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RELIABILITY ANALYSIS OF ELECTROHYDRAULIC SERVO VALVE SUFFERING COMMON CAUSE FAILURES

ANALIZA NIEZAWODNOŚCI SERWOZAWORU ELEKTROHYDRAULICZNEGO NARAŻONEGO NA USZKODZENIA SPOWODOWANE WSPÓLNĄ PRZYCZYNĄ

The electrohydraulic servo valve (EHSV) is widely used in many engineering fields. Its reliability is of great importance to the reliability and safety of entire servo control systems. With the aim of analyzing and evaluating reliability of EHSV, this paper firstly presents the physical structure and functional principle of EHSV. It is followed by the Failure Mode, Effects and Criticality Analysis (FMECA). From the analysis, the common cause failures (CCF) in the studied EHSV are identified. Lastly, a method that can quantitatively analyze reliability and failure rate of EHSV with considering the common cause failures is proposed. It is observed from the study that the failure rate of the EHSV with CCF is lower than the failure rate without considering CCF.

Keywords: *EHSV, common cause failures (CCF), FMECA, β-factor model.*

Serwozawory elektrohydrauliczne (EHSV) mają szerokie zastosowanie w wielu dziedzinach inżynierii. Ich niezawodność ma decydujące znaczenie dla niezawodności i bezpieczeństwa całych układów sterowania serwomechanizmami. W celu analizy i oceny niezawodności zaworów EHSV, w pracy przedstawiono najpierw ich budowę fizyczną i zasadę działania. Następnie przeprowadzono analizę przyczyn, skutków i krytyczności uszkodzeń (FMECA). Na podstawie tej analizy określono uszkodzenia zaworu EHSV spowodowane wspólną przyczyną (CCF). Wreszcie, zaproponowano metodę, za pomocą której można ilościowo analizować niezawodność i awaryjność EHSV z uwzględnieniem uszkodzeń spowodowanych wspólną przyczyną. Badania wykazały, że awaryjność EHSV przy uwzględnieniu CCF jest niższa niż w wypadku nieuwzględnienia CCF.

Słowa kluczowe: *serwozawór elektrohydrauliczny (EHSV), uszkodzenia spowodowane wspólną przyczyną (CCF), analiza przyczyn, skutków i krytyczności uszkodzeń (FMECA), model współczynnika β.*

1. Introduction

The electrohydraulic servo valve (EHSV) is a core component of servo control systems. Due to its advantages such as high level of control precision, quick response, light weight, small volume and high immunity to load variations, EHSV has been applied in many fields, such as astronavigation, aviation, navigation, and military equipment [5, 6, 13]. At the same time, EHSV is one of the most failure prone components, and has a direct and significant impact on the performance and reliability of the entire servo control system. Thus, it is very important to analyze the failure mode, failure effects, failure mechanism and failure rate of EHSV.

The Failure Mode, Effects and Criticality Analysis (FMECA) is effective for reliability analysis and has been used in many products. It can be applied in different life stages of product to find the defects and weak components and to provide basis information for the further reliability analysis [6, 18].

In most studies, it is assumed that failures of different components are independent random events. Such assumption is valid in most cases for electronic devices, but invalid for mechanic products. Common causes failures are multiple failures which are exist at the same time and are a direct result of a shared root cause [20]. Considering that common cause failure would result in a more reliable and accurate analysis [15].

2. Working principle of EHSV

There must be a bridge component in combination of electric and hydraulic device. This interface connection in servo control system is achieved by electrohydraulic servo valve. Such servo valve converts low power electrical signals into motion of a valve which in turn controls the flow and pressure to a hydraulic actuator [16].

The two-stage nozzle flapper electrohydraulic servo valve is the most widely used one[5], as shown in Fig1. Thus, this paper takes it as an example to introduce the working principle of EHSV and conducts the reliability analysis in the ensuing sections. The torque motor, consisting of permanent magnet, armature, spring pipe and feedback rod, is used as electric-mechanic transducer. The nozzle flapper is the first stage hydraulic amplifier, and the spool valve is the second stage hydraulic amplifier.

A servo valve has a hydraulic pressure inlet and an electrical input for the torque motor. The input current controls the flapper position. A small flapper motion creates an imbalanced pressure in one direction or the other on the ends of the spool of the second stage. Obviously the spool will tend to move in response to this imbalance and allow flow Q_L to the actuator. Since continued imbalance in pressure would quickly move the spool to its limits of travel, a form of feedback connects the motion of the spool to the effective displacement of the flap-

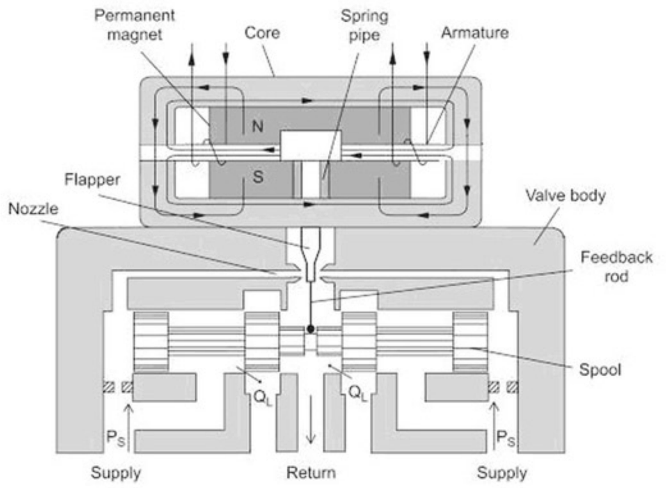

Fig. 1. The schema of EHSV

per. A very small spool displacement will result in a large flow at high pressures typically used.

From reliability engineering point of view, the studied electrohydraulic servo is a series system mainly consisting of the torque motor, the nozzle flapper amplifier, and the spool valve amplifier. The reliability block diagram of the EHSV is shown in Fig 2.

Fig. 2. The reliability block diagram of EHSV

3. FMECA for EHSV

Every product or system has failure modes. It is extremely significant to provide designers or operators with safety assessment methods that help to minimize the adverse effects of failures. Failure mode, effects and criticality analysis (FMECA) is one of the most established and powerful methods for identifying and evaluating system failure. As an engineering tool, it has a fundamental role in any safety or reliability study [19].

The purpose of the FMECA is to provide a systematic, critical examination of potential failure modes of equipment and their causes, to estimate the reliability of systems, to analyze the effect (the consequence of a failure mode) of each failure mode on a system, and to identify corrective actions, i.e., design modifications [21]. FMECA is a bottom-up, inductive analysis method which starts from the lowest Indenture level, and it permits to analyze a system in order to identify potential failure modes, their cause and effect on performance and, when applicable, their effect on the safety of humans, on environment and on the system [4]. FMECA extends FMEA by including a criticality analysis which is used to quantify failure effects and severity.

Risk Priority Number (RPN), a quantitative index, is used to analysis the risk associated with potential problems identified during the failure mode and effects analysis, and to rank the failure modes and effect in the criticality analysis. The calculation of the RPN is based on severity (S), occurrence (O) and detection (D) [3] as follows:

$$RPN = S \cdot O \cdot D$$

Severity quantifies the likelihood of the strength of a failure mode impacts on the system. Occurrence represents the probability that a failure mode will occur. Detection is the estimate of possibility of detecting before it reaches end-users or customers.

In this study, data of a certain type of EHSV have been collected form 6 experts from the research institute where electrohydraulic servo valve has been widely used. On the basis of collected data, FMECA and the evaluation criteria of indices are applied. Fig.3 depicts the framework for FMECA of EHSV.

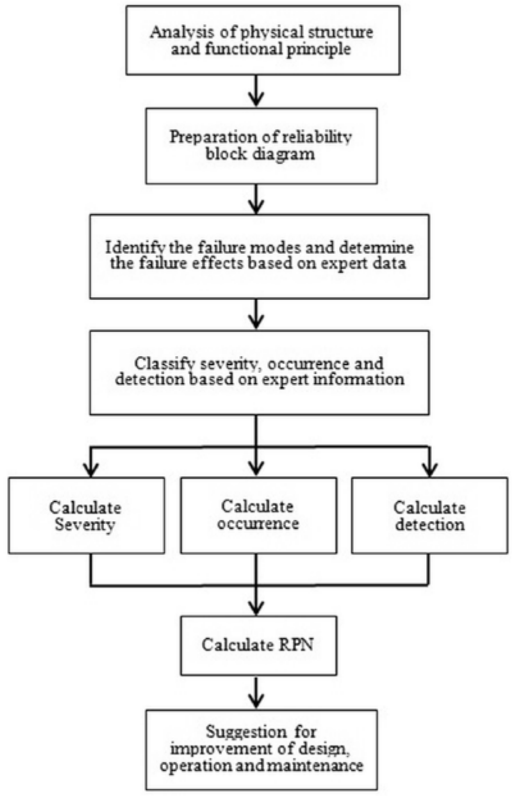

Fig. 3. The framework for FMECA of EHSV

For each of these indices (S, O, D) in the critical analysis, a detailed analysis is needed to identify their appropriate values, related to the type of application and environment. Table 1 shows the evaluation criteria of the three indices in this study. S, O and D are defined in the range of 1 to 4, so the value of RPN is 1 to 64.

Table 1. The evaluation ceriteria for severity, occurrence, and detection

Score	Severity	Occurrence	Detection
1	Insignificant: A negligible effect	Failure is unlikely	High: Can be detected by operator
2	Minor: A minimal effect	Relatively few failures	Moderate: Can be detected by regular detection
3	Critical: A great effect	Occasional failures	Low: Hard to detect, usually need disassembly
4	Catastrophic: causes system failure	Repeated failure	Non-detection: Impossible to detect

According the reliability block diagram of EHSV, as shown in Fig.2, the torque motor, the nozzle flapper amplifier, and the spool valve amplifier are defined as the lowest indenture level. Table 2 shows a part of results of the FMECA analysis. As mentioned earlier, the RPN was used to rank all the failure modes. Furthermore, consid-

Table 2. A part of the FMECA for the EHSV

Lowest Indenture Level	Failure Mode	Failure Cause	Failure Effect	Severity (S)	Occurrence (O)	Detection (D)	RPN
Torque Motor	Coil breakage	Overload or Wear	system failure	4	1	4	16
	Ball end wear	Wear	instability and degradation in performance	2	2	3	12
	Spring pipe fatigue	Fatigue	System failure	4	1	3	12
	Feedback rod bending	Wear	zero deviation increase	3	1	3	9
Nozzle Flapper Amplifier	Nozzle clogging	Oil contamination	zero deviation increase	3	3	2	18
	Orifice clogging	Oil contamination	zero deviation increase	3	3	2	18
Spool Valve Amplifier	Valve core wear	Wear	leakage and degradation in perfomance	3	1	2	6
	Jam fault of spool valve	Oil contamination or Wear	system failure	4	2	2	16

ering the failures modes, effects, based on the RPN values, the plans of improvement and maintenance will be discussed.

4. CCF analysis

4.1. Definition of CCF

Common cause failure is a specific type of dependent failure. The evidence that dependent failures are significant was presented by G. T. Edwards and I. A. Watson in their study [7], and they demanded that the design and operation of some systems must include a concerted approach against the dependent failures. Dependent failures include all definitions of failures that are not independent, encompass common cause failures and cascade failures.

A set of definitions of dependent failure (DF), common cause failure (CCF), cascade failures (CF) and common mode failure (CMF) are given as follows, and Fig.4 shows the relationship between them [1, 2, 8 ,11, 12, 14].

- Dependent failure (DF): The failure of a set of events, the probability of which cannot be expressed as the simple product of the unconditional failure probabilities of the individual events.
- Common cause failure (CCF): This is a specific type of dependent failure where simultaneous (or near-simultaneous) multiple failures result from a single shared cause.
- Cascade failures (CF): These are all dependent failures that do not share a common cause, and they propagate failures.
- Common mode failure (CMF): This term is reserved for common-cause failures in which multiple equipment items fail in the same mode.

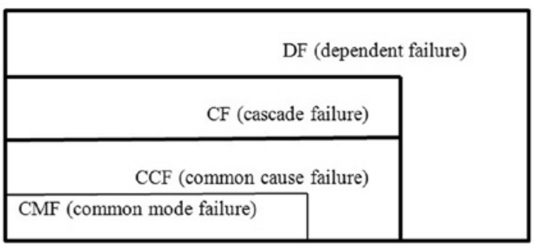

Fig. 4. The relationship between DF, CF,CCF and CMF

The root causes of CCF could be:

- The same design, manufacturer or assembly technology
- The same environmental conditions
- The same personnel dealing with the operation or maintenance or installation and constructions
- A human error

4.2. An overview of methodology for quantitative evaluation of CCF

Common methods for evaluation of common cause failures include:

- Basic parameter model
- Beta factor method
- Multiple Greek letter method
- Alpha factor method

(1) Basic parameter model

The basic parameter model refers to the straightforward definition of the probabilities of the basic failure events. The symmetry assumption is the probability of failure of any given basic event within a common cause component group depends only on the number and not on the specific components in that basic event. The total probability of failure for a component P_c in a common cause group of m components is:

$$P_c = \sum_{k=1}^{m} \binom{m-1}{k-1} \cdot P_k \qquad (1)$$

where $\binom{m-1}{k-1} = \frac{(m-1)!}{(k-1)!(m-k)!}$.

P_k is probability of a basic event involving k specific components, $1 \le k \le m$. Ideally, the values can be calculated from data, but unfortunately the complete data is normally not available. Other models putting less stringent requirements on the data have been developed [2].

(2) Beta factor method

The beta factor method was introduced in 1974 by Fleming [9]. The beta factor method assumes that P_c, which is the total probability of failure for a component, can be expanded into an independent failure contribution P_{IF} and a common cause failure contribution P_{CCF}:

$$P_c = P_{IF} + P_{CCF} \qquad (2)$$

A parameter β is defined as the fraction of total failure rate attributable to dependent failure:

$$\beta = \frac{P_{CCF}}{P_c} = \frac{P_{CCF}}{P_{IF} + P_{CCF}} \\ \Rightarrow P_{CCF} = \beta \cdot P_c \\ \Rightarrow P_{IF} = (1-\beta) \cdot P_c \tag{3}$$

The strength of the β factor model lies on data including historical data collected from both experiment and field. If β factor is not known, a general value of 0.1 can be used.

The beta factor method is the least demanding among the above methods and is used in this study. Because it only requires the estimation of common cause parameter in addition to the independent fail rate to the model the total component failure rate.

(3) Multiple Greek letter method

The multiple Greek letter parameters consist of the total failure probability and a set of failure fractions. The failure probability includes the effects of all independent and common cause contributions to that component failure, whereas the failure fractions are used to quantify the conditional probabilities of all the possible ways which a common cause failure of a component can be shared with other components in the same group, given the condition that the component has failed [10].

The following equation $m-1$ with parameters ($\rho 2$, $\rho 3$,…, ρk) is the general expression for the multiple Greek letter method, m is common cause group size:

$$P_k = \frac{1}{\binom{m-1}{k-1}} \cdot \left(\prod_{i=1}^{k} \rho_i \right) \cdot (1-\rho_{k+1}) \cdot P_c \tag{4}$$

$\rho k+1$ is the conditional probability of the failure of at least one additional component, given that k components has failed, $\rho k=1$, $\rho k+1=0$, $k=1,\ldots, m$.

(4) Alpha factor method

The general expression for the alpha factor method is the following [17]:

$$P_k = \frac{k}{\binom{m-1}{k-1}} \cdot \frac{\alpha_k}{\alpha_t} \cdot P_c \tag{5}$$

where

$$\alpha_t = \sum_{k=1}^{m} k \cdot \alpha_k$$

$$k = 1,\ldots,m$$

αk is the fraction of the total failure probability of events that occur in the system and involve the failure of k components because of a common cause.

4.3. CCF Analysis for EHSV

If R_{EHSV} is the reliability of the EHSV, λ_{EHSV} is the failure rate of the EHSV, R_T is the reliability of the torque motor, λ_T is the failure rate of the torque motor, R_S is the reliability of the spool valve amplifier , λ_s is the failure rate of the spool valve amplifier , R_N is the reliability of the nozzle flapper amplifier, λ_N is the failure rate of the nozzle flapper amplifier.

If the failure events of the three components are independent, R_{EHSV} is calculated based on the reliability model of series systems as follows:

$$R_{EHSV} = R_T \cdot R_S \cdot R_N \tag{6}$$

When it is assumed that all the failure of the three main components obey the exponent distribution, λ_{EHSV} is calculated as:

$$\lambda_{EHSV} = \lambda_T + \lambda_S + \lambda_N \tag{7}$$

It assumes that:

$$\lambda_T = \lambda_S = \lambda_N = \lambda \tag{8}$$

The failure rate λ_{EHSV} can be given by:

$$\lambda_{EHSV} = \lambda_T + \lambda_S + \lambda_N = 3\lambda \tag{9}$$

However, according to the FMECA results, as shown in Table2, there is a common cause failure of nozzle flapper amplifier and nozzle flapper amplifier due to oil contamination. At the same time, there is another common cause failure for all the components of EHSV which is ignored in the FMECA but really exists due to the same design, manufacturer, assembly, environmental conditions and hours of use. The fault tree with considering the two common causes is shown in Fig. 5.

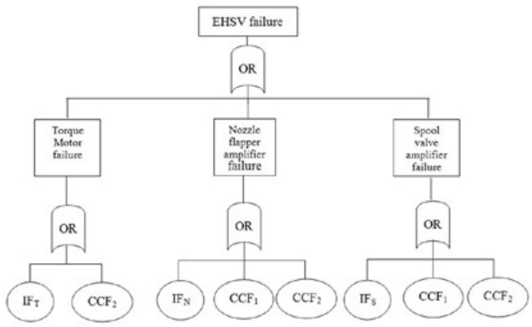

Fig. 5. The fault tree of EHSV with CCF

IF_T: Independent failure of torque motor, and the failure rate of IFT is λ_{IF}^{T};

IF_N: Independent failure of nozzle flapper amplifier, and the failure rate of IFN is λ_{IF}^{N};

IF_S: Independent failure of spool valve amplifier, and the failure rate of IFS is λ_{IF}^{S};

CCF_1:Common failure of nozzle flapper amplifier and spool valve amplifier due to oil contamination, and the failure rate of CCF_1 is λ_{CCF1};

CCF_2:Common failure of torque motor, nozzle flapper amplifier and spool valve amplifier due to same design, manufacturer, assembly, environmental conditions and the hours of use, and the failure rate of CCF_2 is λ_{CCF2};

The minimal cut set of the above fault tree is
{ IFT, IFN, IFS, CCF1,CCF2 }

It is assumed that all the failure rates are constant. The failure rate of EHSV and each component with common cause failures can be calculated by:

$$\lambda'_{EHSV} = \lambda_{IF}^{T} + \lambda_{IF}^{N} + \lambda_{IF}^{S} + \lambda_{CCF1} + \lambda_{CCF2} \tag{10}$$

$$\lambda_{T} = \lambda_{IF}^{T} + \lambda_{CCF2} \tag{11}$$

$$\lambda_{N} = \lambda_{IF}^{N} + \lambda_{CCF1} + \lambda_{CCF2} \tag{12}$$

$$\lambda_{S} = \lambda_{IF}^{S} + \lambda_{CCF1} + \lambda_{CCF2} \tag{13}$$

In this study, β_1 is defined for CCF1, and β_2 is defined for CCF2 based on the beta method, it also assumes $\lambda_T = \lambda_S = \lambda_N = \lambda$ as Eq.(8).

We can get:

$$\lambda_{CCF1} = \beta_1 \cdot \lambda$$

$$\lambda_{CCF2} = \beta_2 \cdot \lambda$$

$$\lambda_{IF}^{T} = (1 - \beta_2)\lambda$$

$$\lambda_{IF}^{N} = (1 - \beta_1 - \beta_2)\lambda$$

$$\lambda_{IF}^{S} = (1 - \beta_1 - \beta_2)\lambda$$

The failure rate λ_{EHSV} can be given as:

$$\lambda'_{EHSV} = \lambda_{IF}^{T} + \lambda_{IF}^{N} + \lambda_{IF}^{S} + \lambda_{CCF1} + \lambda_{CCF2} = (3 - \beta_1 - 2\beta_2)\lambda \tag{14}$$

In order to make it easy to compare Eq. (7) with Eq. (14), we assume $\lambda = 0.001, \beta_1 = 0.3, \beta_2 = 0.6$. According Eq. (7) and Eq. (14), we can get $\lambda_{EHSV} = 0.003$, $\lambda'_{EHSV} = 0.0015$. The calculation of the failure rate of the EHSV with CCF is lower than the failure rate without considering CCF. This means that the assumption that components of a series system fails independently tends to underestimate the reliability of system.

5. Conclusion

The major works of this paper contains three aspects. First, the structure and working principle of the two-stage nozzle flapper electrohydraulic servo valve are analyzed. Second, the method of failure mode, effects and criticality analysis is chosen to conduct the reliability analysis for EHSV, and rank the main failure modes. Third, in the criticality part, the beta method is used to calculate the failure rate of EHSV with common failures. The comparison shows that failure rate of EHSV with CCF is lower than the failure rate without CCF.

The assumption that all the failures of EHSV obey the exponent distribution makes it easy to compare the calculations with or without common cause failure. Nevertheless, the assumption may not reasonable, and the failure rates of the components of ESHV are not constant in fact. In order to evaluate the reliability of ESHV, the lifetime models of components of EHSV will be analyzed by fusing accelerate life testing data, accelerate degradation testing data and field information in future work.

Acknowledgments

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