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Thrusters

Health Monitoring of Steerable Thrusters

Arthur Boogaard, Eddy Engels and Albert Wesselink
Wärtsilä Propulsion Netherlands B.V.

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Abstract

Dynamic Positioning and Dynamic Mooring systems ("DPM systems") deal with a lot of uncertainty. This uncertainty is partly related to the position reference systems and partly related to the machinery side. DPM systems are applied for critical operations as offshore drilling, FPSOs, heavy lift operations etc.

To deal with the uncertainty the ship configuration is such that position reference sensor systems or propulsion and steering devices may fail without endangering the operation. Full duplex, or even triplex, redundant systems are applied. Present DPM solutions are aimed at the application of Extended Kalman Filtering, which is able to detect degraded positional reference sensors or non-responsive propulsion and steering devices. However, all these systems are mainly dealing with safety, which of course is to be of primary concern, but not at reducing operational down-time and extending the operational availability of a platform.
On a lower level, the propulsion units of a vessel are guarded via regular checks and with the aid of alarms. The regular checks may visualize a changing condition of the system, alarms only indicate when the condition has reached an unacceptable level, which may result in stopping the system and repairing it. Furthermore, inspection intervals for complete propulsion units are prescribed by class societies, varying from 2.5 years for intermittent surveys over 5 years for major inspections.
When operating far away, at the deep seas, docking facilities are rare. Modern thrusters systems are under water exchangeable, such that the vessel has not to leave the operational location in search for a dry-dock. But nevertheless also such a replacement interrupts the operation. Downtime will cost tremendous amount of money.

So besides the safety aspects of the DPM system it is worth to have also systems monitoring the health of the propulsion and steering devices, so that preventive actions can be taken in time. A device failure is mostly not catastrophic to such an extent that the device has to be isolated from the operation, i.e. stopped. Mostly the affected device can be loaded lower, whereas the healthiest device can be loaded higher. So a power distribution among the devices based on the measured health will give an extension of its use.

For propulsion and steering devices, actuated by hydraulic means, three aspects are of importance for health monitoring:

1. *Lubrication oil state, such as water ingress, seizes and amount of metal particles and state of additives and viscosity needed for optimal lubrication.*
2. *State of roller bearings and gears, which can be assessed by high frequent acceleration measurements.*
3. *Device response characteristics, which are influenced by the state of valves, pumps, leakages.*

The health monitoring system uses existing sensors of the device control system, but also some additional sensors are added, such as accelerometers and oil sampling sensors.
After signal analysis, the resulting characteristic data are fused to a general health number varying from 0.000 to 1.000 for respectively totally not fit for use to total fit for use.

The paper indicates, which device parameters are to be used for the health monitoring, how the health is determined and how the result is used to improve the operational availability of the vessel.

Contents.

1. Introduction.

Manufacturers of propulsion systems design the machinery such that it is fit for the intended purpose and operational conditions. The machine can deal with the intermittent mechanical loading in the given environment with sufficient safety margins. Nevertheless machines can fail during the operation, mainly due to unexpected environmental conditions, human factors or simply because a part is at the end of life.

Classification societies and owners cope with these possibilities of failing machinery by respectively demanding and applying redundancy in propulsion devices. The typical drill-rig, as depicted in figure 1.1, for example, is equipped with several steerable (azimuthing) thrusters. For dynamic positioning the minimum amount of propulsors needed to maintain the vessels' position in ideal weather conditions, is one bow thruster and one main stern steerable thruster. This amount of propulsors is sufficient to fully actuate the vessel in its surge, sway and yaw directions. Additional number of propulsors gives the vessel more redundancy.

Figure 1.1. The typical drill-rig.

In less ideal weather conditions more thrust and yaw moment may be required in each or one of the horizontal plane directions. However, the total amount of thrust and moment in each direction is such that under the worst operational condition still redundancy exists. I.e. one or more propulsors may be disengaged, while the vessel still can maintain its position above the bore-hole. The over-actuation gives the dynamic positioning system a lot a possibilities how to allocate the thrusts and steering angles among the propulsors. This freedom could be used to extend the drilling period by using the propulsor health state as a constraint in the thrust allocation algorithm of the dynamic positioning system.

Semi-submersible vessels mostly are equipped with steerable thrusters. Figure 1.2 depicts an steerable thruster, which is (de) mountable when the vessel is floating. Obviously this feature avoids the need of a dry-dock, which may be an operational advantage, when operating in remote areas of the world.


Figure 1.2. Underwater (de) mountable steerable thruster.

However, how to determine the need to exchange such a steerable thruster? And, when removed, which part has to be replaced? Is this part available in stock?
The above questions can be answered, when the health state of the various parts in the steerable thruster is known.

Three types of machinery failures are distinguished :

1. **Intermittent fault**. An example is a bad electrical wire connection making one contact and loosing contact the other moment.
2. **Sudden break-down.** This type of fault mostly happens due to unpredictable accidents, having a foreign cause such as collisions.
3. **Slowly developing fault.** This type of fault is caused by processes as wear. The machine is still usable, but the performance slowly degrades.

For machinery health monitoring, the slowly developing fault, has the main focus. The failure can develop slowly or more progressively. At a certain moment, the condition becomes at such a level that further use of the machine is not recommendable. Machinery health monitoring aims to determine this moment in time far ahead of the real occurrence. This allows for pro-active maintenance or an alternative method of thrust allocation in order to extend the time of the operation before the maintenance has to happen.

A predictive Condition-Based Maintenance (CBM) approach is already operational for marine diesel-engines. Various advantages of diesel-engine CBM are mentioned in reference [1], amongst others :

- Ability to pre-stock parts, avoiding unexpected maintenance shut-downs.
- Longer maintenance intervals.
- Optimized operation.

Figure 1.3. gives an overview of the organization of a CBM reporting system for diesel-engines.

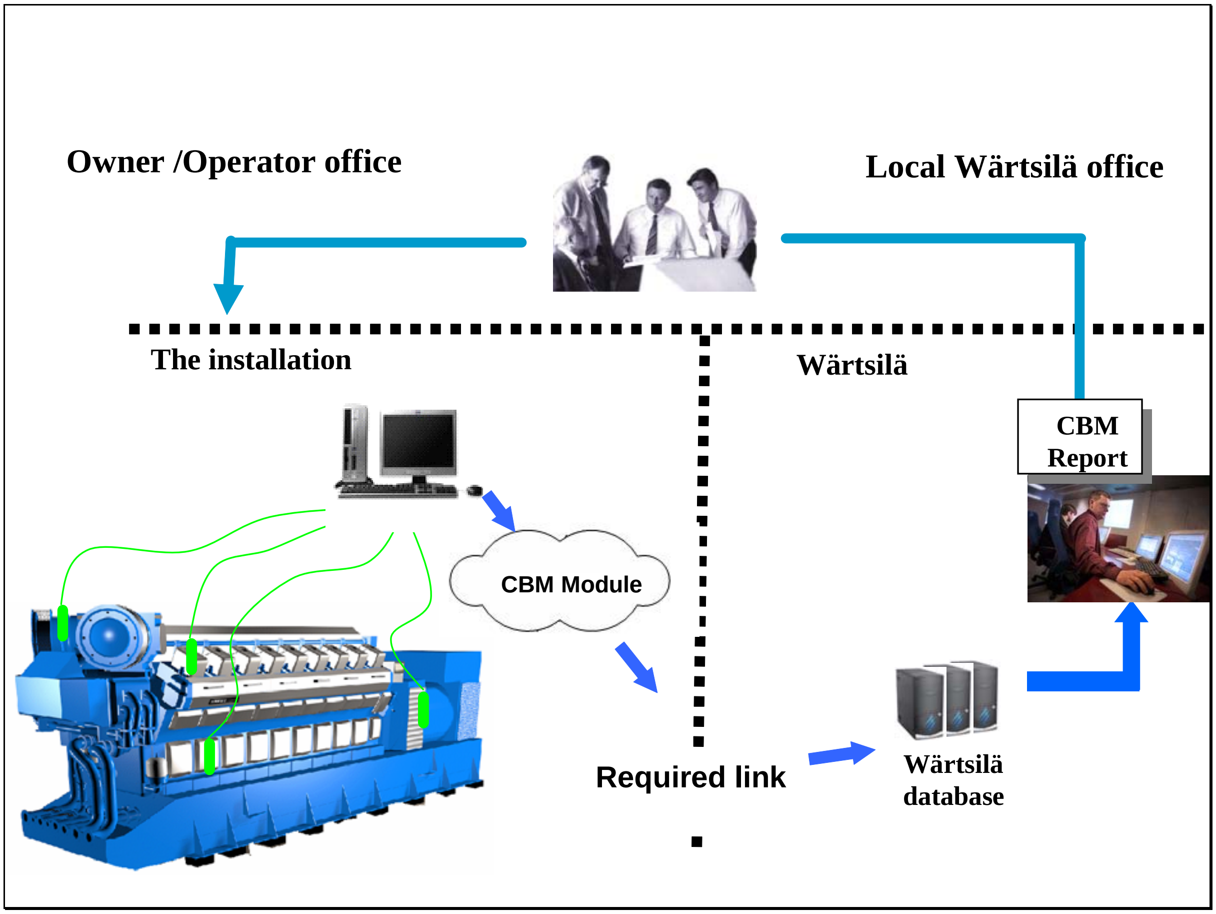

Figure 1.3. Condition-Based Monitoring for diesel-engines.

The use of modern communication means (Internet) allows for remote diagnostics.

In the following sections, a condition based health monitoring system for steerable thrusters will be presented. The same methods can be used for other type of propulsors, such as controllable pitch propellers, water jets etc.

In reference [7] it is mentioned that 80 % of the failures of controllable pitch propellers are due to sudden failures (called “chance” failures). It also mentions that these failures can not be prevented by planned maintenance, which is true. Sudden failures can be coped with by reliability analysis. The challenge is to find new ways to also cope with sudden failures in condition-based monitoring, by using a reliability model.

A typical failure distribution for steerable thrusters is as follows:

- Outside influence, human factors : 24 %
- Insufficient maintenance, wear and tear : 28 %
- Electronics and hydraulic actuation : 28 %
- Interface to ship : 16 %
- Design : less than 1 %
- Unknown : 3 %

The above distribution indicates, that a pro-active health monitoring system can extend the operational time of a vessel equipped with steerable thrusters.

2. Mechanical Steerable Thruster.

2.1. The construction.

When increased maneuverability of a vessel is required, the application of steerable thrusters is a logical option. Because of the ability to rotate around its vertical axis, propeller thrust can be generated at any different (azimuthing) angle.

In general, a steerable thruster consists of the following main components (see figure 2.1.):

- Propeller gear box: a hydrodynamically designed gear box that contains a bevel gear set. This gear set, supported by adequate bearings, transmits the power from the (vertical) input shaft to the propeller shaft, and thus to the propeller. Because the gear box is located in the water, high quality seals are applied at the propeller shaft.
- Upper gear box: this gear box also contains a bevel gear set. Power generated by the main engine is transferred from the horizontal input shaft to a vertical output shaft of the gear box.
- Stem section: this part of the thruster, which protrudes from the hull, is located between the upper gear box and the propeller gear box. In the stem section, all functions for rotating the thruster around its vertical axes are incorporated, e.g. a steering gearbox, steering feed-back unit.
- Auxiliaries: these contain all items related to the hydraulics of a thruster: power packs for the steering system, the lubrication, and, in case of a controllable pitch propeller, the pitch power pack.
- Controls: includes all control cabinets, starters of the E-motors, interfacing to control panels, necessary software, alarms.

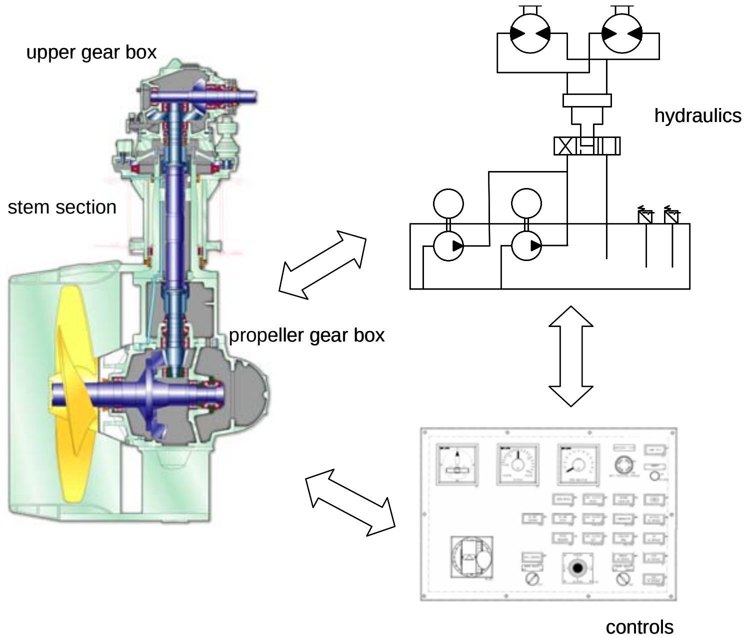

Figure 2.1. Main components of a steerable thruster, in general

For the CBM system sensors are mounted in the propeller gearbox. The location of these sensors is chosen in such way that a minimum of sensors is required whereas all bearings and gearing can still be monitored.

Nowadays a selection can be made out of thrusters with fixed and controllable pitch propellers in different configurations, like containerized, modular, compact, retractable, underwater (de-) mountable, can mounted or habitat mounted. LIPS thrusters can be found in large offshore applications as well as in tugs, workboats, suppliers and other seagoing vessels.

Two types of steerable thrusters are produces by Wärtsilä:

- LIPS Compact Thrusters (LCT).
  LCT's cover the range between 1000 and 3000 kW. They are composed of standardized modules. Different options can be choosen to fit the client's requirement.
- LIPS Modular Thruster (LMT)
  LMT's can be delivered in the range between 1000 and 7000 kW. Main modules are standardized. However, in order to best suit the clients wishes custom made solutions can be incorporated. Special requirements (e.g. special mounting like underwater mounting) can be delivered.

Both types of thrusters can be delivered in vertical drive configuration (L-drive) or horizontal drive configuration (Z-drive). Thrusters can be delivered with open propellers or with nozzles.

One of the special features in which a LIPS Modular Thruster can be delivered is the underwater mountable (UM) configuration.
With UM thrusters, the thruster consists of two parts: the so-called inboard part and the removable part.

The inboard parts comprises the steering and lubrication system, including the relevant power packs, piping systems and header tanks, main engine and (part of) the main drive train (including the upper gearbox in case of a Z-drive).

The removable part consists of the propeller gearbox, including the propeller and nozzle, and the stem section, i.e. the steering part of the thruster.

During the construction of the vessel, a separate part (steel works) is integrated in the vessel. In this part, called the receptacle, all relevant (hydraulic) connections are present for the proper functioning of the thruster. These connections are located at the same positions of the connections in the counterpart, in the removable part.
During the launching of the vessel the removable part is not mounted in the receptacle. Instead, a floating cover is mounted.
After launching this cover is removed by divers. Next, the removable part is hoisted from the main deck of the vessel into the water, and positioned below the receptacle. Three hoisting chains are used for controlled guiding of the removable part into the receptacle. Finally, the removable part is tightly secured to the receptacle, and the drive train is completed applying a vertical floating shaft. See figure 2.2.

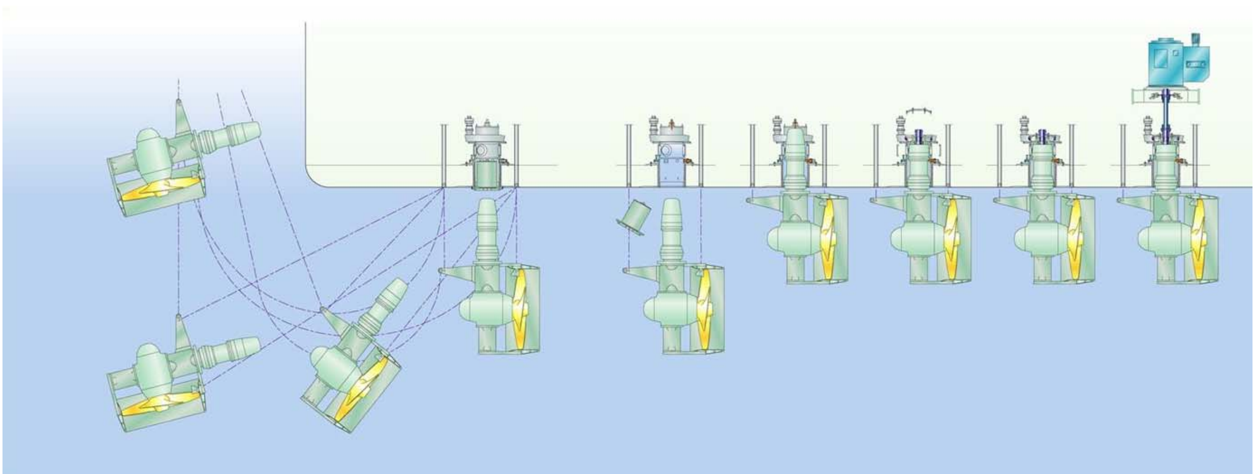

Figure 2.2 Installation of the out-board parts of an underwater mountable thruster

UM thrusters are best applied on vessels that are either too big to go into a dry-dock, or vessels that are intended to stay out of dry-dock for periods longer than the (classification prescribed) docking intervals. When a full inspection is required, the above mounting sequence can be reversed, thus demounting the removable part. Next, the removed part can directly be changed with a spare removable part. If not available, the vessel can be operated at limited power. The removable part can be overhauled either onboard or after shipping it to the shore.
In case a condition based monitoring system is applied to the UM thruster, early detection of faults can be established. Based on the severity of the fault the decision can be made to exchange the removable part of the thruster by the spare one that is onboard. In this way, there is no need to leave the present job and sail to a docking place. The thruster can be removed and replaced by a healthy one.

2.2. Present day maintenance practice.

Nowadays practice to guard the safety of a thruster is done by periodical maintenance and by acting on different alarms integrated in the system. Periodical maintenance implies daily checks, like checking gauges and checking excessive noise (routine maintenance). Periodical maintenance is related to the actual load on the thrusters and the number of operating hours. This type of maintenance, which is also mainly prescribed by the classification societies, consists of e.g. checking the condition of seals, bearings, and gear couplings.

Alarms can be activated in case of a sudden event. In case of external overload of the propeller of the thruster (e.g. grounding) a pressure alarm will be activated.
Alarms can also become activated when the condition of a parameter has deteriorated / changed over a certain period of time. An example of such alarm is the clogged filter alarm.

In this example, an action is performed after the alarm has been activated. If the filter is changed and no further actions are taken, it is not known what the cause of the clogging of the filter was. If, as a second action, the filter is examined to determine the properties of the particles in the filter, a possible cause of a failure or a deteriorating component can be identified. This, however, also indicates that this kind of guarding only provides information of the condition of the thruster if a failure has already occurred, or the deterioration of the component is already in an advanced state.

Applying a more active monitoring of the condition of the thruster can lead to a more early detection of a component that is not functioning properly.

A list of typical alarms and where they are applied is shown in table 2.1:

Alarm related to:	Applied on:
Temperature	Lubrication oil gearboxes
	Oil steering system
Pressure	Pump (lubrication / steering / pitch)
	Hydro-motor
	Filters
	Air pressured tanks
Level	Low / high level (header-) tanks
	Level of oil in gearbox

Table 2.1 Typical alarms for a steerable thruster

2.3. Failure cases.

Failures of bearings, gearing and seals can be considered more critical than other components. Although they are reliable and less susceptible to damage, they are not easily accessible, and thus require relatively more work in case of replacement.

Examples:

I. Effect of water ingress.
The following describes a possible failure of a bearing on the propeller shaft, caused by seawater entering the propeller gearbox.
1. Due to a shaft seal that was damaged by e.g. a cable or fishing line seawater ingress occurred.
2. As a result of the seawater the lubrication capabilities of the oil in the gearbox deteriorate. Lubrication of the roller elements in the bearing is worsening.

3. Because of lack of lubrication and due to the load on the bearings wear occurs. This involves both inner and outer raceway of the bearing, as well as the roller elements. See figure 2.3.
4. Wear particles spread through the lubrication oil. Some of these particles are caught by filter elements. Other particles end up in the gear mesh.
5. Because of the deteriorated oil quality in the gearbox and the presence of wear particles, the gearing also starts to show signs of wear. See figure 2.4.

Both wear of the bearings as the consequential wear of the gears can only be detected either by alarms of filters, or by examining oil samples. In case a bearing condition monitoring system is installed, early detection of wear of the bearings can be detected. Upon detection, the thruster can be put into a schedule for an overhaul. In the meantime, the thruster can be operated at a lower level.

Figure 2.3. Damaged raceway, result of bad lubrication

Figure 2.4. Gear mesh showing wear

II. Effect of impacts.
In case the propeller of a thruster is loaded by an instant force, e.g. by the impact of a foreign part in the water, this impact can lead to an immediate damaged bearing (split roller element, cracked raceway). Because this kind of failure does not show a graduate development that can be monitored, it can not be predicted. Using CBM it can only be monitored that the failure has happened. Shutting down the thruster can be the best solution, in order to avoid consequential damage, e.g. gear damage.
In case of softer damage, operation the thruster may be continued at a reduced level. This is indicated by the CBM system.

2.4. Performance.

When a steerable thruster responses to the demands of the azimuthing angle, the propeller speed and the pitch, such that the actual values follow the demands in a given time and settle with the required accuracy, one could say, that the steerable thruster performs well. It does not say that the steerable thruster is healthy. The World Health Organization defines health as a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. For machines a similar approach is used. To assess the machinery health, other parameters have also to be taken into account. This concerns the health of machinery elements. Which elements are to be taken into account, is subject to experience. The experienced design and service engineers are needed in this process.

Health monitoring gives a diagnosis of the current state of the machine. By use of advanced sensor technology it is able get more information from the machinery elements as simply looking at the device response. In this way slowly developing faults can be timely detected. Prognostics about the remaining life time depend on the trend of failure development. Prognostics build on proper diagnostics. Future developments using Bayes nets (reference [5]) on base of causal relations and historical data will allow for prognostics. However, the health monitoring presented in this paper is for diagnostics on slowly developing faults.

The machinery health on base of diagnostics can be quantified via fuzzification. This results in a health state number between 0.00 and 1.00. “0.00” means totally unfit for use, whereas “1.00” means fully fit for use.

3. Machinery Health Monitoring.

The central ships’ alarming system is well-known. By regulations each ship must have a type-approved central alarming system. This alarming system gives warnings and logs these, when a problem exists. All engineers on-board know that many times alarms are given without any significance, but it is dangerous not to accept the alarm. One alarm may be critical.
When real machinery problems occur, the alarm system log file mostly is used to reconstruct the sequence leading to the failure. This is experienced as boring and laborious searching activity. Still a lot of guesswork is needed as no tendency of signals is known.
Last but not least, the well-known alarming system is reactive. The engineer can not avoid the problem.

Later on other regulatory requirements came, such as to carry a voyage data recorder on-board. This voyage data recorder is intended to execute a diagnosis of the sequence of occurrences leading to an incident. These diagnostics also are reactive.

Machinery Health Monitoring is intended to be pro-active. Ideally, it tells the operator, which machinery component is affected and for which time the operational use of the machine is possible under a defined loading condition.
The objective of Health Monitoring is a better planning of maintenance periods on base of the actual health of machinery parts. Eventually the Health Monitoring system must give sufficient reliable predictions, that regular Class surveys can be replaced by maintenance based on the reported machinery health. This required high reliability of the predictions need the dynamic measurement of various machinery parameters, as well as decision making software. The confidence level must be high. The confidence level is defined as the percentage of actual machinery problems which are well predicted by the Health Monitoring system.

The present day approach for Condition-Based Monitoring of systems as steerable thrusters is the use of only accelerometers to determine the state of roller bearings and gears. These techniques nowadays are well developed (see reference [3]). The confidence level mainly is determined by the quality of the accelerometers and the installation of the accelerometers. The accelerometer must be suitable to measure rather small acceleration over a large bandwidth. This depends on the accelerometer design and the processing electronics, but also on how the accelerometer is installed in the steerable thruster.

Figure 3.1. depicts an accelerometer assembly mounted in a thruster pod. It measures the acceleration of the bearing marked as “B”.

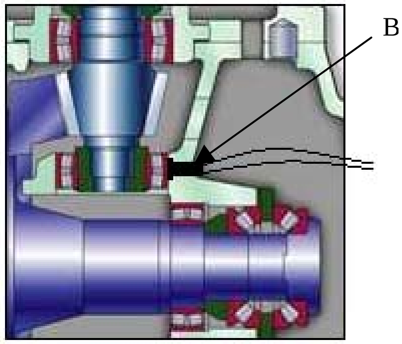

Figure 3.1. Accelerometer measuring health of bearing.

To get sufficient high confidence levels it is not sufficient to only measure accelerations. Lubrication and hydraulic oil quality must not be neglected (see reference [4]). Lubrication oil is to be treated as a construction element. It is essential for gears and bearings. It can be compared with blood in a human being. A lot of future problems start with inadequate oil quality or contaminated oil. Contamination may be due to foreign elements, internal wear processes or water ingress. Also additives can loose their effectiveness.
Another essential element in Health Monitoring is the dynamic response to demands. How do the actual steering angle and the propeller pitch respond to the demands set from the bridge? Are the required settling times and settling accuracies achieved? When these response characteristics are not achieved the dynamic positioning operation, as accurately keeping the required ships' position may be affected. Causes for not achieving the required response may be wrongly adjusted control systems, worn-out pumps, defective valves, leakage in oil distribution boxes or oil with too low viscosity.
During the control typical system parameters as leakage coefficients, valve gains, pump deliveries, actuating forces as well as oil temperatures are measured.

Having all information, it is important to intelligently fuse the measured data and automatically analyze these in order to derive a maintenance advice with the highest possible confidence level for the operator.

Figure 3.2. gives an overview of the structure of a Health Monitoring system.

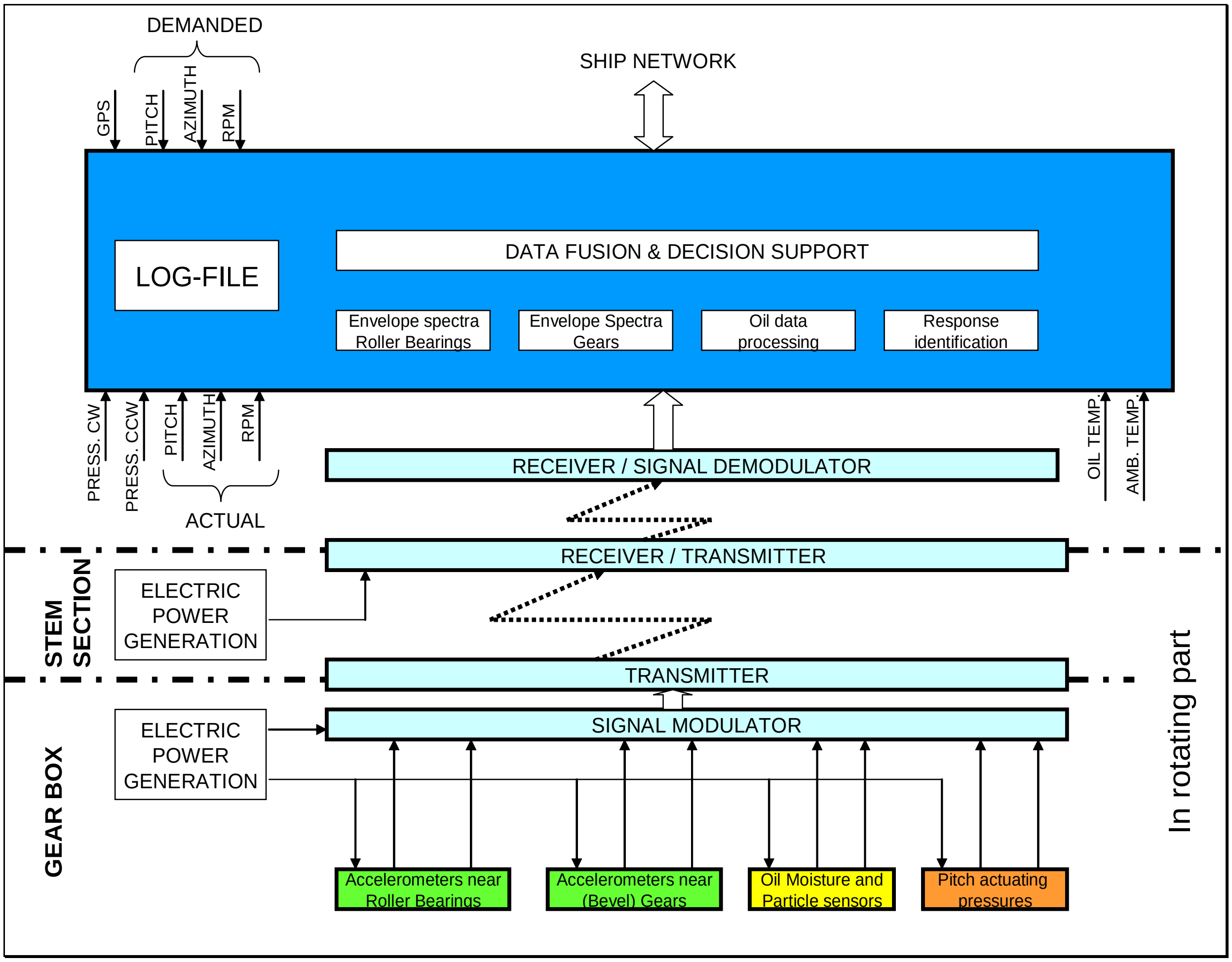

Figure 3.2. Structure of steerable thruster Health Monitoring system.

The reliability of the monitoring system must be a magnitude better than the machinery parts that are monitored.

3.1. Sensors.

Sensor technology is the base of Health Monitoring. The following sensors are used in addition to the sensors already present in the normal actuation control system:

- Accelerometers.
- Oil temperature sensors.
- Moisture in oil sensors.
- Particles in oil sensors.
- Pressure sensors.

To normalize various measurements at different propeller loading conditions the propeller pitch, the propeller rotational speed, the thruster azimuthing angle, the driving motor load and the ship surge speed through the water also is measured. These measurement data are taken from the normal actuator follow-up control system.

Future developments are the application of an on-line oil sensor based on spectroscopy, which will enable the system to detect degrading oil additives, which are needed for proper lubrication of gears.

Sensor technology has seen a quantum leap in development during the last decade. A good example is the development in micro-machined (MEMS) sensors, which also give a drastic cost reduction and an increase in reliability. Reference [2] gives a comparison between the well-known piezoelectric sensor, presently mostly used for bearing and gear vibration monitoring and a MEMS sensor. Since the study has been completed new MEMS accelerometers have been developed with noise levels and a sensitivity, which can meet those of the piezoelectric sensor. In general accelerometers for vibration monitoring must have a measurement range of 2 [mg] to 60 [g] with a bandwidth of more than 5000 [Hz].
Not only the accelerometer characteristics are of importance, but also how and where these are installed. Vibration levels are attenuated in metals and mounting connections. This attenuation level determines the best location of the accelerometers.
Pressure sensors also are MEMS type sensors, giving small dimensions and a high reliability.

Oil parameter sensors are installed in the storage tank, except for the moisture and a particle sensor, which are installed in the pod.

The sensors must comply with certain characteristics in order to be suitable for the task. The main characteristics are:

- The accuracy, bandwidth and threshold must comply with the physical characteristics to be measured.
- The sensor reliability in the machinery environment must be far higher than the reliability of the machinery system to be monitored.

The above requirements seem to be obvious, but are in many cases not explicitly dealt with, which causes big problems in the later application.

3.2. Data processing.

Data processing consists of three layers:

1. **Signal level**: checks health of signal received from the particular sensor and warns when wrong. It also scales the signals to engineering data.
2. **Signal analysis** level to find characteristic values.
3. **Decision level**. At this layer data fusion happens and decisions are taken for advising the operator.

Sensor data from the rotating part is transmitted at a high data rate by a wireless transmission system.
The data processing requires a powerful system, because of the high data sampling rates and the amount of calculations.
The aim of the data processing is to reduce the measured sensor data and to deduct conclusions for the owner.
Eventually the reduced data can be transmitted to the ships' local network for feed-back the various offices via the Internet.
The interface from the data processing unit to the ship's network is of a certified open industry standard (Real-Time Ethernet or another field bus protocol).

Figure 3.3. shows a roller bearing. A roller bearing can have a slow developing fault. The roller bearing possesses a number of typical frequencies:

- ball pass frequency outer raceway
- ball pass frequency inner raceway
- the ball spin frequency
- the fundamental train frequency

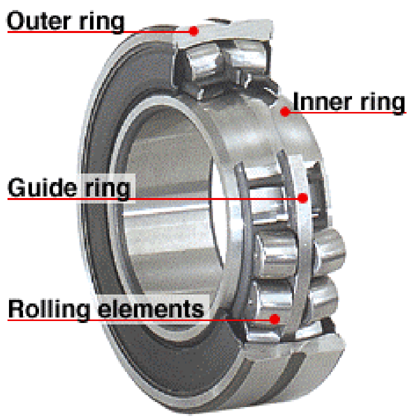

Figure 3.3. Roller bearing.

Several proven techniques based on acceleration measurements and frequency have been developed to detect these frequencies and to deduct a malfunctioning bearing from these measurements.

For gears also proven techniques, based on acceleration measurement exist to find beginning faults.

Figure 3.4. shows frequencies related to a roller bearing and the frequency related to a gear mesh.

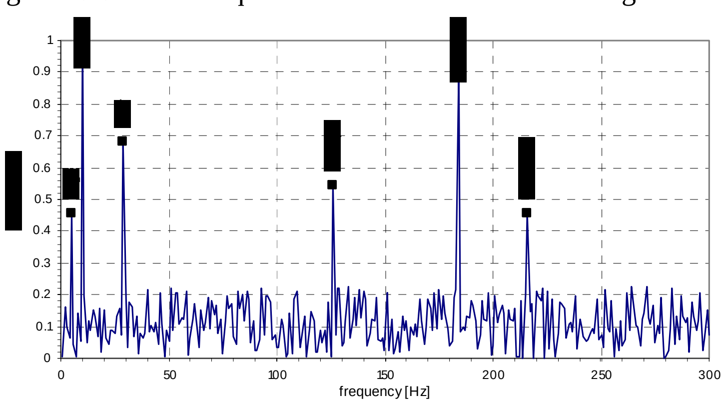

Figure 3.4. Typical frequencies related to roller bearing and gearing

By measuring the pitch and azimuth response to the demands from the dynamic positioning system and the oil temperature and moisture content, critical parameters as oil-distribution box leakages, degrading oil, and hydraulic pump and valve degradations can be identified.

Pitch actuation characteristics and propeller performance are other parameters, which can be taken into account.

3.3. Data fusion.

The sensors and data-processing for each particular parameter produces overlapping information. The individual results of the processed data per parameter many times can not give conclusive results. Data fusion is meant to give health results with a higher confidence level as is possible when looking only at the individual results.

A typical example of data fusion is the acceleration measurement of roller bearings and gears in conjunction with the lubrication oil. For example gear vibration frequencies higher than the gear-mesh frequency can be caused by beginning wear, but also by bad lubrication. By fusing the oil quality measurement and the vibration spectra, a decision can be made for the operator. Either the propeller loading is to be reduced to extend the useful life of the thruster or the lubrication oil is to be renewed. The operator saves time by having the precise information.

The classical approach for data fusion is based on the Boolean method of the “failure tree”. It is based on two possibilities: YES or NO. For example, when the water content in the oil is above a certain level and when a certain gear vibration level is measured, the conclusion can be drawn to discontinue the use of the particular thruster. This method does not give a proper trend in decision making.

Fuzzy techniques are more appropriate than the Boolean method. Fuzzy techniques use linguistic rules, which are understandable for a human being. It follows the natural way a human being is thinking in fault diagnosis. Contrary to neural networks it is not self-learning. However for the purpose of diagnosis and trend analysis it is well suited. It is used to calculate the health state number.

Data fusion has been strongly developed by applying the theoretical work of A.P. Dempster (reference [5]) and G. Shafer (reference [6]). Other than the Boolean method of the “failure tree”-based Failure Mode and Effect Analysis and the fuzzification approach, this method introduces uncertainty and subjectivity. It allows the use of subjective historical information of experienced field engineers.
The Dempster-Shafer approach is based on obtaining a degree of belief for one occurrence from subjective probabilities in conjunction with a related question. Dempsters’ rule combines the various beliefs with independent items of evidence to decisions. It is similar to a self-learning neural network. The method can be used for future prognostic systems.

3.4. Human Machine Interfaces.

The decision taken by the data fusion algorithm within the electronics on-board must be used by the operator for maintenance scheduling. The data also can be used as constraint for the thrust allocator of the dynamic positioning system. Another use of the data is the avoidance of operating the thruster outside its safe operating envelope. These aspects are dealt with in section 4.

The operator on-board has various machines. The operator can not have detailed knowledge of all machines. Machinery Health Monitoring is meant to make life easier for the operator. This means that clear graphical user interfaces are required, both on-board and at the home base of the owner. These graphical user interfaces are to be very close to known standards and are to be in compliance with Internet standards. Ideally the operator gets a picture showing a 3D drawing with the affected machinery element.

4. Operational aspects.

This section explains how machinery health data can be used for maintenance purposes and for an improved thrust allocation of the dynamic positioning system.

4.1. Human factors.

For each propulsion and /or steering device the availability for the intended operation counts. The device should response with a known accuracy to the demand. The crew on-board should be able to easily understand abnormal behavior of the device, which could result in future unavailability. The Health Monitoring should provide the automatic diagnostics to ease this understanding and to advice the crew for corrective actions.
A ship is equipped with many machinery systems. It would be a big burden for the crew, when each machine has its own unique electronic system with its unique Human Machine Interface (HMI) for Health Monitoring. Hence some form of standardization is required. The supervising of the machinery normally happens in the machinery control room. It is here where all machinery must be accessible for Health Monitoring actions. A similar approach is presently followed by the ships' central alarming system.
The above means that central access from the machinery control room to various decentralized machinery Health Monitoring systems must be possible. For this purpose the Web-Server is used and communication from the central machinery control room happens via the (real-time) Ethernet ship network. This also allows for remote access for tele-diagnosis.

The interaction with the graphical user interface must be very intuitive. It must be self-guiding without the need of user manuals.

The Health Monitoring system is organized, such that the decision layer for each machinery system issues a warning, when an abnormality is detected. The operator on-board can then select the monitoring page for the particular machinery system. The abnormal functioning element will be shown in the 3D drawing, including numerical and text information. The latter advises for further actions.

4.2. Thrust allocation.

Figure 1.1. shows a typical semi-submersible steerable thruster configuration. Eight steerable thrusters are installed, i.e. two forward, four mid-ship and two stern.

Figure 4.1. shows the lay-out of the steerable thrusters. The tasks of the thrusters is to deliver two joint thrusts, i.e. the surge thrust and the sway thrust, and one moment, i.e. the yaw moment. In no wind and no current conditions, as well as flat sea conditions, only two thrusters could position the semi-submersible. Even under the most adverse weather conditions not all thrusters are required in accordance with regulations for these types of vessels. This means that for the same required surge and sway thrusts and yaw moment, many solutions exist. The amount of thrusters is selectable as well as the setting in propeller pitch or speed and azimuthing angles. I.e. a high degree of over actuation exists.

The dynamic positioning system is equipped with a module, called thrust allocator. The inputs to this module are the surge thrust demand, the sway thrust demand and the yaw moment demand. These demands are calculated by the higher layer controllers, which compare the demanded vessel position with the measured actual vessel position. The task of the thrust allocator is the distribution of the thrusts vectors among the various devices, such that the vector sum of these device thrusts results in the required surge and sway thrusts as well as the required yaw moment.

For the thrust allocation various constraints exist, such as:

- Limit of thrust: saturation per thruster.
- Minimum energy consumption for position keeping.
- Rate-limits of devices for pitch, speed and azimuth angle.
- Thruster / thruster and thruster / hull interaction, resulting in forbidden azimuthing angles.
- (In) accuracy : difference between demanded and actual device setting for pitch and azimuthing angle.

Various iterative mathematical techniques exist to deal with these constraints.

As practical future application of health monitoring a new constraint could be added: the health state number as per section [2.3]. In the present day solution, a thruster is switched off, when it is not ready for use. This binary approach could be replaced by a more smooth approach, i.e. by using the health state number.

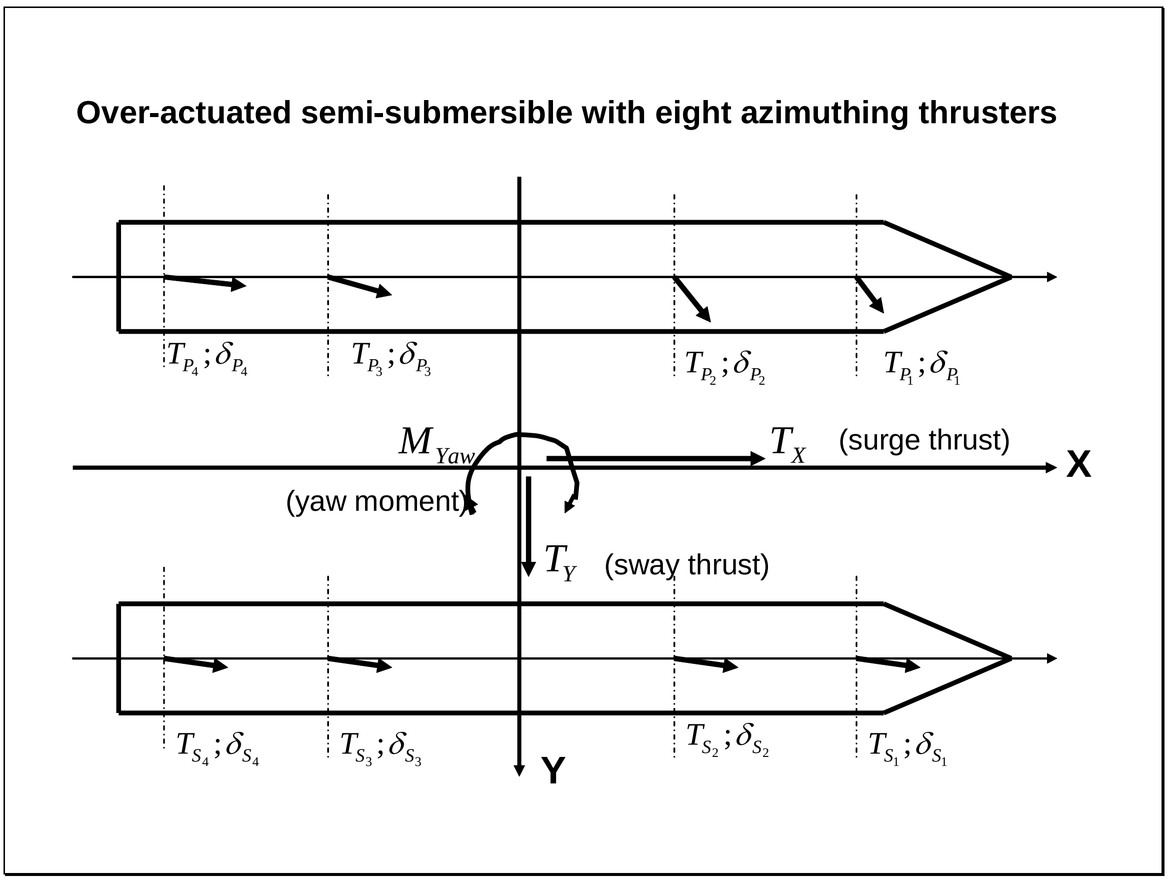

Figure 4.2. Thruster lay-out of a semi-submersible

5. Conclusions.

Machinery health monitoring is a valuable tool for the operator to avoid in many present day failure cases the unexpected shut-down of the machinery, however sudden failures can not be excluded.

Future Machinery monitoring may be in the direction of predicting the remaining life by prognostics, but at present more knowledge must be gained in the development of slowly progressing failures. New methods, as the Dempster-Shafer theory will certainly be needed for prognostics. Also new and lower cost sensor developments are needed for good prognostics.

Diagnostics for slowly developing faults, ahead of the need for a total shut-down of the machine is quite well possible with the present state-of-the-art.

Reliability of Dynamic Positioning and Dynamic Mooring systems mainly rely on the redundancy (duplex, triplex) of the main components of the positioning systems and the machinery systems. The condition of the machinery systems is watched by periodical checks and (intermediate) surveys, either prescribed by the operator or by the class societies.
Present working methods do not consider closely monitoring the continuous state of components, offering the possibility to predict the remaining lifetime of the components.

With a Condition Based Monitoring system the condition of main components of the propulsion units can be monitored, resulting in:

- early detection of deterioration of components like bearings and gearing
- reducing the risk of unplanned maintenance and dry-docking
- decreasing stock
- decreasing down time
- withdrawal or postponement of inspection intervals

all resulting in saving money.

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