RELIABILITY MODEL OF THE CRANKSHAFT-PISTON ASSEMBLY

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Abstract

The laws that govern the durability of crankshaft-piston assembly friction nodes can be proved or at least derived or justified in an intuitive way. Operation of all the friction nodes is disturbed by external factors occurring with randomly changing intensity and also appearing at random. As the crankshaft-piston assembly friction nodes have a series structure and effects of those disturbances accumulate, their fitness for use period can be presented as an image of appearing disturbances with determined effects. This can be done on the probability distribution basis. The crankshaft-piston assembly usual wear and tear process is long, therefore images of the appearing disturbances should be characterised by the degree of wear, i.e. the change of the friction node durability, which is a subject of the Markov chain process.

The friction node surface durability is an effect of many factors (e.g. stress pattern in the contact area, the surface material hardness, chemical properties of the surface material etc.). However, among those mentioned the least known effect is that of the properties of lubricating agent on the fatigue strength of friction node elements in the crankshaft-piston assemblies. Therefore, the paper presents a reliability model allowing estimating the fatigue wear of friction nodes in the crankshaft-piston assembly, operating in a lubrication contact with different loads, temperatures and speeds.

Keywords: *acoustic vibration, durability, friction node*

1. Introduction

Investigation of the fitness for use period of a crankshaft-piston assembly aims at explaining the operation mechanism of all its elements and at finding out relations between the elements, reactions to external factors and the wear and tear processes. These processes are not fully and precisely cognizable and one must stop at some point in searching for the causes. Those overlooked causes become evident as chance behaviour that each phenomenon is subject to. Therefore, the forecast assumes a statistical form, which can pertain to the utility life before the first failure, the first failure moment etc. Failure processes are investigated in order to foresee their occurrence.

The laws that govern the durability of the crankshaft-piston assembly can be proved or at least derived or justified in an intuitive way. Operation of all the crankshaft-piston assembly elements is disturbed by external factors occurring with randomly changing intensity and also appearing at random. As the crankshaft-piston assembly has a series structure and effects of those disturbances accumulate, its fitness for use period can be presented as an image of appearing disturbances with determined effects. This can be done on the probability distribution basis. However, it must be remembered that the crankshaft-piston assembly usual wear and tear process is long, therefore images of the appearing disturbances should be characterised by the degree of wear.

Unserviceability of the crankshaft-piston assembly friction nodes is most often caused by the surface wear and not by the volumetric destruction - break, rupture etc. The friction node surface durability is an effect of many factors (e.g. stress pattern in the contact area, the surface material hardness, chemical properties of the surface material etc.). However, among those mentioned the least known effect is that of the properties of lubricating agent on the fatigue strength of friction node elements. Therefore, the paper presents a reliability model allowing to estimate the fatigue wear of friction nodes in the crankshaft-piston assembly, operating in a high-loaded lubrication contact.

2. Reliability model of the crankshaft-piston assembly friction node

The crankshaft-piston assembly is an object of series structure with n friction nodes. In the simplest reliability model it is a two-state object with non-reversible states. Therefore, it may be assumed that the object passes to the unserviceability state when any friction node passes to the unserviceability state. As the crankshaft-piston assemblies are among the most important objects of a ship engine, it is understood that all the friction nodes are constructed from high-reliability elements. It means that probability of failure of more than one friction node at a time is negligibly small. Graph of a crankshaft-piston assembly has the form of a two-state system [4] (serviceability and non-serviceability states) (Fig. 1). In fact, state of all the friction nodes of that assembly can be characterised in a more subtle way, differentiating the individual life stages. Then the crankshaft-piston assembly graph will take the form of a multi-state system [2, 3] (Fig. 2). Such a conception is used in the Markov chain process which will be applied in the paper.

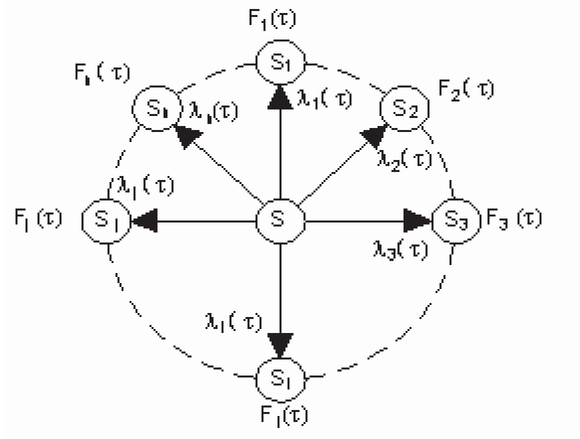

Fig. 1. Two-state graph of a crankshaft-piston assembly consisting of n nodes: $F(\tau)=P(T\leq\tau)$ – unreliability function (distribution of the random variable T), $\lambda_i(\tau)$ – failure rate of the investigated friction node

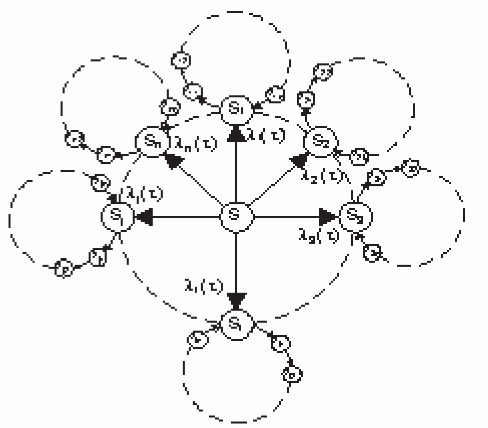

Fig. 2. Graph of the change of states of a crankshaft-piston assembly

Figure 2 presents n friction nodes in a crankshaft-piston assembly, which may be in one of n states depending on the states of n friction nodes $S\subset\{S_1, S_2,\ldots, S_n\}$. Also each friction node may be in one of n states depending on the states of its elements, e.g. $S_j\subset \{s_{j1}, s_{j2},\ldots,s_{jn}\}$. The s_{j1}, $s_{j2},\ldots,s_{jn-1}$ states characterise the degree of wear of the friction node and are numbered in the order of ascending wear. The s_{jn} state means "failure".

It is assumed that passing of an object (e.g. a friction node) from state s_{jn-1} to state s_{jn-2} is impossible because the object cannot become "younger". Passing from one state to the next occurs at moments $\tau_0,\tau_1,\ldots, \tau_k$ in accordance with the following process [1]:

$$\sum_{j=1}^{n} p_{ij} = 1, \tag{1}$$

$$\sum_{i=1}^{n} p_i(\tau_{m-1})\cdot p_{ij} = p_j(\tau_m), \tag{2}$$

where:

$p_i(\tau_m)$ –probability that at moment τ_m the object will be in the state „i",

p_{ij} – probability that object being at moment τ_m in the state „i" will at moment τ_{m+1} be in the state „j" (for $j \geq i$ and for each m = 1,2,…).

Let P_m designate a row vector $(p_1(\tau_m), p_2(\tau_m),\ldots, p_n(\tau_m))$. Formula (2) may be written in the form:

$$Pm=Pm\text{-}1\cdot P, \tag{3}$$

where P is matrix with elements p_{ij}, the so called transition matrix.

This sequence describes the object change process where distribution of the probability of passing from state at moment τ_{m-1} to state at moment τ_m depends only on the state realized at moment τ_{m-1}.

It is a discrete process as the transitions occur at moments $\tau_0,\tau_1,\ldots, \tau_k$ and all the states make a finite set.

The transition matrix was determined by means of a diagnostic model consisting of the modified T-03 four-ball tester friction node [7, 9], operating in accordance with the IP300/82 standard [8]. The testing set (Fig. 3) includes four bearing balls, the upper ball (1), mounted in the spindle, rotates with a given speed n and the other three (2), pressed to it with force P, roll in the special raceway (3). The vibration level is controlled by means of a Brüel&Kjær Type 5370V piezoelectric sensor (4).

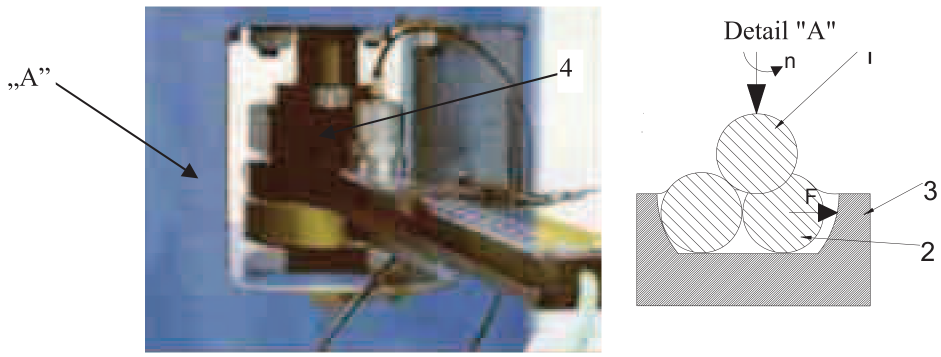

Fig. 3. Friction node with vibration sensor

3. Diagnostic testing with particular attention given to vibroacoustic signals in the friction nodes

Vibroacoustic processes are strongly associated with functioning of the crankshaft-piston assembly. Main causes of vibrations in the crankshaft-piston assembly are aerodynamic (suction, combustion and exhaust), electromagnetic (interaction of magnetic fields), hydromechanical (turbulent fluid flow, inhomogeneity of flow, turbulent pressure pulsations and cavitation) as well as mechanical (inertia forces during motions of elements, friction forces and also impulse forces caused by collisions of cooperating parts due to existing clearances) phenomena.

Diagnostic model of the T-03 tester friction node performs analysis of the friction force action by succeeding chaotic impulses of small intensity and short duration. Friction is connected with broad-band vibration which superimposes on the signal as the background. The most intensive vibration is generated by dry friction. Lubricant decreases friction forces and also vibration. When the lubricated surfaces are completely separated by boundary layer, the dry friction is avoided and vibration is reduced to minimum.

The durability measurements were performed on the friction node of a modernized T-03 tester with balls submerged in the Daewoo 15W/40 lubricating oil. The experimental investigation . covered:

– oil drawn from engine in operation,
– clean lubricating oil.

The T-03 tester friction node consisted of 12.7 mm diameter bearing balls made from the ŁH15 steel in the accuracy class 16 according to the PN-83/M-86452 standard, submerged in the tested lubricating oil. All the tests were carried out at 23°C. Three test procedures were performed, with the assumption that the friction nodes were crankshaft-piston assembly nodes working with the same lubricating oil under different point loads:

1) determination of friction node durability at 500 rpm and under 392 N load,
2) determination of friction node durability at 500 rpm and under 618 N load,
3) determination of friction node durability at 500 rpm and under 785 N load.

The measurement temperature, rotational speed and the friction node load were so selected that only compensation scar diameter appeared on the tester balls.

The tests included three types of friction nodes working with used oil and with clean oil.

4. Analysis of test results

The performed friction node durability investigation resulted in different values of the lifetime determining random variables. Probability distributions of those variables are boundary (extreme) value distributions when the random variables are connected with limiting properties of the modernized T-03 tester friction node.

Analysis of the so far performed tests [5, 6] indicates that vibration in the modernized T-03 four-ball testers is described with the best accuracy by the Weibull distribution. Therefore, Fig. 4-6 present graphical analysis of test results for the Weibull distribution.

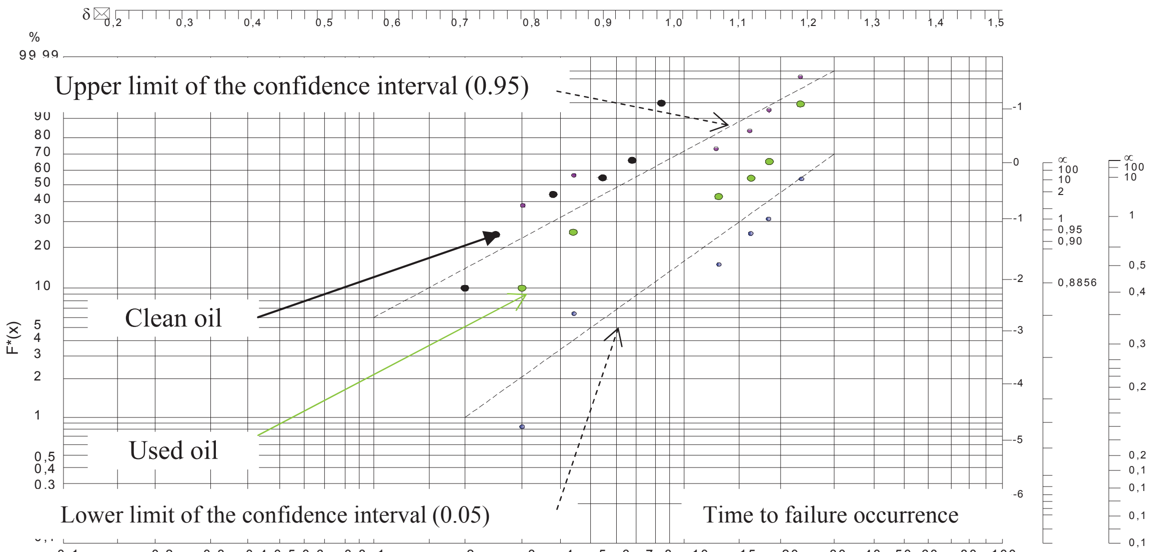

Fig. 4. Graphical analysis of the distribution for 392 N load

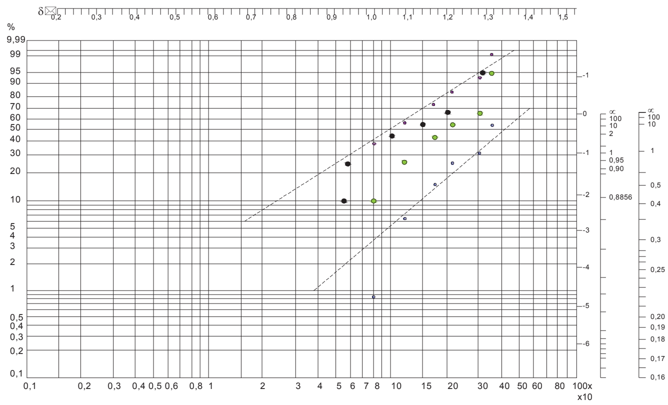

Fig. 5. Graphical analysis of the distribution for 618 N load

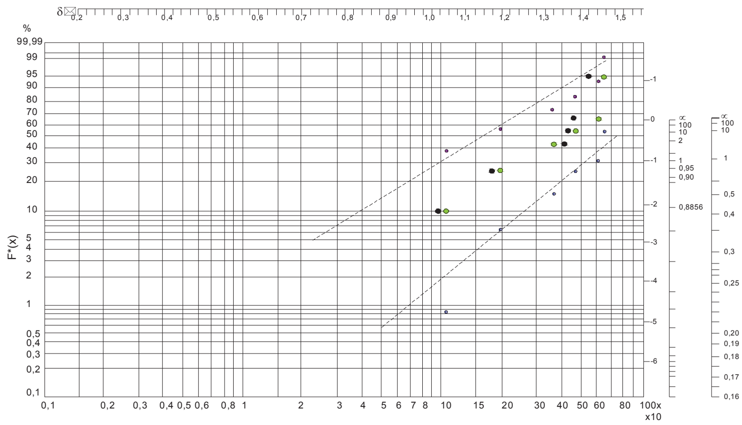

Fig. 6. Graphical analysis of the distribution for 785 N load

The graphical analysis in Fig. 4 shows that samples of the used Daewoo 15W/40 oil are better than samples of clean oil. Verified is the stated hypothesis that, for the 0.98 confidence level, samples of oil used at 392 N load are better than the clean oil. Therefore, friction nodes working with used oil were fully operational whereas friction nodes working with clean lubricating oil were in the state of partial fitness for use at the unit load of 392 N. For higher unit loads the confidence levels appeared much lower, so the hypothesis was discarded.

Then, using the a posteriori probability, distribution of the fitness for use states was determined from the Bayes [3, 4] formula. „A_n" designates event of fully usable friction node. Observation was extended to „N" friction nodes used in three different load conditions (392 N, 618 N, 785 N). The event of friction node working in i-th condition is designated by B_i, where i =1,2,3.

Tab. 1. Number of friction nodes for used lubricant oil

No.	Used Daewoo 15W/40 oil	Load		
		392N	618N	785N
1	Number of friction nodes working in given conditions	6	6	6
2	Number of friction nodes working in given conditions and not damaged after time of τ =100 s	4	5	6
3	$P(B / A_{n1} \cap A_{n2} \cap A_{n3})$	0.16	0.31	0.53

Tab. 2. Number of friction nodes for clean lubricant oil

No.	Clean Daewoo 15W/40 oil	Load		
		392N	618N	785N
1	Number of friction nodes working in given conditions	6	6	6
2	Number of friction nodes working in given conditions and not damaged after time of τ =100 s	0	5	6
3	$P(B / A_{n1} \cap A_{n2} \cap A_{n3})$	0	0.34	0.66

Let's assume that physical and chemical phenomena in the tested friction nodes are similar to those in the friction nodes of an operating internal combustion engine crankshaft-piston assembly. A triangle transition matrix can then be constructed describing the changes taking place in the friction nodes without human intervention. Two degrees of wear and one failure state can be distinguished.

$$P = \begin{bmatrix} 0.16 & 0.31 & 0.53 \\ 0 & 0.34 & 0.660 \\ 0 & 0 & 1 \end{bmatrix}, \tag{4}$$

5. Final remarks and conclusions

The paper presents conception of creating a simple reliability model of the crankshaft-piston assembly. The model consists of any number of friction nodes in the crankshaft-piston assembly. They may operate at different unit loads, temperatures and rotational speeds but with the same lubricating oil.

In order to simplify the analysis of results, the tests were carried out at constant lubricating oil temperature, at a distance from the ball contact and with constant friction node rotational speed. The only diagnostic parameter was the acoustic vibration.

Application of the presented conception to investigation of the internal combustion engine crankshaft-piston assembly reliability requires the similarity theory to be used. It allows comparing the processes taking place in a real friction node with those occurring in the T-03 tester friction node. Therefore, in my opinion it is worth considering that a new criterion value be introduced defining the oil lubricity. It is connected with the necessity of increasing the number of variable diagnostic parameters in the T-03 tester friction node reliability model.

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