OPTIMAL PREVENTIVE MAINTENANCE SCHEDULE OF SLEWING RINGS FOR DEMANDING PRODUCTION MACHINE

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DOI : 10.17973/MMSJ.2018_12_201872

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When designing any demanding production machine should be chosen minimum necessary set of technical components that are necessary to the achievement of the required functions. Moreover, the quality of fulfilling the functions is closely related to its reliability. One of the basic ways of improving the reliability of technical components of demanding production machines is increasing their reliability through preventive maintenance. By design an optimal preventive maintenance schedule of production machine can be timely and effective interventions to prevent the breakdown. This paper describes the design of optimal preventive maintenance schedule of slewing rings intended as rotating parts for demanding production CNC machine with EDM technology.

KEYWORDS

experimental equipment, preventive maintenance, probability, slewing rings, diagnostic signal

1 INTRODUCTION

In manufacturing systems operation, preventive maintenance is performed by taking off-line a technical component to apply a prescribed maintenance task. As a system cannot be maintained at all times, a way is needed to decide when inspection or maintenance is needed. To avoid unnecessary maintenance, which increases the cost and may also increase the risk of further wear, the effectiveness [Malega 2017] of a preventive maintenance schedule should depend on quality, reliability and a lifecycle cost analysis. Preventive maintenance increases the overall operational machinery [Soltesova 2013] reliability while decreasing unanticipated down-time from components failures. In the maintainability the focus is mainly on the design and overall concept of the elements in order to avoid serious disturbances in technical equipment. If there is a serious failure of production machine, which causes the long downtime, a common cause is an absent or inadequate optimal preventive maintenance schedule. Barlow and Hunter [Barlow 1960] did a pioneering work on optimum preventive maintenance policies. Since then, many works have been done along this line. Survey papers such as in [Fabian 2008, Straka 2014] cover the subject of optimal maintenance.

2 PREVENTIVE MAINTENANCE

Preventive maintenance can be defined as actions performed on a time- or machine-run-based schedule that detect, preclude, or mitigate degradation of a component [Panda 2013] or system with the aim of sustaining or extending its useful life through controlling degradation to an acceptable level.

Preventive maintenance is the activity which to be performed at predetermined intervals or according to prescribed criteria. It is focused on reduction of the probability of failure or degradation of the functions of technical equipment.

Basic types of preventive maintenance:

a) *age maintenance* - is based on the exchange element at the time of failure or after the prescribed time,
b) *periodic maintenance* - time based maintenance consists of periodically inspecting, servicing and cleaning equipment and replacing parts to prevent sudden failure and process problems,
c) *random maintenance* - is based on the exchange of the element at the time of failure, or after a certain time of operation.

In connection with increasing requirements to optimize maintenance is also important to mention the important position of predictive maintenance, which is carried out on the basis of predictions derived from the analysis [Stephen 2011] and evaluation [Straka 2013] of the important parameters of degradation device with support non-destructive diagnostics.

Basically, predictive maintenance differs from preventive maintenance by basing maintenance need on the actual condition of the machine [Yan 2018] rather than on some preset schedule.

3 PROBABILITY IN THE PREVENTIVE MAINTENANCE

Maintenance parameters has probabilistic in nature and are capable of analysis by the use of continuous and discrete random variables, probability parameters and statistical distribution division. For the analysis of maintenance it is much smaller number of statistical distributions as for the analysis of reliability. The most common statistical distribution used in the theory of maintenance are exponential, Poisson, Binomic, Weibull or Reliog.

Basic maintenance indicators are equivalent for indicators valid in the reliability theory. The difference, however, lies in the interpretation. For example, the parameter t - time to failure is in theory maintenance interpreted as a parameter t - the time required to restore operability equipment, λ - parameter failure rate as a parameter μ - intensity repairs and parameter $F(t)$ - probability of failure at the time t or $P(T \leq t)$ as a parameter $M(t)$ - probability of the successful completion repair at the time t or $P(T \leq t)$.

4 OPTIMIZATION OF THE PREVENTIVE MAINTENANCE PLAN

The basic criterion of optimization of the preventive maintenance plan is economic efficiency. Is the based on analysis of the life cycle cost equipment which examines impact of maintenance to the total life cycle cost [Zhang 2017]. Input parameters of this analysis are the costs associated with the acquisition of the property and the costs necessary to restore the operability of equipment [Tothova 2013] i.e. removing his failure. The basic principle of optimization of preventive maintenance is to find a point in time operating time equipment which for renewal of equipment will ensure the achievement of the minimum average unit cost of operation and renewal of the object during its all over life-cycle. The data needed to design the optimal plan of preventive maintenance are preventive maintenance cost *Nu*, losses that caused an emergency failure of technical equipment *Ns*, probability of failure based on preventive maintenance interval $F(t_p)$, losses that are caused an emergency failure of technical equipment Ns, functional dependence [Vagaska 2013] of middle preventive maintenance interval on simple interval of preventive maintenance $\bar{t}(t_p)$, functional dependence] of the average cumulative cost of operating the object caused by increasing wear observed functional surfaces of components and groups depending on interval of preventive maintenance $N_{Pu}(t_p)$, functional dependence of the average cumulative cost of operating the object caused by its diagnosis [Krenicky 2011, Prislupcak 2014] (monitoring the technical condition), depending on interval of preventive maintenance $N_{Pd}(t_p)$.

On the basis of opposing cost trends can be established optimum value range of preventive maintenance from the relation for calculating the average costs by the formula (1):

$$u(t_p) = \frac{N_u + N_s \cdot F(t_p) + N_{Pu}(t_p) + N_{Pd}(t_p)}{\bar{t}(t_p)} \quad (€.h^{-1}) \qquad (1)$$

Functional relationship of middle interval i.e. mean time to operation preventive maintenance on a simple interval preventive maintenance $\bar{t}(t_p)$, can be estimated from the experimental data obtained by the formula (2):

$$\bar{t}(t_p) = \frac{1}{n}\left[\sum_{i=1}^{m(t_p)} t_i(t_p) + \sum_{j=1}^{n-m(t_p)} t_j(t_p)\right] \quad (h) \qquad (2)$$

where:
$t_i(t_p)$ - is the period of operation the *i*-th element, which is operated in the state t_p (h),
$t_j(t_p)$ - is the period of operation the *i*-th element, which in the state t_p no longer working (h),
$m(t_p)$ - is the number of elements, which is operated in the state t_p,
n - is the number of observed elements of this type.

5 RELIABILITY OF SLEWING RINGS FOR DEMANDING PRODUCTION MACHINE

The technical equipment was solved for demanding production machine [Pitel 2017]. It was considered that there is a real opportunity to follow experimental equipment (Fig. 1) in the two-state model. Us assume also that for the technical equipment can be monitored and identify the value of each indicators of reliability.

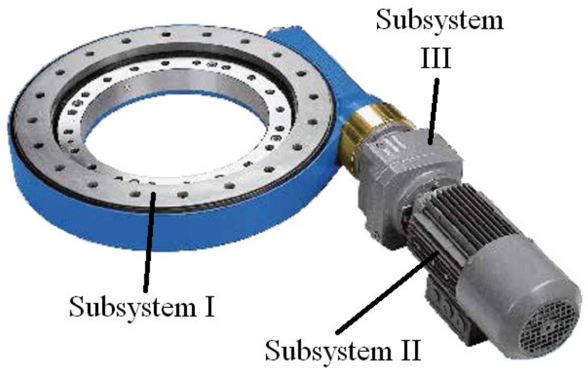

Figure 1. Slewing rings for demanding production machine

The technical equipment shown in Figure 1 has an extensive set of elements. Therefore, only essential elements of the system were considered. Was considers with failure elements for which there the largest prerequisite for the existence failure and at the same time it makes sense to implement of preventive maintenance to avoid critical failure.
These are the elements of the rotating mechanism (subsystem I), drive unit (subsystem II) and transmission device (subsystem III). Elements of the subsystem I with a tendency to critical failure are large-dimensional bearing E_{I1}, toothed wreath E_{I2} and toothed pinion E_{I3}. Elements of the subsystem II with a tendency to critical failure are stator E_{II1}, rotor E_{II2} and E_{II3} bearings. Elements of the subsystem III with a tendency to critical failure are drive shaft coupling E_{III1}, output shaft coupling E_{III2} and gearboxes E_{III3}.
Diagnostic signals (Fig. 2) are random variables with probability density of time to failure $f_1(t)$, $f_2(t)$, ... $f_n(t)$ respect. distribution function $F_1(t)$, $F_2(t)$, ... $F_n(t)$, respect. probability of non-failure operation $R_1(t)$, $R_2(t)$, ... $R_n(t)$ and intensity of failures $\lambda_1(t)$, $\lambda_2(t)$, ... $\lambda_n(t)$.

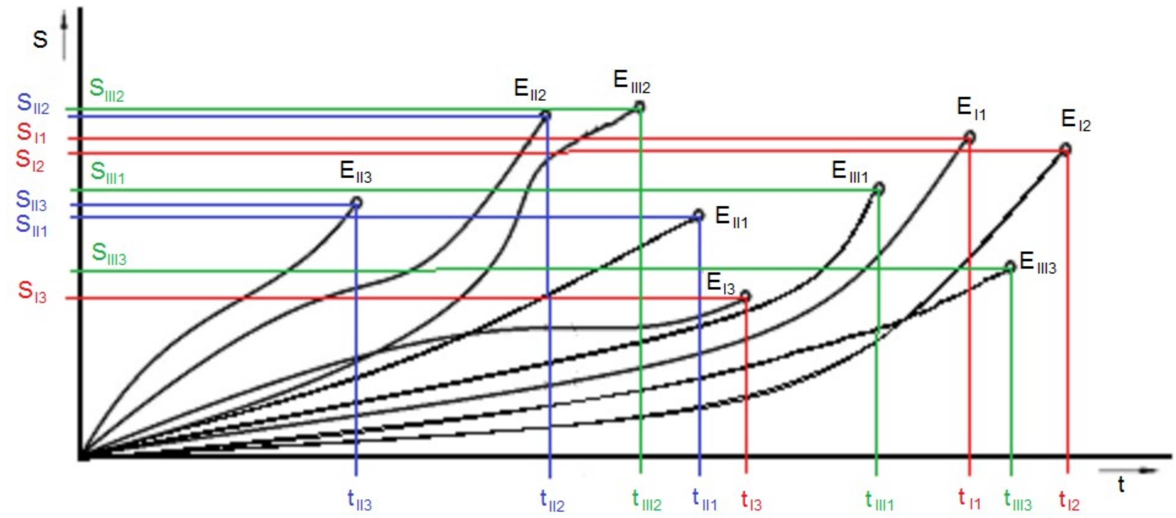

Figure 2. Course of diagnostic signal S at the during time t of the device operation

Optimized value of all diagnostic parameters t_p resp. S_p are dependent on economic and operating conditions of the slewing rings device for demanding production machine. These are subject to change, because the solved technical device will by to operate in extreme or specific conditions. The proposed is the preventive maintenance of the slewing rings device for demanding production machine with a mark plan of periodic preventive maintenance with regenerative maintenance breached and intact element. It´s in practice means that the elements cannot be repaired but replaced them with new ones. The values given are average costs of maintaining the damaged element N_p and intact element N_u, as well as parameter of size β and parameter of shape m Weibull distribution of operation time to failure with probability p.

Table 1. The values of the function $\Gamma\left|1+\dfrac{1}{m}\right|$

m	*p* 0.00	0.01	0.02	....	0.08	0.09
1.6	0.8966	0.8961	0.8956		0.8930	0.8926
1.7	0.8922	0.8919	0.8916	....	0.8898	0.8895
1.8	0.8893	**0.8891**	0.8888	....	0.8877	0.8875
1.9	0.8874	0.8872	0.8871	....	0.8964	0.8863
2.0	0.8862	0.8861	0.8861	....	0.8858	0.8857

Where: $c = \dfrac{N_p}{N_u}$ (3)

Standardized optimal maintenance interval can be determined from the relationship: $z = \dfrac{u^x}{Q(t)}$ (h) (4)

Standardized optimal maintenance interval of the slewing rings device for demanding production machine can be determined from the graph (Fig. 3) for plan of periodic preventive maintenance with regenerative maintenance breached and intact element based on the share of the average cost c and the parameter of shape m.

The mean time of operation to failure element *MTTF* calculated according to formula (5): $MTTF = \beta \cdot \Gamma\left|1+\dfrac{1}{m}\right|$ (h), (5)

Gamma function can be determined from the table 1.

$\Gamma\left|1+\dfrac{1}{m}\right| = 0.8919$ with probability 0.01. (6)

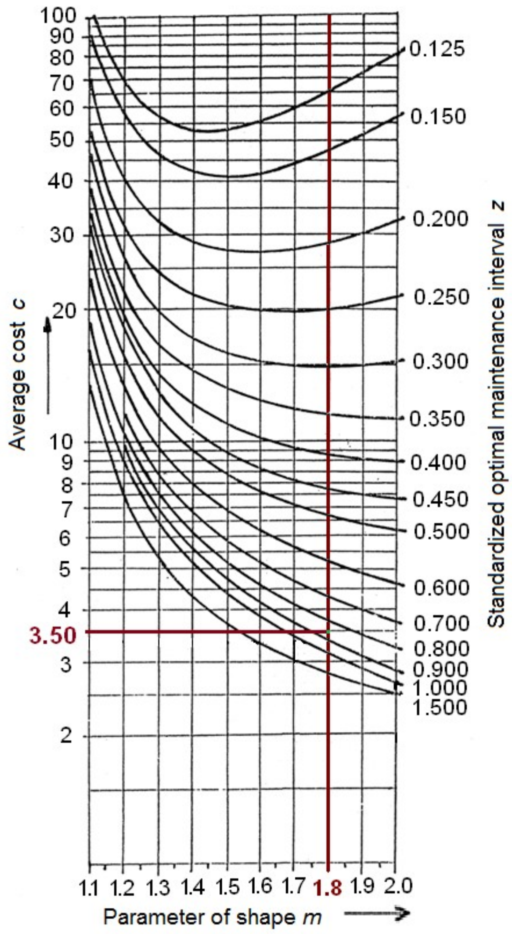

Figure 3. Determination of normalized optimal maintenance interval z on the ratio value of the average cost c and parameter of shape m of the slewing rings device for demanding production machine

Optimal interval of maintenance $u=u^x$ we calculate from the formula (7):

$u^x = z \cdot MTTF$ (h) (7)

The next table 2 provides an overview of the various parameters concerning the optimal plan of preventive maintenance of individual elements of the slewing rings device for demanding production machine.

Table 2. The optimal interval parameters of preventive maintenance of individual elements of the slewing rings device for demanding production machine

Subsystem	Element	The average maintenance costs: damaged element N_p [€]	intact element N_u [€]	The ratio of the average costs *c*	Parameter of size β	MTTF [hours]	Normalized optimal maintenance interval *z*	The optimal interval of maintenance u^x [hours]
I.	E_{I1}	4500	1200	3.75	9000	8000	0.82	6561
	E_{I2}	1500	350	4.28	10000	8861	0.71	6323
	E_{I3}	2500	400	6.25	8000	7112	0.50	3556
II.	E_{II1}	350	100	3.50	7500	6668	0.85	5668
	E_{II2}	400	70	5.71	4500	4000	0.57	2280
	E_{II3}	250	60	4.17	3000	2667	0.70	1867
III.	E_{III1}	270	80	3.38	8500	7557	0.90	6801
	E_{III2}	350	70	5.00	7000	6223	0.63	3920
	E_{III3}	800	240	3.33	9500	8446	0.92	7770

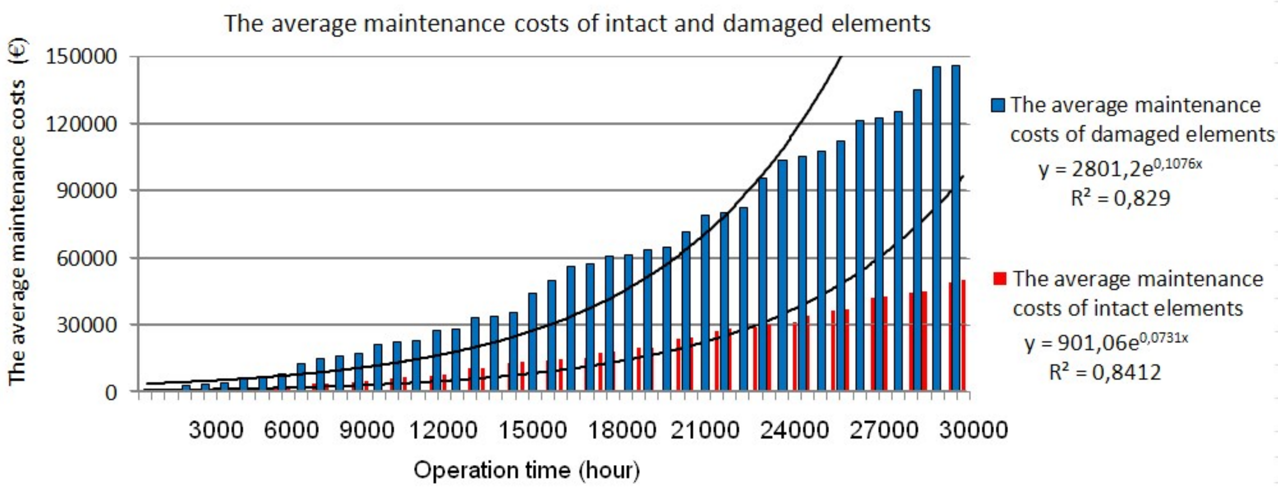

Figure 4. The average maintenance costs of individual elements of slewing rings device for demanding production machine

We found that the optimal interval of preventive maintenance of individual elements of the slewing rings device for demanding production machine with consideration of Weibull distribution of time to failure under consideration subsystem elements I, II and III is between ranges 1867 hours for maintenance element E_{II3} subsystem II (bearings) the gearing to the 7770 hours for maintenance elements E_{III3} subsystem III (gearboxes).

Graph in figure 4 show the experimental plan maintenance and average maintenance costs of the slewing rings device for demanding production machine during its design lifetime of 30000 hours.

The first failure occurs after approximately 3000 hours on element E_{II3} subsystem II (bearings), if it is not implementing of preventive maintenance at the time of 1867 hours from operation startup of slewing rings device for demanding production machine. These are the times that are standard for this type of device. Similar results came from researchers who reported their results at work (Stephen 2011, Zhang 2017).

6 CONCLUSIONS

Very important for maintaining the operability of the each technical device as long as possible is necessary include suitable schedule of preventive maintenance. Its aim is to schedule inspections of technical device, perform cleaning, alignment, lubrication, replacement of components the based on reliability indicators of its individual parts. If you want in order preventive maintenance was not only effective but also efficient, i.e. in order the costs do not exceed the costs of removing emergency failure, it is necessary optimal schedule of preventive maintenance.

Aim of this contribution is proposal schedule of optimal preventive maintenance of the slewing rings device for demanding production machine. Thus achieve as far as possible the efficient operation with minimal failure downtime required throughout the lifetime of the equipment.

The optimal schedule of maintenance interventions of solved technological device it was be chosen according to the power parameter which characterizes the course of its wearing parts. The basis for optimization schedule of preventive maintenance of the slewing rings device for demanding production machine it was the database of data by the period of operation of the individual elements of solved technological device to the physical limit state, i.e. into state where the technological element loses the ability to perform the desired function, for example due to the wear, fatigue fracture and corrosion.

ACKNOWLEDGMENTS

The authors would like to thank the grant agency for supporting research work the projects KEGA, 004 TUKE-4/2017.

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