Prediction of a residual operating life of engines

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Abstract
Results of the executed researches on prediction of an individual residual operating life of engines are pre-sented in article. Prediction is based on the diagnostic information on technical condition of engines ob-tained during the carrying out their maintenance and repair. The analytical equation, the describing regu-larities of change of diagnostic parameters on an operating time and its graphic interpretation are given. The forecasting technique of a residual operating life of mechanisms of engines with use of the lower fidu-cial bound of distribution of their practices to the limiting condition is offered. The technique is approved on the example of forecasting of a residual operating life of cylinder-piston group of the ZMZ-40524.10 engine.

1. Introduction
Prediction of a residual operating life is one of primal problems of diagnosing of a condition of any object including the internal combustion engine (ICE) during maintenance or repair. Definition of a stock of correct work of ICE allows if not completely to avoid opera-tional refusals, then it is essential to reduce their quantity due to timely detection and elimina-tion of the damages which arose in use.

Process of prediction of an individual residual operating life of units and units of the car provides realization of the following stages:
– data collection and processing on operational dependability of the studied object;
– justification of a complex of the diagnostic parameters which are adequating reflecting its technical condition;
– development of the analytical equations describing regularities of change of diagnos-tic parameters on an operating time;
– statistical assessment of the predicted residual operating life.

Results and Discussion
The tests executed in actual practice operation on operational dependability of ZMZ-40524.10 engines showed that exhaustion of the operating life put at its development is caused by gradual accumulation of various damages (wear, fatigue and corrosion destructions, residual deformations etc.). Therefore, at prediction of a residual operating life of engine sys-tems change of diagnostic parameter on an operating time with a sufficient degree of accuracy can be described by a power function:

\[ S(t) = S_m + vt^\alpha \] (1)

where \( S_m \) – initial value of diagnostic parameter; \( v \) – intensity of change of diagnostic parameter on an operating time \( t \); \( \alpha \) – the exponent defining dependence of diagnostic parameter \( S \) on operating time \( t \).

Graphic interpretation of this dependence is presented in Figure 1.
Figure 1. The schedule of change of diagnostic parameter on an operating time: $S_{lim}$, $S_i$, $S_m$ – limit, current and initial values of diagnostic parameter; $t_{pr}$ – predicted operating time to the limiting state; $t_i$ – current value of an operating time; $t_{res}$ – residual operating life; $f(t)$ – density function of operating time to the limiting condition.

From the provided scheme it is visible that the residual operating life of object $t_{res}$ represents the difference between the predicted value of a time to failure and duration of its operation preceding the predicted $t_i$ period.

$$t_{res} = t_{pr} - t_i$$

(2)

Thus, for definition of a stock of correct work, it is necessary, by an extrapolation method, according to measurement of diagnostic parameter during the period previous predicted to determine its further change by an operating time to the limiting value and to develop the analytical equation approximating this change.

The value of the limited time to failure because of influence of a large number of factors of operation is a random value which can be described by a differential cumulative distribution function of $f(t)$. Therefore, actually predicted limiting value of a time to failure represents some average value (on the scheme it corresponds to realization 1), which is defined from expression:

$$t_{pr} = \sqrt{\frac{S_{lim} - S_m}{\sigma}}$$

(3)

As showed the executed researches, when using as the limit operating time its mean value $t_{pr}$ a stock of correct work at a part of engines it will appear less than calculated (in Figure 1 – area A). It leads to errors of prediction and, as a result, increase in number of engine failures on operation. For decrease of negative consequences of such mistakes in this work it is offered to determine a residual operating life not by mean value of $t_{pr}$, and by the lower confidence limit of distribution of this operating life which is defined from expression:

$$t_{low,lim} = t_{pr} - t(p) \cdot \sigma_i$$

(4)

where $t_{low,lim}$ – the lower confidence limit of the predicted time to failure; $t(p)$ – Student’s factor; $\sigma_i$ – average standard deviation of operating time.

Student’s factor is determined by the given confidence probability which value for the structural elements of the car which are immediately not affecting traffic safety can be accepted equal $p = 0.80$ [1, 3].

Expression (2) for definition of a residual operating life on the lower confidence limit will take a form:

$$t_{res} = t_{low,lim} - t_i$$

(5)

Approbation of the developed technique of definition of the predicted residual operating life it is feasible on the example of cylinder-piston group of the engine with use of the diagnostic $S_c$ parameter (a consumption of crankcase gases) when passing the engineering servicing on an operating time of 128 thousand km (at procedural frequency of maintenance the basic car for the III category of an operating conditions $t_m = 16$ thousand km).

Rated and limiting values of the diagnostic parameters estimating a ZMZ-40524.10 engine cylinder-piston group (CPG) condition are established by manufacturer (Table 1).
Table 1. Standard values of the diagnostic parameters estimating an engine CPG condition

| No. | Diagnostic parameter                                                                 | Rated   | Limited                  |
|-----|--------------------------------------------------------------------------------------|---------|--------------------------|
| 1   | $S_c$ – pressure at the end of compression stroke, MPa                                 | 1.18    | 0.94                     |
| 2   | $S_a$ – the relative air leakage at position of the piston in UDC within not less than 5 seconds, MPa | decrease from 0.147 to 0.098 | decrease from 0.147 to 0.074 |
| 3   | $S_g$ – consumption of crankcase gases at 4000 min$^{-1}$, l/min, no more              | 22      | 62                       |

By results of control and diagnostic works the following values of the diagnostic parameters estimating technical state of CPG were received:

- pressure at the end of compression stroke, MPa — $S_c$ 1.02
- the relative air leakage, MPa — $S_a$ 0.089
- consumption of crankcase gases, l/min — $S_g$ 29.6

Exponent $\alpha$ and intensity of change of parameter $\nu$ are determined by practical consideration on the basis of processing of statistical material of field tests of change of diagnostic parameters by a car operating time. For the $S_g$ parameter of their value made: $\alpha = 1.2; \nu = 0.059$.

The power function describing regularity of change of the $S_g$ parameter on an operating time will take a form:

$$S_g(t) = 22 + 0.059 \cdot t^{1.2}$$

The predicted value of an average operating time to achievement of CPG of the limiting state:

$$t_{pr} = \left( \frac{S_{lim} - S_g}{\nu} \right)^{\frac{1}{\alpha}} = \sqrt[\frac{1}{1.2}]{\frac{62.0 - 29.6}{0.059}} = 190.9 \text{ thousand km.}$$

Standard deviation of an operating time to failure of CPG:

$$\sigma_t = \sqrt{\frac{\sum (t_i - t_{pr})^2}{n - 1}} = \sqrt{\frac{6980}{50 - 1}} = 11.94 \text{ thousand km},$$

where $n$ is a sample size of the surveyed engines.

Student's factor at a fiducial probability $p = 0.80$ and number of degree of freedoms of $N = 2$ is equal to $t(p) = 1.29$.

Value of the lower confidence limit of the predicted CPG operating time to failure:

$$t_{low,lim} = t_{pr} - t(p) \cdot \sigma_t = 190.9 - 1.29 \cdot 11.94 = 175.5 \text{ thousand km.}$$

Graphic interpretation of definition of the predicted residual operating life of cylinder-piston group is presented by the scheme in Figure 2.

![Figure 2](image)

**Figure 2.** Scheme of definition of a residual operating life cylinder-piston group of the engine: $t_{pr}$ – mean predicted CPG operating time to failure; $t_{low,lim}$ – lower confidence limit of the predicted operation time to failure; $t_{res}$ – residual operating life.

The predicted CPG residual operating life on the lower confidence limit will make:

$$t_{res} = t_{low,lim} - t_{pr} = 175.5 - 128 = 47.5 \text{ thousand km.}$$

The predicted CPG residual operating life of the studied engine exceeds the established frequency of an upkeep of the basic car (tm = 16 thousand km) therefore there is no need for profound monitoring of its technical condition and carrying out any technical influences. CPG won’t reach the limiting state on the predicted residual operating life $t_{res} = 40.7$ thousand km with the given fiducial probability $p = 0.80$. 

3
Conclusion

Prediction of a residual operating life on the lower confidence limit of distribution of operating times allows to calculate a stock of correct work of ICE with the given probability, it is essential to reduce its refusals in use and the costs of maintenance connected with it.

References

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