Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 20
Non- destructive testing – Part 1

Hello and welcome to the seventeenth lecture, of course, on corrosion, environmental degradation, and surface engineering. In the previous lecture, we started testing requirements, highlighted the importance of testing, and required data to be fed to the software as well. When we do modelling, everything cannot be tested, and we need to get optimisation after doing some sort of test, but a lot of modelling in this case. But testing is important, and we classify testing into two categories: destructive testing and non-destructive testing. In non-destructive testing, we highlighted nine techniques. So that was a slightly different kind of overview in the previous lecture, but we will be covering one technique in detail and then some sort of merits and demerits relationship. Wherever, how do we really go ahead and choose which technique should be selected?

So that kind of overview will be given, and of course, we will continue lecture eighteen on NDT, or non-destructive testing. So, what was mentioned in the previous lecture is that NDT plays a crucial role in quality assurance because we want better and better quality, safety, and preventive maintenance. We say it can be one of the strongest maintenance strategies based on the data. Whatever we get, we can really say that the frame preventive maintenance policy and then reason being that we were being given more emphasis on maintenance, we want early detection of the faults. So, you do not have to wait for the final failure.

If you are able to get early signs of failure, we can mitigate those failures, or we can take necessary or corrective actions for them. So that is why we want early signs so that catastrophic failure can be avoided. On the other hand, we can maximise, or may be enhance, the life cycle of those system components and materials. Again, as I mentioned in the NDT, we have mentioned around nine techniques, but there may be many more because research is still ongoing. When a new technique keeps coming, new principles and new achievements through this kind of technique are possible. As I mentioned in my previous lecture, research is happening to replace destructive testing with a non-destructive technique.

So that will really help society in a big way. However, as I mentioned, the NDT is a collection of techniques; it is not necessary to use only one technique. We may require a combination of techniques to get the right solution. So NDT is a collection of techniques to evaluate the quality of the material, components, and system without changing or damaging the performance or integrity of the system. So that is why it is really required, and we know very well that visual testing has been done for years and years.

The people have been gauging faults just by looking at them, or they may feel that they use a finger to figure out what the surface roughness is or what kind of features this surface will have. So, they also use visual testing, but in this situation, we will try to connect advanced techniques with visual testing. So, during visual testing, it is done by the inspector or whoever is examining the surface, such as the flaws, which are obvious, or it may be the thought that the surface roughness is an obvious flaw, or maybe some sort of irregularity. We know the sharp corners will be there.

You want to just check sharp corners with your fingers. So that is also possible. So, the irregularities in a material are a flaw, and it can be done through a visual inspection. We do not really require special techniques for that. However, if there is some sort of flaw and it is slightly deeper than the top, we will not be able to figure it out.

That is why we require some sort of liquid penetration testing or magnetic particle testing. So, these we call the PT and MT. What they have is a slightly different principle: we use fluorescent liquid or liquid dye to test the surfaces that have crevices. So, we will try to figure out the depth of that and then the flaw as such. While coming to the magnetic particle, instead of this liquid test, or maybe a liquid dye fluorescent liquid, we use some sort of iron particle.

Therefore, you should only apply this technique to ferromagnetic materials. It cannot be utilised for other materials. So, in magnetic particle testing, we detect surface and near-surface defects in ferromagnetic material. So, in a liquid test, we look at only the surface, while in the case of MT, or maybe magnetic particle testing, we can also look at some sort of subsurface crack. The reason being that when there is a magnetic field and then there is some sort of discontinuity, there will not be a continuous chain of particles.

Due to the internal fractures in ferromagnetic materials, particles tend to accumulate, forming clusters. These clusters form because the north and south poles are distributed irregularly rather than sequentially. This phenomenon allows us to detect near-surface defects using Magnetic Particle Testing (MT). Essentially, particles or dye tend to gather in defect zones, indicating an accumulation. Similarly, when dye is used, it accumulates in specific areas, revealing the depth of the defect. This behavior of particles clustering around defects helps in identifying the depth of the flaw.

Coming to the other testing, where we can really look at the subsurface cracks, or maybe say through and through complete surfaces, so we have ultrasonic tests, radiographic tests, electromagnetic induction techniques, and infrared thermal measurements. So, in this present lecture, we will be covering more about UT, which is an ultrasonic test that is basically a high-frequency test. Coming to the radiographic test, we generally use the radiation; it can be gamma radiation, it can be X-ray radiation, and then we try to figure out what the drawback is or what the discontinuities are inside the substance, and we try to capture those using some sort of digitization, or maybe we can really take a photograph of those faults. And then coming to the electromagnetic induction, or what we call the eddy current testing. We can also find the defect, the reason being that they are very sensitive to a discontinuity.

We will determine the depth accordingly. The type of sensor and its sensitivity will be crucial. Additionally, temperature follows a certain pattern, and if the material has a crack or discontinuity, its thermal conductivity will be affected, causing a temperature drop. This allows us to analyse the temperature or heat pattern to identify potential discontinuities or flaws. It’s important to note that no single technique is entirely foolproof. Using multiple techniques will provide a more accurate assessment, ensuring that our judgment is correct and that we arrive at the right solution.

Now, visual testing is one of the most common techniques, and almost everybody is familiar with it. In the few sentences we will say when we think about a visual inspection, excellent lighting is important, and we should also have clear vision. Now, clear vision can also come with magnification. It can be 3x, 5x, or 1000x, too. So, we really require some sort of magnification device, and it has been shown in this case that this angle may be that the angle of this light beam is roughly 5 to 45 degrees**,** which is ideal to get results, and then we here, the person, are able to look at the naked eye, that is, we require clear vision. If there is blurred vision or something, then this will not give the right solution. That is why, to get the result that is acceptable, we require excellent light, clear vision, and some sort of magnification. Now, as I mentioned, visual inspection needs to be done many times. This requires some sort of support from other techniques, and then needs to be done many times. This requires some sort of support from other techniques, and then it can be magnification or some sort of addition to this, and then there is something like a situation where one person is looking at the video scope, which means we are not really reaching that surface; we are not able to see that surface, but we can use some sort of video scope and then figure out what is really happening, and that is why it has been written that there are some additions that are really required for the visual testing. The borescope is a one, a fiberscope, a video scope, as I have shown in this, and sometimes we also use CCTV, which is very common these days because we can do remote monitoring and it is very common in very big industries and buildings where we are not able to reach directly, but we want to really see, and then that is where we use a CCTV. So these are examples of remote VT techniques.

The visual technique has been known for some time, but we continuously add more features to make it increasingly useful. A prime example is the remote VT (visual testing) technique, which is used to investigate areas with limited human access. For instance, a person cannot go inside a long pipe to inspect it, but with a videoscope or a camera fixed inside, we can telecast complete images of that area. This provides crucial local information.

Videoscopes can be used for visual inspections in various contexts, such as tubes, pipelines, and even welds. They yield good results, even in cases like forgings where the inspection occurs inside a surface.

The ASME provides codes and classifications for visual testing. For instance, VT1 refers to normal visual testing, while VT2 involves inspecting the pressurized boundary of fluid-containing systems to locate leaks. This is particularly useful for in-service situations where visual inspection is important. Functional testing is also performed under pressurized conditions to identify the source of leaks.

So, this is a leak test that can be done that way. It can be a bubble test, a leak test, or a soap test, and wherever we can really pressurise the unit, there will also be a hydrostatic test. So, this is where we say the visual test is very important, and the reason is that there are numerous advantages to using visual testing. In fact, whatever we do finally, a visual test will also be attached to that. So, there are numerous advantages to using visual testing, and the person who is really inspecting it only requires the skills, training, or experience if he or she can access the surface immediately. So, with more and more experience and more technical skills, the concerned person will be able to judge the surface easily, or he or she will be recording a lot of software and making a lot of interpretations to judge it.

Visual testing is very important. If we have a skilled person with the knowledge to accurately assess and identify issues with the surface, it becomes invaluable.

This technique typically does not require highly specialized equipment. For instance, CCTV is a common tool used for such purposes. It doesn't involve specialized equipment or consumables, nor does it produce special specimens. There are no disposable sensors or units involved; most of the equipment is permanent or long-term. Therefore, because there is no need for specialized equipment or consumables, visual inspection is one of the most cost-effective methods. From a cost perspective, visual examination, combined with tools like magnification or some sort of mode axis, proves to be very useful in this context.

Another good thing about visual examination is that we can really take photographs or videos as well. Now videos and photographs can be kept for future references; this is basically a record for us as well. So moreover, now this is important, but however we can say, there is only one major drawback: expertization. As I say, the reliance of visual examination is basically on the expertise of the person who is really examining it. So that is one of the major drawbacks, and then if we can automate everything, it will be very good, but there are so many factors that complete automation will be very difficult.

So we really required expertise, we required skills, or we required really good experience to utilise a visual inspection. If we do not have that kind of information, then VT will not be very useful to us. However, as per my understanding, if a person does not have good knowledge, not a single technique will be very useful to him or her. So knowledge is important, science is important, and understanding is important, which is why this course is important from that point of view. Now let us start with the first technique: visual testing, which is a kind of common testing.

While another test, what we call ultrasonic testing, Ultrasonic testing basically means that we know very well that human power or hearing power generally varies from 20 hertz to 20 kilohertz. While we are talking about this testing, it is something like where the power goes from 20 kilohertz to 1 megahertz. However, in a recent technique, they have mentioned that it can go to gigahertz as well. We do not have a restriction on the upper limit.

Now there is a need that it can go on a higher side also. Now, basically, they send some sort of wave and try to transmit the wave, or they retract back so that we get a purposeful, good solution. That is why ultrasonic waves spread linearly until they hit the barrier. So the barrier can now be the interface between the two surfaces, which may be the coating surface and subsurface, or it may be the flaw as such, which may be a crack, a linear crack, a perpendicular crack, or an oblique crack, or it may be some sort of void or some sort of discontinuity in this, or it may be that substance is there, and then there is some sort of grain boundary mix with a flaw; there is also a possibility. So, wherever there is a discontinuity, there is a barrier, or there is no smooth transmission happening.

So that what will happen will change the behaviour, the ultrasonic waves will change the behaviour. So, whenever this happens, some waves will get transmitted, and some will get reflected back. Now we can have two different kinds of sensors. One is really taking only the transmission; the other one is taking the reflected waves.

So, we can have both. So, we will be explaining both in this lecture. We say that some of the wave is reflected towards the interface from where the source is located, while the rest of the wave travels onward through the media. That means there will be a signal passing through. It may be that we have the opposite and some sort of sensor that can receive the signal, or it may be that if you do not have it, it will get transmitted. So, this is important from that point of view. We can have two major techniques as such because there are ultrasonic waves that we are transmitting to the surface. If there is a surface and there is some sort of flaw, then the waves will get reflected; they may be partially, fully, or partially transmitted, depending on the surface or rendition of the flaw.

So that is possible, and we know that there is a discontinuity, something is wrong, something needs to be looked into, and if we know how we can convert, we can really reproduce that kind of fault, and we can show what is really inside the surface. Now, if we get a wave, either transmitted or reflected, we can get information, such as the existence of a fault. The diagram provides information on the material thickness. You can see here and then that we have some sort of cylindrical surface that has a coating, and you are able to see the coating. There is some sort of rupture of the coating, and some coating has come out of the surface. So, in that case, whatever happens, the signal will vary and it will not be smooth, and moreover, we generally look at the signal difference; we do not look at the absolute signal; we mostly look at the signal difference as such. So, you can see here that there is a signal in this zone. We are getting some sort of different kind of signal.

Now this signal does not give as it is a thickness. So, we need to understand what the meaning of this signal is and whether it is amplitude-wise. And if it is amplitude-wise, what is the correlation, and then can we have a linear correlation, or may they have some sort of logarithmic correlation or exponential correlation that requires a science behind that? Therefore, most of the sensors that come are calibrated, and then they are given directly in dimensions. So person or may be that even the company that makes a sensor needs to have complete knowledge, and I have also realised that whenever this sensor is not used for a couple of months and you want to reuse it, you again require a recalibration or time-to-time recalibration. Otherwise, these sensors do not give absolute value; basically, they give relative value, and relative value keeps changing.

So, recalibration is required every time, and then we can get reliable research from that point of view. Another important point is attenuation. If I am transmitting a wave from one place to another, there is a possibility that some sort of energy will be lost, and that energy loss is basically attenuation. So, I will be getting finally some other response.

So if I have the right calibration, everything will be accounted for. If I do not have the right calibration, then I will not be able to account for that, and I will be getting unnecessary and misleading results. There may not be any fault at all, and I say, there is a fault that is why the mitigation is happening, or maybe there is some sort of attenuation happening or some sort of energy consumption happening. It does not, the reason being that there is material and that whatever the media. If we change a medium from air to liquid to solid naturally, the ultrasonic wave, which is passing some sort of attenuation, will change in behaviour. So that is why we really require a recalibration every time, and that gives a good result.

Attenuation refers to the gradual decrease in the energy of a wave as it travels through a medium. When measuring from the surface to the bottom, attenuation must be recalibrated. This calibration is typically valid within a specific range, for example, between 1 and 3 mm. If the measurement is less than 1 mm or more than 3 mm, the laser will not be effective.

Every sensor has a defined lower and upper limit, and the entire unit should be operated within this range. It is important not to exceed these limits and assume the sensor can measure any distance. Instead, always refer to the specified lower and upper limits and operate accordingly.

How do we generate ultrasonic waves? Typically, we use a piezoelectric crystal. When a voltage is applied to this crystal, it vibrates, creating ultrasonic waves. We can control the frequency of these waves, with current technology surpassing the previous limit of 1 megahertz and reaching into the gigahertz range.

As the ultrasonic waves travel through a medium, attenuation occurs, so calibration is necessary. It is important to use an appropriate curve fitting method to obtain accurate results. Once properly calibrated, these ultrasonic waves can be used to detect faults, measure material thickness, or even assess micron-level coating thickness. They can also identify grain boundary reorientations if the sensors are appropriately tuned.

Now, let's explore different techniques for utilizing ultrasonic waves. The first technique is the transmission method, which involves using two transducers placed on opposite sides of the material being inspected. This setup allows for accurate analysis of the material in between.

In this method, we use two transducers, one on each side of the substance. This can be illustrated with two scenarios. In the first scenario, with no flaw in the material, there will be direct transmission, shown by a green arrow. In the second scenario, when there is a flaw, the transmission will not be 100%; some of the energy will be reflected back.

The receiving transducer needs to be tuned to interpret these signals accurately. In the first case, where the material is flawless, the amplitude of the received signal will be high as most of the energy is collected at the receiving end. In the second case, where there is a flaw, the received signal will have a lower amplitude because part of the energy is reflected back due to the flaw. This difference in amplitude helps in identifying the presence of flaws in the material.

So that magnitude has come down, and as I said, these are the relative methods. We do not have an absolute method; we try to compare things like healthy and unhealthy. So, we are getting less energy in this case with this much amplitude, so it is unhealthy compared to this one. So, we can just compare; we cannot and will not be able to give an absolute value as such. So, it has been written that there are two transducers. We are discussing the transmission method, and then these transducers are utilised, one on each side. Now transducers which we been utilised working as a transmitter at one end and other end it is a acting as a receivers.

So one is sending this ultrasonic wave, and the other is a receiving end, and the transducer that is receiving that can be connected to the display system or computer for further calculation. So now, if I really explain this method, we say that when an that when an ultrasonic pulse passes through the material, it encounters the material's interior obstacle, as has been shown using the black colour in this flaw here. So, a material obstacle that can be a grain boundary can be a crack, fissure, void, etc. So, this void and inclusion can be treated as 3D, and the grain boundaries and fissure can be treated as 2D. So, something like we have a linear kind of thing, or we can be linear in the sense that thickness is negligible.

So, I am assuming this is 1D, and then this is a kind of 3D. So we can really look at both 1D and 3D; in this case, of course, 2D, we are not considering these assuming that the thickness will be almost negligible, or either it has one dimension or it has three dimensions as such. Now these hindrances cause interference in the pulse because there is a transmission path that has been shown here, transmission something like that, and suddenly we are trying to introduce some sort of hindrance. So this path is getting cancelled as such. So only the two arrows will be transmitting, and that has been shown in this figure.

So this is what we say: hindrance causes interference in the pulse, changing its characteristics. So whatever we are receiving or receiving, or by the transducer, that will be changed, and as in the captured and modified pulses, they are converted or may be getting different signals. So, it will be converted to electrical signals at the end of the receiving transducer, and this signal is then analysed by an ultrasonic flaw detector or may be some sort of processing software. These are the essential units we need to generate ultrasonic waves effectively.

We required a unit that would receive ultrasonic waves. We required a kind of processing unit that can really figure out how much is in and how much is out, compare it, and then figure out what is really happening. So we really required signal processing software, or what we call an ultrasonic flaw detector. So, these are the essential points. However, many times we do not really consider this reason when we buy some equipment. We went directly in and put on our machine, and we found some sort of result. As mentioned earlier, if we really require valid results or good results, we need to really do good calibration every time, or whenever there is a gap of a couple of months when again I am using the sensor, there should be calibration. So that we get a result, some of the normal results are the right results as such, and another thing comes.

Now, let's consider a crack, which can be oriented in various ways or even occur in multiple locations. It's rare to find only a single crack. The sensors used for detection have limitations; they can't inspect the complete thickness, circumference, area, or volume all at once. Therefore, sensor placement is crucial.

We need to determine whether we require a large number of sensors, such as 1,000, or just a few, like 2 or 3. When studying this technique, it’s essential to decide whether to place sensors directly at the most critical locations or to perform an initial scan to identify the right spots.

First, we might conduct a scan to find the most critical locations, then place sensors there to gather results. After analyzing these results, we decide on the next steps and locations for further inspection. This approach ensures that we achieve accurate and comprehensive results.

So again, this is an iterative procedure, and as I mentioned, there is a possibility there will be multiple cracks and faults in the situation. We really required more than one technique. So that we get more or less comfortable results or reliable results that match each other. There is a minimum, or what we call the deviation, between the two techniques. Now that was one transmission, the second technique is what we call a pulse echo method, and this pulse echo method is basically reflection. In this case, we are using a sensor and only one transducer; it is really releasing the rays and collecting back the rays as well. So one sensor is doing both things, which is why we say the pulse echo method, which is a reflection method that uses an ultrasonic transducer to send a short burst of the short waves of the ultrasonic pulses into the sample material. Here I am using the word sample, whatever the material we are testing, even though when we discuss the DT and NDT, we say very clearly that in DT we make samples, and in NDT we do not make samples.

When I mention "sample," I refer to the material or the real product being tested. It doesn't mean we've specifically prepared a sample for testing; we're simply testing the material as it is.

To generate ultrasonic waves, we use a piezoelectric crystal within the transducer. When an electrical signal is applied to this crystal, it vibrates and produces ultrasonic waves. These waves travel through the material and hit any imperfections or discontinuities. Upon striking these flaws, some energy is reflected back and collected by the sensor.

One transducer, equipped with a piezoelectric actuator, vibrates at a high frequency when an electrical signal is applied, generating ultrasonic waves. These waves strike discontinuities or imperfections in the material, and the reflected energy is collected by the sensor. The advantage of this method over the transmission method is that it uses only one sensor. If there is no flaw, the sensor receives no reflected signal.

So we have only the necessary detail, which is usually really required and more meaningful; only those things will come, but here continuous phenomena cannot happen naturally; there will be some sort of gap we are sending and then we are collecting back. So it has to be more like a pulse mode that we are sending than waiting, and then some sort of delay time, and then we are getting waste back and analysing those. So less equipment, but a softer side on the coding side, has to be better and better compared to other methods. So in this case, we can say that the same transducer that emitted the initial pulse also detects a reflection echo. So this method detects reflected waves and converts those waves into electrical signals. Again, everything is indirect; we are not able to measure anything directly; everything is indirect measurement, and we need to have a science; we need to have a connection; and we need to have a minimum to minimum noise.

If the noise is not minimized, the results will be poor. Energy conversion occurs, and the signal is provided to the device, software, or detector. This signal is then processed by an ultrasonic defect detector, which examines the reflected signals. By measuring the amplitude, time of flight, and other relevant parameters, it evaluates and characterizes the flaws, determining the number, location, and size of faults.

These are ideal situations, but even slight changes in surface roughness can disrupt the process. Although we don't prepare samples specifically for testing, the surfaces to be examined must be clean. Corrosion or rust can interfere with the signal, so proper surface preparation is crucial. The sensors need to be properly attached, and any gaps or irregularities must be smoothed to minimize discontinuities and avoid noise from surface imperfections.

We use ultrasonic waves with frequencies between 20 kilohertz and 1 gigahertz, which include longitudinal waves, shear waves, and surface waves. Each type of wave provides different information about the surface and internal features of the material.

Ultrasonic testing involves various sensing units and wave types, making it a broad topic. This course aims to provide an overview, focusing on one or two techniques in detail. We will refer to resources such as the ASM Handbook and ASTM handbooks for comprehensive information.

In summary, ultrasonic testing uses longitudinal, shear, and surface waves to investigate surface and internal features. This overview highlights the diversity of waves and sensing units in ultrasonic techniques.

It has been shown here that wherever there is a localization, there will be some sort of compression in the wave, and some sort of change in the wavelength will occur. If we are able to diagnose this, that will also give some sort of information about what is really happening at the localised level. Now coming to the transverse wave, it is mostly perpendicular to the direction of the wave motion, while the longitudinal wave is along the line along the wave of motion, while coming to the surface wave, they are a combination of both, and that is why they are able to generate more like circular waves. So, it is along and it is perpendicular, and that is why there is a circular wave. Now what is the advantage, and what is the disadvantage? In longitudinal waves, we use a word mostly for primary waves, and sometimes we use the word P wave.

In this case, the wave travels parallel to the direction of wave propagation. The advantage is that it can pass through solids, liquids, and gases, making it versatile across different media. This method is effective for detecting volumetric defects, which have volume. As mentioned earlier, defects can be 1D or 3D, but we generally don't count 2D defects. This method is particularly good for 3D or volumetric defects, such as voids or inclusions (foreign material within the substance), and larger cracks that have three dimensions. Even at the micron level, longitudinal waves are suitable for detecting such defects.

Now, let's discuss shear waves, or S waves. Previously, we mentioned P waves. Unlike P waves, S waves travel perpendicular to the direction of wave propagation. This has been illustrated with the direction of wave propagation and the direction of the transverse waves. These waves require a solid medium and cannot be used in liquids or gases. S waves are useful for detecting faults or flaws that are perpendicular to the wave path. For example, if there is a perpendicular crack that cannot be diagnosed using longitudinal waves, S waves are required. So again, this kind of knowledge is important. Now coming to the last one is a surface wave, and it was given by Rayleigh, which is why it has been utilized. And then, in this case, it gives a combination of both, so if we are not very clear, we can use this kind of wave. So, we get some sort of indication, and then we can move ahead with a more and more detailed analysis. So, we have two different methods to position the sensor, one in the transmission receiver, and one in the sensor transducer, which can be used as a transmitter as well as a receiver. So, naturally, the associated software will change a lot, and the filtration system will change a lot.

When it comes to wave generation, each method requires specific diagnostic software or units tailored to different modes. These modes provide valuable information about the internal and surface conditions of materials, facilitating effective inspection across various configurations. We may highlight a few examples and possibly present a case study on this.

Now, the question arises: what is the procedure? Developing a comprehensive software or establishing a complete inspection process can be a significant endeavor, possibly spanning three to four lectures to cover thoroughly. While established methods can be used as-is for well-established processes, developing new ones can be complex and requires deep technological expertise.

Measuring nanometer-scale thickness can be challenging due to high noise levels. A robust signal filtration system and expertise in signal conditioning are essential in such cases. Parts that are excessively small, thin, irregularly shaped, or non-homogeneous, or those with numerous defects or cracks, may exceed the measurement capabilities and present limitations.

Cleaning is crucial; removing loose debris, foreign materials like dust or oil ensures accurate results. A general rule is to avoid using the equipment on surfaces with very thin thicknesses or those that are dirty; thorough cleaning is essential before use. Equipment with two sensors and three waves can vary significantly in price, depending on specific requirements for fault detection. While universal machines are costly, investing in proper calibration and using reference materials recommended by the manufacturer are essential steps for reliable results.

Another thing is how to differentiate the signals because I will be getting a number of signals and the various locations. Even if I change the sensor orientation, I will get quite different results. So, we need to have an established chart and then a complete system to say how we go ahead. So, in one case study, we will also say: how do we really check these signals, whether they are from the faulty side or maybe from the healthy side, and how do we compare them? As I mentioned, these signals are not absolute, and we should not rely on absolute signals; they should be only relative. So, what are the important considerations from a procedure point of view? First, we need to have a clean surface. Second, we need the right sensor, and maybe whatever unit we are using should establish the filtration condition. So, then the signals, or maybe the signal-to-noise ratio, is very high, and another one is that we should try to choose the right references also.

We should avoid using sensors on very thin surfaces that produce excessive noise. It's crucial to check the sensor's operational range when purchasing, ensuring it aligns appropriately with our requirements. Sensors typically operate within specific narrow ranges due to calibration constraints, limiting their effectiveness within those ranges.

The calibration constants provided are not universally applicable across the entire frequency spectrum, such as from 20 kHz to 200 kHz or up to 1 GHz. Each sensor and its associated unit will have defined upper and lower limits within which they should be operated. It's essential to adhere to these limits and understand the acceptable or permissible operating range.

Those points are really required whenever we are trying to utilise this kind of technique. So, I will just try to highlight one of the case studies. As I mentioned, we will try to look at one case study. So, this case study has been picked up from the literature and was published in 2020. This case study is basically on the wind turbine blades, and then you can see that the two wind turbine blades. One blade is here, another one has been given here, and then it has been written that this blade is damaged, and this blade is healthy. So, whenever the lab tests are done, most of the time intentional damage is created, and then we know the damage is there with our sensor, whether our unit is able to give the right results or not. And then this kind of transducer can be utilised, and like in this case in the plate, we know that if the energy is going completely through, this is a complete transmission, while if there is some sort of delamination or some sort of irregularity, then it will really reflect back. So, that sensor position will change, and this is shown when there is no flaw at all. The initial way is equal to this.

If there is a flaw, checking the echo's clarity indicates whether the signal has weakened or diminished in this scenario. On the other hand, the alternative method presents a different case.

In this study, researchers initially scanned through the frequency domain, ranging from 20 kHz to 100 kHz, to determine which frequencies provided optimal results for WTB1 and WTB2. They identified that the 50 kHz signal offered a superior signal-to-noise ratio compared to the broader range tested. They conducted experiments in 5 kHz increments (20 kHz, 25 kHz, 30 kHz, etc.) and found that 50 kHz provided the best and most consistent results.

Frequency range scanning is a critical parameter in testing, ensuring that the chosen frequency range delivers optimal results. While 50 kHz may be effective for one setup, different equipment or dimensions may require reassessment to identify the most suitable frequency. Given the unit's dimensions, with a smaller width compared to its length, using just one sensor may not be feasible.

That's why they selected approximately 38 positions and then placed the sensor at a distance of 100 mm. So, may be one has been kept at 200 mm, then 300 mm, then 400 mm, then 500 mm, then 600 mm. So, something like that, and then they found defects at locations A, B, and C, and you can see this itself is that the dimension itself is varying from tip to tip, or, may be, one end is roughly 2300, another one is 2800, and the last one is 3500. Now this is just thinking that these are the defects A, B, and C that have been shown, and then that is what we mentioned here that these are the disbound between this one, and now what they are trying to look at again is that there may be numerous faults or there may not be one, but naturally the question arises as to which kind of faults or there may not be one, but naturally the question arises as to which kind of fault we are trying to diagnose, and then they try to figure out what will be the dislocation or disbound between the honeycomb structure, whatever they are using, and the final scheme. And then another important thing is that honey bone structure is start at the after certain duration or may be say after certain length at the beginning itself honeycomb structure is not starting.

So, again, if we try to figure out some fault in this zone, it may not be useful at all. The reason being, they do not want to see only the delamination between this honeycomb structure or support system and the top skin. So, these are important aspects whenever we are trying to go ahead with a diagnosis or we are using the testing method, and what is really important is that we look at only those. So, if I say that what they did was use two structurally identified honeycomb-cored wires—wide and thin—for the wind turbine blades. So, in short, WTB and those two units were identical; the only the difference was that one was healthy and the and the other had some sort of delamination, which may be some sort of damage to the honeycomb structure as well as, as you know, the top skin as such. So, there was some sort of disconnection between these two.

Now, when the connected transducer is at a different location, naturally all the sensors are on the outer surface; otherwise, it will not be an NDT; it will become a DT. So, they look at only the outer surface; of course, I can go at the other side of that, but again, it will be the outer surface only. So, we did not fit any sensors within, or, as it may be, after damaging the surface. So, either the top surface or the bottom surface—in this case, they have done everything on the top surface. Now, they are housing the top surface naturally; we have a very long length, and that is why they have put a thirty, and then they locate the thirty-eight locations, and then they get a response for that.

Now, when examining responses from different locations such as location 200 and location 300, researchers analyze the differences between the signals using a technique called autocorrelation. A strong autocorrelation between location one and location two indicates continuity without cracks. For instance, if signals collected at 100 mm and 200 mm exhibit high autocorrelation, it suggests that the signals are similar, indicating the absence of cracks or discontinuities. Conversely, a deviation in the autocorrelation factor indicates potential faults.

Then, healthy gives a very good autocorrelation, and bad, unhealthy, or damaged gives a very bad correlation. Some say the correlation factor is 50 when it is healthy and only two when it is unhealthy; naturally, we will know there is something in between these two. So, maybe between 2300 and 2400 there is some fault. So, that is what the technique has been utilised, and this has to vary based on the person's thinking, and then what they selected can be 50 or 150 instead of whatever they selected as the as the gap between the two signals; some may be that the two locations are 100 mm, but you can think about 150 or 350, and then basically, this is an iterative procedure. And we start with maybe, say, 8 locations, and after that, we can define and maybe find that some defect is between 500 and 1000, and I want to really modify, and I want to go for the 8 locations only between 500 and 1000.

This process is iterative and can be approached accordingly. A healthy WTB will exhibit a high correlation with the chosen signal, whereas delamination or defects will decrease the correlation factor, corresponding to the presence of defects.

To illustrate the results, Figure 1 and Figure 2 show correlations labelled as A, B, C, D, along with their respective locations. The signals collected were analysed for correlations across different points: for instance, correlation at signals 200 and 300 in Figure 1, and at signals 700 and 800 in Figure 2. Additionally, correlations were observed at signals 2300 and 2400, and signals 2900 and 3000 in Figure 2, respectively.

So, you can find that there is a difference of 100 in each reading, and then the correlation has been established. If you look at the correlation, this high value is important. Now they could achieve a very high value of almost 300 in the case of the A. So, whatever the signal they got at 200, and whatever the signal they got at 300, the correlation is very high. When comparing B to A, they found a stronger correlation. Now this is again a kind of correlation that is established, almost double that compared to A.

This could be due to more consistent signals or the geometry. However, if I get a similar signal from the damaged one (2), we won't need to delve into it further. In the second damaged WTB, you can see that in case A, they received almost the same signal as before, around 200. For case B, they also received similar results with a maximum value, showing very little difference. The slight variations in A and B are not significant, so there's no need to worry about these results.

So, this is fine. Coming to the C, they find that there is a drop. In this case, suppose there is a 500, and here they are getting only 45 something. So, there is a huge drop, and now this huge drop may occur because of the attenuation as well. You can see that they collected a signal somewhere between 700 and 800, and now they are getting a signal here and then between 2300 and 2004. Now there is a possibility the attenuation should not be accounted for that much because we are counting between the signals of 2300 and 2400.

So, this is only a 100-gap, while in this case we should get the same signal. So, again, they have highlighted that because there is a possibility of internal or other defects, we are not worrying about this either. Well, now you are coming to the damage one they got instead of 45; they are getting this correlation only the 15. So, that is why they are able to see that there is some sort of difference between this signal, which is significant. While coming to the further (d) side, the correlation in this case is roughly the 25 in this case max value, while here is a 4 to 5.

So, there is a significant deviation over here. So, this is noticeable now. Once we get this, we need to repeat the results. It is not that we need to say this is the result; we will finalise it. So, quite possibly, we have some indication that there is something wrong in this range, from 2300 to 2400 to even 2900 to 3000. There is something, and we need to locate what kind of fault we can reproduce. So, these are important, and as I mentioned, that is a kind of iteration, so we really need to look at them. So, what I can say is that they obtained a signal in the 200 to 300 mm range, which shows a lot of consistency with each other and a and a high correlation factor, as shown in Figure 1a. And similarly, they show the correlation when they collected that data at a location of 700 mm and 800 mm, which was also in Figure 1b.

So, these areas appear like you know there is no such problem, and then whatever the variation is happening because of the skin, which is really getting deposited at the honeycomb structure, And that was before the honeycomb structure really started. So, with this signal, they were not worried much. Now coming to Figure 1c, we showed that there is some sort of inconsistency and energy loss at the level, as I say, the correlation varying from 500 to directly 50s or 45s or something like that. So, these defects may be there now, and again, they say that there is a possibility that the elastic wave energy is getting dissipated in the system.

However, they wanted to compare 1c and 2c. So, there is a huge difference between the signals, and that shows very clearly that there is a delamination. Now, coming to the 2D, that shows a very weak correlation; only the correlation factor is something like 5. So, there is a weak correlation, which attributes that there is some sort of inherent flaw, and maybe some of the dissipation happens when there is a delamination, and after that, the signal is not really getting transmitted properly. And this is the delamination, which is very prominently looked at, and that requires a little more iteration to come up with far better results.

However, in this case, they did what they intended, and then they created a fault. So, they knew everything well in advance, but in reality, we will not know about this. So, that is why we require many more iterations to come up with the right results. So, that is why this kind of technique is a bit costlier compared to the visual examination, and then we require more iteration, and finally, we need to judge based on the visual examination. So, visual examination will be inherent in almost all the techniques, and then when we use this kind of technique, we need to have good knowledge about the technique, and we should also have good brainstorming sessions. How to improve the results and how to locate them completely. We should not immediately jump to the conclusion. It is quite possible that we are getting good results, but we may get better results if we go for more iterations as well.

Now, just thinking about the defects, we say that you know delamination is the separation between two surfaces, which is one kind of defect, but the question comes: what are other kinds of defects? So, there is a big category of defects, and it has been established in the literature as well. I am just trying to show in this slide some sort of type of defect in this case. We say there is a possibility of a defect that is dividing the surfaces.

So, there is a linear transverse crack and a longitudinal crack, and you can see that this crack also has a depth. So, whenever we say that a surface breaking a linear crack, that means it has some sort of depth. So, that is why we say that a liquid test can be done or a magnetic test can be done on this. So, those particles can go inside or die inside and figure out what kind of crack it has. So, for most of those surface cracks, I will not go ahead with a UT test; as such, maybe we will go with some sort of liquid test or a magnetic test. So that we get better results. Another thing is something like a surface breaking in the volumetric cracks, and then you can see the depth is there in this case. So, volume is there, which means there is an area on it that is visible, and there will be depth in this case. So, these are the other cases. So, this is the one; this is the two; this is a kind of thing again from within the cracks that are appearing on the surface. I have the option to use VT and potentially a liquid test in addition to the magnetic test, as these methods are significantly less expensive than our other tests.

Now, when it comes to the subsurface, the use of Ultrasonic Testing (UT) is crucial, as it allows us to examine the defects directly. So, MT can be utilized, and the magnetic particle MP can be utilised as such, but in this situation, better results will come from this kind of UT test as such. So, we perceive the near surface as linear and normal to the surface. So, there is a surface, and then there is a perpendicular to this one; the other one is parallel to the surface. So, one is perpendicular to the surface, and the other is parallel to it.

Of course, the crack may also happen like this, or maybe like this. So, orientation can happen, which is why we require better techniques. However, it is below the surface and not visible to us. So, we really required good techniques in this case. So, this is maybe the third kind of crack; this can be four types of cracks.

Now, coming to the subsurface volumetric crack, the big kind of volume you can avoid below the surface is also a possibility. Now, coming to the near surface, this is subsurface; it is not very near the surface, but it is below the surface. While in this case it is a kind of near-surface volumetric crack, it can be a kind of pores just below the surface, and then maybe you know, after a few cycles may be the therapeutic cycles, it may become a big bit also. So, this can be diagnosed using better techniques. So, if I want to really tell it in words, I will say that we have basically six kinds of cracks; we call them the linear flaws, which is what has been shown.

A linear flaw that penetrates the underlying material, creating vertical depth, is a concern. If it's only a superficial scratch without depth, it's less worrisome. However, a crack that divides the surface is considered a surface-breaking linear flaw. Such flaws can develop into fractures over time, potentially leading to catastrophic failure if not addressed promptly. Therefore, identifying these flaws is essential. They are often found in joints or areas with shrinkage, lamination, leaks, or deep cracks.

So, then the deep and big crack as such. So, such cracks basically make the material weak, and that is why the ASTM has a complete norm of 165 for more information. So, if you are interested, you can look at ASTM E165 for more information related to that. Second, what we mentioned about a surface-breaking volumetric fault. So, the fault that is exposed to the surface is not only deep but also has a depth. So, that is why we are using the word a surface-breaking volumetric fault, and these are the defects that extend over a noticeable depth; maybe we can measure the depth.

These are not a kind of scratch, or maybe the biggest scratch; they have some sort of depth. So, and that the flaw that extends beneath the surface can include something like holes, maybe you know initially the crack was only there and there were a number of holes, and then maybe get connected with or maybe there are some sort of inclusions also. So, if these are the kind of common cracks or maybe common defects again, the ASTM E547 standard really clarifies or provides more detail about this kind of defect. So, these are important.

Another type of defect we look at is the near-surface linear defect that is normal to the surface. These defects occur just below the surface, making it impossible to use the first three techniques—visual examination, liquid penetration test, or magnetic particle test—as reliable sources. Instead, we need more sophisticated and costly techniques.

Near-surface linear defects that are normal to the surface often result from material inhomogeneity, residual stresses, excessive mechanical loading, or tensile stress. Environmental conditions can also contribute, such as hydrogen embrittlement, which we discussed in an earlier lecture.

So, this is important. Other than that, there was a near-surface linear and parallel crack. So, one is a normal crack, otherwise parallel to the surface. Most of those kinds of cracks are developed because of the manufacturing type or machining time of a grinding. So, those are the manufacturing defects, and if we are able to figure out the beginning itself, we can really change manufacturing processes, and we can really make a better surface for the better manufacturing processes for that kind of unit.

So, another thing we have studied is something like a near-surface volumetric defect. So, it is again near the surface; it is not on the surface. Again, we require costly techniques to really find out. So, these refer to the non-linear and then 3 dimensional flaws because wherever the volume comes, there will be 3D as such. So, three-dimensional flaws or imperfections are again found closer to the surface; actually, it will be very important for us to find out what is really happening. Now, another term we use is something like a subsurface volumetric defect. It can be referred to as a flaw in a material that goes below the surface; it is not near the surface; it is below the surface, and this is something like a hidden fault; then it can be voids; then it can be inclusions; it can be porosity; it can be big flaws; and most of the time it happens in a casting kind of unit or may be the manufacturing by casting as such. So, we need to really look at the processes or manufacturing processes to improve them.

Sometimes, if the defect is not a manufacturing issue, it can be ignored. We only need to address faults if they are found to affect the material strength significantly or if they might expand and reach the surface. In such cases, adjustments to the manufacturing process should be made. Otherwise, these defects are not critical and need not be given much importance.

Another point is that these defects are already addressed in ASTM standards. By referring to these standards, we can identify potential faults in our unit and choose the appropriate technique for inspection. Finally, in the next lecture, we will study various techniques, including visual and ultrasonic methods, which we covered today.

Now, with so many techniques available, the question arises: which technique should I select? We will cover this in a separate lecture. Here, I'll give an overview of what we've studied. First, we looked at surface-breaking linear cracks. Next, we examined surface-breaking volumetric cracks. Another type we studied is the near-surface linear crack that is normal to the surface. Lastly, we explored the near-surface linear crack that is parallel to the surface. So, this is the 3D, and this is the 1D. This is another 1D, as such. Now, near-surface volumetric, and that has been shown in this case. So, this is 3D, and then finally, subsurface 3D in this case. So, we have just given some sort of ranking to the different kinds of testing processes. So, I am just trying to mention it here. Now, here we have also used A and B. What is the meaning of A and B? We say this can be utilised only for a ferromagnetic material. So, the magnetic particle or AMBE test can be utilised only for ferromagnetic particles, and then coming to the B eddy current base, we can say it is only useful for the conducting materials.

So, if we have a material that is non-ferromagnetic, I can really remove this unit completely. A material which is non-conducting or can cannot conduct it I need to remove this technique. So, this depends on what kind of material we are using and, again, what kind of defects we are thinking of. So, based on the defects, we have a given ranking, and the ranking says that it will not detect 0 means it will not be useful at all, and one is not well suited as such. Two, I sense an average that can be selected if the available sources are available or if I do not have a costly machine available, and this is based on availability.

The third point is that this ideal application and the B machine should be utilized. Now, regarding surface-breaking linear defects, visual inspection can be used. However, I don't give it very high marks and believe it should be complemented with other methods. Similarly, for defects near or on the surface, I wouldn't rate ultrasonic inspection highly. Therefore, for anything on the surface, I wouldn't give high marks to ultrasonic methods. In cases where the defect is clearly visible, visual inspection is preferable and receives better marks compared to ultrasonic inspection, which is more costly.

So, I will not give. Now, below the surface, nothing will work for the visual. So, this is important; another reason is that this is a perpendicular. So, I like that this ultrasonic may not give very good results. So, for that purpose, I am again giving one, only another three. So, if it has more volume and then may not be very thin, which is perpendicular, either I should use some other direction or some oblique direction.

In the normal direction, I will not go higher with an ultrasonic equal to 3. So, this is what I am trying to show. However, in this case, a reasonable volume is there, and I can use the ultrasonic technique as such. However, if I consider the cost, I will not give it a it a very high rank. So, depending on the kind of crack, this ranking is given only based on the type of crack. Similarly, there will be a number of other features whenever I want to select the right process.

Here we have mentioned only material based on the ferromagnetic and conductive material and type of the cracks. So, similar to this feature, there will be a number of other features. We need to consider which market and which technique will be more useful for our purpose. So, that is our aim for this course. So, convey, communicate using the using the right method. So, all the students take the right decision and then give an overall cost-economic solution to society. Thank you for your attention.