Kosse, Vladis (2010) *Revealing design flaws at different stages of product development using anticipatory failure determination (AFD TM) technique*. In: Proceedings of the 6th Australasian Congress on Applied Mechanics, 12 - 15 December 2010, Peth, W.A.

Revealing Design Flaws at Different Stages of Product Development Using Anticipatory Failure Determination (AFD^{TM}) Technique

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Abstract: In this paper a combination of conventional tools for machinery failure analysis, Anticipatory Failure Determination (AFD^{TM}) and Classical TRIZ has been suggested. The use of these tools in combination proved to be highly effective. The effectiveness of this combination has been illustrated with two case studies – one on revealing design flaws at early stages of the rack and pinion mechanism development and the other one on revealing the flaw in bolster design that remained hidden for many years while the bolster assemblies worked under normal operation conditions, but caused significant financial losses when flood happened.

Key words: Design, Product reliability, Failure prediction, AFD^{TM} technique, TRIZ.

1. Introduction

Reliable performance of a product is a function of the following parameters [1]:

- Perfection of design.
- Quality of materials used.
- Built quality.
- Maintenance systems.

Unreliable performance of a product may have highly detrimental effect incurring financial losses and damaging company's image. It is very important to reveal design flaws at early stages of a product development. A conventional approach involves building a prototype, testing it and making design changes to improve performance and reliability. This is a costly way, which does not guarantee that all design flaws are revealed and eliminated. There are cases when hidden design flaws remained in a product, which performed adequately under intended operating conditions, however, under a certain combination of events the hidden design flaw may reveal itself causing substantial financial losses and resulting in costly litigations between consumers, manufacturers and insurance companies.

Until recently there were no effective tools that enable revealing hidden design flaws at early stages of a product development. Well-known tools such as Hazard analysis (HAZAN), Hazard and operability study (HAZOP), Failure mode, effect and criticality analysis (FMECA) are useful in identifying "What may go wrong?" with a process or a machine. Software packages were developed to facilitate analysis, such as FMECA Gold [2]. However, these tools require specialist knowledge, expertise and still are not effective in identifying hidden design flaws. Statistical methods can identify a trend if sufficient data is available, but still do not give the answer "Why something goes wrong?"

In late 90s the Ideation International Incorporation (USA) released a new tool the Anticipatory Failure Determination (AFD^{TM}) method [3], which proved to be very effective both for accidental machinery failure analysis and predicting potential failures at early stages of a product development. It is one of a series of new tools, such as the Innovation Situation Questionnaire (ISQ^{TM}), Problem Formulator and AFD^{TM}, developed by the company in addition to the Classical TRIZ (the Russian acronym for the Theory of Inventive Problem Solving). The AFD^{TM} can be effectively used in a combination with Classical TRIZ tools and conventional tools of machinery failure analysis such as cause and effect analysis, which will be demonstrated in the following sections.

Before cases of machinery failure analysis and prediction are discussed it is useful to identify the kinds of problems associated with machinery reliability and failure analysis. There are two kinds of problems [1]:

1. Specific-knowledge problems (rule-based problems).
2. 2. Event-based problems.

Specific-knowledge problems are based on a pre-defined set of rules and, therefore, can have a single correct answer (e.g. mathematical problems). Event-based problem solving has no predefined set of rules and, therefore, may have many ‘right’ answers. It is important to understand this difference because in most cases problems associated with machinery malfunction and failures are event based. By looking for the ‘right’ answer to event-based problems, we subsequently limit our ability to find creative solutions. The rule-based thinking ignores the most fundamental of all principles: the cause-effect principle. The same event may be the cause and the effect. It is important to identify the *primary effect* and the *root cause*, and distinguish them from *contributing causes* and *interim effects*. If using different tools we can identify the *primary cause* of the event (e.g. failure or potential failure) we can prevent it from occurring.

Main causes of failure can be classified as follows [1]:

1. Faulty design.
2. Materials defect.
3. Processing and manufacturing defects.
4. Assembly and installation defects.
5. Off design or unintended service conditions.
6. Maintenance deficiencies (neglect, procedures).
7. Improper operation.

It is important to exclude as many causes from the above list as possible to narrow down the search when tools such as AFD™ are applied.

There are so called agents of machinery failure [1], which are *force* (could be steady, transient, cyclic), *time* (could be very short, short, long), *temperature* (could be low, room temperature, elevated, or could be steady, transient, cyclic), and *reactive environment* (e.g. chemical, nuclear). It is not easy to identify these agents. The AFD™ enables this identification through analysis of resources available in the system.

2. Bringing together different failure analysis tools

It is beneficial to combine different failure analysis techniques to increase the effectiveness of analysis. It can be done in the following way:

- Establish whether a similar machine is used across the company and its branches. Check whether any historical or statistical data is available and try to identify any trends with emerging problems.
- Interview operators and maintenance workers to establish whether operating conditions were as specified by the design, operators followed outlined procedures, and maintenance was adequate.
- Check whether equipment had been installed properly, any material or manufacturing defects are evident.
- If the above actions still do not reveal any cause-effect links, the design flaws can be suspected. Apply the AFD™ technique.

It is amazing that many companies do not keep detailed records of machinery failure and records of machine condition monitoring, which makes it extremely difficult to identify trends in machine performance and reliability analysis. Companies that have high maintenance culture and practice machine condition monitoring (MCM) keep detailed records of machinery failure and MCM results and have procedures set in place that outline what personnel has to do in the case of an accident. A part of these procedures is to keep a digital camera in every workshop and photograph a broken piece of equipment immediately after an accident because if some parts or objects are moved, displaced or taken away it may obstruct investigation and lead to erroneous conclusions.

When preliminary analysis has been carried out and it did not lead to any insight into the causes of an accident, The Anticipatory Failure Determination™ (AFD™) can be applied. The AFD™ method is based on the following concept [3]. The ineffective or harmful aspect of the technical system is taken and exaggerated to the most extreme form of the failure. This catastrophic condition (inverted problem) now becomes the desired performance. The Ideation -TRIZ methodology is applied to the inverted problem to find the way to achieve it and recommend remedial actions. AFD includes the following nine steps:

1. Formulation of the original problem.
2. Formulation of the inverted problem.
3. Amplification of the inverted problem.

4. Search for apparent solutions to the inverted problem.
5. Identification and utilisation of resources.
6. Search for the needed effect.
7. Search for new solutions.
8. Formulation of hypotheses and tasks for their verification.
9. Development of means to prevent failures.

The resources can be of the following kinds: *substance resources* (readily available or derivative substances); *time resources* (something may happen before, during or after certain event); *space resources* (any volumes, gaps, clearances, dimensions, distances travelled); *field resources* (anything that can transmit energy, e.g. mechanical interaction, friction, gravitational, acoustic, magnetic, electrostatic, thermal, surface tension, etc.). In cases when a control system is a part of investigation, *information resources* can also be considered.

The AFD™ technique is highly effective both for failure analysis and failure prediction at early design stages. It will be illustrated with two different case studies.

3. Predicting potential failures and revealing design flaws at early stages of product development

The rack and pinion mechanism has been designed to operate a sliding door of a furnace by means of a chain connecting the rack with the door (see Fig. 1 below). The door rests on rollers on the inclined surface. The force **F** required to pull the dor up the inclined surface was assessed and used for design calculations of the rack and pinion mechanism. There are no shock loads present and to prevent overloading of the mechanism a limited torque clutch is installed on the pinion shaft. The rack is mounted on two rollers to enable the rack travel in the horizontal plane for up to 500mm in each direction. Sufficient grease lubrication is provided. It is necessary to carry out analysis whether the design is sound and no hidden design flaws are present that may cause malfunction or failure of the mechanism in the future.

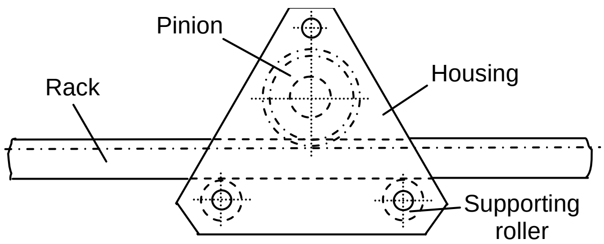

Figure 1: Rack and pinion mechanism

To apply the AFD™ method to identify hidden design flaws, we have to follow the nine-step procedure outlined above.

Step 1. Formulation of the original problem

There is a rack and pinion mechanism that includes a pinion, rack, rollers supporting the rack and flanges keeping all parts together. The rack pulls the furnace dor by means of a chain. Adequate grease lubrication is provided. It is necessary to identify any hidden design flaws that may cause malfunction of failure of the mechanism in the future.

Step 2. Formulation of the inverted problem.

It is necessary to achieve failure of the rack and pinion mechanism.

Step 3. Amplification of the inverted problem.

It is necessary to achieve a catastrophic failure of the rack and pinion mechanism and impose severe damage to the teeth of the rack and the pinion.

Step 4. Search for apparent solution to the inverted problem.

Typical mechanisms that may cause failure of a gearbox are inadequate lubrication or overloading. In this mechanism plenty of grease lubricant is provided and limited torque clutch is installed to prevent overloading. But there may be unforseen processes that may apply forces to the rack and the pinion that significantly exceed the design load.

Step 5. Analysis of resources.

Let us analyse the resources available in the system:

Substance resources. All components of the mechanism are made from steel, grease is present, and the environment is air.

Time resources. The mechanism is used occasionally just to open or close the furnace door. When the mechanism is not in use no external forces are applied other than components' own weight.

Space resources. There are clearances (both axial and radial) between supporting rollers, axles and side flanges. There is a clearance (backlash) between the teeth of the rack and the pinion. There is the space between the side flanges of the housing filled with grease. The rack can travel up to 500mm in the horizontal plane in each direction when the mechanism is in operation.

Field resources. There is a field of mechanical interaction between the teeth. Some heat is released when the mechanism is in operation. There is the surface tension between the lubricant and surfaces of the mechanism. All components are subjected to gravitational forces. When the mechanism is in operation moving parts (rack, pinion, rollers) posses kinetic energy.

Information resources. Information resources are not relevant to this case.

Step 6. Search for the needed effect. It is apparent that when the rack is in the mid-position it is in equilibrium and is supported by two rollers. When it is shifted sideways, the gravitational forces tilt it, the rack is supported only by one roller. Clearances between components allow the rack to take inclined position. Due to the leverage action the rack applies large radial forces to the pinion (see Fig. 2). The limited torque clutch cannot prevent these forces being applied to the mechanism. Every time the mechanism is in operation it works under forces it was not designed for. Large radial forces create contact stresses significantly exceeding allowable contact stresses.

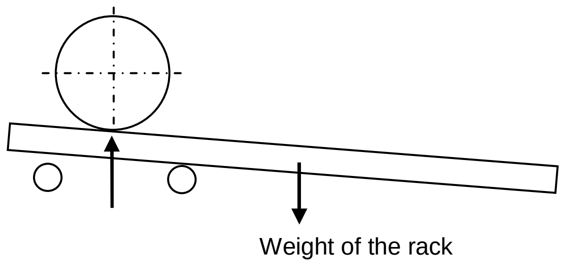

Figure 2: Leverage action of the rack.

Step 7. Search for new solutions. There is no need to search for new solutions because the design flaw is obvious, and if the mechanism is built and installed it will be working under increased loads it was not designed for. This will cause accelerated wear of the rack and the pinion and premature failure.

Step 8. Formulation of hypotheses and tasks for their verification. It is interesting to check what is the weight of the chain and whether it makes any significant impact on forces in gear engagement. No, it does not make any difference, because when the door of the furnace is open the chain is almost straight and the pulling force is applied in the direction of the rack travel.

Step 9. Development of means to prevent failures. One solution could be to put additional supporting rollers outside the flanges to minimise leverage action. An alternative solution could be to turn the mechanism 90^o, so that the rack will travel in the vertical direction, and to put the chain on a sheave so that the rack will be suspended and its weight will not make any impact on forces in gear engagement. Moreover, the weight of the rack will work as a counterweight reducing forces applied to the rack and extending its operating life. These conceptual solutions are depicted in Fig. 3 below (the (a) option with additional supporting rollers, and (b) option with the vertical rack).

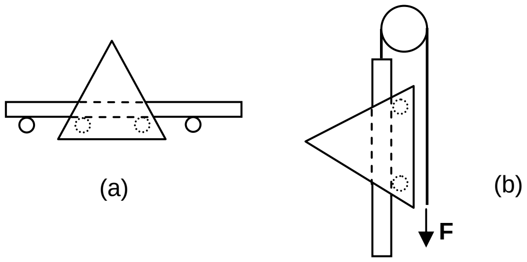

Figure 3: New conceptual solutions of the rack and pinion:
(a) With additional rollers; (b) With the vertical layout.

This case study illustrates how the AFD^{TM} tool can be effectively used to reveal a hidden design flaw in the mechanism, which may cause accelerated wear and premature failure.

4. Establishing the cause of failure using a combination of AFD^{TM}, Classical TRIZ and conventional tools

The following case study is based on a consulting project that the author carried out some time ago. The name of the client cannot be revealed. This case study illustrates how a hidden design flaw did not affect the mechanism performance under normal operating conditions, however, under a certain combination of events it resulted in multiple failures, caused significant damage and financial losses. Bolsters are widely used in carpet industry to produce yarn and carpet threads. A typical bolster assembly is shown in Fig. 4. It consists of the following parts: vertical shaft carrying a spool; spindle built in the shaft and supported by two bearings – a thrust bearing at the bottom and a radial bearing at the upper end. Both bearings are installed in a bolster, which is filled with liquid lubricant. Bolsters are fixed on a frame in groups of up to 30 bolsters. The spindle is spun at a speed of 6000 rpm.

The problem is that the company's premises were flooded for two days with the flood water level up to 0.8 m above the workshop floor. Bolster assemblies were partly submerged. When the floodwater was gone, the maintenance staff replaced lubricating oil with fresh oil in all flooded bolsters, and equipment was switched on. Before fresh lubricant was put in bolsters all accessible surfaces were dried with compressed air and wiped with clean cloth. Soon the maintenance staff realized that the bolster bearing failure rate had increased significantly. The insurance company paid for business interruption, but refused to pay for damage to equipment arguing that there is no direct evidence that the flood water was entrapped by bolsters, and the increased bearing failure rate is directly linked to the flood.

Even two years after the flood bolster bearings continued to fail despite repeated replacement of bolsters and lubricating oil. The company suffering substantial financial losses started purchasing second hand bolster assemblies to replace worn-out bolsters.

Using AFD^{TM}, TRIZ tools and experimental study find the way to prove that the floodwater was entrapped by bolsters, and explain how the short-term and long-term damage occurred.

The company gathered statistical data on bolster bearings failure rate. The bolster bearings started failing in one week after the flood despite action taken by the maintenance staff. Then the failure rate on flooded bolster assemblies stabilised and even two years after the flood stayed at the level of 10 to 12% per month. Initially faulty bolsters were replaced with new ones, but when the cost of replacement started mounting up the company started buying second hand bolster assemblies. Several reputable consultants were engaged to carry out investigation. The findings were as follows: flooded bolster assemblies have operating temperature 10^{o}C to 15^{o}C higher than on unflooded assemblies and the noise level in the flooded premises was more than 5 Decibel higher than in unflooded. However, the consultants could not explain why even two years after the flood bolster bearings continued failing at increased steady rate despite repeated lubricant and bolster replacement.

Besides finding explanations to the bolster failure phenomenon using the AFD^{TM} method, it was necessary to establish whether flood water could have entered the bolster assemblies when they were submerged for two days, and if the answer is "yes", what bolster components were affected by the flood water. This question was addressed experimentally. The flood conditions were reproduced in a laboratory environment by placing a bolster in a barrel with water. In the meantime some Classical TRIZ tools were applied, such as the Ideal Final Result Analysis and the Substance-Field analysis.

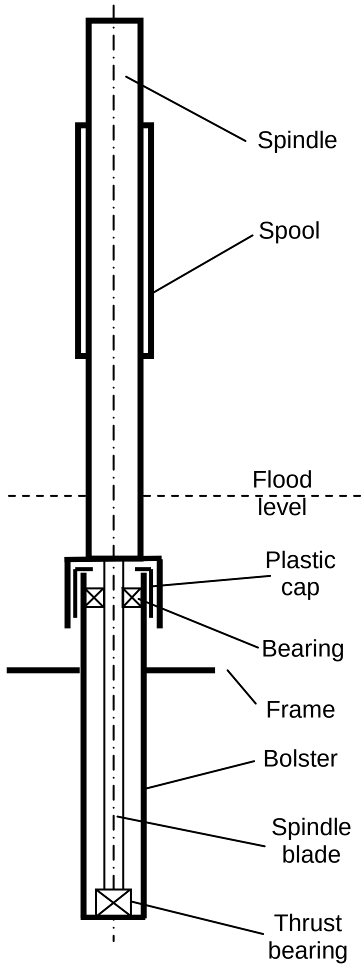

Figure 4: Bolster assembly

The problem is how to prove and document that the water was entrapped. The Ideal Final Result analysis suggests it would happen by itself. In other words, if water is entrapped, it will make itself visible. The question is “how?” Let’s employ the Substance Field analysis [3]. When water (substance $\mathbf{S_2}$) penetrates the bolster, it interacts with inner surfaces of the bolster (substance $\mathbf{S_1}$) through a surface tension field $\mathbf{F_1}$ (see Fig. 5 below). The result is useful but insufficient action (depicted with dashed arrow) – it is difficult to detect water especially if the amount of water entrapped is small. What if to add another substance $\mathbf{S_3}$ that will chemically interact with the water through a field $\mathbf{F_2}$. As a result, substance $\mathbf{S_3}$ will change its colour. Information search showed that such a substance is available on the market. It is called “water finding paste” and is widely used at petrol stations to detect water in petrol tanks. In these experiments the paste from Gilbarco Australia Pty Ltd was used, which initially has a turquoise colour, but in contact with water turns purple. In this study the bolster was disassembled, and its inner surfaces were smeared with the water finding paste. Then flood conditions were modelled in a laboratory. When the bolster was disassembled, plastic cap was purple (see Fig. 6 below), and in some experiments, the spindle blade was also purple. This explicitly proves that flooded bolsters had entrapped water.

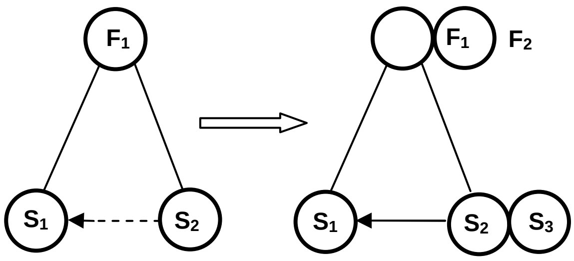

Figure 5: Substance – Field analysis.

However, the insurance company refused to pay damages insisting that the maintenance staff cleaned and dried flooded bolster assemblies and replaced lubricant several times, which removed water from bolsters, so damage to bolsters was not caused by the flood.

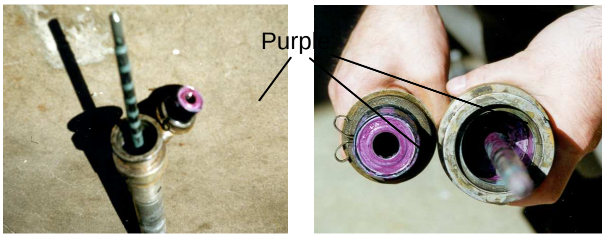

Figure 6: Water-finding paste changed its colour to purple in contact with water

In order to prove that despite repeated lubricant replacement, floodwater caused short-term and long-term damage to bolsters, AFD^{TM} was used (see below).

Step one: Formulation of the Original Problem.

There is a system: The bolster assembly consisting of a spindle; spool; bolster; plastic cap; spindle blade; radial and thrust bearings.

An undesired effect is referred to as excessive and accelerated wear of bolster bearings.

Under the conditions of normal operation. During the flood, bolster assemblies were in a submerged state for two days. Immediately after the flood, the lubricant was replaced with fresh lubricant. Inner surfaces of the bolster were dried with compressed air, and all accessible surfaces were wiped with clean cloth. Later, as prescribed in the maintenance instructions, lubricant was repeatedly replaced. It was experimentally proven that during the flood, water was entrapped by bolsters.

It is necessary to find the cause of this phenomenon. Why and how did the long-term damage to bolster bearings occur despite repeated lubricant replacement that should have removed any water entrapped?

Step two: Formulation of the inverted problem.

It is required to produce damage to bolster bearings.

Under the conditions of the existing production process in the presence of water entrapped by bolsters.

Step three: Amplification of the inverted problem.

It is required to produce extensive damage to race surfaces and rolling elements of bolster bearings.

Under the conditions of the existing production process in the presence of water entrapped.

Step four: Search for apparent solution.

After the flood maintenance staff disassembled bolster units (by pulling spindles out of bolsters) sacked with the syringe contaminated lubricant, dried bolster surfaces with compressed air to remove any traces of floodwater, put fresh lubricant and assembled bolster units. Every 6 months the lubricant was replaced with fresh lubricant. Despite action taken, maintenance staff noticed that bolster temperature and noise level on premises is higher than normal, and bearing failure rate increased by a factor of three.

Possible apparent mechanism of failure may be as follows. Despite actions taken, floodwater could still have been entrapped somewhere inside the bolsters. When bolster assemblies were turned on and warmed up, entrapped water evaporated and stayed inside the bolster assemblies. When equipment was turned off overnight and cooled off, water vapours condensed on inner surfaces, including roller bearing surfaces, causing electrochemical corrosion. When next morning equipment was turned on, bearings were running with ‘sand’ (i.e. highly abrasive particles of Ferro-oxide). This evaporation/condensation cycle repeated for several weeks until entire entrapped floodwater was converted into Ferro-oxides. Wear particles mixed with Ferro-oxide particles fell into lubricating oil causing damage to the thrust bearing. Then, entrapped water caused accelerated lubricant oxidation and deterioration of lubrication properties.

The question is where and how floodwater could have been entrapped despite actions taken by maintenance staff?

Step five: Identification and utilisation of resources

Readily available substance resources: parts of the bolster assembly (steel), liquid lubricant, air, water entrapped somewhere inside the bolster.

Derivative substance resources: products of wear in lubricant, products of lubricant oxidation.

Field resources (and energy sources) are: kinetic energy of rotating bolster parts, heat energy released due to friction, gravitational energy, energy of surface tension in liquid lubricant and water, pressure energy of flood water (pressure head).

Readily available space resources: radial clearances between the bolster and plastic cap divided by ribs in 8 pockets, radial clearance between the plastic cap and spindle skirt, space inside the bolster filled by 2/3 with liquid lubricant.

Time resources: the harmful action (damage to bolster bearings) happens over the months as a concurrent action with the useful action (yarn production).

Step six: Search for needed effect

As it was mentioned earlier, lubricant was repeatedly replaced. So it looks like water was removed from the bolster. However, bearings had indication of abrasive wear, which can take place only in the presence of highly abrasive particles. Abrasive particles can initially form as a result of chemical reaction of water with iron, which produce Ferro-oxides, highly abrasive particles. Debris of worn out surfaces can also contribute to excessive wear of bearings. Thus, we have to search for another possibility of water entrapment in a bolster despite of lubricant replacement. Let's have a close look what happens when floodwater rises. Since floodwater level was above the entry opening between the spindle and the bolster, hydrostatic pressure pushed water in the clearance between the spindle skirt and the plastic cap, and under the plastic cap. Due to small clearances, surface tension and capillary action contributed to water entrapment.

When floodwater was gone, maintenance staff disassembled flooded bolsters, wiped open surfaces with a cloth, sacked the lubricant with a syringe, dried bolster inner surfaces with compressed air, and refilled them with fresh oil. Most likely the plastic cap was not removed and was not inspected, so the water entrapped under the plastic cap remained there. When after maintenance bolster units were assembled and switched on, water entrapped under the plastic cap evaporated due to the operating machine warming up. When the bolsters were switched off overnight, water vapours condensed on inner surfaces including the bearings. Water drops interacting with iron produced highly abrasive particles of Ferro-oxide. When equipment was switched on again the next morning, the bolster bearings were running with 'sand'. Since quite substantial amount of water was entrapped under the plastic cap, evaporation and condensation process took place repeatedly over several days or possibly weeks, causing extensive bearing damage. The peculiarity of bolster bearing is that they do not have an inner ring. Rollers are running over the shoulder on the spindle blade. So, when rollers wear out, they cause extensive wear of the shoulder as well. In this case, replacement of the bolster bearing without spindle replacement is of little or no help, because new rollers are running over the worn-out shoulder. This is how the long-term damage had occurred.

Step seven: Search for new solutions

There is no need to search for new solutions because the mechanism of failure is quite clear.

Step eight: Formulation of hypotheses and tasks for verification.

It is interesting to establish whether the maintenance staff inspected surfaces under the plastic cap. Discussions with the maintenance staff confirmed that during inspection of flooded bolster assemblies plastic caps were not removed and entrapped floodwater stayed there. It might be useful to inspect all bearing shoulders on flooded spindle blades to identify warn-out ones.

Inspection of the flooded bolsters by the author proved that bolster surfaces under the plastic cap were rusty, and the bearing shoulders on the spindle blades were worn out, which was possible to feel even with a finger tip. This validates the hypotheses expressed above.

It is also interesting to inspect inner surfaces of the bolster tube for an indication of products of wear and lubricant oxidation.

Two flooded bolster tubes were dissected along the longitudinal axis and visually inspected. The findings were as follows. There were some deposits that did not belong to materials the bolster is made from. Most likely they were washed from walls and floor of the flooded premises and entered the bolster tube with the flood water. Some surfaces looked lacquered, which is an indication of lubricant oxidation at elevated temperatures.

Step nine: Developing solution

After the flood it was necessary to inspect all flooded bolster assemblies, remove plastic caps from the bolster tubes, and dry them up before putting fresh oil.

Unfortunately the maintenance staff removed water only from accessible surfaces and did not dismantle the plastic cap from bolster tubes. Water entrapped under the plastic cap remained there and caused initially damage to the bearings and then to the shoulder on the needle blade. However at this stage only careful inspection of bearing shoulders on spindle blades and replacement of faulty spindles can help, which is costly.

Conclusions

1. In this paper a combination of conventional tools for machinery failure analysis, such as statistical methods, cause-effect analysis with Anticipatory Failure Determination™ (AFD™) and Classical TRIZ has been suggested.
2. The use of these tools in combination enables effective revealing of design flaws in machines.
3. The effectiveness of the use of AFD™ in a combination with the Classical TRIZ and conventional tools has been illustrated with a case study on bolster bearing failure after a flood, which continued to fail for two years after the flood despite repeated replacement. Several reputable consultants using conventional failure analysis tools could not establish the course of failure and only the use of AFD™ allowed to answer all questions.
4. AFD™ can be also effectively used for revealing design flaws at early stages of a product development and predicting potential failures, which was illustrated with the case study on analysis of the rack and pinion mechanism design. This is especially beneficial because it helps to prevent extensive losses and damaging litigation.

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