Orthogonal optimization of a water hydraulic pilot-operated pressure-reducing valve

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Abstract. In order to optimize the comprehensive characteristics of a water hydraulic pilot-operated pressure-reducing valve, numerical orthogonal experimental design was adopted. Six parameters of the valve, containing diameters of damping plugs, volume of spring chamber, half cone angle of main spool, half cone angle of pilot spool, mass of main spool and diameter of main spool, were selected as the orthogonal factors, and each factor has five different levels. An index of flowrate stability, pressure stability and pressure overstrike stability ($iFPOS$) was used to judge the merit of each orthogonal attempt. Embedded orthogonal process turned up and a final optimal combination of these parameters was obtained after totally 50 numerical orthogonal experiments. $iFPOS$ could be low to a fairly low value which meant that the valve could have much better stabilities. During the optimization, it was also found the diameters of damping plugs and main spool played important roles in stability characteristics of the valve.

1. Introduction

Constant pressure output pressure-reducing valve is a kind of valve which decreases the system pressure for load use and is capable to keep the reduced pressure stable when system input pressure or flowrate fluctuates in a certain range [1-4]. At present, Danish Danfoss company, Germany Hauhinco company, Japan Kayaba company and Finland HYTAR OY company etc. offer mature products in terms of water hydraulic control valve components, but domestic corresponding products are rare in the number. This paper introduces a domestic pilot-operated pressure-reducing valve which is suitable for low viscosity fluid media, such as water [5-6]. The nominal working pressure is 15MPa and nominal working flowrate is 40L/min. Figure 1 illustrates the structural details. The following work is aiming to optimize the comprehensive characteristics of the valve.
2. Orthogonal optimization

In order to achieve a better stability performances of the valve, orthogonal experimental design was utilized to figure out an optimal parameter configuration of the valve’s structure. Orthogonal experimental design is a highly efficient, rapid, economical and scientific method to solve massive possibilities problems by reasonably filtering out few representative cases which are apt to be the “best” solutions [7-8].

2.1. Target determination

An index of flowrate stability, pressure stability and pressure overstrike stability ($iFPOS$) is defined to quantize the stabilities of the valve. Therefore it is intuitive to decide the merits of the orthogonal optimization results by using $iFPOS$. The smaller $iFPOS$ is, the better stabilities the valve has. There

\[
iFPOS = \frac{I_q + I_p}{2} = \left(\frac{\Delta p_q}{p_q} + \frac{p_{o-s-q}}{p_q \times 30\%}\right) + \left(\frac{\Delta p_p}{p_p} + \frac{p_{o-s-p}}{p_p \times 30\%}\right)/2 \times 100\%
\]

Where $I_q = \left(\frac{\Delta p_q}{p_q} + \frac{p_{o-s-q}}{p_q \times 30\%}\right) \times 100\%$, $I_p = \left(\frac{\Delta p_p}{p_p} + \frac{p_{o-s-p}}{p_p \times 30\%}\right) \times 100\%$ are respectively used to describe the valve’s stabilities; subscript $q$ or $p$ refer to the circumstances of inlet flowrate or inlet pressure fluctuating; $p$ is the stable outlet pressure of each period; $\bar{p}$ is the average value of $p$; $\Delta p$ is calculated as the max differential value of $p$ among all periods; $p_{o-s}$ is the overstrike pressure of each period. Changes of inlet flowrate or inlet pressure result in period alterations.

2.2. Factors selection & levels setting

Parameters difficult to adjust are preferentially screened as the orthogonal factors. Therefore six parameters, including diameters of damping plugs $\varphi$, volume of spring chamber $V_s$, half cone angle of main spool $\alpha_m$, half cone angle of pilot spool $\alpha_p$, mass of main spool $m_m$ and diameter of main spool $d_m$, stand out from crowd. Each factor is assigned 5 levels. In this case, the chosen levels are practicable for manufacturing. Then a table of orthogonal factors and levels is formed.

| Factors | diameters of damping plugs $\varphi$ | volume of spring chamber $V_s$ | half cone angle of main spool $\alpha_m$ | half cone angle of pilot spool $\alpha_p$ | mass of main spool $m_m$ | diameter of main spool $d_m$ |
|---------|-----------------------------------|-------------------------------|----------------------------------------|----------------------------------------|--------------------------|---------------------------|
| Level 1 | 0.15mm                            | 35cm³                         | 20°                                    | 10°                                    | 0.06kg                   | 16mm                      |
| Level 2 | 0.20mm                            | 40cm³                         | 25°                                    | 15°                                    | 0.07kg                   | 17mm                      |
| Level 3 | 0.25mm                            | 45cm³                         | 30°                                    | 20°                                    | 0.08kg                   | 18mm                      |
| Level 4 | 0.30mm                            | 50cm³                         | 35°                                    | 25°                                    | 0.09kg                   | 19mm                      |
| Level 5 | 0.35mm                            | 55cm³                         | 40°                                    | 30°                                    | 0.10kg                   | 20mm                      |
2.3. Orthogonal scheme design
As known the number of factors \( n_f = 6 \) and the number of levels \( n_l = 5 \). The entire experimental scheme may contain \( n_f n_l = 5^6 = 15625 \) different combinations. It is exhausted and meaningless to complete all these possibilities. The experiment number can be considerably diminished by the orthogonal way. According to \( n_l \) and \( n_f \), orthogonal table \( L_{25}(5^6) \) is adopted (as seen in Table 2). The number \( i \) (\( i = 1, 2, 3, 4, 5 \)) indicates relatively levels of certain factors and each line means to be one of the orthogonal parameter combinations.

**Table 2.** Table of orthogonal scheme

| ExpNo. | \( \phi \) A | \( F \) B | \( \alpha_m \) C | \( \alpha_p \) D | \( m_e \) E | \( d_e \) F | ColNo. |
|--------|-------------|-------------|----------------|----------------|---------------|---------------|--------|
| 1      | 1(0.15mm)  | 1(35cm³)   | 1(20°)        | 1(10°)         | 1(0.06kg)     | 1(16mm)       | 1      |
| 2      | 1          | 2(40cm³)   | 2(25°)        | 2(15°)         | 2(0.07kg)     | 2(17mm)       | 2      |
| 3      | 1          | 3(45cm³)   | 3(30°)        | 3(20°)         | 3(0.08kg)     | 3(18mm)       | 3      |
| 4      | 1          | 4(50cm³)   | 4(35°)        | 4(25°)         | 4(0.09kg)     | 4(19mm)       | 4      |
| 5      | 1          | 5(55cm³)   | 5(40°)        | 5(30°)         | 5(0.10kg)     | 5(20mm)       | 5      |
| 6      | 2(0.20mm)  | 1          | 2             | 3              | 4             | 5             | 6      |
| 7      | 2          | 2          | 3             | 4              | 5             | 1             | 7      |
| 8      | 2          | 3          | 4             | 5              | 1             | 2             | 8      |
| 9      | 2          | 4          | 5             | 1              | 2             | 3             | 9      |
| 10     | 2          | 5          | 1             | 2              | 3             | 4             | 10     |
| 11     | 3(0.25mm)  | 1          | 3             | 5              | 2             | 4             | 11     |
| 12     | 3          | 2          | 4             | 1              | 3             | 5             | 12     |
| 13     | 3          | 3          | 5             | 2              | 4             | 1             | 13     |
| 14     | 3          | 4          | 1             | 3              | 5             | 2             | 14     |
| 15     | 3          | 5          | 2             | 4              | 1             | 3             | 15     |
| 16     | 4(0.30mm)  | 1          | 4             | 2              | 5             | 3             | 16     |
| 17     | 4          | 2          | 5             | 3              | 1             | 4             | 17     |
| 18     | 4          | 3          | 1             | 4              | 2             | 5             | 18     |
| 19     | 4          | 4          | 2             | 5              | 3             | 1             | 19     |
| 20     | 4          | 5          | 3             | 1              | 4             | 2             | 20     |
| 21     | 5(0.35mm)  | 1          | 5             | 4              | 3             | 2             | 21     |
| 22     | 5          | 2          | 1             | 5              | 4             | 3             | 22     |
| 23     | 5          | 3          | 2             | 1              | 5             | 4             | 23     |
| 24     | 5          | 4          | 3             | 2              | 1             | 5             | 24     |
| 25     | 5          | 5          | 4             | 3              | 2             | 1             | 25     |

2.4. Numerical orthogonal experiments
Numerical analysis was based on AMESim (in Figure 2). The adjustable throttle valve and the relief valve were used to adjust inlet flowrate and inlet pressure of the pressure-reducing valve. Outlet pressure was set at about 10MPa. The numerical results are shown in Table 3.

![Figure 2. AMESim diagrammatic of the pressure-reducing valve](image-url)
Table 3. Orthogonal Experiments Results

| ExpNo. | Factors | Results | iFPOS |
|--------|---------|---------|-------|
|        | $\theta$ | $V_s$ | $\alpha_s$ | $\alpha_p$ | $m_s$ | $d_m$ | $I_s$ | $I_p$ | |
|        | A | B | C | D | E | F | | | |
| ColNo. | 1 | 2 | 3 | 4 | 5 | 6 | | | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1.572% | 2.043% | 1.807% |
| 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1.807% | 1.894% | 1.850% |
| 3 | 1 | 3 | 3 | 3 | 3 | 3 | 1.088% | 1.718% | 1.403% |
| 4 | 1 | 4 | 4 | 4 | 4 | 4 | 1.077% | 1.735% | 1.406% |
| 5 | 1 | 5 | 5 | 5 | 5 | 5 | 1.852% | 1.181% | 1.516% |
| 6 | 2 | 1 | 2 | 3 | 4 | 5 | 1.076% | 1.838% | 1.457% |
| 7 | 2 | 2 | 3 | 4 | 5 | 1 | 0.875% | 1.962% | 1.419% |
| 8 | 2 | 3 | 4 | 5 | 1 | 2 | 1.338% | 1.525% | 1.432% |
| 9 | 2 | 4 | 5 | 1 | 2 | 3 | 0.635% | 1.351% | 0.993% |
| 10 | 2 | 5 | 1 | 2 | 3 | 4 | 1.134% | 1.460% | 1.297% |
| 11 | 3 | 1 | 3 | 5 | 2 | 4 | 1.922% | 1.339% | 1.625% |
| 12 | 3 | 2 | 4 | 1 | 3 | 5 | 2.426% | 1.076% | 1.751% |
| 13 | 3 | 3 | 5 | 2 | 4 | 1 | 2.559% | 0.931% | 1.745% |
| 14 | 3 | 4 | 1 | 3 | 5 | 2 | 1.960% | 0.822% | 1.391% |
| 15 | 3 | 5 | 2 | 4 | 1 | 3 | 1.017% | 0.908% | 0.962% |
| 16 | 4 | 1 | 4 | 2 | 5 | 3 | 1.709% | 1.736% | 1.722% |
| 17 | 4 | 2 | 5 | 3 | 1 | 4 | 1.322% | 0.966% | 1.144% |
| 18 | 4 | 3 | 1 | 4 | 2 | 5 | 1.969% | 1.266% | 1.617% |
| 19 | 4 | 4 | 2 | 5 | 3 | 1 | 3.196% | 2.044% | 2.620% |
| 20 | 4 | 5 | 3 | 1 | 4 | 2 | 1.020% | 0.972% | 0.996% |
| 21 | 5 | 1 | 5 | 4 | 3 | 2 | 1.302% | 1.846% | 1.574% |
| 22 | 5 | 2 | 1 | 5 | 4 | 3 | 1.790% | 2.231% | 2.011% |
| 23 | 5 | 3 | 2 | 1 | 5 | 4 | 1.798% | 2.293% | 2.045% |
| 24 | 5 | 4 | 3 | 2 | 1 | 5 | 1.249% | 1.704% | 1.476% |
| 25 | 5 | 5 | 4 | 3 | 2 | 1 | 2.013% | 1.510% | 1.762% |

$S_i (i=1, 2, 3, 4, 5)$ is the sum of $iFPOS$ with a same level $i$ under a certain factor. For example, $S_2(\text{ColNo.2})=iFPOS(\text{ExpNo.2})+iFPOS(\text{ExpNo.7})+iFPOS(\text{ExpNo.12})+iFPOS(\text{ExpNo.17})+iFPOS(\text{ExpNo.22}),$ and $R=\max(S_i)-\min(S_i).$ Usually $S_i$ is used to indicate the efficiency of different levels. In this case, the smaller $S_i$ is, the more efficient level $i$ is. Differently, $R$ acts on factors. The larger $R$ is, the more significant the factor is for controlling $iFPOS$.

As seen in Table 3, the intuitive optimal combination is A3B5C2D4E1F3 with a lowest $iFPOS$ 0.96%, but the calculating optimal combination is A2B5C3D4E1F3. It was found 4 factors (B, D, E, and F) had reached consensuses (B5D 4E1F3) but there were different views about factor A and C. Further work was needed.

Meanwhile, it is indicated that the sequence of the factors is AFDCEB according to the effectiveness of the factors on stability control.

2.5. Second orthogonal design

Compared to the first orthogonal scheme, the second orthogonal scheme involves 2 factors (A and C) and the same level assignments. So Table 2 can be reused by replacing mutable levels of B, D, E, and F with fixed values. Then Table 4 is obtained as follows.
Table 4. Orthogonal Experiments Results

| ExpNo. | φ  | Vc  | αm | αp | mm  | dm  | lq  | lp  | iFPOS |
|-------|----|-----|-----|-----|-----|-----|-----|-----|-------|
|       | A  | B   | C   | D   | E   | F   |     |     |       |
| 1     | 1  | 5   | 1   | 4   | 1   | 3   |     |     | 1.235%|
| 2     | 1  | 5   | 2   | 4   | 1   | 3   |     |     | 0.997%|
| 3     | 1  | 5   | 3   | 4   | 1   | 3   |     |     | 1.597%|
| 4     | 1  | 5   | 4   | 4   | 1   | 3   |     |     | 1.320%|
| 5     | 1  | 5   | 5   | 4   | 1   | 3   |     |     | 0.909%|
| 6     | 2  | 5   | 2   | 4   | 1   | 3   |     |     | 1.328%|
| 7     | 2  | 5   | 3   | 4   | 1   | 3   |     |     | 0.920%|
| 8     | 2  | 5   | 4   | 4   | 1   | 3   |     |     | 1.104%|
| 9     | 2  | 5   | 5   | 4   | 1   | 3   |     |     | 1.618%|
| 10    | 2  | 5   | 1   | 4   | 1   | 3   |     |     | 1.264%|
| 11    | 3  | 5   | 3   | 4   | 1   | 3   |     |     | 1.614%|
| 12    | 3  | 5   | 4   | 4   | 1   | 3   |     |     | 0.491%|
| 13    | 3  | 5   | 5   | 4   | 1   | 3   |     |     | 1.739%|
| 14    | 3  | 5   | 1   | 4   | 1   | 3   |     |     | 0.770%|
| 15    | 3  | 5   | 2   | 4   | 1   | 3   |     |     | 1.017%|
| 16    | 4  | 5   | 4   | 4   | 1   | 3   |     |     | 2.196%|
| 17    | 4  | 5   | 5   | 4   | 1   | 3   |     |     | 1.955%|
| 18    | 4  | 5   | 1   | 4   | 1   | 3   |     |     | 1.665%|
| 19    | 4  | 5   | 2   | 4   | 1   | 3   |     |     | 1.956%|
| 20    | 4  | 5   | 3   | 4   | 1   | 3   |     |     | 2.289%|
| 21    | 5  | 5   | 5   | 4   | 1   | 3   |     |     | 1.464%|
| 22    | 5  | 5   | 1   | 4   | 1   | 3   |     |     | 1.400%|
| 23    | 5  | 5   | 2   | 4   | 1   | 3   |     |     | 1.181%|
| 24    | 5  | 5   | 3   | 4   | 1   | 3   |     |     | 1.888%|
| 25    | 5  | 5   | 4   | 4   | 1   | 3   |     |     | 1.529%|

| ColNo. |     |     |     |     |     |     |     |     |     |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1      |     |     |     |     |     |     |     |     |     |
| 2      |     |     |     |     |     |     |     |     |     |
| 3      |     |     |     |     |     |     |     |     |     |
| 4      |     |     |     |     |     |     |     |     |     |
| 5      |     |     |     |     |     |     |     |     |     |
| 6      |     |     |     |     |     |     |     |     |     |

The results show the intuitive optimal configuration matches the calculating optimal configuration perfectly. A3B5C4D4E1F3 is the optimal configuration for the valve to achieve a superlative stability characteristic. IFPOS is low to 0.784%. The sequence of the factors is AC, which is in tune with first orthogonal results.

Table 5. Orthogonal Results

| Factors         | diameters of damping plugs φ | volume of spring chamber Vc | half cone angle of main spool αm | half cone angle of pilot spool αp | mass of main spool mm | diameter of main spool dm |
|-----------------|------------------------------|-----------------------------|---------------------------------|---------------------------------|----------------------|-------------------------|
| Optimal configuration | 0.25mm                      | 55cm³                       | 35°                             | 25°                             | 0.06kg               | 18mm                    |

2.6. Orthogonal optimization results

Figure 3 shows the eventual consequences by applying the orthogonal results whose parameters are listed in Table 5. The inlet flowrate changes every 2 seconds with a fixed inlet pressure p_in=15MPa in Figure 3(a), and the inlet pressure changes every 2 seconds with a fixed inlet flowrate q_in=40L/min in Figure 3(b). As seen, the valve accessed to quiet ideal comprehensive characteristics.
3. Conclusions

- The number of numerical experiments plummeted from 15625 to 50. The function of orthogonal experimental design was well verified.
- The pilot-operated pressure-reducing valve is capable of having good comprehensive characteristics by reasonably configuring different parameters and optimizing the structure.
- The diameters of damping plugs and main spool play important roles in stability characteristics of the valve.

Some experimental work was carried out and the conclusions above were correctly proved [5].

References

[1] Hilton D.J. and Lichtarowicz A. 1973. Instabilities in a pressure-reducing valve-pipework system: valve with downstream pipeline only. In Proceedings of Third International Fluid Power Symposium, Turin, Italy, pp. C3.45-C3.71.
[2] Prescott S.L. and Ulanicki B. 2003. Dynamic modelling of pressure reducing valves. J. Hydraul. Engng, 129(10), 804-812
[3] K Suzuki and E Urata. 2008. Development of a direct pressure-sensing pressure-reducing valve for water hydraulic. In Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, (222), 787-797
[4] Z.Y. Li. 2011. Hydraulic Component and System (the 3rd Edition), Beijing: China Machine Press, (in Chinese)
[5] S. Wu, X.Y. Mao, Y.D. Liao, etc. 2011. Static Characteristics Analysis of Seawater Hydraulic Pilot-operated Pressure Reducing Valve, Journal of Wuhan University of Technology, (33): 134-138 (in Chinese)
[6] X.Y. Mao, J.H. Hu, etc. 2017. Characteristic analysis of a water hydraulic pilot-operated pressure-reducing valve, In Proceedings of 3rd International Conference on Advances in Energy, Environment and Chemical Engineering, (69)012072
[7] R.J. Liu, Y.W. Zhang, etc. 2010. Study on the design and analysis methods of orthogonal experiment, Experimental Technology and Management, 27(09):52-55 (in Chinese)
[8] X.L. Wei, B.J. Xue, etc. 2010. Optimization design of the stability for the plunger assembly of oil pimps based on multi-target orthogonal test design, Journal of Hebei University of Engineering (Natural Science Edition), 27(03):95-99 (in Chinese)