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Reliability analysis of direct drive electrohydraulic servo valves based on a wear degradation process and individual differences

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Abstract

Electrohydraulic servo valves play critical roles in modern servo control systems, which require high reliability and high safety. The reliability analysis of a direct drive electrohydraulic servo valve is conducted in this article. First, the failure mechanism of the direct drive electrohydraulic servo valve is investigated by analyzing the structure and the working principle of the direct drive electrohydraulic servo valve. It shows that clamping stagnation, internal leakages and spring fatigue are the main failure modes of direct drive electrohydraulic servo valve. The structure degradation caused by wear enlarges the clearance and results in the increase in null leakages. Then, a gamma process is adopted to describe the internal structure degradation based on the failure mechanism analysis. Heterogeneity among different samples of direct drive electrohydraulic servo valves is studied and handled by introducing unit-specific random effects into the gamma process degradation model. Additionally, in this article, a Bayesian method is used to facilitate the degradation analysis and reliability estimation. The reliability models of sealing, springs and spool valves are presented. Finally, a brief introduction of the experiment of the direct drive electrohydraulic servo valves and an illustrative example of reliability analysis are presented to demonstrate the introduced failure mechanism analysis and the proposed reliability analysis method for direct drive electrohydraulic servo valves.

Keywords

Direct drive electrohydraulic servo valve, spool valves, degradation processes, random effects, Bayesian inference

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Introduction

Direct drive electrohydraulic servo valves (DDVs) play an extremely important role in servo control systems. It has been applied in many fields, such as astronavigation, aviation, navigation and military equipment. The failure of DDVs may result in malfunction of these engineering systems and lead to a horrible disaster. Accordingly, reliability analysis of DDVs is required to identify pivotal failure mechanism, to construct a practical reliability model and to implement a coherent reliability assessment. The leakage caused by the clearance of a servo valve is the main failure mode. It has been investigated by many scholars.[1–3] An internal leakage is usually caused by the degradation of the internal structure. Lot of studies have been presented for degradation modeling; detailed discussion on degradation models and their applications can be found in Nelson,[4] Singpurwalla,[5] Meeker et al.,[6] Bagdonavicius and Nikulin,[7] Elsayed,[8] Wang and Pham,[9] Wang et al.[10] and Ye et al.[11] Among these degradation models, the gamma process is a nature probability model for the degradation process involving independent non-negative increments. It has been adopted by many researchers, such as Singpurwalla[5] and Bagdonavicius and Nikulin.[7] At the same time, for mechanical products, the heterogeneity among different samples is

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common due to the variance of raw materials, the uncertainty introduced by manufacturing process, the subtle difference of the using conditions and so on. Lawless and Crowder[12] and Tseng et al.[13] proposed a method to handle these heterogeneities by introducing random effects into the gamma process model to describe individual differences.

In order to study the reliability of a DDV, the failure modes and causes are analyzed and revealed. The structure wear of a spool valve is described by a gamma process degradation model which has a characteristic of independent degradation increments. Simultaneously, the heterogeneity of mechanical products and competing failure are taken into the reliability model of a DDV in this article. The remaining segments of this article are organized as follows. Section "Working principle of a DDV" introduces the structure and working principle of a DDV. Section "Failure analysis of a DDV" indicates the main failure modes and analyzes the failure causes and mechanisms. In section "Reliability modeling," reliability model and reliability analysis for a spool valve are established. Section "Experiment and illustrative example" uses an example to illustrate the proposed method. Section "Conclusion and future work" presents the conclusion of this article and the remarks for future work.

Working principle of a DDV

There are four major components in a DDV, including a spool valve, an actuator, a digital controller and a position sensor. A schematic description of the working principle of the DDV is presented in Figure 1, where an external pump supplies pressurized flow. The actuator is connected to the spool valve directly and drives the spool to slide back and forth. The sliding motion of the spool opens and closes a valve, which in turn determines the fluid flow rate and direction. The control of the fluid flow can be used to command a hydraulic actuator. A digital controller is designed for controlling the position of the spool according to the input signal for the desired position. To precisely control the flow rate, a position sensor is used to detect the position of the spool and send feedback to the digital controller.

Failure analysis of a DDV

The DDV can be driven by various types of actuators. Moog Inc.[14] designed a DDV, as shown in Figure 2(a), with a permanent magnet linear force motor that provides high actuating power and works in two directions. Yuken Kogyo Company Ltd[15] and Parker Inc.[16] developed DDVs driven by voice coil motors. Lindler and Anderson[17] developed a DDV, as illustrated in Figure 2(b), with a piezoelectric transducer to attain a high-frequency response. Burton et al.[18] designed a DDV with a step motor. Among various types of DDVs introduced above, the digital controllers and position sensors are of various types and different from each other. However, as a commonly used piece of machinery, the spool has a general structure in different DDVs. Accordingly, this study mainly focuses on the spool valve, which is the most failure-prone component of a DDV.

This article takes a two-position two-port spool valve as an example to illustrate the structure and the working principle of the spool valve and to investigate the failure mechanism of the spool valve. In Figure 3, simplified schematic views are presented to indicate the normal and operated positions of the spool valve. The spool valve in the normal position is at the closed stage as illustrated in Figure 3(a). When the spool slides toward right to the operated position driven by the actuator, the centering spring is compressed. As a result, the spool valve is in the open stage, and the hydraulic oil flows through the valve from port P to port A as shown in Figure 3(b). On the contrary, when the spool moves toward left driven by the compressed spring and the actuator (some actuators can work in two directions), the spool valve returns to the closed

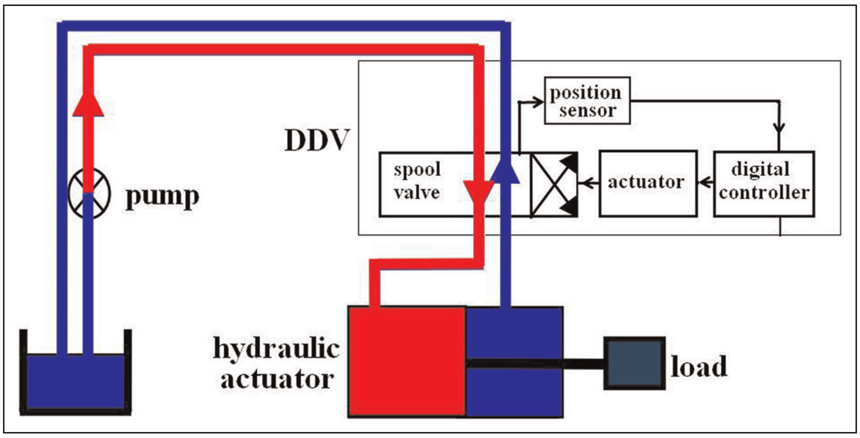

Figure 1. Hydraulic circuit of a DDV with pump supply and load.
DDV: direct drive electrohydraulic servo valve.

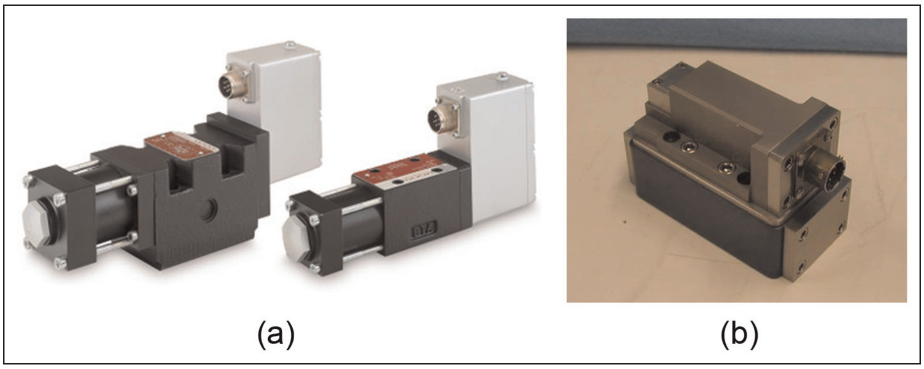

Figure 2. (a) DDVs with permanent magnet motors and (b) a piezoelectric transducer.

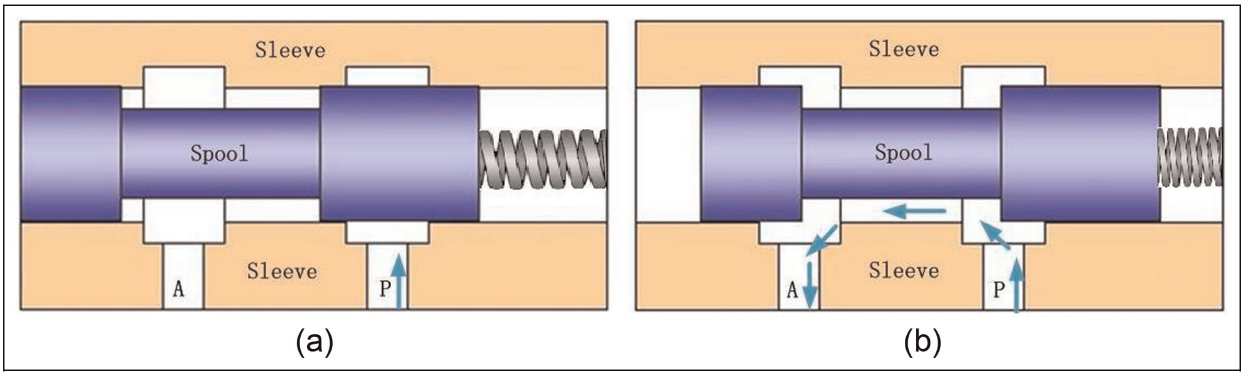

Figure 3. Configurations of the spool valve in (a) closed position and (b) open position.

stage. In this study, the process of a spool moving from the normal position to the operated position and then back to the normal position is called one stroke.

A spool valve has been used widely for many years. Engineering experience has indicated that there are three main failure modes of a spool valve, that is, clamping stagnation, internal leakage and spring failure.

There are two reasons causing clamping stagnation of the spool valve. One is oil contamination that causes mechanical clamping stagnation; the other is clamping force that causes hydraulic clamping stagnation. Clamping force is usually considered to be the premier one because the particles in the contamination of hydraulic oil are always not big enough to jam the spool of the DDV due to the effect of a special filter unit. The clamping force is caused by the uneven distribution of hydraulic pressure.[19] The uneven stress of the spool is usually considered as the result of the manufacture tolerance, which results in the phenomenon that the internal surface of the sleeve and the exterior surface of the spool are not concentric. In recent years, the main hydraulic spool valve manufacturers have taken two strategies to mitigate the hydraulic clamping stagnation. One is to dig some grooves on the spool to reduce the clamping force, and the other is to improve machining accuracy. As a result, clamping stagnation hardly ever happens in the DDV. So, the following of this article mainly focuses on the internal leakage and spring fracture. The reliability assessment of a spool valve will neglect the failure caused by clamping stagnation in this study.

The clearance seal, a non-contact seal technology, is used in most of the spool valves. Compared with other technologies of seal, clearance seal can greatly reduce the wear of the sealing face and improve the reliability of sealing. At the same time, the clearance exists, as shown in Figure 4, and leads to leakages. The quantity of internal leakage fluid passing through an assembled valve in the closed position is called null leakage or seat leakage. The null leakage of a qualified DDV is allowable. When the null leakage increases to a level that cannot be neglected and has some impacts on performance of a DDV, the DDV fails. The maximum allowable internal leakage specified for different valve sealing classes and valve sizes has been defined in some standards, such as American National Standard ANSI/FCI 70-2-2006, European Standard 1349-2008, Chinese National Standard GB/T 17213.4-2005 and IEC 60534-4-2006 3.0, which is enacted by International Electrical Commission (IEC).

Assume that the geometry sizes of the spool valve and the sleeves are ideal. The flow in the narrow circular clearance of a spool valve can be considered as laminar because the height is negligible compared to the width of the clearance. The following equation is valid for a spool valve when the spool and sleeve are steady[20,21]

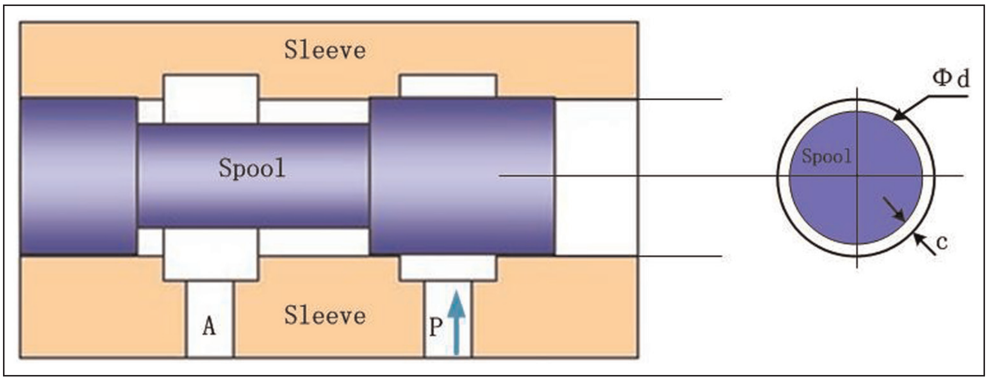

Figure 4. Schema of the spool valve and clearance.

$$Q = \Delta P \frac{\pi d c^3}{12 \mu L} \tag{1}$$

where Q denotes the flow of leakage due to the clearance. ΔP is the pressure difference between both sides of the clearance, π is the circumference ratio, d denotes the valve spool diameter, c is the radial clearance height, L is the clearance length and μ is the dynamic viscosity of hydraulic oil.

As seen in equation (1), the clearance height has much influence on the leakage. Methods of computational fluid dynamics (CFD) can be used to calculate the null leakage well based on clearance. If the maximum allowable value of the internal leakage is given, the maximum allowable clearance can be approximately calculated by using equation (1) or accurately calculated by other methods that are presented in these studies.[22,23] Engineering experience tells us that the rise of internal leakage flow is caused by the wear of the internal structure. For a DDV, the high-frequency response extraordinarily aggravates the wear. The study of some failed DDVs shows that the reason why the internal leakage of a DDV increases is that the wear of spool makes the clearance increase.

The centering spring is another important component in a spool valve. It determines the starting position of the spool and drives the spool back to a normal position. At the same time, the centering spring can make the spool return to a predefined spring-loaded position without overshooting a working position, when the actuator fails. Generally, helical compression springs are the most common type in DDVs. Helical compression springs are generally manufactured by different grades of carbon or alloy steel rods. Fracture and excess plastic deformation are the two main failure modes of a helical spring and both are due to fatigue.[24–26] Fatigue is the weakening of a material caused by repeatedly applied loads.

Reliability modeling

Reliability modeling for sealing

Internal leakage of a spool valve is a degradation failure due to the wear of spool surface. For the spool of a DDV, it is hard to calculate the wear volume according to wear equations. This is because that many parameters of the wear equations are varying and hard to be obtained, such as the number and the diameter of the particles in the contaminated oil, the impacted areas and the relative particle velocity.

In this study, the method for degradation analysis is adopted to study the wear of spool. The non-negative-valued process $\{D(n), n \in N\}$ is used. In the setting here, $D(n)$ is the wear volume after n strokes with $D(0) = 0$. D_M is the maximum allowable wear volume which denotes the failure threshold level for the wear of the spool. D_M can be calculated by subtracting the initial fit clearance from the maximum allowable clearance. The initial fit clearance is a basic parameter for a spool valve. The calculation of the maximum allowable clearance is presented in section "Failure analysis of a DDV."

The lifetime of the seal of a spool valve N_{se} can be defined as $N_{se} = \inf\{t | D(n) \geqslant D_M\}$, where n is the number of finished strokes for a spool valve. The sealing reliability of a spool valve $R_{se}(n)$ can be correspondingly defined as

$$R_{se}(n) = P(D(n) < D_M) \tag{2}$$

We assume that the wear of spool occurs randomly in every stroke and is described by a gamma process

$$\Delta D(n) \sim Ga(\eta \Delta n, \nu^{-1}) \tag{3}$$

where $\Delta D(n) = D(n + \Delta n) - D(n)$ and $Ga(\eta \Delta n, \nu^{-1})$ is a gamma distribution with a shape parameter $\eta \Delta n$ and a scale parameter ν^{-1}.

Meanwhile, as one of the characteristics of mechanic products, the heterogeneity may have a significant impact on the wear degradation of spool. To ensure the accuracy of the reliability modeling and assessment, unit-specific random effects are introduced in the gamma process. The scale parameter is affected by the heterogeneity, but it does not change the shape parameter.[12,13] We assume that ν follows a gamma distribution $Ga(\delta, \gamma^{-1})$ with a probability density function (PDF) given as

$$g(\nu) = \frac{\nu^{\delta-1} \gamma^{\delta} e^{-\gamma \nu}}{\Gamma(\delta)}, \nu > 0 \tag{4}$$

where $\Gamma(\bullet)$ is a gamma function.

Because $D(n)$ is a strictly monotonic increasing function of n, and $\delta D(n)/(\gamma\eta n)$ has an F-distribution whose cumulative distribution function (CDF) is denoted by $F_{2\eta n,2\delta}(x)$, the CDF of N_{se} can be expressed as the following equation

$$F_0(n) = P(N_{se} \leqslant n) = P(D(n) \geqslant D_M) = 1 - F_{2\eta n,2\delta}\left(\frac{\delta D_M}{\gamma\eta n}\right) = \frac{B\left(\frac{D_M}{D_M+\gamma};\eta n,\delta\right)}{B(\eta n,\delta)} \quad (5)$$

Then, the sealing reliability of a spool valve $R_{se}(n)$ can be given as

$$R_{se}(n) = 1 - \frac{B\left(\frac{D_M}{D_M+\gamma};\eta n,\delta\right)}{B(\eta n,\delta)} \quad (6)$$

where $B(x;a,b) = \int_x^1 z^{a-1}(1-z)^{b-1}dz$ is the upper incomplete beta function, and $B(a,b)$ is the complete beta function.

Parameter estimation of degradation

Suppose that N valves are tested. The wear of the spools is observed at some discrete observation times. Let $D(n_{ij})$ with $j = 1, \ldots, m_i$ and $i = 1, \ldots, N$ be the jth wear observation of unit i. Let $d_{ij} = D(n_{ij}) - D(n_{i,j-1})$ be the wear increment of unit i. Following the degradation model introduced above, the wear increments d_{ij} obtained from the wear test are independent and follow a gamma distribution $Ga(\eta\Delta n_{ij}, \nu_i^{-1})$ with $\nu_i \sim Ga(\delta,\gamma^{-1})$ and $\Delta n_{ij} = n_{ij} - n_{i,j-1}$.

Let D denote the wear observations of the spools. Based on these degradation data, parameter estimation for the degradation model and the reliability assessment for the valve can be carried out. In this article, a Bayesian method is used to facilitate the parameter estimation and reliability assessment. By incorporating the Bayesian method, the degradation model with the random effect, which is given as $Ga(\eta\Delta n_{ij}, \nu_i^{-1})$ with $\nu_i \sim Ga(\delta,\gamma^{-1})$, can be handled properly. Moreover, subjective information about the failure mechanism of the valve derived from experts in that domain can be incorporated coherently. When the wear observations of the valves are obtained as D, the information contained in this observed data is presented as the likelihood function

$$L(D,\boldsymbol{\nu}|\eta,\delta,\gamma) = \prod_{i=1}^{N} g(\nu_i|\delta,\gamma^{-1}) \prod_{j=2}^{m_i} g(\Delta d_{ij}|\eta\Delta n_{ij},\nu_i^{-1}) = \prod_{i=1}^{N} \frac{\nu_i^{\delta-1}\gamma^{\delta}}{\Gamma(\delta)}\exp(-\gamma\nu_i) \prod_{j=2}^{m_i} \frac{(\Delta d_{ij})^{\eta\Delta n_{ij}-1}\nu_i^{\eta\Delta n_{ij}}}{\Gamma(\eta\Delta n_{ij})} \exp(-\nu_i\Delta d_{ij}) \quad (7)$$

where $d_{ij} = D(n_{ij}) - D(n_{i,j-1})$, $\Delta n_{ij} = n_{ij} - n_{i,j-1}$ and $\boldsymbol{\nu} = (\nu_1, \ldots, \nu_N)$ includes the scale parameters for the gamma process model for each spool. $g(\bullet|a,b^{-1})$ is the PDF of a gamma distribution with the shape parameter a and the scale parameter b.

Suppose prior information about the wear of spool is obtained and quantified as joint prior distribution for the model parameters as $\pi(\boldsymbol{\theta}) = \pi(\eta,\delta,r)$. We are not going to discuss the derivation of the prior distribution here; for more information, please refer to the works by O'Hagan et al.[27] Following the Bayesian theory, the joint posterior distribution of model parameters is obtained as

$$p(\eta,\delta,\gamma,\boldsymbol{\nu}) \propto \pi(\boldsymbol{\theta})L(D,\boldsymbol{\nu}|\boldsymbol{\theta}) = \pi(\eta,\delta,\gamma)L(D,\boldsymbol{\nu}|\eta,\delta,\gamma) = \pi(\eta,\delta,\gamma)\prod_{i=1}^{N} \frac{\nu_i^{\delta-1}\gamma^{\delta}}{\Gamma(\delta)}\exp(-\gamma\nu_i) \prod_{j=2}^{m_i} \frac{(\Delta d_{ij})^{\eta\Delta n_{ij}-1}\nu_i^{\eta\Delta n_{ij}}}{\Gamma(\eta\Delta n_{ij})} \exp(-\nu_i\Delta d_{ij}) \quad (8)$$

where $p(\eta,\delta,\gamma,\boldsymbol{\nu})$ is the joint posterior distribution for model parameters. It is a description of the combination of prior information and the information contained in the wear degradation data.

The reliability assessment of the spool is carried out based on the joint posterior distribution of model parameters as

$$R_{se}(n|D) = \int_{\eta,\delta,\gamma>0} p(\eta,\delta,\gamma|D) \frac{B\left(\frac{D_M}{D_M+\gamma};\eta n,\delta\right)}{B(\eta n,\delta)} \mathrm{d}\eta\mathrm{d}\delta\mathrm{d}\gamma \quad (9)$$

Since there is no analytical solution to equations (8) and (9), the integrations are carried out through simulation-based method. The Markov chain Monte Carlo (MCMC) method is used to generate samples from the joint posterior distribution. To facilitate the implementation of the MCMC, the software WinBUGS[28] is used in this article. Estimation results of model parameters, such as mean, variance, kernel distribution and interval estimations are summarized from these simulated posterior samples. The calculation of equation (9) is implemented through the generated posterior samples using simulation-based integration. In detail, the joint posterior samples $\tilde{\eta}$, $\tilde{\delta}$ and $\tilde{\gamma}$ are substituted into the main integration part of equation (9) which is given as $B(D_M/(D_M+\tilde{\gamma});\tilde{\eta}n,\tilde{\delta})/B(\tilde{\eta}n,\tilde{\delta})$. The samples of spool reliability are then obtained through the calculations of $B(D_M/(D_M+\tilde{\gamma});\tilde{\eta}n,\tilde{\delta})/B(\tilde{\eta}n,\tilde{\delta})$ associated with the posterior samples of model parameters. Similarly, the estimation results of spool reliability, such as mean, variance and kernel distribution are obtained based on the obtained samples. For more discussion about the MCMC method and the modeling and calculation through WinBUGS, please refer to the work done by Ntzoufras.[29]

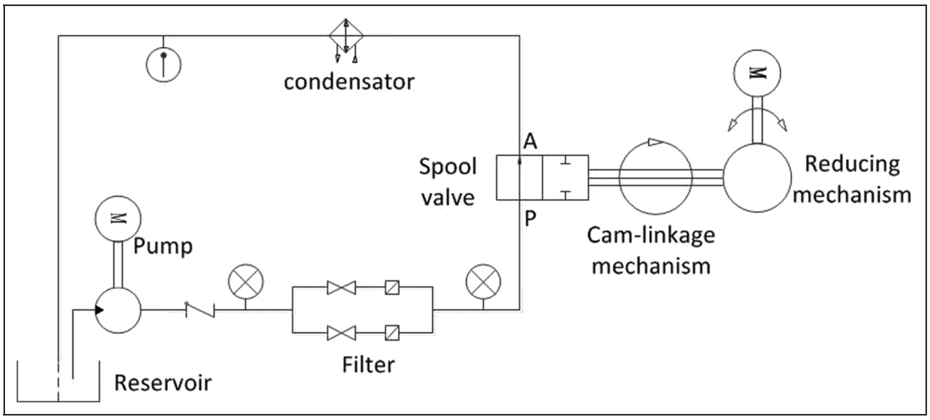

Figure 5. Basic diagram of wear experiment for a DDV.

Reliability modeling for spring

American Society for Testing and Materials (ASTM) defines fatigue life as the number of stress cycles under a specified characteristic that a specimen sustains before failure. For the spring of a DDV, as shown in Figure 3, a stress cycle is a process that it distorts when the spool sliding to right and returns to its original shape when the spool return to the normal position once. Therefore, the number of stress cycles is the same as the number of strokes of a spool.

As a commonly used mechanical component, the spring has been comprehensively studied. Its fatigue lifetime has been demonstrated following a logarithmic normal distribution.[26] In this article, N_{sp} is used to denote the fatigue life of the helical spring of a DDV. The logarithm of N_{sp} follows a normal distribution as $\ln N_{sp} \sim N(\mu_s, \sigma_s^2)$ with a PDF as

$$f_s(n|\mu_s, \sigma_s) = \frac{1}{\sigma_s n\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\ln n - \mu_s}{\sigma_s}\right)^2\right) \quad (10)$$

And the reliability of a valve spring is expressed as

$$R_{sp}(n) = 1 - \Phi\left(\frac{\ln n - \mu_s}{\sigma_s}\right) \quad (11)$$

where $\Phi(\bullet)$ is the CDF of the standard normal distribution, n is the number of strokes for a spool valve which is the same with equation (2), μ_s is the logarithmic mean and σ_s is the logarithmic variance. Methods used for estimating the parameters of fatigue lifetime models will not be described in detail in this article; for more discussion, please refer to Birnbaum and Saunders,[30] Brown and Miller[31] and Engelhardt et al.[32]

Reliability modeling for a spool valve

In this article, $R(n)$ is used to denote the reliability of a spool valve. It is calculated based on the mathematical model of a series system given as follows

$$R(n) = R_{se}(n)R_{sp}(n) \quad (12)$$

Table 1. Basic experimental parameters.

Basic experimental parameters	Value
Rotational speed of motor	1200 r/min
Transmission ratio	3
Pump pressure	10 MPa
Measuring frequency	125 min (50,000 strokes)
Room temperature	300 K
Maximum temperature of hydraulic oil	353 K

where $R_{se}(n)$ is the reliability of spool presented in equation (6) and $R_{sp}(n)$ is the reliability of the spring presented in equation (11).

According to equations (6) and (11), the reliability of spool valve is obtained as

$$R(n) = \left(1 - \frac{B\left(\frac{D_M}{D_M + \gamma}; \eta n, \delta\right)}{B(\eta n, \delta)}\right)\left(1 - \Phi\left(\frac{\ln n - \mu_s}{\sigma_s}\right)\right) \quad (13)$$

Experiment and illustrative example

Brief introduction of experiment

In order to get the wear data of a spool valve, an experiment was designed. Figure 5 shows the basic diagram of a wear experiment of a spool valve used in a DDV. The basic experimental parameters of this study are shown in Table 1.

The circuit of hydraulic oil is composed of a pressure pump, a check valve, a set of filter, a spool valve, a condensator and some necessary valves and sensors. In this study, the fluid flows under the drive of a constant pressure pump at 10 MPa. The spool valve is demounted from a DDV, and a two-position two-port spool valve is taken as an example in Figure 5. The large particles are filtered out to avoid mechanic clamping stagnation. The condensator can bring the oil temperature below

Table 2. Wear of spools observed from test (unit: μm).

Unit	Number of strokes (10,000)															
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
Sample 1	1	2	9	10	10	10	11	11	15	15	16	17	19	20	21	21
Sample 2	4	4	7	17	22	25	25	27	31	31	31	31	32	32	32	35
Sample 3	0	7	8	8	18	21	22	22	22	25	25	25	25	25	35	46
Sample 4	1	5	8	8	9	9	12	16	17	18	34	41	41	51	51	53

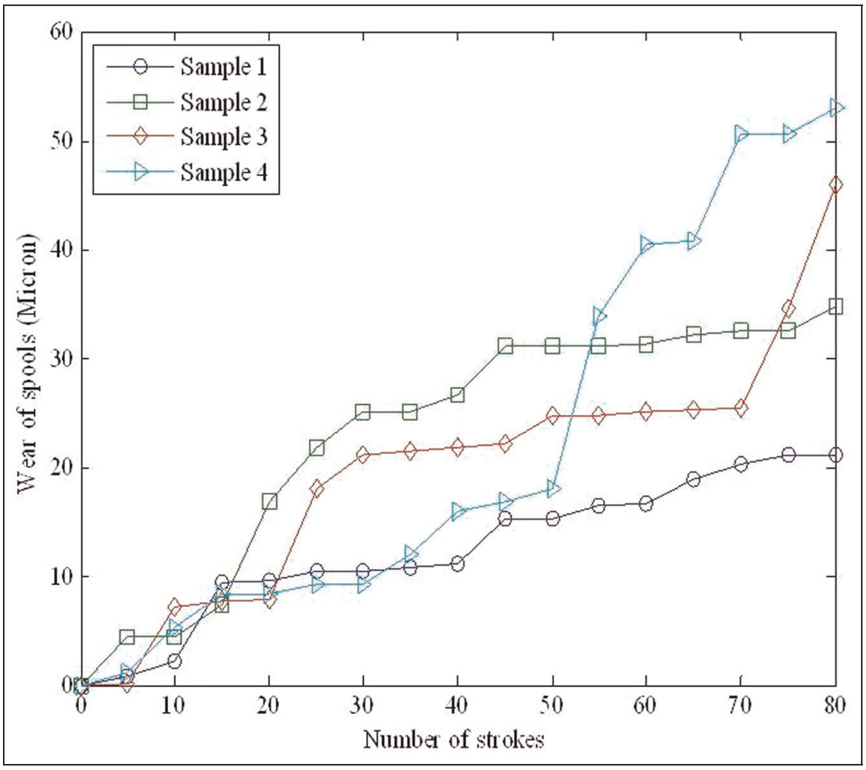

Figure 6. Wear degradation paths of spools.

80 °C. Other pressure sensors, temperature sensors and valves are used to monitor the operational states.

The actuator of a DDV was replaced by a cam-linkage mechanism that is driven by an electric motor. And there is a reducing mechanism between the cam-linkage mechanism and the motor. The working frequency of motor and the transmission ratio of reducing mechanism determine the number of strokes per minute. In this study, the working rotational speed of the motor is 1200 r/min, and the transmission ratio is 3, then spool valve will finish 400 strokes per minute. Every 125 min of this test, the spool is removed to measure the wear volume.

An illustrative example for reliability assessment

For the purpose of protecting proprietary of the data and information, the original data of this experiment will not be revealed in this article. We generated simulated data to demonstrate the rationality of model and parameter estimation. The data are given in Table 2. Largely, however, the nature of the simulated data is the same as the original data.

As shown in Table 2, the number of samples is four, and the wear volumes are obtained per 50,000 strokes. The threshold is set to 40. Then, we can get the wear degradation path of spools as illustrated in Figure 6.

To implement the reliability assessment of spools, a degradation analysis is carried out based on the wear degradation data using the Bayesian method. Since there is a significant variance among the degradation paths as presented in Figure 6, the gamma process with a random effect is used to model the wear degradation of spools. In detail, the degradation increments $d_{ij} = D(n_{ij}) - D(n_{i,j-1})$ with $j = 1, \ldots, 17$ and $i = 1, \ldots, 4$ follow gamma distribution $Ga(\eta \Delta n_{ij}, \nu_i^{-1})$ with $\nu_i \sim Ga(\delta, \gamma^{-1})$ and $\Delta n_{ij} = 5$. Following the procedure presented in section "Parameter estimation of degradation," the estimation of model parameters $\boldsymbol{\theta} = (\eta, \delta, r)$ is implemented.

Table 3. Statistical summarization of posterior samples for parameter estimation.

	η	δ	γ	ν_1	ν_2	ν_3	ν_4
Mean	0.07547	61.89	8.3126	7.072	7.290	7.460	7.573
Confidence interval 2.5%	0.05788	48.29	6.6667	4.622	4.87	5.035	5.171
Confidence interval 97.5%	0.09592	77.31	10.557	10.19	10.44	10.6	10.72

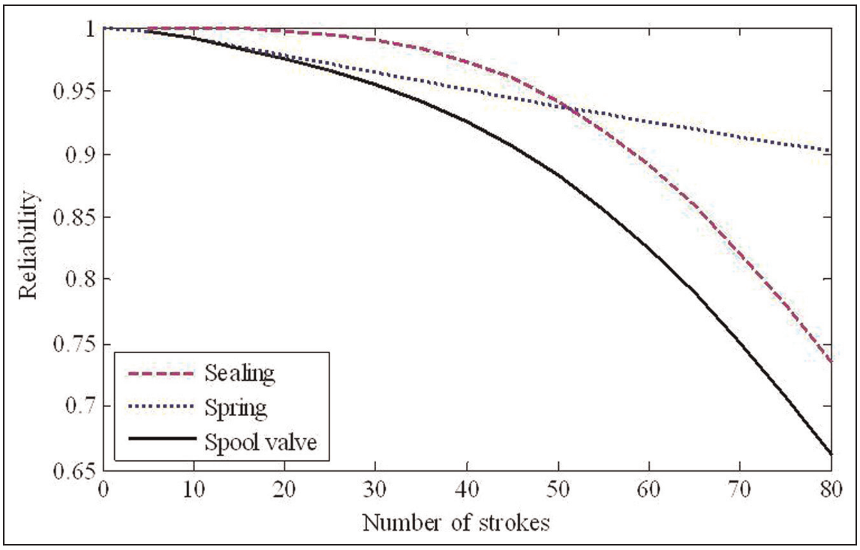

Figure 7. Reliability estimation of the sealing, the spring and the spool valve.

Prior distributions for these parameters are derived based on historical data and subjective information of experts and are given as

$$\delta \sim Ga(64, 1), \gamma \sim Ga(64, 512), \eta \sim \mathrm{U}(0, 10)$$

where $\mathrm{U}(a, b)$ is the uniform distribution with an interval of (a, b). The prior distribution of the parameters δ and γ are obtained from historical data. The prior distribution of parameter η is derived using the interval provided by experts.

By formalizing the likelihood function using the wear degradation data, the joint posterior distribution of model parameters is obtained using equation (8) as

$$\begin{aligned} p(\eta, \delta, \gamma, \boldsymbol{\nu}) &\propto \pi(\eta, \delta, \gamma) L(D, \boldsymbol{\nu} | \eta, \delta, \gamma) \\ &\propto \delta^{63} \exp(-\delta) \gamma^{63} \exp(-512\gamma) \\ &\times \prod_{i=1}^{4} \frac{\nu_i^{\delta-1} \gamma^{\delta}}{\Gamma(\delta)} \exp(-\gamma \nu_i) \\ &\prod_{j=2}^{17} \frac{(\Delta d_{ij})^{\eta \Delta n_{ij}-1} \nu_i{}^{\eta \Delta n_{ij}}}{\Gamma(5\eta)} \exp(-\nu_i \Delta d_{ij}) \end{aligned} \quad (14)$$

The MCMC method is used to generate posterior samples of model parameters. The WinBUGS is adopted to facilitate the implementation of MCMC for the Bayesian degradation analysis of the wear degradation data. In all, 30,000 posterior samples are generated using the WinBUGS with 10,000 samples for burn-in. A statistical summarization of the posterior samples of the model parameter is presented in Table 3.

Based on the joint posterior samples of model parameters generated above, the reliability of the sealing is obtained using equation (6). The simulation-based integration is used to carry out the integration in calculation. The reliability of the sealing is presented in Figure 7.

The parameters μ_s and σ_s are obtained from spring manufacturers and estimated by some classic parameter estimation methods for fatigue lifetime. Let $\mu_s = 6.8658$ and $\sigma_s^2 = 1.9254$. The reliabilities of the valve spring and the spool valve are obtained using equations (9) and (11). Both of them are shown in Figure 7.

As shown in Figure 7, the spool valve reliability and the sealing reliability are similar in downward tendency. It demonstrates that the reliability of a spool valve is dramatically affected by the reliability of sealing. At the same time, the spring reliability is unaffected and maintains a high reliability. In other words, the spring failure and internal leakage are independent of each other in a certain degree.

Conclusion and future work

A comprehensive reliability analysis of DDVs is presented. This article investigates the main failure modes of a spool valve based on the working principle and failure process for DDVs and spool valves. The internal leakage and spring fracture have been identified as the main failure modes of the DDVs. Spring fatigue of a DDV is a weakening caused by repeated movements of a spool. This study used logarithmic normal distribution to describe the fatigue lifetime of spring. Internal leakage of a spool valve is a degradation failure due to the wear of spool surface. Based on the identification of wear degradation failure mechanism of spools, a gamma process degradation model is introduced to describe the structure degradation of spools and to derive the reliability and lifetime of spools. Moreover, random effects are introduced into the gamma process degradation model to represent the heterogeneity of different spools. The reliability models of the sealing, the spring and the spool valve are derived. According to the degradation modeling and reliability analysis, we can conclude that the reliability of a spool valve is dramatically affected by the reliability of sealing. In addition, the wear degradation of the spool does not affect the reliability of the spring. In other words, these two components are independent of each other in a certain degree. This study is significant for lifetime prediction and maintenance decision-making for a DDV. In addition, a brief introduction of wear degradation experiment for the spools is presented for further reference. The proposed failure analysis and reliability assessment for DDVs are illustrated with a simulated engineering example.

This article has some limitations. The experiment is designed under normal condition. However, as a long-life product, a DDV may experience some extreme states, such as extreme temperature and over-vibration. In such cases, there may be excess wear or damages that are not considered in this study. Further investigation of a degradation model considering random shocks is critical. In addition, the confidence intervals of parameter estimation are large because of insufficient samples. A coherent method for handling the issues introduced by insufficient sample needs further investigation.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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