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Mechatronic colorimetric system for measuring operational degradation of engine oil as a means to enhance the reliability of motor vehicles

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Article info

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The article presents the results of a study on the operational degradation of engine oil under the working conditions of internal combustion engines (ICE) used in agricultural and automotive machinery, where the operating environment is classified as particularly severe: high air dustiness, irregular loads, frequent engine starts, and extended idling periods. These factors accelerate the wear of friction pairs, deteriorate lubricating properties, and reduce the overall reliability of power units. Existing maintenance regulations do not consider real operating conditions, which creates the need for inter-schedule monitoring of oil condition – possible only through technical measurements and digital analysis of degradation parameters. The aim of the research is to develop a methodology and conduct experiments to determine the resource indicators of engine oil based on color change using colorimetric equipment equipped with mechatronic system elements. The study is based on comparing the color of fresh oil with that of oil after operational wear. RGB/HSL colorimetry tools and statistical processing were applied. A laboratory setup was developed based on the STM32H747XI microcontroller and the TCS3472 color sensor, enabling the detection of oil color changes and evaluation of its degradation linked to engine operating hours. Calibration was performed between reference samples and boundary conditions corresponding to the full service interval. The investigation of VAG Special G 5W-40 engine oil (BSE engine) over 400 engine hours demonstrated a stable functional dependence between impurity saturation and engine runtime. The average increase in contamination confirmed a reliable correlation between color variation and actual wear of friction components. The proposed methodology enables inter-schedule monitoring of engine oil condition and prediction of optimal replacement timing based on real operating conditions. The practical significance of the study lies in the increased reliability of ICE, reduced maintenance costs, and prevention of premature equipment failures. The proposed mechatronic colorimetric system can be integrated into service centers and precision farming systems as a component of digital diagnostics of machine technical condition.

Keywords: engine oil, oil degradation, mechatronics, wear of components, inter-schedule maintenance.

Мехатронна кольориметрична система вимірювань експлуатаційної деградації моторної оливи як засіб підвищення надійності автотранспортних засобів

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У статті представлено результати дослідження експлуатаційної деградації моторної оливи в умовах роботи двигунів внутрішнього згоряння (ДВЗ) сільськогосподарської та автомобільної техніки, де умови експлуатації належать до особливо тяжких: підвищена запиленість повітря, нерівномірні навантаження, часті запуски двигуна і тривала робота на холостих обертах. Ці фактори прискорюють процес зношування елементів тертя, погіршують властивості мастильних матеріалів та знижують надійність силових агрегатів. Відомі регламенти технічного обслуговування не враховують реальних умов експлуатації, що обумовлює потребу у міжрегламентному контролі стану оливи, який можливий лише за умов застосування технічних вимірювань і цифрового аналізу параметрів деградації. Метою дослідження є розроблення методики та проведення експериментів для визначення ресурсних показників моторної оливи за зміною її кольору з використанням кольориметричного обладнання, оснащеного елементами мехатронної системи. Дослідження базуються на порівнянні кольору базової оливи та оливи з експлуатаційним наробітком. У роботі використано інструментальні засоби RGB/HSL-колориметрії та статистичну обробку результатів. Розроблено лабораторну установку на основі мікроконтролера STM32H747XI з фотодатчиком TCS3472, що дозволяє фіксувати зміну кольору оливи та визначати ступінь її деградації в прив'язці до мотогодин роботи двигуна. Калібрування проведено між еталонним станом та граничними значеннями, що відповідають повному сервісному інтервалу. Дослідження моторної оливи VAG Special G 5W-40 (двигун BSE) протягом 400 мотогодин показали стабільну функціональну залежність насиченості домішками від наробітку. Середні значення зростання забруднення підтверджують достовірний кореляційний зв'язок між зміною кольору та фактичним зносом елементів тертя. Застосування запропонованої методики забезпечує можливість міжрегламентного контролю стану моторної оливи та прогнозування моменту її заміни з урахуванням реальних умов експлуатації. Практична значущість роботи полягає у підвищенні надійності ДВЗ, зниженні витрат на технічне обслуговування та запобіганні передчасним відмовам обладнання. Запропонована мехатронна кольориметрична система може бути інтегрована у сервісні центри та систему точного землеробства як елемент цифрової діагностики технічного стану машин.

Ключові слова: моторна олива, деградація оливи, мехатроніка, знос деталей, міжрегламентне обслуговування.

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Introduction

Mechanized technologies in the agricultural sector rely on the intensive use of internal combustion engines, which serve as the basis for the operation of tractors, motor vehicles, and self-propelled harvesting machines. The efficiency and stability of agricultural production directly depend on the performance of power units, their ability to perform technological operations without failures, as well as on the cost of maintenance and repair services. Studies conducted in most regions of Ukraine [1–3] confirm the need to modernize the machine and tractor fleet and to implement advanced systems for monitoring the technical condition of equipment. This will contribute to the reduction of emergency repairs and financial losses for agricultural enterprises.

One of the key factors determining the reliability and durability of internal combustion engines (ICEs) is the quality of fuel and lubricants. It has been established that the use of low-quality fuel can reduce the failure-free service life of machinery by up to 70 %, resulting in premature wear of fuel and lubrication system components, higher service costs, and the need for major overhauls [4]. Numerous research works [5–7] present the results of a correlation analysis between the physicochemical properties of fuel and the operational performance of ICEs, the wear intensity of friction elements, and the environmental characteristics of exhaust gases. Researchers propose methods for monitoring the composition of the air-fuel mixture, controlling combustion regimes, and diagnosing fuel system components to improve the overall efficiency of the engine [8, 9].

However, fuel quality is only one component of the operational reliability of power units. An equally important factor is engine oil, which ensures heat dissipation, friction reduction, clearance compensation, and prevention of dry contact between working surfaces. It is well known that during operation, the oil undergoes degradation, accumulating oxidation products, abrasive particles, soot, and contaminants that significantly reduce its functional properties [10, 11]. The deterioration of lubricating characteristics leads to increased wear of friction assemblies, loss of compression, partial seizure of components, and uncontrolled temperature rise, which accelerates engine failure.

From a scientific perspective, the operational degradation of engine oil can be assessed by changes in its color, which reflects the accumulation of mechanical impurities and products of incomplete fuel oxidation [12, 13]. The main sources of contamination include: metal micro-particles (chips) generated by precision friction pairs; sulfur, ash, bitumen, and resinous compounds derived from diesel fuel; fuel vapors penetrating the lubrication system through piston rings; and products of exhaust gas recirculation.

In agricultural machinery, the operating conditions of internal combustion engines are classified as particularly harsh: high air dustiness, fluctuating loads, frequent engine starts, and prolonged idle operation. These factors increase the stress on the lubrication system and necessitate a well-founded determination of oil replacement intervals. Existing maintenance regulations do not consider real-world operating conditions; therefore, there is a need for inter-service monitoring of oil condition, which can only be implemented through technical measurements and digital analysis of degradation parameters [14].

Image processing technology based on video offers an innovative approach for extracting dynamic characteristics and has already been successfully applied in such fields as medical diagnostics, robotic vision, and intelligent transportation systems. In particular, for wear analysis, video recording is valuable as it prevents particle adhesion (agglomeration) during motion, enabling accurate extraction of the characteristics of individual wear particles. Although particle movement may cause image blurring, color information can be restored using image color enhancement techniques. As reported in studies [15, 16], an online image processing system was used to obtain video footage of moving wear particles in lubricant. Specialized preprocessing methods, including motion blur restoration, were employed to effectively isolate the particles prior to color extraction. Real-time monitoring of oxidative wear confirmed the system's practical applicability for early detection and assessment of wear progression in operating equipment.

Currently, the development of a mechatronic system for determining operational changes in engine oil color is a relevant research direction. Such a system would enable the diagnosis of oil service life in engine hours, detection of critical contamination levels, prediction of replacement feasibility, and optimization of maintenance schedules.

Therefore, the main objective of this study is to develop a methodology for resource analysis of engine oil using elements of a mechatronic colorimetric measurement system, which will enhance the reliability of motor vehicles and provide a scientific basis for inter-service maintenance intervals.

The aim of the study

The aim of the study is to develop a scientifically grounded methodology and conduct experimental and comparative research to evaluate the resource indicators of engine oil in the lubrication systems of internal combustion engines using laboratory equipment equipped with elements of a mechatronic system for technical measurements.

To achieve this objective, the following scientific and applied tasks must be addressed:

1. To perform an analysis of existing designs, technical solutions, and scientific studies aimed at determining the operational properties of engine oils based on their color as an indicator of degradation and contaminant accumulation.
2. To develop a laboratory setup for resource analysis of engine oil through instrumental determination of its colorimetric parameters using elements of a mechatronic system.
3. To establish a calibration methodology for the laboratory setup and conduct experimental research with reference to the operating modes of internal combustion engines and the oil service intervals.
4. To justify practical recommendations regarding the application of the laboratory setup for inter-service

diagnostics of engine oil under service and maintenance conditions of motor vehicles.

Materials and methods

The methodology of comparative studies of the physicomechanical characteristics of engine oil in internal combustion engine (ICE) lubrication systems is based on the analysis of color changes during operation. For this purpose, the color of the fresh (baseline) oil at the start of operation is compared with the color of the oil after the accumulation of operational service life.

1. Color evaluation as an indicator of engine oil condition

Oil color is considered an important indicator of its quality because it: is the first visible sign of change observed by the operator; may reflect the degree of purification and level of contamination; indicates the presence of mechanical impurities, oxidation products, and fuel residues.

However, color is not a universal criterion for assessing the quality of a lubricant; therefore, its use as a resource-forming indicator (oil service life) requires justification and a standardized measurement methodology.

To enable high-precision determination of liquid color, the following methods are commonly used:

1. Spectrophotometric method – measures light absorption across the entire visible spectrum and constructs a spectral curve (a "color signature"), ensuring high accuracy in color identification and comparison.
2. Colorimetric method – measures light intensity at predefined wavelengths to rapidly determine the concentration of substances based on color depth.
3. Visual comparison – compares a sample with standardized reference scales under regulated lighting conditions.

For standardized measurement of liquids with different transparency levels, specialized color scales are applied: Hazen scale (APHA/Pt-Co) [17] – for evaluating the yellow color intensity of petroleum products and solvents; Gardner scale [17] – for assessing the color of light and yellow-brown liquids (oil, resins, varnish); Saybolt scale [18] – for characterizing very light petroleum products; ASTM D1500 scale [18] – for determining the color of fuel oil, diesel, and lubricants.

In this study, the emphasis is placed on instrumental color determination followed by mathematical conversion into resource indicators of engine oil.

2. Use of the RGB color model and digital methods

To obtain a quantitative description of color, an additive RGB model [19] is applied, where color is formed by combining three fundamental components of light: R – Red, G – Green, and B – Blue.

The total color intensity can be formally expressed as a vector equation:

$$C = rR + gG + bB, \tag{1}$$

where C is the resulting color intensity;

R, G, B are the basic components;

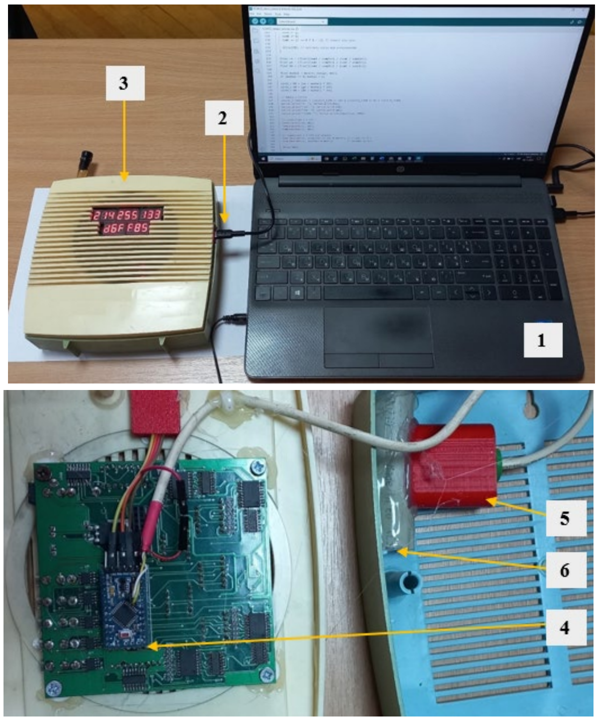
r, g, b are the coefficients of their intensity (saturation).

Considering the characteristics of human visual perception, gamma correction is applied in digital systems to ensure a more adequate correspondence between the physical light intensity and the perceived brightness. The processing of the obtained digital data (including linear and nonlinear transformations) is carried out using methods of digital signal and image processing.

3. Color Measurement Equipment

There is a range of portable color measurement devices used in industry for quality control. One example is the LUTRON RGB-1002 analyzer, which can determine the color of samples in both the RGB and HSL color systems, perform calibration based on a reference sample, and transfer data to a PC via the RS232 interface.

Within this study, a specially designed laboratory setup (***Fig. 1***) was used to determine the relative indicators of mechanical impurity content in engine oils (and other technical fluids).



a

b

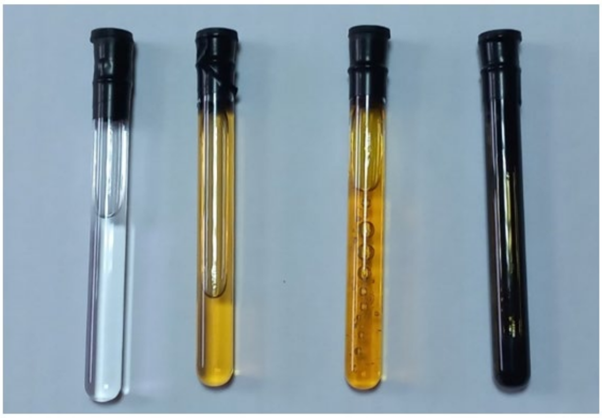
Fig. 1. Laboratory setup for determining impurities in engine oils:
a) general view of the setup; b) internal view of the setup.
1 – personal computer; 2 – special cable; 3 – measuring instrument; 4 – controller; 5 – color converter; 6 – sample under investigation.

Oil samples are stored in sealed test tubes (***Fig. 3***). The following samples were used for calibration:

– transparent reference sample (colorless sample) (***Fig. 2a***);

– fresh engine oil without operating hours (0 engine hours) (***Fig. 2b, c***);

– engine oil after reaching the limit service life of the engine (400 engine hours, equivalent to ≈15.000 km of vehicle mileage) (***Fig. 2d***).



a b c d

Fig. 2. Samples of the tested fluids:
a – transparent reference sample; b, c – baseline engine oil without operating hours; d – engine oil after the limit service life of the engine.

4. Software and Processing Algorithm

The laboratory software consists of two logical modules:

1. Color Measurement Module, which provides: signal acquisition from the TCS3472 sensor; conversion of raw data into encoded RGB and HSL formats; visualization of the results on a PC screen; data logging for further analysis.

2. Resource Analysis Module – implemented in Microsoft Excel. It performs: mathematical conversion of encoded color parameters into the oil service-life indicator; calculation of the relative impurity saturation level; generation of recommendations regarding the necessity of oil replacement.

The algorithm is designed to compare the color intensity of the tested sample with that of the reference samples (fresh oil and oil with the limit service life), allowing the formation of a correspondence matrix between color and contamination level.

5. Research Procedure

The experimental methodology consists of two main stages:

1) Calibration of the measuring system. The objective of calibration is to establish the boundary range of engine oil color change – from the initial (reference) state to the state of maximum operational contamination with mechanical impurities. For this purpose: the RGB and HSL color parameters of fresh, unused oil are measured; the corresponding parameters of oil after the limit operating time (400 engine hours) are measured; the obtained values are entered into a specially designed Microsoft Excel spreadsheet, which serves as the basis for constructing a transition scale from “clean” to “contaminated” oil.

2) Practical determination of engine oil condition. Measurements are carried out at specific stages of equipment operation, taking into account load modes, operating conditions, and fuel quality [20].

The oil sample is collected through the dipstick port and placed into the holder of the laboratory device. After data acquisition, the values are entered into the electronic spreadsheet, where the program calculates the relative impurity saturation. Based on this, the system generates a recommendation: continue operation, or perform oil replacement.

The impurity saturation is described by the following functional dependence:

$$H = f(\lambda), \qquad (2)$$

where H is the impurity saturation relative to the maximum operational service life, %;

λ is the engine operating time, measured in engine hours.

Thus, the developed methodology enables the correlation of the oil’s colorimetric parameters with its resource indicators and allows the obtained dependencies to be applied for diagnosing the condition of the lubricant under actual operating conditions.

Results and discussion

The experimental studies were carried out using VAG Special G 5W-40 engine oil, which was operated in a BSE engine of a 2012 Skoda A5 vehicle. Each measurement was performed in four replications, and the operating range of the engine oil reached up to 400 engine hours, corresponding to approximately 15.000 km of inter-service mileage.

Based on the obtained results, the values of the relative impurity saturation (H) of the engine oil were determined depending on the engine operating time. The summarized results are presented in ***Table 1***.

Table 1
Relative impurity saturation of engine oil (H, %)

Engine operating time, h	0	40	80	120	160	200	240	280	320	360	400
Relative impurity saturation, %											
Experiment 1	2.6	3.85	3.45	5.84	8.97	12.58	20.25	35.25	54	80	100
Experiment 2	2.7	3.88	3.39	5.9	8.9	12.59	20.2	35.2	54	81	99
Experiment 3	2.55	3.79	3.42	5.91	8.91	12.54	20.8	35.3	54.8	82	100
Experiment 4	2.59	3.85	3.49	5.69	9.1	12.6	19.8	35.25	53.8	79	100
Average value	2.61	3.84	3.43	5.83	8.97	12.57	20.26	35.25	54.15	80.5	100

A change in the color of engine oil demonstrates a stable exponential trend, indicating the gradual accumulation of mechanical impurities and wear products. A particularly sharp increase in impurity saturation is observed after 200–240 engine hours, which corresponds to a critical transition zone, where irreversible changes in the structure of the lubricating layer begin to occur.

Based on statistical data processing, a functional dependence was established (***Fig. 3***), which describes the color-based degradation of the lubricant: $H = 1{,}4065 \cdot e^{0.3913\lambda}$.

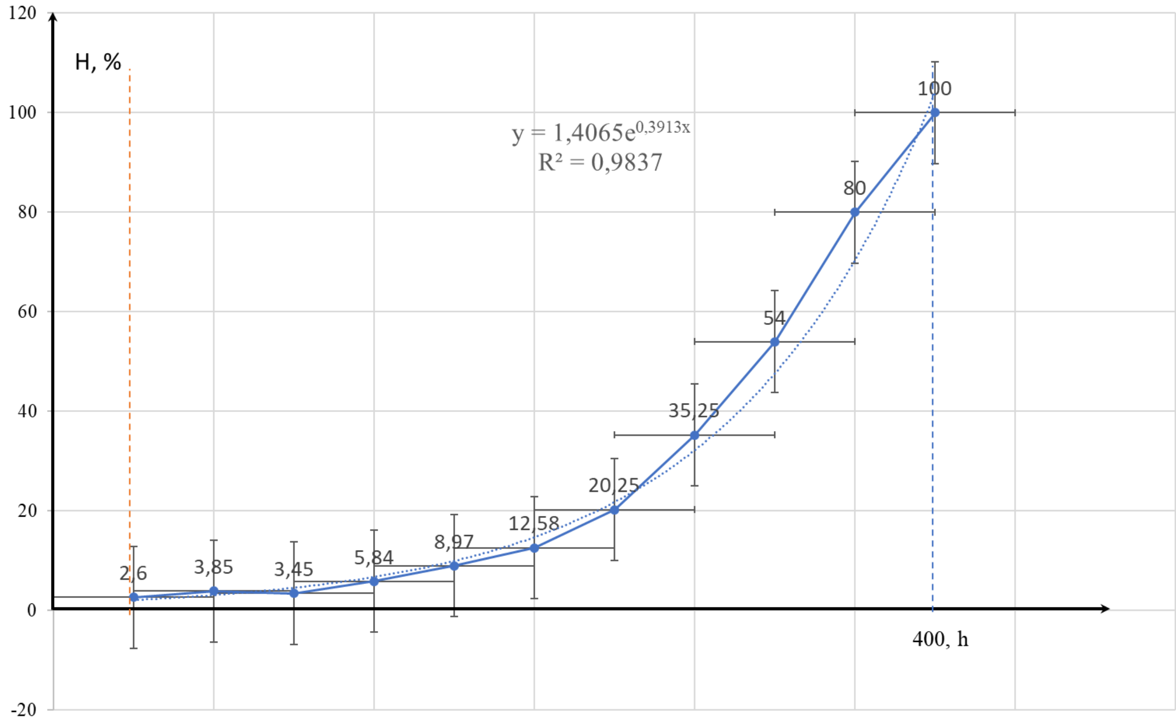


Fig. 3. Graph of impurity saturation in engine oil based on experimental data as a function of ICE operating time under real operating conditions.

The obtained dependence shows that when the operating time exceeds 360–400 engine hours, the lubricant reaches 100 % conditional contamination, which justifies the need for oil replacement regardless of the standard service schedule.

The accuracy of the conducted measurements complies with the general requirements for experimental research, confirms the reproducibility of the results, and allows the obtained data to be used for practical diagnostics of lubricant condition.

To implement the proposed methodology under production conditions, it is advisable to introduce periodic sampling of engine oil and its analysis using the mechatronic laboratory system. This approach enables:

– accounting for real operating conditions;
– evaluation of fuel and lubricant quality;
– monitoring the degree of component wear;
– determining the feasibility of inter-service maintenance;
– preventing engine failures;
– increasing the failure-free operational life of motor vehicles.

Thus, the proposed method may serve as the basis for an applied diagnostic system for ICE condition and as an element of a service-oriented mechatronic system for technical operation support.

Conclusions

1. It has been established that engine oil color can be applied as an informative diagnostic parameter that correlates with the intensity of lubricant degradation and the operating time of the internal combustion engine. The application of a colorimetric approach is appropriate for inter-service monitoring of the technical condition of machinery.

2. A laboratory mechatronic setup has been developed for assessing the contamination level of engine oil and determining its conditional service life in engine hours. It ensures digital color measurement in RGB and HSL systems, automated data processing, and the generation of operational recommendations regarding the feasibility of oil replacement.

3. Based on the experimental results, a consistent exponential trend of lubricant degradation was identified, confirming a clear dependence between oil color and contamination with mechanical impurities. The obtained data are reproducible and comply with the requirements for experimental research.

4. The proposed method for determining engine oil condition based on color allows for consideration of real operating conditions, fuel quality, ICE operating modes, and loading – which cannot be achieved when relying solely on standard service regulations. This opens the possibility of optimizing maintenance schedules.

5. The practical implementation of the methodology under production conditions enables the reduction of component and assembly wear within the ICE, improves the reliability and failure-free operation of vehicles, facilitates inter-service monitoring of technical condition, and reduces repair and maintenance costs.

6. Scientific prerequisites have been formed for the development of mechatronic systems for service diagnostics of technical fluids, which may form the basis for creating intelligent monitoring systems for motor vehicles and agricultural machinery.

Conflict of interest

The author (s) state that there is no conflict of interest.

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