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Reliability Design for Impact Vibration of Hydraulic Pressure Pipeline Systems

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Abstract: The research of reliability design for impact vibration of hydraulic pressure pipeline systems is still in the primary stage, and the research of quantitative reliability of hydraulic components and system is still incomplete. On the condition of having obtained the numerical characteristics of basic random parameters, several techniques and methods including the probability statistical theory, hydraulic technique and stochastic perturbation method are employed to carry out the reliability design for impact vibration of the hydraulic pressure system. Considering the instantaneous pressure pulse of hydraulic impact in pipeline, the reliability analysis model of hydraulic pipeline system is established, and the reliability-based optimization design method is presented. The proposed method can reflect the inherent reliability of hydraulic pipe system exactly, and the desired result is obtained. The reliability design of hydraulic pipeline system is achieved by computer programs and the reliability design information of hydraulic pipeline system is obtained. This research proposes a reliability design method, which can solve the problem of the reliability-based optimization design for the hydraulic pressure system with impact vibration practically and effectively, and enhance the quantitative research on the reliability design of hydraulic pipeline system. The proposed method has generality for the reliability optimization design of hydraulic pipeline system.

Key words: hydraulic pressure impact, vibration systems, probability perturbation method, reliability design

1 Introduction

When hydraulic valves is closed suddenly or moving parts braking apace, the liquid pressure rises sharply and forms the maximum pressure, which may cause device sealed, or the damage of pipe and hydraulic components, even cause the vibration of the equipment, generate large noise, cause the system operates abnormally. It is thus clear that the reliability design of vibration systems under hydraulic pressure impact has practical engineering and academic value.

In the recent thirty years, it has been understanding clearly about the cause of hydraulic pressure impact in the field of hydraulic system design, and puts forward the corresponding prevention and control measures[1]. Now the theory and method of reliability design have reached a certain level, some have been applied in the actual mechanical design[2–8]. These studies can help engineers to establish the structure tolerance safety and made the mechanical equipment safe under the influence of control random parameters, make the forecast of mechanical equipment more in line with actual working performance, so the equipment will safety and more cheaper.

CHARNES, et al[9], used stochastic programming method to optimize the random design parameters in engineering, then the method was widely used in structure safety design. The other way to solve the reliability optimization design problem was established the reliability optimization model using the reliability index, then was solved using existing optimization algorithm[10–12], In half a century, there are many reliability optimization design theory and method, Refs. [13–14] describe the history and the development of the reliability-based optimization design. The reliability of hydraulic components and system research began in the 1970 s, and many scholars had reached considerable achievement in different levels, such as: the reliability modeling of hydraulic excavator system[15] and the reliability of hydraulic structures considering unit hydrograph uncertainty[16] . They assessed the reliability of hydraulic shovel system using fault trees[17] and researched the systems reliability of mechanical and hydraulic drive systems[18]. Reliability-based design and analysis on hydraulic system for synthetic rubber press[19] was discussed and the safety and reliability analysis of a thermal-hydraulic passive system was investigated using the failure mode and effect analysis application[20].

Hydraulic components and system reliability researches become even more important because they have the various failure modes and complex failure mechanism. The paper puts forward the method of reliability design of hydraulic pressure impact vibration systems. This study derives the numerical characteristics of state function of hydraulic pressure impact vibration systems using probability perturbation method and reliability technology, derives the reliability of hydraulic pressure impact vibration systems

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and explores the transfinite damage and solve the reliability problems of hydraulic pressure impact vibration systems. It can realize the reliability design of hydraulic pressure impact vibration systems through computer program, and ensure the safety and reliability of the hydraulic system.

2 Hydraulic Pressure Impact Vibration Systems

In the pipe which the hydraulic valve closed suddenly, the hydraulic pressure makes the pipe vibration, this kind of transient pressure and vibration will make the pipe broken, and reduce the working efficiency. As shown in Fig. 1, it assumes that the pressure of the system under normal work is p (Pa), the maximum pressure is

$$p_{\max} = p + \Delta p, \tag{1}$$

where Δp is the maximum increment of hydraulic impact pressure(Pa). Set cross sectional area of pipe as A(m^2), length as L(m), the speed of liquid flow in the pipe as v(m/s), liquid flow stop immediately when fluid flow abruptly closed at the pipe end, the hydraulic impact pressure increment (Pa)[21] as

$$\Delta p = \rho v \frac{\sqrt{\dfrac{K}{\rho}}}{\sqrt{1+\dfrac{d}{E}\dfrac{K}{\delta}}}, \tag{2}$$

where K is liquid bulk modulus of elasticity (Pa), ρ is liquid density (kg/m^3), d is inner diameter of pipe (m), E is material modulus of elasticity of pipe (Pa), δ is the thickness of pipe wall (m). Eq. (1) applicable for pipe closed suddenly, that is time of liquid flow in the pipe after hydraulic valve closed is less than time the pressure wave passing back and forth needed, that is

$$t \leqslant t_c = \frac{2L}{c}, \tag{3}$$

where t is time of liquid stopping flow in the pipe after hydraulic valve closed(s), t_c is critical closing time(s), c is the spread speed of shock wave in pipe (m/s), L is the length of the pipeline from the hydraulic valve to the hydraulic system (m).

The situation accords with Eq. (3) called perfectly impact, otherwise called imperfectly impact. For the short pipe, if t=0.005 s and the length of pipe is not more than 3 m, it is imperfectly impact. The pressure rise caused by imperfectly impact was lower than caused by perfectly impact. It should set hydraulic valve instantaneous closed when calculating pipe vibration caused by hydraulic impact, the result of the computation is more precise. Therefore, it should increase t, reduce L.

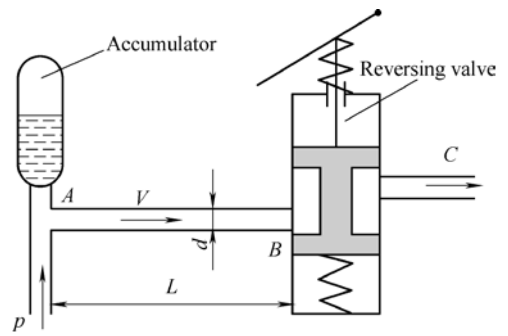

Fig. 1. Vibration by shut hydraulic pressure valve

3 Reliability Design

One of goals of reliability design is calculating reliability

$$R = \int_{g(\boldsymbol{X})>0} f_{\boldsymbol{X}}(\boldsymbol{X})\mathrm{d}\boldsymbol{X}, \tag{4}$$

where $f_{\boldsymbol{X}}(\boldsymbol{X})$ is joint probability density of basic random parameter vector $\boldsymbol{X}=(X_1, X_2, \cdots, X_n)^{\mathrm{T}}$, these random parameters on behalf of the load, characteristics of parts, etc. $g(\boldsymbol{X})$ is state function,

$$\begin{cases} g(\boldsymbol{X}) \leqslant 0, & \text{failure state,} \\ g(\boldsymbol{X}) > 0, & \text{safe state.} \end{cases} \tag{5}$$

Ultimate state equation $g(\boldsymbol{X}) = 0$ for an n-dimensional surface, called the ultimate state surface or failure surface.

Random parameter vector $\boldsymbol{X}$ and state equation $g(\boldsymbol{X})$:

$$\boldsymbol{X} = \boldsymbol{X}_{\mathrm{d}} + \varepsilon \boldsymbol{X}_{\mathrm{p}}, \tag{6}$$

$$g(\boldsymbol{X}) = g_{\mathrm{d}}(\boldsymbol{X}) + \varepsilon g_{\mathrm{p}}(\boldsymbol{X}), \tag{7}$$

where ε is a small parameter, $g_{\mathrm{d}}(\boldsymbol{X})$ is the definite part of random parameters, $g_{\mathrm{p}}(\boldsymbol{X})$ is the random part of random parameters with zero-mean. Obviously, here the request of definite part is more important than that of random part. Mathematical expectation of Eq. (6) and Eq. (7) are as follows[22–23]:

$$\mathrm{E}(\boldsymbol{X}) = \mathrm{E}(\boldsymbol{X}_{\mathrm{d}}) + \varepsilon \mathrm{E}(\boldsymbol{X}_{\mathrm{p}}) = \boldsymbol{X}_{\mathrm{d}}, \tag{8}$$

$$\mathrm{E}\left[g(\boldsymbol{X})\right] = \mathrm{E}\left[g_{\mathrm{d}}(\boldsymbol{X})\right] + \varepsilon \mathrm{E}\left[g_{\mathrm{p}}(\boldsymbol{X})\right] = g_{\mathrm{d}}(\boldsymbol{X}). \tag{9}$$

Similarly, the variance on the basis of matrix algebra and random analysis theory are as follows:

$$\mathrm{Var}\left[\boldsymbol{X}\right] = \mathrm{E}\left[(\boldsymbol{X} - \mathrm{E}(\boldsymbol{X}))(\boldsymbol{X} - \mathrm{E}(\boldsymbol{X}))^{\mathrm{T}}\right] = \varepsilon^2 \mathrm{E}\left[\boldsymbol{X}_{\mathrm{p}} \boldsymbol{X}_{\mathrm{P}}^{\mathrm{T}}\right], \tag{10}$$

$$\mathrm{Var}\big[g(\boldsymbol{X})\big]=\mathrm{E}\Big[\big(g(\boldsymbol{X})-\mathrm{E}\big[g(\boldsymbol{X})\big]\big)^2\Big]=\varepsilon^2\mathrm{E}\Big[\big(g_{\mathrm{p}}(\boldsymbol{X})\big)^2\Big], \tag{11}$$

Expand the state function $g_{\mathrm{p}}(\boldsymbol{X})$ to the first-order approximation in a Taylor series of vector-valued functions and matrix-valued functions at a point $\mathrm{E}(\boldsymbol{X})=\boldsymbol{X}_{\mathrm{d}}$, then

$$g_{\mathrm{p}}(\boldsymbol{X})=\frac{\partial g_{\mathrm{d}}(\boldsymbol{X})}{\partial \boldsymbol{X}^{\mathrm{T}}}\boldsymbol{X}_{\mathrm{p}}. \tag{12}$$

Substituting Eq. (12) into Eq. (11), we can obtain

$$\mathrm{Var}\big[g(\boldsymbol{X})\big]=\varepsilon^2\mathrm{E}\left[\left(\frac{\partial g_{\mathrm{d}}(\boldsymbol{X})}{\partial \boldsymbol{X}^{\mathrm{T}}}\boldsymbol{X}_{\mathrm{p}}\right)\left(\boldsymbol{X}_{\mathrm{p}}^{\mathrm{T}}\frac{\partial g_{\mathrm{d}}(\boldsymbol{X})}{\partial \boldsymbol{X}}\right)\right]= \frac{\partial g_{\mathrm{d}}(\boldsymbol{X})}{\partial \boldsymbol{X}^{\mathrm{T}}}\mathrm{Var}\big[\boldsymbol{X}\big]\frac{\partial g_{\mathrm{d}}(\boldsymbol{X})}{\partial \boldsymbol{X}}, \tag{13}$$

where $\mathrm{Var}\big[\boldsymbol{X}\big]$ is the variance matrix that includes all variance and covariance of the random parameters.

The reliability index is defined as

$$\beta=\frac{\mu_{\mathrm{g}}}{\sigma_{\mathrm{g}}}=\frac{\mathrm{E}\big[g(\boldsymbol{X})\big]}{\sqrt{\mathrm{Var}\big[g(\boldsymbol{X})\big]}}. \tag{14}$$

On the one hand, reliability index can be directly used to measure the reliability of the product, on the other hand, if the basic random parameter vector $\boldsymbol{X}$ is normally distributed, with the point of failure at the state of the surface of the tangent plane approximation to simulate the state surface, we can get a first-order estimate of reliability

$$R=\varPhi(\beta), \tag{15}$$

where $\varPhi(\bullet)$ is the standard normal distribution function.

4 Reliability Optimization Design

There are three contents in the reliability optimization design of mechanical system: quality (weight), cost and reliability. Optimization is concerned with achieving the best outcome of a given operation.

If the design is requested as

$$P\big\{g(\boldsymbol{X})\geqslant 0\big\}\geqslant R_0, \tag{16}$$

then

$$\int_{-\infty}^{\beta_0}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\theta^2}{2}\right)\mathrm{d}\theta=\int_{-\infty}^{\varPhi^{-1}(R_0)}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\theta^2}{2}\right)\mathrm{d}\theta. \tag{17}$$

So

$$\beta_0=\frac{\mu_{\mathrm{g}}}{\sigma_{\mathrm{g}}}\geqslant \varPhi^{-1}(R_0), \tag{18}$$

$$\mu_{\mathrm{g}}-\varPhi^{-1}(R_0)\sigma_{\mathrm{g}}\geqslant 0. \tag{19}$$

Set the constraint meet the probable value R_0, the value of $\varPhi^{-1}(R_0)$ could find out in the normal distribution function table, $\mathrm{E}(g)=\mu_{\mathrm{g}}$ and σ_{g} could find from Eq. (9) and Eq. (13).

Probability optimization design model could be converted to the deterministic model as follows:

$$\begin{cases}\min\ f(\boldsymbol{x})=\mathrm{E}\{f(\boldsymbol{x})\}=f(\bar{\boldsymbol{x}}),\\ \text{s.t. } R(\boldsymbol{x})\geqslant R_0,\\ \quad g_i(\boldsymbol{x})\geqslant 0,\ \ i=1,\cdots,m,\\ \quad h_j(\boldsymbol{x})=0,\ \ j=1,\cdots,q<n,\end{cases} \tag{20}$$

where $R(\boldsymbol{x})$ is the reliability of hydraulic pipe system, R_0 is scheduled reliability of hydraulic pipe system, $f(\boldsymbol{x})$ is cost function or other properties, parameters function of hydraulic pipe system, $g_i(\boldsymbol{x})\geqslant 0,\ i=1,\cdots,m$, m is the number of inequality constraint equation, $h_j(\boldsymbol{x})=0$ ($j=1, 2, \cdots, q, q<n$) is equality constraint equation, and q is smaller than n, the number of design variable.

5 Numerical Example

The example is a hydraulic pipe system, inner diameter of pipe d (24, 0. 12) mm, pipe thickness δ (2, 0.01) mm, original velocity of hydraulic oil in normal working v=(2.0, 0.1) ms, oil pressure at hydraulic directional valve p=(2.0, 0.1) MPa. Set bulk modulus of hydraulic oil $K=(1.226\times10^3,\ 61.3)$ MPa, modulus of elasticity of material of pipe shell $E=(2.06\times10^5,\ 1\ 000)$ MPa, density of hydraulic oil ρ=(900, 45) kg/m^3, material strength of shell of pipe r=(443, 27.5) MPa, rated pressure of hydraulic system p_r=(6.3, 0.39) MPa. The inner diameter of pipe d and the thickness of pipe δ are associated random variables, the correlation coefficient of d and δ is $\rho_{d\delta}$□ 0.7. Calculating the reliability of pipe and devise the reliability optimization design of shell of pipe when the vibration of pipe generation and the emergence of hydraulic impact, if hydraulic directional valve suddenly closed (Fig. 1).

(1) Calculating the reliability of pipe based on materials strength. According to the known condition, the corresponding parameters are obtained:

$$\sqrt{\frac{K}{\rho}}=\sqrt{\frac{1.226\times10^9}{900}}\ \mathrm{m/s}=1\ 167.1\ \mathrm{m/s}.$$

Substituting the known number into Eq. (2), intraductal pressurizing Δp can be obtained when the vibration made hydraulic impact appeared at the time of hydraulic directional valve closed:

$$\Delta p = \frac{2\times 900\times 1167.1}{\sqrt{1+\dfrac{0.024\times 1.22\,6\times 10^{9}}{2.06\times 10^{11}\times 0.002}}}\ \text{Pa} = 2.029\,631\times 10^{6}\ \text{Pa}.$$

Pressure peak value is the sum of oil pressure value and pressure increment value:

$$p_{\max} = p + \Delta p = (2.0 + 2.029\,631)\ \text{MPa} = 4.029\,631\ \text{MPa}.$$

According to the material mechanics knowledge, stress of material of shell of pipe could be obtained from stress formula:

$$\sigma = \frac{p_{\max} d}{2\delta} = \frac{4.029\,631\times 0.024}{2\times 0.002} = 24.177787\ \text{MPa}.$$

Hydraulic impact will be produced when hydraulic valve closed suddenly, the pipe vibrated, meanwhile, pressurizing of pipe $\Delta p = 2.029\,631$ MPa, stress of material of shell of pipe $\sigma = 24.177\,787$ MPa.

So, reduce the pressure increment when hydraulic valve closed suddenly, made the hydraulic impact appear imperfectly impact, Eq. (3) could be rewritten into

$$t > t_c = \frac{2L}{c}.$$

So it should increase the time of closing hydraulic change valve t, reduce the length of pipe from hydraulic directional valve to the system L, this can reduce hydraulic impact, so as to reduce the pipe vibration.

According to the Stress-Strength Interference Theory, the stress limit state equation of state is

$$g(\boldsymbol{X}) = r - \sigma = r - \frac{p_{\max} d}{2\delta} = r - \frac{(p+\Delta p)d}{2\delta} = r - \frac{\left(p + \rho v \dfrac{\sqrt{\dfrac{K}{\rho}}}{\sqrt{1+\dfrac{d}{E}\dfrac{K}{\delta}}}\right) d}{2\delta},$$

where r is material strength of shell of pipe, the basic random variable vector $\boldsymbol{X}=(r, p, \rho, v, K, E, d, \delta)^{\mathrm{T}}$. The mean value $\mathrm{E}[\boldsymbol{X}]$ and variance and covariance $\mathrm{Var}[\boldsymbol{X}]$ of the basic random variable vectors are known:

$$\mathrm{E}[\boldsymbol{X}] = (\mu_r\ \mu_p\ \mu_\rho\ \mu_v\ \mu_K\ \mu_E\ \mu_d\ \mu_\delta)^{\mathrm{T}},$$

$$\mathrm{Var}[\boldsymbol{X}] = \begin{pmatrix} \sigma_r^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_p^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_\rho^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_\upsilon^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_K^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_E^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma_d^2 & \rho_{d\delta}\sigma_d\sigma_\delta \\ 0 & 0 & 0 & 0 & 0 & 0 & \rho_{d\delta}\sigma_d\sigma_\delta & \sigma_\delta^2 \end{pmatrix}.$$

The random variables are normal distribution. The partial derivative of state function $g(\boldsymbol{X})$ with respect to the basic random variable vector $\boldsymbol{X}$ is

$$\frac{\partial g(\bar{\boldsymbol{X}})}{\partial \boldsymbol{X}^{\mathrm{T}}} = \left[\frac{\partial g}{\partial r}\ \ \frac{\partial g}{\partial p}\ \ \frac{\partial g}{\partial \rho}\ \ \frac{\partial g}{\partial v}\ \ \frac{\partial g}{\partial K}\ \ \frac{\partial g}{\partial E}\ \ \frac{\partial g}{\partial d}\ \ \frac{\partial g}{\partial \delta}\right].$$

Substituting above all the formulas and known conditions into mean values and the variance formula of state function, it can obtain the mean value and variance of state function. Then substituting reliability index and reliability formula, it can obtain the area of section A and the reliability index β and reliability R of hydraulic pipe system:

$$A=0.000\,163\,3\ \text{m}^2,\ \beta=18.890\,881\,98,\ R=1.$$

The calculation results show that the reliability of the pipe is high enough to meet the engineering requirements when the hydraulic pipe system running under the normal condition even though the vibration and the impact engender in the pipe.

(2) Calculating the reliability of pipe based on rated pressure of hydraulic system.

Usually, the hydraulic system pressure should meet the requirement for rated pressure in order to ensure the hydraulic equipment running in the normal operation because the hydraulic system pressure is related to hydraulic equipments' working environment and accuracy, etc.

According to the Stress-Strength Interference Theory, the hydraulic system pressure limit state equation of state is

$$g(\boldsymbol{X}) = p_{\mathrm{r}} - p_{\max} = p_{\mathrm{r}} - (p+\Delta p) = p_{\mathrm{r}} - \left(p + \rho v \sqrt{\frac{K}{\rho}} \Big/ \sqrt{1+\frac{d}{E}\frac{K}{\delta}}\right),$$

where p_{r} is the rated pressure of the hydraulic system, the basic random variable vector is $\boldsymbol{X}=(p_r, p, \rho, v, K, E, d, \delta)^{\mathrm{T}}$. The mean value $\mathrm{E}[\boldsymbol{X}]$ and variance and covariance $\mathrm{Var}[\boldsymbol{X}]$ of the basic random variable vectors are known:

$$\mathrm{E}[\boldsymbol{X}] = (\mu_{p_r}\ \mu_p\ \mu_\rho\ \mu_v\ \mu_K\ \mu_E\ \mu_d\ \mu_\delta)^{\mathrm{T}},$$

$$\mathrm{Var}[\boldsymbol{X}] = \begin{pmatrix} \sigma_{p_r}^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_p^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_\rho^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_v^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_K^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_E^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma_d^2 & \rho_{d\delta}\sigma_d\sigma_\delta \\ 0 & 0 & 0 & 0 & 0 & 0 & \rho_{d\delta}\sigma_d\sigma_\delta & \sigma_\delta^2 \end{pmatrix}.$$

The random variables are normal distribution. The partial derivative of state function $g(\boldsymbol{X})$ with respect to the basic random variable vector $\boldsymbol{X}$ is

$$\frac{\partial g(\bar{\boldsymbol{X}})}{\partial \boldsymbol{X}^{\mathrm{T}}} = \left[\frac{\partial g}{\partial p_r}\ \frac{\partial g}{\partial p}\ \frac{\partial g}{\partial \rho}\ \frac{\partial g}{\partial v}\ \frac{\partial g}{\partial K}\ \frac{\partial g}{\partial E}\ \frac{\partial g}{\partial d}\ \frac{\partial g}{\partial \delta}\right].$$

Substituting all the formulas above and known conditions into mean values and the variance formula of state function, it can obtain the mean value and variance of state function. Then substituting reliability index and reliability formula, it can obtain the area of section A and the reliability index β and reliability R of hydraulic pipe system:

$$A=0.000\ 163\ 4\ \mathrm{m}^2,\ \beta=2.256\ 546\ 779,\ R=0.987\ 981\ 795.$$

Numerical results can provide a quantitative basis for project planner to design hydraulic piping system accurately, the above calculation results are in accord with the qualitative analysis results.

(3) Optimization design. The design of reliability condition needs $R=0.999$ and it needs to optimize inner diameter of pipe d and the pipe thickness δ.

Firstly, establishing target function: make the weight of pipe minimum, it needs to minimize the area of section A:

$$\min f(x) = \pi\left[\left(\frac{d+2\delta}{2}\right)^2 - \left(\frac{d}{2}\right)^2\right].$$

Set the design variable $\boldsymbol{x}=[d, \delta]^{\mathrm{T}}$.

Secondly, establishing constraint condition: The constraint conditions of hydraulic system should be set according to the characteristics of the hydraulic system, i.e., the inner diameter of the pipe must be in allowed pressure then meet the flow requirements. In some cases, it can determine the minimum pipe diameter according to the equation:

$$d_0 = \sqrt{\frac{4Q}{\pi v}},$$

where Q is the flow through the pipe (m^3/s), set$Q$=32 L/min=0.534×10^{-3} m^3/s.

Subject to

$$\begin{cases} R(\boldsymbol{x}) - R_0 \geqslant 0, \\ d_0 \leqslant d\ \ (\mathrm{mm}), \\ 1 \leqslant \delta \leqslant 5\ \ (\mathrm{mm}). \end{cases}$$

Thirdly, optimization: the paper uses constraint random direction method to optimize the parameters. Set the initial values as follows: Inner diameter of pipe d=24 mm and thickness of pipe δ=2 mm. According to the given data, inner diameter of pipe d and the pipe thickness δ and the area of section A are as follows:

$$d=18\ \mathrm{mm},\ \delta=2.203\ 772\ \mathrm{mm},\ A=0.000\ 139\ 877\ 9\ \mathrm{m}^2.$$

It can be seen, after optimization, the area of section A of the pipe is greatly reduced.

6 Conclusions

(1) The reliability design method puts forward from the paper can reflect the inherent reliability of hydraulic pipe system exactly. It will create the balance design attuning reasonable reliability and achieve the best product reliability requirements.

(2) The mathematical mechanical model can use in the practical calculation to estimate or predict the reliability of hydraulic pipe system under the specified working conditions, and reveal the essentiality of reliability design of hydraulic pipe system.

(3) Using the reliability optimization design method put forward in this paper, the design cycle can be shortened, it can save test funds and improve the level of design. It is universal for reliability optimization design of hydraulic pressure impact vibration of hydraulic pipe system, and can be used in all kind of reliability optimization design of mechanical hydraulic industry.

References

[1] WEN Bangchun, ZHANG Yimin, ER Zhongkai, et al. *Machine design handbook*[M]. 5th ed. Beijing: China Machine Press, 2010. (in Chinese)

[2] ANG A H-S, TANG W H. *Probability concepts in engineering planning and design*[M]. New York: John Wiley & Sons, 1984.

[3] XU Hao. *Reliability design of mechanical strength*[M]. Beijing: China Machine Press, 1984. (in Chinese)

[4] GAO Zhentong. *Fatigue applied statistics*[M]. Beijing: National Defense Industry Press, 1986. (in Chinese)

[5] YANG Weimin, SHENG Yixing. *System reliability digital simulation*[M]. Beijing: Beihang University Press, 1990. (in Chinese)

[6] HE Guowei. *Reliability design*[M]. Beijing: China Machine Press, 1993. (in Chinese)

[7] LIU Weixin. *Reliability design of machine*[M]. Beijing: Tsinghua University Press, 1996. (in Chinese)

[8] ZHANG Yimin. *Reliability design of automobile components*[M]. Beijing: Beijing Institute of Technology Press, 2000. (in Chinese)

[9] CHARNES A, COOPER W W. Chance constrained programming [J]. *Management Science*, 1959, 6(1): 73–79.

[10] FRANGOPOL D M. Sensitivity of reliability-based optimum design[J]. *J. Struct. Eng., ASCE*, 1985, 111(8): 1 703–1 721.

[11] LEE T W, KWAK B M. A reliability-based optimal design using advanced first order second moment method[J]. *Mech. Struct. Mach.*, 1987, 15(4): 523–542.

[12] NIKOLAIDIS E, BURDISSO R. Reliability-based optimization–a safety index approach[J]. *Comput. Struct.*, 1988, 28(6): 781–788.

[13] FRANGOPOL D M. Structural optimization using reliability concepts[J]. *J. Struct. Eng., ASCE*, 1985, 111(11): 2 288–2 296.

[14] MOSES F. Problems and prospect of reliability-based optimization[J]. *Eng. Struct.*, 1997, 19(4): 293–301.

[15] MAJUMDAR S K. Study on reliability modeling of a hydraulic excavator system[J]. *Quality and Reliability Engineering International*, 1995, 11(1): 49–63.

[16] ZHAO B, TUNG Y K, YEH K C, YANG J C. Reliability analysis of hydraulic structures considering unit hydrograph uncertainty[J]. *Stochastic Hydrology and Hydraulics*, 1997, 11(1): 33–50.

[17] SAMANTA B, SARKAR B, MUKHERJEE S. Reliability assessment of hydraulic shovel system using fault trees[J]. *Transactions of the Institution of Mining and Metallurgy Section A-Mining Technology*, 2002, 111: A129–A135.

[18] AVONTUUR G C, VAN DER WERFF K. Systems reliability analysis of mechanical and hydraulic drive systems[J]. *Reliability Engineering & System Safety*, 2002, 77(2): 121–130.

[19] YAO C Y, ZHAO J Y. Reliability–based design and analysis on hydraulic system for synthetic rubber press[J]. *Chinese Journal of Mechanical Engineering*, 2005, 18(2): 159–162.

[20] BURGAZZI L. Failure mode and effect analysis application for the safety and reliability analysis of a thermal-hydraulic passive system[J]. *Nuclear Technology*, 2006, 156(2): 150–158

[21] QU Weide, TANG Hengling. *Mechanical vibration handbook*[M]. 2nd ed. Beijing: China Machine Press, 2000. (in Chinese)

[22] ZHANG Yimin, CHEN Suhuan, LIU Qiaoling, et al. Stochastic perturbation finite elements[J]. *Comput. Struct.*, 1996, 59(3): 425–429.

[23] ZHANG Yimin, LIU Qiaoling. Reliability-based design of automobile components[J]. *P IMechE D-J AUT*, 2002, 216(D6): 455–471.

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