THE ANALYSIS OF MODE, CONSEQUENCES AND CRITICALITY AT POTENTIAL FAILURES OF GEAR PUMP

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Abstract: The analysis of mode and effects of failures (FMEA) is the procedure for the estimation of reliability of the device in all phases of its operating circle, which is based on observing all potential failures of items and their effects on the device. FMEA is a systematical technique and formal help in thinking which enables the weak places in technical system known from the experience, the potential failures, consequences and risks, to be seen on time, and to be brought into the process of decision making together with measures of corrective maintenance.
Here we present a short instruction to perform the procedure of FMEA and analyses of mode, effects and criticality at failures (FMECA), namely the procedures FMEA / FMECA, with the description of the steps to perform the procedure. The process of performing the procedure FMEA /ANEKO is illustrated on the example of hydraulic system, precisely on the example of its subsystem – gear pump.

Key words: gear pump, failure modes, effects and criticality analysis (FMECA)

1. INTRODUCTION

The method of FMECA has many advantages in comparison with the other methods of failure analysis, but some comparative disadvantages as well. The advantages of FMECA are:

- Possibility of systematic evaluation of relations between causes and consequences at certain failures
- Pointing to the forms of failures especially undesirable for the work of the system
- Pointing to the forms and systems not previously expected, actually not analyzed or neglected
- Clarification of previous failures which were not enough observed, namely more realistic evaluation of certain actions which might cause failure of the system
- Thus we especially stress that the analysis by the method of FMECA is very useful in the cases without enough experience or relevant information. This refers largely to the new systems, which are being designed, or in developing phase or installation.

The disadvantages of FMECA are the following:

- Huge tabular statements with much data, even for relatively simple systems
- Difficulties in embracing all important facts, e.g. the difference in operating time of certain items (compared with operating time of the system), working conditions, possibilities of restoration etc.
- Impossibility of direct performing of mathematical model describing the possibility of system failure, namely its reliability
- Difficulties in the analysis of system with complex structural correlations between the items (e.g. `specific correlations` which have the qualities of even and parallel, under the same conditions) etc.

Failure Modes and Effects Analysis (FMEA) represents one of methods in analysis of potential failures in components of the system and could come true in each phase of system operating circle. The aim of the analysis is to discover the causes of component failure in order to decrease the consequences of failure in performing the functional aim of the system [1]. FMEA is possible to be performed on any level of system division. The system is divided into subsystems, which are divided into structures, substructures and items. To maintain correct performing of FMEA all potential modes of system failures should be exactly identified. Different code systems are used and one of them can be performed like this:
A – technological system
A.B – substructure, which gets into A
A. B. C – structure which gets into B
A.B.C.D – substructure, which gets into C
A.B.C.D.E - item which gets into D

Code system can be solved with numbers as well using the same principle as the larger number on a certain level of division represents numbers in rising line.
For each item of the lowest level of division the data on reliability are provided. The most appropriate is to

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use the average intensity of failure (for irreparable items) or average operating time between failures (for reparable items).

Based on structural and functional analyses and experiences in exploiting the system all consequences of system failure are formed, and all potential modes of item failures at the lowest level of division are listed, respecting the code system.

To perform the procedure of FMEA, all the consequences of failure are classified in four categories:

- I catastrophic consequences for the system and or the operator
- II final break of exploiting the system
- III jamming of the system or setback of output parameter system
- IV slight jamming of the system

Going from hierarchic higher to hierarchic lower levels, the items of the lowest levels are chosen causing severe consequences. This information gives the possibility (depending on the phase of operating system circle of decision making on eliminating and preventive modes of failures taking to severe consequences (according to accepted classification).
The analysis of criticality of failure can be added to the procedure of FMEA. The criticality of failure is the degree of quality performing the function within the limits of allowed variation. Each mode of failure is added corresponding criticality in accordance with serious consequences of failure. Mutual procedure FMEA and Criticality Analysis (CA) of failure is named Failure Modes and Effects and Criticality Analyses. The procedure of FMECA including Criticality Analysis of failure enables increasing of system safety by taking into consideration of potential failures consequences.

The procedure of Criticality Analysis is performed in three basic steps:

1. Defining the criticality mode of failure, which causes p category of failure consequences (P=I, II, III, IV). In other words, this is prognosis of number j mode i item.

$$C_{ij}^{(p)} = \alpha_{ij} \cdot \beta_{ij}^{(p)} \cdot \lambda_i \cdot t_i \qquad (1)$$

where:

$\lambda_i = \sum_i \lambda_{ij}$ - intensity of i item failure

λ_{ij} - intensity j mode failure i item

t_i - operating time of i item

λ_{ij} - `weigh` (heavy part, relative part, measure of frequency) j mode of item i failure

$$0 \le \alpha_{ij} \le 1, \ \sum_j \alpha_{ij} = 1$$

$\beta_{ij}^{(p)}$ - conditioned possibility that j mode of item i failure will cause p category of consequences according to the accepted classification under the condition for this mode of failure to appear.
Values $\beta_{ij}^{(p)}$ are given roughly, using the recommendation of table1.

Table 1. Rough values of conditioned probability $\beta_{ij}^{(p)}$

Degree of p category of failure consequences	$\beta_{ij}^{(p)}$
Certain	1
Probable	0.1 ÷ 1
Remote	0 ÷ 0.1
Very unlikely	0

Calculation $C_{ij}^{(p)}$ enables separating of the most important (from the safety aspect) modes of item failures, in order to eliminate their causes.

2. Defining criticality of failure i item, which causes p category of failure consequences:

$$C_i^{(p)} = \sum_j C_{ij}^{(p)} \qquad (2)$$

Calculation $C_i^{(p)}$ enables separating the most important items whose failure takes to undesirable consequences.

3. Defining criticality of n consequence of system failure:

$$C_{p(n)} = \sum_i \sum_j C_{ij(n)} \qquad (3)$$

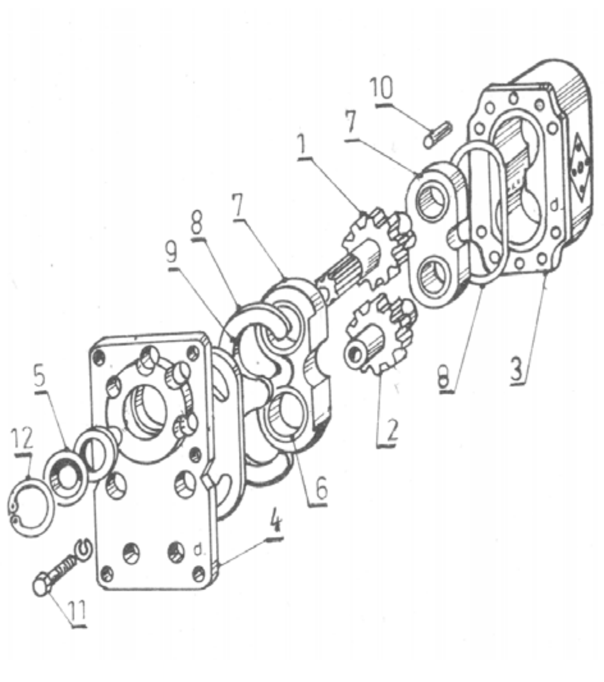
where $C_{ij(n)}$ - criticality of failure j mode i item takes to n failure consequence.
Defining these potential failures on system components goes on in the procedure of exploiting on the basis of observation in regular technical checking, based on listed failures, expert analysis for maintenance and diagnostic tests.

The mode of failure detection provides mode for reliable parameters defining, thanks to which the type of failure is defined by the observation of operator. Sensor or donor also does this. Detection of failure can be normal, abnormal or wrong. At normal detection, parameters show normal values for the correct system work. Abnormal detection shows that the system

doesn't function properly. Improper sensors or donors or wrong conslusion of the operator causes wrong detection.
Through this procedure it is necessary to predict the activities for the failure elimination. It includes corresponding spare parts, security and safety measures used for the protection of the failure as well as corresponding alternative to continue the operation while some item failed. It is also important to identify the effects caused by improper system handling at the appearance of abnormal process or detection of the failure.

2. ANALYSIS OF MODE, CONSEQUENCES AND CRITICALITY OF ITEM FAILURE OF GEAR PUMP

The complex procedure FMEA is done at the hydraulic system in which gear pump represents its subsystem. Therefore structural functional division of gear pump was performed in hydraulic system. Corresponding code sign of belonging is added to each functional unity.
In the picture, there is a cutting of gear pump which consists of: operating cogwheel shaft 1, operated cog wheel shaft 2, casing 3, cover 4, packing 5 and bearing 6.



Picture 1. Component detail of the gear pump

2.1 Gear pump- the principle of the work

Operating cogwheel shaft rotates toothed pair, making sub pressure on the absorbed side, the oil gets to the cogwheel and is pressed through between teeth area, which is closed by inside surface of casing (3) in the pressing line. Precise construction of cogwheel doesn't let the oil go back. The mentioned constructive form with the preciseness of construction provides gear pump with huge capacity of efficiency (0.9 to 0.98)
Bearing flanges (7) stick to head surface of cogwheel (1 and 2). Surface A_2 (limited by static packing 8 and 9) is connected with the zone of high pressure (pressing line). The pressure between bearing flanges and head surface of cogwheel is adjusted not to cause jamming. By connecting the surface in front of the packing (5) with absorbing line, the leaking of the oil between packing (5) and operating cogwheel (1) is prevented.
On the pressing side of gear pump, the pressure is higher than on the absorbing side which takes to wearing out of split flange (6), therefore to wearing out of gear pump casing at the absorbing line.

2.2 Allocation of reliability

The procedure of allocation reliability searches for the adjustment of certain characteristics in separated items into the real probability of their manifestation. This procedure requires at least rough values of failures at all system items.
Distribution of necessary reliability on certain items is performed proportionally to `statistic weight` of corresponding accepted failure intensity values through the coefficient of allocation (ARINC method):

$$\omega_i = \lambda_i / \sum_{i=1} \lambda_i = \lambda_i / \lambda_s \quad (4)$$

where:
λ_i - is allocated subsystem failure intensity, namely items for the period t
λ_s - system failure intensity
Coefficients of allocation must meet the condition

$$\sum_{i=1}^{n} \omega_i = 1 \quad (5)$$

The permitted value of failure intensity considering terms (4) and (5) is:

$$\lambda_i^* = \omega_i \cdot \lambda_s \quad (6)$$

If the system reliability of gear pump is modeled as 11 connected items (Tab.2.) with the exponential law of distribution and if it is accepted with the value of failure intensity for certain items according to the literature [2], the coefficients allocation value of each item can be calculated. In the literature [2] there is a data for failure intensity of hydraulic pump
$\lambda = 1{,}68 \cdot 10^{-6}$ (čas^{-1}) The intensity of each item failure is calculated based on this data and calculated coefficients of allocation.
Comparing the data of intensity form with the reccomemded in the table (2) there is a huge difference. Therefore, the failure intensity is defined

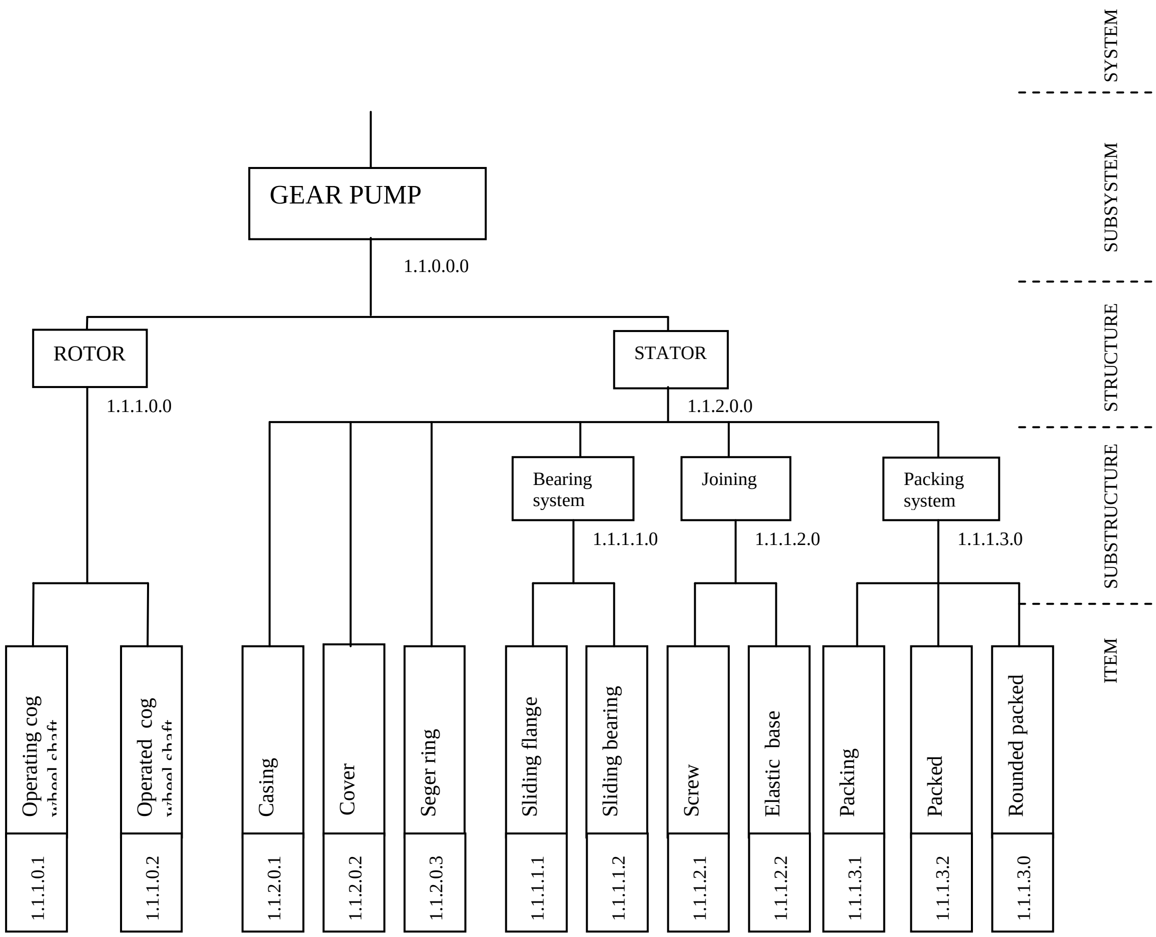
according to the average operating time (judging by the data of Prva petoletka Trstenik), taking into consideration that on average the pump works 300 days in two shifts (16 hours) in the period of 10 years, which makes 48000 of operating time. Considering the supposition of exponential distribution of reliability of system items, the intensity of system failure represents reciprocal value of the average operating time. So $\lambda = 20{,}8 \cdot 10^{-6}$ ($čas^{-1}$).is an initial data for the definition of failure intensity at the items of gear pump.

Considering the values of allocation coefficients previously defined, the intensity of failure for all items is calculated.

These values largely match the recommendations in the literature. Therefore they are taken as initial for the calculation of failure criticality.

Based on the criticality analysis it is obvious there are catastrophic failures of gear pump connected with parameters of hydraulic system (pressure, flow, amortization), and then comes the items of the gear pump as shown in the table number 4.

As the final consequences 2, the complete break of exploitation of the gear pump, the biggest influence has packing and cogwheel shaft.



Picture 2. Scheme of subsystem division of gear pump

Table 2. Table form FMEA of substructure-gear pump

Code	Item	Type of failure	Code type of failure	Cause of failure	High effect	α_{ij}	$\beta_{ij}^{(p)}$	λ_{ij} $\cdot 10^{-6}$ (h^{-1})	λ_i $\cdot 10^{-6}$ (h^{-1})	$C_{ij}^{(p)}$ $\cdot 10^{-6}$ (h^{-1})
11101	Operating cog wheel shaft	Damage of teeth sides	N1	Surface pressure, cavitations, bad thermo processing	P.2	0.5	1	2.01	4.02	2.01
		Wearing out of head surfaces of toothed wheel	N2	Overloading	P.3	0.2	0.5	0.804		0.402
		Wearing out of journal of shaft	N3	Metal sawdust in fluid	P.2	0.2	0.5	0.804		0.402
		Error fabricate groove	N4	Non-axis shafts, badly shaped	P.2	0.1	0.1	0.402		0.040
11102	Operated cog wheel shaft	Damage of teeth sides	N5	Surface pressure, cavitations, bad thermo processing	P.2	0.5	1	2.01	4.02	2.01
		Wearing out of head surfaces of toothed wheel	N6	Overloading	P.3	0.2	0.5	0.804		0.402
		Wearing out of journal of shaft	N7	Metal sawdust in fluid	P.2	0.2	0.5	0.804		0.402
		Error fabricate groove	N8	Non-axis shafts, badly shaped	P.2	0.1	0.1	0.402		0.040
11201	Casing	Wearing out of casing	N9	Bad centering of toothed wheel in relation to journal	P.1	1	0.5	0.33	0.33	0.165
11202	Cover	Bad gasket	N10	Bad evenness, damage of packing	P.2	1	1	1.77	1.77	1.77
11131	Packing	Deformation of packing mouth	N11	Harshness, age, expansion, change of solidity	P.2	0.95	1	5.082	5.35	5.082
		Damage of spring	N12	Change of inflexibility, breaking	P.3	0.05	0.1	0.267		0.027
11112	Sliding bearing	Wearing out of sliding bearing	N13	Porosity, non-straighten teeth sides	P.2	0.4	1	0.708	1.77	0.708
		Annulment of the gap between journal and deposit of flange	N14	Non-axis shafts	P.1	0.4	0.1	0.708		0.071
		Uneven wearing out on intake and lifting sides	N15	Overloading	P.3	0.2	0.8	0.354		0.283
11111	Sliding flange	Bad gasket	N16	Bad evenness, damage of packing	P.2	1	1	1.77	1.77	1.77
11132	Packed	Improper installment	N17	Montage	P.3	0.05	0.1	0.066	1.33	0.007
		Aging of rubber	N18	Pressed filter carbon dust	P.3	0.95	1	1.263		1.263
11130	Rounded packed	Aging of rubber	N19	Pressed filter carbon dust	P.2	1	1	1.33	1.33	1.33
11121	Screw	Breaking of screw head	N20	Mode of galvanic protection	P.3	1	0.1	0.027	0.027	0.027
11203	Seger ring	Breaking	N21	Improper montage, bad thermo processing	P.2	1	0.1	0.27	0.27	0.027
10000	System	Jamming of toothed wheel	N22	Unfitted parameters of hydraulic system (Pressure, flow, amortization)	P.1	1	1	100	100	100

Table 3. Criticality type of failure at P.1

Code	Item	Type of failure	Code type of failure	High effect	α_{ij}	$\beta_{ij}^{(p)}$	λ_i	t_i	Criticality type of failure
10000	System	Jamming of toothed wheel	N22	1	1	1	100	1.00	100
11201	Casing	Wearing out of casing	N9	1	1	0.5	0.33	1.00	0.165
11112	Sliding bearing	Annulment of the gap between journal and deposit of flange	N14	1	0.4	0.1	1.77	1.00	0.071

Table 4. Item failure intensity

1	2	3	4	5	6
Pos.	Item	$\lambda \cdot 10^{-6}$ (h^{-1})	ω_i	$\lambda \cdot 10^{-6}$ (h^{-1})	$\lambda \cdot 10^{-6}$ (h^{-1})
1	Operating cog wheel shaft	3	0.193	0.324	4.02
2	Operated cog wheel shaft	3	0.193	0.324	4.02
3	Casing	0.25	0.016	0.026	0.33
4	Cover	0.05	0.016	0.026	0.33
5	Packing	4	0.257	0.431	5.35
6	Sliding bearing	1.32	0.085	0.142	1.77
7	Sliding flange	1.32	0.085	0.142	1.77
8	Packed	1	0.064	0.107	1.33
9	Rounded packed	1	0.064	0.107	1.33
10	Screw	0.2	0.013	0.021	0.27
11	Seger ring	0.2	0.013	0.021	0.27

3. THE CONCLUDING NOTES

One of the basic elements in gathering reliability data of technological system represents a subsystem of the analysis of mode, consequences and criticality of failure items (FMECA).

The procedures FMEA and FMECA are done on the example of hydraulic system, namely its subsystem, gear pump. The analysis ends in ranging the items of the observed subsystem according to the level of criticality of failure type and criticality of items.

There are certain difficulties due to lack of evidence on reliability of the items at the lowest level. In some cases these can be solved if instead of dotted values of failure intensity a certain value diapason is given.

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