Break-line Mode Valve Operation in Large Oil Hydraulic Systems *

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Oil column separation in the return line of a large oil hydraulic system is studied analytically, and the relation between the valve operation of the break-line mode and the rejoin surge pressure is investigated. The valve operation of the break-line mode, which has a lower operation speed near the closing point, shortens the valve closing time without increasing the rejoin surge pressure following the oil column separation. There is a region of the dimensionless valve opening corresponding to the break point of the valve operation, in which the rejoin surge pressure is lowered. The critical value of this region depends upon the dimensionless parameters which describe the return line. The result obtained in this study is available for the design of the breakline mode valve operation which shortens the valve closing time.

Key Words: Unsteady Flow, Fluid Power System, column Separation, Valve Operation

1. Introduction

In large oil hydraulic systems, due to a large volume of oil to be controlled, the main valve is often controlled by the pilot system equipped with electro-hydraulic servo valves. Generally, in the hydraulic systems, to suppress the surge pressure which accompanies the rejoining of separated oil columns caused by a sudden closing of valve at the down stream of flow line, valves with partially tapered spool are frequently used, but in the large systems, for the necessity of large suppression of rejoin surge pressure and for greater safety in operation, the operating speed of main valve is frequently maintained at low value.

In the large hydraulic system such as a large free forging press where quick control of a large volume flow is required for the efficiency of operation, the low operation speed is most undesirable since it reduces the number of operations in unit time. It is very important to establish an operating procedure which is capable of suppressing the surge pressure without reducing the number of operations, and if this improvement is accomplished simply by modifying the valve operating procedure, it will be very valuable for the industries which use a large hydraulic system.

Driels⁽¹⁾ proposed an operating procedure of the valve for reducing the rejoin surge pressure of oil column separation which occurs as a transient phenomenon near the valve in the downstream. His procedure is fundamentally based on the reduction of flow volume at a constant rate which requires a complicated control, that is, the valve closing rate has to be precisely controlled in all the range of the valve

stroke, and for this reason, it is difficult to apply his procedure to a system such as a large free forging press which is operated under a variety of complicated conditions.

Contrary to the procedure by Driels, the break-line procedure which employs only two valve closing speeds makes the valve operation very easy.

Driels⁽²⁾ has investigated the relation between the surge pressure without the column separation in the upper stream of valve and the condition of break-line valve operation and has reported the optimum break-points for many kinds of valves.

The author⁽³⁾ has investigated the rejoin surge pressure caused by the oil column separation in the down stream of the valve by experiments and has suggested the possibility of surge pressure reduction by employing the break-line valve operating procedure.

In an other paper⁽⁴⁾ the author has analyzed the oil column separation occurring under the linear-closing condition of valve by the characteristics curve method and has clarified the process of oil column separation and rejoining.

The objective of the present study is to make an analysis of break-line valve operation in relation to the oil column separation and the rejoin surge pressure for establishing an operating procedure which is effective to reduce the surge pressure and to shorten the valve operation time. Through the study, the rejoining of slow valve closing which is required in the break-line operation will be clarified, and a simplified equation for the calculation of valve speed in the slow speed region will be shown, and further, the operating condition of valve, the relation between the valve opening and the stroke which is non-linear will be investigated employing the concept of effective valve stroke reported previously⁽⁴⁾.

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Nomenclature

A : area of pipe
 a : wavespeed
 D : inner diameter of pipe
 f : Darcy-Weisbach friction factor
 g : gravitational acceleration
 H : absolute pressure head
 H_r : reservoir head
 $H_0 = aQ_0/gA$
 $H' = H/(aQ_0/gA)$
 $H_r' = H_r/(aQ_0/gA)$
 H_{max} : dimensionless rejoin surge pressure head
 ΔH_0 : full-opened valve head loss
 L : pipe length
 Q : flow rate
 Q_0 : initial flow rate
 $Q' = Q/Q_0$
 $R_f = (fLQ_0^2/2gDA^2)/(aQ_0/gA)$
 $R_v = \Delta H_0/(aQ_0/gA)$
 S : valve stroke
 S_{12} : valve stroke at break point
 S_{e0} : effective valve stroke
 t : time
 $t' = t/(L/a)$
 W : volume of oil column separation
 $W' = W/(LQ_0/a)$
 x : distance along pipe
 $x' = x/L$
 τ : dimensionless valve opening
 τ_{crit} : critical value of τ for slow operation
 $\bar{\tau}_{crit}$: approximate value of τ_{crit}
 τ_{12} : τ of break point
 Subscripts
 A, B, C, P : grid intersection points
 L, R : left and right hand sides of grid intersection point

2. Method of Numerical Analysis

Fig.1 shows a schematic model of the return line. The down end of line is connected to the reservoir and the oil column separation is generated by closing the valve at the up-stream of the line.

By converting the flow rate in the line to a dimensionless value by taking the initial flow rate Q_0 as the standard and the surge pressure by taking the initial pressure H_0 corresponding to the initial flow rate as the standard, three parameters R_v , R_f and H_r' expressing the characteristic of the system are obtained⁽⁴⁾. R_v and R_f denote the ratios between the initial head loss at the valve and H_0 , and between the head loss caused by the friction of fluid and H_0 respectively. H_r' indicates the ratio between absolute head pressure in the reservoir and H_0 .

The following equations were obtained by transforming the equation of motion of fluid into a total differential equation to be differentiated at the grid intersection point on the $x'-t'$ plane. Since the flow rates on both sides of grid intersection point generally take different values, the flow rates on both sides are identified by subscripts L and R . We have

$$C^+ : H_P' = C_P - Q_{LP}' \quad (1)$$

$$C^- : H_P' = C_M + Q_{RP}' \quad (2)$$

where

$$C_P = H_A' + Q_{RA}' - R_f \Delta t' Q_{RA}' |Q_{RA}'|$$

$$C_M = H_B' - Q_{LB}' + R_f \Delta t' Q_{LB}' |Q_{LB}'|$$

To simplify the boundary condition of oil column separation, the pressure in the resulting cavity was assumed to be absolute zero. When the column separation is not taking place at the subdivided point in the pipe, the calculation is made on the condition $Q_{LP}' = Q_{RP}'$. When $H_P' < 0$, the column separation is assumed to be taking place, Q_{LP}' and Q_{RP}' are recalculated by setting $H_P' = 0$. The relation between the volume of column separation and the flow volume is expressed by the following Eq.(3).

$$W' = W_R' - W_L' \quad (3)$$

where

$$W_R' = \int_0^{t'} Q_R' dt' \quad (4)$$

$$W_L' = \int_0^{t'} Q_L' dt' \quad (5)$$

The volume of oil column separation is calculable by the following equation (6) which has been obtained by differentiating Eq.(3) at the grid intersection points PC.

$$W_P' - W_C' = (\Delta t'/2)(Q_{RP}' + Q_{RC}' - Q_{LP}' - Q_{LC}') \quad (6)$$

If W_P' is assumed to be less than zero, the variables are recalculated by setting $Q_{LP}' = Q_{RP}'$ in Eq.(6) assuming that the cavity has collapsed. At the valve, Q_L' is considered the volume of fluid flowing through the valve, and Q_R' the volume after the valve. The following Eq.(7) is used to express the boundary condition at the valve additionally to Eq.(2).

$$Q_{LP}' = \tau \sqrt{(R_v + R_f + H_r' - H_P')/R_v} \quad (7)$$

The same process of calculation is used for the calculation of oil column separation at the valve and at the subdivided point in the pipe.

3. Relation between Break-line Valve Operation and Oil Column Separation

Since the dimensionless valve opening τ in this study is expressed by two crossing lines on the graph according to time, the process to time, the process is named the break-line operation. In large valves, the valve opening and the valve stroke are not necessarily proportional to each other, so the stroke in the break-line operation is not necessarily proportional to time, but by employing the concept of "effective stroke" proposed by the author in the previous report⁽⁴⁾, it is possible to express the relation between the valve

Fig.1 Model for return line

opening and the stroke by a simple equation.

Fig.2 shows the rejoin surge pressure calculated for the break-line operation. The dimensionless valve openings at the break-point τ_{12} are plotted on abscissa. The values of parameters H'_r , R_f , R_v are set close to those reported previously⁽⁴⁾. Three conditions or valve closing rates t'_{12} in the slow rate region are employed. The rejoin surge pressure H'_{max} varies sharply at around a certain value of τ_{12} (≈ 0.45 in this case).

Fig.3 shows a schematic graph of starting point of the column separation. In the break-line operation, the valve is closed according to the line connecting points S, B, and E, and the column separation starts from a certain point C on the line. If the point B is moved from S to E₁ along the line SE₁, the starting point of the column separation C moves along the shadowed broken line from C₂ toward C₁. When the break point B reaches the point C₁, the point C reaches C₁. Further movement of the point B toward E₁ does not cause the movement of C₁.

Fig.4 shows the relation between valve

Fig.2 Relation between rejoin surge pressure and valve opening at break point

Fig.3 Starting point of column separation

opening τ_c at the start of column separation and that τ_{12} at the break point. The valve opening may be divided into two regions, region 1 and region 2. In region 1 ($\tau_c > \tau_{12}$), the column separation begins during the quick closing operation and in region 2 ($\tau_c < \tau_{12}$), during the slow closing operation. Applying the same regional division to Fig.2, it becomes apparent that H'_{max} increases in region 1 as τ_{12} decreases and that it is nearly constant and independent of τ_{12} in region 2.

Since, in region 1, the starting point C₁ of the column separation is nearly constant and independent of the break point, the flow rate Q'_c at the start of oil column separation is nearly constant as shown in Fig.5. Since the volume W'_R calculated by Eq.(4) is a cumulative volume passing through the pipe after the valve, the maximum value of W'_R which is denoted by W'_{Rmax} is also constant as shown in Fig.5. The value W'_L which is a cumulative volume passing through the valve, its maximum value W'_{Lmax} takes a smaller value for a smaller value of τ_{12} due to a shorter valve closing time. For the reasons mentioned above, the maximum volume of column separation W'_{max} , which is a difference between W'_{Rmax} and W'_{Lmax} , takes a larger value for a smaller value of τ_{12} .

Fig.4 Valve opening at start point of column separation

Fig.5 Maximum volumes W'_L , W'_R and flow rate Q'_c

In contrast to region 1, in region 2 the value $W'_{\max}$ is almost the same as observed under the condition, $\tau_{12}=1$. Since it may be considered that the maximum volume of oil column separation corresponds to the rejoin surge pressure, the surge pressure is nearly constant in region 2 while it takes a larger value for a smaller τ_{12} in region 1.

4. Design of Break-line Operation

In the application of break-line operation for the shorter valve operating time, the set combination ratio of periods for the rapid and the slow operations is very important. If the period of slow operation is too long, the total operating time becomes long. If the period of rapid operation is too long, the rejoin surge pressure becomes high and the merit of employing the break-line operating procedure will be lost.

A border separating the two regions in Fig.2 gives the critical value of valve opening τ_{crit} in setting the break point in the break-line operation. Since the two regions are not sharply separated as shown in Fig.2, the value of τ_{crit} varies to some extent. For example, the relations between τ_{crit} and dimensionless parameters R_v , R_f , and H'_r as shown in Fig.6 are obtained by the numerical analysis applying the values $t'_{11}=1$ and $20 \leq t'_{12} \leq 40$. Since the break point and the starting point of oil column separation nearly agree in neighbourhood of the border between the regions as shown in Fig.2, the approximate value $\bar{\tau}_{crit}$ of τ_{crit} can be calculated by the following Eq.(8).

$$\bar{\tau}_{crit} = \frac{1 - R_f - H'_r}{\sqrt{(R_v + R_f + H'_r)/R_v}} \quad \dots\dots\dots (8)$$

Eq.(8) is obtained by assuming that the head pressure ($R_f + H'_r$) after the valve decreases to zero with a sudden change of valve opening from 1 to $\bar{\tau}_{crit}$.

Fig.6(a) shows the relation between τ_{crit} (or $\bar{\tau}_{crit}$) and R_v . The value τ_{crit} is expected to come somewhere in the shadowed area between broken curves, and the rigid curve shows the calculated value $\bar{\tau}_{crit}$. R_v is a dimensionless parameter representing the head loss when the valve is full open, and for a larger value of R_v , the value τ_{crit} increases toward unity suggesting that the increase of R_v makes the range of high speed valve operation narrower. Since the calculated value $\bar{\tau}_{crit}$ is in the shadowed portion, it may be used in place of τ_{crit} as an approximation.

The relation between R_f or H'_r and τ_{crit} is shown in Figs.6(b) and (c). τ_{crit} takes a smaller value for a larger R_f or H'_r . $\bar{\tau}_{crit}$ decreases faster than τ_{crit} as the value of R_f becomes larger, and there is an increasing tendency of difference between $\bar{\tau}_{crit}$ and τ_{crit} .

For the condition of $R_v=0.08$, not all the areas between broken lines are shadowed as shown in Fig.6(c). This is due to the fact that column separation does not always take place in the area below the dotted broken line AB.

In the case of $t'_{12}=20$, the column

separation does not occur when τ_{12} is larger than the value corresponding to the area above the line CD. This means that the line CD shows the border of conditions which cause or do not cause the column separation, and the value of τ_{crit} below the line AB also gives the condition where there is no oil column separation. The same interpretation is applicable to the case of $R_v=0.02$.

(a) τ_{crit} versus R_v

(b) τ_{crit} versus R_f

(c) τ_{crit} versus H'_r

Fig.6 Relation between τ_{crit} and dimensionless parameter

5. Application of the Effective Stroke

In the previous paper⁽⁴⁾, the author has reported that the relation between valve opening and valve stroke is linearized within the extent of effective stroke by introducing the concept of effective stroke. In Fig.7, the relation between valve opening and the stroke is shown by the line connecting the points A_0 , A_1 , and A_2 . This characteristic is approximated by the line $A_0A_1A_2$ by applying the concept of effective stroke. The stroke corresponding to the point A_1 is the effective stroke S_{e0} . If the flow characteristic of valve is expressed by the break-line $A_0A_1A_2$ in approximation, the valve opening τ according to time in the break-line valve operation is expressed by lines L_1 , L_2 , and L_3 , and the results of analysis in the previous sections are applicable without a change to the transient phenomena after the time t'_0 .

Attention has to be paid, however, to the relation between τ (τ_{A1} in Fig.7) and τ_{crit} . If the value τ_{crit} is larger than the value τ_{A1} the expression of flow characteristic in terms of effective valve stroke is not always useful in the design of break-line valve operating procedure.

Fig.8 shows the relation between the valve stroke S_{12} at the break-point and the rejoin surge pressure in the break-line operation. The broken lines show the calculated characteristic based on the non-linear characteristics of an actual valve, and rigid curves do calculated results for the break-line operation based on the concept of effective valve stroke. Experimental results obtained for the same apparatus which have been reported previously⁽⁴⁾ are also shown in Fig.8 for comparison. The division on τ_{12} axis is based on the effective stroke. Since in this case the value τ which corresponds to valve opening at the point from where the proportional relation between the valve opening and the stroke begins to disappear

is larger than the value τ_{crit} , the concept of effective stroke is useful.

Due to simplification of boundary condition at the point of column separation in the present study, there is some difference between the calculated surge pressure and the experimental results, but from the fact that the tendency of surge pressure is the same for both calculated and experimental results, it may be expected that the break-line operation and the expression of valve stroke based on the concept of effective valve stroke are useful in the design of actual hydraulic system.

6. Conclusions

As a guide for the design of break-line valve operating procedure aiming at the reduction of rejoin surge pressure caused by the column separation in the return line of a large hydraulic system, the following conclusions were reached.

- (1) In the break-line operation in which rapid valve closing rate is employed until the break point to shorten the valve operating time, there is a region in which the break point may be set without causing an increase of rejoin surge pressure. The value τ_{crit} corresponding to the limit of this region depends upon specifications of the system and is obtainable through numerical analysis.
- (2) In the region when the valve opening is larger than τ_{crit} , the column separation starts during the low speed valve operation, and when the valve opening is smaller than τ_{crit} it starts during the rapid valve operation.
- (3) An approximate value of τ_{crit} is calculable by the equation based on the above conclusion (2).
- (4) In the design of break-line valve operating procedure, it is necessary to judge whether the expression based on the concept of effective stroke is pertinent or not by the relation between the value τ_{crit} and flow characteristics of the valve.

Fig.7 Break-line mode valve stroke operation

Fig.8 Relation between rejoin surge pressure valve stroke at break point

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