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Change to Component Health Monitoring for Massive Equipment Reliability Improvement

Abstract

Change to Component Health Monitoring for Massive Equipment Reliability Improvement. Many condition monitoring (CM) techniques require that your machines and equipment reach a near failed state before they detect the symptoms of failure. This guarantees that you will have many machines in your operation always near-to-failure. Outstanding reliability instead requires you to create the conditions of long-lasting machinery health and to ensure those conditions are always present. As a consequence of having a machine health improvement focus you proactively cause equipment wellness in your operation and thereby create huge reliability growth.

Keywords: machine health monitoring, condition monitoring, failure elimination

When condition monitoring is used wrongly it is sure that your machines will fail. CM techniques look for evidence of a problem and by the time they detect the symptoms your equipment and machines are already in trouble. Because you use CM to identify danger you permit your machines to degrade to the point where they must be fixed. CM makes you wait for failure and so your machines always need rectification and repair. If you use CM only for warning before you act to address the problem then you easily and quickly become a failure-driven organisation.

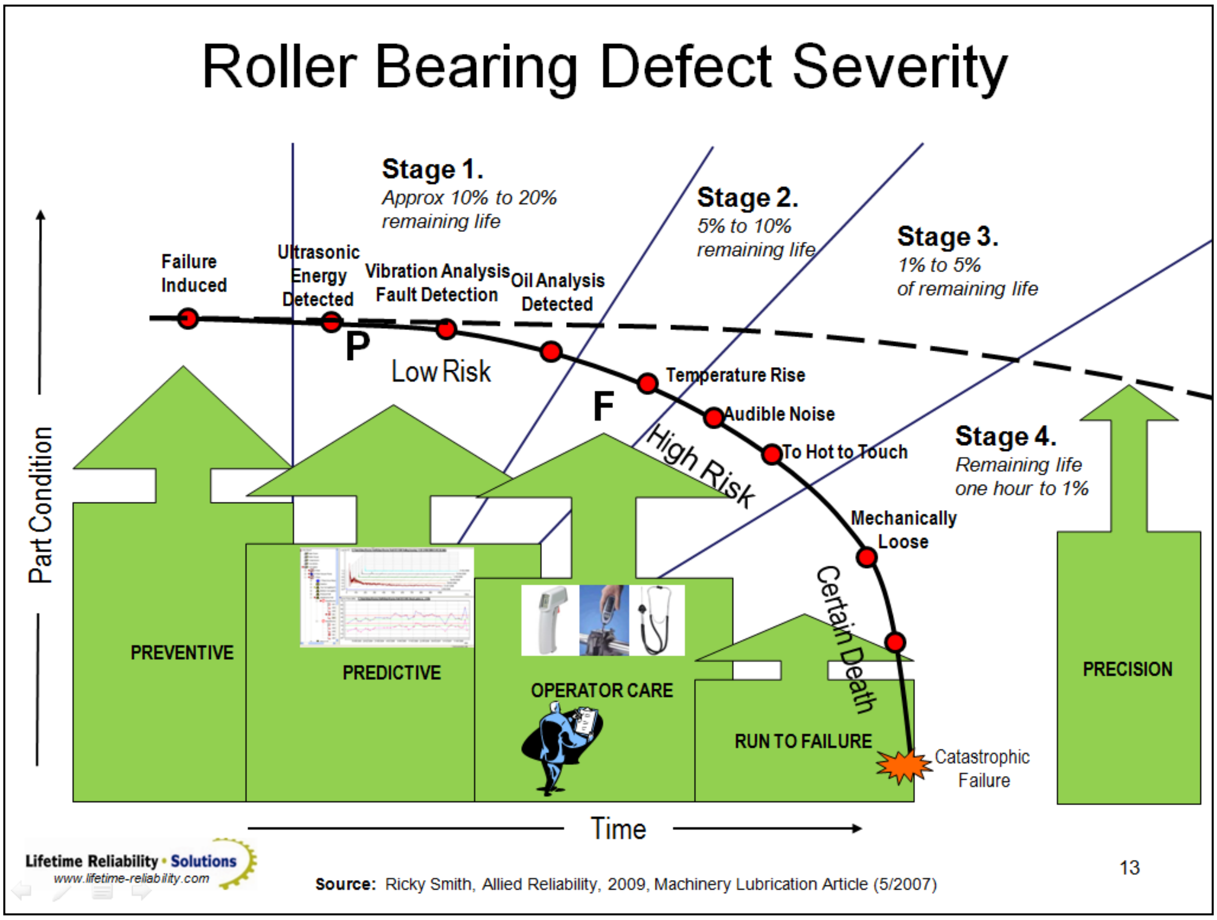

Figure 1 Roller Bearing Symptoms During the Four Stages of Bearing Failure

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The Danger in Using Condition Monitoring is that it is Used as a Lagging Indicator

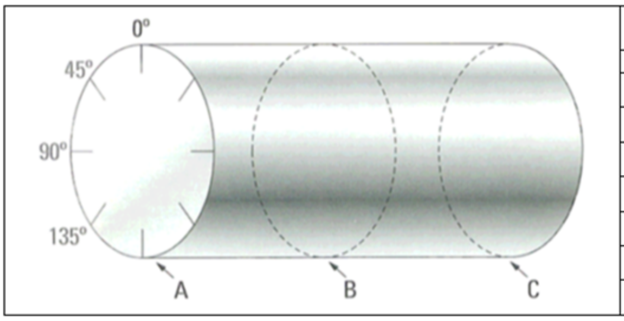
Condition monitoring is failure-focused—you must first have failure so that you can look for the signs of failure, which means that when you find them the breakdown is now close-by. Figure 1 shows you the four stages of roller bearing failure and the positions on the degradation curve where various CM technologies identify evidence of a problem. Even if using the best available condition monitoring technology, by the time you detect a problem a bearing has only 10% to 20% of its life remaining before its total failure. CM tricks you into sending your equipment to its death.

Condition monitoring is too often wrongly used as a feedback methodology to give you historic information from the after-effects of what is destroying your machines. When used that way CM provides lagging indicator information You cannot take your company to world class operational performance, where high plant reliability abounds, if you use CM to find evidence of failure because your machines are already failed and must then be repaired.

Condition monitoring will let you prevent the breakdown, but that does not improve reliability. CM will save you some maintenance costs because with sufficient warning you can properly plan the repair and schedule an outage for when it causes least production disruption. But the equipment has to be stopped and the taken-out of operation to do the restoration work. That plant outage reduces your mean time between failure and your equipment reliability falls. When CM is wrongly used it cannot make your plant reliable because your equipment is already dying and now you must fit it.

Case Study: Shaft Quality Control Check
(Bearing Health Monitoring)

A 150mm spherical roller bearing will be mounted on the shaft using a tapered sleeve. What will be the reliability of the bearing? Will the bearing last its full design life?



Shaft Diameter mm		Tolerance h9 µm		Form IT5 µm	Form IT7 µm
over	incl	high	low	max	max
18	30	0	-52	9	21
30	50	0	-62	11	25
50	80	0	-74	13	30
80	120	0	-87	15	35
120	180	0	-100	18	40
180	250	0	-115	20	46
250	315	0	-130	23	62

Shaft condition requirements for full bearing life as advised by the manufacturer or from appropriate engineering specifications

Thanks to CBC Bearings and Rod Bennett for the information and example

Figure 2 Shaft Health Condition Criteria Specified by the Bearing Manufacturer

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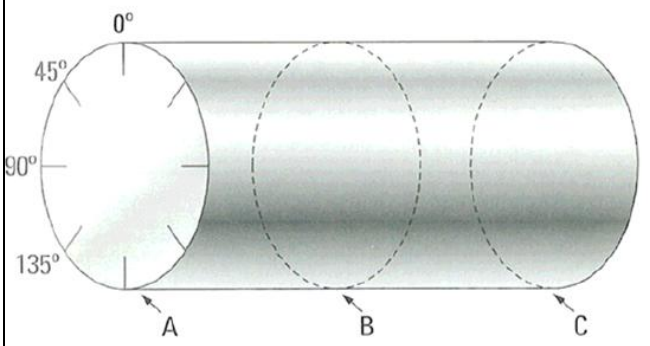
Health Forecast Techniques for Feed-Forward Equipment Monitoring

There is a proactive way to monitor your plant, equipment and machines that provides feed forward indication of equipment reliability. Health forecast techniques are leading indicators of machinery life and let you predict if your equipment will or will not be reliable. It requires you to inspect for evidence of the good health of your machine and not for evidence of approaching death. Figures 2 to 6 show you an example of how to apply health monitoring checks on a shaft carrying a roller bearing to determine if the roller bearing will have the chance of a full service life.

The makers of roller bearings design their bearings for a minimum service life and they provide you with the information you need to check whether the shaft and housing are in the proper condition for the bearing to reach full-life. Figure 2 lists the SKF requirements for shaft condition needed by a bearing to have a good chance of a long, trouble-free operating life. The SKF catalogue advises that for a 150mm spherical roller bearing mounted on a tapered sleeve you need a shaft of h9 tolerance **and** a form better than IT5 (International Tolerance Grade 5).

Is the 150mm Shaft In Tolerance?



Shaft Diameter		Tolerance h9 µ		Form IT5 µ
over	incl	high	Low	max
10	18	0	-43	8
18	30	0	-52	9
30	50	0	-62	11
50	80	0	-74	13
80	120	0	-87	15
120	180	0	-100	18
180	250	0	-115	20
250	315	0	-130	23
315	400	0	-140	25
400	500	0	-155	27
500	630	0	-175	32
630	800	0	-200	36
800	1 000	0	-230	40
1 000	1 250	0	-260	47

As an example, the measurements for a 150 mm shaft might look like this:

	0°	45°	90°	135°	Plane Average
Plane A	149.98	149.99	149.98	149.99	149.99
Plane B	149.97	149.94	149.98	149.95	149.96
Plane C	149.98	149.98	149.95	149.99	149.98

Shaft Tolerances for Bearing Adapter Sleeves

Figure 3 Shaft Condition is within Tolerance of the Bearing Manufacturer Requirements

To check the condition of the shaft it is measured around its circumference in three planes at the place on the shaft where the bearing sleeve will be located. Plane A and C are at the ends of the sleeve and Plane B is at the centre of the sleeve. The measurements at the 0, 45, 90 and 135 degree positions are taken with a digital micrometer and the readings recorded in a table.

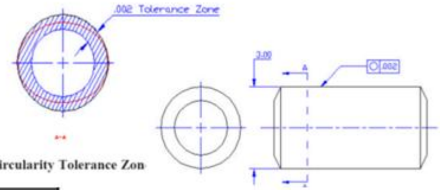
The first bearing health check done is to prove the shaft is in tolerance. The h9 tolerance specified by the bearing manufacturer means the shaft can be a size from 150.000mm to 149.900mm. The highest value in the table is 149.99mm and the smallest is 149.94mm. The shaft is in tolerance.

During my fitter and machinist apprenticeship I was taught to make shafts and housings. I was trained to micrometer them and check that they were in tolerance. I was very good at both tasks. Because of my training I thought ensuring that the tolerance was within range was all you had to do to prove the shaft was properly made. But I was trained wrongly because there is still more checks needed to prove the full condition of the shaft—we must check the shape form of the shaft. Even when I became a professional engineer and studied mechanical engineering at university no one told me of my mistaken belief, and because no one corrected this thinking I carried that misunderstanding into my professional engineering career.

Vital Proof Tests to Check on Shaft Form to Predict Bearing Reliability

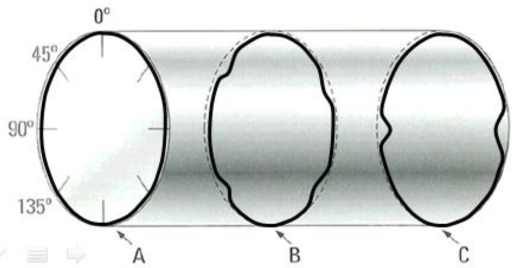
Is the 150mm Shaft Round?

b. Roundness Evaluation
Compare the maximum and minimum values for Plane A.
If the difference is less than the IT5 tolerance, then this plane is okay roundness.
Repeat for Planes B and C.



	0°	45°	90°	135°	Plane Average	Max-Min
Plane A	149.98	149.99	149.98	149.99	149.99	0.01
Plane B	149.97	149.94	149.98	149.95	149.96	0.04
Plane C	149.98	149.98	149.95	149.99	149.98	0.04

In this example the "Max-Min" values are 0.01, 0.04, and 0.04.
The tolerance is 0.02, so Planes B and C are out of round.



Shaft Diameter		Tolerance h9 µ		Form IT5 µ
over	incl	high	Low	max
10	18	0	-43	8
18	30	0	-52	9
30	50	0	-62	11
50	80	0	-74	13
80	120	0	-87	15
120	180	0	-100	18
180	250	0	-115	20
250	315	0	-130	23
315	400	0	-140	25
400	500	0	-155	27
500	630	0	-175	32
630	800	0	-200	36
800	1 000	0	-230	40
1 000	1 250	0	-260	47

Figure 4 Shaft Health Condition for Roundness does not Meet Bearing Life Requirements

The next health checks are for shaft shape form. Using the same measurements we check the roundness of the shaft at each plane. Plane A varies by 10 micron, which is well within the maximum 18 micron allowed by the IT5 requirement. But both Plane B and C vary by 40 micron; more than twice the maximum allowed for the bearing if it is to get its full service life.

The circles sketched on the shaft in Figure 4 shows that Plane A is adequately round, but Plane B dips at the 45 degree and 135 degree positions, and Plane C dips at the 90 degree location.

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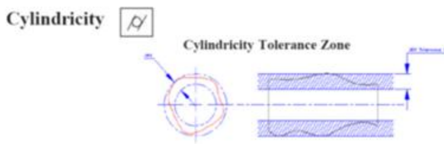
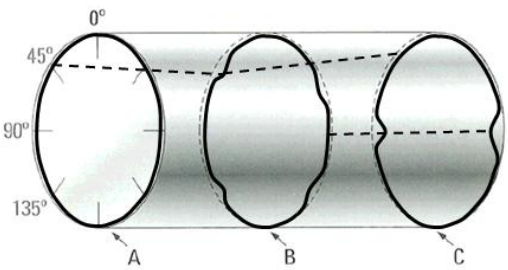
Is the 150mm Shaft Cylindrical?

c. Cylindricity Evaluation
Compare the maximum and minimum values for each angle of measurement.
If the difference is less than the IT5 tolerance for all angles, then the shaft is okay for cylindricity.

	0°	45°	90°	135°	Plane Average
Plane A	149.98	149.99	149.98	149.99	149.99
Plane B	149.97	149.94	149.98	149.95	149.96
Plane C	149.98	149.98	149.95	149.99	149.98
Max-Min	0.01	0.05	0.03	0.04	



In this example the "Max-Min" values are 0.01, 0.05, 0.03 and 0.04.
The tolerance is 0.02, so the shaft is not cylindrical.



Shaft Diameter		Tolerance h9 μ		Form IT5 μ
over	incl	high	Low	max
10	18	0	-43	8
18	30	0	-52	9
30	50	0	-62	11
50	80	0	-74	13
80	120	0	-87	15
120	180	0	-100	18
180	250	0	-115	20
250	315	0	-130	23
315	400	0	-140	25
400	500	0	-155	27
500	630	0	-175	32
630	800	0	-200	36
800	1 000	0	-230	40
1 000	1 250	0	-260	47

Figure 5 Shaft Health Condition for Cylindricity does not Meet Bearing Life Requirements

A further shape form check that needs to be done is to see how cylindrical the shaft is under the bearing sleeve. In Figure 5 we again use the measured diameters and in this case we look down the shaft from Plane A to Plane C along the 0, 45, 90, and 135 degree lines.

The 0 degree line varies 10 micron, which is well inside the 18 micron maximum. But for the 45, 90 and 135 lines the variation is well outside of allowance. The sketch shows that along the 45 degree line there is a dip at Plane B, and along the 270 degree line the shaft falls away from Plane B to Plane C. This is further proof that the shaft is not to the minimum dimensions to provide the necessary support to the bearing for it to get its full design life.

The final form check is for taper. Figure 6 sketch shows the average diameter of Planes A, B and C. The shaft is shaped like an hourglass. Under the sleeve the shaft is tapered toward Plane B. When the sleeve is mounted it will sit on the two outer planes and flex inwards at Plane B every time a loaded rolling element passes over. This flexing causes fatigue of the sleeve and bearing rings as exaggerated in Figure 7. When an oval shaft turns to the horizontal the rolling elements and inner and outer rings are squeezed by massive forces because of the out-of-roundness. These rollers are also not in the lubricated zone at the bottom of the bearing and get overloaded without the presence of oil to distribute the stresses. When the oval shaft turns to the vertical the operating load is on fewer rolling elements than the bearing manufacturer requires and again the rolling elements and bearing rings are overloaded. Very quickly the bearing fails from failure mechanisms such as spalling. The bearing does not have a chance of getting to full design life because the shaft

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was not sufficiently round from the start. The rolling elements and rings will be impacted and hammered by the out-of-roundness with every revolution of the shaft. This bearing will spall early and release contamination into the oil; then fail shortly after.

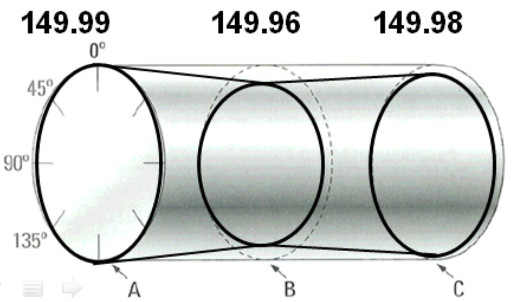
Is the 150mm Shaft Tapered?

a. Taper Evaluation

Compare the maximum and minimum average diameters for the three planes.
If the Max-Min is less than the IT5 tolerance, then the shaft is okay for taper.

	0°	45°	90°	135°	Plane Average
Plane A	149.98	149.99	149.98	149.99	149.99
Plane B	149.97	149.94	149.98	149.95	149.96
Plane C	149.98	149.98	149.95	149.99	149.98
Max-Min					0.03

In this example the "Max-Min" value is 0.03.
The IT5 tolerance is 0.02, so the shaft has excessive taper.



Shaft Diameter		Tolerance h9 µ		Form IT5 µ
over	incl	high	Low	max
10	18	0	-43	8
18	30	0	-52	9
30	50	0	-62	11
50	80	0	-74	13
80	120	0	-87	15
120	180	0	-100	18
180	250	0	-115	20
250	315	0	-130	23
315	400	0	-140	25
400	500	0	-155	27
500	630	0	-175	32
630	800	0	-200	36
800	1 000	0	-230	40
1 000	1 250	0	-260	47

Figure 6 Shaft Health Condition for Taper does not Meet Bearing Life Requirements

This shaft is failed—it is not in the right condition to deliver bearing reliability. If you use this shaft the bearing will not last anywhere close to its full life. The bearing will fail early even if the lubrication to it was perfect. If you only used condition monitoring you would wait to detect the bearing failure and then schedule a repair. By using component health checking you don't need to wait until the condition monitoring detects an impending failure to tell you that there will be a breakdown. This simple shaft health check makes it very clear that already the bearing on this machine is in serious trouble.

You can chose to use the shaft and fit the bearing on it and then put the machine back into service. No one will stop you. But do not expect trouble-free operation for long. That will be impossible because the out-of-round, non-cylindrical shaft will cause the bearing to fail early.

If you must install the shaft at least you know you have a problem and can make sure that during operation the machine is treated gently and condition monitoring is use to observe the bearing for its rate of degradation. In the mean time you will get a new shaft made to the correct quality and have it waiting, properly protected against rust and damage, until the CM tells you the bearing is failing; upon which you plan the replacement and install the good quality shaft.

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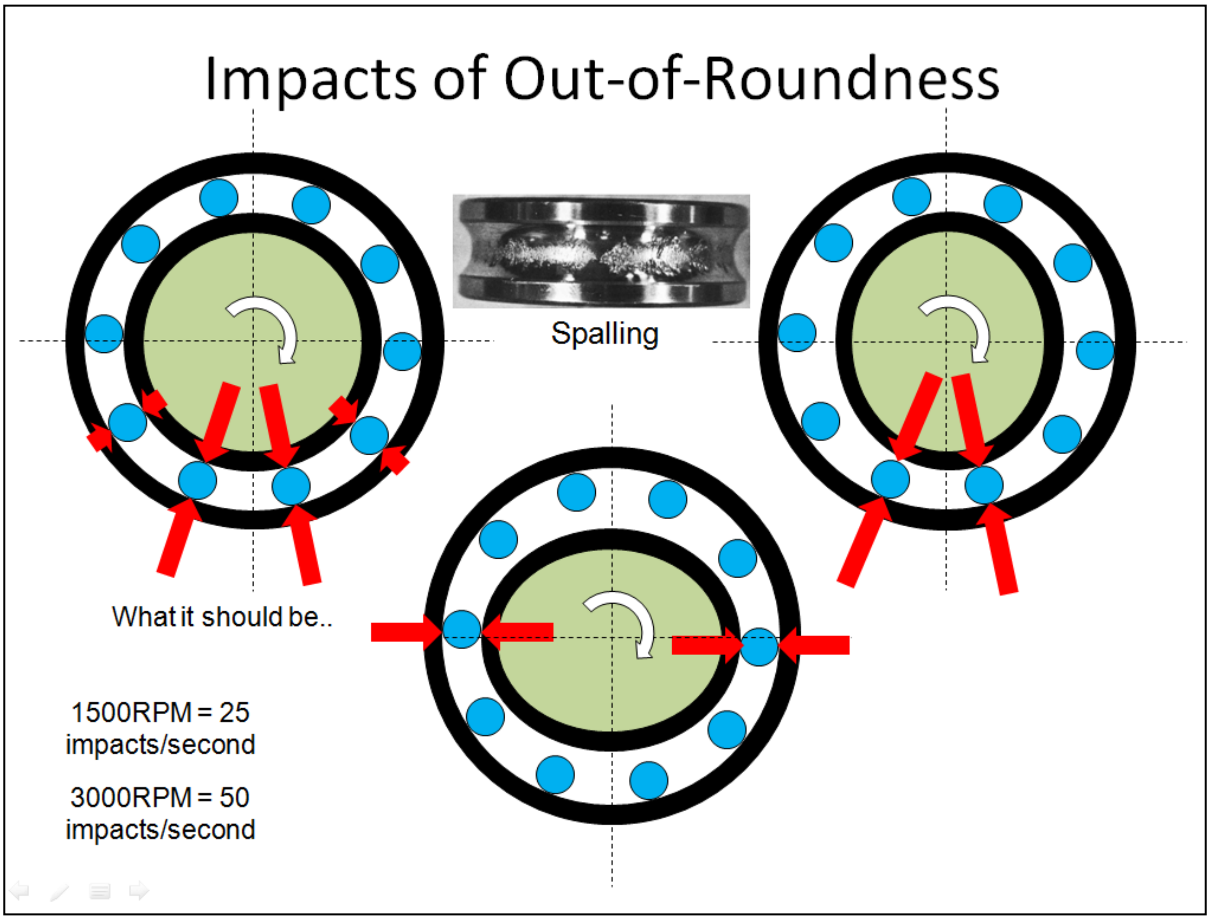

Figure 7 How Shaft Out-of-Roundness Causes Bearing Failure

The Great Value of Doing Machine Component Health Checks

This shaft condition check is an example of a machine health check. By measuring the shaft condition and checking it against the necessary minimum quality standards you have a method of proving component health. You have a feed-forward method to predict the reliability of the bearing from the level of quality of the shaft.

Dimensional tests need also to be done for the bearing housing to prove its health status. A classic example of what great value a bearing housing health checking can bring is in the story of a forced draft fan bearing failure. The rear roller bearing on the fan concerned never lasted more than about two months after a repair. The downtime was an expensive and great inconvenience. To prevent a breakdown the maintenance group replaced the bearing every six weeks. It was also put on vibration analysis observation. After several replacements they collected enough vibration data to diagnose a pinched outer bearing race. The rear bearing housing had been machined oval when manufactured and it squeezed the new bearing out-of-round every time it bolted up.

You could say that vibration analysis condition monitoring did wonderfully well. But the truth is the repair procedure badly failed the organisation. If there had been a task in the procedure to measure the quality of the bearing housing roundness and compare the dimensions to allowable target measurements they would have found the oval-shaped hole at the very first rebuild. There was no need for the bearing to fail after the first time. A badly written procedure without quality tests of the housing condition had let the root cause of the failed fan go undetected for years.

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Whereas had the bearing housing accuracy been checked with a proof test for quality and tolerance they would have found the problem on the first repair and fixed it permanently.

Health checking provides you with the maximum warning time and prediction of the reliability of your machines. A condition monitoring check looking for failure can do nothing to improve machine reliability because the parts have already started to fail by the time you learn about it and you must then replace them. But a health check predicts the future of your machines.

Condition monitoring would detect a failing bearing but a shaft and housing health check done as part of the machine assembly procedure would find quality problems and allow you to correct them to the condition that ensures the machine is built to deliver a long, trouble-free operating life.

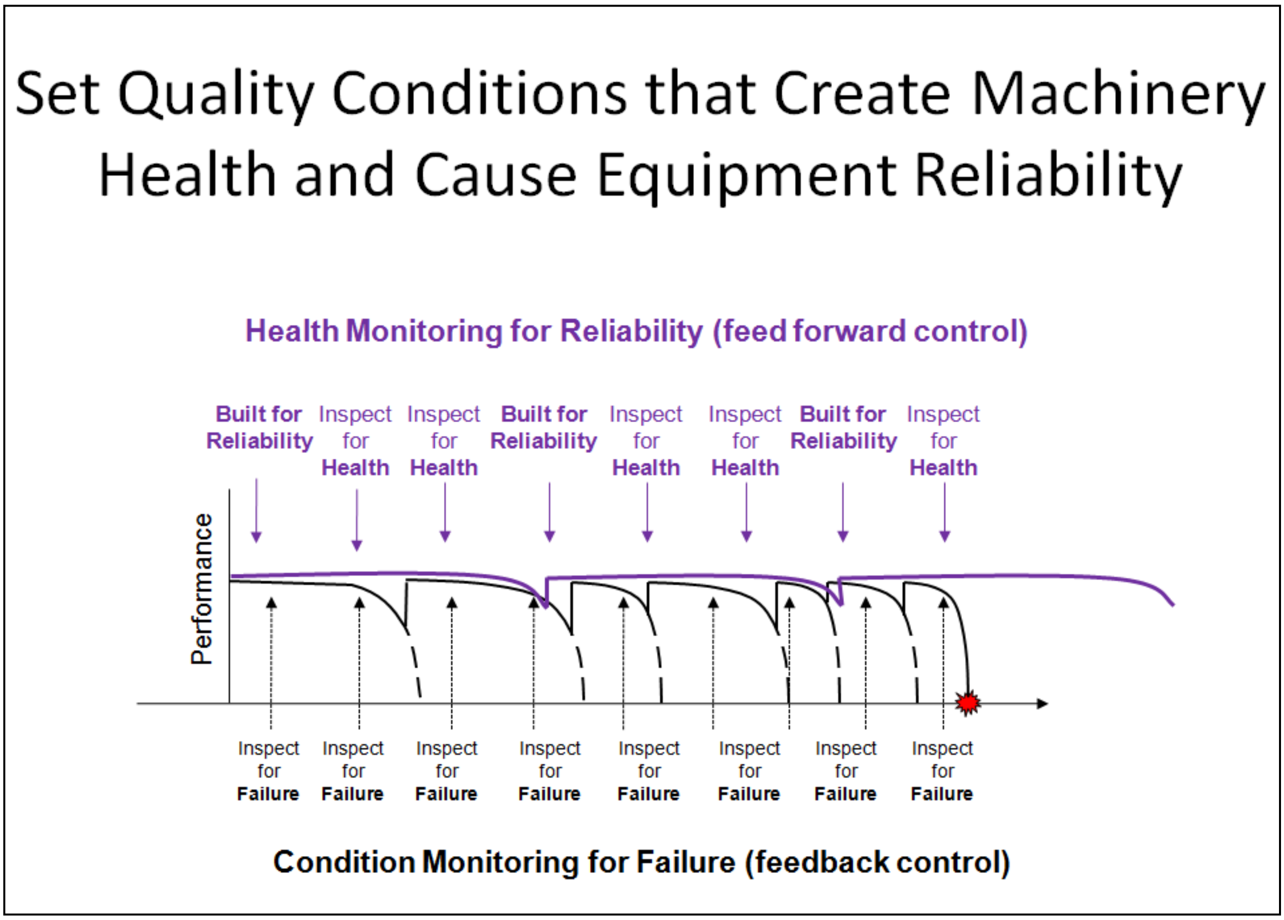

Figure 8 Health Monitoring Leads to High Reliability, More Production and Less Maintenance

You do need to use condition monitoring and you do need to do it well. It will save you from having disastrous breakdowns. But CM provides after-the-fact measurement on the state of a machine. By the time CM warns you of a problem the equipment is already in serious trouble. CM makes you focus on finding failures and so failures is always what you will have.

In Figure 8 we see the effect over your machinery lifetime from using CM to monitor equipment condition. The lower degradation curves result from applying condition monitoring . With CM you find an impending failure and you fix it. Then you monitor the machine again waiting for the next failure and you fix that one. The cycle repeats because you require failure to start before CM can detect its symptoms. CM finds evidence of failure and this makes you intentionally wait until

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equipment failure is certain. CM can save you from breakdowns but it also produces much unnecessary production downtime, more maintenance costs and unending repairs.

The money CM saves you in breakdowns prevented is limited by the amount of money you spend on extra maintenance created by waiting until your machines and equipment are nearly failed. Condition monitoring for evidence of failure puts you into a failure-detection mindset, and that approach cannot lead you to world class operational performance.

In the upper curve of Figure 8 the mindset is different; it is health-focused not failure-focused. In this mindset you do failure elimination, defect prevention and improve the condition of your machines' health. In such a world you create high reliability by controlling to precision quality standards—you prove the quality of manufacture and assembly will deliver outstanding reliability. During operation you do quality condition checks regularly to prove the machine is still healthy. In this way you naturally remove the causes of failure and create the causes of outstanding reliability.

Considerations and Requirements for Lasting Machinery Health

From my training as a tradesman and professional engineer I would have accepted the 150mm shaft as good to use based on the tolerance check alone. I did not know the critical importance of doing a check on shaft shape form until I was over 50 years old and had worked in engineering for more than 30 years. I blame our education system for most of poor equipment reliability problems throughout the world. I was taught by people that did not know what was important to know and so I did much harm during my working career. (There is still much more I need to learn and I am wiser; these days I look to learn from those people who know what is important to know.)

Most operations would measure the bearing vibrations on their machines, like pump sets and compressor sets, looking for evidence of failure. They would regularly monitor the motor bearings and machinery bearings for noise and take oil samples for analysis. They would wait until the condition reports confirmed a machine/motor was failing and then stop the plant to repair it. These companies are practicing failure-focused condition monitoring and so never-ending failures and repairs are what they will always get.

Much better would be to intentional introduce regular health checks where you inspect your machines for the state of their health. An example is to stop your machinery every year and check that the shaft alignment from driver to driven equipment is still within tolerance. If the alignment is out-of-condition correct it immediately and put the machine back into a healthy state. If the alignment is well in tolerance you do nothing more and put the machine back into service until the next health check. In this way your health inspections create long-lived plant and equipment because you always make sure your machines are in a highly reliable state when in operation.

This is the quickest path to world class operational excellence—use feed forward quality proof tests to make sure that your machines are built healthy and always remain healthy. Do not use condition monitoring by waiting for your equipment to become so sick that the only outcome left for them is death. You will only waste your money, resources and time on unending repairs.

My best regards to you,

Mike Sondalini
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