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Research paper

Condition-Based Maintenance for medium speed diesel engines used in vessels in operation

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HIGHLIGHTS

- Condition-Based Maintenance is defined for medium-speed diesel engines in operation.
- ANNs have proved to be suitable to model engine performance of commercial vessels.
- Fishing vessels with medium speed diesel engines are assessed as a case study.
- A novel data monitoring and processing strategy is presented for fishing vessels.
- An affordable onboard Condition-Based Monitoring approach for vessels is achieved.

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ABSTRACT

Condition-Based Maintenance for diesel engines has contributed to reliability, energy-efficiency, and cost reduction. Both, the modelling of engine performance and fault detection require large amounts of data; usually, these are obtained on a test bench. In contrast, in operative engines, provoking faults onboard is not a viable proposition. Condition-Based Maintenance, fault detection and diagnosis need to be solved on engines installed in commercial vessels: the present contribution answers this need. A medium-speed diesel engine was monitored using thermocouples, pressure sensors, a propeller shaft torque meter and fuel oil flow-meters, during more than 10,000 running hours. Monitored data were used to train a three-layer feed-forward neural network, to generate the engine performance model; thus, determine the engine's fuel consumption and faulty conditions. The faulty conditions considered were: (1) a polluted turbine; (2) a dirty air filter/compressor; (3) a dirty air cooler; (4) and bad fuel injection, i.e. bad combustion. The sensor's precision and the experience gained by monitoring the engine served as a baseline to define the fault threshold values. The results proved the feasibility of installing a Condition-Based Maintenance, for vessels in operation, by monitoring engine performance and analysing the data with the aid of artificial neural networks.

1. Introduction

International shipping emits some 2.7 % of the global greenhouse gas (GHG) emissions. Following the foreseen growth in shipping, and in the absence of policies, it is expected that shipborne GHG emissions will increase by a factor of 2–3 (compared to emission in 2007) by 2050 [1]. As such, more effort is needed to revise the way that fuel is consumed [2]. Research is growing within the published literature regarding energy efficiency. For example, in the fishing sector, research has focused upon: energy audits; the monitoring of the engine and consumption parameters; the optimisation of fishing gears; and energy management and saving solutions [3].

Optimised maintenance of engines is another solution to improve energy efficiency. Engine properties change in relation to the years spent in operation, together with the reparations carried out throughout those years. Hence an optimal maintenance helps reducing unnecessary expenses and pollution. The only exception is NO_x emission that it is reduced due to incorrect maintenance and

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engine malfunction, as found in a laboratory-scale experiment that simulated a fuel pump malfunction [4]; and in engines with faulty injection pressures [5].

Shipowners have adopted three maintenance strategies, to ensure that engines function under their optimal conditions. The traditional corrective maintenance, i.e. corrective repairs, takes place once a part is broken, or a machine has stopped working. Secondly is the scheduled maintenance or the routing servicing, which replaces parts subjected to degradation or wear, after a certain period of operation. The last, the least applied, is Condition-Based Maintenance (CBM), which predicts when the failure will occur; this is based upon engine monitoring and performance indicators. Despite the fact that the scheduled maintenance and the CBM are complementary, the CBM is by far the most cost-effective approach and the one which enhances the life expectancy of the engine [6].

Many authors have tried to monitor and model engine performance, to predict parameters such as fuel consumption. Examples are the performance maps developed for an eight cylinder four stroke diesel engines proposed by Çelik [7], and the prediction model for the brake specific fuel consumption, effective power, average effective pressure and exhaust gas temperature of an eight cylinder four stroke methanol diesel engine proposed by Çay [8], both using intelligent algorithms. However, only a few have linked both, i.e. the modelling of the engine performance and the CBM, as the way to reduce costs and optimise the energy consumption onboard.

The input and output variables, faults, and modelling methods used in such models are varied. Regarding the variables the engine speed, engine power, cooling water temperature and the combustion pressure of the engine cylinders are the most common; all but the cooling water temperature that is used as an input variable, appear interchangeably as input and outputs in the consulted literature [7–9]. However, there are other variables, such as engine vibration and exhaust temperature [10]. A similar diversity can be found in the selection of faults, which include leak failures [9] as well as shaft imbalance, cylinder misfire, and clogged intake [10]. However other researchers have adopted a more comprehensive approach including the previously mentioned faults and those related to exhaust gas, turbine and compressor performance [11]. Likewise, the techniques used to design the engine performance predictive model and the maintenance model go from the usage of intelligent algorithms, such as: Artificial Neural Networks (ANN) [10,12], genetic algorithms [13], and fuzzy logic [14]; to less sophisticated approaches, e.g. non-linear multivariate statistics [15]; and experimental formulae based upon thermodynamics [16]. One of the most innovative studies is probably that presented by Mesbahi [12]. Here the author proposes not only a model that predicts the fuel consumption, based upon several inputs, but a failure detection system is also presented; this is based upon pattern recognition, which optimises the input data using reverse modelling.

Most of the contributions on the CBM of marine diesel engines are based upon data collected from tests produced under controlled laboratory conditions. In such cases, data acquisition is not subjected usually to field operation problems; thus, quality data are easier to obtain. More significantly, the faults are always induced by the authors; this facilitates the definition of 'failure threshold values'. In contrast, onboard commercial ships data collection is not as straightforward. Sensors and measuring equipment are subjected to harsh environments, where inducing faults onboard is unviable. Likewise, the activity pattern of fishing vessels is more complex than that of commercial ships. Furthermore, data acquisition in adverse conditions hinders data quality; as such, data anomalies are common. Since data quality is essential for modelling an engine performance, the data need to be selected carefully and transformed.

This study analyses how to implement a CBM for a medium-speed marine diesel engine, as used in operative fishing vessels. Since most of the models considered use ANN to develop successfully prediction model of engine performance and the failure detection, the same approach has been adopted in this contribution. Likewise, the strategies followed to establish a CBM onboard a commercial fishing vessel are explained. Also, the monitoring of the engine parameters and the application of ANN method are introduced. The main difference in utilising published literature lays in the complexity of designing a CBM strategy, for an operative engine.

2. Material and methods

2.1. The engine and its use

The engine monitored here is a typical medium-speed diesel engine, which is used commonly in fishing vessels and tugboats, as the main engine; likewise, in shipping, as an auxiliary engine burning heavy fuel oil. The engine lies within the low power range of medium-speed engines; as such, the methodology applied in this study can be applicable to larger engines, which are being used in operative vessels. The basic technical details of the engine are listed in Table 1.

The engine monitored is used in a commercial bottom-otter trawler. More information regarding the vessel and its working pattern are available elsewhere [3]. Summertime is used to perform any required reparations and maintenance.

The vessel is equipped with a shaft generator (or alternator), which is connected to the main engine. The power demand of the engine originates from the propeller and the alternator: the first is used to move the vessel; the second to run the onboard electric-consuming equipment, including the fishing gears.

The electric load is somewhat constant whilst the vessel is cruising (from the port to the fishing ground and *vice-versa*, and between two fishing grounds); it suffers small changes, due to the larger electric-consuming equipment used only during fishing activities. Furthermore, during cruising, the alternator is coupled most of the time. When uncoupled, the power demand comes from the propeller to move the vessel. For certain cruising speed, such

Table 1
Technical details of the engine studied.

Parameter	Value
Number of cylinders	8
Cycle	Medium-speed 4 stroke
Induction system	Turbocharged
Compression ratio	15.5:1
Stroke × bore	210 mm × 290 mm
Displacement	80,36 L
Mean Effective Pressure	1923 MPa
Max. Combustion Pressure	18.14 MPa
Nominal Speed	800 rpm
Net power	1030 kW
Cooling system	Water cooled (fresh water)
Fuel system	Mechanical
Type	Injector/1 pump per cyl.
Injection pump	Bosch Type
Injector	8 orifices
Nozzle opening pressure	35 MPa
Governor type	Hydraulic
Fuel type	Marine Diesel Oil
Activity	Used within Fishing Vessel (stern trawler)