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DESIGN FMEA OF HYDRAULIC POWER-STEERING SYSTEM OF LIGHT COMMERCIAL VEHICLES

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SUMMARY

In the first part of paper, next to the description method of Failure Modes and Effects Analysis - FMEA, the history of the development and application of methods with special emphasis on the use of FMEA in the automotive industry is given. Furthermore, the definition and methodological connection of different variants of FMEA method used in the product development phase are presented. The procedure of implementation of the project FMEA method is explained in detail. The determination of the critical elements of a hydraulic power steering of light commercial vehicles in terms of reliability and functional safety is performed by applying design FMEA method. Taking preventive measures to reduce their criticality is the optimal way to increase the reliability and dependability, and by doing that and the quality of the entire system.

Key words: *types of FMEA, design FMEA, motor vehicles, hydraulic power-steering system*

1. INTRODUCTION

Failure Modes and Effects Analysis (FMEA) is one of the basic and the most used method for analyzing the safety and reliability of technical systems [1]. FMEA is basically an inductive method. It is based on consideration of all potential failures of the system's components and their effects on the system. Efficiency of FMEA method application is the greatest if used in the phase of design of mechanical systems by multi-disciplinary team of experts. FMEA may be defined as a systematic group of activities intended to [2, 3, 4]: recognize and evaluate the potential failure of a product/process and the effects of that failure, identify action that could eliminate or reduce the chance of potential failure occurring and document the entire process.

The FMEA was developed for the U.S. military purposes as a technique for assessment of reliability through determination of effects of different failure modes of technical systems [5]. Failures were classified according to their impact on mission success and personnel/equipment safety. This method dates from November 9th, 1949, as an official document in a form of an American military standard. Outside the military, FMEA began to be used in the aircraft and

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space industry [6]. Although FMEA is considered an useful tool for improving product quality, this method is beginning to be used in the automotive industry only in the early seventies. In 1971 Ford Motor Company introduces an internal standard that refers to the FMEA method [7]. In 1994, the Society of Automotive Engineers (SAE) published SAE J-1739, Potential Failure Mode and Effects Analysis In Design (Design FMEA) and Potential Failure Mode and Effects Analysis In Manufacturing and Assembly Processes (Process FMEA Reference Manual) [8].

Motor vehicle's steering system is a mechanical system that has to meet high demands regarding reliability [9, 10]. Steering systems, according to the working principles, can be derived as a mechanical, mechanical with hydraulic servo-amplifier and hydraulic, until power amplifiers can be pneumatic, hydraulic and electric. In order to make the steering of heavy vehicles easier, hydraulic power assisted steering is installed. Hydraulic power assisted steering is the vital subsystem of the motor vehicle's steering system. It presents a typical example of a complex device on motor vehicle, which structure is conditioned by the complex function that this device must conduct [11]. Importance of the motor vehicle's steering system for humans' safety demands a detailed analysis of structural components in the light of the occurrence of the failure during exploitation. Practical application of design FMEA is illustrated with the FMEA of hydraulic power-steering applied in the steering systems of light commercial vehicles. Observed hydraulic power-steering is developed by "Prva Petoletka" company from Trstenik.

2. TYPES OF FMEA IN THE DEVELOPMENT STAGE

From the standpoint of the object of analysis in the product development phase, there are three types of FMEA method [2]: conceptual, design and process FMEA. The same methodology and form for documenting the proceedings, for all three types of FMEA method, is used. Mutual differences are in the object of analysis, the time of implementation, the function of the company that is the holder of activities, etc.

Conceptual or system FMEA is the highest level. This type of FMEA is used to detect and prevent failures of system and sub-systems in the early stages of designing the project. Based on the completed concept, the interaction of subsystem and components within the complex system is considered. Conceptual FMEA is used to confirm that the specification of the designed systems reduces the risk of failure during the design.

Design FMEA is used as an aid to identification and prevention of failures whose causes are directly related to the design of products. The basis for the implementation of the project FMEA is completed design documentation.

Process FMEA is used to identify the causes of potential failure modes that may occur during manufacture or assembling parts or assemblies and to define measures to eliminate identified defects. The basis for this method is completed technological documentation. It should be emphasized that the FMEA process is not limited to technological processes. It is possible to analyze and quantified other processes in a similar way.

A methodological connection among the above procedures FMEA in product development phase is shown in Figure 1. The figure is obtained by generalizing methodological connections of different types of FMEA in the development phase of ignition distributors of an internal combustion engine shown in this paper [12]. According to the figure, process FMEA is based on the results of design FMEA, and it based on the results of conceptual FMEA.

Types of FMEA	Product Process	Function	Failure effects	Failure mode	Cause of failure
Conceptual FMEA	System name	Function of system	Influence on user and environment	Failure of the system	Failure of the component
Design FMEA	Component name	Function of component	Failure of the system	Failure of the component	Process fault
Process FMEA	Process name	Process function	Failure of the component	Process fault	Cause of process fault

Fig. 1 Methodological connection between different types of FMEA in product development phase

The cause - effect chain in Figure 1 represents a hierarchical ladder system's activity: the production process, from the components to the system, i.e. from the causes of failure to failure modes, from the failure modes to its effects, and all that is followed by FMEA method. Figure 1 shows also the sequence of different types of FMEA in product development phase. By the analysis of operation modes of the system it can be reached potential failure modes that result in total or partial failure of the objective function of the system. By detailed analysis of each individual system failure, the causes and effects of those failures can be identified. The causes of system failures are actually failures of its components. The analysis of the failure's causes of components leads to identification of defects in the production process that cause them. Between the conceptual, design and process FMEA strictly separation must be carried out. Transition between these concepts is gradual. It should be borne in mind that only after the determination of the manufacture procedure may estimate risk factors of design FMEA. However, the separation between different types of FMEA is done for reasons of reducing the complexity of the task.

Time coordination of implementation of FMEA methods with other development activities represents one of the crucial factors for the success of the project. Like other developmental processes, FMEA is carried out before the start of production, perfectly respecting the time demands. In order to FMEA become successful, it must be finished before the realization of products or processes. Time synchronization of implementation of different types of FMEA in product development phase enables automatic taking into account the results of previous FMEA and feedback data on changes in projects of products or processes, thus reducing the need for subsequent changes and significantly reduces time and costs of development. The phases of implementation of different types of FMEA as a function of the individual phases of the product life cycle are given in Table 1 [2].

Tab. 1. FMEA timing in the product development cycle

Product development timing	Conceptual FMEA	Design FMEA	Process FMEA
Design concept	Initiate		
Design simulation	Complete	Initiate	Initiate
Detailed design		Update	
Prototype test		Complete	Update
Product launch			Complete
Field usage	Update	Update	Update

Since the FMEA is a "living" document, the term completion marks the end of the first

iterative circle of FMEA and directing obtained results to the FMEA entrance of the next circle to correct. Start of implementation of project and process FMEA is a phase-shifted for the time required for obtaining necessary information from conceptual FMEA.
FMEA should be updated as the project development progresses. All changes in design of products or processes and changes of the initial specifications must be properly reviewed and accompany through the process of FMEA. Properly applied FMEA is an interactive iterative process that never ends. FMEA is a type of document that is constantly adapting to changes that occur in the product development process.

3. PROCEDURE FOR DESIGN FMEA

Systematic of design failure modes and effects analysis in the product development phase is ensured by FMEA operation plan [12], which is the base for formulation of the flowchart of the procedure for application of project FMEA method [13]. According to the presented flowchart, application of design FMEA method goes through the following phases:
1. Creating of FMEA team. Organisation of work on FMEA and appointment of responsible person (leader) for FMEA team creation in the company are defined by corresponding instruction. For construction FMEA, FMEA team leader comes from product design department and for process FMEA, FMEA team leader comes from technology design department. Selection of other team members is done by agreement between the person responsible for creation of the FMEA team and the heads of the technical departments from which team members are appointed.
2. Work plan and preparation for analysis are of the outmost importance for successful conduction of the FMEA procedure. In the preparation phase, the team leader acquaints the FMEA team members with the structure of the observed system and its operation modes using corresponding documents (design assignment, basic data on product and its structure, technical conditions, design documentation and other). After having been acquainted with the object of the analysis, each team member, in his further work, prepares relevant documentation and information on the subject of the analysis from the area that his functional unit covers in the company. Based on gathered information, each team member reaches his own conclusions.
3. Analysis of potential failures. By systematic analysis of the operation modes and functional parameters of individual components of the system, all possible influences on system operation, possible causes and effects of the system component's failure are detected. Identification of potential failure modes may be conducted by application of Fault Tree Analysis - FTA or by using Ishikawa chart. For the purpose of assessment of failure risk, it is necessary to record scheduled control measures for failure cause detection in this phase.
4. Project assessment. Team evaluation of occurrence rating of the failure mode, *O*, severity rating of failure effects (weighting factor), *S*, and detection rating for a potential failure mode, *D*, and calculation of risk priority number, *RPN*, as their product, is conducted in the project assessment phase, based on acquired data on every cause-failure couple. By ranking of calculated values for risk priority number and by adoption of criteria for failure acuteness, a basis for dispatching priority for conducting measures for quality improvement is made.
5. Work on quality improvement. For every critical failure mode, preventive/corrective measures are proposed in order to reduce some or all risk factor values. Persons responsible for conduction of these measures are selected and deadlines for their execution are set. Invention of quality improvement measures should be obtained in multidisciplinary working groups, with application of corresponding creativity techniques.
6. Assessment of preventive/corrective measures effects. After quality improvement

measures are introduced, the FMEA team has a task to establish the effects of their application, by assessment of new risk factors values using the same assessment criteria. FMEA analysis concludes if adopted acuteness criteria are met, both for individual risk factor values and for total risk. If, even after introduction of quality improvement measures, the risk factor values are larger than adopted limit values, new measures are defined and conducted until the assessment values are satisfactory.

7. FMEA documentation. A blank form is used for FMEA documentation and it is fulfilled parallel with conduction of individual phases of the procedure. Every change in the project must be followed by FMEA documentation change.

4. DESIGN FMEA OF THE ELEMENTS OF HYDRAULIC POWER-STEERING

Design FMEA procedure for power steering is conducted according to the operating plan. To perform a design FMEA there are two requirements. The first requirement is the identification of the appropriate form. The second requirement is the identification of the rating guidelines. For processing and presentation of data, it was used FMEA form (Table 2) which was created by synthesis a number of forms for FMEA in product development phase that can be found in the literature. This form can be used for design and process FMEA. Assessment of risk factors was done according to criteria of the standard SAE J-1729 [8].

At the first step of the FMEA procedure, a FMEA team is formed with representatives from the design department of the observed system, department of corresponding technology design, department of product quality control and service department. At the second phase, acquisition and detailed analysis of documentation and enormous literature on research object are conducted. Gathered documentation related to the structure, way of functioning and comparative analysis of different design solutions of hydraulic power-steering systems, should be a constituent part of FMEA documentation.

For design FMEA, based on the manufacturer's documentation [14], it is necessary to record and code all constituent parts of the observed object. Since the conception of the FMEA procedure allows the analysis to be conducted at any system division level, the structural parts were considered at the assembly level in design FMEA of hydraulic power-steering. Only parts, which failure leads to the total failure of the steering system of the motor vehicle, were considered at the lowest structural level – the level of elements (worm shaft, segment shaft and power-steering lever). The names of the observed parts and corresponding keys are given in the first column of the FMEA form in Table 2.

Categories of potential failure modes (CF) are written in the second column of the FMEA form. Roman number I denotes component failure modes that lead to total failure of the steering system of the motor vehicle or to the total or partial reduction of the power-action. Number II denotes failure modes that cause the occurrence of gaps in the steering system or degradation of other operating features of the assembly. Failure modes that lead to slow leakage of oil are denoted with III.

Results of the FTA are used for recording of the potential failure modes of the hydraulic power-steering with installation [15]. Basic events in source fault tree and corresponding independent sub-trees present the primary and the secondary failures of the hydraulic power-steering with installation components. Data given in the third column of FMEA form are obtained by grouping the basic events by components. Causes and effects of potential failure modes are determined by detailed analysis of potential failure modes of the observed components. Individual failure modes of constituent parts of the observed object have several causes and effects. Only the most frequent causes and effects are given in corresponding columns of the Table 2.

Planned control measures for detecting the failure causes in individual phases of design and mounting procedures for hydraulic power-steering parts are written in the FMEA form column selected for scheduled control measures.

Copies of partially filled FMEA form with previously mentioned data have been given to the rest of the FMEA team members for detailed analysis and giving suggestions regarding corrections of the gathered data. Afterwards, joint meeting of all FMEA team members has been organised, at which the gathered data were brought up to date and risk factor evaluations were coordinated. Final risk factors evaluation and calculated value of risk priority index are given in Table 2 within the cell for evaluation of the existing state.

After all necessary data were gathered, ranking of potential failure mode causes according to risk priority number has been done using the computer program. Since the ranking of potential failure mode causes is done from the highest to the smallest value of the risk priority number RPN, only the initial part of the output list of the design FMEA program is used most frequently for further analysis. Hence, only the first page of the list is given in the paper as Table 3. Based on Table 3, the highest value of risk priority factor belongs to porosity of the power-steering casing emerged from defective manufacturing. The second place belongs to the non-hermetic of intake connections caused by loose links. Non-adjustment of the control distributor due to defective coil pins for centring is in the third place. The fourth place belongs to fracture of pipes and hoses due to defective manufacture. Different failure modes of vane pump elements, most frequently caused by the existence of residual metal chippings and send coming from casting in oil or by defective mounting, come next.

If oil is regularly controlled and added, slow oil leakage due to porosity of the power-steering casing or due to loose links between pipe and hose connections, do not lead to hydraulic system failure. However, pedantic statisticians have calculated that even the oil leakage in hydraulic systems measured in drops may lead to greater loss of material means in a longer period of time. Besides, oil leakage creates a bad picture of a product and of the producer and leads to environmental pollution.

Defective manufacture of the power-steering casing, having the risk priority number RPN = 144, belongs to the group of high risk failures, according to criteria given at the bottom of the first page in Table 3. For $S = 4$, critical risk values are $R_{crit} \geq 120$, based on approximate values of intervention limits depending on failure severity of effects. Based on previous discussion, both criteria imply the necessity of taking measures in order to reduce risk priority number value of occurrence of casing porosity. Thus, a potential problem has been detected. In order to rich its solution, it is necessary to conduct detailed analysis of casing manufacture procedure, that is, it is necessary to conduct process FMEA.

The rest of potential failure mode causes for hydraulic power-steering components have medium and low risk levels and, according to that criterion, they do not demand taking into consideration and introduction of preventive measures. However, according to criterion of approximate values for intervention limits depending on failure effect weight, critical risk values for shaft fracture and seizing of bearings, having the risk factor $S = 9$, are $R_{crit} \geq 40$. Since their value of risk priority number is $RPN = 72$, it is necessary to introduce preventive measures in order to reduce the risk. According to individual risk factor values, the reduction of the risk priority number may be easily influenced by more strict control of the cleaning procedure of the parts prior to mounting, which increases the possibility to detect the failure cause. Thus, the value of the risk priority number is reduced below the intervention limit.

Based on the complete output list with ranked potential failure mode causes and according to the risk priority index, it may be seen that fractures of power-steering parts which lead to the total failure of the steering system, have small values of total risk *RPN*, even with maximal risk factor S = 10. It is achieved due to a long-standing production and constant improvement of critical parts of hydraulic power-steering systems similar in design.

According to technical conditions for receipt and testing of power-steering [14], mounting is conducted with the use of predicted tools and devices and only with parts that completely correspond to design documentation. The mounting order and demands given by design documentation regarding clearance, jamming torque, etc., must be strictly followed.

Demands given by design documentation regarding position and jamming torque for connection elements must be strictly followed during mounting of power-steering in vehicle. Mounted power-steering must not be subjected to bending. Also, power pump must not be mounted obliquely, because it leads to considerable reduction of pump bearings life-time and increased wearing of fan belts. System components must be positioned at sufficient distance or isolated from heat sources, so the oil would not be heated too much. Maximal allowed oil temperature is 100^{o}C.

Purity of the operating fluid – oil is of great importance for reliable and safe operation of hydraulic power-steering. Presence of metal particles, dust and other impurities in oil is the basic cause of a great number of basic events at the fault tree of hydraulic power-steering with installation and it gives a special importance to oil filtering. According to the producer's maintenance instructions, it is necessary to change oil and oil filter after certain distance in kilometers is passed which depends on a type of hydraulic power-steering.

5. CONCLUSIONS

Application of FMEA method in the phase of development of mechanical systems enables scientific foundation of problem solving consisting of: detection and identification of potential failure modes and defects, determination of their causes, creation of the base for suggestion of preventive or corrective measures for overcoming the problem and definition of quantitative indices that confirm the success of application of adopted measures. Determination of critical elements of mechanical systems that limit reliable and safe operation of the system and taking of preventive measures in order to reduce the acuteness present the fastest and the cheapest way to increase reliability and, accordingly, the product's quality.

Use value of FMEA results is in proportion to volume and credibility of starting data. This points to need that every company should form information system for acquisition and processing of data on errors, defects and failures of company's products. Organised system for data acquisition must provide continuous data flow, their processing and availability. In order to get complex and credible database on modes, causes, effects and operation periods before failure of mechanical systems or elements occurs, data must be collected from the design phase, development phase and from product's exploitation.

As it is well known, reliability of mechanical systems is based in design phase, provided in manufacture phase and realised in exploitation process. That is why it is equally important to anticipate measures in the areas of production and exploitation in accord with the efforts made in the phase of development of mechanical systems in order to provide its reliable and safe operation.

Tab 2. Design FMEA of hydraulic power-steering

"PRVA PETOLETKA" TRSTENIK	**FMEA** ☒ - Design ☐ - Process	☒ - New product/process ☐ - Optimization ☐ - Problem analysis	Product name: Hydraulic power-steering Model/System/Making:	FMEA Number: D001
			Drawing number: 5033 975 100	Page/Pages: 1/5
	Org. unit/deliverer: D. D. "Servoupravljaci"	Person in charge:	Ordinal number/Last modification date:	Created: I 15. 11. 2008. II 11. 02. 2009.

Product Component / Process Operation	CF	Potential failure: Modes	Potential failure: Effects	Potential failure: Causes	Current state: Current controls prevention	O	S	D	RPN	Recommended actions	Responsibility and realisation dynamics	Action results: Actions taken	O	S	D	RPN
Oil reservoir 61110.00	I	Reservoir exploding.	Intensive oil leakage (total loss of servo-power).	1.Carbody vibration. 2.Residual stresses in welded joints.	Normalization control after welding.	3 1	7 7	1 5	21 35							
	III	Porosity of welded joints.	Slow oil leakage.	Defective making.	Porosity testing.	2	4	5	40							
	II	Filter filthiness.	Reduction of device efficiency, air intake, damage of gasket elements and operating noise.	1. Badly cleaned installation during mounting. 2. Untimely oil change. 3. Disregard at oil pouring.	Control of cleaning of parts before mounting. Remark in maintenance instruction.	3 5 2	5 5 5	4 2 2	60 50 20							
	II	Air vent closed.	Mixing of oil and air (heavy operation pf device).	1. Deformation due to impact. 2. Filthiness due to atmospheric dust.	Control of the mounting place of reservoir in vehicle.	2 3	4 4	1 1	8 12							

Occurrence probability	O	Severity	S	Detection probability	D	Risk assessment: Eval.	Risk assessment: RPN	FMEA team: Participants	FMEA team: Functions
None	1	Negligible	1	Very large	1				
Small	2÷3	Small	2÷3	Large	2÷5	Low	1÷50	Nastic R.	devel. chief
Medium	4÷6	Medium	4÷6	Medium	6÷8	Medium	50÷100	Pantic R.	institute dir.
Large	7÷8	Large	7÷8	Small	9	Large	100÷200	Andric M.	q. c. chief.
Very large	9÷10	Very large	9÷10	Negligible	10	Critical	200÷1000	Trifunovic V.	service chief

Tab. 3. Results of ranking of potential failure mode causes according to risk priority number

"PRVA PETOLETKA" TRSTENIK	FMEA ☒ - Design ☐ - Process Org. unit/deliverer: D. D. "Servoupravljaci"			☒ - New product/process ☐ - Optimization ☐ - Problem analysis Person in charge:					Product name: Hydraulic power-steering Model/System/Making: Drawing number: 5033 975 100 Ordinal number/Last modification date:		FMEA Number: D001 Page/Pages: 1/5 Created: I 15. 11. 2008. II 11. 02. 2009.				
Product Component / Process Operation	CF	Potential failure			Current state							Action results				
		Modes	Effects	Causes	Current controls prevention	O	S	D	RPN	Recommended actions	Responsibility and realisation dynamics	Actions taken	O	S	D	RPN
Power-steering casing 61210.00	III	Casing porosity.	Slow leakage of oil.	Defective manufacture.	Porosity testing.	6	4	6	144	FMEA of process						
Parts of hydraulic installation 61100.01-22	III	Non-hermetic connections of intake.	Slow leakage of oil and air intake.	Loose link between connections.	Periodical control of jamming torque.	3	5	6	90							
Piston 61240.00	I	Non-adjustment of control distributor.	Occurrence of clearance in the steering system or self activation of device.	Damaged coil pin for centring.	Control of pin hardness on a cone.	2	6	7	84							
Parts of hydraulic installation 61100.01-22	I	Fracture of pipes or hoses.	Intensive oil leakage.	Defective manufacture.	Reception control.	2	8	5	80							
Vane pump 61120.00	I	Shaft fracture.	Total failure of vane pump.	Seizure of vane pump elements.	Checking of cleaning procedure of parts before mounting.	2	9	4	72	Enhanced control.	Product quality control division.	Increased number of controllers.	2	9	2	36
Vane pump 61120.00	I	Seizure of bearings.	Aggravated operation of vane pump.	Residual metal chippings and sand coming from casting in oil.	Checking of cleaning procedure of parts before mounting.	2	9	4	72	Enhanced control.	Product quality control division.	Increased number of controllers.	2	9	2	36
Vane pump 61120.00	I	Valve failure.	Aggravated or to easy turning of steering wheel.	Residual metal chippings and sand coming from casting in oil.	Checking of cleaning procedure of parts before mounting.	3	6	4	72							
Vane pump 61120.00	III	Casing porosity.	Slow oil leakage.	Defective manufacture.	Porosity testing.	3	4	6	72							

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