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APPLICATION OF FMEA MATRIX FOR PREDICTION OF POTENTIAL FAILURES IN HYDRAULIC CYLINDER

ZASTOSOWANIE MACIERZOWEJ ANALIZY FMEA DO PRZEWIDYWANIA POTENCJALNYCH WAD SIŁOWNIKA HYDRAULICZNEGO

A b s t r a c t

This paper presents Failure Mode and Effects Analysis using relations diagrams and matrices similarity method application on the hydraulic cylinder. Functions for each hydraulic cylinder components were identified as well as a pairs for interacting components. Also potential failures were defined. Using the principle of matrices similarity the rank of hydraulic component due to performed functions has been prepared.

Keywords: *FMEA*, *analysis*, *failure*, *hydraulic cylinder*

S t r e s z c z e n i e

W artykule zaprezentowano analizę przyczyn i skutków powstawania potencjalnych wad (FMEA), dla siłownika hydraulicznego, stosując diagramy zależności oraz metodę podobieństwa macierzy. Określono funkcje dla poszczególnych elementów siłownika. Zidentyfikowano zależności zachodzące pomiędzy parami współdziałających elementów oraz ich potencjalne wady. Korzystając z zasady podobieństwa macierzy, dokonano uszeregowania elementów siłownika ze względu na realizowane funkcje.

Słowa kluczowe: *FMEA*, *analiza*, *wada*, *siłownik hydrauliczny*

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List of symbols

c – component of hydraulic cylinder
C – a set of hydraulic cylinder components
e – function of interacting pair
p – pairs of interacting components of hydraulic cylinder
P – a set of interacting components of hydraulic cylinder
f – failure
$\mathbf{EP}$ – matrix function-pair
$\mathbf{PF}$ – matrix pair-failure
$\mathbf{EF}$ – matrix function-failure
$\overline{\mathbf{EP}}$ – matrix function-pair created with normalized vectors
$\mathbf{EP}^T$ – transposed matrix function-pair
$\lambda_{\mathbf{PE}}$ – similarity matrix pair-function

1. Intruduction

Over the last twenty years, the drive and hydraulic control are used in many industrial branches. Among them it can be distinguished the construction industry, mining, agriculture, and aerospace, military and automotive industries. In working machinery drive systems are commonly used hydraulic cylinders that are exposed to external environment factors such as: polluted air, variable temperature and dynamic loads. Although the hydraulic cylinders belong to a group of devices with relatively uncomplicated structure are susceptible to damage and failure. Identification of defects in the early stages of its formation allows to undertake an appropriate actions and preventive measures to eliminate. Ignorance of the possible defects negatively affects the work performed by systems equipped with hydraulic cylinders. This may lead to the system malfunctioning or cause oil leaks to the environment and even a risk to use. Therefore, the methods to detect potential faults and their causes are still developed. The advantages and benefits of using qualitative methods are increasingly being noticed. One of methods that allow for the early identification of possible defects is FMEA.

The paper presents a matrix FMEA analysis to identify potential defects in the hydraulic cylinder using the method of the similarity matrix.

2. The object of investigation

The object of the research is the double action hydraulic cylinder with swivel bearing [1]. The structure of the cylinder is shown in Figure 1, where: 1 – cylinder body, 2 – piston rod, 3 – gland, 4 – piston sleeve, 5 – nut, 6 – self aligned bearing, 7 – cylinder end with self aligned bearing, 8 – piston seal, 9, 11, 12 – sealing ring, 10 – wiper ring, 13 – guide ring.

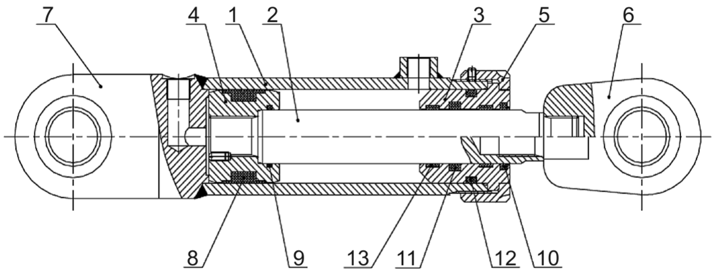

Fig. 1. Scheme of hydraulic cylinder

Rys. 1. Postać konstrukcyjna siłownika hydraulicznego

3. Input data to FMEA analysis

In order to analyze FMEA in the actuator design distinguishes ten elements (*c*), which may affect its improper operation. These are: cylinder body(c_1), piston sleeve (c_2), piston rod (c_3), sealing ring (c_4), piston seal (c_5), wiper ring (c_6), ring (c_7), gland (c_8) nut (c_9) and self aligned bearing (c_{10}). Among the distinguished components occurring relations that have an influence on the work of the hydraulic cylinder. Figure 2 shows a graph of dependencies that exist between the interacting components (Fig. 2).

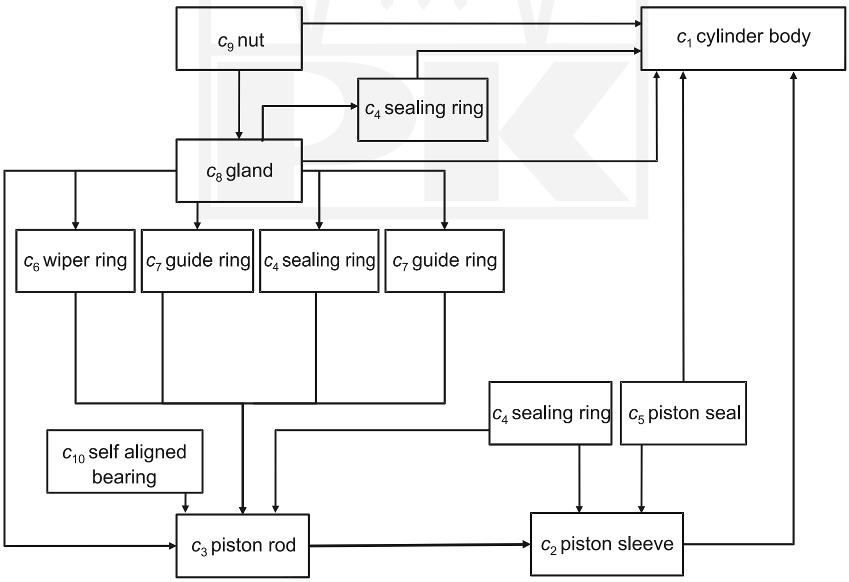

Fig. 2. Graph of relations between the interacting elements of hydraulic cylinder

Rys. 2. Graf relacji zachodzących pomiędzy współdziałającymi elementami siłownika

Using decomposition of the hydraulic cylinder and the relationship graph a seventeen pairs have been identified of interacting components. These are the following: p_1 $(c_1–c_2)$, p_2 $(c_1–c_4)$, p_3 $(c_1–c_5)$, p_4 $(c_1–c_8)$, p_5 $(c_1–c_9)$, p_6 $(c_2–c_3)$, p_7 $(c_2–c_4)$, p_8 $(c_2–c_5)$, p_9 $(c_3–c_4)$, p_{10} $(c_3–c_6)$, p_{11} $(c_3–c_7)$, p_{12} $(c_3–c_8)$, p_{13} $(c_3–c_{10})$, p_{14} $(c_4–c_8)$, p_{15} $(c_6–c_8)$, p_{16} $(c_7–c_8)$, p_{17} $(c_8–c_9)$. The relationships between a set of hydraulic cylinder components (C) and a set of interacting pairs (P) can be determined by relation occurring between the interacting components of the hydraulic cylinder:

$$C \subset P \tag{1}$$

For all pairs from a set P functions (e) have been specified that realizing in the hydraulic cylinder. Four functions have been identified:
- Fixing (e_1) – the correct position of the hydraulic cylinder components,
- Converting (e_2) – converting fluid pressure energy into mechanical motion straight-back, the main function of hydraulic cylinder,
- Preventing (e_3) – prevents against of dust, dirt, grains of sand, removes impurities,
- Protecting (e_4) – preventing oil leakage, seal cylinder, piston and piston rod guided in the cylinder, the lateral loads and vibration resistance.

In the next step of analysis based on the identified defects ten failures have been identified (f) for interacting pairs at hydraulic cylinder. These are: abrasive wear (f_1), crevice corrosion (f_2), fretting corrosion (f_3), seizure (f_4), fatigue friction (f_5), pitting (f_6), thermal fatigue (f_7), adhesive wear (f_8),oxidation wear (f_9), buckling (f_{10}).

4. Matrix FMEA analysis

The FMEA analysis includes creating of two diagrams of dependence. The first diagram (Table 1) shows the relationship between the pairs of interacting components (p_j) and realized functions (e_i). For each element of the matrix e_ip_j assigned value of 0 or 1. If a pair does not perform assigned function than value is 0, if the function is realized than the value is 1.

Table 1

Diagram of the relationship between functions and pairs (EP)

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}
e_1	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1
e_2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
e_3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0
e_4	0	1	1	1	0	0	1	1	1	0	1	1	0	1	1	1	0

The resulting graph is size [4×17], and contains 68 elements. A value of 0 has 50 elements of the matrix.

The second diagram of dependencies (Table 2) shows the relationships between interacting components (p_i) and their potential failures (f_j) defined in Chapter 2. For each pair of matrix

pf_j a value of 0 or 1 have been assigned. A value of 0 is assigned if the defect does not occur for the pair. The value of 1 if the defect occurs. The resulting matrix PF has dimensions [17×10] and has 170 elements. Over 100 elements of the matrix has a value of 0 Fragment of PF matrix [10×10] is shown below.

Table 2

Diagram of the relationship between the pair and their potential disadvantages (PF)

	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}
p_1	1	0	1	1	0	1	1	1	1	0
p_2	1	0	0	1	0	0	0	0	0	0
p_3	1	0	0	0	0	0	0	0	0	0
p_4	1	0	0	1	1	0	0	0	0	0
p_5	1	1	0	0	0	0	0	0	0	0
p_6	1	1	0	0	1	1	0	0	0	0
p_7	1	0	0	1	0	0	0	1	1	0
p_8	1	0	0	0	0	0	0	0	0	0
p_9	1	0	0	1	0	0	0	0	0	0
p_{10}	1	1	0	0	0	0	0	0	0	0

In the last stage of matrix FMEA analysis, on the basis of diagrams **EP** and **PF**, using the principle of multiplication of the matrix:

$$\mathbf{EP}\ x\mathbf{PF} = \mathbf{EF} \qquad (2)$$

a diagram showing the probability of failures (f) has been built, for pairs of interacting components (p) due to the function (e) performed by the pair in the hydraulic cylinder [2]. Table 3 shows the probability of occurrence of failures in the range of 0 to 11. Value 11 indicates the highest probability of failure for a given function.

Table 3

Diagram function – defect (EF)

	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}
e_1	4	3	1	2	0	1	1	1	1	1
e_2	1	1	0	0	1	1	0	0	0	0
e_3	2	2	0	1	0	0	0	0	0	0
e_4	11	3	1	9	2	0	1	1	1	0

For investigated hydraulic cylinder the highest probability is for failure abrasive wear (f_1) for pairs of realizing the protecting function (e_4). These are the following pairs: p_2, p_3,

p_4, p_7, p_8, p_9, p_{11}, p_{12}, p_{14}, p_{15} and p_{16}. FMEA analysis result for abrasive wear is presented in Figure 3, where the x-axis represents function of pairs while the y-axis represents the value of the analyzed failure.

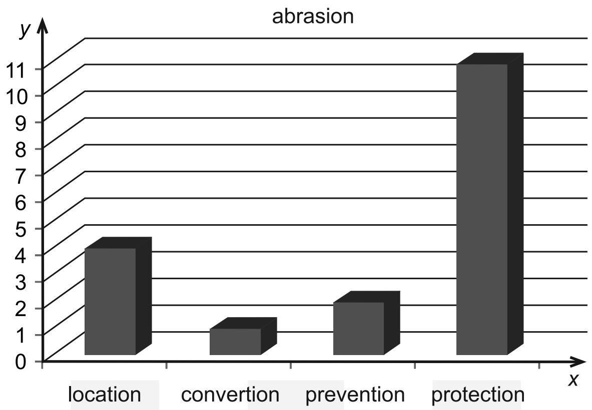

Fig. 3. Result of FMEA analysis for abrasion failure

Rys. 3. Wynik analizy FMEA dla wady zużycie ścierne

5. Application of the similarity matrix FMEA

Using the method of similarity (λ) presented in [3] it can be searched and grouped pairs of hydraulic cylinder components due to the realized functions (same or similar). These data can be used to make changes to the existing cylinder, or at the development of a new solution.

Similarity matrix $\boldsymbol{\lambda}_{\mathbf{PE}}$ (pair – component) is obtained by multiplying the transposed matrix function – pair ($\mathbf{EP}^T$) by a matrix function – pair ($\mathbf{EP}$). This matrix $\boldsymbol{\lambda}_{\mathbf{PE}}$ is a symmetric matrix described by the equation:

$$\overline{\mathbf{EP}^T} x \overline{\mathbf{EP}} = \lambda_{\mathbf{PE}} \tag{3}$$

Matrix $\overline{\mathbf{EP}}$ is a transformed matrix $\mathbf{EP}$ described in Chapter 2. It was built with normalized vectors of a matrix – a pair (Table 4). Normalization was carried out against the columns of the matrix $\mathbf{EP}_P$.

Tabela 4

Matrix built from normalized vectors ($\overline{\mathbf{EP}}$)

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}
e_1	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0
e_2	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
e_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0
e_4	0.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	0.0	1.0	0.7	1.0	0.0

Using Equation 3, the similarity matrix $\boldsymbol{\lambda}_{\mathbf{PE}}$ has been created. The resulting matrix with dimensions [17×17] is presented in Table 5.

Table 5

Similarity matrix pair – function ($\boldsymbol{\lambda}_{\mathbf{PE}}$)

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}
p_1	×	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0
p_2	0.0	×	1.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	0.0	1.0	0.7	1.0	0.0
p_3	0.0	1.0	×	1.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	0.0	1.0	0.7	1.0	0.0
p_4	0.0	1.0	1.0	×	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	0.0	1.0	0.7	1.0	0.0
p_5	1.0	0.0	0.0	0.0	×	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0
p_6	0.0	0.0	0.0	0.0	0.0	×	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
p_7	0.0	1.0	1.0	1.0	0.0	0.0	×	1.0	1.0	0.0	1.0	1.0	0.0	1.0	0.7	1.0	0.0
p_8	0.0	1.0	1.0	1.0	0.0	0.0	1.0	×	1.0	0.0	1.0	1.0	0.0	1.0	0.7	1.0	0.0
p_9	0.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	×	0.0	1.0	1.0	0.0	1.0	0.7	1.0	0.0
p_{10}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	×	0.0	0.0	0.0	0.0	0.7	0.0	0.0
p_{11}	0.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0	×	1.0	0.0	1.0	0.7	1.0	0.0
p_{12}	0.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0	×	0.0	1.0	0.7	1.0	0.0
p_{13}	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	×	0.0	0.0	0.0	1.0
p_{14}	0.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	0.0	×	0.7	1.0	0.0
p_{15}	0.0	0.7	0.7	0.7	0.0	0.0	0.7	0.7	0.7	0.7	0.7	0.7	0.0	0.7	×	0.7	0.0
p_{16}	0.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	0.0	1.0	0.7	×	0.0
p_{17}	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	×

PE similarity matrix $\boldsymbol{\lambda}_{\mathbf{PE}}$ has values in the range 0.0 to 1.0 Each element of the matrix $\boldsymbol{\lambda}_{\mathbf{PEij}}$ represents the similarity between pairs of components *i* and *j*. Value of 1.0 indicates the total similarity (realization of the same function) and 0.0 lack of common functions. The values on the diagonal of the matrix ($i = j$) are x (the relationship that occurs between the same pairs). Based on the PE matrix $\lambda_{\mathbf{PE}}$ a pairs of components has been grouped depending on the performed functions (Table 6).

Table 6

Grouped pairs depending on performed functions

Level	Group	Function	Pair	The similarity of the realized functions
I	1	protecting	cylinder – sealing ring	$p_3, p_4, p_7, p_8, p_9, p_{11}, p_{12}, p_{14}, p_{16}$
	2	fixing	cylinder – piston sleeve	p_5, p_{13}, p_{17}
II	3	converting	sleeve piston – psiton rod	–
	4	preventing	piston rod – wiper ring	–
		preventing	gland – wiper ring	–

Pairs were classified in two levels and four groups. To the first level belongs the first and the second group of pairs which perform the same or similar functions. These pairs are perform fixing function (including 4 pairs) and protecting function (including 10 pairs). The second level is the third and the fourth group of pairs which do not have equivalents (pairs that correspond to the carried out functions). These are the pairs which perform the converting and preventing functions.

Similarity matrix pair – function calculated for each component provides information about the possible modifications of components. It also allows to find and rank the components that perform similar functions.

6. Conclusions

The paper presents the method of similarity matrix FMEA to identify potential failures in the hydraulic cylinder. A set of pairs of interacting components (*p*) has been identified, for which the potential failures (*f*) and function (*e*) was determined. The using of matrices transformation allowed to obtain diagram of function-failure and detect the failure with highest probability of occurrence. Relation between failures and functions has been presented in the diagram function-failure. By the using of matrices similarity a pairs of hydraulic cylinder which perform the same functions have been classified. The calculation on matrices were performed in Mathcad software.

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