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MATHEMATIC MODEL OF CRITICAL CONDITION OF PRECISION SURFACES OF FUEL INGECTION EQUIPMENT OF DIESEL LOCOMOTIVE ENGINE

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Abstract:

In this article authors considered the mathematic model of determination of critical conditions of precision surfaces of details and assemblies of fuel ingection equipment of diesel locomotive engines in operation. Critical wear of precision surfaces is the most important problem impacting on work process of heat engine practically at all rotational frequencies and loads, including modes of idling and small loads (non-nominal modes), and determination factor of fuel injection misses and non-uniformity of injected fuel by cycles and cylinders.

Solution of heat engine working process stability is restrained by absence of theoretically grounded and experimentally confirmed law of heat transfer providing stable indicator indexes of work process of power assemblies heat transfer in all range of rotational frequencies and loads. In developed mathematic model is presented the calculation of pressure forces in fuel supply channels of injector spray nozzle. Requirements and conditions of air-tightness in fuel supply channels are formulated. Qualitative estimation of fuel injection equipment work in real time at all rotational frequencies and engine power is shown. Impact of precision wear of details and blocks of fuel injection equipment on work process of diesel locomotive engine is considered. Proposed mathematic model is maximally approximated to its use in engineer calculation by engineer-technical personnel of locomotive depots.

Key words: mathematic model, precision surface, parts of fuel apparatuses, wear, diesel, working process

Introduction. It is known that working capacity and technical condition of precision surfaces of fuel injection equipment (FIE) of diesel locomotive engines cause significant impacts on quality of work process and to significant degree depends on conditions of operation. A range of domestic and foreign scientists states indisputable arguments about impact on law of fuel supply (along with constructional peculiarities of FIE) of wear of precision surfaces of plunger pairs of fuel pumps and injector spray nozzles [1, 2, 3], changing in operation. Authors also state the thesis about the problem of tracing and restoration of FIE precision surfaces wear in real time of operation.

Existing practice of estimation of technical condition and working capacity of FIE precision blocks in locomotive depots and locomotive rebuilders is outlined by frames of requirements of Rules of depot and plant repairs, anticipating inspection of air-tightness, hydraulic density and fuel pumps, injector nozzles, quality of fuels spraying by injector nozzles on specialized stands of fuel injection equipment site. Quite often inspection and analysis of results are conducted without deep system approach to indexes of fuel injection equipment and its technical condition and reduces to formula fit – unfit fuel pump, injector nozzle.

In case of doubts the main technologist of locomotive depot or plant is not capable to re-check received results due to absence of device base on sites of fuel injection equipment (strain-gauge stations, oscillographs, amplifiers etc.) and, as result, subjective segmentary indexes of different FIE parameters are recorded. Quite often the conducted analysis does not allow to determine the change in real time of operation of multiple mutually impacting separate parameters; in result of this there is no ability of forecasting of reliability and receiving of complex estimation of FEI operation in general. To conduct quality estimation of reliability and working capacity of precision surfaces of fuel injection equipment for whole life-cycle at stages of designing is possible with application of modern methods and hydro-dynamic calculation. Absence of general method of such calculation is one of important factors, restraining the development of fuel supply systems providing elimination of fuel injection misses and non-uniformity of cycle supplies by cycles and cylinders at non-nominal frequencies and capacity of power energy assemblies. In this work, on basis of generalization of experience received at analysis of constructional peculiarities of nozzle injectors with traditional of special constructional scheme, is composed the universal mathematic model of nozzle injector.

Methods. In order to achieve this goal was for the first time proposed matrix-vector form of equation records that allowed to use for mathematic modeling of nozzle injector the universal method of dynamic calculation of hydro-mechanic unit described in [4]. Contemporary physical model of any nozzle injector is composed of elements of two types: systems with distributed parameters - pipelines and springs, and system with concentrated parameters - so called *hydro-mechanical units* (i.e. aggregation of cavities and valves, directly connected to each other). Nozzle injector usually consists of two such units - filter and spray (fig. 1), but there are known exceptions from this rule. Waves of pressure and deformation are spread by pipelines and spring at terminal rate, that's why at nozzle injector's dynamic calculation, the change of parameters of any of its units in limits of this step by time does not have a time to impact at changing of parameters of other units, and equation of this units are able to integrate independently from each other.

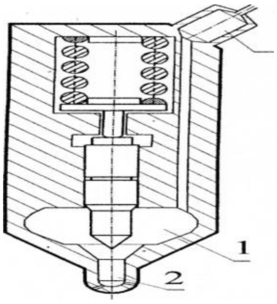

Fig. 1. Cavities of nozzle injector unites: 1,2 – spray pocket and channel; 3 – filter

Methods of hydrodynamic calculation of pipelines and dynamic calculation of fuel injection equipment springs are described in [5 - 7]. Method [6] is universal and with equal success can be applied for calculation of pressure pipeline and separate fuel supply channel in nozzle injector (Fig. 2).

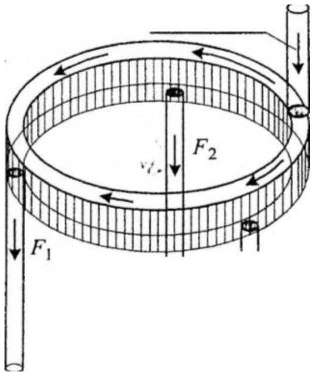

Fig.2. Scheme of fuel distribution by three fuel supply channels in diesel nozzle injector D50.

The best methods of nozzle injector spray calculations for fuel injection equipment with traditional scheme were developed by prof. Yu.Ya. Fomin [8]. For some special constructions of sprays were developed special methods of their mathematic modeling (see, for example, [5]); results of this work were taken into account at creation of described below universal mathematic model of hydro-mechanical unit of nozzle injector.

Let's compose the equation of hydro-mechanical unit of nozzle injector. Let's consider the unit consisting of *n* cavities and *m* valves. Volume *i* – th cavity we will designate as v_i, fuel pressure in it - p_i, velocity and motion of *s* - th valve with $_s$ and h respectively. Square of effective section of nozzle injector channel that connects *i*-th and *j*-th cavities we will designate as μf_{ij}, square (or a part of square) of valve cross section at which impact the pressure difference between cavities *u* and *j* - $f_{i\,j}^{(s)}$. Some unit cavities acre connected to pipelines; cross-section squares of k - th pipeline connected with i-*th* cavity we will designate as f_{ik}^{mp} .

With taking into account of accepted designations, equations of volume (mass) balance of fuel for i - th cavity and equation of motion of s - th valve would assume the following form:

$$av_i \cdot dp_i / dt = -\sum_j \left[\mu f_{ij} \cdot s\left(p_i - p_j\right) + \sum_s f_{ij}{}^{(s)} \cdot c_s \right] - \sum_k \frac{f_{ik}^{\text{тр}}}{a \cdot p} \cdot \left[p_i - p_{\text{зал}} - 2 \cdot F_{ik}(t)\right]; \quad (1)$$

$$m_s \cdot dc_s / dt = \sum_{i,j} f_{ij}^{(s)} \cdot (p_i - p_j) - k_s \cdot \left[c_s(t) + 2 \cdot \sum_{l=1}^{\infty} c_s(t - l \cdot T_s) \right] - F_{\text{пр.о}}^{(s)} - F^s(t); \quad (2)$$

$$dh_s / dt = c_s(t), \quad (4)$$

where: $s(\Delta p)$ - linear speed of fuel motion between cavities at pressure difference between them Δp,

$$s(\Delta p) = \sqrt{(2/p) \cdot |\Delta p|} \cdot \sin gn(\Delta p); \quad (5)$$

α , ρ - coefficient of fuel compressibility and density;

$F_{ik}(t)$- value of direct pressure wave going through k – th pipeline in the moment of time t (see [3]);

m_s - weight of valve;

k_s - coefficient of proportionality of formula [4] for determination of spring force with taking into account of longitudinal oscillations of its loops,

$$k_s = 0.5 \cdot z_s \cdot T_s; \quad (6)$$

$z_s, F_{\text{пр.о}}^{(s)}$ - roughness and efforts of previous tightening of valve spring;

T_s - period of free oscillations of this spring loops,

$$T_s = 2 \cdot \sqrt{m_{\text{пр}}^{(s)} / z_s}; \quad (7)$$

$m_{\text{пр}}^{(s)}$- weight of moving spring loops;

$P_{\text{зал}}$ - remaining pressure in pipeline;

$F^{(s)}(t)$- other drive forces, for example, electromagnetic

We should note that some of pressures p_j, used in right part of equations (1), (2), can be known function of time t or constants and are not related to dynamic paramenenters of unit. Therefore, for example, is take into account the pressure of gases in diesel cylinder; it's clear that this value in equation (2) is not used in fact, because the respective square is $f_{ij} = 0$. At hydraulic lock of nozzle injector needle (fig. 3) the reverse situation is observed: here for pressure p_j in over-needle cavity the square is $f_{ij} \neq 0$, but $\mu f_{ij} = 0$.

Equations (1) become closed after addition of known formulas to them (see, for example, [5]), that are determining parameters of liquid a, α, ρ dependently of pressure value $p_i(t)$, and also squares μf_{ij} and volumes v_i dependently of valves motion.

Major part. At estimation of quality side of FIE work within life-cycle of internal combustion engine (ICE), authors of work [9, 10] are using aggregated effective index of work quality (EIWQ) that is divided into several groups with respective rating. After introduction of particular index the authors received the ability to trace, with any periodicity, the worsening of reliability and working capacity of this index in course of operation, and also its transfer from one group of reliability and working capacity into another. Usually with rating decrease. As a criterion of reliability the authors select recorded and processes average statistic characteristics of segmentary parameters for each part or unit of internal combustion engine (ICE). Parameters are measured at the same moments of operation time and further are aggregated in effective index of work reliability (EIWR) of ICE. Received values of measured and statistically processes parameters in this case are submitted to normal law of distribution with high anticipated result.

In article [11] is proposed to conditionally divide all parameters of work of diverse units and parts of ICE into three groups (actually, the number of such groups can be bigger), additional division into sub-groups by major, secondary third-rate parameters is also possible. In this case ti the first group are related specific values of fuel, oil and air consumption, and some other parameters, related to effective indexes of engine's work. Second group was taking into account parameters related to maximum values of combustion and compression pressure, temperature of exhaust gases. Third group was taking into account wear indexes, both of precision units and gaps in divers parts of ICE. Authors underline that on worsening of ICE technical conditions are impacting both separate parameters of all groups introduced into consideration and also all their possible joint combinations. In this connection was introduced the generalized index of worsening of ICE technical condition $\eta(t)$:

$$\eta(t) = k\{\alpha(t)p_1(t) + \beta(t)p_2(t) + \gamma(t)p_3(t) + \alpha(t)\beta(t)p_1(t)p_2(t) + \alpha(t)\gamma(t)p_1(t)p_3(t) + \beta(t)\gamma(t)p_2(t)p_3(t) + \alpha(t)\beta(t)\gamma(t)p_1(t)p_2(t)p_3(t)\}, \quad (8)$$

where – $\alpha(t)$, $\beta(t)$, $\gamma(t)$ are non-decreasing functions of ICE work parameters of first, second and third groups that are normalized by united scale by means of standardization of respective size values; $p_1(t)$, $p_2(t)$, $p_3(t)$ – weight characteristics of accordingly first, second, third groups of parameters; k is a scale multiplier. Parameters α(t), β(t), γ(t) represent scale discrete valued and dependencies.

At statistic analysis of working capacity and reliability of precision surfaces of sprays and plunger pairs the information received by researcher represents segmented censored (usually by the main technologist) selections. At this the analysis and estimation of selections by wears of precision surfaces practically always undergo a subjective approach of technologist. For purpose of exclusion of subjectivity in estimations of working capacity and reliability of limited number of precision parts of locomotive FIE, the effective methods of estimation accuracy at different combinations of complete and incomplete development and at selections of different number of diesel locomotive engines precision parts is needed.

Development of such method was conducted on basis of application of parametric methods of Nelson and Johnson, allowing to conduct the comparison of precision wears with minimal device and instrumental accompanying. At conduction of researches the interest was presented by comparison of wear of precision surfaces of FIE parts by non-parametric method too, allowing to conduct a gradual transfer to new coordinate system - from parametric to non-parametric method of FIE parts precision surfaces comparison.

Comparative researches was conducted gradually with accuracy of calculation by average wear of precision surface and further development up to extreme condition impacting on process of fuel supply. Calculation researches were conducted on basis of developed software of statistic methods of statistic tests at number of experiments 3000 for each combination of complete and incomplete developments (wears of diesel engine FEI precision surfaces).

As modeling distributions of developments to failure were selected normal arrangement of precision details with coefficient of variation v = 0.1; 0.2; 0.3 and distribution of Weibull-Gnedenko with parameters of precision surface wear b = 1.0; 1.5; 2.0; 3.0; 4.0 (corresponding to coefficient of variation v = 1.0; 0.679; 0.523; 0.363; 0.280). At selection of value of parameter of wear form of precision surface was decided not to consider cases when sprayer and plunger pairs underwent run-in at plant-manufacturer (reference variant is supposed), that's why the variant $b < 1$ was not researched.

For modeling of censored (wear) selection was selected engineer approach, applied in practice in conditions of industrial enterprise. A continuous observation of N precision FEI pairs from the moment of their operation start was conducted, Within observation period t failed n of them, at this the moment of their failure were recorded in journals of current maintenance and repair of locomotives. Then the received statistic material is n complete and $k = N\text{-}n$

incomplete wears of FEI precision details. At partial wear of precision surfaces this part is not replaces, and at *n* complete or *k* exceeding the average wear and approaching to maximum wears of precision surfaces are replaced by new ones.

In accordance to selected test model (maximally approached to operational conditions) were modeled censored (usually by main technologist) wears, including *n* and *k* complete and incomplete wears. There were generated *n+k* developments distributed by selected law. Among them were selected *k* developments in a random manner. Further for each of them was generated a random number, uniformly distributed in interval $(0,\tau_j)$, j=1, k,

where - τ_j is the respective complete development. In order to increase the accuracy of calculations were used probability grid proposed in methods of Nelson and Johnson. That's why for calculation's conduction was necessary to apply respective transformation of integral functions of distribution.

At modeling of precision wear by method of Nelson the function of sidtibution of development (wear) till failure (extreme condition) is presented in form:

$$F(t) = 1 - e^{-\Lambda(t)}, \tag{9}$$

for coordinate grid and is respectively build in coordinates.

Modeling of precision wears and their distribution by method of Weibull-Gnedenko in two-parameter form is presented in form:

$$\Lambda(t) = \left(\frac{t}{a}\right)^b, \tag{10}$$

$$\ln \Lambda(t) = b \ln t - b \ln a = \ln\{-\ln[1 - F(t)]\}, \tag{11}$$

where a is the scale parameter; b - parameter of form, and for normal distribution

$$\Lambda(t) = -\ln[1 - F(t)] = -\ln\left[1 - \Phi\left(\frac{\mathrm{t - m}}{\sigma}\right)\right], \tag{12}$$

where $\Phi(\mathrm{z})$ - standard function of normal distribution.

In case of application of Johnson method the grid is build in coordinates $\{\ln t, \ln[1 - F(t)]\}$

In case of determination and distribution of precision surfaces wear by method of Weibull-Gnedenko is applied expression

$$\ln\{-\ln[1 - F(t)]\} = b \ln t - b \ln a, \tag{13}$$

For each modeled selection, by method of least squares were calculated, on basis of law of distribution, average wears and wears till failure (extreme condition) pf precision surfaces. In result of analysis of distribution of average wears and wears till failure (extreme condition) was received the method of sequential tranfer to new system of estimation coordinates, from parametric to non-parametric.

Method of sequential transfer allowed to calculate average arithmetic mathematical expectation, left- and right-side deviation of modeled value from average, and also left- and right-side intervals relatedly to modeled value pf precision wear of FIE detail surface.

Method of sequential transfer allows to model the selection on wears of precision surfaces of locomotive diesel engines FIE parts in conditions of industrial enterprises. On basis of analysis and technical condition of precision wears in conditions of locomotive depots is proposed the method of renovation and restoration [12] of precision surfaces of locomotive diesel engines fuel injection equipment parts.

Summary. Mathematic model of estimation of critical condition of precision surfaces of fuel injection equipment of locomotive diesel engines, developed in base of method of sequential transfer from parametric condition to non-parametric one, allow engineer-technical personnel of locomotive depots and locomotive rebuilders to calculate and estimate the average arithmetic mathematic expectation of precision surfaces wear in real time of operation.

Conclusions. Proposed method of tracing of FIE precision wears in operation, on basis of established law of fuel supply, realized by nozzle injector spray with hydro-dynamic device [6] allowed to trace quality side of work process of engine in all range of rotation frequency and capacity, and also forecast the reliability and working capacity of locomotive diesel engines in real time of operation. Proposed mathematic model allowed to estimate the impact of stable process of fuel supply (at whole range of rotation frequencies and capacity of engine) on wear of precision surfaces and determine the critical condition (wear) of precision surface of pair needle-housing of spray in conditions of operation. For restoration pf precision surfaces of fuel injection equipment parts (in case of their critical wear in operation) is proposed the method of their restoration [12].

References

1. Antipov V.V., 1972. Wear of precision parts and violation of characteristics of diesel fuel injection equipment. M: Machine construction, 177.
2. Bobrov V.F., 1960. Research of impact of wear of plunger pairs on fuel injection, Kharkov, (Works of KhIET, Issue 35):143.

3. Zonov V.D., 2014. Conception of diagnostic provision of energy-saving technologies of break-in tests of mainline and shunting diesel locomotives. Newsletter of BFTU named after V.G. Shukhof No. 4. 180-182.
4. Grigoriev A.L., 2000. Universal method of dynamic calculation of hydro-mechanic unit. Newsletter of KhSPU (Issue 104): 75-84.
5. Fomin Yu.Ya., 1973. Hydro-dynamic calculation of diesel engines fuel systems with use of EDC. Machine construction: 144.
6. Grigoriev A.L., 1999. Amended method of accounting of hydraulic resistance of pipeline at hydrodynamic calculations of diesel engines fuel injection equipment. Internal combustion engines: Newsletter of KhSPU, 1999. Issue 58: 58-68.
7. Grunauer A.A., Tartakovskiy I.I., Grigoriev A.L., 1985. On connection of spring force with the law of its deformation. Theory of mechanisms and machines. Kharkov: High school. Issue 39: 7-22.
8. Rosenblit G.B., Gigoriev A.L., Zonov V.D., 1999. Analysis of reasons and determination of conditions providing the air-tightness of flat differential valve of nozzle injector. Internal combustion engines: Newsletter of KhSPU, Issue 58: 82-91.
9. Kudelin O.G., Nikolaev A.G., 2006. Estimation of quality of ICE technical condition. Works of International scientific-technical seminar "Research, design and operation of marine diesel engines". Under edition of O.K. Bezyukov. SPb. ParkCom: 117-123.
10. Zonov V.D., 2005. Mathematic modeling and research of energetic characteristic of fuel supply in nozzle injectors of special construction. Inter HEI collection of scientific works. Kharkov: UkrSART, 2005. Issue 70: 112-122.
11. Zonov V.D., Danko N.I., 2006. Criterion of control of quality index of energetic characteristics of fuel supply by nozzle injectors of special construction. Scientific-practical magazine "News of science of Pridniprovie" (1):25-28.
12. Zonov V.D., Yakovlev E.A., Zinkova V.A.. Kostoglodov D.C. Patent of invention of RF No. 2582418. Method of restoration of worn sites of surfaces of locking cones of needle and hosing of nozzle injector spray of internal combustion engine. April 01, 2016.