FUZZY FAILURE MODES AND EFFECTS ANALYSIS (FMEA) FOR HYDROSTATIC TRANSMISSION SYSTEM (HTS)

Velibor Karanović [1] [ORCID 0000-0002-4208-0411], *Marko Penčić* [1] [ORCID 0000-0002-2244-5698], *Mitar Jocanović* [1] [ORCID 0000-0003-1088-5028], *Maja Čavić* [1] [ORCID 0000-0002-3663-8458]

[1] *University of Novi Sad, Faculty of Technical Sciences, Department of Industrial Systems and Management, Novi Sad*

[2] *University of Novi Sad, Faculty of Technical Sciences, Department of Mechanization and Design Engineering, Novi Sad*

Abstract: *Hydrostatic transmission system (HTS) is a crucial part of mobile working machines, which uses pressurized fluid to transmit power from the engine to the wheels or tracks and provides precise and efficient control over the machine's speed, torque, and direction. When the transmission system works improperly, productivity and/or safety can be highly impacted. This paper focuses on the identification, risk assessment, and prioritization of potential failure modes for the HTS with split configuration, to serve as a foundation for maintenance strategy to minimize or eliminate adverse effects and ensure safety. To analyze and rank all improper HTS working modes, a fuzzy Failure Modes and Effects Analysis (FMEA) method is applied. There are determined 11 HTS failure modes with their causes-effects, and Occurrence (O), Severity (S), and Detectability (D) scores were assigned with the help of experts. Using a base of 125 rules and a fuzzy FMEA model, the failure modes were prioritized based on calculated Risk Priority Numbers (RPN).*

Key words: Failure modes and effect analysis, fuzzy FMEA, maintenance, hydrostatic transmission system (HTS), closed hydraulic circuit

1. INTRODUCTION

The transmission system is used to transfer power from the engine to the wheels or tracks, enabling the machine to perform various tasks efficiently by transmitting the necessary torque and controlling the speed and direction of movement (Chen, 2020). This makes the transmission system one of the most important parts of any vehicle or moving machine. The design, durability, reliability, and performance of the transmission system can significantly impact the overall machine operation efficiency, safety, and productivity, which is why there is continuous development of transmission systems between manufacturers. There are several transmission types such as manual, automated, continuously variable, dual-clutch, automated manual, hydrostatic, electric, and hybrid transmissions (Chen, 2020). Each type of transmission has its own specifics, which makes it suitable for certain applications.

Hydrostatic transmission systems (HTS) have a compact design and well-proven performances, which suits them well for propulsion control of heavy-duty off-road machinery such as agricultural, mining, quarry, forestry, and earth moving (Singh et al, 2013), (Guo and Vacca, 2021.). Basically, the HTS is a closed hydraulic circuit system consisting of an axial-piston pump directly connected to a hydraulic motor, which greatly simplifies transmission system design and contributes to higher system reliability.

In order to justify the high installation costs, and ensure safety, and a long operational life, it is necessary to regularly carry out adequate maintenance. Failure causes and their effects can be identified meticulously using Failure Modes and Effects Analysis (FMEA) method, well-proven reliability tool.

This paper presents a comprehensive attempt to analyse possible HTS failure modes and prioritize them in order to propose adequate preventive maintenance actions which should be taken to avoid expensive shutdowns and repairs.

2. MATERIAL AND METHOD

2.1 HTS design

There are two basic configurations of the HTS:

- Integrated (or close-coupled) which physically can be connected in the form of an In-line, U-shaped, or S-shaped configuration;
- Split (non-integral) configuration.

Integrated HTS solutions, in general, are suited for light-duty applications (such as garden tractors, logistics, transportation vehicles, etc.), while split HTS configuration is mainly intended for heavy-duty off-road machinery (Zarotti, 2003). This paper will focus solely on split systems, which can typically be implemented in four configurations, of which the configurations with a variable displacement axial-piston pump and a variable or fixed displacement motor are the most commonly used. A typical HTS hydraulic circuit is shown in Figure 1.

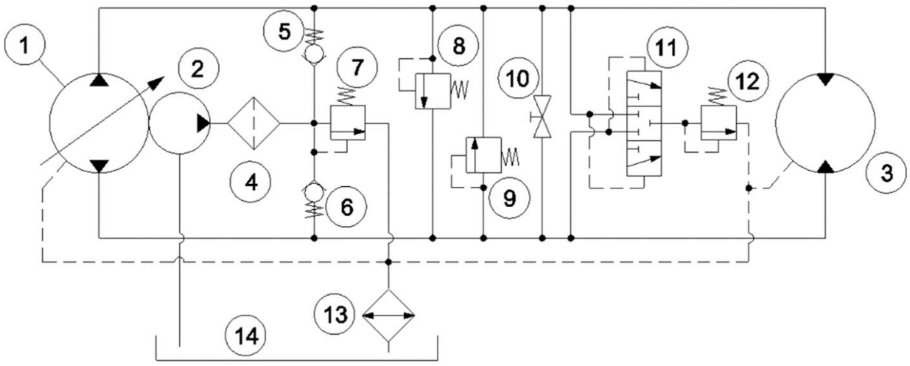

Figure 1: The basic design of the HTS hydraulic system

Basically, the HTS consists of an axial-piston pump (1) which is mechanically connected to the prime mover (IC engine), axial-piston motor (3) which is connected to the wheel shaft(s), filter (4), makeup check valves (5, 6), charge pump relief valve (7), cross port pressure relief valve (8, 9) for pressure overload protection, towing (bypass) valve (10), hot oil flush (shuttle valve) valve (11), flushing relief valve (12), oil cooler (13), and a reservoir (14). Unlike the open-circuit axial-piston pump, the closed-circuit pump (1) is the one that must have a charge pump (2). The charge pump is the vital component of the closed hydraulic circuit system and it has several functions: fluid replenishment, sufficient fluid supply on the low-pressure side of the pump in order to prevent cavitation, fluid filtration, to enable activation of pump servo controls, and in some cases to enable auxiliary functions (such as parking brakes control) with providing pressurized fluid. All valves shown in Fig. 1, are usually integrated into the pump or the motor housing which contributes to the compactness of the HTS.

2.2 Expert profiles

In FMEA experts play a crucial role in identifying potential failure modes, their causes, effects, and the effectiveness of existing or proposed mitigation measures. The experts' insights and experience are valuable in evaluating the severity, occurrence, and detection ratings for each failure mode, which are key factors used to prioritize and determine the level of risk associated with different failure modes. The experts who took part in this study have 5+ years of working in the field experience, in different companies (construction, agricultural company, and academy), and all of them have mechanical engineering degrees. Regardless of the type of machine (excavator, loader, tractor, self-propelled mobile working platform, etc.), all engaged professionals worked with a split configuration HTS, featuring a variable swash-plate axial pump and a fixed swash-plate axial motor. Thus, no weight was assigned to them during the rule-based fuzzy FMEA calculation.

2.3 FMEA

One of the most used methods for the identification and analysis of failures, in order to propose measures to prevent them, is FMEA. It provides a systematic approach to identifying, analysing, and prioritizing failure modes to develop preventive maintenance actions (Liu et al, 2016). FMEA is widely used in industries such as automotive, aerospace, manufacturing, healthcare, and many others to improve product reliability, quality, and safety. In order to prioritize which failures should be managed first, FMEA uses Risk Priority Number (RPN) which is obtained by multiplying Occurrence (O), Severity (S), and Detectability (D) scores, previously determined by experts.

2.4 Fuzzy FMEA

Although FMEA is a popular risk assessment method, it also has its drawbacks and limitations and has been criticized by researchers:

- The assumption that the three failure mode indexes (O, S, and D) are all equally important (Franceschini and Galetto, 2001);
- Different combinations of S, O, and D levels can yield the same RPN, but the associated risk implications might vary significantly, potentially leading to critical failures being overlooked (Liu et al, 2014);
- The RPN scale exhibits non-intuitive statistical characteristics. While it is commonly assumed that the scale starts at 1 and ends at 1000, this often results in erroneous assumptions about the middle of the scale (Seyed-Hosseini et al, 2006);
- The Risk Priority Number (RPN) is solely determined by multiplying the input elements, neglecting any indirect correlations between these components (Yazdi et al, 2017).
- Subjective input data and results (Liu et al, 2016).

In the literature (Ceylan, 2023), (Ahmed and Gu, 2020), (Balaraju et al, 2019), a fuzzy FMEA is employed to address the aforementioned limitations. Generally speaking, fuzzy logic is introduced to enhance decision-making systems, particularly in situations where traditional binary logic or deterministic models may fall short due to uncertainties and imprecise data. It finds applications in various fields, such as control systems, artificial intelligence, data analysis, and decision support systems.

Fuzzy logic had an algorithm that contains the following steps: 1) Define input and output variables; 2) Linguistic variable definition; 3) Membership function design; 4) Rule base construction with AND, OR, NOT operators; 5) Fuzzification; 6) Rule evaluation and aggregation; 7) Defuzzification.

The study is structured around four primary steps (Figure 2). The first step contains the detection of failure modes, and possible causes and consequences. The second step includes the selection of the inference engine, input-output membership functions, and the construction of the study's rule base. The third step implies O, S, and D ranking by experts and fuzzy RPN calculation, and finally, the fourth step is the prioritization of failure modes.

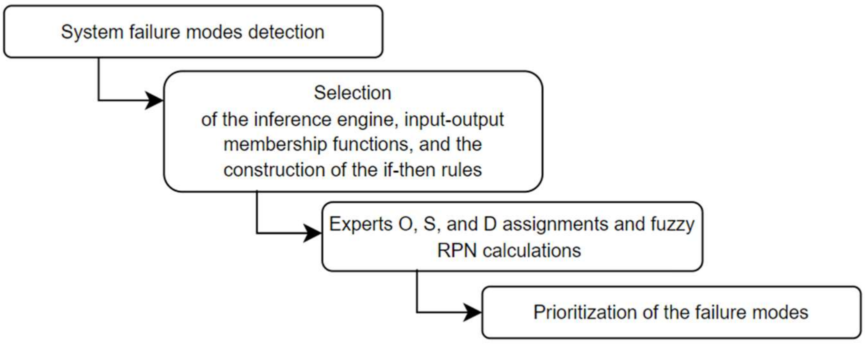

Figure 2: The methodical approach of the study

3. HTS FAILURE MODES AND EFFECTS ANALYSIS

This section presents, the implementation of the systematic approach to the HTS. As a result, fuzzy RPN values for every HTS failure scenario are calculated, and a ranking of failure modes was performed.

3.1 Failure modes

The HTS is the subsystem responsible for delivering engine power to the wheels of mobile machinery. Accordingly, any malfunction of this subsystem affects the safety and productivity of the machine. Therefore, this section defines potential failure modes, factors that can cause them, and their consequences, with the help of experts. HTS failure modes, causes, and effects are shown in Table 1.

Table 1: HTS failure modes, possible causes, and effects

Code	Failure mode	Possible cause	Effect
FM01	Insufficient system pressure	Problem with crossport relief valve (8, 9); Excessive internal or external fluid leaking; Open towing valve (10); Improper swash plate angle regulation, …	Inability to develop the proper torque and move the mobile machine
FM02	Excessive peak pressure	Crossport relief valve not functioning properly; Defective pump/motor compensator; Servo pressure too low to maintain firm control; Excessive decompression energy rates (improper hoses size), …	Heating of hydraulic oil, noisy working of the HTS

FM03	Insufficient pump outlet flow	Excessive internal or external fluid leaking; Open towing valve (10); Improper swash plate angle regulation (1); Problem with a hot oil shuttle valve (11); Defective hoses and/or connections; Problem with charge pump (2); Pump cavitation, …	Inability to achieve operational wheels speed
FM04	No system power, no pressure or flow	Damaged drive shaft; Damaged coupling; Prime mover doesn't work; Wrong direction of rotation; Charge pump (2) suction line clogged or disconnected; Low fluid level in the reservoir, …	No operation
FM05	The system works only in one direction	Problem with crossport relief valve (8,9); Problem with swash plate control valve; Problem with makeup check valve (5,6); Control input malfunction (hydraulic, mechanical, or electrical); Problem with a hot oil shuttle valve (11), …	Inability to safely and properly operate with mobile machine
FM06	System starts prematurely	Mechanical neutral position not set correctly; Hydraulic neutral position not set correctly; Control input malfunction (hydraulic, mechanical, or electrical), …	Extremely high safety risk
FM07	Excessive noise and/or vibrations	Air/foam in fluid; Low fluid level in the reservoir; Obstruction present in suction line; Pump cavitation; Improper fluid viscosity; Excessive wear or damage of the charge pump; Bearing damage; Piston ball is loose in piston shoe socket; Excessive wear on Fulcrum ball and socket of shoe retainer…	Stressed components with higher failure rates, heating of hydraulic oil, and unpleasant noisy working of the HTS
FM08	System is overheating	Excessive loads; Low fluid level in the reservoir; Problem with heat exchanger-clogged; Clogged inline pressure filters (4); Crossport relief valve (8,9) leaking or regulating continuously; Excessive pump and motor case drain; Open towing valve (10); External heat source too close to pump; Flushing flow too low…	Inadequate lubrication, increased wear, excessive leakage, underrated motor speed
FM09	Unresponsive or sluggish (or erratic) system control	Problem with charge pump (2); Problem with charge pump relief valve (7); Problem with hot oil shuttle relief valve (11); Control input malfunction (hydraulic, mechanical, or electrical); Swash block and/or saddle bearings worn or damaged; Partially activated towing valve (10); Contaminated, degraded or unsuitable fluid…	Unstable control
FM10	Irregular or unsteady operation	Problem with charge pump (excessive wear or damage…); The suction line is not sealed properly; Obstruction present in suction line; Worn swash block; Control input malfunction (hydraulic, mechanical, or electrical); Crossport relief valve (8,9) not regulating properly; Faulty output circuit components (cylinder, motor) …	Significantly lower productivity, and compromised safety
FM11	Leakage from the shaft seal	Case drain pressure is too high; Seal is worn or damaged; Improper shaft alignment	Loss of system fluid

3.2 Failure modes

After identifying the failure modes, causes, and consequences of the HTS, the experts allocated scores for O, S, and D as documented in Table 2. Ratings for O, S, and D range from 1 to 10.

Table 2: Rankings provided by experts for O (Occurrence), S (Severity), and D (Detectability)

Code	Failure mode	Expert 1			Expert 2			Expert 3		
		O	S	D	O	S	D	O	S	D
FM01	Insufficient system pressure	3	3	1	5	6	1	2	2	2
FM02	Excessive peak pressure	2	10	3	3	8	5	3	8	3
FM03	Insufficient pump outlet flow	4	5	4	5	5	6	4	3	4
FM04	No system power, no pressure or flow	4	4	1	1	5	1	1	3	1
FM05	The system works only in one direction	3	5	1	1	4	1	1	3	1
FM06	System starts prematurely	5	10	1	2	8	1	1	10	1
FM07	Excessive noise and/or vibrations	7	8	2	2	10	4	3	9	1
FM08	System is overheating	6	10	5	7	10	6	3	9	2

FM09	Unresponsive or sluggish system control	4	5	1	2	2	2	2	3	1
FM10	Irregular or unsteady operation	3	10	2	1	6	3	2	10	1
FM11	Leakage from the shaft seal	8	2	7	3	2	9	2	1	6

**For O a rating of 1 indicates a very low likelihood of occurrence, and 10 signifies an unavoidable event; for S a rating of 1 signifies negligible impact, while a rating of 10 implies catastrophic consequences; for D, a rating of 1 means the event is easily detectable, while a rating of 10 indicates that the event is very difficult to detect.*

3.3 Input-output membership function, inference engine selection, and rule base

The study's fuzzy model comprises three input variables (O, S, and D) and one output (fuzzy RPN). The fuzzy logic system utilizes various membership functions, such as triangular, trapezoidal, and Gaussian membership function. While the triangular membership function is frequently chosen in fuzzy logic due to its simplicity, interpretability, and versatility, the Gaussian membership function enables higher smoothness of the transition. For the study, a 5-level Gaussian input and output membership function was employed which comprises very low, low, medium, high, and very high levels.

In fuzzy logic, an inference engine is a crucial component of a fuzzy system that processes the fuzzy rules and input data to generate meaningful output. In order to establish the fuzzy model, the Mamdani inference engine was utilized in this study. It is widely adopted across various applications due to its intuitive and linguistic approach to handling uncertainty and imprecision and allows easy integration of human expertise and knowledge into the fuzzy system's decision-making process.

Rules are of utmost importance in fuzzy logic modeling as they form the foundation for making decisions in systems that deal with uncertainty and imprecision. The rule base has 125 rules, defined by experts involved. Each rule is an "if-then" statement that describes a condition based on the input variables and specifies the corresponding output action.

3.4 Fuzzy RPN results

Based on the scores provided by the experts for O, S, and D, the mean values were calculated, which were input into the fuzzy model to compute the fuzzy RPN values given in Table 3.

Table 3: Average O, S, and D values, and calculated RPN and fuzzy RPN values

Code	Average values			RPN	Fuzzy RPN
	O	S	D		
FM01	3,33	3,67	1,33	16,30	3,08
FM02	2,67	8,67	3,67	84,74	4,85
FM03	4,33	4,33	4,67	87,63	4,45
FM04	2,00	4,00	1,00	8,00	2,39
FM05	1,67	4,00	1,00	6,67	2,36
FM06	2,67	9,33	1,00	24,89	4,36
FM07	4,00	9,00	2,33	84,00	4,18
FM08	5,33	9,67	4,33	223,41	6,82
FM09	2,67	3,33	1,33	11,85	2,54
FM10	2,00	8,67	2,00	34,67	3,71
FM11	4,33	1,67	7,33	52,96	2,57

3.5 Prioritization of failure modes

The last step in the methodological approach of this study is the prioritization of failure modes based on calculated fuzzy RPN values. In Figures 3 and 4, the prioritization of failure modes is presented graphically. The top failure mode according to traditional FMEA and fuzzy FMEA is FM08 – overheating. Due to the operating conditions with heavy-duty off-road machines, it often happens that this phenomenon is not detected in time, and it is ranked high because the consequences can be catastrophic for the hydraulic system of the HTS. Failure modes FM02 and FM03 have switched positions, but using the logic of the defined fuzzy model, it has been concluded that the high severity rating (S factor) for FM02 takes precedence over the product of OSD factors for FM03. Therefore, FM02 is ranked second on the fuzzy FMEA list. A similar situation applies to failure modes FM06 and FM07, where the fuzzy model, due to greater consequences (despite the infrequent occurrence of this failure), ranked FM06 failure in fourth place. Furthermore, it can be observed that failures FM06 and FM11 have different positions, while the positions of the others remain the same on both diagrams.

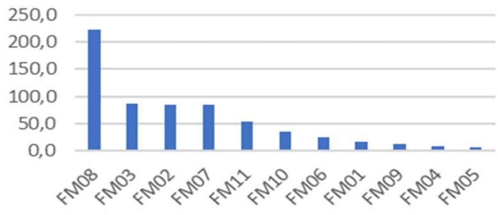

Figure 3: Failure mode prioritization by RPN

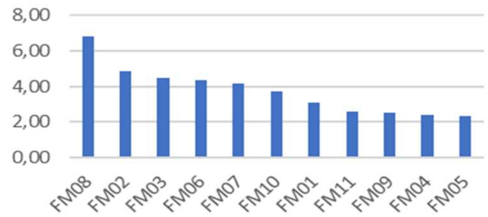

Figure 4: Failure mode prioritization by fuzzy RPN

4. CONCLUSION

The paper deals with the hydrostatic transmission system failure modes identification and prioritization by using the fuzzy FMEA method. The results obtained using the fuzzy FMEA method slightly deviate from the results obtained through the implementation of the traditional FMEA method. However, this approach has minimized subjectivity in assessing failure modes and reduced the disparity in calculated RPN values. According to the results top failure is system overheating (FM08), so analysis of failure causes is the next step which should be conducted by maintenance personnel in order to eliminate or minimize the risk of failure. Also, this study can be extended by using the same approach on other critical parts of heavy-duty off-road machines.

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