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Concept of the multidimensional diagnostic tool based on exhaust gas composition for marine engines

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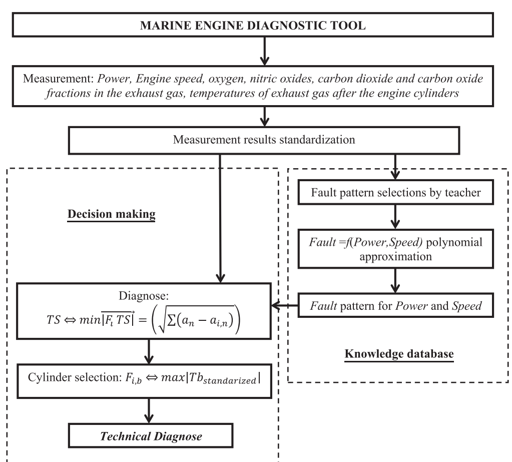
HIGHLIGHTS

- A multidimensional diagnostic tool for marine engines based on exhaust gas composition was proposed.
- Diagnostic signals were selected from attributes of the composition of exhaust gas.
- An algorithm of the implementation methods for operational marine conditions was introduced.
- Diagnoses were verified by means of experiments – active and passive.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents the concept of a multi-dimensional marine engine diagnostic tool. The dimensions of the tool are diagnostic signals, which form a vector in affine space. The distance of the resulting vector from reference vectors for considered technical states of the engine is the result of diagnosis. Moreover, diagnostic signals, derived from the composition of the exhaust gas, are also considered. The chosen diagnostic signals are the nitric oxide, carbon oxide, carbon dioxide and oxygen contents in the exhaust gas and the temperatures behind all engine cylinders of the marine engine. Analyses were based on laboratory tests of a 4-stroke marine engine. The operation of the proposed diagnostic tool has been partly verified by a passive experiment under sea operation conditions of a main propulsion marine engine.

1. Introduction

Diagnosis and service of marine equipment are the responsibilities of any ship's crew, wherein the schedule of checks and diagnostic activities depends largely on the knowledge and experience of the engineer. Any error of marine engine operators is costly and may result in a threat to the environment. It should be remembered that a marine engine with a power of 10,000 kW burns nearly 50 tons of fuel and emits approximately 3 tons of nitrogen oxides into the atmosphere. Any deterioration in technical conditions of the engine causes an increase in fuel consumption and

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Nomenclature

CO	carbon oxide fraction in exhaust gas (ppm)
CO_2	carbon dioxide fraction in exhaust gas (%)
$F_{1\ldots i}$	pattern of the *i*-th fault (−)
N	the engine rotational speed (rpm)
NOx	nitric oxides fraction in exhaust gas (ppm)
$O_{1\ldots 10}$	observations during the passive experiment (−)
O_2	oxygen fraction in exhaust gas (%)
P	the engine power (kW)
T	temperature of exhaust gas after the cylinder (°C)
TS	technical state of the marine engine (−)
$a_{1\ldots n}$	value of the *n*-th diagnostic signal
b	number of engine cylinders (−)
stand	standard value of a signal (−)
n	number of diagnostic signals/number of diagnostic space dimensions (−)
i	number of considered fault patterns (−)

an increase in the emission of harmful substances into the atmosphere.

Insufficient or incorrect diagnosis of an engine's technical condition can lead to its stoppage, which in adverse weather conditions can lead to the loss of the ship and the death of the crew. For this reason, the correct diagnosis and operation of marine equipment is an important task. The presented determinants induce the design of automated diagnostic tools, which are aimed to assist in the troubleshooting of marine equipment. It is all the more important that stoppage and repair of a marine engine cannot be performed at any time during operation.

The simplest solution supporting diagnostic decisions is systems that automatically signal when the permissible operating parameters of the engine have been exceeded. Such systems allow for the prevention of sudden damage that can lead to a stoppage of the engine. The presented method is the most popular during onboard operation and maintenance. Some extensions of the mentioned method are diagnostic systems proposed by ship engine manufacturers. Examples of such systems are the CoCoS Engine Diagnostic System of MAN or DICARE of Caterpillar. Both systems allow monitoring of engine parameters, reporting and simple trend analysis. Solutions of this type detect damages but do not prevent them. In such cases, there is also no possibility of controlling the level of toxic emissions into the atmosphere and reducing fuel consumption. Solutions to this problem are believed to be the installation of additional sensors in the functional systems of the engine. One such solution is a diagnostic system based on speed deteriorations of the engine crankshaft [1,2] charging pressure analysis [3], or the acoustic emission [4]. Such a course of action improves the accuracy of diagnosis but increases the maintenance costs.

An alternative solution is to search for methods of analysis of the measured parameters. In [3], neural networks were used, which, after correct learning, allow for engine diagnostics. A similar method was used to analyze the malfunction of the rotor together with the bearing [5], as well as diagnosing Variable air volume systems [6] and twin gas turbines [7]. It should be noted that the use of artificial neural networks requires the collection of large amounts of data sets (usually more than 100), which are used to teach the network. There is also the risk of inaccurate learning or overtraining of the neural network. In the case of overtraining, the neural network correctly detects the system conditions that are close to the test conditions but also mistakenly detects conditions not included in the training data. Other methods applied in technical diagnostics are ones based on fuzzy logic [8–10]. These methods allow the use of linguistic variables, collected from experts or collected with the use of statistical methods. The literature concerning the diagnosis of complex technical systems also sees the use of methods based on Rough Set Theory [11], Dempster–Shafer evidence theory [12], combinations of pseudo-intelligent algorithms [13], comparisons of diagnostic parameters with pattern models, [14], bond graph theory [15,16] and more. A classification of methods for fault diagnosis of technical systems can be found in [17]. The methods proposed thus far have not been widely implemented for marine operation. The reasons for this should be sought in the need for a complex mathematical apparatus and/or the collection of a significant amount of diagnostic information. The solution to this problem is to use diagnostic signal analysis based on multi-dimensional geometry theory. In 2004, Tax and Duin [18] proposed a diagnostic method based on principles of multi-dimensional geometry. This method, named Support Vector Data Description (SVDD), lies in finding the distance between the central point of a hypersphere, determining the condition of a diagnosed device, and a point in *n*-dimensional space, determining the current condition of the device. The mentioned method was used for fault detection of chillers in [19]. However, usage of this method was limited to a statement of chiller fault without an indication of the type and size of the fault. The author believes that it is possible to extend the application of the mentioned method of diagnosis. This extension is the ability to identify the type and size of the malfunction. Therefore, this paper proposes a relatively simple and easy-to-implement method for diagnosing a marine engine based on the theory of multi-dimensional geometry. It allows for the detection of engine malfunction on the basis of available measurement equipment on the ship and that hopefully installed in the future. The possibility of polynomial approximation of reference areas of selected marine engine malfunctions was also tested. The aim of the mentioned approximation is to reduce the costs associated with the acquisition of reference areas of engine malfunctions for different load and speed conditions. For the purpose of the proposed method, diagnostic signals were selected from the marine engine's exhaust gas composition. This approach is new and has not been used in marine applications. The mentioned selection was made based on laboratory tests.

Assumptions of the proposed diagnostic method and the selection of diagnostic signals were verified under maritime conditions.

2. Proposed method

As already mentioned, the proposed method is similar in principle to the SVDD method proposed in [18] and modified by Zhao et al. [19] for chiller diagnosis. It is considered that the SVDD method can be used not only to determine the correct operation of a complex technical system (marine engine) but also to indicate the type and size of the malfunction. The technical condition of a marine engine or other complex technical system (TS) can be described by the values of the measurement signals ($a_1 \ldots a_n$). The values of these signals may be the coordinates of the TS in the *n*-dimensional affine space:

$$TS = (a_1, a_2, \ldots, a_n) \tag{1}$$

A change in the engine's technical condition moves it to a point in space, which is the result of changes in the values of the mentioned parameters. There are some areas in said space corresponding to the