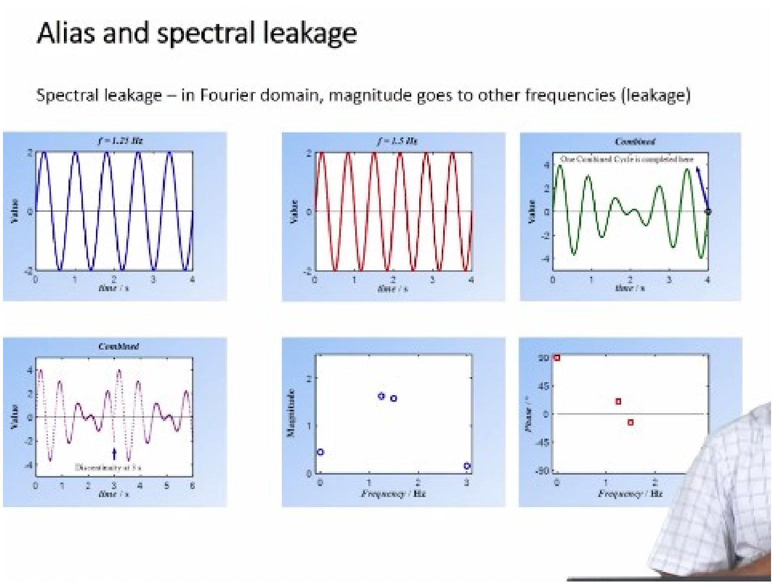

So here I want to show 2 waves with an amplitude of two and frequencies are 1.25 and 1.5. If you combine them, you can get a complete wave with a period of 4 seconds. So the first wave has a period of less than 1 second, second wave has a period of less than 1 second, combined wave has a period of 4 seconds. Let us say that I do not want to wait for 4 second. In this example, I am going to wait for 3 seconds take the data for 3 seconds and then replicate it. The logic here is each one needs less than 1 second for 1 cycle, if we go to 3 seconds, I have many cycles, so averaging will probably give me good enough data. Of course this is just an example, in reality you will want to combine many waves because if you are going to spend 3 seconds here you would rather spend 1 second for the first data 1 second or less than 1 second for the first cycle, second cycle and be done with that, but let us say that we want to cut it at 3 seconds. Take this data and do Fourier transform of the plate potential. So I had to take only 0 to 3. Here I have just shown you an illustration of what is to be expected when you copy it and paste it again and again. If you do Fourier transform you find the energy level is not 2 or the amplitude is not 2 (Magnitude vs. frequency). Also, at 0 and 3 hertz you get some magnitude. The power has leaked from 1.25 and 1.5 hertz to 0 and 3 hertz. You also get phase values, we expect 0 phase values at 1.25 and 1.5 hertz, of course at the DC there is no meaning of phase. At 0 and 3 we expect random value of phase provided this is phase values at 1.25 and 1.5 hertz are zero. If this is nonzero, we are going to believe that this is the real value. Therefore, if you have an incomplete wave and you do Fourier transform you will get into some problem and one of the problems is the spectral leakage.

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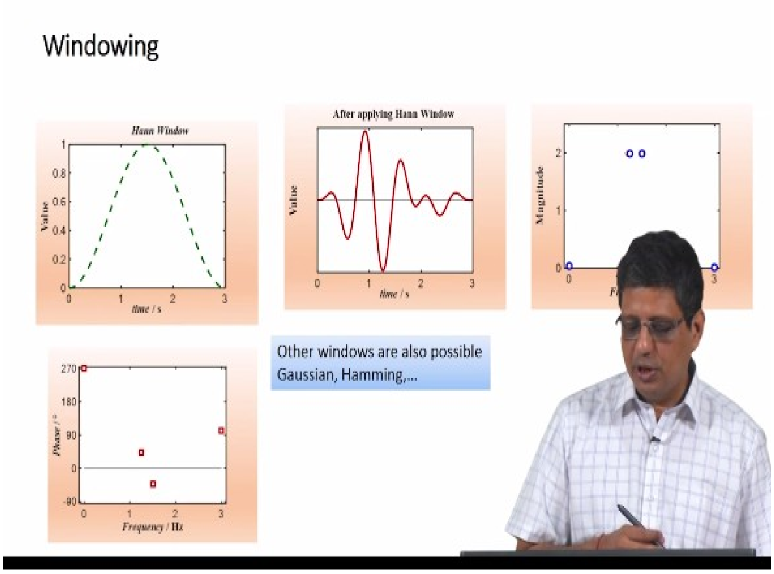
When you have spectral leakage it is possible to overcome it to some level using a technique called windowing okay.



Here we take data from 0 to 3 seconds. So whatever data we get it is potential here, you can also get the current. You can apply or multiply that by a particular function called Hann function. Similarly, you can multiply by other function. Notice the function starts at 0 and ends at 0, that means if I go to the previous level 0 to 3 each data point, I multiply by the windowing function. So the first point will be forced to come to 0. Even if it were not 0. The last point will be forced to come to 0. That means when I put one cycle the combined function will start at 0 and end at 0 and when you replicate it there would not be any discontinuity. You can see the discontinuity in the previous example which you can avoid by this. So if I multiply the previous function with the Hann window, the resulting function will start at zero and ends at zero (fig 2 from top left). Similarly, this is the potential applied, you will get a current value, you will have to multiply by Hann function to get a resulting value. Then if we apply Fourier transform on this, or frequency filter to get the correct result. If you look precisely the magnitude would not be exactly 2, but it will be close enough to that. And you will get more or less 0 at the starting and ending frequencies. So magnitude will come correctly if you use proper windowing. Phase would not be correct, there will be an offset. So you will have to account for that when using windowing have to correct for the phase.

Usually windowing is used in digital signal processing and there most of the time people do not worry about the phase, they just look at the magnitude. Whereas in the impedance spectra we want to know both the phase and the magnitude. When you apply a multi-sine in an instrument, manufacturers do not tell you what they do. They will say these are the frequencies. You may have some choices such as the upper limit, the lower limit, number of frequencies in a range, and also spacing between them (log or linear). You may have some choices, but it will run faster and it cannot run faster if they take complete cycles. You have to be aware of that and they are using some windowing, they do not tell you what it is, they probably use some empirical correlation; they have some method of calculating the impedance out of this. It will work correctly when you use simple electrical circuits and simple reactions. It may or may not work well when you have complicated reactions. You have to be aware of it, that is all I want to emphasize here. It is not as simple as add these things, put them together do Fourier transform you will get the result. You will not get the correct result unless the cycles are completed. This at least in my opinion is a cautionary note. Therefore, you have to be extra careful when you apply a multi-sine. Here, I am giving you two examples of windowing, Gaussian and Hamming window. There are few other types of windowing functions that can be used.

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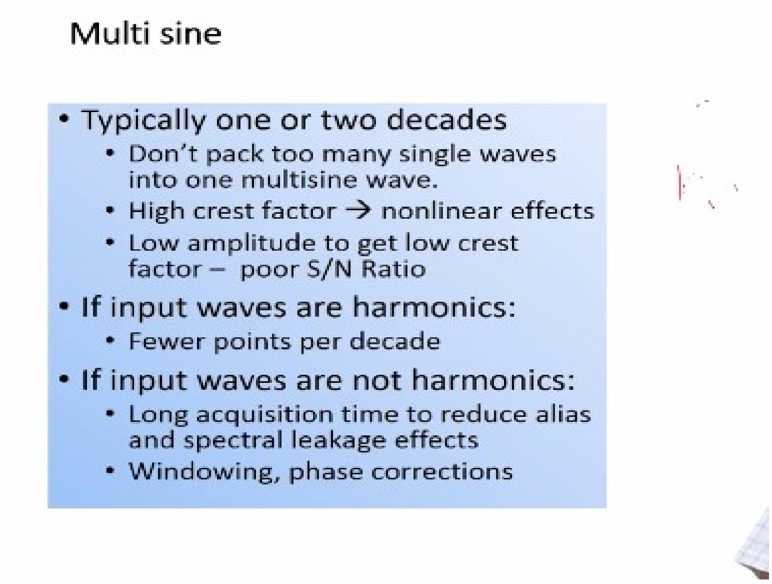

Typically, 1 decade or 2 decade is what is used. For example, we can combine frequencies from 1 to 10, or 1 to 100 and create a multi-sine. It is possible to combine from 1 milli hertz to 1 kilo hertz. but if you combine too many waves, each with certain amplitude, the peak value will be very high. Therefore, do not pack too many single sine wave into 1 multi-sine wave. This results in nonlinear effects.

And if you put small amplitude sine waves, peak value will not be high, but the results that we get will have poor signal to noise ratio. That means it will be very noisy. Therefore, one cannot really say that instead of combing two waves, I will combine 2 waves anyway I am going to pay little bit of penalty, I will reduce the time. Again you will have problem. So in summary if the input waves are harmonic, you have fewer points per decade. If they are not harmonic, you have to either wait for long acquisition time and to acquire many samples to reduce the aliasing effect. See if I have 1000 hertz and 1 hertz and anything in between and combine them together, in order to measure the 100 hertz wave form correctly I need to sample at least at 2000 hertz, preferably at 10,000 hertz or more. If I have 10 points per cycle, to sample the 1 hertz data, I need to wait for at least 1 second. So if you measure at the rate of 10,000 hertz for 1 second, I have to measure 10,000 points. If I do only 1000 hertz, I can sample at 10,000 hertz, do it for 10 cycles, or 15 cycles, I will have 10 samples per cycle. So I would say if I am sampling, I am applying a wave of 1 kilohertz my sampling is 10 kilohertz. I can do 10 cycles that means 10 points per cycle. I will have 100 points in a data acquisition. If I apply 1 hertz alone, I can do 10 points per cycle. I can do this for 1 second, I will get 10 points to be stored in the buffer. If I combine these 2 waves, I have to sample at 10 kilo hertz and I have to measure for 1 second. Here at 10 kilohertz I will measure for maybe 2 milliseconds that will give me 2 cycles of this 1 kilohertz. If the wave is 1 kilohertz in 1 millisecond it will complete 1 cycle, in 2 milliseconds it will complete 2 cycles. If I take 10 points per cycle, I will need to take only 20 points to get 2 cycles of this. And I can do Fourier transform, I will get good enough data.
If the wave is 1 second, I do not need to sample at 10 kilohertz. I can sample at 10 hertz. Therefore, in 10 points in 1 second, I can get good enough sampling, I can do Fourier transform and we can get the data. If we combine these 2 to generate the wave, I need to sample at this rate and I cannot stop at 2 millisecond, I had to do that for 1 second, because I want to detect both 1 kilohertz data and 1 hertz data. So, if it is a low frequency, single sine wave, you can sample at larger intervals or longer intervals, you can use few points and

collect the data. If it is high frequency you have to sample fast, but you do not need to collect data for a long time. That means the number of points that you need to collect is limited.

When you combine these 2, you need to collect at a fast rate for long time and the data buffer is limited in actual measurement. You might be able to store gigabytes of data in the hard drive or you might be able to store megabytes without thinking. When you collect the data using that chip that buffer there is limited in size. It will not be able to collect, either the time will go off (it would not collect it at the appropriate time) or buffer will overrun.

There are difficulties in practically implementing proper multi-sine. People still implement it using certain tricks, but you have to be careful in taking the data at face value. It is lot easier to say that and do it in simulation. In simulation you can use large size array, it may run slower, but you will get the result. It does not mean somebody comes with a very nice way of doing multi-sine and tell you, you can do that, it is not necessarily easy to implement it in the hardware.