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PROFESSOR: Well, today, we have a chance to put away the equations and have some fun. With me is Professor Sandy Hill from the University of Massachusetts at Amherst. And Sandy, maybe you could just give us a quick tour of what we have here.

SANDY HILL: OK. We'll be dealing with about four instruments today. Two of them generate signals, and two of them display and analyze signals. The first, and perhaps simplest, is simply an RC audio generator, that will put out a variety wave shapes. And we'll look at that in a moment.

Over to the right is a device that will allow us to study amplitude modulation and the various flavors of it. Down below is a standard oscilloscope to look at the signals in the time domain so we can see their shape. And then, finally the spectrum analyzer will analyze the signal into its Fourier components. And we'll display those, so you get to see the spectral content of a signal.

PROFESSOR: Now, we'll be seeing all of these in a fair amount of detail as we go through the demonstrations. But maybe we can begin just with the signal generator.

SANDY HILL: OK, let's look quickly at the various buttons involved. There's a lot of flexibility with this device. The top three buttons here allow us to change from one simple wave form to another one, a sine wave, a triangle wave, a square wave.

And right below it is a button that will allow us to change the size of the signal. Moving over towards the left, we can change the DC offset which varies the signal, the level upon which the signal rides.

PROFESSOR: And we'll be using that actually when we demonstrate amplitude modulation.

SANDY HILL: That's right And then finally, there's a way of changing the frequency of the signal,

either changing it by a factor of 10 or a vernier adjustment, if you want very specific adjustments, very delicate changes.

PROFESSOR: OK. So maybe we can just vary some of this and see what a little bit of it looks like.

SANDY HILL: All right. What we have displayed at this point is the effect of pushing the sine wave button. And so displayed down here is a 500 Hertz sine wave. In fact, let's listen to that.

PROFESSOR: Great.

SANDY HILL: And the scope is said to have one millisecond for each division here. By varying the amplitude knob can make the sine wave smaller or larger. The ear isn't too sensitive to that.

By changing the DC offset, it simply rides on a different level. It's like putting a battery in series. And changing the frequency, you get a very perceptible change, a lower frequency. It takes longer to sweep through a period.

Higher frequency, it takes a shorter amount of time. And also, we can change the wave shape itself from a sine wave to a triangle wave-- and you notice that has a richer sound to it-- and then finally to a square wave, which is an even brighter sound.

PROFESSOR: And actually, as you realize from the previous lectures, with the triangle and square wave with the same fundamental as the sine wave, the richness comes in because of the higher harmonics in the Fourier series representation.

OK, well let's go back to the sine wave. And we'll use that to take a closer look at the spectrum analyzer.

SANDY HILL: OK.

PROFESSOR: We'll look at a block diagram of the spectrum analyzer shortly, but first let's just look at a few quick things to get a feel for it. We have, of course, the time domain display of the sine wave. And the spectrum analyzer gives us a frequency domain analysis

and display.

And the vertical axis is the amplitude. The horizontal axis is frequency. And as it's set currently, the frequency axis goes from DC-- zero-- up to 2 kilohertz. And that, of course, can be varied on the spectrum analyzer.

And since we have a sine wave input, we get, as we would expect, a line spectrum, corresponding to the frequency of the sine wave. Now, in fact, we can measure that frequency because the spectrum analyzer has a cursor associated with it, which I've just enabled. And this line is the cursor line. There is a read out for the frequency and a read out for the amplitude.

And let's position the cursor on the frequency of the sine wave. And we're getting close. And there we are at the frequency of the sine wave. And we can read out, in fact, that it's 500 cycles. And this is the amplitude. And, of course, you could verify the frequency also in the time domain display, simply by measuring the frequency or the period.

SANDY HILL: This is set at still one millisecond per centimeter. So that is 500 Hertz.

PROFESSOR: OK. Well now maybe what we can do is vary the frequency. Let's vary the frequency of the sine wave generator. Maybe also listen to it?

SANDY HILL: I'll turn on the tone. Yep. OK, I'll make the frequency higher. And you'll see a correspondence in the time domain. The frequency clearly goes up, and that line of the spectrum also migrates up away from the cursor.

PROFESSOR: OK, and let me just point out again that this is the cursor line. This isn't the spectra line. And this is the frequency content of the sine wave.

SANDY HILL: We can also change the amplitude of that line by making the sine wave itself smaller. And you notice the intensity of it goes--

PROFESSOR: While you do that, let me just position the cursor if I can on the sine wave. And now as you vary the amplitude, we should, in fact, see this vary.

SANDY HILL: Well, that's right.

PROFESSOR: OK. Now as Sandy varied the frequency, he did it slowly and we saw the line move as a single line. Maybe now, Sandy, you could vary the frequency more rapidly. And what will happen is that, in fact, what we'll get if I--

SANDY HILL: There'll be a spreading as we go--

PROFESSOR: Let me turn the cursor off. And what we'll see is a spreading of the line, so that the frequency content is richer. And, in fact, the analysis of this is considerably more complicated. It corresponds to frequency modulation, where Sandy is now the modulating signal.

SANDY HILL: That's right.

PROFESSOR: And we won't really be going into issues of frequency modulation in any more detail in this demonstration.

SANDY HILL: Right.

PROFESSOR: OK, well now let's go to the overhead projector and take a look at a block diagram of the spectrum analyzer. The specific spectrum analyzer that we're using in the demonstration is made by Rockland Systems, referred to as the Rockland Systems Model FFT 512. And basically, the idea is to sample the incoming wave form, convert that into digital form, and then the spectrum, in fact, is computed digitally using a microprocessor.

So the overall system block diagram first consists of a system which is a low pass filter. And this low pass filter is used in advance of the sampling process to basically reduce the artifacts that are introduced due to sampling. And although we haven't talked yet about sampling and the associated artifacts, basically, as we'll see in the upcoming lectures, in order to sample a wave form and convert it into digital form, it requires that the wave form first be low pass filtered.

So this low pass filter is referred to-- and will be in later lectures-- as an anti-aliasing filter. And this low pass filtered wave form is then converted to a sequence. And so

a sequence is generated for which the sequence values are simply samples of the low pass filtered input.

This low pass filtered input is then put into digital memory. Basically, a time block of it is put into digital memory, and so that's what we have down here. Here is the sequence. The sequence is put into digital memory. And then an arithmetic processor computes for the samples in this memory. It computes the Fourier transform or the spectrum.

And after the spectrum is computed and put either into the same or a different memory, that is then put through a conversion process back to a continuous time signal, and finally, put out on the display that we've been seeing in the demonstration. And so this is just indicative of the display.

So basically, the idea then is that the input wave form comes in. It's filtered and sampled and captured on a block basis, put into a digital memory, and then, a digital computer or microprocessor computes the Fourier transform. And then that Fourier transform is what we see on the display.

So what we're computing, of course, are samples of the Fourier transform. And so, for example, if the input-- let's say-- was a rectangular pulse whose Fourier transform is of the form of a $\sin(x)/x$ function, what we would, in fact, see on the display are samples of that at discrete frequencies. Or if as we have an input which is a square wave, what will generate through the spectrum analyzer are the Fourier series coefficients or equivalently, the harmonics associated with the square wave.

OK, well, let's now go back to the equipment and look at the spectrum analyzer. We'll look at the square wave through the spectrum analyzer shortly, but first what we have is what we saw before, which is the sine wave. And just to point out, again, the fact that the sine wave spectrum, of course, is just a single line corresponding to the fundamental frequency.

And here we have a frequency scale now that goes from 0 to 5 kilohertz. And this is

then the 500 cycle sine wave. And, in fact, we can flip the cursor on and I happen to just magically have it positioned correctly. And we see that it's a 500 cycle sine wave.

SANDY HILL: Might be interesting, Al, to go and look at a richer set of signals, such as the triangle wave and the square wave-- things that are conveniently on the signal generator itself. I'll switch over to a square wave now. And what you see is all the harmonics coming up, being displayed.

PROFESSOR: OK, it's actually interesting to point out, I think, that the square wave, as we know, is an odd harmonic function. And so, in fact, the even harmonics are missing in the square wave. So this is the fundamental. This is the third harmonic, fifth harmonic, et cetera. And then the amplitude of the square wave decays proportional to 1 over f , which is the kind of analysis that we've gone through in looking at Fourier series.

SANDY HILL: Right, and if we switch to the triangle wave, instead of their decaying as 1 over f , the harmonics decay as 1 over f squared. And you see they drop off much more quickly.

PROFESSOR: And again, of course, it's an odd harmonic signal. And so the even numbered harmonics are missing. And maybe just to kind of emphasize the point, we can show the sine wave again and the square wave again.

SANDY HILL: We'll go through from the most bland to the richer to the richest.

PROFESSOR: OK, and it's really kind of interesting and dramatic--

SANDY HILL: It's fun to do that.

PROFESSOR: --to see the harmonics pop in.

SANDY HILL: While we're at the square wave, let me fiddle with the frequency of the square wave, and we can see the duality of the time and frequency domains. That is, as you compress things in the time domain, such as this, going to a higher frequency square wave, the harmonics wonder further away from each other.

SANDY HILL: So this is the fundamental. The second harmonic is missing. This is the third harmonic. And of course, the fifth.

SANDY HILL: And as we take this to an extreme by going to very low repetition rate square waves, all those harmonics come scurrying in and cluster together near DC.

PROFESSOR: Kind of fun with Fourier transforms. Well, speaking of time and frequency scaling, recall that we had demonstrated time and frequency scaling previously with the glockenspiel. And what we had done there was to record a particular glockenspiel note, and then we played that back at half speed. And what we had done in that case is expanded things in time, consequently compress them in frequency.

And so, comparing that with a note an octave lower than we saw that, in fact, the time scaling had led to a frequency scaling. And then we also played the same note back at twice speed. And in that case, the frequencies were all scaled up by a factor of 2. And again, we illustrated that by comparing with the glockenspiel note a full octave up.

Now when we did that, we didn't actually look at the time wave forms or spectra. And having the equipment that we have here gives us kind of a nice opportunity to do that. So what I have is the tape that we had originally made of the glockenspiel, the original note that we recorded. And what we'll do is look at the spectrum of that, and then compare that spectrum when we play the tape at half speed and also play it at twice speed.

So let's play the tape. And what we have is the glockenspiel right now displayed on a frequency scale from 0 to 5 kilohertz. Let's just change that to zero to 10 kilohertz. So here is this spectrum. Over here we have the time wave form. And here is then the first spectral line, and we can see where that is by setting up the cursor. And magically, once again, I have the cursor positioned at just the right spot. The first spectral line is at 1.775 kilohertz. And so this is the spectrum then of the original glockenspiel note.

All right. Let's stop the tape and rewind it. And now what we want to do is play that

back at half speed. Played at half speed, the frequencies should be scaled down. And, in particular then the first spectra line should be at a lower frequency.

So let's play that now.

SANDY HILL: There are really very complicated signals, aren't they?

PROFESSOR: They really are. Here we have the first spectral line. And we can compare that with the first spectral line that we had before which was at 1.775 kilohertz. And, once again, you see that the time wave form over here has been scaled by a factor of 2.

So, once again, we see that time and frequency scaling really works. Incidentally as Sandy pointed out, and rightfully so, the glockenspiel really is a pretty complicated signal, as a graduate student and I found out when we were preparing the original glockenspiel demo.

SANDY HILL: Speaking of complicated signals, one of my favorites is to look at speech. I set this up so that what's coming into my microphone is indeed what you're going to see on the two screens. The telephone company thinks of speech, basically in terms of bandwidth, that it extends from about 300 Hertz to 3,300 Hertz.

But, as we'll see in the spectrum analyzer, there's a lot of leakage outside of that. The telephone company just filters out everything outside of that and things of that as a speech signal. So it doesn't have the high fidelity that you might have on high fire equipment.

As we look at the scope, again, the time wave form is extremely complicated, seems to have some periodicities in it, although they're short-lived, and then it goes on to some other periodic chunk. And over in the frequency domain, you can see as we extend from 0 to 10 kilohertz, that as I speak, there are trenches that have spectral content in them, covering that entire band.

I can try some simpler signals. A whistle is almost a sinusoid, but as you'll see isn't terribly sinusoidal.

[HIGH-PITCHED WHISTLE]

That's the best I can do. I can sing, a little bit embarrassedly, a B,

[HIGH-PITCHED] Boo, and things like that.

PROFESSOR: They don't ask me to, Sandy.

SANDY HILL: And then different vowel sounds have a lot of energy in, like the letter A. (SUNG) A. Whereas some of the others are very impulsive, like--

[HISSING]

Or puh and tuh. And it's a little hard to grab them at the right time. But what's fascinating is just to stare at equipment like this and try different speech sounds, and you begin to get sort of a sense of the complicated nature of them.

PROFESSOR: OK, well that's a look at some spectra signals. And now what we'd like to focus on is the modulator and talk a little bit about modulation and demodulation and demonstrate it. And let's begin that by first taking a look at a block diagram of the modulator system.

Well, as we've discussed in a previous lecture, amplitude modulation basically consists of multiplying the modulating signal by an appropriate carrier, illustrated here, as we've seen previously, for the case of a sinusoidal carrier. And then, specifically for sinusoidal amplitude modulation, we may or may not inject some carrier signal-- A times the carrier. Or equivalently, if we look at the modulated output, the injection of the carrier is equivalent, mathematically, to simply adding a DC offset or a constant to the modulating signal.

And, as you recall when we talked about this, the idea of injecting a carrier or not is related to the issue of whether or not we want to do synchronous or asynchronous demodulation. The asynchronous demodulation corresponding to the simple use of an envelope detector.

And to remind you of the wave forms that are involved, again, I show two that we saw previously. And for the case, this is for one value of the amount of carrier that's

injected. And this is for an amount of carrier injected that's less. And this, in fact, corresponds to what we refer to as 50% modulation, and this is the case of 100% modulation.

Well, the modulating system that we're using in this demonstration is basically of the form that we're indicating here. And a simple block diagram for it is more or less identical to what we just saw. Specifically, the modulating signal is multiplied by the carrier. And there also is the capability of injecting some additional carrier, meaning adding it to the output of this product. And so the modulated output can have a variable percent modulation-- the percent modulation being changed, depending on how we set this variable gain.

Now, in addition to sinusoidal modulation-- in fact, for the particular system that we're using, we have somewhat more flexibility. We can use, in addition to a sinusoidal carrier at this point, we can alternatively choose a square wave carrier or a triangular carrier. And, as we'll indicate in a moment when we illustrate this, there are some specific advantages to using, for example, a square wave carrier.

So this is a somewhat simplified version of-- or rather block diagram of the modulating system that we're demonstrating. The external modulating input here, a choice of carrier with also the capability for injecting some additional carrier into the output.

OK, now let's go back to the equipment and take a look at this. Well, Sandy, maybe to begin, you can just point out what some of the controls are on the modulator box.

SANDY HILL: OK, there are some interesting points to look at here. This is an input for an external signal. We'll be taking a signal right out of the signal generator and putting it in here. And that will be the signal that will be modulated, according to the carrier.

The carrier is generated internally in this device. And there are several ways of controlling it. One is the amount of carrier injection. One is the wave form of the carrier itself-- and this is typically sinusoidal in the broadcast industry, but others are interesting to look at as well.

The output that will be displaying on both the spectrum analyzer and scope comes out here. And then farther over to the left, there are some knobs for changing the frequency of the carrier signal.

PROFESSOR: OK, let me also just point out again for emphasis that changing the carrier level, as we've talked about, is mathematically equivalent to changing the DC level of the modulating signal. And that's also what affects the percent modulation as we had just discussed. Now what we have set up is a sinusoidal modulating signal and a sinusoidal little carrier. And, as usual, we have the time wave form displayed here. And so this is the modulated signal.

And then on the spectrum analyzer, we have the spectral display. And this is the carrier signal. That's the carrier frequency. And these side bands then correspond to the side bands associated with the modulating signal. So this is the spectrum of the total modulated output, right?

SANDY HILL: Right. It's interesting to vary some of these parameters. You can see the sinusoidal modulating shape at this point. Let me switch that to a triangular shape. And, again, it's a little hard to sink in both the modulating signal and the carrier, so you see the carrier kind of wondering by, but there it is.

Another thing that can be varied is the amplitude of the modulating signal. I'll make it smaller-- you'll see the side bands go away-- until finally we have a pure sinusoidal carrier-- as I bring them back in. Again, this is triangular. There would be harmonics there that maybe they're a little hard to see in the spectrum analyzer. I'll go back first to a square wave modulating signal, which is, again, you can see the square wave on top and one on the bottom.

PROFESSOR: And so all of this, then, represents side bands. Is that--

SANDY HILL: That's right. Those are the side bands due to the square wave modulation. Going back to the simplest, the sinusoidal carrier. Another thing we can do is to vary the frequency of the sinusoidal signal that's modulating it. I'll make it higher. And you'll notice that the side bands wander away from the carrier signal in the spectrum. The

spectrum, the carrier signal of that, doesn't have a frequency that's changing as I do this. It's just the width of the band, due to the modulating signal.

PROFESSOR: So this is the carrier. And these are the side bands.

SANDY HILL: That's right. Now as we go out very far, those side bands get gobbled up by the carrier itself. I'll come back to a nice reasonable point there.

PROFESSOR: OK, now, we can change also the carrier frequency and, as Sandy's indicated, various parameters. Now let me just point out, since I didn't previously, that the frequency scale that we're looking at here is a frequency scale out to 20 kilohertz. And we had talked about-- or Sandy had indicated-- that we can change the carrier signal shape.

And let me change the carrier signal from a sine wave to a square wave. Now you haven't seen any change on this particular display , but let me change the frequency scale. And what you see now is the modulating signal showing up around harmonics associated with the carrier. And those harmonics will go away when we go back to a sinusoidal carrier.

SANDY HILL: This is actually called a ring modulator. It's very simple to multiply a signal by a square wave. It's just a chopping process. And so a square wave carrier signal is very convenient to generate. And then you simply filter out the higher order harmonics.

PROFESSOR: Right, I'll go back to the scale that we had before. And Sandy had also commented that we can change the carrier level. And let's do that on the modulator box. We could do that either by changing a DC offset on the modulating signal or by changing the amount of carrier that's injected.

And as we decrease the amount of carrier, in fact, going down to no carrier at all or almost no carrier. That's suppressed carrier. We have only the two side bands and the signal is now highly over-modulated. We bring the carrier back up and when we do that, then we are reducing the percent modulation and simultaneously obviously related to that is changing the carrier level.

Now I had indicated in previous lectures that reducing the carrier is efficient in terms of power transmission, but requires a synchronous demodulator, whereas if there's carrier injected, as we have here, so that we're not over-modulating-- the percent modulation is less than 100-- then because of the shape of the time wave form, as you can see here, you can do the demodulation with a more or less simple envelope detector. And in fact, a envelope detector of the type that we've talked about before is exactly what is used in AM radios, because of the fact that it's so inexpensive. And so here the power transmitted required is higher, but the demodulator, based on using an envelope detector, is considerably simpler.

Well, speaking of AM radios, what we'd like to now demonstrate is modulation and demodulation with an AM radio, which Sandy happens to have here. And let's see, I guess, what you're going to do, Sandy, is take it apart for us, right?

SANDY HILL: Right. I've taken off the back. And I'm just now going to slip out the guts of it all, and try and set it up so you can see it conveniently, such as right there.

PROFESSOR: Now, this is your daughter's radio that you promised to give back.?

SANDY HILL: I would say was my daughter's radio. And now let's start attaching clip leads, because what we're going to want to do is to be able to see the signals coming out of the radio. We want to see both the audio and then the modulated signal and try and see them on the oscilloscope. So I'll start setting that up now.

PROFESSOR: OK. Let me-- while you're doing that-- also just comment that the kind of AM radio that we're looking at here is called a superheterodyne receiver. And the way that it does the demodulation is not exactly the way we've talked about it in the lectures. It's very close.

The idea is this the RF signal, the radio frequency signal, first gets modulated down to what's called an IF stage-- the intermediate frequency stage. And then it's that signal that goes to an envelope detector of the type we've talked about to generate the demodulated signal. So, I guess what Sandy has some probes on are the RF input and a ground--

SANDY HILL: That's right. The red lead here is a ground. It's common for both the signals we'll be looking at. This is at the audio. We're actually looking at the signal going directly into the speaker across these two leads. And then this probe down here, which I found by hunting and pecking, is the IF signal, the intermediate frequency signal, with a station on it that I'll now try and get something that sounds reasonable.

[RADIO FEEDBACK]

SANDY HILL: OK. A little sports.

PROFESSOR: Never quite know what you're going to get when you turn this on.

SANDY HILL: That's right, you don't. Make some adjustments there. And what you can see right here is the audio signal. I'll give it a little bit more game. And this is the actual intermediate frequency, modulated by the audio. And there's a correspondence between them that goes by awfully fast, but I think it's pretty simple to see.

PROFESSOR: So basically the top trace is the envelope of the bottom right.

SANDY HILL: That's right. This is what comes out of the envelope detector. And this is the signal into the envelope detector, in this particular radio.

What I'd like to do for a last experiment is what we've been doing at this point-- I'll turn this off for a moment-- is we're taking something that's coming in over the airwaves, as they used to say, and we're simply viewing it. What I'd like to do now is generate our own radio frequency signal, tune it up so this radio is going to hear it-- whatever that means-- and display it here.

What we're going to do then is use the audio oscillator, along with the amplitude modulator. And we're going to take from the output now the lead here. And this will act as the antenna.

This device was not designed to put out a lot of power. But fortunately we don't have a lot of distance to go over. What I'm going to do is turn myself into an antenna-- I'm basically 150 pounds of salt water-- and when I touch this, the signal

coming in here, which is radiating a little from the wire, is going to suddenly radiate from my whole body and hopefully will be enough to be picked up.

So what I'll do is I'm going to turn this on-- excuse the noise. Now I've set this up so it's tuned to a particular radio station, and I hope I can find it now. It takes a little fussing. That's not it. That sounds like it now. OK.

PROFESSOR: So this gets billed as Sandy Hill, human antenna.

SANDY HILL: That's right. What you're looking at here is I've got the antenna at this point, and what we're going to do is you're seeing the audio signal. This is coming from the signal generator up here.

And this is the intermediate frequency signal again. You can hear it's much stronger when my body becomes the antenna. And I'll leave it on for a second. And I can switch to square wave-- doesn't look much like a square wave. Various things.

There's significant distortion, because of all the transformations that the signal is going through. But it does indeed work, and we're picking up a frequency that the radio is tuned to. And that's it.

PROFESSOR: So Sandy has now been modulated and demodulated.

SANDY HILL: That's right.

PROFESSOR: Well, hopefully, all the things that we've gone through in the process of this tape and this set of demonstrations gives you a feel for at least some of the things that we've talked about so far in the course. And Sandy, I'd really like to thank you for joining us, for sharing your insights with us, as well as sharing your equipment with us.

Thanks a lot.

SANDY HILL: It was a treat. Thank you.