Stochastic Models of Ship ICE Service Life Estimate According to their Thermo-structural Parameters

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Abstract. A problem of forecasting internal combustion engines service life according to their thermo-structural parameters has been considered. Stochastic models of engines service life estimate have been developed basing on multiple-factor regression analysis of statistical data. A negligible error of the models allows to apply them for practical engineering calculations.

1. Introduction

Forecasting internal combustion engines (ICE) service life is an acute task. During all the ship’s service life, adequate reliability of its propulsion unit, especially of marine diesel engine, is to be provided. Reliability is determined at the design stage and cannot be further enhanced without making structural changes. Reliability is a complex notion. It can be estimated by index numbers of failure-free performance, durability, maintainability and retention depending on the object’s purpose and operating conditions. Service life, as well as durability, is a lifetime performance characteristic determining the engine stamina expressed in working hours from the beginning of life up to transition into the extreme limit state. To estimate the adequacy of the engine service life and its failure-free operation indices set by technical requirements, ICE reliability tests are carried out. The service life is determined by bench tests at the production factory and thereafter is adjusted basing on operation data. Engine tests are time-consuming and require considerable material and, as a result, financial costs.

According to the test results, the designer is expected to make a decision of the work process optimization. Therefore, the engine full-scale production is delayed for a long time. Long-term tests – are total service life tests in bench-scale conditions according to the programme which fully considers engine operating peculiarities in actual environment (operating programme). However, at greater service life values (3000...4000 h and more) carrying out long-term tests according to the operating programme turns out to be impractical and even impossible, as checking the actions aimed at eliminating defects and enhancing the service life is time-consuming let alone the costs. For example, it takes over a year to carry out long-term engine 4000 h service life tests. In actual operating conditions, engine service life prior to the overhaul is determined by the observed life prior to failures and extreme limit states of parts and units. The observed life is not a determined value, it follows stochastic patterns. For this reason, the service life shown in bench-scale conditions by one particular diesel does not often appear to be the same for series-produced diesels. Bench tests conditions can considerably differ from real operating conditions being affected by operating modes, trigger conditions, loading and reverse, maintenance and repair system organization. Thus, practically applied forecasting marine diesel engine service life based on bench tests results can be recommended only on the prototype and type tests stages as not fully considering factors affecting the overhauls. At the series-production stage it is necessary to consider operating peculiarities.
When manufacturing a new engine, designers have to baselessly set its service life basing on the data of the engine-prototype having been in operation for the same purpose for a long time on condition that the long period of time operation data are valid.

2. Service life forecasting proposals

We believe that it is possible to forecast the engine service life basing on the regression model, current statistical data for Diesel series of domestic manufacture having the same purpose and similar operating conditions. As for foreign-made engines service life, the manufacturing companies do not reveal such data for considerations of momentary advantage.

Let us consider the obtained statistical dependences for the service life of the main four-cycle ship engines prior to the first overhaul $T_1$ and the service life prior to the major overhaul $T_2$. Original information to obtain these dependences has been taken from the nomenclature reference documents of Heavy Engineering Ministry (Mintyazhmesh) USSR [1], [2].

Let us explain the reasons for choosing official reference data as the original information. Each specific engine service life is known to depend on many factors (e.g. under-load operation conditions, observation of maintenance and repair periods, proficiency of service personnel etc.)

It is out of the question that statistical data of a vast variety of factors affecting service life of each of even one-type engines is practically impossible to obtain.

At the same time it is necessary to clearly understand that there is a range of tasks it is necessary to know all operation conditions of specific engines of at least the same dimension. For example, these factors are worth considering in case the task is of forecasting the remaining service life of specific series of engines being in operation.

The task to justify and obtain a kind of dependences adequate for forecasting the engine service life at the design stage has been set and solved. For these purposes the official reference data are available characterizing the engine service life in average operation conditions. Moreover, having obtained the expressions to determine the engine service life at the design stage, it is possible likewise to obtain the expressions for estimating the engine service life in specific operation conditions. Success in getting these expressions depends on preparing proper original information.

The following dependences are proposed:

\[
T_{1,2}n/60 = f\{P_z/P_e; S/D\},
\]

\[
T_{i,2} = f\{P_z; P_e; \epsilon_m; D\},
\]

\[
T_{i,2} = f\{n; P_e; S/D\},
\]

where $P_z/P_e$ – peak firing pressure to mean effective pressure ratio;
$S/D$ – piston stroke to cylinder diameter ratio;
$P_r$ – peak firing pressure (kgf/sm²);
\( P_e \) – mean effective pressure (kgf /sm²);
\( c_m \) – average piston speed (m/s);
\( D \) – engine cylinder diameter (sm);
\( n \) – engine crankshaft speed (rpm).

Parameters dimension corresponds to nomenclature reference documents.

The choice of engine parameters as factors determining its service life is proved by the obtained design and operation experience. Herewith, \( S/D \) ratio has a considerable impact on service life. It has become common to consider \( S/D \) ratio impact on engines wear and service life. \( P_e, P_f, P_r, c_m, n \) and engine cylinder diameter \( D \) affect engine wear and service life as well.

Multiple-factor regression analysis of statistical data experience has been also used. Service life dependences on engine parameters are approximated by the following expressions:

\[
T_{1,2} = \frac{n \times 60}{12} = \frac{\pi}{12} \times f_1 \left[ \frac{P_e}{P_r} \right] \times f_2 \left[ \frac{S}{D} \right],
\]

(4)

\[
T_{1,2} = \frac{\pi}{12} \times f_1 \left[ P_e \right] \times f_2 \left[ f_3 \left[ c_m \right] \times f_4 \left[ D \right] \right],
\]

(5)

\[
T_{1,2} = \frac{\pi}{12} \times f_1 \left[ n \right] \times f_2 \left[ \frac{P_e}{P_r} \right] \times f_3 \left[ \frac{S}{D} \right],
\]

(6)

where \( T_{1,2} \) – is service life average value (hour), \( \pi \) – is engine crankshaft speed average value (rpm).

Functions \( f_1, f_2, f_3, f_4 \) are in general polynoms.

With respect to dependences (1)–(6), expressions for determining engine service life prior to the first overhaul and major overhaul have been obtained.

3. Calculation sample according to the proposed dependences

As an example, the following expressions for determining engine service life by dependency (5) are given:

\[
T_1 = 5500 \times (0.8452867 - 0.7005145 \times 10^{-3} X_1 + 0.495723 \times 10^{-6} X_1^2) \times

\times (0.97332 - 0.166932 \times 10^{-1} X_2 - 0.116668 \times 10^{-2} X_2^2 + 0.108981 \times 10^{-2} X_2^3) \times

\times (1.00527 + 0.25532 X_3 - 1.60885 X_3^2 - 50.0857 X_3^3),
\]

(7)

where \( X_1 = n - 1084.4; \) \( X_2 = P_e - 9.1046; \) \( X_3 = S/D - 1.20431; \)

\[
T_2 = 26666.6 \times (0.811890 - 0.129198 \times 10^{-2} X_1 + 0.499583 \times 10^{-6} X_1^2 + 0.420306 \times 10^{-9} X_1^3) \times

\times (1.00396 - 0.460347 \times 10^{-1} X_2 - 0.311526 \times 10^{-2} X_2^2 + 0.122307 \times 10^{-2} X_2^3) \times

\times (0.99386 - 0.868259 X_3 + 1.86559 X_3^2 + 39.353 X_3^3),
\]

(8)

where \( X_1 = n - 1040.62; \) \( X_2 = P_e - 9.69479; \) \( X_3 = S/D - 1.20727; \)

4. The proposed dependences applicability estimate

Applicability of dependences (7) and (8) has been estimated to forecast the engine service life at the design stage or feasibility study. When determining service life prior to the first overhaul according to expression (7), root-mean-square error is 386 hours. When calculating service life prior to the major overhaul according to expression (8) the analogous error was 2633 hours. Error of models (7) and (8) is shown in the table data.

Table 1. Error estimate

| №   | GOST Engine specification           | Manufacture mark | Error,% |
|-----|-------------------------------------|------------------|---------|
| Sr.No. | 4393-74, GOST P 53638-2009       |                   | By formula (7) By formula (8) |
Probable relative root-mean-square error when forecasting service life is 6%. For engineering calculations, coefficients in brackets of expressions (7) and (8) can be rounded to two or three digits, practically without detriment to the accuracy. For example, for $\Gamma$-70 engine when rounding formula (7) coefficients to three digits, the error is $+0.008\%$, and when rounding to two digits the error is $-0.12\%$.

Thus, the dependences obtained can be used for service life approximate estimate when designing engines and service life estimate of the existing engine according to its thermo-structural parameters. For example, for marine engine 6ЧРН 36/40 ($\Gamma$-95) having parameters $n=600$ (rpm), $P_r=18.45$ (kgf/cm), $S/D=1.11$, calculations have shown the following results. The service life prior to the first overhaul is 11576 hours, the service life prior to the major overhaul is 48200 hours. Experimental works carried out at the diesel engine plant show that reliability design indices are achievable for marine engines with such parameters.

5. Conclusion
The following conclusions can be made:
– forecasting service life according to its parameters is more objective as compared to forecasting by time extrapolation;
– prior to the first overhaul, service life rating comparison with mean life values between operational engines failures demonstrates approximately eightfold to up-to-tenfold preponderance of the former over the latter ones. For example, if the service life prior to the first overhaul is 4000-5000 hours, then the mean life values between failures can reach up to 500 hours respectively;
– the link between engine reliability indices allows to use the expressions obtained to determine its failure-free operation at the design stage and feasibility study.
– the ability to forecast the engine service life at the design stage will allow to determine its cost with the help of regression models allowing 8-10% error on the plus or minus sides;
– service life estimate at the early design stage is of considerable interest for designers when optimizing engine cycle parameters.

References
[1] Internal combustion engines. Nomenclature reference documents. M.: NIIinformtyazhmash, 1979, part 1–88pp.
[2] Internal combustion engines. Catalogue. M.: Mintyazhmash USSR,1989.-58pp.