Application of Simulation-X® based Simulation Technique to Notch Shape Optimization for a Variable Swash Plate Type Piston Pump

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Abstract *– This paper focuses on the development of a simulation technique that can calculate the reduction effect of the pressure/flow ripples. First,, the theoretical kinematic analysis according to the variable swash plate angle will be presented to establish the mathematical theory of single piston in order to design single piston pump using the Simulation-X®. Based on this kinematic analysis, the simulation of variable swash plate type axial piston pump will be conducted by changing a notch shape in the valve plate part through modifying the opening area of intake and discharge and thereby figuring out the pressure of outlet. The simulation result according to notch type will show that a V type notch results in smaller pressure pulsation, compared with a circular type notch. Using one-dimensional simulation model of single piston pump, we will connect nine piston pump models by using Simulation-X® for the overall variable swash plate type piston pump, and then proceed with investigation through simulation for searching for the optimal notch design specifications for minimizing pressure and flow ripples. It can be pointed out that the contribution of this paper can be referred to as a the development of Simulation-X® based Simulation Technique to be applied to notch shape optimization for a variable swash plate type piston pump.*

Keywords: Simulation-X® based Simulation Technique, Variable Swash Plate Type Piston Pump, Notch Shape Optimization, Circular Type Notch, V Type Notch, Pressure Pulsation, Flow Ripple.

1 Introduction

Hydraulic systems have been used broadly for construction equipment due to significantly higher power capacity. In addition, most hydraulic parts have a strong durability, which well suits the characteristics of construction equipment in rough work environment. [1] In particular, an excavator's track driving motor or a piston pump needs consideration for the safety of a driver, requiring durability of higher standard. In the case of hydraulic piston pump, mechanic noise from pressure pulsation and flow ripples may heavily affect the safety and convenience of the driver. Moreover, pressure pulsation is generated through the flow ripples generated at the piston pump as well as the mutual interaction of the hydraulic transfer characteristics due to the construction of hydraulic circuits. Such pressure pulsation not only causes the mechanical vibration of system components but also becomes a cause of noise of the hydraulic system. Thus, to develop a simulation technique that can calculate the reduction effect of pressure pulsation / flow ripples becomes a very strong design support in terms of conducting a measure for low-noise of the hydraulic system.[2]

As for the swash plate type hydraulic pump, the power pushing the valve plate gets periodically changed as the pressure inside the cylinder is repetitively changing from low-pressure to high-pressure and also reversely. Such phenomenon generates a negative impact on speed control at a low-speed. Thus, it is necessary to mitigate the pressure variation rate inside the cylinder through optimizing the notch shape of the valve plate appropriately.[3] Currently, it is developed by several dedicated simulations for the swash plate type hydraulic system; however, none of these has a detailed description about the hydraulic model being utilized and there are many ambiguous points in terms of setting the parameters.[4]

This paper deals with pressure pulsation as to the single piston, and then completes the perfect piston shape through connecting nine pistons. This research is supported by kinematic analysis of piston displacement as to the single piston pump. After then, we will conduct investigation as to the pressure variation inside the cylinder, which may become a cause of pressure pulsation, and also carry out a study as to the flow ripples of the nine pistons. Finally we will proceed with investigation simulation for searching for the optimal notch design specifications for minimizing pressure and flow ripples. All simulation process will be performed by using one-dimensional hydraulic analysis software, Simulation-X®.

2 Kinematic Analysis of Piston Displacement for a Single Piston pump

The basic structure of the variable swash plate type axial piston pump is shown in Fig. 1. It is a structure to be pumped by piston motion due to the swash plate, and the control part for the angle of swash plate is composed of a yoke, a spring and a control valve, as depicted in Fig. 1.

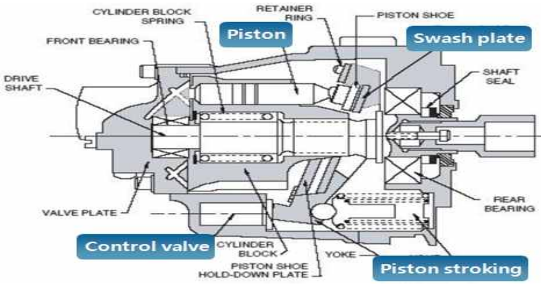


Fig. 1 Basic structure of swash plate type axial piston pump[6]

In this section, we examine the theoretical kinematic concept according to the variable swash plate angle. It aims to interpret in a kinematic term through the mathematical theory of single piston in order to design single piston pump using the Simulation-X®. As shown in Fig. 2, the displacement of piston can be expressed in the consecutive rotations of the drive shaft angle (φ) and the angle of swash plate (α). These rotations are shown in Fig. 3, *i.e.*, the concept diagram of single piston. Thereby a single piston pump has two degrees of freedom. The cylinder block and piston are composed of both the rotatory motion (φ) (which rotates based on the X_0 axis) and the rotary motion (α) of swash plate (which rotates based on the Z_0 axis). Notation of Fixed angle rotation[6] will be utilized as to the displacement of single piston since the single piston rotates by φ based on the fixed X_0 axis and then rotates by α based on the fixed Z_0 .[7] It is possible to calculate the location of the piston number 1 (Point P1) in the system of two degrees of freedom by the number of rotation (φ) of drive shaft and the angle of swash plate (α) as in Fig. 4.

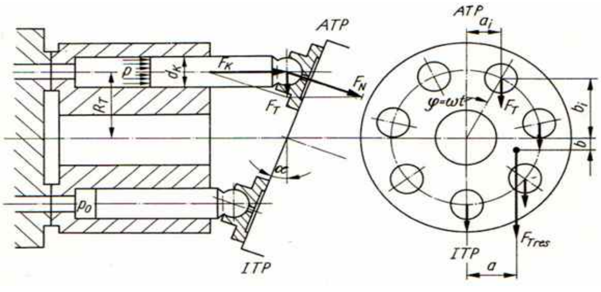


Fig. 2 Variable at the axial piston pump

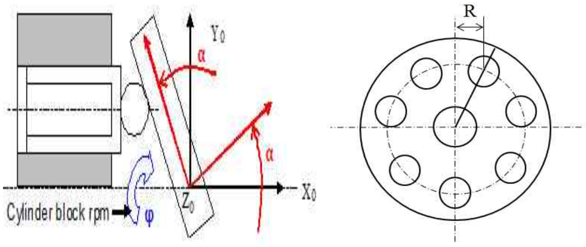
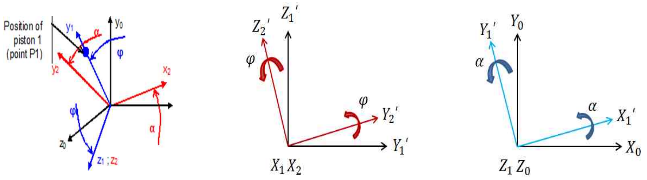


Fig. 3 Coordinate system in piston and swash plate[6]



(a) Coordinate system

(b) Cylinder block rotation

(c) Swash plate rotation

Fig. 4 Coordinate system corresponding to the 2-DOF

The rotation of cylinder block about X_0, followed by the rotation of swash plate about Z_0 can be deducted in eq. (1), which is summarized in eq. (2) of fixed angle of rotation.

$$
\begin{aligned}
{}^0_2R &= {}^1_2R \cdot {}^0_1R \\
&= R_Z(\alpha) \cdot R_X(\phi)
\end{aligned}
\tag{1}
$$

$$
[\hat{X}_0\, \hat{Y}_0\, \hat{Z}_0] \xrightarrow{R_{X_0}(\varphi)} [\hat{X}_1\, \hat{Y}_1\, \hat{Z}_1] \xrightarrow{R_{Z_0}(\alpha)} [\hat{X}_2\, \hat{Y}_2\, \hat{Z}_2]
\tag{2}
$$

As shown in eq. (2), ${}^0_2R$ performs two consecutive rotations based on the fixed angle rotation as shown in Fig. 5. This leads to finding out the location of piston when doing the rotation of coordinate systems about the fixed X_0, followed by the rotation about the fixed Z_0.

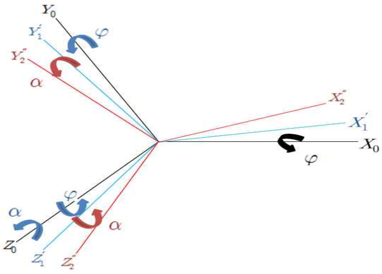


Fig. 5 Two fixed angle rotations

Now ${}^0_2R$ of eq. (1) can be given as follows:

$$
\begin{aligned}
{}^0_2R &= {}^1_2R\cdot{}^0_1R \\
&= R_Z(\alpha)\cdot R_X(\phi) \\
&= \begin{vmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{vmatrix}\cdot\begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{vmatrix} \\
&= \begin{vmatrix} \cos\alpha & -\sin\alpha\cdot\cos\phi & \sin\alpha\cdot\sin\phi \\ \sin\alpha & \cos\alpha\cdot\cos\phi & -\cos\alpha\cdot\sin\phi \\ 0 & \sin\phi & \cos\phi \end{vmatrix}
\end{aligned}
\tag{3}
$$

Lastly, the equation to find out the displacement of piston can be deducted as follows. In more specific, the location of piston with respect to the base coordinate system, *i.e.,* {0}, can be calculated as follows. As seen in eq. (4) , in the case of ${}^2P_{P1}$, it is the location of piston 1 seen from the coordinate system {2}. Then the consecutive rotation ${}^0_2R$ is performed on ${}^2P_{P1}$. In eq. (4), R denotes the radius of piston cyliner as shown in Fig. 3.

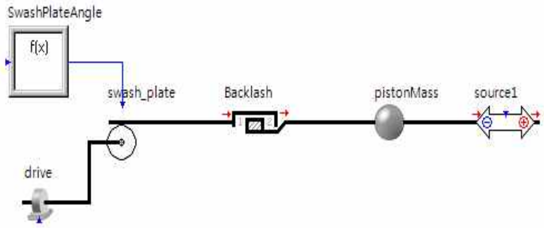
$$
\begin{aligned}
{}^0P_{P1} &= {}^0_2R\cdot{}^2P_{P1} \\
&= \begin{vmatrix} \cos\alpha & -\sin\alpha\cdot\cos\phi & \sin\alpha\cdot\sin\phi \\ \sin\alpha & \cos\alpha\cdot\cos\phi & -\cos\alpha\cdot\sin\phi \\ 0 & \sin\phi & \cos\phi \end{vmatrix}\cdot\begin{vmatrix} 0 \\ R \\ 0 \end{vmatrix} \\
&= \begin{vmatrix} -R\cdot\sin\alpha\cdot\cos\phi \\ R\cdot\cos\alpha\cdot\cos\phi \\ R\cdot\sin\phi \end{vmatrix}
\end{aligned}
\tag{4}
$$

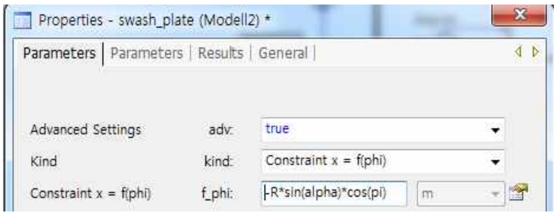
$$XO_{P1} = -R\cdot\sin\alpha\cdot\cos\phi \tag{5}$$

$$YO_{P1} = R\cdot\cos\alpha\cdot\cos\phi \tag{6}$$

$$ZO_{P1} = R\cdot\sin\phi \tag{7}$$

The only expression on the piston position in X_0, *i.e.*, eq. (5), is applied to the Simulation-X®-based model for one-dimensional anaylsis, as shown in Fig. 6, even though we have all the expressions of *x, y*, and *z* of the piston position. Especially, In the model of Fig. 6, the back lash element is added to the piston displacement in order to take dynamic effect between a swash plate and a piston cylinder block into consideration for Simulation-X®-based dynamic analysis. Thus, the single piston pump modeling has been completed as shown in Fig. 7 by using Simulation-X®.[8].




Properties - swash_plate (Modell2) *

Parameters | Parameters | Results | General

Advanced Settings adv: true

Kind kind: Constraint x = f(phi)

Constraint x = f(phi) f_phi: -R*sin(alpha)*cos(pi) m

Fig. 6 Simulation-X®-based model of e variable swash plate single piston pump for one-dimensional analysis

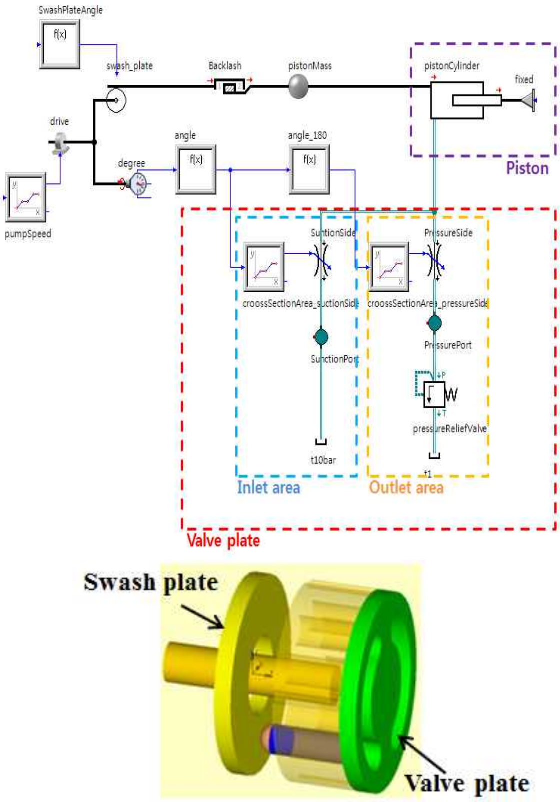


Fig. 7 Single piston model of swash plate type piston pump using the Simulation-X®

3 One-dimensional Simulation of Single Piston Pump

As mentioned in Section 2, Fig. 7 represents the single piston model of variable swash plate type axial piston pump for one-dimensional analysis for which our investigation will be conducted. This model is currently composed of the piston part and the valve plate part (inlet area and outlet area in the upper diagram of Fig. 7). Here hydraulic intake and discharge occur simultaneously in the valve plate part.

As for pressure pulsation, our investigation will be conducted by changing a notch shape in the valve plate part through modifying the opening area of intake and discharge and thereby figuring out the pressure of outlet. In specific, the opening area of notch shape on intake and discharge will be reduced or enlarged in order to find out the change of pressure pulsation, based on the existing opening area of a circle type notch. Table 1 shows the parameters of the modeling to be used for one-dimensional (pressure pulsation) analysis of single piston pump.

Table 1 Parameters of the model

Variable	Value
Swash plate angle (deg)	14
Pump speed (rpm)	100
Piston cylinder	10
Stroke (mm)	10~30
The number of piston (ea)	9

The piston cylinder increases or decreases the opening area of notch by being rotated on the notch of valve plate area (or when the piston cylinder gets into a notch region), which in turn results in pressure pulsation during intake and discharge strokes. As for the notch region, a precise calculation of the opening area is required since it is the main interest region called as "*pressure transition region*". In this paper, a research will be performed for the simulation upon applying a V-shape notch which might become better for reducing pressure pulsation phenomenon after analyzing an existing half-moon (or circular) notch shape. The V-shape notch is selected based on the following reasoning: when the cylinder port comes across a high-pressure opening for the first time as passing through the Outer Dead Point (ODP)[9] in Fig. 8, a flow area of which a cylinder port is overlapped with the opening area of V-shape notch is gradually increasing so that pressure pulsation can be reduced. Figure 9 shows both the (existing) circular type notch shape and the (proposed) V type notch shape.

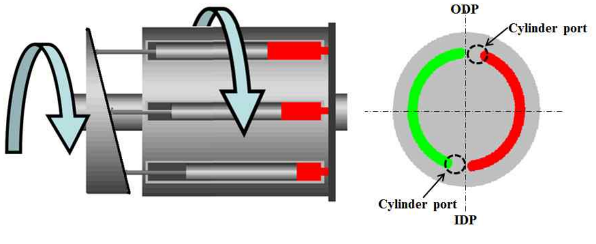
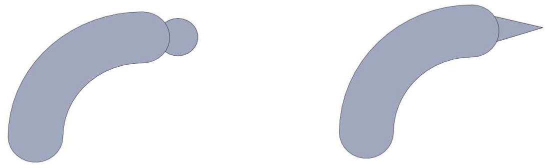


Fig. 8 Internal structure of swash plate type axial piston pump[4]

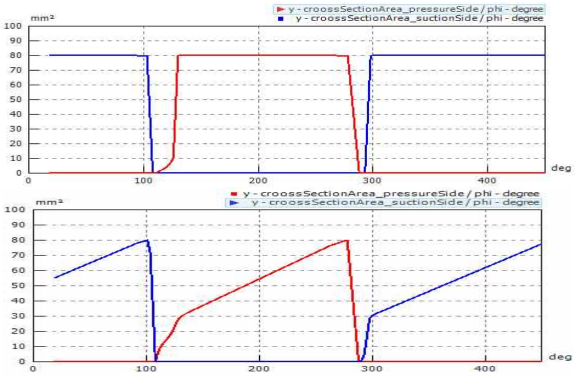


Circular type Notch V type Notch

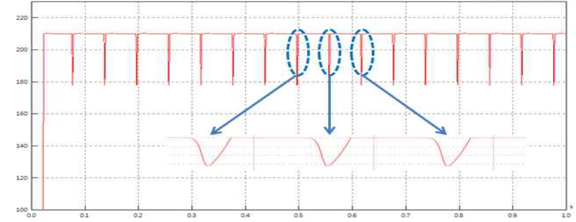
Fig. 9 Circular type and V type notch shapes

Currently, the area of circular type notch is selected as 80mm^2. We assume that the entire area of the V-shape notch can be regarded to be almost the same as that of the circular type notch. But the area in which the cylinder port is overlapped with the notch is different depending on both the location of cylinder port on the valve plate and the type of notch shape, when the cylinder rotates on the valve plate. Thus, according to notch type (circular type or V type), an investigation on pulsation is conducted through enlarging and reducing the overlapped area per percentage considering the existing entire circular type notch area as 100%..

The first simulation result according to notch type is illustrated in Fig. 9. Figure 9-(a) shows the overlapped area *vs*. cylinder port location for circular type notch (above) and V type notch (below). In addition, Fig. 9-(b) confirms the pressure pulation phenomenon of circular type notch, which is compared with that of V type notch in Fig. 10. Figure 10 confirms that the V type notch results in smaller pressure pulsation, compared with the circular type notch, since the flow area of which a cylinder port is overlapped with the opening area of V type notch is gradually increasing as shown in Fig. 9-(a).



(a) Overlapped area *vs*. cylinder port location for circular type notch (above) and V type notch (below)



(b) Pressure pulsation phenomenon of circular type notch

Fig. 9 Flow area and pressure surging of notch type

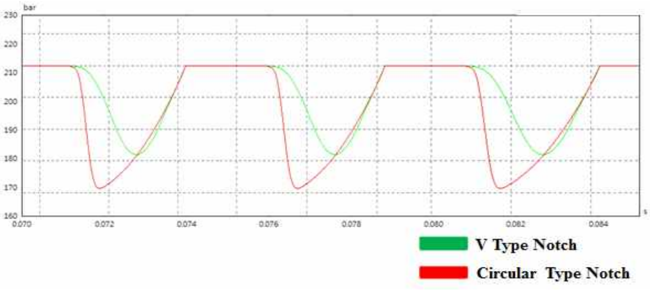
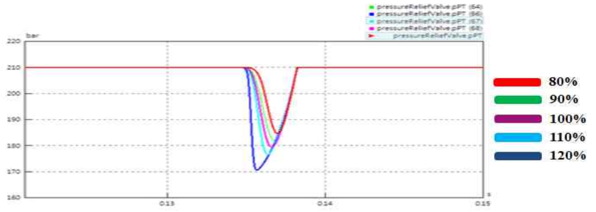
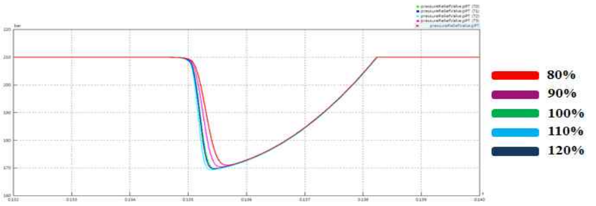


Fig. 10 Pressure pulsation *vs*. Notch type

Now we conduct the second investigation on pressure pulsation of circular type notch and V type notch as enlarging or reducing the area per percentage (80%, 90%, 100%, 110%, 120%) based on the existing entire (circular type notch) area. In Fig. 11, the location of cylinder port on the valve plate is assumed to be same for both the circular type notch and the V type notch. As shown in this figure, the V type notch results in smaller pressure pulsation when compared with the V type notch. This was already pointed out in Fig. 10 that the flow area of which the cylinder port is overlapped with the opening area of V type notch is gradually increasing as shown in Fig. 9-(a). On the other hand, the V-shape notch was not significantly affected by the overlapped area as shown in Fig. 11. Thus it is expected that the V type notch can reduce the impact of pressure pulsation, compared with the circular type notch since the overlapped area increases gradually as the cylinder rotates even though the area gets enlarged.



(a) Circular type notch



(b) V type notch

Fig. 11 Pressure pulsation of circular and V type notches

4 One-dimensional Simulation of Overall Variable Swash Plate Type Piston Pump Using Simulation-X

Using one-dimensional simulation model of single (variable swash plate type) piston pump (which was described in the previous section), we connect nine piston pump models by using Simulation-X$^{®}$ for the overall variable swash plate type piston pump as shown in Fig. 12. Thus far we have looked into the change of pressure pulsation according to the overlapped area of each notch. Now, we will proceed with investigation through simulation for searching for the optimal notch design specifications for minimizing pressure and flow ripples.

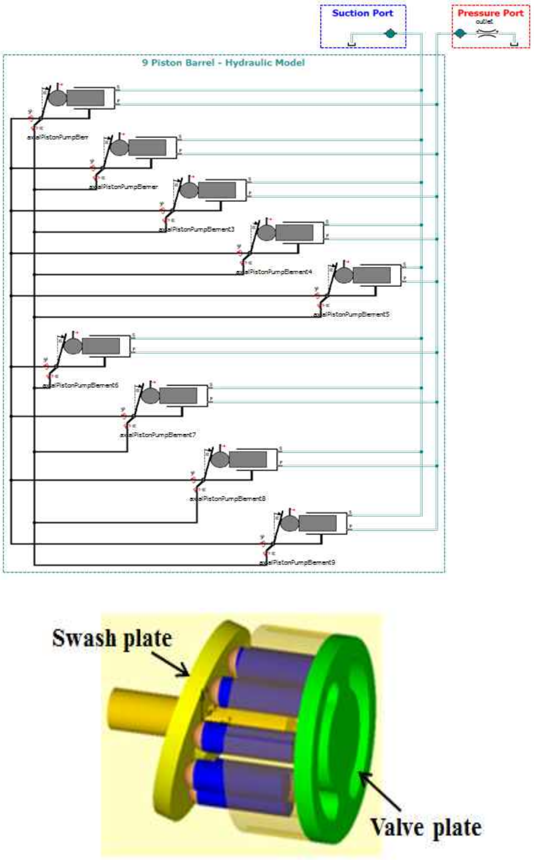


Fig. 12 Overall nine piston pump model using Simulation-X$^{®}$

For this purpose, we first investigate the effect of circular type notch on pressure and flow ripples as follows. Table 2 shows the overlapped areas which are given by a design specification of circular type notch, according to the rotating angles of a cylinder port. This design specification has been illustrated in Fig. 9-(a). Based on the design specification of Table 2, we noticed that the overlapped area rapidly expands (when moving from 5 to 10 degrees). Figure 13 shows the result of simulation implemented by applying the design values of Table 2. As can be seen in this figure, pressure and flow ripples occur in the section where pressure rises from low to high.

Table 2 Parameters of Circular type notch model

deg	area (mm^2)
0	0
2	0
4	0
5	0
8	65
10	80
20	80
170	80
175	80

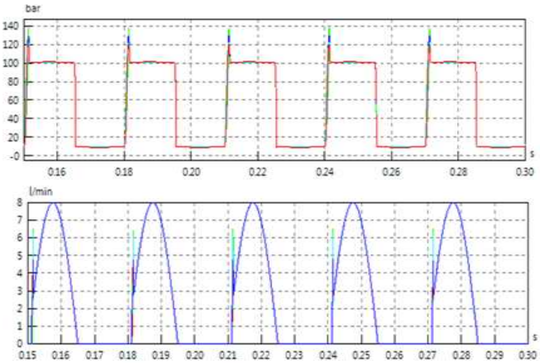


Fig. 13 Pressure ripple (above) and flow ripple (below) of circular type notch

In the case of V type notch, as mentioned earlier, we noticed in Figs. 9 and 10 that pressure pulsation was better than the existing circular notch type. But the design values of V type notch should not be applied randomly just because V type notch is better. Thus we have prepared 5 (candidate) design specifications (recommended by a field engineer) in Table 3 in order to search for the optimal design specification to minimize pressure and flow ripples. By applying each design specification to Simulation-X® -based simulation, we got the results shown in Fig. 14. Based on our examination through above simulations, type 5 (indicated by the green circle) results in no pressure and flow ripples, compared with other 4 design candidates. Also, as seen in Table 4, the best design candidate of type 5 for V type notch has decreased pressure peak by 26.4% (especially without overshoot (see the side figure of Fig. 14) when compared with that of circular type notch. Therefore the best design specification of V type notch can be obtainable by using one-dimensional simulation model of single (variable swash plate type) piston pump and then connecting nine piston pump models, based on Simulation-X®.

Table 3 5 Candidate design specifications of V type notch

Type deg	1 [mm^2]	2 [mm^2]	3 [mm^2]	4 [mm^2]	5 [mm^2]
0	0	0	0	0	0
2	0	0	0	0	0
4	3	8	11	13	14
5	5	10	20	18	20
10	15	20	33	30	35
20	80	80	80	80	80
170	80	80	80	80	80
175	80	80	80	80	80

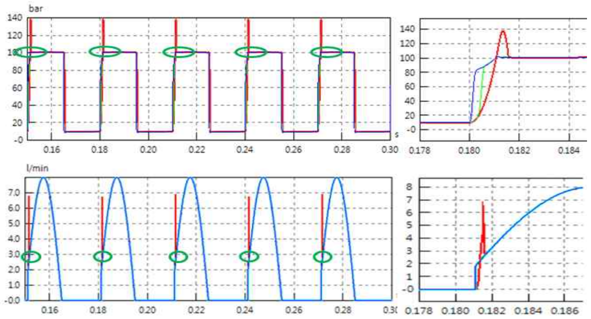


Fig. 14 Pressure Fluctuation and the Flux Pulse after the Alteration

Table 4 Comparion of Intial with Optimal Design

	Value		Improvement Rate
	Circular type notch	V type notch	
Pressure [bar]	139.16	102.36	26.4% (decrease)

5 Conclusion

Usually an excavator's track driving motor or a piston pump needs consideration for the safety of a driver, requiring durability of higher standard. In the case of hydraulic piston pump, mechanic noise from pressure pulsation and flow ripples may heavily affect the safety and convenience of the driver. This paper amis at developing a simulation technique that can calculate the reduction effect of the flow ripples, which becomes a very strong design support in terms of conducting a measure for low-noise of the hydraulic system.

In this paper, the theoretical kinematic analysis according to the variable swash plate angle has been performed to establish the mathematical theory of single piston in order to design single piston pump using the Simulation-X®. Based on this kinematic analysis, a single piston model of variable swash plate type axial piston pump has been conducted by changing a notch shape in the valve plate part through modifying the opening area of intake and discharge and thereby figuring out the pressure of outlet. The first simulation result according to notch type has shown that a V type notch results in smaller pressure pulsation, compared with a circular type notch, since the flow area of which a cylinder port is overlapped with the opening area of V type notch is gradually increasing.

Using one-dimensional simulation model of single (variable swash plate type) piston pump, we have connected nine piston pump models by using Simulation-X® for the overall variable swash plate type piston pump, and then proceeded with investigation through simulation for searching for the optimal notch design specifications for minimizing pressure and flow ripples. Therefor our contribution can be referred to as a the development of Simulation-X® based Simulation Technique to be applied to notch shape optimization for a variable swash plate type piston pump.

Acknowledgement

The authors of this paper was also supported by ‘‘ Domestic development of a driving device core module for 8~10 ton construction equipment’’ of which project was conducted by Korea Industrial CompleX (KICOX)..

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