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Reliability Evaluation Method of Pseudo-failure Life Distribution for Industrial Robot Servo System Based on The Generalized Lambda Distribution

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Reliability Evaluation Method of Pseudo-failure Life Distribution for Industrial Robot Servo System Based on The Generalized Lambda Distribution

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ABSTRACT: A reliability evaluation method of pseudo-failure life distribution for Industrial Robot Servo System (IRSS) based on The Generalized Lambda Distribution (GLD) was proposed in the paper. The IRSS pseudo-failure life GLD distribution was established. Quantile estimation method was applied to estimate the GLD parameters. The proposed method had no need of presetting specific distribution morphology, and thus improve the accuracy of IRSS pseudo-failure reliability modeling. In the application experiment, the IRSS pseudo-failure life distribution reliability evaluation method based on GLD was used to obtain the IRSS failure life, the reliability evaluation result was consistent with the design failure life, which indicated the validity of the proposed method.

1. introduction

Industrial Robot Servo System (IRSS) is the execution unit used to complete the specific trajectory motion of Industrial robots, and is the core component of Industrial robots. The reliability of IRSS is directly related to the normal service life of Industrial robots [1]. IRSS are typical products with long life and high reliability. Its reliability evaluation is faced with the problem of insufficient reliability test data due to the lack of test samples and limited test time. The reliability evaluation method based on performance degradation can better study the reliability evaluation of long-life and high-reliability products [2-3], and its reliability evaluation modeling method includes PFA (Physics of Failure Analysis)-based method and PSA (Performance degradation data Statistics Analysis)-based method. PFA-based method assumes that IRSS failure is caused by the degradation of a single key part (such as bearing, motor rotor, stator insulation, etc.), and the model established by the method is hard to meet the system-level reliability research and analysis under the joint action of multiple failure mechanisms [4-5]. Whereas, the PSA-method establishes the degradation model by statistical analysis method, can better analyze the IRSS degradation process [6-8]. However, the PSA-method should be based on a reasonable distribution assumption.

Address to the issue, the paper proposed a reliability evaluation method of pseudo-failure life distribution for IRSS based on The Generalized Lambda Distribution GLD. The idea is that making use of the characteristics of various distribution forms of GLD to modeling the IRSS pseudo-failure life distribution, so as to improve the accuracy of pseudo-failure reliability modeling of IRSS without presetting specific distribution forms.

2. the gld-based pseudo-failure life distribution reliability evaluation methodology

Figure 1 is the flow chart of IRSS pseudo-failure life distribution reliability evaluation method, including: i. Set pseudo-failure level, and obtain the IRSS pseudo-failure life data set based on the IRSS performance degradation data; ii. Expand IRSS pseudo-failure life data set used the Bootstrap method; iii. Establish the IRSS pseudo failure life distribution based on the GLD distribution method; vi. Extrapolate IRSS life distribution under failure threshold to complete reliability assessment.

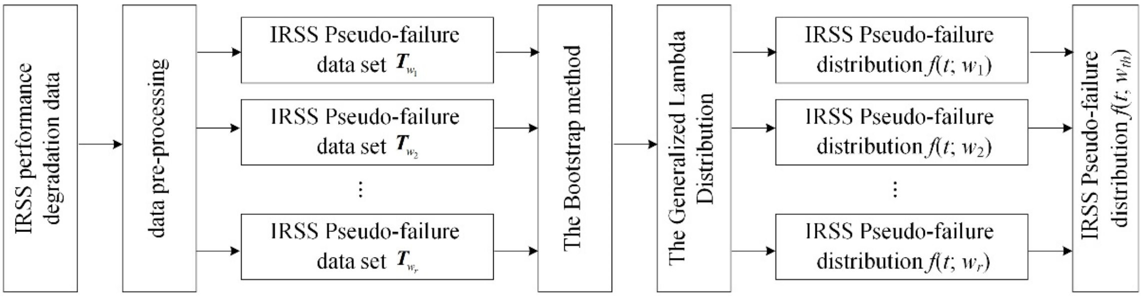


Figure 1. The flow chart of IRSS pseudo-failure life distribution reliability evaluation method

2.1 GLD-based method for IRSS pseudo-failure life distribution estimation

Suppose that the position and scale parameters of generalized λ distribution are λ_1 and λ_2, and the shape parameters are λ_3 and λ_4, Table 1 shows the relationship between typical probability distribution and the generalized λ distribution parameters. It can be concluded that the generalized λ distribution can approximate the morphological characteristics of a variety of distributions, without the prior distribution preset, which is very suitable for IRSS pseudo-failure life distribution fitting.

Table 1. The relationship between typical probability distribution and the generalized λ distribution parameters

Typical probability distribution	Distribution expression	Distribution parameters	The generalized λ distribution parameters
Normal distribution	$f(x)=\frac{1}{\sqrt{2\pi}\sigma}\cdot e^{-(x-\mu)^2/2\sigma^2}$	μ=0; σ=1	λ_1=0; λ_2=0.1975 λ_3=0.1349; λ_4=0.1349
Logarithmic normal distribution	$f(x)=\frac{1}{x\sqrt{2\pi}\sigma}\cdot e^{-(\ln x-\mu)^2/2\sigma^2}$	μ=0; σ=1/3	λ_1=0.8451; λ_2=0.1085 λ_3=0.0102; λ_4=0.0342
Exponential distribution	$f(x)=\mu e^{-\mu x}$	μ=1	λ_1=0.0100; λ_2=-10^{-3} λ_3=-10^{-6}; λ_4=-10^{-3}
Gamma distribution	$f(x)=\frac{x^{\alpha-1}e^{-x/\beta}}{\Gamma(\alpha)\cdot\beta^{\alpha}}$	α=5; β=3	λ_1=10.761; λ_2=0.0145 λ_3=0.0252; λ_4=0.0939
Weibull distribution	$f(x)=\alpha\beta x^{\beta-1}\exp(-x^{-\alpha x^{\beta}})$	α=5; β=1	λ_1=0.9935; λ_2=1.0491 λ_3=0.2121; λ_4=0.1061

Suppose $T_{w_i}^{j*}$ from the IRSS pseudo-failure extended data set $\boldsymbol{T}_{w_i}^{*}$ obey the generalized λ distribution, $Q(u)$ is the quantile function of the generalized λ distribution, where $j\in[1, N_{w_i}]$, and N_{w_i} is the number of samples of $\boldsymbol{T}_{w_i}^{*}$, $u\in[0, 1]$. Thus $T_{w_i}^{j*}$ = Q(u) generates a random variable:

$$Q(u)=\lambda_1+\frac{1}{\lambda_2}\cdot[u^{\lambda_3}-(1-u)^{\lambda_4}],\ \ 0\le u\le 1 \tag{1}$$

According to the inverse function derivation rule, the probability density function of IRSS pseudo-failure life distribution can be obtained [9]:

$$f(l)=\frac{\lambda_2}{[\lambda_3 u^{\lambda_3-1}+\lambda_4(1-u)^{\lambda_4-1}]}\quad l=Q(u) \tag{2}$$

2.2 IRSS pseudo-failure life distribution GLD parameter solution

The relationship between the first four moments of the generalized λ distribution and parameters (λ_1, λ_2, λ_3, λ_4) is more complex than that between the quantile and parameters (λ_1, λ_2, λ_3, λ_4). Therefore, the Quantile-based GLD parameter estimation method is applied [10]. Based on the IRSS pseudo-failure extended data set $\boldsymbol{T}_{w_i}^*$, estimate the median $\hat{\rho}_1$, 10-quartile difference $\hat{\rho}_2$, 10-quartile ratio $\hat{\rho}_3$ and 10-quartile difference ratio $\hat{\rho}_4$ as the following:

$$\hat{\rho}_1=\pi_{0.5}\,;\quad \hat{\rho}_2=\pi_{0.9}-\pi_{0.1}\,;\quad \hat{\rho}_3=\frac{\pi_{0.5}-\pi_{0.1}}{\pi_{0.9}-\pi_{0.5}}\,;\quad \hat{\rho}_4=\frac{\pi_{0.75}-\pi_{0.25}}{\pi_{0.9}-\pi_{0.1}} \tag{3}$$

where, π_p is the p-quantile of $\boldsymbol{T}_{w_i}^*$.

The median ρ_1, 10-quartile difference ρ_2, 10-quartile ratio ρ_3 and 10-quartile difference ratio ρ_4 of the GLD can be obtain based on the GLD quantile function $Q(u)$ as the following:

$$\begin{aligned}
\rho_1&=Q(0.5)=\lambda_1+\frac{1}{\lambda_2}\cdot(0.5^{\lambda_3}-0.5^{\lambda_4})\,;\\
\rho_2&=Q(0.9)-Q(0.1)=\frac{1}{\lambda_2}\cdot[(0.9^{\lambda_3}-0.9^{\lambda_4})-(0.1^{\lambda_3}-0.1^{\lambda_4})]\,;\\
\rho_3&=\frac{Q(0.5)-Q(0.1)}{Q(0.9)-Q(0.5)}=\frac{[(0.5^{\lambda_3}-0.5^{\lambda_4})-(0.1^{\lambda_3}-0.1^{\lambda_4})]}{[(0.9^{\lambda_3}-0.9^{\lambda_4})-(0.5^{\lambda_3}-0.5^{\lambda_4})]}\,;\\
\rho_4&=\frac{Q(0.75)-Q(0.25)}{Q(0.9)-Q(0.1)}=\frac{[(0.75^{\lambda_3}-0.75^{\lambda_4})-(0.25^{\lambda_3}-0.25^{\lambda_4})]}{[(0.9^{\lambda_3}-0.9^{\lambda_4})-(0.1^{\lambda_3}-0.1^{\lambda_4})]}\,.
\end{aligned} \tag{4}$$

Establish the corresponding relationship between {$\hat{\rho}_1$, $\hat{\rho}_2$, $\hat{\rho}_3$, $\hat{\rho}_4$} and {ρ_1, ρ_2, ρ_3, ρ_4}:

$$\rho_k=\hat{\rho}_k\,,\ k=1, 2, 3, 4 \tag{5}$$

It is difficult to directly solve λ_1, λ_2, λ_3, and λ_4. The initial values of λ_3 and λ_4 can be obtained by referring to the table in [9], and then applied Gauss-Newton method iteratively solve λ3, λ4 based on the function as below:

$$\rho_3=\hat{\rho}_3\,,\quad \rho_4=\hat{\rho}_4 \tag{6}$$

The objective function is as below:

$$\min[(\rho_3-\hat{\rho}_3)^2+(\rho_4-\hat{\rho}_4)^2]<\varepsilon \tag{7}$$

where, ε is the iteration stop condition parameter.

Substitute λ_3 and λ_4 into equation $\rho_2=\hat{\rho}_2$ 、 $\rho_1=\hat{\rho}_1$, then λ_1, λ_2 solved. Substitute λ_1, λ_2, λ_3, and λ_4 into equation (1) and (2), the IRSS pseudo-failure life distribution obtained.

3. application of the proposed method in the reliability evaluation of industrial robot servo system

Table 2 shows the IRSS pseudo-failure life data based on the performance degradation data of a certain type IRSS. Suppose $\boldsymbol{T}_{w_i}$ is the IRSS pseudo-failure life data set under pseudo-failure level w_i ($i\in[1, 7]$), apply the Bootstrap method expand $\boldsymbol{T}_{w_1}$, $\boldsymbol{T}_{w_2}$, $\boldsymbol{T}_{w_3}$, $\boldsymbol{T}_{w_4}$, $\boldsymbol{T}_{w_5}$, $\boldsymbol{T}_{w_6}$, $\boldsymbol{T}_{w_7}$. The repeated sampling times is 100, IRSS pseudo-failure life expanded data set $\boldsymbol{T}_{w_1}^*$, $\boldsymbol{T}_{w_2}^*$, $\boldsymbol{T}_{w_3}^*$, $\boldsymbol{T}_{w_4}^*$, $\boldsymbol{T}_{w_5}^*$, $\boldsymbol{T}_{w_6}^*$, $\boldsymbol{T}_{w_7}^*$ obtained.

Table 2 IRSS pseudo-failure life data (unit: h)

IRSS No.	Pseudo-failure level						
	w_1	w_2	w_3	w_4	w_5	w_6	w_7
1	104.08	232.42	405.09	542.07	703.75	852.99	987.99

2	108.08	266.73	410.62	558.09	707.83	841.19	991.83
3	101.33	247.65	411.56	550.13	698.85	865.74	985.56
4	89.74	244.16	435.11	570.63	721.53	837.22	989.39
5	116.09	261.53	416.84	551.88	693.67	848.89	987.72

Apply the GLD method to obtain the IRSS pseudo-failure life distribution based on the IRSS pseudo-failure life expanded data set. Table 3 shows the GLD parameters of each pseudo-failure level w_i ($i \in [1, 7]$).

Table 3 The GLD parameters of each pseudo-failure level

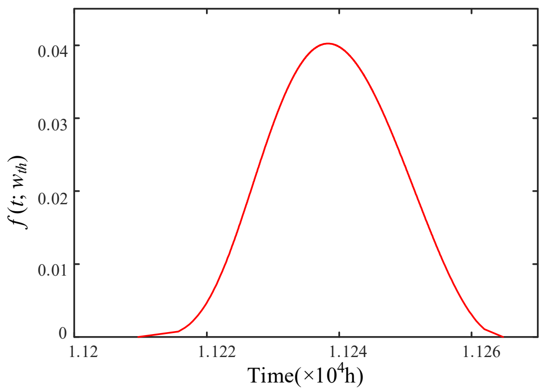
GLD parameters	Pseudo-failure level						
	w_1	w_2	w_3	w_4	w_5	w_6	w_7
λ_1	103.6518	259.1295	422.5463	557.4715	691.5579	840.7216	985.9855
λ_2	0.0391	0.0247	0.0122	0.0210	0.0236	0.0248	0.1087
λ_3	0.2966	0.4433	0.3417	0.1770	0.0060	0.2372	0.0361
λ_4	0.2474	0.1421	0.0799	0.1525	0.5111	0.5904	0.5945

Extrapolate the GLD parameters under IRSS failure threshold w_{th}, they are λ_1=11237.2016, λ_2=0.0363, λ_3=0.2197, and λ_4=0.3311. Substitute λ_1, λ_2, λ_3, and λ_4 into equation (1) and (2), IRSS failure life distribution quantile function $Q(u)$ ($u \in [0, 1]$) and probability density function $f(t; w_{th})$ are obtained.

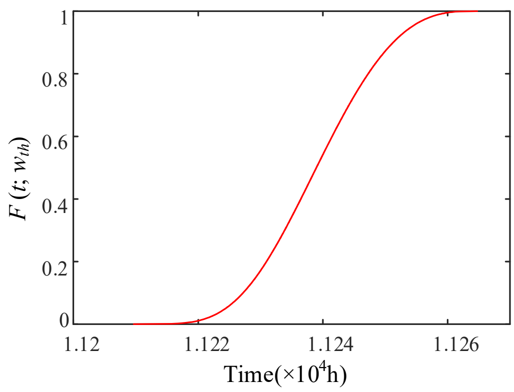
$$Q(u) = 11237.2016 + \frac{1}{0.0363} \cdot [u^{0.2197} - (1-u)^{0.3311}];$$

$$f(t; w_{th}) = \frac{0.0363}{\left[0.2197u^{0.2197-1} + 0.3311(1-u)^{0.3311-1}\right]} \quad t = Q(u);$$

Figure 2 (a) and (b) shows the IRSS failure life distribution probability density function diagram and failure distribution diagram. IRSS failure life $T_{failure}$, characteristic life $T(e^{-1})$ and median life $T(0.5)$ are 11264.75h, 11238.96h and 11242.32h respectively, which are close to the IRSS design failure life 10000h. It shows the validity of the proposed pseudo-failure life distribution reliability estimation method based on GLD.



(a) IRSS failure life distribution probability density function diagram



(b) IRSS failure distribution diagram

Figure 2. IRSS reliability evaluation result

4. conclusion

A reliability evaluation method of pseudo-failure life distribution for Industrial Robot Servo System (IRSS) based on The Generalized Lambda Distribution (GLD) was proposed in the paper addressed to the issue of insufficient reliability test data due to the lack of test samples and limited test time. The proposed method has no need to preset the life distribution, overcome the problem of the lack of prior distributions for the IRSS life distribution. The reliability evaluation of IRSS performance degradation is carried out by experiments, and the reliability evaluation method of IRSS pseudo-failure life distribution based on GLD series method proposed in this paper is applied. The reliability evaluation result is: $T_{failure}$= 11264.75 h, $T(e^{-1})$= 11238.96 h, $T(0.5)$= 11242.32 h, which are closed to the IRSS designed failure life, indicating the validity of the proposed pseudo-failure life distribution reliability estimation method based on GLD.

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