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Advanced ship systems condition monitoring for enhanced inspection, maintenance and decision making in ship operations

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Abstract

Structural and machinery failures in the day-to-day ship operations may lead to major accidents, endangering crew and passengers onboard, posing a threat to the environment, damaging the ship itself and having a great impact in terms of business losses. In this respect, this paper presents the INCASS (Inspection Capabilities for Enhanced Ship Safety) project which aims bringing an innovative solution to the ship inspection regime through the introduction of enhanced inspection of ship structures, by integrating robotic-automated platforms for on-line or on-demand ship inspection activities and selecting the software and hardware tools that can implement or facilitate specific inspection tasks, to provide input to the Decision Support System (DSS). Enhanced inspection of ships will also include ship structures and machinery monitoring with real time information using 'intelligent' sensors and incorporating structural and machinery risk analysis, using in-house structural/hydrodynamics and machinery computational tools. Moreover, condition based inspection tools and methodologies, reliability and criticality based maintenance are introduced. An enhanced central database handles ship structures and machinery data. The data is available to ship operators and are utilized by the DSS for ship structures and machinery for continuous monitoring and risk analysis of ship operations. The development and implementation of the INCASS system is shown in the case of a machinery system of a tanker ship. In this way the validation and testing of the INCASS framework will be achieved in realistic operational conditions.

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Keywords: ship safety; structures; machinery; condition monitoring; real-time data; decision making

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1. Introduction

Regular structure and machinery failures in the ship operations may cause hazardous accidents. These casualties can endanger crew, passengers onboard, posing a threat to the environment, damaging the ship itself or third party property. Any of these accidents may cause business performance instability of reputation and income loss. Moreover, with the introduction and building of a large number of new ships, their monitoring and inspection from both regulatory bodies and Classification Societies has become more and more difficult in order to obtain the optimum inspection results and eliminating the hazards posed by high-risk and sub-standard ships. In this respect, the INCASS project aims to tackle the issue of ship inspection by enhancing cooperation of maritime stakeholders aiming to avoid ship accidents, promote maritime safety and protect the environment (EC, 2009). INCASS project introduces innovative solutions to ship inspection regime. The proposed solution establishes a flexible framework by taking into account both ship structures and machinery and equipment. The introduction of enhanced inspection of ship structures combines robotic-automated platforms for on-line or on-demand ship inspection activities.

Ship machinery risk assessment involves the design and implementation of a reliability tool for probabilistic failure case scenario analysis. The presented tools facilitate specific inspection tasks and provide input to the Decision Support Systems (DSS) for both structures and machinery. The Structural and Machinery Risk Assessment tools (SRA and MRA respectively) are integrated with an enhanced central database including ship structures and machinery data available to ship operators and crew members. The deployment of the overall INCASS framework will be based on case studies such as a tanker, a bulk carrier and a container ship. In this way the validation and testing of the INCASS framework will be achieved in realistic operational conditions. INCASS comprises dedicated and experienced partners including universities such as the University of Strathclyde Glasgow (USG), Universitat De Les Illes Balears (UIB), Classification Societies such as Lloyd’s Register EMEA (LR), RINA Services SPA, Bureau Veritas (BV), ship owners/managers (Danaos Shipping Company and AP&A) service providers (Glafcos Marine., Atlantec Enterprise Solutions GMBH (AES), Technicas Y Servicios De Ingenieria S.L. (TSI), Shipcon and research institutes such as Deutsches Forschungszentrum Fuer Kuenstliche Intelligenz GMBH (DFKI).

The first section of this paper introduces INCASS project, followed by the research background on ship structures and machinery Condition Monitoring (CM) as well as known CM assessment tools. The next section demonstrates the INCASS framework and developed tools (i.e. SRA, MRA, DSS and central database). The application of MRA is established through a case study combined with the practicalities of the MRA-DSS approach. The next section demonstrates the case study results followed by discussion, conclusions and future work considerations.

2. Literature review

Research background undertaken for this study shows that ship accidents can frequently lead to failure of structures and machinery. Particularly, the latter increases the risk for humans, environmental damage and pollution, damage or loss of property and distraction of the ship’s functioning which consequently direct to operational losses. Hence, the maritime bodies such as Flag states, Port State Control authorities and Classification Societies have increased their cooperative efforts towards the promotion of safety the last years. In all cases, all bodies attempt to preserve the highest standards in the maritime industry while at the same time make every effort in order to minimize the high-risk and sub-standard ships.

In this respect, maintenance structure is transformed from budget gain perspective to investment for continuous, safe and reliable asset service. This can be perceived as maintenance’s transition through time from a reactive manner to a more proactive approach. It is commonly found that inspection and maintenance departments in shipping companies are the largest in work force and expense (Dikis et al., 2015). On top of the above, ship managers/operators still try to find a way to combine the rich practical knowledge acquired in the actual marine field with the technological advances stemming from the relevant information technology sector in an effective way. The latter comes in addition to the effects of not applying the appropriate maintenance sequence onboard a ship. This section presents briefly the latest aspects with regard to Hull Condition Assessment (HCA), image recording and processing, Condition Based Maintenance (CBM) and CM technologies and tools.

2.1. Hull Condition Assessment (HCA)

HCA involves the CM and reliability analysis of the structural members of ships. Hence, HCA ensures the vessel's ability to sail safely by taking into account precondition parameter for the ship herself and the crewmembers. Furthermore, HCA performs a key role in inspection and maintenance as the ship's hull and the structural members have a significant monetary value for ship operators. An accurate and well-designed HCA allows for better scheduling of maintenance activities and prohibits failure propagation effects by reducing the risks.

The need for HCA in the maritime transport sector has been identified by two European Commission (EC) funded research project presented by Barltrop et al. (2010) and Emmett et al. (2011). Both projects propose decision support tools to assist in the decision making process, prediction for possible areas of defect depending on various parameters. The parameters are listed as ship's type, age and size, with knowledge/information collected from past experience (databases) and updated with current survey data. On the other hand, INCASS project aims to utilize real-time information and integrate it with the influence of the hydrodynamic performance of the ship. This is an approach that existing research has not considered so far. Moreover, the analysis is performed on risk-based approaches, thus identifying the critical ship structural areas and consequently ships.

2.2. Vessel's defect detection utilizing image processing

The automated or semi-automated inspection of vessels has been the goal of a number of previous research and engineering efforts, with both a commercial (Newsome and Rodocker, 2009) and research and development orientation. Most of them refer to the inspection of the external part of the hull by means of Remotely Operated Vehicles (ROV) Akinfiev et al. (2008) and Cormack (2006), while just a few proposals use unmanned vehicles, e.g. see (Damus et al., 2006). The main goal of these systems was to assist with the detection of the loss of the external coating, detection of accelerating corrosion, detection of artificial objects attached to the hull, and weld inspection. INCASS project aims to tackle this issue by developing and utilizing autonomous vehicles such as quadcopters and magnetic crawlers for image recording and automated processing.

2.3. Condition Based Maintenance (CBM) methodology and monitoring technologies

The scope of CBM and fault diagnosis as defined by Mechefske (2005) is to detect the upcoming failure before even incipient failures take place, enhancing machinery's availability, reliability, efficiency and safety, by reducing maintenance costs through controlled spare part inventories. In the industrial domain, SKF (2012) supports that CBM clarifies risks and predetermination of strategic actions. Hence, implementation of CBM should lead to reliability and cost reduction by integrating information and management of critical components for time reduction of expensive and challenging maintenance phases such as dry-docking and overhauling. In this case, Condition Monitoring (CM) technology is applied through various tools, recording and evaluating measurable parameters such as vibration signal analysis, thermography and lube oil analysis. These technologies are assessed and considered for the purpose of INCASS project as actual validation of the designed methodologies will be carried out by involving recorded data for three ship types (i.e. tanker, bulk carrier and container).

Vibration monitoring is mostly applied on rotating machinery as it can detect unbalanced rotating machinery parts, excess sleeve or bearing wear, misalignments, damaged gear teeth and damaged bearings. The data record involves measurement of physical magnitudes such as displacement, velocity or acceleration (INCASS, 2014a). This measurement is converted into a proportional electrical signal that can be examined into fundamental frequencies. On the other hand, thermography is CM tool applicable to both electrical and mechanical equipment, and is deployed to identify hot and cold spots providing early signs of equipment failure. According to Bagavathiappan et al. (2013), Infrared Thermography (IRT) is one of the most accepted CM tools. Due to the non-contact function is suitable for detecting structural, machinery, electrical and material malfunctions. Recording handheld devices are used such as thermal cameras and thermometers. The third under assessment CM technology is lubrication oil analysis. According to Jiang and Yan (2008), oil analysis is achieved through laboratory concentration analysis in lubricant, which deals with shape, size, composition of wear particles and lubricant degradation analysis for physical and chemical characteristics. Lube oil analysis is time consuming as it requires transportation of oil samples from the ship to onshore. However, it seems to be the most efficient diagnostic tool as from a small amount of fluids the condition of the entire lubricant in each machinery can be determined.

3. INCASS framework

The overall INCASS platform is embedded in two explicit areas, the onboard environment (i.e. local) for technical decision-making and the onshore (i.e. global) for economic and maintenance planning. The INCASS framework incorporates ship structure and machinery related data gathering, assessment and risk and reliability evaluation. Three tools are developed within the inspection capabilities framework as shown in Fig. 1, the Structural and Machinery Risk Analysis tools (SRA and MRA respectively) and the central database for data processing.

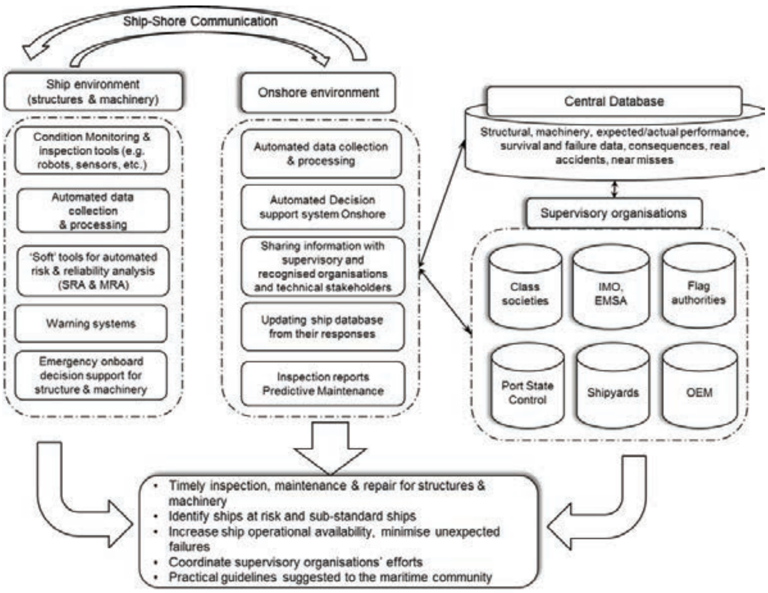

Fig. 1. INCASS framework.

Each tool is integrated with a DSS assisting for maintenance scheduling. SRA tool integrates traditional structural load assessment techniques with innovative real-time CM. The project platform introduces new pattern recognition and image processing methods by employing robotic platforms and state-of-the-art technologies for vessel status data collection such as quadcopter and magnetic crawlers. SRA and MRA tools employ automated risk and reliability analysis methodologies using various types of data. These input data types are listed among historical, expert and real-time monitoring sensor data. The ship's structures and machinery condition is performed leading to warning systems in emergency cases. Hence, the output of these tools is led into onboard DSS for structures and machinery aspects, enabling decisions for maintenance actions. Last stage of the INCASS framework processes involves the transfer of outcomes of the DSS to the central database. These results consist of inspection reports and predictive maintenance tasks, which are in place onshore updated with maritime stakeholders' responses as well. In this case, the central database comprises of information for ships' structures and machinery, their expected and actual performance, survival and failure data as well as potential failure consequences. This in turn enables the central database being updated including the latest information.

4. INCASS developed tools

INCASS project consists of three main tools. These are the Structural and Machinery Risk Analysis (SRA and MRA) and the central database. Their functionalities and innovations are examined and analyzed in this section.

4.1. Structural and machinery risk analysis

Firstly, input data from various source are gathered. The data types involve historical from previous ship inspections (e.g. digitalized and hard copies, surveys, annual reviews and actual ship accidents), expert input/judgement that is introduced in the DSS and real-time sensor data for current state control and reliability predictions. Furthermore, external databases are considered such as Offshore Reliability Database (OREDA), which includes failure rates for components and maintenance intervals. The combined input data from these sources are fed into the SRA and MRA soft tools. At first, SRA involves elements such as Risk Based Inspection (RBI) and structural inspection oriented towards the risk analysis results. The structural real-time information gained from robots is used to check the current-status of the ship structure for the DSS. The inverse Finite Element Method (iFEM) approach for real-time monitoring of structures is utilized to assist both the calibration process and the overall DSS.

On the other hand, MRA takes into account the Reliability and Criticality based Maintenance (RCBM) process for specified machinery systems (Lazakis and Olcer, 2015). The classification of reliability level per system, subsystem and component is considered into a measurable approach, enabling ship risk management and comparison of reliability performance for hierarchical maintenance action planning. Various reliability modeling tools are reviewed such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and Bayesian Belief Networks (BBNs) in order to select the appropriate for the INCASS MRA modeling requirements. The selected quantitative risk tool is the BBN as it allows modeling flexibility and system, subsystem, component interconnectivities. The latter feature is an innovative approach of assessing interdependencies among components. Furthermore, BBN allows the implementation and integration of decision and cost parameters. MRA tool considers the time dependence of system, subsystem and component degradation performance. In the case of dynamic modeling, the time dependencies and state division of the reliability input are developed in parallel with the BBN model by employing the mathematical tool of Markov Chains (MC) (Fort et al., 2015). MC is mathematical approach of modeling the state transition through time intervals. The entire development of MRA and DSS is carried out in--house by utilizing JAVA Object Oriented Programming (OOP) language. This programming language is chosen due to the cross platform features and the flexibility of executing processes in any Operating System (OS).

The soft tools (SRA and MRA) interact with the INCASS central database and their DSS. The short-term decision making tool includes the data mining process giving warnings of impending high risk and eventually providing decision support following a ship incident. A maintenance management system is employed for the long term decision support, so as to detect the required maintenance activities, arrange for the approval of maintenance and repair jobs to be performed onboard as well as enable the provision for spare parts and logistics requirements from OEMs and suppliers.

4.2. Central database

The central database is considered as the collection point of structural and machinery raw, pre-processed, processed and predicted data and risk analysis takes place through the use of new developed tools. The data sources are classified among existing designs from Classification Societies, CAD designs, as well as ship and system specifications and description. The Hull Condition Monitoring (HCM) adapter permits import of structural design details and life-cycle information. Once the required information is imported the initial risk analysis and assessment calculations take place. Hence, the system functions on decision support mode. Furthermore, while ship operates, updated information is available and it is added on-board as recorded real time sensor data. As a result of a large amount of input data, pre-processing and filtering take place before the data is stored in the system. In a similar manner, outcomes from inspections are added by inserting the results using HCM adapter. Consequently, when updated data is available, the risk assessment iteratively is repeated.

5. INCASS MRA and DSS case study

INCASS project consortium consists of partners such as universities, Classification Societies as well as ship operators, managers, owners and service providers. Hence, the inspection and maintenance CM requirements differ among the INCASS members. Thus, an extensive research took place (INCASS, 2014b) in order to examine those requirements and specify on the machinery and equipment selection that INCASS project will focus on. Moreover, a case study on MRA is presented utilizing a marine diesel engine. On the other hand, a case on the MRA DSS shows the tool's functionalities and the model's application.

5.1. Stakeholders' requirements

The INCASS project stakeholder requirement assessment examines the prerequisites of Classification Societies and ship operators, managers, owners and service providers. The role of Classes is to check that safety standards of ships are met throughout surveys, inspections, tests and controls. Hence, the introduced CM technology has to ensure that ship machinery and equipment demonstrates relevant acceptable and safe reliability and operational levels. All ship related stakeholders have the greatest interest in collecting ship machinery and equipment data for a number of reasons. From ship operators, managers, owners, service providers' perspective, the reasons for monitoring and collecting information on ships are related to environmental protection, human safety onboard, minimizing business risk and costs. In INCASS stakeholders' requirements specification, a comparative research study is considered. The systems that project members agreed on their operational importance ensuring all considered requirements are the Main Engine (M/E), Turbochargers (T/C), critical selected pumps such as ballast, steam powered tanker ship cargo pump, cooling water, firefighting and fuel oil pump and steering gear system.

5.2. DSS and MRA case study model arrangement

First of all, Fig. 2 presents the MRA DSS analysis of failure predictions through a user-friendly Graphical User Interface (GUI). The user has available information related to cost analysis, maintenance actions, reliability performance predictions and symptoms due to reliability loss. In Fig. 2 is shown the current subsystem and component reliability performance and the associated warning and failures.

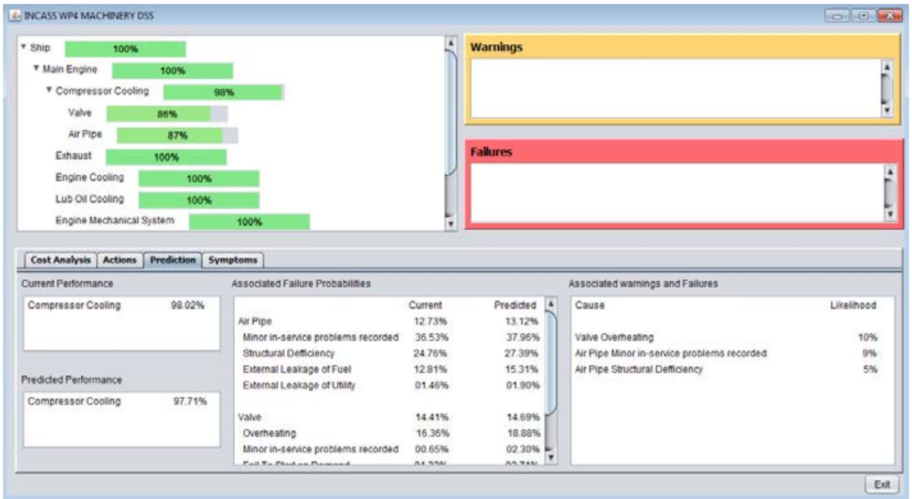

Fig. 2. MRA DSS Analysis of failure prediction.

On the other hand, Fig. 3 demonstrates the symptoms tab in a graphical format and five days prediction in advance from the current moment. The graphs are presented in days for this occasion and with the grid marking four-hour intervals on the time axis. This is to coincide with the regular four-hourly visits the engineers onboard the ship perform.

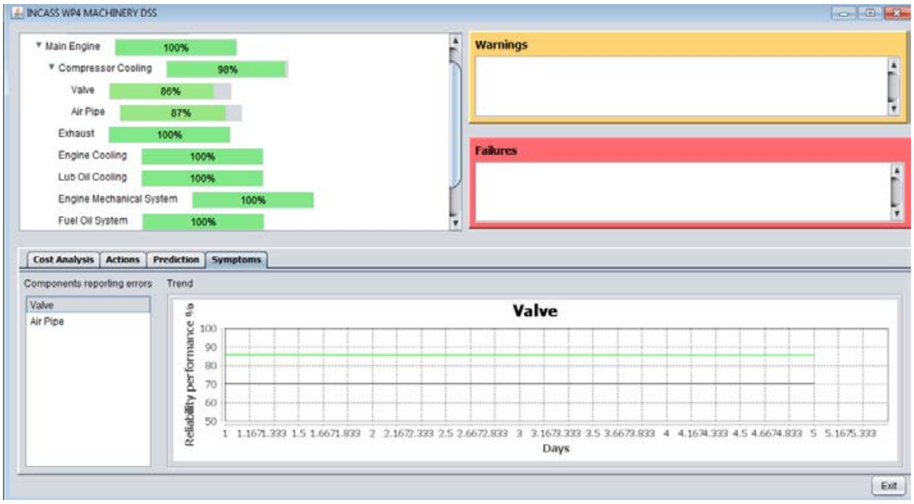

Fig. 3. MRA DSS Graphical representation of component trend.

The MRA case study involves the main engine system, the cooling and the engine block subsystems and their components as shown in Fig. 4, whereas the DSS case study demonstrates the cooling subsystem of the main engine. Furthermore, various failure modes are taken place by linking the reliability performance on system, subsystem and component level with defects.

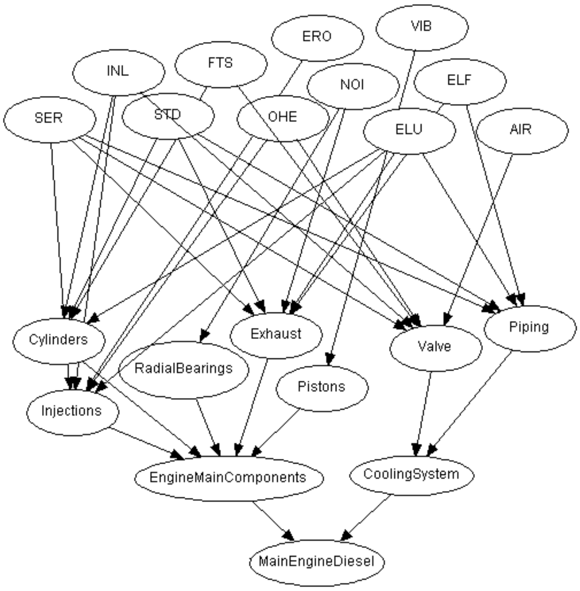

Fig. 4. Main Engine MRA network.

The failure modes provide the initial input data sourced by OREDA. The input data is linked with at least one of the components' nodes. On the other hand, the components are arranged in subsystems and the latter in systems. The two involved subsystems are the engine block and the cooling. The first subsystems consists of components such as cylinders, injections, radial bearings, exhaust and pistons. The cooling subsystem involves the valve and piping. Table 1 lists the failure mode selection for the MRA main engine case study.

Table 1. Failure mode selection for MRA main Engine.

Abbreviation	Meaning
AIR	Abnormal Instrument Reading
ELF	External Leakage of Fuel
ELU	External Leakage of Utility medium (i.e. lubricant, cooling water)
ERO	Erratic Output
FTS	Fail To Start on demand
INL	Internal Leakage
NOI	Noise
OHE	Overheating
SER	Minor in-service problems
STD	Structural Deficiency
VIB	Vibration

5.3. MRA case study model results

This section presents the MRA results of the M/E case study. The outcomes are demonstrated on component, subsystem levels. Fig. 5 (left) demonstrates the degradation on the engine block and cooling subsystems and the components that they consist of. The case study shows mean working reliability performance of cylinder at 86.5%, exhaust at 90%, injections at 76.65%, pistons at 99.74%, radial bearing at 99.93%, piping at 87% and valve at 77.4%. On subsystem level, engine block performs 92% and cooling 94%.

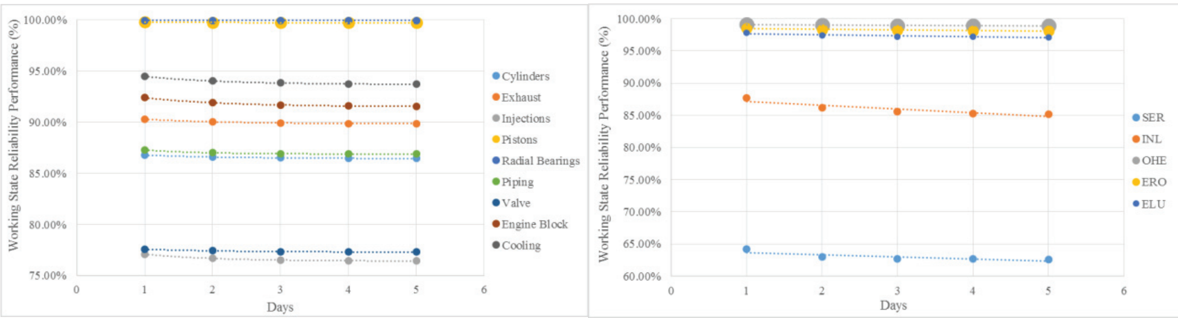

Fig. 5. M/E reliability performance at subsystem and component levels (left), injection at failure mode level (right).

On the other hand, Fig. 5 (right) shows the reliability performance of injections at failure mode by prioritizing the most probable to cause failure. The results are validated by industry experts such as ship owners, operators and service providers. Most of the outcomes show acceptable operational levels. However, the upcoming research phase involves the identification of warning levels and specification of the lowest acceptable reliability outcomes. These warnings and safety levels will include manufacturers' maintenance considerations, Classification Societies' policy and International Standards Organization (ISO) concerns. In a similar manner, Fig. 6 demonstrates the working state reliability performance at component level with respect to the involved failure modes. The relation among components and failure modes is utilized according to records of the historical preprocessed data. Hence, Fig. 6 presents the reliability performance of Main Engine's (M/E) cylinders, pistons and radial bearings. Firstly, cylinders are predicted to be affected by External Leakage of Utility medium (i.e. lubricant, cooling water) (ELU) at 98%, Fail To Start on demand (FTS) at 90–92%, Internal Leakage (INL) at 97% and Structural Deficiency (STD) at 90–92%. Lastly, pistons are predicted to fail due to Vibration (VIB) and radial bearings due to Noise (NOI) from 90% degrading down to 88%.

The predicted results of the working state reliability performance at component level with respect to involved failure modes demonstrate acceptable operational levels according to experts. However, pistons and radial bearings seem to perform the lowest reliability and cause of this reliability loss has to be identified in future planned research work in order to classify, prioritize and suggest inspection and maintenance actions. These inspection and maintenance actions aim to enhance the reliability performance, increase the overall Main Engine's (M/E) availability and decrease the operational costs.

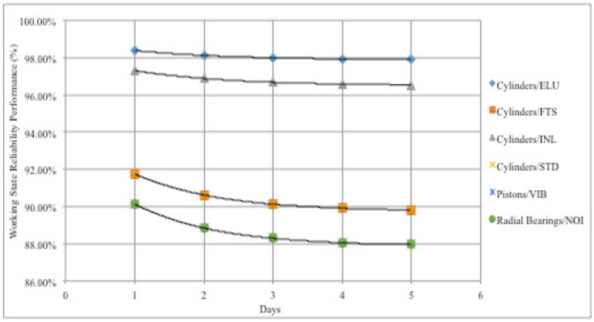

Fig. 6. M/E reliability performance of cylinders, pistons and radial bearings at failure mode level.

6. Discussions and conclusions

INCASS project introduces innovative solutions in ship inspection and maintenance for both ship structures and machinery. The paper presented the latest literature review on Hull Condition Assessment (HCA), image processing, Condition Based Maintenance (CBM) and the state-of-the-art in condition monitoring techniques. Moreover, the pioneering INCASS framework and its functionalities are demonstrated. The INCASS framework consists of advanced risk and reliability soft tools (SRA and MRA) integrated with decision making tools for onboard and offshore assistance. A central database is designed to manipulate the input and processed data during all operations. The MRA and DSS case study is presented considering the main engine, engine block and cooling subsystems and the involved components and failure modes. The results show acceptable operational levels of the reliability performance according to ship owners and operators. Conversely, safety thresholds should be considered in the study by consulting warnings with regards to Classification Societies, ship owners and operators and manufacturers.

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