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Fault diagnosis of marine 4-stroke diesel engines using a one-vs-one extreme learning ensemble

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ABSTRACT

This paper proposes a novel approach for intelligent fault diagnosis for stroke Diesel marine engines, which are commonly used in on-road and marine transportation. The safety and reliability of a ship's work rely strongly on the performance of such an engine; therefore, early detection of any type of failure that affects the engine is of crucial importance. Automatic diagnostic systems are of special importance because they can operate continuously in real time, thereby providing efficient monitoring of the engine's performance. We introduce a fully automatic machine learning-based system for engine fault detection. For this purpose, we monitor various signals that are emitted by the engine, and we use them as an input for a pattern classification algorithm. This action is realized by an ensemble of Extreme Learning Machines that work in a decomposition mode. Because we address 14 different faults and a correct operation mode, we must handle a 15-class problem. We tackle this task by binarization in one-vs-one mode, where each Extreme Learning Machine is trained on a pair of classes. Next, Error-Correcting Output Codes are used to reconstruct the original multi-class task. The results from experiments that were conducted on a real-life dataset demonstrate that the proposed approach delivers superior classification accuracy and a low response time in comparison with a number of state-of-the-art methods and thus is a suitable choice for a real-life implementation on board a ship.

1. Introduction

In maritime environments, 4-stroke Diesel engines are commonly used in on-road and marine transportation. For this reason, these types of engines are a major source of toxic emissions into the atmosphere. The harmful compounds that are emitted from Diesel engines are carbon and nitrogen oxides and unburned hydrocarbons. The deterioration of the technical state of Diesel engines will decrease their efficiency. As a result, there is higher fuel consumption and increased emissions of harmful compounds into the atmosphere. For this reason, in addition to research on improving the structures of Diesel engines, it is important to perform research on diagnostic methods for these devices. Technical diagnostics of Diesel engines is especially crucial in marine engine maintenance and operations. Based on a simple calculation, it can be estimated that a ships engine with 20 MW output power consumes almost 100 tons of fuel and emits into the atmosphere approximately 6 tons of nitric oxide (NOx) per day. The technical diagnosis of marine engines is an important and relatively difficult task for the marine engine operators. The reason is that the diagnostic signals are changed not only from changing the technical condition of the engine but from the changes in the load and/or speed of the engine.

The presented conditions tend to create automated diagnostic tools that are aimed at assisting the detection of marine equipment malfunctions. The simplest solutions for supporting the diagnostic decisions are systems of automatic signaling when the permissible operating engine parameters exceed their boundaries. Such systems allow for the prevention of sudden damage that could lead to a stoppage of the engine, but only during the engines relatively heavy load operation. The presented method is the most popular during on-board operations and maintenance. Some extensions of the mentioned method are diagnostic systems that have been proposed by ship engine manufacturers, such as the CoCoS Engine Diagnostic System of MAN or DICARE of Caterpillar (Woodyard, 2009). Both systems allow the monitoring of engine parameters, along with reporting and simple trend analysis. In each of the mentioned diagnostic systems, the decision is made by the engine room operator based on his/her knowledge and experience. It should be noted that insufficient or incorrect diagnosis of the engines technical conditions could lead to environmental risk and stoppage of the ship. In such cases, there is, in addition, no possibility of controlling the level of toxic emissions into

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the atmosphere and reducing the fuel consumption. A solution to this problem is the installation of additional sensors in the functional systems of the engine. One of such solutions is a diagnostic system that is based on fast deterioration of the engine crankshaft (Yang et al., 2001; Renaudin et al., 2010; Dereszewski, 2014) analysis of the boost pressure (Wu and Huang, 2011), combustion pressure (Pawletko, 2015) or acoustic emission (Pontoppidan et al., 2005). To prevent negative effects on the environment, the International Maritime Organization introduced Annex VI to the Marpol 73/78 Convention. This Annex forces ship owners to limit NO_x emissions from ship engines. According to the mentioned regulation, every on-board engine that is above 130 kW that is introduced to operation is obligated to have a valid certificate that confirms the acceptable emissions of NO_x. If ship engines are subjected some alterations during the operation period, they will have to extend the certificate. Prolonging the certificate consists of checking sets of parameters and the structural parts of the engine that influence the NO_x emission. Any changes in the design or adjustment of the engine beyond the framework established during the certification entails the need for direct measurement of the NO_x emission. Therefore, ship owners are encouraged to install systems for the direct measurement of the composition of the exhaust gases on-board. Installation of the systems to exhaust gas analysis on-board can utilize the results of the measurements for the diagnosis of marine Diesel engines. For this reason, the aim of the presented work is diagnostic signal identification in exhaust gas identification of marine 4-stroke Diesel engines. Achieving the objective requires conducting an active experiment that consists of registration of the influence of selected marine engine failures on the composition of the exhaust gas. The obtained results were used for the selection of the diagnostic signals that allow for the technical diagnosis of the engine. To verify the results, a set of computer experiments was conducted that involved the classification of the results by a neural network ensemble (Woźniak, 2014) that utilized the Extreme Learning Machine (Ding et al., 2015) principles and worked in the decomposition mode. We propose to use a one-vs-one approach, where the discussed multi-class problem is divided into a number of simpler pairwise tasks, and each base classifier is trained on a simplified problem. Error-Correcting Output Codes (Dietterich and Bakiri, 1995) are then used to reconstruct the original multi-class decision from a set of binary outputs. In this way, we can achieve improved recognition accuracy by exploiting local specializations of the classifiers in the ensemble.

The main contributions of this paper are as follows:

- A novel approach for monitoring marine 4-stroke diesel engines based on a set of diagnostic signals.
- Design of effective and intelligent fault-detection system using machine learning techniques.
- Ensemble of binary Extreme Learning Machines in one-vs-one mode utilizing Error Correcting Output Codes.
- Extensive experimental results on a real-life dataset collected by the authors, which prove the high quality of the proposed ensemble-based fault detection in terms of an excellent accuracy and low response times and which allow for the potential to have an on-board implementation in marine vehicles.

The remainder of this manuscript is organized as follows. The next section describes in detail the problem of engine failure description, the proposed diagnostic signals and the considered types of engine failures. Section 3 describes the details of the proposed intelligent fault-detection system based on an ensemble of randomized neural networks, while Section 4 presents the details of the experimental study that was performed and the obtained results along with their thorough analysis. The final section presents the paper's conclusions.

2. Problem of engine failure description

In this section, we present a detailed description of the used engine model, the measured diagnostic signals and the considered types of possible faults to be detected.

2.1. Laboratory research

This study was conducted on a marine, 3-cylinder, 4- stroke, direct injection diesel engine with an inter-cooler system. The engine was loaded with a generator that was electrically connected to the water resistance and supercharged by a VTR 160 Brown-Boveri turbocharger. During the tests, the engine was fueled by diesel oil with known properties and operated at a constant speed, equal to 750 rpm. The fueling system of the engine consists of mechanically controlled Bosh type fuel pumps connected to injectors with multi-hole type nozzles. This type of engine is commonly used as a power generator or main propulsion system with a variable pitch propeller (Carlton, 2012). A total of 56 parameters of the laboratory stand, including the engine load and speed, the parameters of the turbocharger, the systems of cooling, fueling, and lubricating and the air exchange were measured. The composition of exhaust gas was also recorded using an electro-chemical gas analyzer with an infrared carbon dioxide sensor. The pressure, temperature and humidity of the air were also recorded by the laboratory equipment. All of the mentioned results were recorded with a 1-s sampling time. The injection and combustion pressure in all of the cylinders of the engine were also recorded. The scheme of the laboratory stand is presented in Fig. 1, while the most important engine parameters are presented in Table 1.

The laboratory tests consisted of the engine operation with the following faults:

- the throttling of the exhaust gas duct (two adjustments),
- the throttling of the air inlet duct (two adjustments),
- the shift of the fuel pump cam on the camshaft, which causes a delay in the fuel injection,
- the leakage of the air inlet valve,
- the leakage of the exhaust gas valve (two adjustments),
- the decrease in the opening pressure of the fuel injector,
- the increase in the opening pressure of the fuel injector,
- the chocked fuel injector,
- the discalibrated fuel injector,
- the leakage of the fuel injection pump (two adjustments).

The test procedure, the parameters of the measuring devices and the analysis of results are presented, i.e., in Kowalski (2014, 2015a, b).

2.2. Classification problem description

Any fault of the internal combustion engine causes changes in the organization of the combustion process in the engine cylinders and causes changes in the composition of the exhaust gases. Usually, the change in the fuel fraction in the combustible fuel mixture causes a change in the carbon monoxide (CO) and carbon dioxide (CO_2) emissions in the exhaust gas from the engine. The engine faults that are located in the air/exhaust gas exchange system result in changes in the amount of air supplied to the engine cylinders. The resulting effect could be a change in the oxygen (O_2) content of the exhaust gas of the engine. Furthermore, changes in temperature, pressure and time of the combustion in the cylinder results in changes in the (NO_x) content of the exhaust gas. The content of NO_x in the exhaust gas is also dependent on the humidity, temperature and pressure of the charging air. This description is very generalized and simplified; however, it presents the desirability of the use of the mentioned exhaust gas components as carriers of the diagnostic signals. It should be noted that the presented carriers of the diagnostic signals do not allow the

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