ANALYSIS OF HYDRAULIC POWER SOURCES DISPOSITION AND ENERGY CONSUMPTION FOR HYDRAULIC DRILL RIG①

He, Qinghua
Department of Machine Engineering,
Central South university of Technology, 410083 Changsha

ABSTRACT Several hydraulic circuits designed for underground and surface hydraulic drill rig have been analysed aimed at saving drilling energy, namely, drilling with maximum power efficiency and minimum "design pressure loss". The results are useful for guiding the design of hydraulic drill rig.

Key words: hydraulic drill rig hydraulic power source disposition energy consumption

1 INTRODUCTION

The key component supporting the operation of any underground or surface hydraulic drill rig is the hydraulic system. Selecting a rational system disposition to diminish the system installing power as much as possible and improving the efficiency of its motive power machine are of great important for fully utilizing the high efficiency and high energy saving characteristics of the hydraulic drill. However the installing power can not be completely used is an objective fact because of that a part of the un-utilized power is inavoidably consumed in hydraulic loss of conduit pipe, etc; another part may be consumed in pressure loss resulting from non-suitable design scheme of system disposition, e.g. regulating oil-flow via throttle valve, and/or using a surplus match between the installing power and actually necessary power. All pressure losses excepting the in-avoidable one are termed with "design pressure loss" in this paper.

There are many indexes for describing the efficiency of a hydraulic system, however here only the efficiency of the motive power machine's power and the design pressure loss are selected to analysis and evaluate the energy consumption of hydraulic drill rig's hydraulic system with variable disposition scheme for searching the right way to improve power efficiency and diminish the design pressure loss.

2 PARAMETERS AND SYMBOLS

The hydraulic system of any underground and surface hydraulic drill rig is consisted of three basic circuit—impact circuit, rotation circuit and feed circuit—to support the drilling operation of its hydraulic drill. For analysis convenience the following parameters and symbols are introduced preferably.

2.1 *Parameters Concerning the Hydraulic Circuit of Impact*

N_i —impact power, p_i —impact pressure, Q_i— impact oil-flow.

In regard to the hydraulic drill with stroke regulating function, the above parameter's values differ with the variation of regulation stage and method[1].

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2. 2 *Parameters Concerning Hydraulic Circuit of Drill Rod Rotation*

p_{rn}— normal hydraulic pressure of rotation, producing normal twisting moment to rotate the drill rod and overcome the rotation resistance during normal drilling;

Q_{rm}, Q_{rs}— rotation oil-flow needed to satisfy the reguirement of maximum and minimum rotation speed, generally

$$Q_{rm} = K_{rq}Q_{rs} = (1.1 \sim 1.4)Q_{rs} \qquad (1)$$

Besides, a certain amount of spare twisting moment should be possessed to handle the ordinary accident of drill string sticking or for dismounting the thread of the extension rod. Thus the maximum hydraulic pressure of the rotation circuit could be calculated as

$$p_{rm} = K_{rp}p_{rn} = (1.5 \sim 2.2)p_{rn} \qquad (2)$$

In spite of the larger the($p_{rm} - p_{rn}$) value, the easier the antisticking/dismounting of the drilling string, but the K_{rp} value should not be too large owing to the restraint of the stability of drill rig and the strength of the drilling string. Principally in case of large and deep hole drilling a large value, e. g. 2. 0, should be selected and vice-versa.

However in case of large twist moment being used the rotation oil-flow Q_{rh} and the corresponding rotation speed could be decreased greatly, so that taking $Q_{rh} = (1/3 \sim 1/5)Q_{rm}$ is available.

2. 3 *Parameters Concerning Feed Circuit*

p_{fn}— normal feed pressure producing rational feed thrust to push the rock bit being contacted with hole bottom during drilling and is generally regulated by pressure reducing valve for holding a constant value.

Q_{rn}— normal feed oil-flow needed to satisfy the requirement for drilling at maximum speed, e. g. 2 m/min.

Usually normal feed power($N_r = p_{fn}Q_{fn}$) is much small than that of impact power ($N_i = p_iQ_i$) and rotation power($N_r = p_rQ_r$).

Being similar with the rotation circuit, the feed circuit should also satisfy the requirement of"spare speed" and "spare thrust" for drill's rapid move during return stroke and drawing out the drilling string easily. In case of large diameter and deep hole drilling both "spare speed" and "spare thrust" needed are quite large because the rapid move speed is generally reached to 12 ~ 25 m/min and the powerful thrust is much larger than the normal one, thus the maximum feed pressure p_{fm} and oil-flow Q_{fm} should be

$$p_{fm} = K_{fp}p_{fn} = (1.25 \sim 2.30)p_{fn} \qquad (3)$$

$$Q_{fm} = K_{fg}Q_{rn} = (6 \sim 15)Q_{rn} \qquad (4)$$

In case of large and deep hole drilling a larger value of K_{fp} or K_{fg} should be selected and vice-versa.

The following paragraph will show how does the correct selection of"spare moment", "spare speed" and "spare thrust" affect upon the improvement of power efficiency and the diminishing of design pressure loss.

3 SINGULAR DRIVING SYSTEM WITH CONSTANT DISPLACEMENT PUMP

As far as the hydraulic drill with no stroke length regulating device is concerned, the installing power is $N_i = p_iQ_i$, power efficiency $\eta = 1$, design pressure loss naught. However for the hydraulic drill with stroke length regulating device, the situation will be different. Thus according to Ref. [1] the following analysis should be carried out:

(1) Regulating stroke length under constant pressure. The installing power should be disposed according to the requirement of impact with low frequency and high energy and the power efficiency equals 1. However in case of high frequency and low energy impact, the power efficiency will be

$$\eta_i = N_{i1}/N_{i2} = \sqrt{K_{sp}} = 0.837 \sim 0.992 \qquad (5)$$

Meanwhile owing to the oil-flow of high frequency impact is lower than that of low frequency impact, the surplus oil-flow is forced to drain out through throthle valve, resulting in large design pressure loss.

(2) Regulating stroke length under con-

stant power. The installing power must satisfy the requirement of both large oil-flow for low frequency impact and high pressure for high frequency impact, thus as far as high frequency impact is concerned,

$$\eta_i = N_{i1}/N_{i2} = \sqrt[3]{K_{sp}} = 0.888 \sim 0947 \qquad (6)$$

the power efficiency is lower than 1, and the un-utilized power is consumed with the form of design pressure loss. But for low frequency impact the design pressure loss is naught in spite of its power efficiency holds the same as those of high frequency impact.

The coefficient K_{sp} in formcelae (5), (6) represents the ratio of stroke length varied; the footnote 1 and 2 for other parameters indicate high frequency impact and low frequency impact respectively (see Ref. [1]).

In case of the drill runs in lowest normal rotalion speed, the efficiency of circuit power must be in lowest state, hence

$$\eta_r = \frac{p_{rn}Q_{rs}}{p_{rm}Q_{rm}} = \frac{1}{K_{rp}Q_{rq}} = 0.32 \sim 0.61 \qquad (7)$$

The oil-flow and pressure needed during normal drilling are quite small, the power efficiency

$$\eta_f = p_{fn}Q_{fn}/(p_{fm}Q_{fm}) = 1/(K_{fp}K_{fq}) = 0.29 \sim 0.133 \qquad (8)$$

Owing to the circuit must be designed according to anormalous "spare speed" and "spare thrust", η_f is very small and the corresponding design pressure is very large.

The above analysis indicates that, in spite of the singular driving system using constant displacement pump is simple and reliable, it's power efficiency is low, design pressure loss is large and those of the rotation and feed circuit are even worse in special. Therefore such system is only used for hydraulic drill rig with small power or small variation in hydraulic pressure of rotation feed circuit.

4 NON-SINGULAR DRIVING SYSTEM WITH CONSTANT DISPLACEMENT PUMP

4.1 *Combined Impact & Feed Circuit*

Fig. 1 shows such a combined-circuit. It can be seen from Fig. 1 that, when electricity in double position double way electromagnetic valve was switched off the drill enters normal drilling state for realizing pressure reducing drilling or high thrust rapid hammer return; when electricity was switched on the drill is changed to hammer rapid forward or backward under high thrust. Because the $p_{fn}Q_{fn}$ value of normal drilling state is very small the power of impact circuit is correspondingly not large, and the impact action has been usually stopped during hammer rapid forward or backward. Thus the power $p_{fr}Q_{fn}$ being greatly larger than $p_{fn}Q_{fn}$ in singular driving system is now almost solved, leading to the resolution of the questions of "spare speed" and "spare thrust", and the power efficiency is increesed to

$$\eta_f = \frac{Q_{fr}p_{fn}}{Q_{fm}p_{fm}} = \frac{1}{K_{fp}} = 0.43 \sim 0.8 \qquad (9)$$

For favouring the use of the circuit, it is appropriate to equal neerly the impact and feed pressures, the impact and rapid forward/backward oil-flows. Otherwise the hydraulic system could be complicated and the energy saving effect may be diminished.

4.2 *Combined Rotation & Feed Circuit*

Fig. 2 which is very similar to Fig. 1 indicates the basic principle of the combined rotation and feed circuit. It's power $p_{fn}Q_{fm}$ is so small as almost can be completely omitted, its

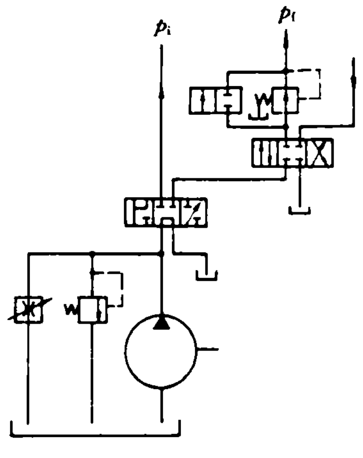

Fig. 1 Combined impact and feed circuit

feed power is also calculated by formula(9).

Owing to the hydraulic pressure and oil-flow of the rotation circuit matches the feed circuit easily, the combined circuit shown in Fig. 2 is better than that of Fig. 1.

4. 3 *The Combined Circuit with two stepped pressure double pump*

In spite of the problems of "spare speed" and "spare thrust" could be basically solved using combined rotation-feed circuit with a great diminishing of system power, the problems of "spare twist moment" and power diminishing of the rotation circuit, and the correspondingly low power efficiency phenomena during normal drilling with a drill rod rotation pressure being much lower than the anti-sticking pressure are unsolved yet. However the problem of "spare twist moment" can be solved by a combined circuit using double pump with tow stepped pressure (Fig. 3) of which the rotation and feed oil is supplied with big/small pump, namely during normal rotation/feed and rapid feed the hydraulic oil needed is supplied by both big and small pumps synchronously with the right side over flow valve being regulated at a lower normal rotation pressure (p_{rn}); but when "spare twist moment" and "spare twist" are needed, the high pressune (being regulated to maximum rotation pressure — p_{rm}) and small oil - flow (being regulated to Q_{rn}, which is much less than Q_{rm}) hydraulic oil is only supplied by the small pump, meanwhile the big one is unloaded by the right side overflow valve.

Therefore in case of double pump circuit being used two operation modes—low twist moment and high rotation speed (for normal rotation of drill rod), high twist moment and low rotation speed (for anti-sticking and dismounting of drill rod)—can be achieved by rotation circuit, and the circuit power is calculated according to the former mode; three feed modes—low feed thrust and rapid hammer forward/backward move, normal feed—can be achieved by feed circuit. Those modes are very useful to deep hole drilling with extensi on rod, and their

$$\eta_{rf} = p_{rn}Q_{rs}/Q_{rm}p_{rh} = 1/K_{rg} = 0.71 \sim 0.91 \qquad (10)$$

Attributting to $p_{rr}Q_{rm} > p_{rm}Q_{rh} \gg p_{fr}Q_{fn}$, the power efficiency calculated by formula (10) is much higher than that of (7).

4. 4 *The Combined Circuit With Feedback of Rotation Pressure*

Here another way solving the problem of "spare rotation twist moment" is discussed.

As shown in Fig. 4 there is a hydraulically controlled unloading valve installed in the impact circuit to recieve the feedback pressure of rotation circuit. When the drill string was sticked and the rotation pressure was exceeded p_{rn}, the impact circuit is then partly unloaded and the hydraulic drill is operated in a light impact state, which leads to both preventing

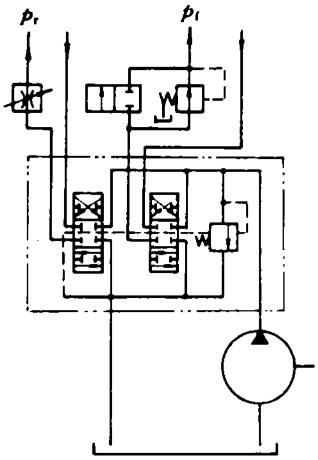

Fig. 2 Combined rotation and feed circuit

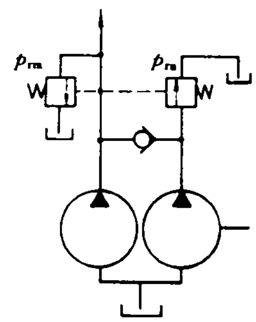

Fig. 3 Combined circuit with two stepped pressure double pump

the drill string from further sticking and the system power being decreased.

And it is quite easy to make the decreased power of the impact circuit being equivalented to the "spare anti-sticking power of the rotation circuit"—($p_{rm} - p_{rn})Q_{nm}$, thus total power of the system is

$$N_t = N_i + N_r + N_f$$
$$= p_iQ_i - p_{rr}Q_{rm} + p_{rn}Q_{fn}$$
$$= p_iQ_i + p_{rn}(Q_{rn} + Q_{fn}) \quad (11)$$

Obviously the power efficiency of this scheme is increased significantly as that of the above scheme but the goal of decreasing total installing power could only be achieved at the condition of using one motive driving machine, and there are significant design pressure losses when rotation speed and stroke length are regulated. The scheme is essentially one part of the anti—sticking circuit.

5 VARIABLE DISPLACEMENT PUMP DRIVING SYSTEM

5. 1 *The Combined Circuit With one Hydraulic Pump*

As shown in Fig. 5 one constant pressure variable displacement pump is used cooperatively by impact, rotation and feed circuits, which is designed to prevent excessive speed

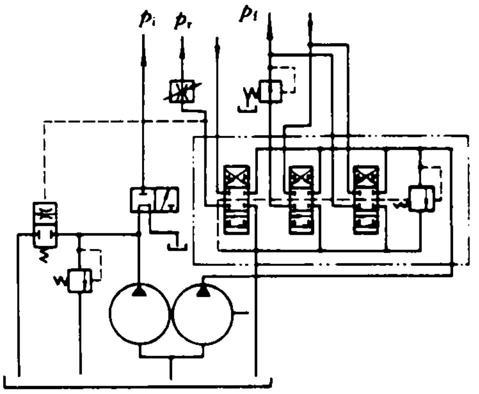

Fig. 4 Combined circuit with pressure feedback

increment from the decreasing of rotation twist and to prevent the decreasing of impact pressure from high pressure complementary ability. Because the rotation speed is regulated using speed regulating valve, the normal oil-flow of feed circuit and the oil-flow variation resulting from loading variation are quite small, the influence on impact pressure from oil-flow is also small, thus the maximum oil-flow can be calculated as when normal feed flow is relatively small.

$$Q_{pm} = Q_i + Q_{rm} + Q_{fn} \quad (12)$$

Considering the match with rotation-feed pressure the circuit of oil-flow variation at constant pressure should preferentially be adopted for impact system and its oil-flow needed should be determined according to that of low frequency and high energy impact. The corresponding maximum rotation/feed hydraulic pressures p_{rm}, p_{fm} are also determined by impact pressure p_i, i. e. $p_{rm} = p_{fm} = p_i$. The impact power efficiency is determined by formula (5) getting lowest value at high frequency impact stage, but the rotation power efficiency is determined by formula(7) because of there is no design pressure loss in this circuit attributing to the complementary action of constent pressure pump and the calculated value is very low.

The feed power efficiency is also determined by formula (9), which is much higher than that of singular constant displacement circuit. This circuit is very suitable for middling and small power hydraulic drill rig, of which the power efficiency is significantly high and the design pressure loss is small when the pressures of impact, rotation and feed differed not much.

5. 2 *Manually Operated Variable Displacement Pump Circuit With Rotation Pressure Feedback*

For those hydraulic drill rigs with necessities of stroke length and rotation speed regulation, the design pressure loss is significantly large when constant displacement pump as shown in Fig. 4 is used. However the design pressure loss will be decreased provided that the constant displacement pump in Fig. 4 is displaced by manually operated variable displacement pump as shown in Fig. 5, i. e. a volumetric speed regulation method is used to fit the necessity for stroke length regulation and rotaion speed variation, resulting in power efficiency decreasing.

The stroke length regulation and rotation speed variation during drilling are occurred discontinuously, so that the using of manually operated variable displacement pump circuit is feasible, and of cause it is also cheep and reliable:

5. 3 *The Combined Rotation and Feed Circuit Using Two Steped Pressure Double Pump*

The scheme of using rotation pressure feed back to unload the impact pressure partly, shown as Fig. 4, can certainly decrease the total installing power, but only suit for the case of which single motive driving machine is used. But if the low pressure big pump in Fig. 3 is displaced with a manually operated variable displacement pump instead of the rotation feed pump shown at the right side of Fig. 4

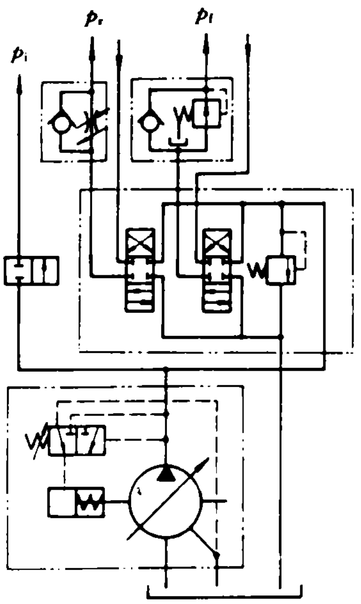

Fig. 5 Combined circnit with one hydraulic pump

and cancelling the feedback of rotation pressure, the system's propertics could be improved significantly as: (1) The demerit of excessive rotation power resulting from "spare twist" moment is eliminated; (2) The design pressure loss during rotation speed variation is also removed; (3) There is no restriction for that only single, motive driving machine can be used.

5. 4 *Automatically Variable Displacement Double Pump Circuit*

As shown in Fig. 6, the impact oil is provided using one constant pressure variable displacement pump, and the stroke length regulation either under constant pressure or at constant power can be realized via pressure regulating. The installing power and power efficiency are the same as that described in paragraph 3. 1, the extra design pressure loss is not existed at any operation state.

Using one double-stepped pressure variable displacement pump for combined rotation and feed circuit has the following merits:

(1) Selecting of suitable rotation speed can be carried out via regulating maximum displacement, i. e. the volumetric speed regulating methd, with no design pressure loss;

(2) The installing rotation power design-

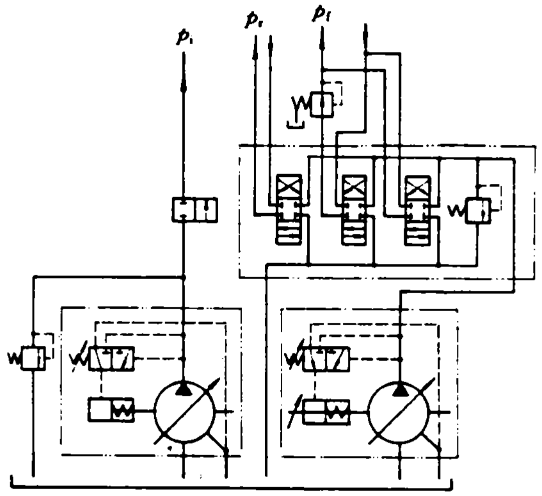

Fig. 6 Automatically variable displacement double pump circuit

ed in the light of normal rotation pressure p_{rn} and maximum rotation flow Q_{rm} is decreased signifieantly. The displacement of the pump can be diminished automatically to Q_{rn} and even further decreased until maximum rotation pressure being arrived when normal pressure is exceeded thus enough rotation twist moment for preventing drill string from sticking and rotaion speed can be guaranteed under rational rotation power.

From the comparison to the preceded circuits, it can be understood that for non-single, motive driving machine this circuit is the best one and specially suits for middling and big drill rig.

6 CONCLUSION

To sum up, the following questions should be attended when the hydraulic system of hydraulic drill rig is designed.

(1) Be paid attention to the decreasing of design pressure loss when designing the hydraulic system of a hydraulic rig;

(2) The key to improve the system power efficiency and diminish the design pressure loss is the treatment of rotation circuit's "spare twist moment", feed circuit's "spare thrust" and "spare speed";

(3) The combined circuit with rational match between pressure and oil-flow should be selected as can as possible. Mean-while manually or automatically operated variable displacement hydraulic pump should be used, the most effective way for improving the system power efficiency and diminishing the design pressure loss lies in such schemes as rotation pressure feedback.

Besides, it is worthful to mention that the hydraulic circuits for some auxilliary facilites, such as flushing pump, dust adsorber, etc, of the advanced hydraulic drill rig could be designed in the light of the design thought of the paper provided thouse auxilliary facilites are drived by hydraulic system.

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