Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 30
Maintenance: An Introduction

Hello and welcome to the 27th lecture of our course on corrosion, environmental degradation, and surface engineering. The topic of this lecture is maintenance, with an introductory focus. Although we have touched on this subject in previous lectures, I felt it warranted a dedicated session on maintenance itself.

If we look at the dictionary definition of maintenance, it generally refers to keeping something in good condition. This applies to everything from maintaining our bodies to everyday tools like bicycles, motorbikes, cars, and other equipment. In this course, our focus is primarily on machines and buildings, with an emphasis on machinery.

In my own words, I would define maintenance as the process of monitoring machines to identify and correct potential failures before they occur.

Now, earlier, I put an emphasis on the fact that faults need to be identified and corrected. When failure occurs, we cannot correct it immediately; perhaps we can correct the next design. So that is why we are using the word potential failure, a fault that will be leading to the failure or which has the potential to fail. So potential failure word has been utilised in this case.

So again, what can I say? They are monitoring machines to identify and correct potential failures before they really happen in the event of failure. Two common maintenance approaches have been utilised, and I am not going to cover those two. One is preventive maintenance; the other is corrective maintenance. What is preventive maintenance? It involves conducting regular inspections, such as removing dirt, oiling, or cleaning, and identifying any necessary preventive maintenance. This process can be scheduled either once a week or once every 14 days, depending on the situation. Corrective maintenance involves maintaining a comprehensive inventory of all items. When a failure occurs, we simply replace the affected part, restoring the machine's functionality. This is why many companies have adopted these two approaches over the years. Over the number of years in number of companies, these are the popular, and I am not going to describe these two approaches, which will basically go over the condition-based monitoring.

Now why there is a need to give emphasis to a to a separate lecture on maintenance? The reason being that most of the companies feel that maintenance is a kind of burden, is a kind of necessary evil on them, particularly burden on the operation, and treat this maintenance aspect as an unneeded overhead. Therefore, many companies allocate a specific portion of their budget, typically around 5 percent, solely for maintenance; if this budget is exceeded, it becomes unavailable. So, try to minimise the maintenance as low as possible, and that creates more problems, which is why we are switching over to condition-based maintenance. So, instead of going for the corrective maintenance where we have a lot of inventory, which will be causing a lot, and we know very well in inventory if the item is kept for the 3 years or 5 years again that the life will be over and we need to discard it, and it particularly happens with a number of machine components. Similarly, preventive maintenance is time-based maintenance; after 2 weeks, we will do it; after 1 month, we will do it. "Preventive maintenance is often time-based, but instead of relying solely on time, we should shift towards a usage-based approach. This involves considering how much a machine has been utilized and determining the appropriate corrective actions to minimize the chances of failure. However, many companies treat maintenance as an unnecessary overhead and try to avoid it, not realizing its critical importance.

To emphasize this, let's take the example of the Bhopal gas tragedy that occurred in 1984 in India. The tragedy involved the leak of methyl isocyanate (MIC), which caused approximately 2,500 deaths according to one report, although the exact number varies. Over 200,000 people also suffered lifelong injuries and illnesses. The societal loss was immense, and the company responsible faced severe consequences, including financial ruin. In trying to save a portion of their costs, they ultimately lost much more.

One major reason for the disaster, as reported, was that the refrigeration system meant to keep the MIC at a stable temperature of around 0°C had been shut down months before the incident to cut costs. Without refrigeration, the temperature rose to 20-40°C, common in Indian cities, increasing the likelihood of MIC leaking into the air. Additionally, a gas scrubber, which should have absorbed any leaked MIC, was also non-functional, further exacerbating the disaster.

So, it was not in working condition. So, first failure, then second failure. Then comes the third: if the gas gets leaked also, then we have big chimney pipes, and then finally, it should go to the very high air, and then the atmosphere maybe the height of the around 30 meters to 40 meter, and then it gets a release under that environment, and then there is a possibility to burn that gas itself. However, maintenance was also neglected due to a corroded pipe, which led to the shutdown of the unit. So, in a sequence, one is a refrigeration system, then comes a scrubber, then comes a corroded pipe.

If we adopt a strategy focused on cutting maintenance costs, it can lead to significant failures, ultimately causing society to bear the consequences. This is why we emphasize the importance of maintenance. While it's essential to optimize and reduce maintenance costs, avoiding maintenance altogether can result in major losses.

Before deciding on the right approach, it's important to conduct a thorough risk analysis to determine whether maintenance is necessary, or if replacement or corrective actions will suffice. If these calculations indicate that corrective maintenance isn't appropriate due to the associated risks, we should not take maintenance lightly. In such cases, it's critical to switch to condition-based maintenance, which is the focus of this lecture.

As discussed in previous lectures, almost every physical system, including its subsystems and components, deteriorates over time. This deterioration can happen for various reasons, which we covered in detail in lectures 2, 26, and 27, including how to detect and address these issues.

So, every physical system or component deteriorates with the time. So, maintenance procedures are essential to ensure safety and effectiveness—safety for the machine, safety for the people, and safety for the environment also. Therefore, when it comes to ensuring the safety of people, the environment, and the company, maintenance is crucial, especially for systems that pose a significant risk. This is why maintenance must be carried out to ensure risk is continuously managed. Therefore, we must maintain the risk well within its limits, take it seriously, and initiate maintenance whenever the operation commences.

Another aspect to consider is the continuous monitoring during operational time, also known as condition-based monitoring, which we will delve into later. They should be conducted to monitor and repair, and wherever there is a need to repair immediately, we should look into that. So, we do not want failure; we want to detect probable failure, potential failure based on faults, and that is about the complete theme of this course: detect. Other fault levels should not proceed towards the failure, and for that purpose, condition-based maintenance is important, and that is what we are going to discuss today or may be in this lecture. To shed further light, several studies have demonstrated the impact of inadequate maintenance on machine failures. Among these, I'm referring to a 2014 publication. They analysed various big accidents that happened from 2000 to 2011, and they quoted around 183 accidents related to chemical industries, and the chemical industry required or may incorporate hydrocarbons and some sort of hazardous chemicals that are really very essential to be capped within a unit itself; they should not be released in an environment.

They analyzed material handling equipment, processing units, and storage devices and found that, out of 183 cases, 44% of failures occurred even though some level of maintenance was performed. They also noted that if maintenance had been more thorough, the problems could have been even worse.

This led to the conclusion that there was a decline in accidents in 44% of industries where maintenance was conducted to some extent, though not fully based on condition-based strategies. Additionally, they reported that around 50% of failures or accidents happened due to a lack of barriers or insufficient maintenance. The study further identified that 85% of the problems stemmed from deficient design, poor organizational structure, and inadequate management, highlighting that maintenance was not given the proper attention it deserved.

There will be some defect naturally when we design or fabricate that needs to be identified and corrected. Now, because of the deficient design, if the failure happens naturally, there is no maintenance strategy at all. Similarly, if there was less interest in the organisation and resources were not aligned, particularly whenever there was some sort of fault, and then we say let it go, no worries about that, and then there will be a major accident. So, this is a very big percentage: 85 percent. Another observation was that, despite the presence of maintenance activities, there was a significant lack of effective planning, scheduling, and fault diagnosis.

And they mentioned that fault diagnosis is very important, and that percentage is also huge—69 percent (69%). So that is why the major incident happened when we do not really go ahead with the fault diagnosis, we wait for the failure naturally, the major accident will happen, or we do not give resources for the maintenance. If we fail to align our strategy accordingly, there is a risk of failure. Therefore, it is crucial to closely examine the data we receive once the equipment commences operation. We keep getting data, and then based on the data, we should make a maintenance strategy. So let me express in the manner that if we have some maintenance strategy, maybe we have picked up maintenance strategy from some data book, from some existing literature, or maybe from our seniors who have made some maintenance strategy, but that maintenance strategy should be changed with time and maybe the new technologies and new sensors.

If a maintenance strategy was designed in the past without effective fault detection methods, continuing with that same strategy is ineffective. As technology improves, maintenance strategies must also evolve, and this is the focus of today's lecture.

In previous lectures, we consistently discussed various degradation mechanisms. For example, surface degradation was explained in Lecture 2, while the possibility of failures due to wear and wear mechanisms was covered in Lectures 3, 4, and 5. We dedicated three lectures to wear mechanisms, followed by discussions on fatigue, melting, diffusive wear, fracture, and surface degradation in Lectures 6, 9, and 10. Lecture 11 focused on the energetic effects related to surface degradation. In each case, we examined potential failure mechanisms in detail, providing a deeper understanding of why failures occur. With this knowledge, we can design better maintenance strategies.

We also explored fractography to understand how environmental changes, even when the system is functioning well, can cause surface degradation. These topics were addressed over three lectures, along with several case studies. We discussed how products, despite being well-designed and functioning properly in the market, can face problems due to environmental changes. Detecting these issues is crucial, and we covered that in those lectures.

Additionally, we discussed various testing methods, including guidelines, principles, and sensors. This was introduced in Lecture 16, and non-destructive testing methods were detailed in Lectures 17 to 20, including how to select the most appropriate method. We also recognized the importance of learning from past experiences and existing literature. Given that much of the engineering data is available in graphical form, we discussed how to digitize this literature to make it more accessible.

We need to convert the data into digit form and then implement a data-driven approach. We can construct a model based on any available data. We make some sort of regression model or maybe some other model, and based on that model we apply a digital-driven, or data-driven, approach, and as we are getting newer and newer data during operation, we should keep changing our model, which has been made from historical data. We also mentioned that there may be many factors. When I start working on any design, or maybe any failure mechanism or any fault diagnosis, there will be many parameters available to us.

We need to identify which parameters are most sensitive and have the greatest impact. That's why we performed a Principal Component Analysis (PCA), which helped us determine that selecting the top 3 to 5 parameters can account for around 90% of the overall effect.

We also discussed the distinction between faults and failures, and in Lectures 25 and 26, we covered Failure Mode and Effect Analysis (FMEA). This provided a deeper understanding of existing systems. In the previous lecture, we focused entirely on permanent magnetic bearings, a newer system, and investigated why failures occurred. Initially, it was assumed that these bearings would perform flawlessly, with no wear or friction, yet we discovered failures still occurred.

To properly understand and improve such systems, FMEA is essential. It helps identify potential failure modes and provides a framework for improvement. It's possible to build models based on FMEA and apply them to current situations for better performance.

The data may vary over time as there is a need for continuous updates. For instance, while the criticality of certain issues like CVD levels may remain constant, the frequency of occurrence can change due to different conditions.

For example, in certain scenarios, the formation of soot can lead to increased abrasive wear or other types of wear that need to be considered. This change in occurrence highlights the need for a data-driven FMEA approach.

In today’s lecture, we will build on the previous two lectures on FMEA by discussing how data-driven FMEA is necessary for significantly improving condition-based maintenance. Incorporating this approach allows us to continuously update and refine our maintenance strategies.

Although this is an introductory lecture, we will touch on maintenance strategies briefly. To provide a complete picture, I'll also revisit a concept we’ve discussed in wear mechanisms—the 'bathtub curve.' The bathtub curve shows that the failure rate, or front mortality rate, decreases over time, while wear increases as the system ages. The combination of these two trends forms the familiar bathtub shape over time.

This was discussed earlier. Now the shape may be a little bit different, but the way we are trying to project the shape will be like a bathtub curve; it can be something like this, this, and this. Also, there is a possibility, right? However, the underlying mechanism will remain largely unchanged. A similar kind of curve can now be used for a possible failure. Perhaps there exists a literature that suggests this as a potential failure curve, which can then be used to explain a maintenance strategy. Even though there may be a number of drawbacks to this curve, we are not going to highlight those, even though if you go through the literature, people will mention the number of drawbacks. It has a limitation, but just to explain maintenance on one slide, this is what I believe is a good method. In this case, it has been mentioned that maintenance is not necessary during the design phase, but it becomes necessary during the installation phase.

We've also noticed that initially, we don't encounter many issues, as the company typically handles the installation, ensuring everything is done with great precision. A company employee who is well-versed in the system may be able to learn from this individual, but their knowledge may not be comprehensive. So that this curve says that during the installation period, maybe say whatever the daytime gives, most of the time the companies give some sort of one-year maintenance fee or something, or maybe 6 months free or 3 months free. It is quite possible that they did not have many failures at the time. Real failure will start after that, and that is the P point. So installation to P, they find there is no failure; this curve says that, but may not be correct for every situation, but maybe for some system.

Now, the point at which failure may begin is here; failure may begin does not mean the failure will occur. Maybe there is a possibility that the fault generation and final failure are happening at the F point. Therefore, P represents the onset of a fault, while F represents the point at which the fault has significantly advanced and a failure occurs. So this is how they define the P to F, whatever this interval will be like: a life of the system. So the residual useful life of the system means that as time progresses, this RUL will continuously decrease.

So if you have defined maybe 3 years as the life of the component and then already you have covered 1 actually remaining, it will be 2 years. So this is what they try to indicate. Now beyond that, there is a functional failure. Maybe the system has not broken in 2 parts, but the intended function of a system is not really fulfilling the function. So that is the functional failure, and after that, what will we do? Either if it happens at the system level, we cannot do much, but if it happens at the component level, then we can do breakdown maintenance or corrective maintenance. We will replace any components that have failed, such as a bearing, gear, clutch, or brake.

That is what we call a breakdown maintenance system. It will be on a halt for some time—maybe a few hours, maybe a few days, maybe a few months—depending on whether the component is available in inventory or not. This is why many companies maintain a high level of inventory, and I have observed that many bearings are kept in stock. You just tell them that this bearing has failed immediately; they will bring it back, and maybe in a half an hour the system will be up. So there is another one that inventory management they do, and this is what we call the corrective maintenance or the breakdown maintenance, and sometimes people say they run to failure. We do not worry about the maintenance; let it fail. Once it fails, then I will replace it.

This is also a viable strategy for maintenance, especially for low-risk products where the risk is minimal. We know it is not going to deteriorate the environment at all, and whatever we are working on, the system is not very highly sophisticated, and it is not really going to give a lot of bottle mix because of the failure. It's almost like we have many units like this. So do not worry about that. If one machine fails for half an hour, in one hour we will shift to the other machine, and then we will continue.

So there is a lot of redundancy available. So this is another one strategy, but we are not talking about it. As previously mentioned, the majority of precision maintenance is carried out at the company's level, and they will handle it completely. So this is not of our use; this is also not of your use. Next in line is a type of maintenance known as condition-based maintenance. Sometimes people use the word predictive maintenance to describe what will happen, and if I know the failure, if I know the fault, and I am able to estimate what will be the residual useful life, and when the failure progresses to a significant level, I can do an appropriate maintenance strategy.

Our one is the time-based maintenance, which we call primitive maintenance, and this is again based on the data available: oil needs to be changed once every 5 years, once every 2 years, or once every 6 months. Those are the primitive maintenance, or maybe we need to do this kind of regular cleaning, or maybe we need to do overhaling once a month or something like that. So, this kind of thing can be used. However, in this case, we've also realized that a number of parameters can be used as a signature. It's possible that over time, the vibration level, oil colour, oil viscosity, oil acidic number, or oil basic number will all change. Similarly, the temperature profile will also change over time, or maybe the noise level will be different, or maybe heat generation will be different. These variables are available, and if we have sensors to detect them, we can effectively relate to them. Alternatively, we can implement condition-based maintenance, also known as predictive maintenance, based on these available variables.

I have given only the 5 parameters here, but that does not mean only these 5; there can be a huge number depending on the system that we are going to utilize. As I mentioned in the beginning itself, for this curve I am just trying to utilise only for the understanding purpose. I don't vouch for the validity of this curve; it primarily serves to explain the various types of maintenance and how to formulate a maintenance strategy. And then again, it depends on the requirement. Some people go ahead with a lot of inventory, some people say no, there is no need for inventory, and then we can order because we already will have some sort of time available. We know that this motor is going to fail after 4 months, or maybe this bearing is going to fail after 5 months. We have ample time to place our order, ensuring delivery within 3 or 5 days.

I do not have to keep any inventory every time I receive a new batch of material, and we do not really need that much inventory either. So in this case, as I already mentioned, here the probability of the failure is checked, which is why there is a sometime relation between the failure probability and the residual useful life. And in the beginning itself, I mentioned that this IP interval few companies may not believe at all. Once it is started, it is our responsibility; there should not be a new failure, and this is more common in the airline sector, particularly the aerospace industry, where they do not believe in IP intervals. Once the machine has been started, or perhaps once the aircraft has been put into service, we should consider an immediate maintenance plan. So this is a very important aspect if I express it in a slightly different word. In the curve, what we call the PF curve, we thought about potential failure and functional failure; they are two different terms. Now what we say the potential failure is something like an early stage when the potential failure exists but has not yet occurred.

We can detect certain faults using additive methods or employ sensors to identify the type of fault. Additionally, we can use an analytical model, such as failure mode analysis, to understand what's happening, what could happen next, and the potential impact. Based on this, we can determine the severity number or occurrence number. As mentioned earlier, several indicators—such as abnormal vibrations, temperature rise, noise, or other deviations from normal operating conditions—can point to issues like clearance problems. We also maintain a database of normal operating conditions to compare sensor data with. For instance, as discussed previously with the gear example, we evaluated a gear in normal condition, one with a crack, and another that was broken. By comparing the current condition to the baseline, we can identify deviations, estimate residual useful life, and take timely action.

At this point, I believe condition-based maintenance can be effectively implemented when done properly. This approach seems to be the most appropriate.

We also talked about functional failure, which means the failure has progressed to a point where the system is no longer operational. In such cases, the system experiences a complete breakdown, causing downtime. If safety is a concern, we must prevent this stage. However, if there's no safety risk and no immediate breakdown, we can sometimes afford to delay intervention, especially if there are redundant systems in place. In such cases, corrective maintenance can be sufficient, and this can be acceptable for us.

Now, defining functional failure can vary. Some may say that if efficiency drops below 95%, it's considered functional failure, while others might set the threshold at 85%. Some may only define functional failure when there's complete breakdown or irreparable damage.

So this is a slightly subjective now; it can vary from one company to another company, one team to the other company, another team. So in this situation, whatever the residual or possibly remaining usable useful life or RUL is, it will also be slightly different. So this is important to understand. Maybe one company says RUL is 5 years, another company says 10 years, and another company says 3 years. All 3 are possible because there is a definition, or they will have a different definition of the functional failure. As I mentioned earlier, corrective maintenance is implied and may only be useful when condition-based or preventive maintenance is neither technically feasible nor feasible. We do not have so many units available; we do not have sensors; we do not have any technology at all, and then the kind of machine that I am using is in the age range, so we do not have to worry too much, or we already have data related to cost.

So we say it is not really cost-effective to implement maintenance, condition-based maintenance, or even preventive maintenance, or maybe to some extent. I can use the preventive maintenance. These factors are crucial:

firstly, the technology is not readily available; secondly, safety is not a concern; and thirdly, the machine is reasonably priced. So why shall I use maybe say there is a machine cost overall of 1 lakh rupees and then somebody says the maintenance cost is 5 lakh rupees? Naturally, we will not go for the maintenance based. So, these are some sort of data, and however, I am assuming that condition-based maintenance is really required. Now the question comes: whatever the curve I showed, the PF curve is completely time-based, and I am talking something like a condition based. Are they really related? No, they are not that much related.

So in my view, condition-based maintenance is a better approach compared to the time-based maintenance that is useful for preventive maintenance. But that is to describe the overall approach related to maintenance, which is why I adopt that curve or PF curve; otherwise, I may not really require the PF curve to go ahead with the condition-based maintenance, and it is only just to explain other maintenance strategies. This allows me to define the concept of condition-based maintenance clearly. Let's now see what condition-based maintenance is. In NDT, we covered almost 4 to 5 lectures, and then we had a different kind of sensor suit sensor unit everywhere. Once the sensors are available, we get some data from that, and then those data acquisitions happen either through some sort of FAQ method or, maybe, some sort of data acquisition system, and once the data acquisition system has happened, we need to do some data processing.

There may be the possibility of denoising the data; there is a possibility of data being missing; there may be some sort of lack of the data; then we need to really bridge those data we need to do processing so that we do not have a discontinuity in data. So data processing is very essential, and then based on that, we can think about a diagnosis system that we have got, and we process the data to determine what kind of failure is there. So we try to detect the fault, and then we can go ahead with the separation between the noise and useless data and the fault-related data. That is why we are using the word fault isolation, and then based on that, we can go ahead with the fault identification, and this fault identification requires some data from a previous and the knowledge to compare. Once it has been identified, this is the kind of fault, maybe the kind of wear fault, or maybe the kind of misalignment fault, or maybe the the kind of misalignment fault, or maybe the kind of thermal degradation fault, or maybe some sort of fault that is already known in a system. After identifying a fault, a prognostic approach emerges. What is a prognostic approach? What is the real relationship? How do I proceed with maintenance? I know there is a crack, maybe 5 mm below the surface. How do I take a strategy to really go ahead with the next either? I calculate a residual life. I say no, there is a crack. maybe after 2 years it will fail like this.

So everything has been known to us, and then maybe there is a major overhaul and we can change the system, so that comes a prognostic approach. So that is why we say that based on the past performance of the system prognostic approach, we estimate how long a part will work under certain conditions, so that is one way. How one is that maybe use some sort of element to bridge that crack to close the crack, maybe change the load condition, maybe some sort of additional requirements, and of course this completely depends on the functional requirement. What are our functional requirements, what kind of efficiency, what kind of temperature requirement, what kind of wear tolerances, and maybe what are the available resources for us to compare? Based on these factors, we can determine a maintenance strategy, which can either be automated or determined by the maintenance manager. It depends now if it is automated, then we really require many data to be processed continuously and updated constantly. However, the maintenance manager may possess extensive exposure and experience, which will enable them to effectively monitor the situation and take appropriate action based on the data.

These are the key factors associated with condition-based maintenance. So what we say is that to get the best quality dependability and availability, the decision maker, or maybe the manager, or maybe it can be automated, needs to handle information well and make a good decision. So even if the tested knowledge person has a lot of exposure, he or she should document those as well. So the future somebody should learn it should not happen the person gets retired and maybe another person comes and then everything changes. This is a crucial factor, and we should base all our decisions on well-documented criteria.

Sometimes, when we increase automation, data analytics becomes essential for gaining insights into maintenance planning. Analytics helps us evaluate how previous maintenance decisions have impacted performance—whether improvements were made or if there was any deterioration. This feedback allows us to enhance maintenance management for future cycles. Automation can support better decision-making by maintenance personnel or managers, leading to improved overall results.

We've previously discussed various methods for monitoring system conditions. Fault detection can be achieved through sensors, and the type of sensor depends on the situation. For example, in vibration monitoring, we use accelerometers to measure amplitude versus time or frequency data points.

The data points can be converted from a time domain to a frequency domain, depending on the situation. Once the faults are diagnosed and data collected, data processing is necessary to determine the type of fault. There are various methods available, including eddy currents, acoustic emission sensors, strain DIC methodology, thermographic imaging, and ultrasonic sensors. Many sensor types are well-documented in the literature.

In my lab, we primarily use vibration analysis, oil analysis, and infrared thermography. These are the three main methods we rely on. We also conduct wear debris analysis as part of our oil analysis process. For vibration analysis, we typically use accelerometers, which can be either unidirectional or three-axis. We calculate temperature over time, collect time-based data points, convert them to frequency data, and compare amplitudes to diagnose issues such as misalignment, imbalance, bearing wear, or mechanical looseness. Vibration analysis is especially useful for motors, pumps, and other rotating equipment.

Vibration analysis is widely used, with estimates suggesting it is applied in 60–65% of cases involving rotating machinery. In contrast, oil analysis is particularly effective wherever lubrication is involved. Since lubricants continuously circulate, we can measure temperature, detect wear debris, assess moisture content, and evaluate potential corrosion risks by analyzing the oil.

So, this provides me with the presence of wear debris and some sort of pollution, even the dust if there, or maybe the soot formation is there, or maybe some sort of black powder, or maybe even the fatigue. Some sort of debris keeps coming, or even oil has oxidised because of the air entrapped, or maybe some other reason there is a change in viscosity, either viscosity thinning or viscosity thickening. There is some sort of depletion of additives. Maybe the oil that has been utilised has spent its own life, maybe 2 or 3 years, and needs to be replaced. Engines, gearboxes, hydraulic systems, and any other machine that uses lubricating oil commonly employ this type of analysis. So if oil has been supplied to the two machines, then we will go ahead with the oil analysis. If oil is not there, or maybe only grease is used and there is no circulation of oil, then I will go with a vibration analysis.

Now somewhere and the vibration and then it is not really giving very good results, and I know there is some sort of high friction, high impact, or maybe some sort of then the temperature is increasing somewhere in places.

Therefore, I can consider using infrared thermography, a technique we have studied in non-destructive testing. We use cameras to capture infrared radiation, which is typically emitted by the body when it is operating, potentially reaching temperatures higher than absolute 0 Kelvin. This allows us to detect localized overheating anywhere. So in oil analysis we can give a generalised heating, while in this case we can get really an open point, which portion is getting overheated, or there is some sort of electrical failure, maybe current is not getting passed, or maybe there is some sort of breakage, or maybe there is some sort of insulation problem. There is an over friction or maximum or more friction; those things can be detected using infrared thermography. However, these are just indicative, but there are many sensors that can be utilised for diagnosing the condition of a system. Now as I mentioned in our lab what we do we do a number of other systems, but here I have described something like how to monitor the condition of a spur gear, and a spur gear unit has been mounted over here in this case, and then we have a coupling, and we have a debris sensor also to figure out what is the number of debris that is coming out, maybe it gives a really good signal to us, and this has been shown and in addition. Whatever the moisture gets mixed with the oil, that can also be measured, even the change in viscosity of the oil that can also be measured using this kind of unit.

So we have a pretty complete setup to figure out, and then what is going wrong with a gear mechanism? Here, we are using only spur gear, but helical gears can also be used; other gear can be used; whichever gets lubricated can be used. In addition, we also mount the gearbox and then the accelerometer on the gearbox to collect the signals. We do necessarily TCA and then necessary condition monitoring, whatever the analysis tools utilise, and then try to figure out comparing the matching frequencies, and then whether there is some sort of damage to the surface or there is some sort of misalignment, those can be diagnosed also. Now here in this case, I am just showing the results of that test setup, which has been shown, then the gear somewhere of the steel, and then the wear particle will contain iron in this, and then that has been shown here, and this in the graph is showing some sort of variation in this case, and this value is a mean value of 61,000 particles, while in this case there are 73,000 particles and there are 66,000 particles that have been shown. We now have a highly sensitive setup capable of detecting particles larger than 40 μm, 16 μm, and even 100 μm. With this system, we can observe how the gear behaves when exposed to minimal or acidic conditions.

So that is why we also perform the test on that 0.000025% of HCl or aqueous HCl, which has 36% HCl and remaining water. Those things were utilised, and of course to test different kinds of materials and the impact of the materials on the lubricating conditions or on the overall failure of the system, we also use nanoadditives. Using this approach, we can observe a comprehensive reaction, revealing that the addition of HCl, even in the absence of HCl, results in 66,000 particles corroding the media. Naturally, the corrosion has increased the wear rate, and the more particles are coming when we are thinking about nanoadditives, because in earlier case studies we also mentioned that whenever nano powders or nanotechnology is utilised, we are getting better and better results. So in this case also nanoadditives were used, so instead of 66,000 without HCl, now with HCl, nanoadditives really give significantly good performance even in the presence of corroding media. This suggests that, regardless of the type of corrosion or the presence of atmospheric corrosion, the application of technology and science can still yield superior results.

So that has been shown in this case, while in this case we have shown that as the size of the particle increases, the wear damage to the surface will increase. These particles are associated with the wear on the gears. As we discuss the corrosion of the gear, we observe an increasing number of particles, each becoming larger in size. With HCl, the red color block is always on the higher side, and in this case, the smaller one has been demonstrated with a nanoparticle. So even somewhere, which was happening on a very large particle size, that has shifted to this side.

Again, the presence of nanoparticles significantly reduces wear, which is an advantage. So when we understand the science and then we utilise nanotechnology, many surface degradation processes can be halted, reduced, and minimised. So in this case we have used a sensor online a few sensors, of which we have another one, the mask sensors, and then we, as I mentioned, wear debris metallic sensors. The company's name also has been mentioned as to where we have purchased this. Now we will just take one example that has been picked up from a literature that was published in 2021, and the title of that paper is a data-driven failure mode effect analysis.

So, FMEA has already been covered. In this case, they have utilised a data-driven approach with a FMEA to enhance the maintenance planning. So how do we really improve the maintenance? So with a base on FMEA, I can plan some maintenance, but when we get actual data, can we improve that? So that is what with the data-driven approach. So they suggested some sort of framework over here.

You can see the first module is a physical world, which means the system. Earlier in FMEA, we said that you understood the system. So they understood the system, and then they figured out what the different kinds of failure modes are related to that system, and then what kind of maintenance strategy people are using for that purpose. So they have done it. Now after that, when we mount the sensor and then we try to procure with the key features and even permanent magnetic bearing, we mention about the key features, what are the failure modes, and then if we keep getting the data based on that, we understand the system slightly better and better manner, we may improve the system or may be data processing and we bring to the cyber world.

In this case, the cyberworld represents a novel concept. We are attempting to implement a simulation, specifically a 3D simulation of a real or physical system, which is why I've heard the term "cyber system." Now what is really in this case? Basically, when we are thinking about the data-driven approach in RPN, in this case we know the initially known severity is known to us detection sensor. We are not yet changing, but occurrence will change. If I go ahead with only physical mode in this space, there will be some sort of occurrence. It can be you know the 5 different failures and then occurrence may be the number may be 1 to 10 we can say 6, 8, 9 and then here in real situation maybe 6 turns out to be 7 or 6 turns out to be 5. So, in the in the actual case, this is based on history what initially we made, while this is in a real situation what we are getting.

So this is important when data-driven FMEA we get real data and then we change we can change the occurrence number which has been in this case particularly they have given 1 to 10 and in my previous lecture I mentioned it can be 1 to 5 or 1 to 10. While in this case, this paper gives a 1 to 10 ranking of each fault, and then that is why they have mentioned it, and once that is done, it finally becomes a decision. What kind of decision should be taken? Suppose we say that the damage D's RPN is 216, which should be corrected first. So naturally, whatever the corrections the way in the finite under this permanent magnetic bearing we have improved the system, those can be corrected in this manner. So in this case we say that damage B and damage D give a maximum gives in the maximum weightage you take a decision how to change a maintenance strategy.

So that this number can be under 100 or under 150. So, that is the kind of strategy that can be chosen. Why is the data-driven approach being discussed? The reason being that whatever the data we initially got, we do not have actual environmental influences. Now there is a possibility that environmental conditions keep changing, and we may change continuously the maintenance strategy in different environments, or even the person, the pilot, who is flying it, may have different ways to handle the flight. Even in that situation, the maintenance strategy may change to some extent.

This is what has been discussed here. As I mentioned earlier, some refer to a "cyber-physical system," while others, like the author in this case, use the term "cyber-physical production system." Both terms refer to similar concepts, but in this context, the focus is on the integration of computational models, 3D simulations, and physical processes.

The system leverages data-driven approaches to provide the most up-to-date operational data. By using iterative procedures, we can optimize both the data and the maintenance strategy for better efficiency.

So in the real world of data acquisition, we keep changing the maintenance strategy. Otherwise the maintenance strategy used to be well defined within advance maintenance strategy will be like this, but in this situation now it depends on every time the RPN is being calculated and the RPN calculation will keep shifting, what should be done next right? So in this situation, what happens when we talk about in-situ arrangements or continuous data acquisition? In this case, they are continuously acquiring data, processing data, and then they also need to fit in whatever the models are, which we made based on the initial understanding of the physical system. So those models need to be changed also, which is why they collect the data; they try to utilise the data, whatever they are supposed to 100 data they collected. They will use 70 data points for training, whether it's a new model they're proposing or even a delta variation in the current model. However, these must undergo training, testing, and validation.

This method goes beyond the traditional "cow food" approach. Instead, machine learning algorithms or artificial intelligence are used to continuously update the system. In this particular paper, the authors trained their model using 70% of the available data, even from existing systems. The training allows certain coefficients to adjust, followed by testing and validation to ensure accuracy. This approach was adopted to achieve better results.

To summarize, they used a data-driven method to calculate the Risk Priority Number (RPN). The severity level was already known, and the occurrence rate was continuously updated, while detection methods remained constant. However, if there’s a technological improvement in detection, the RPN could decrease, as better detection would naturally lower the associated risk.

What they did was conduct fault prediction for each failure mode separately, similar to the approach used with passive or permanent magnetic bearings. For each fault, they calculated the Risk Priority Number (RPN) individually. The predicted fault probability for each failure mode was then scaled between 1 and 10. For example, a failure probability of 84% was assigned a rank of 8, a 90% probability was given a 9, and a 94% probability was ranked as 9.4.

Initially, they used this method of ranking from 1 to 10, but later they refined it further by incorporating decimal values. However, it’s generally preferable to use whole numbers on a 1 to 10 scale for simplicity.

So 27 percent 27%, like a 2.7, and then we round it off to 3. So they are both approaches. We can do a rounding off or go with the decimal. I will prefer rounding off instead of going for the decimal because there is some sort of subjectivity and there may be some sort of noise in the data. We round up those set values. In this method, the occurrence value undergoes a complete change, and a new risk priority number is calculated each time. In the case of the permanent magnetic bearing, we made a decision to alter the structure instead of using a stainless steel structure, or to use a rubber material in between. Again, different results were obtained from this process. This process is fundamentally iterative in nature. So in this case, a new risk priority number will be decided based on whatever we have done, and then it will act as a decision support tool for maintenance recommendations, and then it can define a different maintenance strategy.

Now what is the maintenance strategy to allocate the different resources? How many people should be given for this kind of maintenance activity, and what is the priority of this maintenance activity? So these are the approaches that are really required, and then let us take what they did. Now they found two areas, area 1 and area 2. They discovered the left wing failures in this area, and then separated the left wing failure into two parts, known as failure mode A and failure mode B.

The RPN number for the failure mode is 64; the RPN number for the failure mode is 216. And the same thing area 2 in this case they use a left wing here, they use a tail in this case, and then in this case a failure C RPN number is around 140, and this failure mode is RPN number 504, and they have given this as a red mark. And what is the red in this situation now if this can be utilised in the if else comment or if then comment? This is an in if RPN is greater than the predefined threshold. Suppose they have kept the threshold of 400 and it has come to the 504, naturally the inspection will be done, and then whatever the resources should be allocated for this purpose. So this is what we can say. So in this situation we can say there is a failure of the D, which has been given the maximum emphasis on how to avoid this, or maybe if there is a number, how to bring down this number.

The focus here is on the tail portion of the analysis. Even though there are numbers associated with failures A and B, they are both below 504. The decision on when to take action depends on the maintenance team's threshold. In this case, they decided that 504 would be the maximum threshold for now, using it as an example to reduce this number over time.

The reason for this decision lies in the various damage mechanisms we've already discussed, such as environmental factors, including passing through clouds, temperature variations, and dust exposure. Another factor is the human element—specifically, the pilot using the system.

Thus, there are two major domains of variables in this case: environmental factors, which consist of many variables, and the human factor. The pilot's behavior—whether flying on the left or right side, at high or low speeds, or passing through clouds—also affects the system, depending on the type of control system in use.

So they utilise this kind of instruction. We look at the area A and area 2 they defined. They now say that after moving forward with the strategy, they have changed. Now here in this, after the necessary modification, they again recalculate, and they found the area A here, area 2 and area 3. So initially the tail portion was area 2, but they did the necessary actions. I am not discussing what they have done because these complete aerospace-related techniques will come.

They try to reduce the tail portion RPN, which was above 500, to 99.6. Again, I am mentioning here that they reduced it now because this is a less severe thing. Now what are the other severe things? The fault B becomes a severe fault, and the fault and the fault D becomes a severe fault. Here the red colour even in the fault C in the fault B and D and fault C also they have mentioned. Now there is a need to look at why this kind of problem is coming. We look at the form, and then in this failure mode A, they find a severity, which we do not have control over for time being failure B. There are three levels of severity: failure mode C, failure mode D, and failure mode E. Now, look at the detection failure mode. Detection is slightly more complex compared to failure mode B, that is, we need to look at what kind of sensors. Now this is for the left wing. Now coming to failure mode C, a force is the same, but failure mode D is a 6. Why there should be 6 here? It has already been 3; then I should make an appropriate arrangement and use appropriate sensors for that.

This point is crucial—don't rely solely on mathematics when analyzing failure modes. For instance, if the sensor is effective in detecting a particular failure mode, there's no reason to assign a high rating like 6 when a lower number, such as 3, would be more appropriate. This would unnecessarily inflate the values.

In another example, one failure has a probability of 94%, while another has a 42% probability. This variation could be due to different usage patterns by the individual operating the aircraft. In terms of probability ranking, a 94% chance was assigned a 9.4, but it could have been rounded down to 9. Similarly, a 67% probability was given a 6.7, which could have been rounded up to 7. Some adjustments are needed in these cases.

This approach is a fully data-driven Failure Mode and Effect Analysis (FMEA), which can be highly useful when developing maintenance strategies. It helps us minimize surface degradation, reduce environmental pollution, and lower costs. When applied with logic, this method can yield excellent results.

I hope this lecture has been helpful to you. Thank you for your attention.