The development of a dependent mathematical model of dielectric properties of an engine oil to the concentration of soot formation

A A Khaziev¹, N N Sugatov¹, A V Laushkin¹

¹ Department of Operation and servicing of motor vehicles, Moscow Automobile and Road Construction State Technical University (MADI), 64, Leningradsky ave., Moscow, 125319, Russian Federation

E-mail: madi-chim@mail.ru, nsugatov@gmail.com, lav82@mail.ru

Abstract. The frequency of engine oil replacement reaches 150 thousand km for modern trucks, which increases the load on the lubrication system, leads to an increase in the level of contamination and to a greater level of oil degradation. The accumulation of dirt in the oil and, above all, soot leads accelerated wear of bearings, valves and camshafts, and increases the rate of formation of sludge and deposits on the piston rings. All this significantly reduces the engine life. The purpose of the work is to estimate the soot concentration in engine oil by its dielectric parameters measured by the waveguide method. To study the dependence of the dielectric parameters of engine oil on the soot concentration, the transmission line method was chosen and an installation was created that allows measuring the signal amplitude in a given frequency range. Tests performed on various engine oils at soot concentrations in the oil from 0 to 1.06% allowed us to identify the most optimal frequency regions where high sensitivity of the method is achieved. The nature of the change in the dielectric constant of engine oil with an increase in the concentration of soot in it is established. Diagnostic indicators such as the frequency of peak peaks and the signal amplitude at the optimal frequency are identified. Mathematical models of the dependence of the peaks amplitude and frequency on the soot concentration in engine oils are constructed.

1. Introduction

The aim in reducing the maintenance costs of vehicles, and the elimination of the negative impact on the surrounding environment over the years generates a tendency to an increase in the periodicity of engine oil change. The periodicity of engine oil change varies for modern vehicle makes, 60000 km for light weight vehicles, and 150000 km for heavy duty vehicles, which in keeping to this recommendation leads to the pollution of the environment, and the degradation of the engine oil. In order to reduce the concentration of NOx in exhaust gases, an exhaust gas recirculation system (EGR) is used, where part of the exhaust gas is supplied to the intake manifold of the engine. The particles of soot in an engine with the EGR system is 20-30% denser, in comparison to soot particles in an engine without the EGR system. The combustion products that were supposed to be exhausted falls back into the cylinder as well as into the engine oil, leading to the increase in the accumulation rate pollution products in the engine oil. In order to keep the large impurities in suspension,
manufacturers usually increase the dispersing forces of the engine oil, which adversely affects the corrosion of parts in the engine due to the presence of primary amines in the oil.

Purpose of studies is the estimation of the concentration of soot in an engine oil based on its dielectric properties, measured using the frequency method

2. The effect of the concentration of soot in an engine oil and the technical state of the engine

Of the soot formed by the combustion of diesel fuel in the engine, only 29% flows through the exhaust pipe, the rest remains in the engine oil, on the walls of the cylinder and on the piston base [1-5]. Soot in oil leads to accelerated wear of the cylinder-piston group and gas distribution mechanism (GDM).

The more the soot in an engine oil, the greater the possibilities of wear of the piston rings, the cams of the camshaft, the rocker arms, the guide valves and other components of the engine.

Soot’s aggravates the wear of those contact surfaces with the least lubrication. The most intensive wear occurs with the GDM, as it is located in the upper part of the engine, which is not sufficiently lubricated, especially during cold starts, due to low pressure in the lubrication system and the high viscosity of the oil, which are normally observed during idling.

The concentration of soot in an engine oil can attain 3…4%. At same time, there is a common opinion that its content in an engine oil must not exceed 1%.

The high concentration of soot in an engine oil significantly increases the formation of sludge and sedimentation. Sedimentation on the piston rings is harmful, as this will lead to the ring losing its mobility and eventually ends up jamming. The limited freedom of motion of the piston rings will lead to the deterioration of the hermitization between the piston and the walls of the cylinder and the entrance of gases into the crankcase, which will lead to a further deposition of soot’s. The analysis of fig.1 shows that an increase in the concentration of soots brings about an increase in the kinematic viscosity of the lubricants. It should be noted that, a 2% presence of soot in an engine oil will lead to an increase in viscosity of more than 12.5 mm²/c [6].

Figure 1. The change in the kinematic viscosity of an engine oil at 40°C depending on the concentration of soot
3. Experimental Research

Recently, there has been a trend in the use of small-size sensors for determining the dielectric characteristics of engine oil, based on which it is possible to judge the qualitative characteristics of engine oil [7-9]. Therefore, now it is actual to investigate and develop mathematical models of dependence of qualitative characteristics of motor oil on its dielectric parameters. Carbon black has a significant effect on the dielectric constant of motor oil [10-12].

To study the dependency of the dielectric properties of an engine oil to the concentration of soot, the transmission line method was chosen [13], of which a setup was developed consisting of a measuring cell representing a rectangular waveguide with dimensions 32 x 16 x 166 mm, and a scalar network analyzer assembled on the basis of a USB-TG124A generator, and an analyzer USB-SA124B manufactured by Signal Hound company. The setup allows measuring the amplitude of the signal transmitted through the measuring cell in the frequency range from 2 to 12 GHz. The measured characteristic is an indirect indicator characterizing the dielectric properties of the engine oil under studies.

The measurements were carried out on synthetic, semi-synthetic and mineral engine oils with the concentration of soot in the engine oil in the range of 0 to 1.06% by volume. For each type of oil, 9 measurements were taken.

The measured amplitude-frequency response (AFC) of a measuring cell filled with synthetic oil, depending on the concentration of soot, is shown in Fig. 2. The AFC with an increase in the concentration of soot shifts to the left, in the direction of decreasing frequency. This explains the fact that the relative permittivity of soot is 18.8, which is significantly different from the dielectric constant of fresh oil (~ 2) [14, 15], and with an increase in the dielectric permittivity of the aggregate, decreases the cut-off frequency.

The boundary frequency determines the maximum wavelength that can propagate along the frequencies. Four (4) peaks can be selected for each AFC. The frequencies of the peaks correspond to the modes of electromagnetic waves that can exist at these frequencies. It should be noted that peaks 1-3 have a steeper peak than peak 4.

![Figure 2](image-url)  
**Figure 2.** Frequency response characteristic of synthetic motor oil with different soot content
Fig. 3 shows an enlarged peak regions of 1 and 2 AFC in comparison to fig. 1. The graphical analysis shows practically no change in the amplitude of the peaks, but with a step by step increase in the frequencies of the peaks 1 and 2, due to an increase in the concentration of soot.

![Figure 3](image)

**Figure 3.** Frequency response characteristics of a synthetic motor oil with different soot contents at frequencies ranges from 3375 to 3725 MHz

4. The analysis of the results of experimental studies

The dependency of the coefficient of correlation of soot concentration to the frequency for each type of engine oil, shown in fig. 4, allows to identify the most optimal frequency regions, where high sensitivity of the method is achieved.

![Figure 4](image)

**Figure 4.** The dependency of coefficient of correlation of soot concentration of an engine oil to frequencies
The most optimal signal frequencies for each type of oil were found, at which the maximum values of the amplitude differences for soot of 0% and 1.06% were obtained. The dependency of the signal amplitude on the concentration of soot in the engine oil at the selected optimum frequency is shown in fig. 5.

![Amplitude values vs Soot concentration](image)

**Figure 5.** The dependency of the signal amplitude of a synthetic engine oil to soot concentration at a frequency of 3495 MHz

Table 1 shows the optimal frequencies, the results of the correlation analysis, and the approximating functions that determine the dependency of the signal amplitude to the concentration of soot in oil.

**Table 1.** The optimal frequencies, the results of the correlation analysis, and the approximating functions that determine the dependency of the signal amplitude to the concentration of soot in oil

| Oil type           | Optimal frequency, MHz | Coefficient of correlation | Determinant coefficient | Mathematical model, $y = k \times x + b$ | Standard error of the angular coefficient, $k$ | Standard error of the free member, $b$ |
|--------------------|------------------------|----------------------------|-------------------------|------------------------------------------|---------------------------------|---------------------------------|
| Synthetic          | 3495                   | 0.99                       | 0.99                    | 22.39$x - 38.18$                         | 0.79                            | 0.49                            |
| Semi-synthetic     | 3495                   | 0.97                       | 0.93                    | 30.79$x - 46.22$                         | 1.82                            | 2.98                            |
| Mineral            | 3485                   | 0.96                       | 0.91                    | 30.32$x - 46.63$                         | 3.24                            | 1.98                            |
Table 2 shows the results of the correlation analysis for peaks 1-4. An example of constructing an approximating function for the dependency of the frequency of peak 1 on the concentration of soot is shown in fig. 6.

**Table 2.** The analysis of the dependency of peak frequencies 1-4 on the concentration of soot

| Oil type        | Optimal frequency MHz | Coefficient of correlation | Determinant of coefficient | Mathematical model, $y = k*x + b$ | Standard error of the angular coefficient, k | Standard error of the free member, b |
|-----------------|------------------------|----------------------------|----------------------------|-----------------------------------|-------------------------------------------|------------------------------------|
| Synthetic       | 1 0.99 0.98 78.08x + 3580.5 | 4.13 2.53 |  |
|                 | 2 0.98 0.95 75.78x + 3714.3 | 5.9 3.6  |  |
|                 | 3 0.99 0.97 89.82x + 3936.9 | 5.79 3.55  |  |
|                 | 4 0.93 0.84 89.28x + 4218.3 | 8.34 13.63  |  |
| Semisynthetic   | 1 0.998 0.99 97.65x + 3603.1 | 2.62 1.6  |  |
|                 | 2 0.995 0.99 100.21x + 3738.9 | 3.87 2.37  |  |
|                 | 3 0.995 0.99 115.75x + 3962.8 | 2.7 4.42  |  |
|                 | 4 0.97 0.92 105.56x + 4236.6 | 6.74 11.01  |  |
| Mineral         | 1 0.998 0.99 97.91x + 3597.7 | 1.7 2.78  |  |
|                 | 2 0.995 0.99 101.32x + 3734.4 | 2.45 4  |  |
|                 | 3 0.99 0.98 111.58x + 3955.2 | 5.65 3.46  |  |
|                 | 4 0.7 0.41 60.99x + 4207.4 | 23.71 14.52  |  |
The high correlation coefficients indicate a practically functional dependency of the amplitude on the selected optimal frequencies, and the peak frequencies on the concentration of soot. The determinant coefficients are high, and this means that the models constructed explain 93 ... 99% of the variation in values relative to their mean value.

5. Conclusion
The complex of experimental studies made it possible to establish the character of the change in the dielectric permittivity of the engine oil with increasing soot concentration. Obtained are the diagnostic parameters, such as the peak frequencies, and the amplitude of the signal at the optimum frequency, where measurements most informatively describe the change in the state of the engine oil.

The mathematical model dependencies of peak frequencies and amplitude of various engine oil samples to the concentration of soot is being obtained. It should be noted that the obtained dependencies are almost completely identical for semi-synthetic and mineral oils, which can be explained by their relative chemical composition.

References
[1] Sam G, Santhosh B, Vishaal G, Mridul G 2007 Effect of diesel soot on lubricant oil viscosity Tribology International Vol 40 5 809-818 Available at: http://dx.doi.org/10.1016/j.triboint.2006.08.002
[2] Yudin A V 2014 The method of controlling the effect of oxidation and thermal degradation processes on the antiwear properties of motor oils Dissertation 05.11.13 (TPU, Tomsk – Krasnoyarsk)
[3] Runda M M 2014 The method of monitoring the state of motor oils during long-term storage of machinery Dissertation 05.11.13 (TPU, Tomsk – Krasnoyarsk)
[4] Belyaev S V 1993 Motor oils and engine lubricatio (Petrozavodsk: PetrSU)
[5] Grigoriev M A, Bunakov B M, Doletsyky V A 1981 Engine oil quality and engine reliability (Moscow: Standards)
[6] Rigol S, Schenk M., Perryman R., Hosny W M 2009 Challenges in the onboard oil condition monitoring Proceedings of Advances in Computing and Technology, (AC&T) The School of Computing and Technology 4th Annual Conference, University of East London pp 26-34 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.426.9180&rep=rep1&type=pdf
[7] Mauntz M, Kuipers U, Gegner J 2011 New Electric Online Oil Condition Monitoring Sensor – an Innovation in Early Failure Detection of Industrial Gears IMETI 2011 - 4th International Multi-Conference on Engineering and Technological Innovation, Proceedings
[8] Perez A T, Hadfield M 2011 Low-cost oil quality sensor based on changes in complex permittivity Sensors 11 10675-10690
[9] Bouaïcha A, Fofana I, Farzaneh M, Seytashmehr A, Borsi H, Gockenbach E, Béroual A, Aka N T 2009 On the Usability of Dielectric Spectroscopy Techniques as Quality Control Tool IEEE Electr. Insul. Mag. Vol 25 1 6-14
[10] Carey A A 1995 The Dielectric Constant of Lubrication Oils (USA, OH, Cleveland: CRC press)
[11] Rigol S 2011 Monitoring Concept to Detect Engine Oil Condition Degradations to Support a Reliable Drive Operation. A thesis submitted in partial fulfilment of the requirements of the University of East London for the degree of Doctor of Philosophy
[12] Zhu J, Yoon J M, He D, Qu Y, Bechhoefer E 2013 Lubrication oil condition monitoring and remaining useful life prediction with particle filtering Int. J. Prognosis Health Manage Vol 4 2-6
[13] Sugatov N N and Khaziev A A 2013 Selection of the optimal method for assessing the quality of a running engine oil by dielectric properties Modernization and scientific research in the transport complex (Perm: Perm National Research Polytechnic University) 343-354
[14] Green D A and Lewis R 2008 The effects of soot-contaminated engine oil on wear and friction: A review Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering 222 (9) 1669-1689 Available at: https://www.researchgate.net/publication/245391734_The_effects_of_soot-contaminated_engine_oil_on_wear_and_friction_A_review
[15] Khaziev A A, Postolit A V, Sugatov N N, Laushkin A V 2017 Investigation of the effect of water concentration on the dielectric properties of motor oil Bulletin of the Moscow Automobile and Highway State Technical University (MADI) 1 (48) 21-27