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A Study on the Optimum Design of Cylinder Block in Swash Plate Type Oil Hydraulic Piston Pump

Ilhyun Baek, Ihnsung Cho[1], Jaeyoun Jung[2,†], Byungin Choi[3] and Seokhyung Oh[4]

[1]*Department of Precision Mechanical Engineering, Chonbuk National University, Jeonju, Korea*
[2]*Division of Mechanical & Aerospace System Engineering and RCIT, Chonbuk National University, Jeonju, Korea*
[3]*Division of Mechanical & Aerospace System Engineering, Chonbuk National University, Jeonju, Korea*
[4]*Division of Mechanical Engineering, Kunsan National University, Kunsan, Korea*

Abstract: Recently, requirements relating to performance, environment and noise in the oil hydraulic system of the heavy construction equipment have been reinforced continuously. In order to solve these technical trends, studies on the system compactness, operation under high pressure and great rotating speed, electronic control, substitute oil, and noise reduction have been progressed briskly. Among these recent studies, the system operation under high pressure is quite difficult to carry into effect due to mechanical limitations; that is, for realizing the system operation in the hydraulic pump under high pressure, the improvements or innovations on the design techniques, the manufacturing techniques, and the lubrication performance of the working oil are required. Accordingly, in this study, the stress distribution and optimum design factors under the maximum pressure were discussed by using stress analysis on the cylinder block of the hydraulic axial piston pump, which is one of the most important relative sliding regions.
Keywords: Hydraulic piston pump, cylinder block, stress analysis, optimum design, finite element method

1. Introduction

Recently, restrictions of performance, environment and noise on the oil hydraulic system of heavy construction equipment have been reinforced continuously. In order to solve these problems, studies on compactness of the system, operation under high rotating speed and pressure, electronic control, substitute oil, and noise reduction have been progressed quickly [1].

The hydraulic axial piston pump used as a main power source in the hydraulic system is no exception to these technical trends. The axial piston pump is suitable for operation under high pressure and great rotating speed, and easier to realize variable displacement than other hydraulic pumps. Consequently, it is used as the main pump in the heavy construction equipment.

Recent studies relating to the axial piston pump show the following technical trends.

(1) Compactness of size and weight through improvement of structure and reduction of total length.
(2) Realization of high pressure and performance through the change of design factors such as material, surface roughness, and dimension.
(3) Reduction of noise and pressure pulsation.
(4) Realization of electronic control for optimum control of pressure and flow rate.

Of the above classifications, the operation of the system under high pressure has been studied continuously. However, its realization is very difficult due to mechanical limitations. In other words, if the pressure of the hydraulic pump increases, oil film which exists in relative sliding regions breaks, then adhesion can be accordingly generated by excessive load and stress.

At present, the Max pressure of the oil hydraulic piston pump for heavy construction equipment is generally about 35 MPa. Accordingly, pump makers must try to exceed the existing pressure limit up to some higher pressure above 40 MPa. For realizing the operation of the system under higher pressure, the improvements or innovations on the design techniques (hydraulic mechanism, material, and surface treatment, etc), the manufacturing techniques (accuracy of dimension, management of surface roughness, etc), and the lubrication performance of the working oil are required [2].

In this study, in order to satisfy those demands under high pressure, the stress distribution and optimum design factors under the Max pressure were discussed by using stress analysis on the cylinder block of the hydraulic axial piston pump, which is one of the most important relative sliding regions [5].

2. Modeling and Analysis

2.1. Model for Analysis

Fig. 1 shows the structure diagram of the swash type oil hydraulic piston pump.

The cylinder block, which is in motion relative to the valve plate and all the pistons compose the main rotary part of the axial piston pump. In the relative sliding motion between the cylinder block and valve plate, the Max sliding velocity of the

†Corresponding author; jungjy@chonbuk.ac.kr
Tel: +82-63-270-2372, Fax: +82-63-270-2388

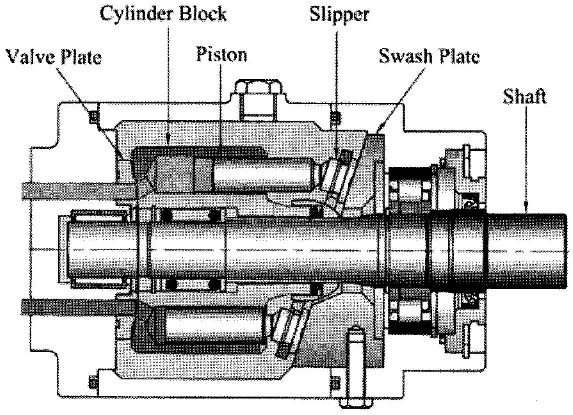


Fig. 1. Diagram of oil hydraulic piston pump.

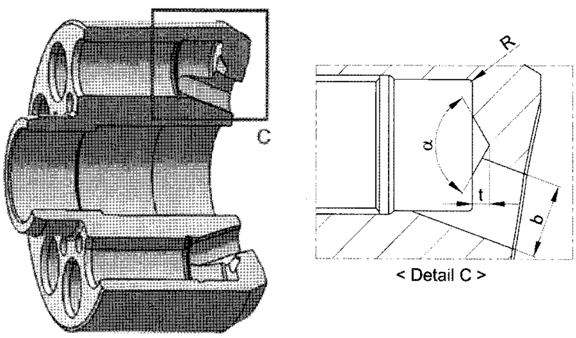


Fig. 2. Drawing of cylinder block.

cylinder block relative to the valve plate is known as 16~23m/s, and oil film is built up by the equilibrium of the compression force which pushes the cylinder block in the direction towards the valve plate and the separation force which tends to counteract that compression force.

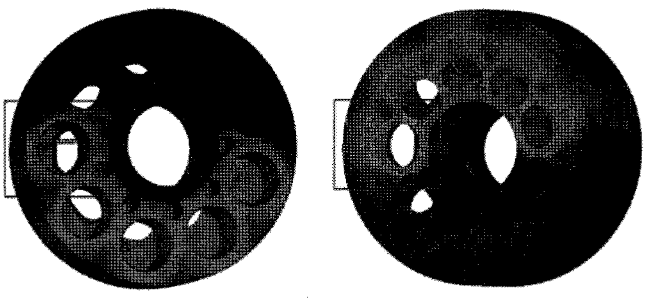
In the relative sliding movement between the cylinder block and the pistons, the Max relative sliding velocity of the piston to the cylinder block is known to be 2.5~4 m/s [10].

Usually, steel is used for the main body of the cylinder block, and brass alloy of LBC types is fusion-spliced in the sliding region by the side of the valve plate and copper alloy is indented in the sliding region by the side of the pistons.

The object of analysis in this study was the cylinder block of the swash-plate type axial piston pump. This pump is used in the excavator with the displacement of 140 cc/rev and the discharge pressure of 35 MPa as shown in Fig. 2, and it was 3D-modeled for the analysis. To exceed the existing pressure limit, the experimental pressure set for the analysis was 40 MPa.

2.2. Design factors

There are so many design factors undetermined in the cylinder block that the stress analysis on the cylinder block is difficult to carry out. Therefore, the original data of the cylinder block in the excavator was used as a reference standard for analysis. Fig. 3 shows the results of the stress analysis on this model and the point of Max stress was found at the edge of the bottom in the cylinder bore (Box in Fig. 3).



(a) View B **(b) View C**

Fig. 3. Results of stress analysis of standard model.

Thus, design factors for analysis were identified to be fixed around the region with the Max stress value according to the analysis results on the standard cylinder block with original data.

Consequently, since the phenomenon of the stress concentration appeared at the bottom of the cylinder bore, factors for analysis were designed around this region shown in Detail C of Fig. 2.

All these factors, such as the radius of the edge of the bottom of the cylinder bore (R[mm]), the drilling depth (t[mm]), the drilling angle (α[°]), and the width of the port connected to the valve plate (b[mm]), have their own three levels.

Table 1 shows all the factors and their corresponding levels for analysis and Table 2 shows the orthogonal array table of L_9 (3^4) generally used for 3-level and 4-factor analysis [3,4,6].

Table 3 shows the mechanical properties of materials used in this study. Generally, the sliding motion between both hard materials receives more wear than that between a hard material and a soft material in the tribological aspect, so the soft materials such as brass alloy were used in the cylinder bore and the spherical surface part. In this study, SCM440 was used

Table 1. Design factors and level for analysis

Level \ Factor	R (mm)	t (mm)	α (°)	b (mm)
0	1	1.5	110°	13
1	3	3.5	120°	15
2	5	5.5	130°	17

Table 2. Orthogonal array table of L_9 (3^4)

No \ Factor	R	t	α	b
1	0	0	0	0
2	0	1	1	1
3	0	2	2	2
4	1	0	1	2
5	1	1	2	0
6	1	2	0	1
7	2	0	2	1
8	2	1	0	2
9	2	2	1	0

Table 3. Material properties of cylinder block

Cylinder Block	Main body part	Fusion-Spliced and indented part
Material	SCM440	Yellow Brass
Young Modulus	205 GPa	105 GPa
Poisson Ratio	0.29	0.346
Density	7850 kg/m^3	8470 kg/m^3
Yield Strength	580 MPa	435 MPa

in the main body, and yellow brass was fusion-spliced in the spherical surface part and indented in the cylinder bore as well.

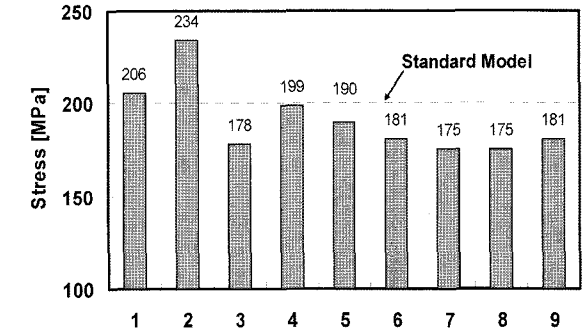


Fig. 4. Comparison of max stress.

3. Results and Discusssions

3.1. Result of stress analysis

Fig. 4 shows the results of the stress analysis performed one by one according to the orthogonal array table of Table 2. The highest pressure shown in No. 2 was higher than that in the standard model (200 MPa) by 17%, while, the highest values in No. 7 and No. 8 were lower than it by 12.5%.

Fig. 5 shows all the Max stress values from No. 1 to No. 9. In the case with the Max stress value over 190 MPa, the stress concentration appears at the bottom of the cylinder bore, and its critical value is about 32% of the yield strength of the

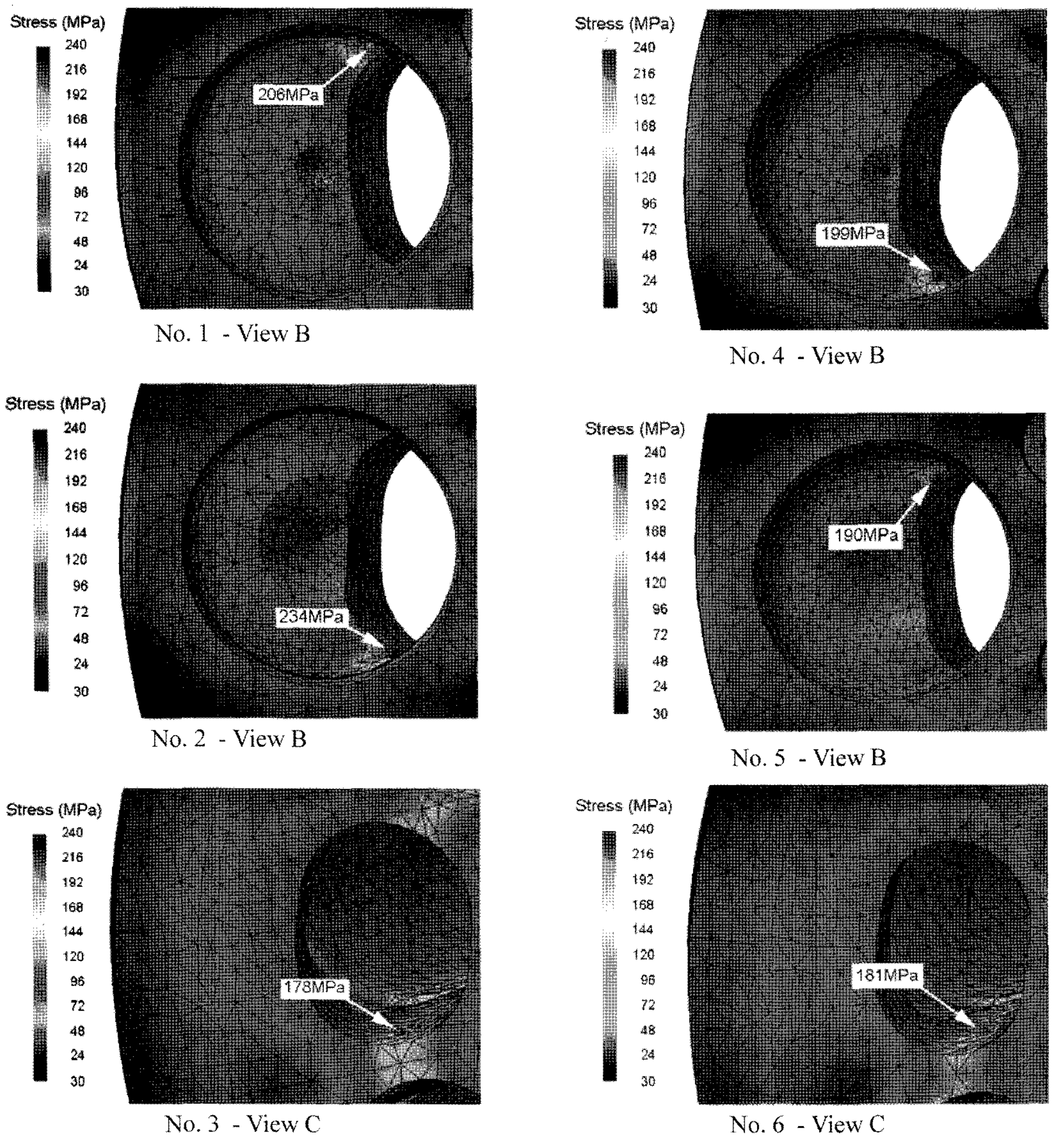


Fig. 5. Results of stress analysis by orthogonal array.

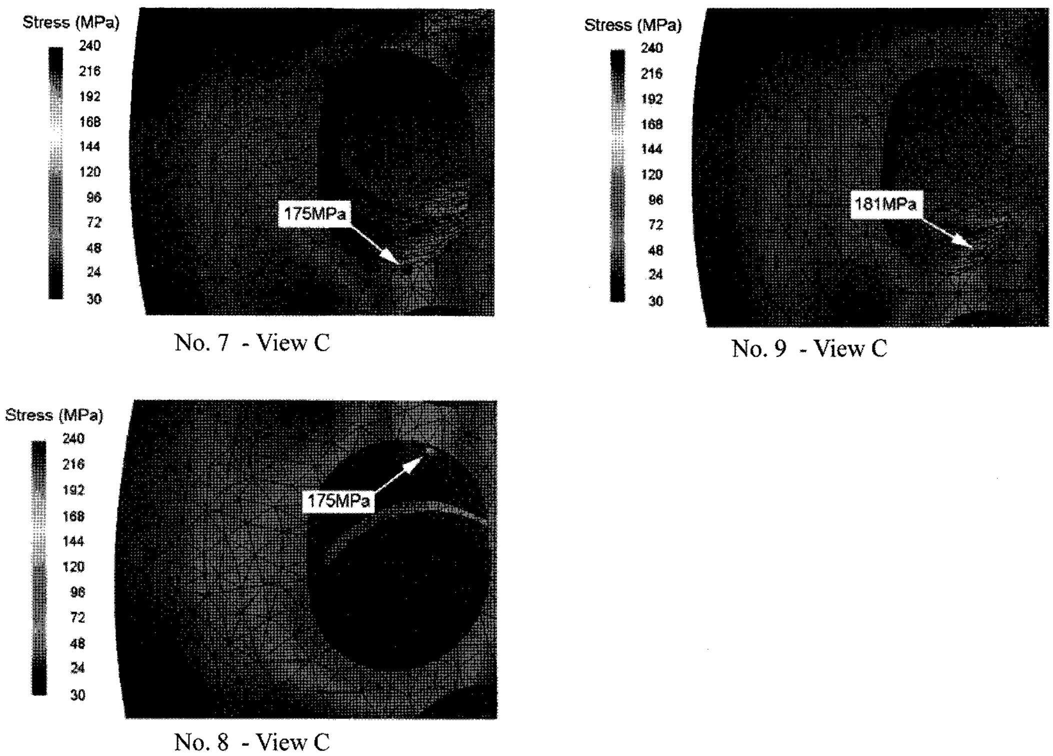


Fig. 5. Continued.

material. However, in the cases with the Max values below 190 MPa such as No. 7 and No. 8, the concentrations of stress appear at the inner wall of the port connected with the valve plate, and they were about 30% of the yield strength of the material.

In order to figure out the optimum design factors, which could minimize the Max stress value, analysis of variance table (ANOVA) was accordingly carried out by using the result of Fig. 4.

The total sum of squares S_T can be described as the sums of variations for each factor.

$$S_T = S_R + S_t + S_\alpha + S_b \tag{1}$$

$$S_R = \sum_{i=0}^{2} \frac{T_{i...}^2}{3} - CT \tag{2}$$

$$S_t = \sum_{j=0}^{2} \frac{T_{.j..}^2}{3} - CT \tag{3}$$

$$S_\alpha = \sum_{k=0}^{2} \frac{T_{..k.}^2}{3} - CT \tag{4}$$

$$S_b = \sum_{l=0}^{2} \frac{T_{...l}^2}{3} - CT \tag{5}$$

Here, the correction term $CT = T^2/N$. In addition, the mean square V can be described as $V = S/\phi$. When the value of V is large, it is effect on the variance become larger. Therefore, based on the pattern where the larger the value of V is, the larger the effect on the stress of the cylinder block is, it can be deduced that the design factors influence in the order of [R > α > b > t] as shown in Table 4.

In order to determine the optimum combination of design factors that can minimize the Max stress value, the one-way table of four factors was composed as shown in Table 5. Therefore, the optimum condition is a combination of [R_2, α_2, b_2, t_0].

3.2. Comparison between Standard Model and Optimum Model

Table 6 shows the values of the design factors of both the standard model and the optimum model obtained in the previous phrase.

Table 4. Analysis of variance table

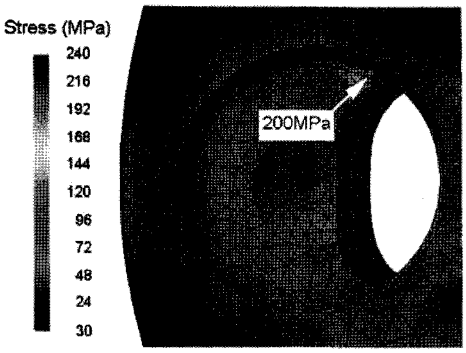
Factor	S	ϕ	V
R (mm)	1,266.0	2	633.00
t (mm)	604.7	2	302.35
α (°)	900.7	2	450.35
b (mm)	704.2	2	352.10
T	3,475.6	8	-

Table 5. One-way table for max stress

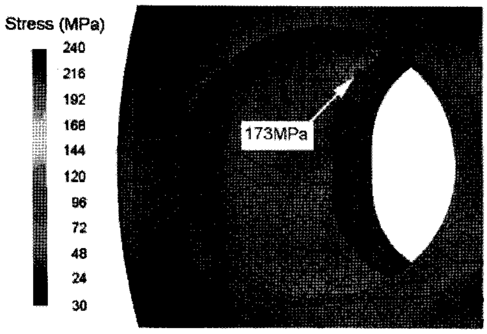
Factor / Level	R (mm)	α (°)	b (mm)	t (mm)
0	618	562	577	580
1	570	614	590	659
2	531	543	552	599

Table 6. Design factors for optimum analysis

Factor	R (mm)	α (°)	b (mm)	t (mm)
Standard	1	120°	15	3.5
Optimum	5	130°	17	1.5



(a) Standard Model



(b) Optimum Model

Fig. 6. Comparison of max stress between standard and optimum model.

Fig. 6 highlights the stress distributions in both the standard model and the optimum model. The Max stress value of the standard model is 200 MPa, and that of the optimum model is 173 MPa, which makes a reduction of 13.5%. The regions where the Max stress values appear in the two models are both around the edge of the bottom of the cylinder bore, and their values are 34.5% and 29.8% of the yield strength respectively.

Here, it should be noted that the Max stress region of the optimum model takes place in the edge of the cylinder bore. In the cases of No. 7 and No. 8, the Max stress regions are located in the inner wall of the discharge port connected with the valve plate, so it is possible that the stress concentration is severely generated in the real operated condition of hydraulic piston pump.

However, the Max stress value of the optimum model obtained from the analysis of variance has the same region as the standard model, and the Max stress value was below 30% of the yield strength of the material. Thus, it was concluded that the stress characteristics of the optimum model were stable.

Conclusion

In this study, in order to achieve the stability of material and satisfy the demands for the high pressure of the hydraulic system, the stress distribution and optimum design factors were discussed by using the stress analysis of the cylinder block, which is one of the most important relative sliding parts of the hydraulic piston pump. The following conclusions were obtained from the study.

(1) As a result of the analysis by using orthogonal array, it was evident that the influential extent of design factors on the Max stress value is in the order of [R > α > b > t].

(2) Optimum design factors with R = 3 mm, α = 130°, b = 17 mm, and t = 1.5 mm were identified through a one-way table.

(3) The Max stress value of the optimum model was reduced by 13.5% (173 MPa), compared with that of the standard model.

(4) The Max stress value of the optimum model was below 30% of the yield strength, so it is supposed that the design factors for this optimum model could be applied to the new generation model for a discharge pressure exceeding 40 MPa.

Nomenclature

b: width of port
CT: correction term
N: number of data
R: radius of edge of bottom of cylinder bore
S: sum of squares
t: drilling depth
T: total
V: mean square
α: drilling angle
ø: degree of freedom

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