Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 29
Failure Mode and Effect Analysis (FMEA)-2

Hello and welcome to the twenty-sixth lecture of the course on corrosion, environmental degradation, and surface engineering. In this lecture, we will continue our discussion on Failure Mode and Effect Analysis (FMEA). The previous lecture, Lecture 25, also covered FMEA, making this the second lecture in sequence on the topic. In the last session, we focused on how to apply FMEA to an established product, such as a journal bearing. Today, we will shift our focus to applying FMEA to a new product.

We will be naming this as a passive magnetic bearing and then some sort of failure modes of the passive magnetic bearing and how they affect the operation. This topic is relatively new because passive magnetic bearings have been utilised, but we do not have extensive literature available, particularly the failure mode. The majority of the literature focuses on the mathematical modelling of passive magnetic bearings and their subsequent stories. However, we understand that without understanding the failure modes, we cannot effectively address major problems. So, that is why we made magnetic bearings, and we try to diagnose whether a magnetic bearing is really working well or not.

The possible failures that were identified may have arisen due to factors such as lack of knowledge, insufficient fabrication facilities, or issues with assembly and manufacturing. These problems surfaced, and we aimed to highlight them. The content of this lecture is based on our own publication, which was released in 2016. The paper, titled "Failure Mode and Effect Analysis of Magnetic Bearings," was published in *Engineering Failure Analysis*. I'll be discussing it with an emphasis on keeping the lecture focused, not solely on the research, but presenting it as a case study for better understanding. The goal is to explain it in a simplified, easy-to-understand manner without delving into complex mathematical models or finite element analyses that are typically required for magnetic calculations.

In this case, we have conducted experiments to determine the severity of the failure modes and to develop methods for detecting them. So, these are the two important aspects to first figure out what the failure modes are, and then how to detect them. And then, based on those calculations, we figure out what the RPN number is, which is a major number or a major factor to understand the failure mode and effect analysis. We then suggest some corrections, keeping in mind that the FMEA process itself is an iterative procedure. We identify the problems, address those with a high Root Cause Number (RPN), and then repeat the modification process. After implementing the modifications, we must create a new box sheet for the failure mode analysis, make necessary corrections, and conduct another experiment to confirm the accuracy of our actions.

We have completed the task, implemented the correction, and conducted additional experiments to showcase the suggested remedy, regardless of its nature. Therefore, the decisions made have been implemented effectively. Now, in FMEA, a first step itself is to understand the product to review the product, study the product, and if the product is not existing, do some sort of experiment on that. First, do a mathematical model, then fabricate a unit, then perform an experiment, and then start FME on that as well. If you examine the figure in the context of passive magnetic bearings, it resembles a journal bearing.

I can relate this to a journal bearing, which typically consists of a shaft and a housing or bearing. In the case of a journal bearing, we refer to the shaft as the journal, while in a magnetic bearing, it is often called the rotor. Essentially, they serve the same purpose. In a permanent magnetic bearing (PMB), the rotor, shaft, or journal is suspended in air, creating separation from the sleeve or bearing. As a result, we experience nearly negligible friction, with any friction that occurs being due to air resistance. There is no contact between the two surfaces, as we assume a strong repulsive force exists between the magnetic surfaces. These magnetic surfaces usually involve mounting a magnetic ring or element on the shaft itself. The part within the bearing, known as the journal or rotor, and the housing will contain a permanent magnet.

In the case of a permanent magnet versus a permanent magnet, we aim to maintain a repulsion force that creates a separation between the two surfaces. Separating the two surfaces prevents mechanical contact, which in turn prevents any wear. In this scenario, if we maintain the separation and use air as the fluid separation medium, there is no need for additional liquid or solid lubricant from the outside. So, that is the advantage—no need of the lubrication, zero wear, almost negligible friction—because air density or air viscosity is very low and the resistance against the shaft rotation will be very low, unless the RPM is very high, like 1 lakh RPM or something like that. As a result, the question of friction will be almost negligible.

Another point to note is that, in recent times, neodymium iron boron magnets have become readily available at a reasonable price. For example, you can purchase a significant number of magnets for around 10,000 rupees, making them quite affordable. These magnets are easy to obtain—simply order them, and they'll be delivered. The advantages of these magnets include nearly zero friction, zero wear, no need for lubrication, and the availability of high-strength neodymium iron boron magnets at low cost. Due to these benefits, permanent magnetic bearings (PMBs) are now being used in various applications, such as flywheels, artificial hearts, and molecular pumps. The question arises regarding how they are applied and controlled, as most available documentation does not provide complete information on this.

There is some information available, but it is often incomplete. If you attempt to purchase the technology for magnetic bearings from the market, it can be very expensive buying the complete product is usually more affordable. Therefore, it's important to develop the technology in-house when considering magnetic bearings. One of the immediate challenges that comes to mind involves the neodymium iron boron magnets. As the size of the magnet increases, the magnetic field becomes less regular. For instance, if you have a permanent magnet shaped like a half-sector, covering 180 degrees, it is likely that the magnetic field will not be uniform across the entire surface.

So, there will be some sort of nonuniformity, and we need to model those things. In this case, the unevenness of the magnetic field presents a problem, and this unevenness will continue to worsen over time. Therefore, the permanent magnet undergoes a process of demagnetization. This is a like common process, and then the demagnetisation may happen after 1 year, 2 years, or 3 years, and there are a number of modes of the demagnetisation itself. Another thing is that if the little bit of variation we can model appropriately, or maybe you know we can take some factors, and then we can implement design in such a manner that up to 5 percent (5%) change in magnetic field of density over a surface will not really give it more problems.

But if it is exceeding 10 percent (10%) variation, actually there will be some sort of unwanted vibration in the system, and then because of the unwanted vibration in the system, it will create an unbalance or imbalance. Now, if there is an unbalance or imbalance, we utilize active magnetic bearings, which are primarily designed to control the shaft position to the desired level. Therefore, once a permanent magnet bearing is designed, it cannot be altered, whereas an active magnetic bearing allows for this flexibility. So, we also have one publication on active magnetic bearings, specifically fault diagnosis systems. I am not going to describe that about electronic systems, but I am just mentioning whenever there is more sophistication required, we add an active magnetic bearing with a permanent magnetic bearing. To achieve an optimal solution, I am focusing specifically on permanent magnetic bearings. Due to variations in the magnetic field, there is a risk of unsteady rotor motion, which can lead to vibration problems. If the rotor makes contact with the stator, it can damage the system. Since permanent magnets are fragile, such contact could cause them to break, leading to a complete system failure. While permanent magnetic bearings offer many advantages, they also carry significant risks. This is why calculating the Risk Priority Number (RPN) is crucial, so that appropriate corrective measures can be taken. As mentioned earlier, this topic was covered in a paper published in 2016, which I am using as a case study. Figures 1, 2, and 3 in the paper illustrate different configurations that were examined.

If you look at the case of the rotor or maybe the shaft or the journal on which is mounted on the shaft itself, we are using some sort of permanent magnet. In this case there are 6 magnets; in this case there are 4 magnets; in this case there are 3 magnets. We use this type of magnet when the magnets are attached to the shaft, whereas in Figure 1, the stator, we utilize a 360-degree arc, indicating a full circular or cylindrical magnet. In configuration 2, we utilize a 180-degree angle, whereas in the final configuration, we only employ a 90-degree angle. So, there is a variation; we want to see what the shape factor effect will be, or maybe a full circle, a cylindrical, half cylinder, or maybe the one-quarter cylinder. What impact will this shape have on the behavior of a permanent magnetic bearing? So, this is what we have done: pressure magnets can be arranged in a variety of ways to form the permanent magnetic bearing.

We tried 3 layouts, which have been shown in figures 1, 2, and 3, and then showed that figure 1 is a configuration 1, figure 2 is a configuration 2, and figure 3 is a configuration 3. What is the configuration shown in Figure 1? It utilizes a 50 mm full-ring stator magnet and a 360 degree full-ring, as previously mentioned. Of course, it is, and then the rotor is also utilised as a full ring, and then this is a 48 mm OD, and then we use the 8 mm thickness magnet and the 6 magnet to make it a 48 mm length as such. Now, for configuration 2, we use the half-ring a 180-degree stator magnet, and then we use the four magnets in this case. Hence, the sum of 8 plus 8 plus 8 plus 8 equals 32.

So, in this case, length is 32, but we kept stator length as 30 mm. Coming to the third one, we use only the 90-degree sector at the bottom, and now to bring more stability, we use a 45-degree arc on the top also. Well, in this case, we kept the stator length at 24 mm, which is 8 mm, 8 mm, and 8 mm. Therefore, the sum of 8 + 8 + 8 equals 24 mm. This corresponds to the rotor length of 24 mm, which has been mentioned previously.

We have implemented these three segments. What are the advantages and disadvantages of the three configurations? Configuration 1 is rigid; stiffness will be very high in this situation, but load-carrying capacity will be very low. So, we can do a detailed mathematical model, but for the time being, I am not going in those modelling cases, and I say this has a higher stiffness but a low load-carrying capacity, and then configuration 2 has a high load-carrying capacity because the 180-degree arc and then weight are in a downward direction, and immediately repulsion will occur. If the angle is 60 degrees, repulsion will also emanate from the top. The load-carrying capacity will decrease, but in this scenario, the load-carrying capacity will grow, and there won't be any resistance from the top.

So, top stiffness will be removed, or maybe say almost 0, and it will hit on the outer surface. That is why we wanted to know what the different configurations are and then how we study stiffness and the load-carrying capacity based on these configurations. Thus, configuration 2 has a high load-carrying capacity but low load stiffness. Configuration 3 has a modern stiffness and moderate load-carrying capacity compared to Configuration 1. In this configuration, we have achieved a very high load carrying capacity, almost negligible stiffness, moderate load carrying capacity, and relatively moderate stiffness, followed by a low load carrying capacity and high stiffness. So, these are the 3 configurations we kept.

Additionally, we have constructed our experimental setup for conducting experiments, and as you can see, the disc has been mounted. Now, because there are a number of holes in this disc. If the disc has multiple holes, I can insert any number of bolts into it. Perhaps you've already conducted this type of experiment in the lab. This type of setup can be used to create unbalance or eccentric loading in the rotor system. And then an aluminium housing or a stainless housing can be utilised, and this we have made on a T channel. So, in a T channel, basically, housing will be mounted rigidly.

Using a drill hole for mounting could potentially reduce the rigidity of the housing. In this scenario, we aim to secure the housing firmly on a base plate, resulting in a bifurcated housing that connects its upper half as required. Now, we also did an experiment in the hybrid mode, but presently, in this case study, we are considering only permanent magnets. In a hybrid mode, we have not yet started working on the liquid lubricant. So, in this case, we also worked on the liquid lubricant to help reduce the vibration and increase the performance.

What can be said with certainty about this experiment? We designed and built this experiment setup to accommodate the three magnetic bearing configurations mentioned earlier. A set of magnets were attached to the aluminium housing; in this case we have used aluminium; it can be stainless steel; also, aluminum is a better option. It should be securely fixed on the T channels that have been done, which are on the base plate, and the rotor magnets were mounted in stainless steel. What will happen if I use a ferromagnetic material? Dissemination of the magnetic field will occur. So, we want to retain the permanent magnet strength only on a short span, maybe only in the rotor side, or possibly the rotor, which is mounted on a shaft, which is a stainless-steel shaft, and this has been used with a stainless steel shaft, as shown here.

Now, how has the overall configuration been? One end of the shaft is free, and another one is coupled with an induction motor. And then you are able to see there is a motor here and there is a coupling, which will maybe be in another diagram. I will show more clearly that there is a spiral coupling on that. We use an ABB frequency drive to change the rotational speed to figure out what will be the impact of the rotational speed and visually what problem comes when we are running this permanent magnet magnetic bearing on a some C-D speed, and then we do not find many problems. But costing up and costing down that means increasing speed to a certain level and then finally shutting down to decreasing that time we find a lot of instability in a magnetic bearing, and that is what we wanted to study: what will be the performance under the transient condition. And we find that permanent magnet bearing will not be a very good option in a transient condition, and it may require some sort of additional support, either hydrodynamic action or maybe active magnetic bearing action; those things are really required.

Now, in this table we have given all the details. You can see the rotor magnet axial length has been shown in configuration 1, 48, configuration 2, 32, and configuration 3, 24. In all three cases, we maintained the OD at 48 mm due to the rotors' identical dimensions, and we mounted the ID on the shaft in this particular instance. So, the ID of the shaft has been maintained as 5 mm. So, most of the rotors in the magnet have been mounted on a 5 mm shaft. Coming to the standard magnet, we change the length in one case slightly, the bigger or maybe the longer compared to the rotor magnet, the other case slightly shorter, and the third case slightly weaker.

Now, this can be we can do this permutation combination and come up with a right figure or right equation or we can use a PCA on this, but for the present case only we are just concentrating only on FMEA, and we do not want to go ahead with any other topic. Now, this has been shown, and then, in this case, rotor weight has been mentioned. Clearly, rotor weight has been kept various things because it depends on the magnet length. And in this case a maximum length of the rotor than the for the 600 grammes, while 32 in this case around 400 grammes in the 24 mm length there is a lesser something like that. These are the loads that have been presented. Now, in various configurations, we applied the load in a different manner.

We chose to apply the maximum load in configuration 2 because its load-carrying capacity is significantly higher. Using a configuration with a lower load capacity would not be suitable, as under low applied loads, the rotor could potentially collide with the outer housing, causing major issues. Passive magnetic bearings should be designed according to specific load requirements, whether it’s based on the applied load, maximum load capacity, rotational speed, or tangential speed, depending on the operating conditions. The first step in the process was to thoroughly study the product to understand these requirements.

I have provided a brief overview of the permanent magnet, detailing its manufacturing process, assembly method, and dimensions. The second step involves identifying the components that are susceptible to failure and determining which component is most likely to fail. Firstly, the mounting of the rotor magnet on a stainless steel shaft increases the likelihood of failure. The second factor is the stator magnet, which is also susceptible to failure. Once the stator magnet is in use, the casing may also fail, or the fixed casing may also fail. Finally, the entire stator magnetic bearing assembly is connected to a motor through a coupling.

So, there is a possibility of coupling failure. We identified failures in the stator magnet, the casing, and the couplings. So, these are the possible things. Now, let us start with the rotor failures. There may be a number of other failures, but in our case, we found 5 types of failures. Specifically, we conducted experiments to identify the failures.

Now, those failures are what category, as I mentioned in the previous lecture, that we need to categorize. Now, in this case, wear is one category, cracking is another category, and demagnetisation is a third category. The new thing that I have understood is new pole development. The whole technology of new pole development has been utilised in magnetic particles; that is what we have studied in the non-destructive testing on magnetic particles.

Whenever there is some sort of crack or subsurface crack, a number of poles will get formed, and because of that, wherever there is a crack inside a surface or over the surface, suddenly the magnetic field will increase significantly. The change in a magnetic field, or instead of one north and one south pole, there will be many south poles and many north poles, and that is what really is worrisome, particularly in a permanent magnetic bearing. The last one is a fracture. So, 5 categories: one is a wear category, cracking category, demagnetisation, new pole development, and fracture.

When we consider rotor wear, we typically use permanent magnetic bearings with the assumption that there will be no wear. However, in this case, we found rotor wear, indicating that something has gone wrong—whether it’s due to insufficient knowledge, a manufacturing error, or an assembly mistake. This is what we’re trying to uncover. We observed that the coating on the rotor magnets, which is applied to the surface of the permanent magnets, tends to strip off under operating conditions. Initially, the magnets have a shiny appearance, but after use, due to wear, large patches of the coating are worn away. This same wear is evident in configuration 2, where we can clearly see the worn-out surface.

Even if permanent magnets are not properly designed, they can lead to rotor wear, as seen in this case. Additionally, the second major issue we encountered is cracking. We observed cracks in the surface of the permanent magnet, as shown in configuration 1 and configuration 3. Since permanent magnets are known to be brittle, even a small impact can cause cracks or, in some cases, split the magnet into halves or more. These findings are clearly highlighted in the study. Regarding rotor wear, we found that each configuration exhibited significant wear, as shown in the corresponding figures. Moreover, we also observed a notable increase in temperature, which further contributed to the wear.

If otherwise in permanent magnet bearing, there should not be any temperature rise, but there is a mechanical contact between two surfaces, and there is rubbing and scrapping of the coating so that there is more friction. So, there is more friction and a higher temperature. So, permanent magnet bearing, which was thought to give a very good solution with low wear negligible friction and no almost 0 temperature rise, all bad things happened to this system. Now, coming to the crack, as I said, this is what we've realized: this happens because of unsteady rotor motion. That means whatever we want, the shaft should rotate concentrically at the bearing centre; it was not happening.

The motion of the shaft appears to be random, a phenomenon known as unsteady rotor motion, which is further complicated by the lack of sufficient stiffness in the unsteady motion. So, there was an infrequent collision, or maybe the occasional collision between a stator also happened, and because of this collision between two permanent magnets, the cracks started. It has been mentioned that this leads to the cracking of rotor magnets, a phenomenon that was observed during periods of coasting up and coasting down. That means that when you start the motor and it starts rotating from 0 to 1500 rpm, there is a possibility that the rotor will go and knock 2, 3 times stratum. The same thing happens when you run the motor at 1500 rpm for a certain amount of time, such as 3 or 5 hours, and then decide to shut it down. However, once it reaches 0 rpm, it may continue to spin, indicating a problem.

In this situation, whenever the coasting up and coasting down phases occur, we should consider using an alternative support system as a possible solution. This is one of the key takeaways from conducting these types of experiments.

Next, we looked into demagnetization. We learned that when using permanent magnet bearings, if there is a difference in magnetic strength between the rotor magnet and the stator magnet, the stronger magnet will demagnetize the weaker one.

In our case, we used a stator magnet with a magnetic strength of 1.4 Tesla and a rotor magnet with a strength of 1.04 Tesla. As a result, the rotor experienced demagnetization. However, the stator magnet remained unaffected. This happens due to the difference in magnetic strength between the two magnets.

From this, we learned that the magnetic strengths of the materials should ideally be the same. Initially, we struggled to find stators and rotors with matching magnetic strengths, which is why we later adopted a different configuration. We'll discuss those adjustments in 4-5 slides.

To summarize, the rotor demagnetized because its magnetic strength was lower than that of the stator magnet.

However, if we keep the same magnetic strength for the boats, at least this kind of demagnetisation will not occur. However, there is a possibility that if there is a mechanical contact between the two permanent magnets, again it will cause demagnetization. A demagnetization could occur if a mechanical action hits and knocks, as demonstrated here. We can say that in this case, figure 3a, we are able to see there is an offset. That means, shaft other than the shaft as rotor, and if the rotor is in the permanent magnet stator, there will be some sort of shifting; it will not be self-centring of the permanent magnet bearing.

Permanent magnetic bearings are known for their self-centering properties. However, in configuration 1, we did not observe self-centering, and there seems to be some demagnetization occurring.

When we examined the unused rotor’s magnetic strength, we found consistent data regarding the magnetic strength. However, when we looked at the used rotor, we noticed that although one side retained similar magnetic strength, demagnetization had occurred in several areas. This suggests that the rotor surface may have come into contact with the housing or the stator at some point.

There is a change in the magnetic field, as shown in Figure 3.5 and 3.3b, which depicts the variation in the magnetic field along the circumference before and after the experiment. Before the experiment, we observed minimal variation across the surface. The stator magnet initially had a higher magnetic field strength of 1.4 Tesla, while the rotor magnet had 1.04 Tesla. However, after the experiment, the rotor’s magnetic strength was further reduced.

This imbalance caused by the rotor magnets is due to the non-uniformity of the permanent magnet, leading to eccentric motion of the shaft and generating disturbing forces within the permanent magnetic bearing. This is another issue with permanent magnetic bearings.

Additionally, we observed pole formation. For this, you can use a pole finder sheet, which is readily available in the market.

If there is a uniform magnetic field with a single north pole and a single south pole, there won't be any significant issues. You would mainly see a consistent black color on the surface. However, if you notice fluorescent lines, it indicates changes in the magnetic field. This can happen when permanent magnets are axially attached.

In this case, we observed the generation of multiple north and south poles, which could be due to surface rubbing or the presence of cracks. The continual rubbing of the rotor against the stator can generate new poles on the rotor's surface. This is a key principle behind magnetic particle non-destructive testing: if additional poles are formed, magnetic particles will accumulate in those areas, where the density of the magnetic field suddenly increases.

We refer to this as pole formation. With continued rotor-stator rubbing, more poles are created on the rotor. It’s not just a single pole, but potentially several, as we’ll show in subsequent slides. We used a pole finder sheet, which is readily available in the market, to identify the formation of these new poles. The figure demonstrates how the pole finder sheet was applied to the rotor for this purpose.

Finally, we encountered a more severe issue—fracture. There were cracks forming in different directions, which eventually merged, causing a large portion of the magnet (up to 120 degrees) to rupture and break into 2 or 3 pieces. This type of fracture is a drastic failure.

While permanent magnetic bearings were expected to perform well, offering negligible friction, zero wear, and an ideal bearing solution, they failed catastrophically. In this case, the rotor magnet fractured as a result of a strong collision between the rotor and stator magnets. This led to significant damage. At this point, it became crucial to consider FM (Failure Modes) to identify the appropriate solutions moving forward.

Now, the next one is a stator second component, and we also found a similar kind of it because there is also a permanent magnet and relative speed, and some sort of loading more or less. The failures are also more common in the wear category, cracking category, demagnetisation category, new pole formation category, and fracture category kept in the same way. We study each of the five categories for the rotor separately. Now, in one slide, I am trying to show all those you can see here: some sort of crack in a stator world; there is some sort of crack in the axial direction; in this configuration 3, you can see the number of cracks. Now, these are the configurations that we have been shown. Now, interestingly, the demagnetisation happens even after cracks. So, there is a crack formation, and demagnetisation will happen, and interestingly, you can see here there is a crack that is passing like this.

Now, the magnetic field is around 760 gauss, and maybe 660, then 550, and the minimum is 250. So, if there is a huge variation in a magnetic field, it will create a lot of disturbance, and then the rotor will really vibrate a lot. This is what has been demonstrated above. Now, this is the demagnetisation coming to the new pole formation. You can see if the new magnet there is no green colour visible as such, which means the permanent magnet that is there does not have many poles in this area. Now, however, if you install this permanent and then the pole sheet in a particularly damaged magnet, you can see there are so many green color lines.

So, the green colour is visible; there are many green colour lines in this case, which means there are some poles. Not only this, but we are able to find many green colours in this also. Even in this case also the figure 1 or maybe the configuration 1, we are able to find out the green color. So, there are a number of rubbing marks and crack marks, and we are able to see those things, and finally, comes a fracture. If there is a deep crack in this case, if you try to remove the whole piece, it comes out, and then we found the top view in this manner. So, there is a that has been shown in the side view, or maybe the front view in this case, and this is the top view, and then we can remove this complete piece, that is, the magnet has been fractured in the two pieces.

So, this is a motion relative to the stator. Now, coming to the third part that is housing, even in housing we found particularly for configuration 2 because we use only 180 degree arc at the bottom in top was without any arc and we observe that rotor has the rubbed against a housing also. So, that is why the contact region has been shown, and the last one is a spiral coupling; the spiral coupling also has failed, which means there is some sort of unbalance in a rotor, and then there is more compression, extension, compression, tension, and because of that, there is a fracture of this spiral coupling. So, as a result, that is the bad failure. So, what we call housing failure modes: rubbing of the stratum at the top of the casing occurs in a permanent magnetic bearing, the reason being only half of the sector magnet, which was kept purposefully to increase the load-carrying capacity, but it has failed, the reason being there was no stiffness to resist the motion of the rotor. However, because the top side PMB has no rigidity, the rotor scraps against the top housing during the rotation, resulting in case wear or maybe the wear of the casing, and that has been shown for configuration 2.

The failure occurred in the spiral coupling, which connects the shaft holding the PMB rotor to the motor. When the rotor rubs against the stator, the frictional force increases significantly. This results in higher torque, forcing the motor to compensate. In such situations, the spiral coupling fails due to the increased torsional load, eventually fracturing into two pieces, as shown.

In step 4, we assess the severity, occurrence, and detection rankings. In a previous case study, we used a ranking scale of 1 to 10. However, since this is a relatively new component and system, we opted for a 1 to 5 scale, which is more appropriate when dealing with new systems with limited knowledge.

If we gain more knowledge, we may use a 1 to 10 scale, and with extensive data, we might use a 1 to 100 scale. In this case, 1 represents the lowest score and 5 the highest, with lower scores being preferable. The ranking is based on existing knowledge, expert opinions, and in this case, a combination of modeling and experimental data to derive the values.

And based on the expert opinion, we could not figure out who is the expert in this area nearby. So, we did not; we could not get an expert opinion in this case, but existing knowledge, which is available in literature, we used, and then we did some testing on that. Now, how do I determine the severity? In this case, we do theoretical modeling, followed by experimental studies to determine the severity of the failure and rank it accordingly. For that purpose, what we did was then have some software available; those softwares were also utilised to get more and more knowledge. So, for the formation of the surface crack on a magnet, we use the pole sheet to determine that there are not many north poles and many south poles.

So, from the from the formation of the surface crack on a magnet, we figure out that it will alter the characteristics of the magnetic field, and then it causes the failure of the permanent magnet. We say that this is the progressive failure condition leading to the catastrophic failure or catastrophic fracture, and then we use a finite element method. I am not going into those details, but I will just show the results of a magnet with a crack. Now, what has been done? We can see here the version magnet, a new magnet with no crack at all, and then if we make a crack through and through across the length, and then maybe give a 3, 4, or 5 version with no crack, one fourth thickness crack, one half crack, or maybe say three fourth crack, some kind of study that can be done. So, a magnet with a crack but having a different dimension—those things were simulated. So, what we did in this case, as I mentioned the version magnet, was we took a 180-degree arc second magnet ID was given as per the requirement OD was given, thickness was given, and the thickness in this case is a ligand length was utilised.

Here, we present a solid representation using Pro/Engineer software to model the system. As I mentioned earlier during the FMEA process, it's important to have detailed drawings or 3D models to better utilize FMEA. In this case, we created a 3D model, highlighting various types of cracks on the magnet.

The model was created using Pro/E software, and for magnetic field analysis, we used Maxwell and Soft14, specialized software for this purpose. These tools were employed to analyze the magnetic field and provide the results. A key feature we utilized in this analysis was the adaptive meshing feature.

Adaptive meshing allows us to begin with an initial set of elements—such as tetrahedral elements—starting with a base number, like 10,000 or 15,000. In this case, we initially used around 42,000 elements. The adaptive meshing feature automatically increases the number of elements after each pass, optimizing the analysis as needed.

Finally, it comes with some sort of convergence criteria in this case, particularly related to energy, that the continuous calculation of energy and energy error should be minimum as per the requirement of the software of what was mentioned here. These criteria were provided here, and as you can see, the number of elements increased from 42,000 to 1 and 158,000. This represents an almost 4-fold increase in the number of elements needed to analyze a permanent magnet crack and its various forms in this case. So, what we consider the 5 cases of the crack: one is the magnet without any crack at all, and one is one-fourth of the magnet thickness. So, one-fourth of the magnet thickness, then one-half of the thickness, then three-fourth, and then through and through the crack will there be significant variation if there is a crack happening in this manner. Now, I've presented the results, and perhaps I can explain them in this way: if a south pole is present on one end of the surface, and a north pole is present on the other end, then the results should be represented accordingly.

So, there is a continuous flow of the north-south pole, and there is a definite structure. If there is a crack, there will be a south pole and a new north pole coming, and this is a major problem. There was a repulsion that was supposed to be the surface should be repelled, and suddenly the pole changes. So, repulsion will become attraction, and because of this attraction, wear is bound to happen. So, surfaces that are supposed to repel do not attract at all, and because of the new crack formation, there is a change in a magnetic field, changing from the south pole to the north pole, and we find that there is a major issue. So, if there is any crack in a permanent magnet, results will be very bad, and that is why we need to avoid those kinds of cracks.

For each type of crack, we observed that the magnetic field, specifically the sinusoidal magnetic field, changes near the inner surface of the magnet. This is highlighted here. As cracks begin to form, even at the surface, the magnetic field undergoes significant changes, with an increase in field strength observed. At the edges, the magnetic field is weaker, but near the crack initiation, there is a sudden and substantial increase in magnetic field strength. This was a key finding from the analysis—the sudden spike in the magnetic field near the crack.

This change is shown graphically here. As I mentioned before, we can digitize the graphs to conduct a more detailed analysis. In this case, you can see that without any cracks, there is no variation in the magnetic field, as represented by the violet line, which shows no change in the field when no cracks are present.

In the case of a 25% crack, as shown by the blue line, you can observe a sudden drop where the magnetic field shifts from positive to negative. Similarly, with 50%, 75%, and 100% cracks, there is a noticeable change in the magnetic field. This indicates that even the initiation of a crack is enough to alter the magnetic field, and as the crack progresses, repeated impacts (or 'knocking') will occur.

We found that as the crack grows from one-quarter of its length to a full-through crack, the variation in the magnetic field and the load-carrying capacity changes by approximately 17%. While the 17% variation in the field may not seem too concerning, the key takeaway is that the very initiation of a crack is a critical issue for the performance of the permanent magnetic bearing.

Now if we say that to evaluate the performance of PMB permanent magnetic bearings, then what did we do? We did a sensor analysis to figure out what is really happening, and details of this will be given in the next lecture when we will be discussing the maintenance aspects. Therefore, this is somewhat related to maintenance. Therefore, we utilize two proximity sensors to determine the rotor's position in relation to the housing. This allows us to determine if the rotor is positioned concentrically in the correct manner or if it is repeatedly hitting the stator. That's why we utilize two proximity sensors, which typically provide information about the motion of the rotor or shaft in both the x and y directions. We purchased a DAQ system from National Instruments, then plotted the results using a Lab View interface. In this case, we initially consider seven different configuration scenarios.

We considered seven different scenarios for the experimental work: a PMB without any defects, a PMB with a wear mark, a stator with a wear mark, a rotor with a crack, a stator with a crack, demagnetization of the rotor, and demagnetization of the stator. For each scenario, we mounted two proximity sensors to capture data, following a data-driven approach. This approach provides valuable insights for maintenance.

In the case of the PMB without defects, we observed excellent rotor behavior. The rotor remained perfectly concentric, represented by this dot, and ran smoothly for hours without any issues. Even when mechanical wear occurred, the rotor continued to function well, with only a slight increase in dimension, but no major concerns. The same was true for both rotor and stator wear.

So, rotor wear and stator wear are not really causing major issues in this case. However, rotor wear and stator wear will change the magnetic field because we have found a number of north poles and south poles also. So, that is going to have a real impact on it. However, this type of behavior was not observed in proximity sensors. Coming to the cracked rotor, you can see the chaos. The really rotor goes hits again and again, housing even though there is a gap of 1 mm, like in an overall diameter clearance of 2 mm, it hits again and again and damages the whole surface in a very short span of time.

When it comes to the cracked stator, it's not that sensitive. A cracked rotor poses a significant problem, whereas a cracked stator does not pose such a significant issue. So, this data, of course, in this case you can see this is slightly bigger than others; may be it will take a very long time to come to this kind of failure; it will take many hours to come into this kind of failure, but otherwise there is not a problem as such. The demagnetization of the stator or rotor is the next step. Now, in this case, particularly the demagnetisation stator and rotor, we find kind of an orbit on the rotor, and slowly it is progressing right. So, you know, if the seven factors—we say that a cracked rotor has a very high importance—it should be addressed immediately, then demagnetisation is next.

This indicates that the demagnetization occurs due to the stator's 1.4 Tesla magnetization and the rotor's 1.04 Tesla. So, the magnetisation strength of both the rotor and stator must be the same. However, we were not getting permanent magnets of the same strength as the rotor and the stator because the stator is hollow and the rotor is kind of having very good thickness.

We had a different configuration of the rotor and stator when the stator was used, which is why we were not achieving the same strength. Although we desired the same strength, we were unable to achieve it. However, in this case, even the wear of the surfaces, even the removal of the coating to some extent, was not really affecting much. So, the major issue was the was the cracked rotor, the formation of the rotor, and then again the demagnetisation.

These issues are significant and warrant careful consideration. Moving back to the FMEA, we need to assign CVOT rankings to each defect. The CVOT ranking system measures the severity of effects, where 1 indicates no effect at all and 5 signifies a serious effect. Since this is a relatively new product, we are using a 1 to 5 ranking scale instead of the 1 to 10 scale mentioned in previous lectures.

We also need to assess how frequently these defects occur. Based on the 12 to 15 experiments we conducted, we're reporting our findings, but it's clear that a larger data set and more extensive testing are necessary to gain a comprehensive understanding.

We observed a higher frequency of wear, with a higher likelihood of coupling failure. However, we only observed a single failure, and the formation of poles, primarily due to rotor cracks or shorter cracks, was significantly reduced. Now, we observed rubbing on the casing only in one case, specifically when configuration 2 was used, and we also observed a higher incidence of demagnetization. Cracking, crack generation, heating, and stability were also more likely to occur in this case, particularly in stator and rotor capos. When it comes to detecting this type of failure, we find that no single failure truly receives a score of 4 or 5, as the failure of the coupling can be easily observed, and the fracture of the rotor or pole formation can be easily identified due to the availability of a sheet that we could use immediately for analysis. Now, and then coming to demagnetisation, a Gauss meter cannot be used and was slightly difficult for us, and even the two found the wear of it because we did not have any lubricant to be analysed.

Now, we were having little difficulty compared to the liquid-lubricated bearing in finding out the wear of the particles in this situation. These are the rankings, and the overall RPN number, a risk priority number, is calculated by multiplying these three severity occurrences and detections. We can observe that the overall failure encompasses the housing, rotor, stator, and coupling, while the overall RPN number appears here. In ranking the defects, crack formation is assigned a high priority with a score of 4 for severity, 4 for occurrence, and 2 for detectability, totaling 32 ($4 \times 4 \times 2$). The second-highest rank also relates to crack formation, but in the stator. Although crack formation in the stator alone has a lesser impact, when combined with demagnetization, it significantly affects performance. Stator pole formation is ranked third, while the demagnetization of both the rotor and stator is ranked fourth.

Given these top four issues, we need to address them systematically. We might choose to tackle one or two issues initially before moving on to the next solutions. This approach summarizes our overall FMEA strategy.

Next, we focus on methods to reduce the failure rate of permanent magnetic bearings. One key factor is that increased magnetic strength and brittleness heighten the likelihood of crack formation, which, as mentioned, plays a major role. To prevent cracks, one potential solution is to use finer particles in the material. By employing fine particles or creating a fine-grain structure, we can improve the material’s performance and reduce the progression of cracks. This approach has been applied in our case to enhance the durability of the bearings.

We say the merging of small magnets to create a whole ring magnet, then maybe purchase a small small magnet. So, we can get equal field for the rotor and equal field for the stator, and there is no difference in a permanent magnetic in the strength. So, we are able to maintain the same magnetic strength, and then we have a larger number of segments. So, cracks are already there, and there will not be a chance to further increase in the crack. So, those things were utilised for this purpose, and then we got this later work. You can observe that we bought these inexpensive square magnets, embedded them in a rubber housing, and then stored the housings in a permanent setup. Now when we did it so, what we say is that to prevent a rotor and a stator from colliding with each other, rubber is used to isolate magnets and absorb the vibration. Now if the rotor moves near the stator and because there is rubber available on the back side. So, it can really isolate or move a little bit backside, and the foil bearing works. So, you see, this whole concept was worked for was taken from a foil-bearing point of view.

They have a little less stiffness in the rubber. So, it will go back easily, and the permanent magnet can have a slight room for displacement. So, this was done; however, after getting this setup again, the experiments were conducted. We conducted experiments using the proposed PMB structure. Now, what's the problem here? Currently, the rotor and stator are not colliding as much.

What happened? The next problem arose because of the rubber material. So, the shear strength of the rubber material is very bad, and then this had another piercing effect, which means that permanent magnets start piercing into the shape itself. The cracks were developed in a rubber material, and then, because once a rubber is getting cracked, it will not have that kind of flexibility. So, again, the major problems will come. So, for this purpose, then we see instead of going for alone rubber, we should have an aluminium housing with a rubber material and a permanent magnet, and the new structure was made, and then finally, a patent was filed on this, and we got good results.

To achieve consistent magnetic field performance on the stator and permanent magnet, it's essential to prevent demagnetization and ensure there is sufficient space to absorb vibrations or shocks from external surfaces. This setup allows for a certain degree of coasting up and coasting down behavior.

In steady-state conditions, permanent magnetic bearings perform well. They are an excellent solution for continuous 24/7 operation. However, if there are frequent changes in speed—such as transitions from 0 to 1500 RPM or 0 to 3000 RPM—the coasting periods can introduce significant variations. These variations can lead to increased vibrations and a higher risk of collisions between the rotor and stator.

However, if there is some sort of shock observer isolator, then that behaviour can be reduced significantly. So, we are trying to bring some sort of damping from the outside environment, and then there was a change because we were not getting the same strength magnets. If we get the same strength magnet stator and rotor, then we do not have to go with the square magnets; we can directly use them, but if we do not get them, then how do we really come up with a solution that has been shown in this overall. In conclusion, the findings led to the filing of a patent. Now coming to the summary, I covered this case study reason being the new products can be developed when we have a failure mode and effect analysis and more and more creative ideas will come. We often assume there is only one problem, but we try to solve that problem, which may cause two problems. And again, we try to solve those two problems, and four problems may emerge, but sequentially, if we try to address all those, we will get a good solution; that is the theory of the failure mode and effect analysis.

To summarize this lecture, we conducted a Failure Mode and Effect Analysis (FMEA) on permanent magnetic bearings. Through our analysis, we identified approximately 13 potential failure modes for these bearings. We calculated the Risk Priority Number (RPN) for each failure mode to determine their significance.

The most critical failure identified was a decrease in the magnetic field. This issue arises when there is a discrepancy between the magnetic fields of the rotor and stator. Bridging this gap can lead to effective solutions, which is why we employed square magnets made of rubber and aluminum materials to address this problem.

Another significant issue was the non-uniformity of the magnetic field. By using smaller square magnets, we were able to reduce this non-uniformity effectively.

Now whatever the non-uniformity, it is already known to us and is not going to change significantly. Therefore, we are able to model it and optimize it effectively. Another we found new formation of the poles, whereas, rubbing, and now because of the new configuration, there is no worry about the new formation of the poles. The last one is a fracture of the magnet; we use a square magnet. So, already, it has been fractured, and no further expansion of the crack will be possible, and there is sufficient damping for the coasting and coasting down.

Regardless of the major issues, we are actively working to resolve them. Now, in this case, the last one is a rubber isolator in an aluminium framework that could be used to prevent a magnet from combining or becoming damaged. So, these are two sequential case studies; the methods were used in affair mode, and the final mode and effect analysis were used for this purpose to give us a good solution. I hope this will be useful to you, and then you can implement it on some of your projects and then get a good result. Thank you for your attention, and we will cover the maintenance aspect in the next lecture. Thank you.