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An Innovative Approach to the Study of the Effect of Alternative Fuels on the Vibration Activity of Internal Combustion Engines

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ABSTRACT

BACKGROUND: The use of ammonia (NH₃) as a diesel fuel additive is of great interest for addressing environmental and operational challenges, such as reducing harmful emissions and improving engine efficiency. However, the influence of ammonia on vibration parameters of diesel engines is still understudied, thus requiring detailed research.

AIM: This study aims to analyze the influence of ammonia (NH₃) as a diesel fuel additive on vibration parameters of a diesel engine using an artificial neural network (ANN) designed to predict these parameters.

METHODS: The study employs modeling methods based on neural networks. TensorFlow and Keras frameworks were used to develop and train the neural network. Parameters of the engine (engine bore, speed, compression ratio, etc.) and fuel mixtures containing 5%, 10%, and 15% NH₃ were used as inputs. The model's accuracy was assessed based on experimental data.

RESULTS: The developed ANN showed high vibration prediction accuracy (up to 98.67%). Experimental data showed that increased ammonia additive ratio in the fuel mixture results in increased engine vibration. The highest vibration amplitude was 11.67 m/s² at 15% NH₃. The results indicate potential risks of lower engine performance when using ammonia, despite its environmental advantages.

CONCLUSION: The study showed that ammonia additives in diesel fuel increase engine vibration, which could affect its reliability and durability. Despite the high accuracy of neural network predictions, the observed increase in vibration requires further investigation. Additional research is required to ensure the safe use of NH₃ as a fuel additive by focusing on optimal mixture proportions and the influence of other factors, such as pressure and temperature.

Keywords: ammonia (NH₃); diesel fuel; engine vibrations; neural network; environmental additives; prediction; vibrational activity.

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Оригинальное исследование

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Инновационный подход к исследованию влияния альтернативных видов топлива на виброактивность двигателей внутреннего сгорания

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АННОТАЦИЯ

Обоснование. Использование аммиака (NH_3) в качестве добавки к дизельному топливу представляет значительный интерес для решения экологических и эксплуатационных проблем, таких как сокращение выбросов вредных веществ и повышение эффективности двигателей. Однако влияние аммиака на вибрационные характеристики дизельных двигателей остаётся малоизученным, что требует детального исследования.

Цель работы — анализ влияния аммиака (NH_3) в качестве добавки к дизельному топливу на вибрационные характеристики дизельного двигателя с помощью искусственной нейронной сети (ИНС), разработанной для прогнозирования этих параметров.

Методы. В работе использованы методы моделирования на основе искусственной нейронной сети. Для создания и обучения нейросети применялись фреймворки TensorFlow и Keras. В качестве входных данных использовались параметры двигателя (диаметр цилиндра, частота вращения, степень сжатия и др.) и характеристики топливных смесей с содержанием NH_3 (5%, 10%, 15%). Точность модели оценивалась на основе экспериментальных данных.

Результаты. Разработанная ИНС продемонстрировала высокую точность прогнозирования вибраций, достигая 98,67%. Экспериментальные данные показали, что увеличение концентрации аммиака в топливной смеси приводит к росту вибрационной активности двигателя. Максимальная амплитуда вибрации составила 11,67 м/с² при концентрации NH_3 15%. Полученные результаты указывают на потенциальные риски ухудшения эксплуатационных характеристик двигателя при использовании аммиака, несмотря на его экологические преимущества.

Заключение. Исследование показало, что добавление аммиака в дизельное топливо приводит к повышению вибрационной активности двигателя, что может негативно сказаться на его надежности и долговечности. Несмотря на высокую точность прогноза нейронной сети, выявленное увеличение вибрации требует дополнительного изучения. Для безопасного применения NH_3 в качестве топливной добавки необходимы дальнейшие исследования, направленные на оптимизацию состава смеси и изучение влияния других факторов, таких как давление и температура.

Ключевые слова: аммиак (NH_3); дизельное топливо; вибрации двигателя; нейронная сеть; экологические добавки; прогнозирование; виброактивность.

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BACKGROUND

The use of ammonia (NH_3) as a fuel additive is an important research area for solving modern environmental and operational problems of energy and vehicle technology sectors. In the context of increased energy consumption and associated increased greenhouse gas emissions, ammonia has unique advantages that can improve engine efficiency and reduce its negative environmental impact.

Key relevance factors of this study include the increased exposure to harmful emissions associated with the combustion of conventional hydrocarbon fuels. Some research show that ammonia is a carbon-free compound significantly reducing nitrogen oxide (NO_x) and other pollutant levels. For example, Kobayashi et al. [7] described how the use of NH_3 during the combustion reduces emissions and improves engine performance.

In addition to environmental aspects, research shows that ammonia can improve the calorific value of fuel mixtures. NH_3 may be used as a hydrogen carrier and help improve combustion leading to the increased overall engine performance. However, regardless of the available data on the benefits of NH_3 , available studies often disregard its influence on vibration parameters of diesel engines, requiring detailed research in this area.

As pure ammonia is fairly toxic, experimental studies involving its use and mixing pure ammonia with fuel for combustion are highly complicated. Therefore, the analysis of the available powertrain and fuel mixture parameters of a specific engine for possible vibrations using an artificial neural network (ANN) is a perfect alternative to conventional engine bench tests with vibration sensors.

Solving this problem requires the development of a sufficiently trained ANN that can predict the influence of diesel additives, such as ammonia, on engine vibration depending on the fuels used in the mixture.

Thus, this study is relevant and unique as it offers new approaches allowing to analyze the influence of additives on the vibration of diesel engines. This study will allow to develop more efficient and environmentally friendly fuel mixtures and reduce dependence on conventional hydrocarbon energy sources.

AIM

This study aims to analyze the influence of innovative diesel fuel additives, such as ammonia (NH_3), on the vibration of a diesel engine. Given contemporary requirements to low emissions of harmful substances and improved engine efficiency, NH_3 research is of particular interest to the energy sector.

In addition to the applicable empirical relationships of vibration and engine dynamics and the parameters of studied fuel mixtures, vibration studies of engines running on conventional and alternative fuel will be used as inputs for the neural network. This approach allows to verify the neural network outputs and assess the potential benefits of ANN used to analyze engine vibration parameters.

Thus, the main aim of the paper is to determine the influence of additives on the vibration of diesel engines and to confirm the hypothesis that the NH_3 additive both reduces emissions and affects the engine performance.

METHODS

To achieve the aim of this study, i.e. to analyze the influence of ammonia (NH_3) as a diesel fuel additive on engine vibration properties, we developed an approach that involves the development and training of an artificial neural network (ANN) and the prediction of diesel engine vibration test results for fuel mixtures with different ammonia levels.

Modeling a process using an artificial neural network

Neural networks are mathematical models operating as real neurons in the human brain. They have multiple layers and each layer contains neurons that connect to other layers. During the training, the network adjusts connections between neurons to find data dependencies. For example, in this study, the neural network determines how engine and fuel parameters affect vibration amplitude. This ability to find nonlinear relationships makes neural networks indispensable predictors for complex systems, including internal combustion engines.

In tests conducted at the Wrocław University of Science and Technology [1], vibration acceleration of the tested engine was determined in different operational modes. These data, together with engine design parameters and fuel properties, allow to define a running engine model to determine relationships of parameters.

To read the values, the neural network requires input data, i.e. a file containing row-by-row parameters of the engine state at a particular time. The data set size may vary depending on the frequency and the duration of vibration sensor measurements. In our case, the measurement frequency was 8.5 kHz, which, with a measurement duration of 10 seconds, provides a data set of 85,000 rows. During engine operation, its design parameters and fuel properties (in short-term tests) do not change; therefore, in a measurement set that corresponds to a certain engine speed, only the vibration

amplitude will differ—and it will be different for each sensor measurement. When switching to the next engine operating mode, the crankshaft speed also changes. This, together with the vibration sensor measurements, will provide another data sample.

This data format is required for the neural network to read the parameter variations. An example of such data format is shown in Table 1; it includes two random rows from the total sample of engine operation data at a crankshaft speed of 1,200 rpm.

An important initial task is to prepare, normalize, and adjust the data to a common format and type (in this case, FLOAT [floating point numbers]). Data normalization involves transforming the inputs so that their values belong to a common scale with the range from 0 to 1. This step is extremely important when training a neural network as it improves the model convergence and prevents numerical instability. If the parameters (properties) used have different ranges (e.g. the engine speed is measured in '000 rpm and the compression ratio is measured in digits), the model may prioritize the parameters with the highest absolute value. Normalization process solves this issue.

After splitting and normalizing, the data were formatted so that they were easily understood by machine learning tools, including TensorFlow or Keras. Each input parameter (e.g. bore diameter or fuel viscosity) corresponded to a separate neuron in the input layer of the model. A single output neuron predicted the engine vibration amplitude for a given set of input parameters. These actions are key to successful training of the neural network as they ensure the correct operation of machine learning algorithms, minimization of errors associated with incorrect data preparation, and an unbiased quality assessment of the model.

The vibration data have a temporal structure, i.e. it represents values obtained over certain time intervals; thus, a recurrent neural network was initially chosen for the study. However, due to the large number of parameters, we have decided to use a fully connected neural network as it is more suitable for regression and prediction, allows to efficiently process multidimensional data, and generates accurate outputs. All data preparation steps performed in the study proved critical

to the successful training of the model. This ensured the stable operation of machine learning algorithms, mitigated the risk of errors caused by insufficient data processing, and provided for an unbiased and reliable model quality assessment.

Fig. 1 shows the layered structure of the neural network.

The number of input layer nodes is determined by the parameters used in the study; the parameters, in turn, are determined by the depth of the available data and computational power.

Cloud computing plays a key role in contemporary machine learning research. Renting a cloud server allows researchers to use high-power computing resources without having to invest in their own hardware. Training a neural network is a fairly resource-intensive process; therefore, a cloud server was rented from Selectel to perform computational tasks required to train the neural network.

The server was running on Ubuntu operating system compatible with common machine learning libraries, such as TensorFlow and Keras. All data, including 12 key parameters (e.g. engine speed and fuel viscosity), were prepared, normalized, and downloaded in CSV (Comma-Separated Values) format. These data were used to train a neural network with optimized hyperparameters, allowing to achieve high prediction accuracy. Computing power ensured efficient data processing and reduced model training time; it allowed us to focus on data analysis and eliminated the need to solve infrastructure problems. Thus, the study was completed within the specified period.

The number of neurons in the input layer directly depends on the number of studied parameters. In this case, these are parameters describing the engine design, fuel properties, and vibration amplitude as the target variable. For example, Table 1 lists 12 input parameters:

1. Engine bore
2. Crankshaft speed
3. Stroke
4. Compression ratio
5. Piston weight
6. Crankshaft moment of inertia
7. Exhaust valve diameter

Table 1. Parameters of the input layer of the neural network

Таблица 1. Параметры входного слоя нейросети

Engine bore (mm)	Crankshaft speed (rpm)	Stroke (mm)	Compression ratio	Piston weight (g)	Crankshaft moment of inertia (kg·m ²)	Exhaust valve diameter (mm)	Fuel density (kg/m ³)	Fuel viscosity (mm ² /s)	Cetane number	Vibration amplitude (mm)
69.6	1,200	82	17.6	310	0.2	30.5	820	3	50	1.64875
69.6	1,200	82	17.6	310	0.2	30.5	820	3	50	1.60124

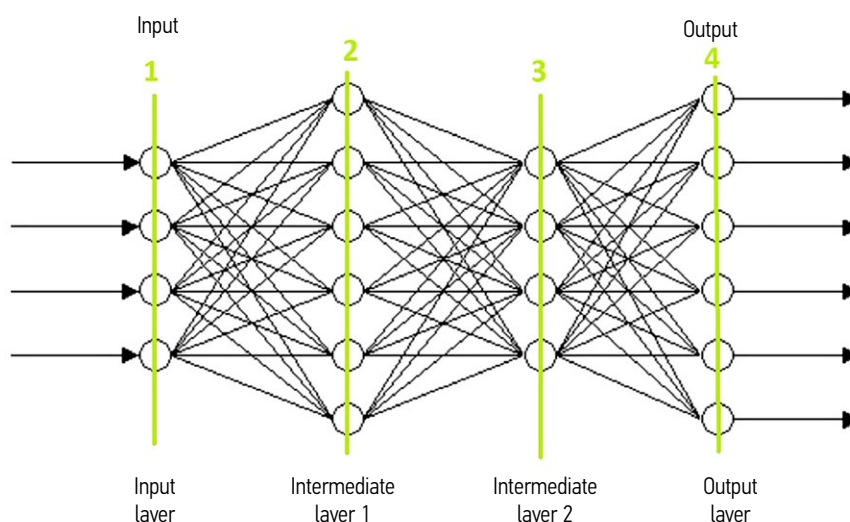


Fig. 1. A diagram of the layered structure of a neural network.

Рис. 1. Схема послойной структуры нейросети.

8. Fuel density
9. Fuel viscosity
10. Fuel cetane number
11. Fuel calorific value
12. Vibration amplitude (target variable).

These parameters provide a detailed description of the system and allow the neural network to learn complex relationships.

Activation functions introduce nonlinearity to the data processing at each network layer. This allows the neural network to effectively process the data where the input and output relationship is nonlinear, similar to engine parameters and vibrations.

Activation functions play a key role in the operation of neural networks as they allow models to capture complex nonlinear data relationships. Without activation functions, any neural network would be reduced to a simple linear model this would significantly limit its ability to solve complex problems, such as predicting engine vibrations based on multiple inputs.

Configuration of the neural network used the ReLU (Rectified Linear Unit) function providing an acceptable balance of predictive accuracy and computational efficiency. Due to its shape, the ReLU function effectively extracts significant data patterns, which is especially important when processing a lot of input parameters, as is the case in our study.

When using biodiesel fuel parameters, outputs of the artificial neural network model were as close as possible to the experimental data that had been obtained during tests at the Wrocław University of Science and Technology [1]. This confirms that the model is consistent with real-life data and able to accurately reproduce the complex processes occurring in the engine. During the pre-training stage, the data was divided into two

groups, i.e. a training set (70% of the total size) that was used to fine tune the model and a test set (30%) designed to test the training set's performance on new observations that were not used for training.

The model training was focused on reducing the mean square error widely used in linear regression problems as the main quality metric of predictions.

This metric is calculated as follows. For each observation, the difference between the predicted and actual values is calculated then this difference is squared to eliminate possible negative values, and the result is averaged over the entire data set. This approach allows to effectively estimate the overall error of the model and seek to minimize it.

At the training and validation stages, the model accuracy was 98.67%. It shows both the high prediction accuracy and the model's consistency with real-life experimental data, which is especially important for its application in studies of complex systems. The data predicted by the neural network have proven to be correct therefore, the model is a reliable tool for further research involving the analysis of the influence of various parameters on engine vibration properties. A comparison of experimental and predicted data is shown in Fig. 2.

Prediction of ammonia-related engine vibration

To predict engine vibration in cases with ammonia additives in diesel fuel, we did three iterations of calculations by simulating engine operation with 5%, 10%, and 15% ammonia by volume added to the fuel mixture. These ratios were chosen based on specified safe levels of ammonia in fuel systems and its influence on combustion processes. At each iteration, the input fuel

parameters were changed, including density, viscosity, and cetane number, to match the physicochemical properties of the mixture at each ammonia level. The remaining input parameters related to the engine design were kept constant, allowing to only focus on the effect of fuel proportions.

At the first calculation stage, the neural network predicted marginal vibration changes for a mixture with 5% ammonia additive ratio compared to pure diesel fuel due to minor calorific value and mixture viscosity changes. At 10% ammonia additive ratio, the prediction showed an increased vibration amplitude, which may be associated with impaired ignition and heterogenic mixture properties. The predicted diagram of engine vibration accelerations is shown in Fig. 3. In the third iteration with 15% ammonia additive ratio, the model predicted a more significant change in vibration, indicating increased vibration loads on the engine. These outputs highlight the need for careful optimization of fuel proportions and engine fine-tuning for each ammonia level to reduce negative impact on engine durability and stability.

Analysis and comparison of results

Our study showed that with increased ammonia (NH_3) additive ratio in the fuel mixture, engine vibration tends to increase. This effect is associated with changes in combustion behavior caused by the physicochemical properties of ammonia.

For example, NH_3 has a lower calorific value compared to diesel fuel, affecting ignition behavior and flame propagation.

With 5% ammonia additive ratio, the basic engine vibration parameters remain generally the same.

A slightly increased amplitude is associated with a change in the mixture density and viscosity. However, these changes are not critical for the overall engine operation.

At 10% ammonia additive ratio, a noticeable increase in vibration amplitude is observed. This is associated with lower combustion stability and may result in uneven pressure distribution in the cylinders and additional dynamic loads on the piston block and the crank gear.

The highest increase in vibration was recorded at 15% additive ratio. The vibration amplitude reaches 11.67 m/s^2 , indicating significant changes in the combustion behavior. Unstable ignition and higher combustion rate of the NH_3 mixture create additional vibration loads that may lead to accelerated wear of engine components.

We focused on the relationship of vibration and engine speed. We found that in all tested NH_3 additive ratios (5%, 10%, 15%), the vibration amplitude decreased as the engine speed increased from 1,200 to 2,400 rpm. The highest vibration levels were observed at 1,200 rpm, which corresponds to engine idling. Vibration increases as NH_3 additive ratio in the fuel mixture increases it is associated with uneven combustion typical of high ammonia level.

The described relationships are shown in Fig. 4.

CONCLUSION

The study was designed to investigate the influence of ammonia (NH_3) additives in diesel fuel on the vibration parameters of a diesel engine. It shows that the use of 5%, 10%, and 15% NH_3 resulted in increased vibration. Analysis of the predicted data shows that the acceleration

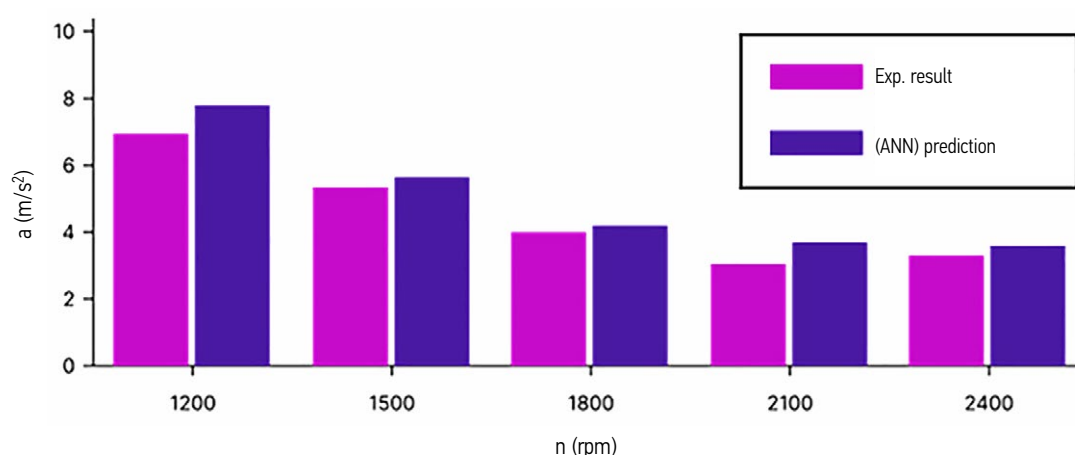


Fig. 2. Comparison of experimental and forecast data on vibration activity of a biodiesel engine (vertically: the acceleration value of the engine; horizontally: the rotational speed of the crankshaft of the engine).

Рис. 2. Сравнение экспериментальных и прогнозных данных виброактивности двигателя, работающего на биодизеле (по вертикали — значение ускорения двигателя; по горизонтали — частота вращения коленчатого вала двигателя).

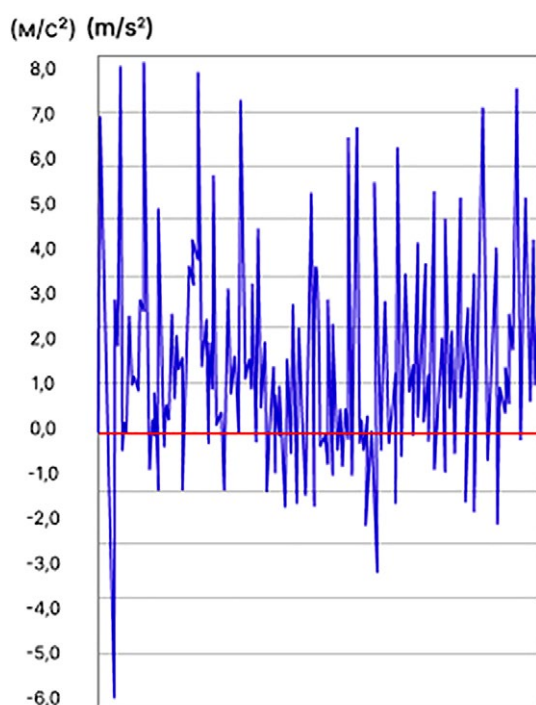


Fig. 3. The forecast diagram of the vibration acceleration of the engine when running on a fuel mixture of 10%NH₃ (acceleration values are displayed vertically, similar to the measurements obtained from the vibration sensor).
Рис. 3. Прогнозная диаграмма виброускорений двигателя при работе на топливной смеси 10%NH₃ (по вертикали отображены значения ускорения, подобные измерениям, полученным с вибродатчика).

amplitude reaches 11.67 m/s² at the highest ammonia level in the mixture (15%). This highlights that ammonia additive affects engine behavior, indicating the need for further research.

The study disputes the expected effectiveness of NH₃ as a means of improving engine performance

and reducing harmful emissions. Increased vibration associated with increased ammonia level may affect the operational reliability and durability of the powertrain. This increase is caused by changes in the physicochemical properties of the fuel, resulting in uneven combustion and, therefore, increased vibration loads on the engine structure.

It should be noted that artificial neural networks (ANN) used to simulate vibration parameters showed high prediction accuracy (nearly 99%). However, despite the high accuracy of the model, its predictions do not always correlate with actual operating data, especially as ammonia level increases above 10%.

This discrepancy may be caused by model restrictions and complexity of describing all combustion aspects of ammonia mixtures.

The results highlight the importance of further research aimed at in-depth understanding of the physicochemical properties of NH₃-added fuels and their influence on diesel engine performance. The research should focus on studying the influence of factors such as pressure, temperature, and various fuel proportions on engine operation stability. These factors can have a significant impact on the fuel combustion behavior, heat exchange, and vibration.

In the premises, this study creates advanced research areas for further study of possible use of ammonia as a fuel additive. However, the identified risks of increased vibration highlight the need for a cautious and comprehensive approach to the use of NH₃ as a diesel fuel component. To achieve this goal, it is required to develop technologies capable of mitigating the negative effect of ammonia and further optimize the fuel mixtures to ensure their environmental safety and stable engine operation.

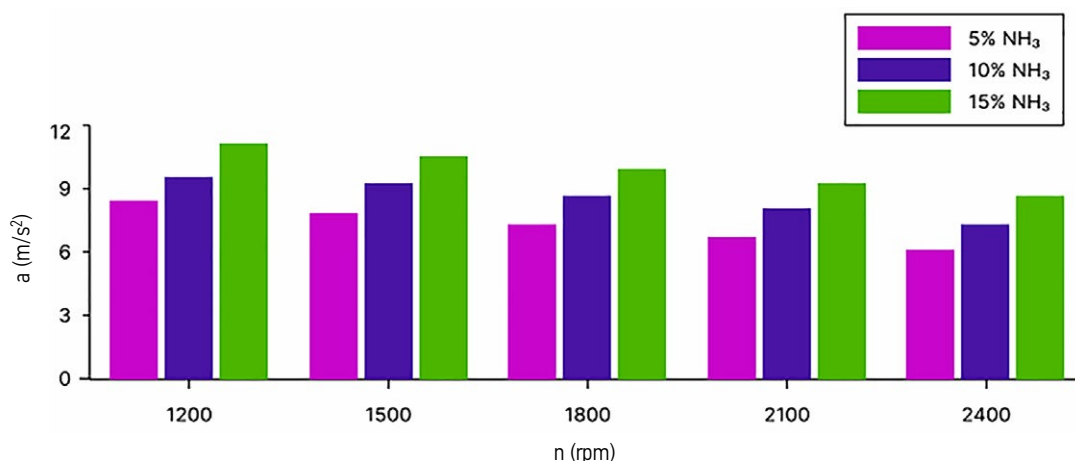


Fig. 4. Comparison of vibration activity levels depending on the NH₃ content in the fuel mixture (vertically: the acceleration value of the engine; horizontally: the rotational speed of the crankshaft of the engine).

Рис. 4. Сравнение уровней виброактивности в зависимости от содержания NH₃ в топливной смеси (по вертикали — значение ускорения двигателя; по горизонтали — частота вращения коленчатого вала двигателя).

ADDITIONAL INFORMATION

Author contributions: E.V. Telpiz: literature review, collection and analysis of literary sources, writing text, working with graphs and diagrams and editing the manuscript; V.G. Rybachuk: literature review, collection and analysis of literary sources, work on creating and training a neural network, preparing and writing the text of the manuscript. Thereby, all authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

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ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад авторов. Е.В. Тельпиз — обзор литературы, сбор и анализ литературных источников, написание текста, работа с графиками и диаграммами и редактирование статьи; В.Г. Рыбачук — обзор литературы, сбор и анализ литературных источников, работа по созданию и обучению нейросети, подготовка и написание текста статьи; все авторы одобрили рукопись (версию для публикации), а также согласились нести ответственность за все аспекты работы, гарантируя надлежащее рассмотрение и решение вопросов, связанных с точностью и добросовестностью любой её части.

Этическая экспертиза. Неприменимо.

Источники финансирования. Отсутствуют.

Раскрытие интересов. Авторы заявляют об отсутствии отношений, деятельности и интересов за последние три года, связанных с третьими лицами (коммерческими и некоммерческими), интересы которых могут быть затронуты содержанием статьи.

Оригинальность. При создании настоящей работы авторы не использовали ранее опубликованные сведения (текст, иллюстрации, данные).

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Рассмотрение и рецензирование. Настоящая работа подана в журнал в инициативном порядке и рассмотрена по обычной процедуре. В рецензировании участвовали один внешний рецензент, член редакционной коллегии и научный редактор издания.

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