HYDROSTATIC TRANSMISSIONS FOR WHEEL LOADERS

- AN EXPERIMENTAL STUDY OF A MULTIPLE-MOTOR CONCEPT

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ABSTRACT

A modern hydrostatic transmission for an off-road vehicle must have a high power capacity, a wide speed range and good overall efficiency. A concept that can meet these requirements is one that uses two motors controlled in sequence. The motors are then connected to each other via gearing and are driven at different rotational speeds. To utilise the capacity, one of the motors must be controlled to zero displacement and disconnected at high vehicle speeds. The challenge of the concept is the reconnection procedure, in which the disconnected motor must be accelerated, synchronised and finally locked to the output shaft of the transmission, all in a fraction of a second. In this paper, two principles for establishing the reconnection are investigated in a complete two-motor laboratory test stand. In the first method, the reconnecting motor synchronises using secondary control, in the other it does so by means of a mechanical synchronising mechanism. The aim of the tests is to compare and evaluate different control strategies and hardware configurations.

KEYWORDS

Fluid power, Hydrostatic transmission, Multiple motors, Secondary control

NOMENCLATURE

B : Viscous friction coefficient [Nms/rad]
 D : Displacement [m³/rad]
 J : Inertia [kgm²]
 n : Rotational speed [rad/s]
 Δp : Pressure difference [Pa]
 T : Torque [Nm]
 U : Gear ratio [-]

ϵ : Displacement setting [-]
 ω : Break frequency [rad/s]

Subscripts

0 : Zero-motor
 acc : Acceleration
 h : Hydraulic system
 m : Motor
 p : Pump
 $sm0$: Zero-motor servo
 sv : Servovalve

INTRODUCTION

Nowadays, hydrostatic transmissions for heavy, slow vehicles need to provide high power capacity, a wide speed range and high efficiency. To meet these requirements, modern concepts often have several stages of gearing, multiple motors or uses "power split" technique [4, 8]. A promising multiple-motor concept uses two sequence-controlled motors, see Figure 1. The motors are connected via mechanical gearing, which means that the motors are driven at different rotational speeds. The motor capacities are fully utilised by allowing the motor with the higher speed to be controlled to zero displacement and to be disconnected at high vehicle speeds. The benefits of this concept have been demonstrated and experimentally verified in [5, 7]. The challenge of the concept is the reconnection procedure, in which the disconnected motor, henceforth called the zero-motor, must accelerate, synchronise to the output speed of the main motor and finally lock to the output shaft of the transmission, all in a fraction of a second.

Figure 1 A hydrostatic transmission with two sequence-controlled motors joined by a gear unit

The reconnection can be achieved and controlled in several ways. A simple way is to use a disc clutch and control acceleration and synchronisation from that. On the other hand, the method that makes the smallest demands on the clutch is to achieve the acceleration and the synchronisation by controlling the fluid power system. In this case, closed loop secondary control of the zero-motor is necessary. A third method is to combine the first two by letting the fluid power system produce the major part of the acceleration, and to use the clutch for the final synchronisation. The two latter methods have been discussed earlier in [5, 6] and will be evaluated here in a complete laboratory test stand.

TEST SETUP

A sketch of the test setup is shown in Figure 2. From left to right a diesel engine simulator system, the transmission and a load simulator system can

be seen. The transmission consists of one variable in-line pump. It feeds two bent-axis motors, one of which has been rebuilt to allow control to zero displacement. The shafts of the motors are connected to a normal car gearbox. The shaft of the main motor passes right through the differential of the gearbox, which is locked, and is connected directly to the load. The zero-displacement motor is connected via the normal input end of the gearbox to a synchromesh gear (normally the fifth gear in the gearbox) which also connects to the differential. The gearbox shift mechanism allows the zero-motor to be mechanically disconnected or connected by simply slipping the gear into neutral and back again.

The hydrostatic transmission is electrohydraulically-controlled and is also equipped with sensors for measuring pressures, speeds and displacement settings. All measurements and control are done with the simulation package HOPSAN [1], which runs on a personal computer. This makes it easy to switch between different control laws. Measurement signals used in control loops are filtered at 100 Hz using analogue filters. In addition, all plots in this paper have been filtered at 20 Hz.

Simulation of engine and load

The diesel engine system can be divided into two subsystems, the governor and the engine. A black-box model of the engine can be described with a gain, a delay and a first-order low-pass filter, as can the governor, except for the delay [3]. The engine part is simulated by the servovalve-controlled motor as indicated in Figure 2. This servo system is speed-controlled using a PI-controller and will imitate the engine lowpass filter. Delay, governor time-constant and feedback gain are added by software. The total diesel engine bandwidth will be of about 1 Hz and the engine compliance which is added using pump torque measurements is set to 0.1 rad/Nms.

The transmission load is simulated using a servovalve-controlled pump/motor. The torque is measured and controlled using a closed loop PI-controller. The controller parameters are adapted for both flow and pressure changes. The simulator has four-quadrant capability and can handle both speed-dependent and speed-independent loads and can also to some extent add extra inertia load. In this paper the simulator is used only to add speed-independent load. The load simulator can be further studied in [2].

Operation area and general control of transmission

The output speed of this kind of transmission is assumed to be controlled in sequence. Pump control is then used in the low-speed region, while motor control is activated at high speeds. For the particular tests discussed in this paper, a pump control where

Figure 2 Sketch and photograph of the test setup. The power level of the whole rig is 300 kW and of the tested transmission 50 kW

the displacement setting is a linear function of the current engine speed is used. The general motor control principle is not important for the tests. Changes normally take place very slowly and will not interfere with the reconnection procedure. The default main motor setting is at maximum throughout the tests. As well as being used in the general control, the pump and main motor are also used for flow and speed compensation during the zero-motor reconnection procedure, further discussed below.

The operation area of the test setup is shown in Figure 3. The area covers most conceivable operating points for reconnection and is more or less equivalent with the reconnection region. The region where the reconnection makes the greatest demands on control and hardware is also marked. This region will dominate the tests and discussions in this paper.

Figure 3 Operation area of test setup

RECONNECTION USING CLOSED LOOP SPEED CONTROL

As mentioned earlier, the challenge with this kind of multiple motor transmission is the reconnection procedure of the zero-motor. One way of achieving the connection is to control acceleration and synchronisation using secondary control [9] of the motor. The speed of the motor is measured and compared to a reference derived from the main motor output speed. The speed error controls the displacement setting of the motor via a PI-controller. This continues until the speed difference is zero and the clutch can be locked, see Figure 4.

Stability, softness and connection time

Secondary control of a motor is normally used in constant-pressure systems equipped with an accumulator. This makes the pressure dynamically independent of the control of the motor. In this case the 'constant pressure' is derived from the vehicle load, and the pressurised volume is very small. The pressure is therefore influenced by the motor control and the result is parasitic feedback between the motor control and the main transmission system. In [7] it is shown that the feedback can cause instability, especially at high speeds and low loads. The instability appears only in the synchronising phase and is not no-

Figure 4 Acceleration and synchronisation controlled mainly by the fluid power system. Plots are measurement results at about 20 MPa (constant load)

ticed when the clutch is locked. However, to minimise the demands on the clutch, synchronisation must be smooth without large oscillations.

In [5], two methods for stabilising the control are discussed. One way is to control the pump so that the zero-motor flow is compensated. This method is excellent as long as the pump control is fast enough and full pump displacement has not been reached. The second method, working more generally, is to high-pass filter the reference signal to the zero-motor control. The filter is designed in such a way that the feedback gain is reduced at the system resonance frequency, see [5]. In practice the filter decreases the zero-motor flow consumption if the main motor speed is disturbed from the reconnection. In the example shown in Figure 5 the speed reference is reduced by the filter. The zero-motor displacement and flow will be limited and the result is stable and fast acceleration and synchronisation.

To prevent the filter distorting the reference signal when the speed is changed by the driver and not as a result of the zero-motor acceleration, it is of course

Figure 5 Zero-motor synchronisation using secondary control. The reference signal is filtered using a high-pass filter. The load is constant and the clutch is never activated in the example

important to distinguish ordered speed changes from disturbances. This is compensated for by using a value of the ordered speed changes, detected for example by pump speed and pump displacement inputs.

As been mentioned, unstable behaviour only appears under conditions of low load and high speed. When the pressure is high, which is the case when the extra motor is actually needed, the connection procedure is fully stable and fast. The two compensation methods will however also be suitable for use in these situations, in this case for softness reasons. The pump compensation reduces the vehicle speed drop and the pressure drop, which also makes the zero-motor acceleration faster. The influence from the filter has already been indicated. In this case, the relation between acceleration time and softness can be adjusted by the filter parameters. An alternative, or complementary way of improving the softness is to limit the zero-motor displacement setting.

Naturally, the zero-motor flow cannot be compensated at high speeds by increasing the pump displacement, since the pump displacement is fully utilised. Some compensation can however be achieved by actively controlling the main motor in these situations (provided of course that the main motor is variable). The idea is to reduce the main motor displacement in such a way that the flow needed to maintain the speed is reduced by the same amount as the zero-motor takes for accelerating. In contrast to using pump compensation, main motor compensation introduces a number of new parasitic feedback loops in to the system. A simple way to avoid interactions from feedback loops is to make the compensation dynamically slow.

In Figure 6 the difference between using and not using flow compensation with the main motor is shown. Apart from reducing the output speed disturbance, the compensation makes the pressure 'come back' faster after the initial shock when starting the acceleration. This makes the zero-motor accelerate faster.

Another way of helping the controller is to feed-forward a precalculated reference value of the zero-motor displacement setting in parallel with the PI-controller. The input to the control card will then not rely only on the speed error. This makes it possible to decrease the control gain and thereby increase the robustness.

In conclusion, there are six different controllers or controller extensions which are suitable for use in the short time in which a reconnection takes place, see Figure 7.

Next in importance to the control configuration, is the bandwidth of the zero-motor displacement servo. The motor used in the laboratory test stand is equipped with a simple electromagnetic control with

Figure 6 Zero-motor synchronisation at high speed and low constant load. In the left plot, no flow compensation is used, in the right, the main motor is used for compensation

PI-controller The main controller

Reference filter Stabilises and softens the connection

Flow compensation by pump Stabilises, softens and speeds up the connection

Flow compensation by main motor Softens and speeds up the connection

Displacement limitation Softens the connection

Predicted displacement setting Increases the controller robustness

Figure 7 Conclusion of alternative zero-motor control concepts

internal mechanical position feedback. The bandwidth is about 20 rad/s but this can easily be doubled if a complementary external position feedback, which also includes the control card and the solenoid in the loop, is used.

Adaptation of control parameters

Reconnection of the zero-motor should be possible over a wide range of speed and pressure. This calls for using control and compensation parameters adaptive to the operating point. The PI-controller parameters will be selected according to the open-loop transfer function of the secondary-controlled motor, see for example [7]. Parameters influencing the integration frequency will have limited variations, so that this can be left constant. The proportional constant may be set inversely proportional to the pressure. However,

in reality the secondary control response is very robust when working with low inertia and load, which is the case here. If the pressure is not measured for other reasons, the proportional constant can also be left constant.

Two of the controller parts shown in Figure 7 depend on a prediction of the zero-motor displacement setting; the displacement limitation and the prediction itself. The setting is affected by operating conditions and can be written as

$$\epsilon_{m0} = \frac{n_m U_m B_{m0} + T_{m0}}{D_{m0} \Delta p} \quad (1)$$

Pressure and main motor speed can easily be measured but the friction coefficients B_{m0} and T_{m0} are also very important. These vary with temperature, pressure and speed and can be hard to predict. In this paper, fixed coefficients are used but an alternative which increases the accuracy is to use a predetermined grid where the predicted displacement setting is a function of speed, pressure and temperature.

The parameters of the reference filter are also related to the displacement of the zero-motor. The predicted setting can be used here. However, it is simpler and more accurate to use the actual setting or a prediction based on the signal to the control card. The filter parameters in the reference filter also depend on the main motor displacement setting and the eigenfrequency of the main transmission system (which also changes with the main motor displacement). Adjustments for these are also included. As already mentioned the filter parameters may also be adjusted for softness reasons. The adjustment can be related to reference speed or pressure. The former is used in this paper in such a way that the filter influence increases with the speed reference.

Comparison of control strategies

A fast, smooth and stable reconnection of the zero-motor can no doubt be realised. It is all a matter of complexity, cost and reliability involved in the controller design. The simplest control strategy to think of is a simple PI-controller with fixed parameters without any other compensation. This concept works quite well under high-pressure conditions where the control is inherently stable and the flow disturbance caused by the accelerating zero-motor becomes small. A pressure detector checks whether reconnection is allowed.

Adding flow compensation with pump and main motor and high-pass filtering of the reference signal, makes the control much more flexible. This makes reconnection possible at low pressure levels as well. The compensation might make demands on the pump and the main motor servo control, but no additional sensing is needed. In practice this may be the simplest

control to use, since limiting the reconnection only to high-pressure conditions is too probably restrictive. Apart from this basic controller design, it is possible to define three main ways of improving the reconnection procedure.

- A The basic design as been described above.
- B The basic design extended with a measurement of the pressure which allows all the control facilities described in Figure 7.
- C The basic design but with an improved bandwidth of the zero-motor displacement servo. This allows higher gain and improves stability, rapidity and accuracy.
- D The basic design but using a toothed clutch with synchronising mechanism to reduce the demands for a perfect hydraulically-controlled synchronisation.

These items can of course be used separately or in combination. They are all related to extra costs but one difference between their reliabilities is that the pressure sensing method not only relies on the sensing but partly also on a model of the zero-motor friction. The other two methods are more robust in that sense.

Figure 8 shows an example in which the simplest control is compared to each one of the extended designs described above. When using simple control, imprecise synchronisation prevents the toothed clutch locking immediately. When using pressure sensing, the zero-motor acceleration is restrained by limiting the displacement setting. The controller is also better adapted to the working conditions by an adjusted gain and a feedforward of the displacement setting. The result is a smoother acceleration, which allows the clutch to lock immediately when the speeds are synchronised.

Figure 8 Example of response difference when using different control qualifications

When using a fast displacement servo, the connection time is reduced thanks to the faster control. Here the synchronisation is fast and exact, which allows the clutch to lock very shortly after the beginning of the synchronisation. In the last example, mechanical synchronising is used. Here, the oscillations in the first example are avoided by locking the clutch distinctly when the speed difference is near zero.

The plots of the pressure and the reference value give an insight into the disturbance felt by the driver. Note that a well-matched acceleration, which is the case when using pressure sensing, decreases the disturbance. On the other hand the fast servo seems too fast as the disturbance here becomes larger. When comparing designs A and D it will also be noted that the force from the mechanical synchronisation does not affect the transmission pressure in this example.

Figure 9 shows examples of connection times and pressure disturbances as a function of the operating point for the four controller designs. At low reference speeds the reconnection procedure is greatly affected by the start friction of the zero-motor. At medium speeds the controller is allowed to work without limitations, and at high reference speeds the results depend mostly on the flow compensations and the filtering of the reference signal.

Figure 9 Example of reconnection times with different controller designs at a pressure level of about 25 MPa. The controller designs correspond to the ones defined above. Also shown is the pressure drop due to disturbances from the zero-motor connection.

RECONNECTION USING OPEN MOTOR CONTROL AND SYNCHRONISING MECHANISM

The previous section discussed a reconnection method where the zero-motor acceleration and synchronisation were mainly controlled by the motor itself. The other extreme is to use a disc-type clutch and accelerate the zero-motor as a dead inertia. A princi-

ple which combines the two is to take the acceleration power from the fluid power system and just do the final, precise synchronisation by the clutch. The advantage is that the zero-motor can be controlled without using feedback, which ensures stability. A toothed clutch will be used, only supplemented with synchronising rings.

Control algorithm

A connection procedure starts with the motor controlled so that it starts to accelerate. When the speed is nearly the same as the reference, the motor is controlled to stop accelerating. At the same time the synchronising clutch is engaged and does the final synchronisation and locking, see Figure 10. The flow disturbance is preferably reduced by using compensations with the pump and the main motor in the same way as was done when using closed loop speed control.

Figure 10 Reconnection controlled by the fluid power system and the clutch. The plots shown are measurement results at about 20 MPa (constant load)

The control of the zero-motor can be divided into three phases; control of the acceleration torque, choice of confirmation which interrupts the acceleration and finally the control immediately after the interruption. The well-adapted acceleration torque is necessary to avoid large flow and pressure disturbances in the main transmission system on the one hand and on the other to achieve fast acceleration. Matching of the acceleration interruption is important for reducing synchronising torque, and by matching the control while the clutch is locking, the flow and pressure disturbances can be reduced. The motor control must thus be well adapted to achieve a smooth connection.

Adaptation of control parameters

The acceleration torque can be controlled by adjusting the displacement setting of the motor. But the amount of the acceleration torque also depends on the pressure difference across the motor and is to some degree also affected by friction forces, see equation (2). The need to measure and compensate for pressure

changes is obvious. There might also be reasons to compensate the control for changes in the friction. However, in this paper fixed friction parameters were assumed.

$$T_{acc} = \epsilon_{m0} D_{m0} \Delta p - B_{m0} n_{m0} - T_{m0} \quad (2)$$

To obtain as good a synchronisation as possible before engaging the clutch it is necessary to interrupt the acceleration before the reference speed has been reached. The reason is that the acceleration will continue for some time after the interruption has been ordered, depending on the response and setting time of the motor servo. A neat solution is to regard the servo as a first order low-pass filter which means that the interruption time is always the same.

To avoid pressure peaks after the acceleration interruption it is important also to have matching motor control while mechanical synchronisation takes place. The locking will be smooth if the motor rotates by its own effort at this moment. A matching displacement setting is determined according to equation (1).

Example of test results

Figure 11 shows an example of the reconnection procedure using open control of the zero-motor. The operating point is the same as in Figure 8. Seemingly, the result is about equivalent to the three examples using an extended closed loop control. Open control provides two of these extensions; adaptation to pressure level and use of a synchronising clutch.

Figure 11 Reconnection procedure using open motor control and a synchronising clutch

In common with the method using closed speed control, reconnection is easiest under high-pressure conditions. Figure 12 shows a difficult situation which can also be compared with closed loop control (Figure 5). In the case that uses closed loop control, the situation was tackled by high-pass filtering the speed reference. This method cannot be used for open loop control. The result is that, under low-pressure conditions, the zero-motor can easily consume too much

flow, so that the pressure falls, interrupting the acceleration. An extremely well adapted displacement reference is necessary to avoid the vehicle speed drop shown in Figure 12. To handle this, some kind of closed loop control is necessary. This eliminates the idea of avoiding feedback loops.

Figure 12 An example of reconnection using open control at a low pressure level

DISCUSSION AND CONCLUSIONS

The main conclusion from this experimental study is that switching between using one or two motors in a two-motor transmission can be done quickly and without causing any significant disturbances.

Of the two main principles tested, the one using closed loop speed control of the reconnecting motor, is the most convenient. However, it is also shown that this method requires the speed reference signal to be high-pass filtered to ensure stable operation under all operating conditions. The filter also greatly improves the connection softness. The alternative method using open control of the reconnecting motor is inherently stable but cannot be actively compensated in the same manner as the other method.

Other compensation methods, such as flow compensation using control of pump and main motor, zero-motor control adaptive to pressure and use of a clutch equipped with a synchronising mechanism are beneficial for both the principles. The advantage of using those is greater for the method using open motor control than for the one using closed loop control. In the latter method the compensations have barely any effect at all if the pressure is high. An alternative to using compensations could then be to set a pressure limit below which no reconnection is allowed. However, this might put a too strong limit on the vehicle capability.

Test results also show the advantages of having a zero-motor displacement servo with a high bandwidth. A typical electrohydraulic servo with internal

position feedback, which is commonly seen on modern motors, will manage the control. However, an improved bandwidth reduces delay times, speeds up synchronisation and handles start friction phenomena better. Start friction becomes a problem if using closed loop control at low reference speeds. Here, "stick-slip" effects may appear. One way of avoiding this problem is to use mechanical synchronisation. Such a design also makes reconnection possible at slow speeds without having to activate the zero-motor control.

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