UDC 620.192, 620.2, 621.432 DOI: 10.30977/VEIT.2023.24.0.6

Application of logical methods in expert analysis of automotive engine failures in operation

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Abstract: Problem*. It is known that the causes of failures in automotive engines can be determined based on existing experience in studying various engine malfunctions. However, an analysis of known methods for determining the causes of car engine failures shows that their use in practice, including in diagnosing the technical condition of engines, requires a lot of work and highly qualified personnel that in many cases is practically ineffective. Logical-probabilistic methods are also known, including those based on fault tree analysis. However, it is not possible to use such models and methods in searching for the c auses of engine failure.* ***Goal.*** *The purpose of the study is to create a methodology for determining the causes of faults and failures in engine operation, which can be applied with help of a logical way and applicable not only by the specialists with expert level, but also the wide qualification.* ***Methodology.*** *The solution to this problem was found in several stages. Initially, by structuring the symptoms, a fault tree was constructed that logically describes the cause-and-effect relationships between the failure event and the original damage that caused it. Data from expert studies of engine failures were used to construct the graph. This was done for each of the engine failure types selected for analysis. Next, a modified (inverted) fault tree was developed for a finite number of selected failure types.* ***Results.*** *Obtained logical graphs allow you to perform a simple logical analysis in the opposite direction from the generally accepted one, from the event of a system failure to the basic damage events that cause it. After obtaining logical graphs for each type of failure, a modified engine fault tree can be compiled, common to the considered types of failures.* ***Originality.*** *The proposed method was widely used previously in the study of reliability of various technical systems, however, this method for the first time has been proposed to determine the causes of engine failures.* ***Practical value.*** *As a result of using the proposed methodology in practice, it it became possible to determine the causes of failure in the engine with enough reliability for practice and minimal time expenditure.*

Keywords*: internal combustion engine, fault, failure, logical method, fault tree analysis.*

Introduction

A large amount of scientific research, design work and technological advances have significantly improved the reliability and durability of automobile engines [1]. Despite this, the high technical level of new engines does not guarantee the absence of further operational failures. [1]. At the same time, effective troubleshooting requires correct identification of the causes of such failures [2]. However, known diagnostic methods do not always fully meet the needs of practice.

It is the problem of correctly identifying the causes of failures that repair organizations and vehicle operators often face [3]. This problem is due to the fact that in practice there are often no simple and reliable methods for determining the causes of failures that provide the accuracy and reliability necessary for practical problems [4].

Typically, difficulties in creating such techniques are caused by the difficulty or even impossibility, in contrast to process research and engine design, of formalizing damage processes. It is also difficult to identify patterns suitable for creating universal and simple algorithms in order to further describe them with simple formulas. In addition, differences in engine design require the collection and processing of large volumes of statistical data on the nature and characteristics of failures and destruction of specific engines.

As a result, the correct determination of the causes of engine faults in practice is most often only possible by a specialist with significant expert experience in investigating the failures [2, 4]. In other cases, the operator risks making a mistake, causing a second failure and doubling or sometimes tripling the costs for repairing the vehicle engine. Thus, there is every reason to assert that despite the serious efforts and successes achieved in engine research and design, to date, reliable methods for determining the causes of engine failures have not been created.

Analysis of the latest research and publications

In general, there are three main groups of methods and techniques that allow us to determine the causes of malfunctions and failures of automobile internal combustion engines in operation.

The first group consists of troubleshooting tables of various kinds and details, in which the main symptoms of faulty operation and their corresponding causes are stated [3, 5]. This is supposed to help the consumer with troubleshooting.

However, such a simple presentation, for all its accessibility and seems to be understandable even for untrained operators – vehicle owners, drivers and operators, has a rather low practical value. Moreover, in many real-life cases, the tables make it difficult to determine the real causes. This is due to the ambiguity of the indicated causes of failures, when tables usually give dozens of possible causes if the symptoms are similar. Moreover, the more detailed the table is, the more causes it gives [4]. As a result, using tables in practice is so labour-intensive that it is virtually ineffective. As a result, consumers in operation, as a rule, find it difficult to determine the cause of engine failures using this method.

The second group of techniques combines fault reference books [6, 7]. In general, these are the same tables, but illustrated with photographs of damaged parts and provided with a detailed description of the damage itself and its causes. Despite the more solid appearance, this method suffers from the same problems of ambiguity. For example, to find the real cause of failure, it is generally necessary to perform dozens of tests of different versions.

What both methods have in common is that, in fact, they require not just technical knowledge, but special training and expert experience, which prevents their use in practice. An untrained operator or service worker will most likely not be able to find a failure cause by using reference books. A highly qualified specialist, in contrast, is quite capable of finding a fault without tables or reference books, relying just on his knowledge and experience. In addition, since tables and fault reference books are compiled primarily by component manufacturers, it is almost impossible to find descriptions of manufacturing defects in them. This is quite logical, since the indication of a defect in the manufacturer's technical literature is perceived by the average consumer as an admission by the manufacturer of its own fault. However, on the other hand, the absence in a reference book or table of any mention of production causes of failures immediately makes this information incomplete and not entirely reliable.

The third group combines methods for diagnosing the technical condition of internal combustion engines [8, 9]. In general, these are long-standing and well-developed scientific methods that make it possible to identify various faults by measuring certain parameters and their corresponding mathematical processing. Some diagnostic techniques are used as basic algorithms in a number of diagnostic devices (for example, in motor testers [10]). This really helps to detect various deviations in engine operation and even find the causes of individual malfunctions.

However, not all diagnostic techniques are in demand in practice, where their use is limited, on the one hand, by the need to have special knowledge and serious training. For example, one can hardly expect a service mechanic to have fundamental scientific knowledge and the ability to apply scientific methods when repairing an engine. On the other hand, diagnostic equipment usually has a high cost. Moreover, the diagnostic methods are often poorly applicable to many types of engine damage and failures, especially in mechanical parts of the engines that usually are not detected by diagnostics at all.

Purpose and statement of the study

The purpose of the study is to create a methodology for determining the causes of faults and failures in engine operation, which can be applied with help of a logical way and applicable not only by the specialists with expert level, but also the wide qualification. To achieve this goal, it is necessary to do the following tasks:

– based on the logical-probabilistic method of fault tree analysis, we develop a general principle and methodology for determining the causes of a unit failure as an integral part of the engine;

– using the data obtained, we develop a methodology for determining the causes of specific types of engine failures.

General principle and methodology for determining the causes of a unit failure as an integral part of the engine

A logical-probabilistic method of fault tree analysis (FTA) [11] was widely used previously in the study of reliability of various technical systems [12, 13]; however, this method for the first time has been proposed to determine the causes of engine failures.

At the preliminary stage of the study, the main provisions of the proposed methodology were formulated, a general approach was chosen, and a logical algorithm was drawn up. An internal combustion engine unit, a supercharging turbocharger, was chosen as an object for preliminary research, on which the proposed methodology was tested with the aim of further extending its application to the entire engine as a whole.

To solve the problem, the fault tree analysis method was used [14]. As is known, a fault tree (Fault Tree Analysis – FTA) is a multi-level graphological structure (graph) of causal relationships in the system (Fig. 1). Fault tree analysis is a common method for modeling the reliability of complex technical systems. It is usually done at the design stage [11].

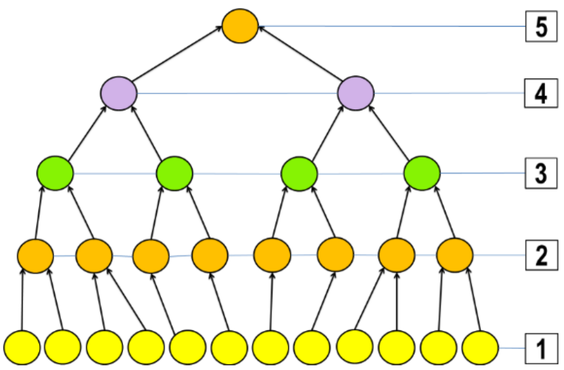

Fig. 1. Fault tree diagram: possible impacts (1) on the system cause damage (2), which leads to failure of elements (3), then components (4) and the entire system as a whole (5)

Fault tree analysis is a common method for modeling the reliability of complex technical systems. This is usually done at the design stage [11], when it is easy to calculate probabilistic reliability characteristics (for example, probability of failure, time between failures, etc.). In this case, the analysis itself is done in the direction from cause to effect.

The fault tree of the unit in question was compiled using several successive approximations [14]:

– structuring the research object by dividing it into separate units and combining them into a block diagram (Fig. 2);

– identification of possible sources, causes and signs of faults in a given object;

– detailing and structuring of signs and causes of failures for selected blocks (units) of the object with their detailed description;

– drawing up a direct failure tree of an object for one selected cause of failure;

– expansion of the direct fault tree to other causes of object failures;

– modification of the direct fault tree in order to simplify the logical diagram and its analysis, including the assumption of a logical connection of the event in question with several previous events;

– reverse of the direct fault tree of the object in order to bring it to a form which makes it possible to use the logical way of searching for the cause of the failure.

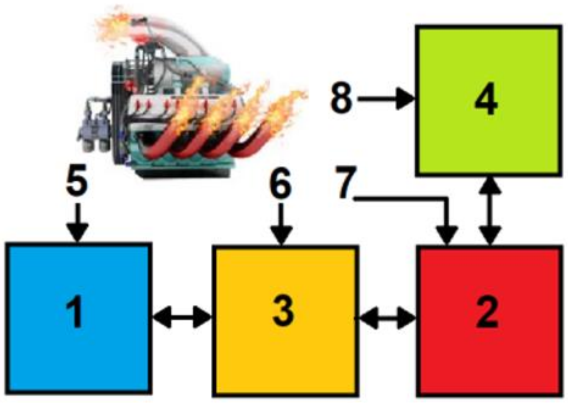

Fig. 2. Turbocharger block diagram: 1 – compressor, 2 – turbine, 3 – bearing assembly, 4 – control system; external influences on the turbocharger (from the internal combustion engine), including: 5 – engine intake system, 6 – oil system and engine crankcase, 7 – engine cylinders and exhaust manifold, 8 – engine control system

Then it is possible to make a logical diagram in the form of a modified inverse (inverted) fault tree. It clearly highlights not only the intermediate states of components and elements, but also describes in detail the signs by which the driver and/or service mechanic usually determine the failure (Fig. 3). Then the cause of the failure can be easily determined simply by following the logical diagram.

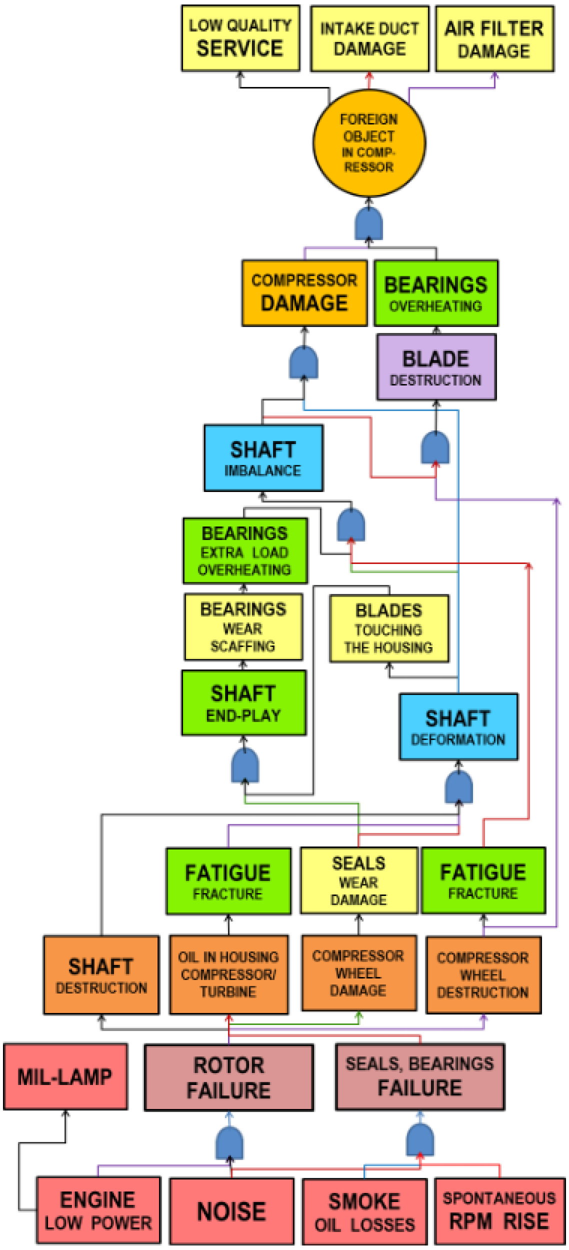

Fig. 3. General view of modified reversed fault tree of one failure (a foreign object entering a turbocharger [14])

However, it is not possible to directly transfer and extend the results obtained in [14] to the entire engine as a whole. The reason is that in a turbocharger the number of components and parts is small, and they are all closely interconnected. For example, the rotor rotates at very high speed, when even a slight breaking of the operating mode of one element not only develops quickly over time, but also causes a large scale of damage to many parts [14, 15].

As practice shows [2-4], in internal combustion engines there is no such global relationship between components and parts. On the contrary, in the operation of automotive engines, failures are more often caused by local damage to individual mating parts, which often occurs without the damage spreading to many other elements, components, cylinders, etc. In accordance with this, the structuring method, which used when studying one unit, may turn out to be ineffective for the entire engine as a whole.

Indeed, structuring and dividing the entire engine, including multi-cylinder ones, into separate units is not a new method. It is quite common in various studies using fault tree analysis to calculate reliability characteristics [12, 13]. However, if the problem of finding the cause of failure is solved, then it is formulated not as a search for a universal formula or calculation of the probability of failure, but as determining the cause of a failure that has already occurred. In this case, structuring the object does not give anything, and work should be begun by identifying possible sources, causes and signs of faults for the given object as a whole. It means it's about structuring the failure event, not the object.

In addition, when developing a logical graph of an engine fault tree, it is advisable to accept a limitation on the number of failure modes under consideration. Indeed, it seems unjustified to overextend the fault tree to cover many or all possible faults, since such work is extremely complex and hardly meaningful. In this study, the range of considered types of engine failures was limited, on the one hand, to the most serious ones, which cause so-called severe damage associated with breakage of the synchronization of the reciprocating and rotational motion of the parts. On the other hand, common failures that were caused by engine oil degradation were also considered.

The causes and symptoms of the failures in question include, but are not limited to:

– destruction of the connecting rod after a hydraulic lock due to various liquids entering the cylinder;

– valve destruction due to various manufacturing or repair defects;

– destruction of the crankshaft and connecting rod bearings due to lubrication failure;

– breakage of axial fixation and destruction of the piston pin due to manufacturing or repair defects;

– abrasive wear by abrasive particles supplied with air;

– temperature damage due to cooling failure.

From the data obtained at [14] it follows that to compile a fault tree of such a complex object as an internal combustion engine, the most important, is the division (structuring) of features into three groups. These are the main signs, confirming (main) signs and clarifying (type and location of the damaging effect) ones. In this case, it is possible to present a simple logical graph with the direction of analysis from the initial damage to the engine entire failure for each of the failures considered, Fig. 4.

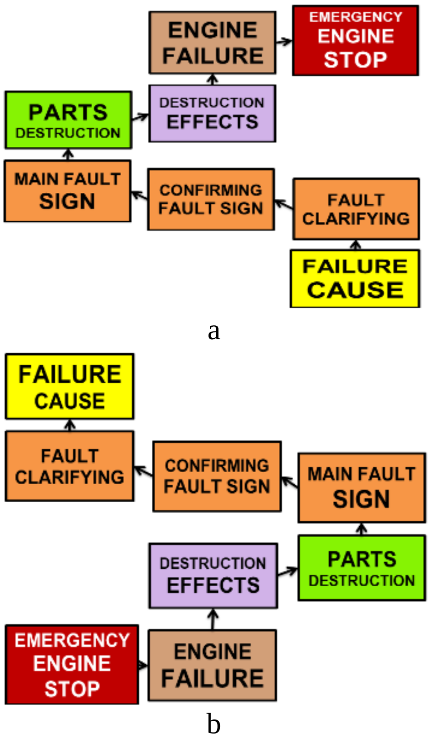

Fig. 4. Direct (a) and reverse (b) logical diagrams (direction of analysis – bottom-up), describing data on a separately identified failure from amongst those given in [16]

Based on such a logical scheme, it is not difficult to create a detailed graph for each failure considered.

Methodology for determining the causes of specific types of engine failures

In Fig. 5, it shows a modified and inverse graph for a failure caused by a hydraulic lock in one of engine cylinders from the ingress of water, oil, fuel or coolant [14].

In accordance with this, it is necessary to first construct a modified graph. Such a graph is direct and does not allow searching for the cause of the failure (Fig. 5). However, if the straight graph is inverted (reversed), the logic diagram allows to do the analysis in the direction from the failure event to its cause (Fig. 6).

Similarly, logical fault tree diagrams can be developed for other reasons under consideration [4, 16, 17, 18], including destruction of the bearing and connecting rod due to lubrication failure (Fig. 7), valve destruction [14], abrasive wear and temperature damage. Using data from [4, 14], it is also possible to compile an engine fault tree for cases associated with the piston pin, including its destruction and axial fixation breaking.

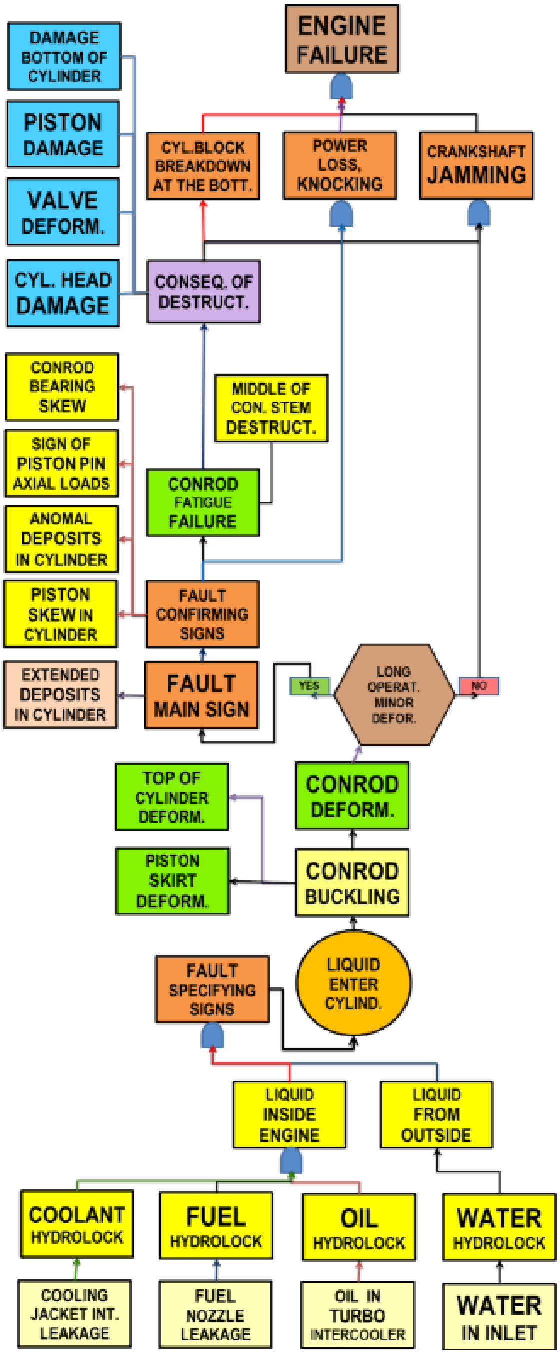

Fig. 5. General view of the direct modified engine failure tree during hydraulic lock

If we consider in detail all the signs of all the listed types of failures, then, on the one hand, we can find some similarities in the consequences of these failures (Fig. 8). However, a detailed analysis of both the symptoms and the logical structure of each type of failure (except for failures associated with the piston pin) does not allow us to identify common or similar branches of the failure tree.

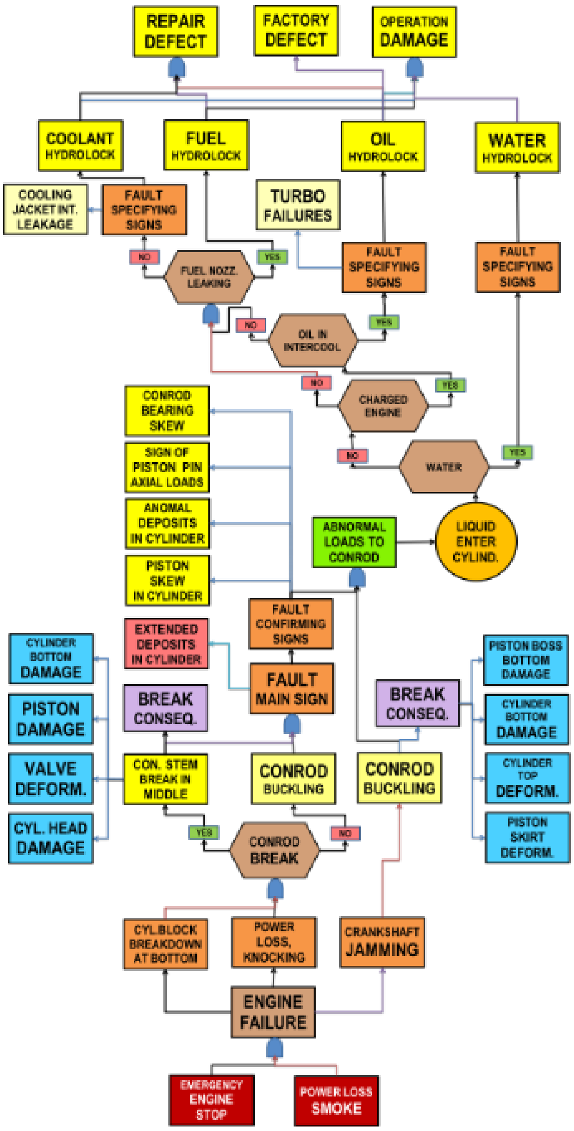

Fig. 6. General view of the reversed modified engine failure tree during hydraulic lock

Indeed, by compiling a fault tree separately for all considered types of failures, you can reduce them into one logical diagram. The results (Fig. 6 and 7) show that the resulting graphs are noticeably different in structure from the similar one built for a separate engine unit [11]. This is explained by the above-mentioned difference between an engine and a turbocharger, where, due to the high rotor speed, failures, as a rule, result in more general damage. This feature is associated with the local nature of engine failures noted above, when the damage is localized, for example, in a damaged cylinder and does not extend to most engine parts.

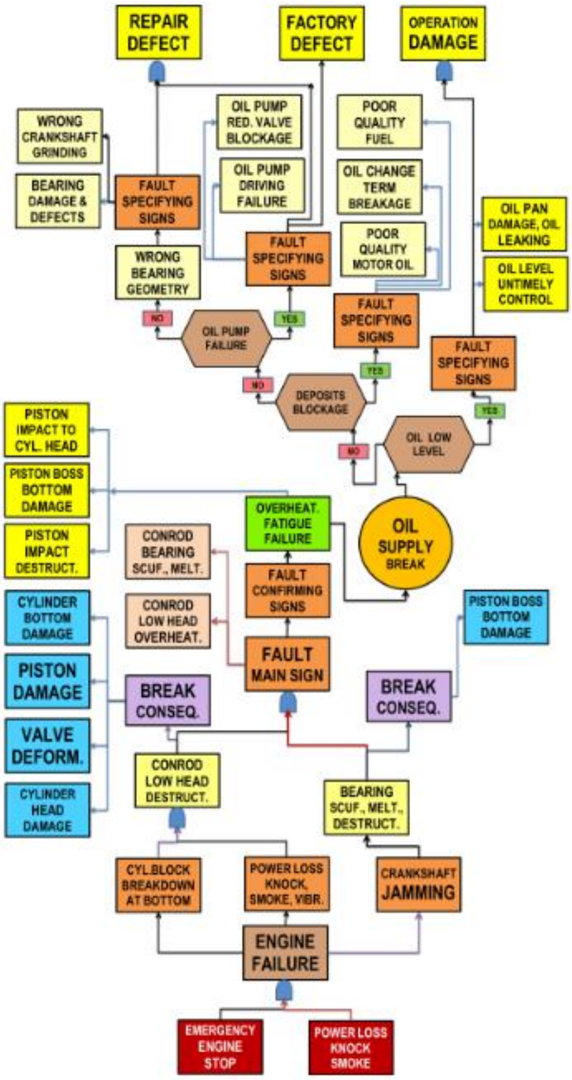

Fig. 7. General view of the modified reversed fault tree when the bearing fails

The result obtained in the form of a logical graph (Figs. 6 and 7) clarifies and details the data [16] on the causes, signs and consequences of severe damage, associated mainly with breaking of the synchronization of progressively moving and rotating parts. In addition, this method is applicable for other tasks related to engine failures, for example, due to oil degradation [16]. In this case, unlike the severe damage considered, there can be no significant damage to the engine, and external signs usually indicate changes in oil properties. However, determining the reasons for such changes is no less difficult than in the case of significant damage to the engine due to other reasons [14].

a

b

c

Fig. 7. Similar consequences of severe engine damage caused by failures due to disruption of the synchronization of the reciprocating motion of the parts [4, 16]: a) piston and conrod destruction due to insufficient oil supply to the conrod bearing, b) destruction of the conrod and piston after hydrolock, c) destruction of the piston after valve destruction

Thus, to determine the cause of failure in the case of severe damage, instead of a troubleshooting table, you can use a logical search algorithm by moving along the graph from the failure event upward towards the cause of failure.

Moreover, testing [11] showed that the apparent bulkiness of the graph is not a problem for its use in practice. Structuring the fault signs using logic easily leads to the desired group of causes. Next, all that remains is to identify clarifying signs in order to accurately determine the cause of failure.

Conclusions

Based on the results of the study, it was determined that despite the successes in the development of methods for diagnosing the technical condition of automotive internal combustion engines, using such methods to find the causes of failures is actually ineffective. To assess the reliability characteristics and risks of failure of technical systems, logical and probabilistic models are also used, including the method of fault tree analysis, but they do not correspond to the task of finding the causes of failures. The lack of necessary techniques leads to incorrect determination of the cause, repetition of failures and unreasonably high operating costs for repeated repairs.

Determining the causes of engine failures can be done by logical analysis in the opposite direction to that generally accepted when drawing up a fault tree. For this purpose, it is necessary to create a modified inverted fault tree. As a result, a logical method for determining the cause of a failure allows us not only to eliminate gross errors when investigating the causes, but also to do this with minimal time.

Further research in the development of methods for determining the causes of failures using logical methods can be aimed at developing the structure of logical graphs to cover a wider range of possible faults and failures.

Acknowledgments

We would like to express our gratitude to the Center for Machining «AB-Engineering», Odesa, and personal of the International Motor Bureau, Nemeshayevo, Kyiv region, Ukraine, for technical support, including for the provision of expert research materials, workplaces, samples of engines, units, as well as for assistance in their disassembly and examination.

Conflicts of interest

The author declares that he has no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Застосування логічних методів під час експертного аналізу відмов автомобільних двигунів в експлуатації

Анотація. Постановка проблеми. *Відомо, що причини відмов двигунів внутрішнього згоряння можна визначити на основі досвіду дослідження різних несправностей двигунів. Однак аналіз відомих методів визначення причин відмов двигунів автомобілів показує, що їх використання на практиці, у тому числі при діагностиці технічного стану двигунів, потребує великої праці та високої кваліфікації персоналу, що у багатьох випадках практично неефективне. Відомі також логіко-імовірнісні методи, у тому числі засновані на аналізі дерева відмов. Однак використовувати такі моделі та методи для пошуку причин відмови двигуна неможливо.* ***Мета дослідження*** *– розробити логічну методику визначення причин несправностей та відмов двигунів в експлуатації, що застосовується не тільки для фахівців експертного рівня, а й для фахівців середньої кваліфікації.* ***Методика.*** *Розв'язання цієї проблеми було знайдено у кілька етапів. Спочатку шляхом структурування симптомів було побудовано дерево несправностей, що логічно описує причинно-наслідкові зв'язки між подією відмови та первісною шкодою, що її викликала. Для побудови графа використано дані експертних досліджень відмов двигунів. Це було зроблено для агрегата двигуна – турбокомпресора, а також для кожного з типів відмов двигуна, вибраних для аналізу. Далі було розроблено модифіковане (інвертоване) дерево відмов для кінцевого числа вибраних типів відмов.* ***Результати.*** *Отримані логічні графи дозволяють виконати простий логічний аналіз у напрямку, протилежному до загальноприйнятого – від події збою системи до базових подій, що ініціює збій. Після отримання логічних графів для кожного виду відмов можна скласти модифіковане дерево несправностей двигуна, загальне для видів відмов, що розглядаються.* ***Наукова новизна.*** *Запропонований метод широко використовувався раніше для дослідження надійності різних технічних систем, проте вперше цей метод запропоновано визначення причин відмов двигунів.* ***Практична значущість.*** *В результаті застосування запропонованої методики на практиці стало можливим визначати причини відмови двигуна з достатньою достовірністю та мінімальними часовими витратами.*

Ключові слова: *двигун внутрішнього згоряння, несправність, відмова, логічний метод, аналіз дерева відмов.*

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