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Determination of power loss of combine harvester travel gear

L. Beneš*, P. Heřmánek and P. Novák

Czech University of Life Sciences Prague, Faculty of Engineering, Department of Agricultural Machines, Kamýcká 129, 165 21 Prague 6, Czech Republic;
*Correspondence: benesl@tf.czu.cz

Abstract. This contribution aims at determining the power loss in hydraulic circuits of the John Deere S680i combine harvester travel gear. The individual elements of the circuit were measured, followed by an energy intensity analysis. The analysis includes the calculation of pressure losses in direct piping, local resistance, as well as pressure losses in the individual elements of the circuit. Subsequently, power loss was calculated based on pressure losses. In the case of the John Deere S680i combine harvester, the power loss equals 16.95 kW.

Key words: combine harvester, hydrostatic travel, pressure loss, power loss.

INTRODUCTION

Combine harvesters are machines in which we require, in terms of the content of their work, sensitive control and continuous travelling speed variation. Consequently, hydrostatic transmission is the most frequently used in combine harvester travel gear (Kutzbach, 2000).

Hydrostatic transmission is a transmission mechanism with a pump and hydraulic motor as its basic elements. The principle of mechanical energy transfer through the hydrostatic transmission rests in the transformation of mechanical energy into pressure energy of the fluid in the pump and, vice versa, pressure energy of the fluid into mechanical energy in the hydraulic motor (Kučík & Strážovec, 2000). The transmission consists of a closed hydraulic circuit and an auxiliary open hydraulic circuit (Lou Xi-Yin, 2014). The auxiliary hydraulic circuit fulfils the following tasks:

- it cleans the fluid;
- it refills the fluid in a closed circuit;
- it maintains the required pressure of the fluid in a low-pressure branch of the closed circuit;
- it cools the fluid down;
- it is a source of required energy when controlling regulation piston converters (Roh, 1992).

The diagram of hydraulic circuits of the hydrostatic transmission of the John Deere S680i combine harvester is shown in Fig. 1.

The auxiliary circuit includes a gear pump (P16), which draws in the fluid from the tank (R1). The fluid runs both into the servo-valves (Y119 and Y126) and the servo-cylinders (C40 and C41), when adjusting the position of the swing plate of the pump and of the hydraulic motor, and into the closed circuit through non-return valves (V160) or (V161), depending on which branch of the closed circuit currently has low fluid pressure. The auxiliary circuit is protected against overload by a pressure valve (V198).

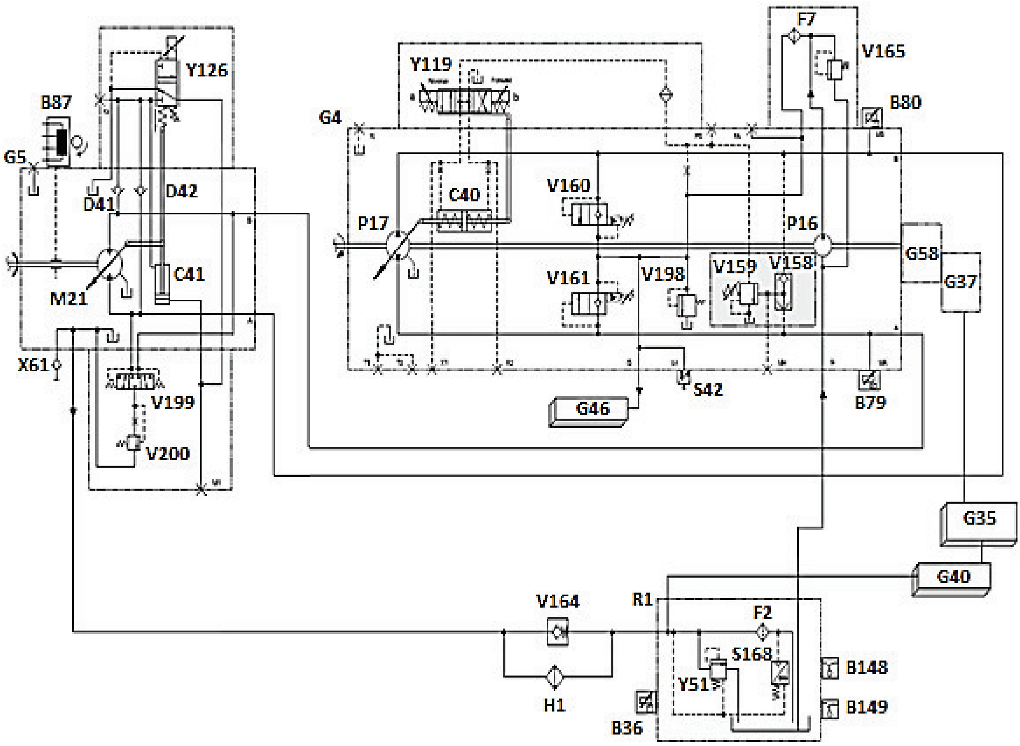

Figure 1. Diagram of hydraulic circuits of the hydrostatic transmission of the JD S680i combine harvester.

The valve block of the hydraulic motor is equipped with a hydraulically controlled distributor (V199), which connects the low-pressure branch of the closed circuit with the discharge pipe. The fluid, however, must pass through the bypass valve (V200) maintaining the required charging pressure in the closed circuit. The fluid passes from the filling pump (P16) through the axial piston pump (P17) and axial piston hydraulic motor (M21) and it exists the hydraulic converters through the hydraulic elements (V199 and V200). The cooler (H1), through which the fluid flows back to the tank, is placed separately. If the fluid is cool, it runs through the bypass valve (V164) which puts up lesser resistance than the cooler. The discharge fluid is joined by waste, so-called leakage, fluid, leaking around the moving parts of the pump and the hydraulic motor. The pressure-relief filling valve of the circuit (V198) is usually adjusted to a pressure of 4.2 MPa, the bypass valve (V200) is usually adjusted to a pressure of 2.8 MPa and the high-pressure valves (V160 and V161) are usually adjusted to a pressure of 49 MPa.

The presented complex hydraulic circuits clearly indicate the occurrence of pressure losses and, consequently, power loss. We classify pressure losses occurring in hydraulic circuits into three types:

- losses in direct piping;
- losses in local resistances;
- losses in the individual elements of the circuit (Roh, 1989).

Calculations performed in this article provide a better understanding of hydraulic losses of combine harvester travel gear. At the same time, these values will be used in future for comparison with the real measured values. And for comparison of the energy intensity of travel gear of combine harvesters with wheeled and tracked chassis.

MATERIALS AND METHODS

Measurements were carried out on the John Deere S680i combine harvester owned by the Agricultural Business Co-operative Zálabí with its registered office in Ovčáry.

Materials for measurement were prepared based on the obtained diagram of hydraulic circuits of the combine harvester hydrostatic transmission. We measured all the necessary external dimensions of the hydraulic circuit (piping length, diameter), ascertained the number of elbow pipes, tees, etc. The internal dimensions of these elements have been ascertained from the catalogues of manufacturers based on the external dimensions measured. The parameters of the pumps and hydraulic motor, such as geometric volume, working pressures, speeds and efficiencies, have been ascertained from the machine's technical manual. The pump capacities have subsequently been calculated based on these parameters. For subsequent calculations in the high-pressure circuit, we assume a maximum flow rate at which the combine harvester reaches the maximum travelling speed. The technical manual also provided the set pressures of pressure-relief valves, pressure losses of some elements (cooler, filter). It was also necessary to ascertain the specifications of the working fluid (kinematic viscosity, density) which were obtained from the materials of the fluid manufacturer.

Each element is registered under a 'code' determining its parameters. In the direct piping, the hoses are designated as **H** and steel pipes are designated as **R**. A number of items can also be indicated before the letter. The letter is followed by a number indicating the internal diameter of the element in millimetres; the number after the slash indicates the length of the element in millimetres. For example, **3xR30/200** means that the circuit contains **3** steel pipes with an internal diameter of **30 mm** and a length of **200 mm**. In local resistances, the number of items is designated similarly, before the name of the element. The name of the element is followed by a number indicating the internal diameter of the element in millimetres and the figure after the slash represents the bending of the element in degrees. For example, **elbow pipe 25/100°** means an elbow pipe element with an internal diameter of **25 mm** and a bending of **100°**.

To calculate the power loss P_Z, we use the equation (1), where we multiply each element of the pressure loss at the given point of the circuit by the flow rate at the given point of the circuit.

$$P_Z = p_Z \cdot Q \tag{1}$$

where: P_Z – power loss (W); Q – working fluid flow rate ($m^3\ s^{-1}$); p_Z – pressure loss (Pa).

The flow rate at the given point of the circuit was calculated using the parameters of the pump indicated by the manufacturer using the equation (2).

$$Q = \frac{V_g \cdot n \cdot \eta_Q}{1{,}000} \tag{2}$$

where: Q – working fluid flow rate ($m^3\ s^{-1}$); V_g – geometric volume of the pump(m^3); n – pump speed (s^{-1}); η_Q – flow efficiency of the pump (-).

Losses in the direct piping, i.e. losses in hydraulic hoses and steel pipes, represent the first component of the pressure loss. They are calculated from the equation (3) and related formulas.

$$p_Z = \lambda \cdot \frac{l}{d} \cdot \frac{v^2}{2} \cdot \rho \tag{3}$$

where: p_Z – pressure loss (Pa); λ – coefficient of linear losses (-); l – hydraulic piping length (m); d – hydraulic piping internal diameter (m); v – fluid flow velocity through piping ($m\ s^{-1}$); ρ – working fluid density ($kg\ m^{-3}$).

First, it is necessary to calculate the flow velocity of the fluid through piping (4) using the formula for calculation of the cross-section of hydraulic piping (5).

$$v = \frac{Q}{S} \tag{4}$$

where: Q – working fluid flow rate ($m^3\ s^{-1}$); S – hydraulic piping cross-section (m^2); v – fluid flow velocity through piping ($m\ s^{-1}$).

$$S = \frac{\pi \cdot d^2}{4} \tag{5}$$

where: S – hydraulic piping cross-section (m^2); d – hydraulic piping internal diameter (m).

For the coefficient of linear losses (7, 8, 9, 10), it is necessary to first calculate the so-called Reynolds number and classify it into the correct group for the given flow situation.

$$\mathrm{Re} = \frac{v \cdot d}{\upsilon} \tag{6}$$

where: Re – Reynolds number (-); v – fluid flow velocity through piping ($m\ s^{-1}$); υ – kinematic viscosity ($m^2\ s^{-1}$).

$Re < 2{,}300$ - laminar flow range
$2{,}300 < Re < 5{,}000$ - transition range
$5{,}000 < Re$ - turbulent flow range
For laminar flow in hoses:

$$\lambda = \frac{80}{\mathrm{Re}} \tag{7}$$

For laminar flow in pipes:

$$\lambda = \frac{64}{\mathrm{Re}} \tag{8}$$

For transition flow range:

$$\lambda = \frac{0.316}{\sqrt[4]{\mathrm{Re}}} \tag{9}$$

For turbulent flow range:

$$\lambda = \left(\frac{200}{\mathrm{Re}}\right)^2 \tag{10}$$

Losses in local resistances, the so-called local losses, represent the second component of pressure losses. The calculation (11) is similar to that in the case of pressure losses in direct piping; only the coefficient of linear losses λ and the ratio of direct piping length l to its internal diameter d is replaced by the coefficient of local resistance ξ which is determined empirically for each element of the circuit.

$$p_Z = \xi \cdot \frac{v^2}{2} \cdot \rho \tag{11}$$

where: p_Z – pressure loss (Pa); ξ – coefficient of local resistance (-); v – fluid flow velocity through piping (m s^{-1}); ρ – working fluid density (kg m^{-3}).

The third component is represented by pressure losses in the individual elements (12). They are determined based on efficiencies of the elements stipulated by the manufacturer where the calculation requires primarily the pressure efficiency η_p. For other elements, we directly indicate the pressure loss stipulated by the manufacturers of the particular hydraulic elements.

$$p_Z = (1 - \eta_p) \cdot p \tag{12}$$

where: p_Z – pressure loss (Pa); η_p – pressure efficiency (-); p – pressure in piping (Pa).

To obtain the resulting value of power loss, we add up the power losses of the individual components.

RESULTS AND DISCUSSION

After the substitution in the previous formulas, using MS Excel software, we calculated the values for pressure losses and power losses in the elements of the direct piping circuits, local resistances and the individual elements of the circuit (tables 1, 2, 3).

Table 1. Pressure loss and power losses in direct piping

Element Code	p_Z (kPa)	P_Z (W)
H30/4250	1.78	8.13
H30/3855	1.61	7.38
H25/5555	13.89	12.22
H25/3500	8.75	7.70
H25/1700	4.25	3.74
H25/550	1.38	1.21
H25/450	1.13	0.99
3xR30/200	0.08	1.15
2xR30/100	0.04	0.38
R30/400	0.17	0.77
R30/660	0.28	1.26
2xR25/300	0.75	1.32
R25/900	2.25	1.98
R25/500	1.25	1.10
R25/200	0.50	0.44
R25/100	0.25	0.22
Total	39.31	50.00

Table 2. Pressure loss and power losses in local resistances

Element Code	p_Z (kPa)	P_Z (W)
3x elbow pipe 30/90°	26.51	364.21
elbow pipe 30/135°	30.04	137.59
6x elbow pipe 25/90°	2.03	10.71
elbow pipe 25/100°	2.30	2.02
elbow pipe 25/135°	2.10	1.85
4x tee-piece 25	2.03	7.14
inlet into tank 25	1.35	1.19
outlet from tank 25	1.35	1.19
Total	136.96	525.91

Table 3. Pressure loss and power losses in individual elements

Element Code	p_Z (kPa)	P_Z (W)
gear pump	76.09	66.96
axial pump	1,616.49	7,403.55
axial hydraulic motor	1,616.49	7,403.55
cooler	800.00	704.00
filter	900.00	792.00
Total	5009.08	16370.05

The resulting tables indicate that the lowest losses occur in the direct piping. By contrast, the highest losses are in the individual elements of the circuits which is 96.6% of the total losses in the circuits of the travel gear hydrostatic transmission.

We can find out the total power losses by adding up the power losses of all components of the circuits specified in Tables 1, 2, 3. This indicates the power that is taken from the combustion engine of the combine harvester to overcome the losses in the circuits of the travel gear hydrostatic transmission at its maximum travelling speed.

$$\boldsymbol{P_Z} = 50.00 + 525.91 + 16370.05 = 16945.96 \text{ W} = \mathbf{16.95\ kW}$$

Taking into account the fact that the combustion engine of the combine harvester has a rated power (according to ECE R120) $P = 353$ kW, the percentage representation of hydrostatic transmission according to the formula (13) equals **4.8%**. This is reflected in the energy performance and the fuel consumption (Jokiniemi et al., 2012).

$$\frac{P_Z}{P} = \frac{16.95}{353} = 0.048 \Rightarrow 4.8\% \qquad (13)$$

From the results it is clear that the proposal to improve the direct piping and the local resistances of the hydraulic system is unnecessary. The losses are negligible. The biggest losses occur in the individual elements which have given construction, thus given losses.

CONCLUSIONS

After measuring all elements in the circuits and their calculation, we have determined the pressure losses and power losses in the direct piping, in local resistances and in the individual elements of the circuit. Losses in the individual elements of the circuits, i.e. 16.37 kW (96.6%), constitute the greatest fraction of the total losses. The total losses in the circuits of the travel gear hydrostatic transmission of the combine harvester equal 16.95 kW. This value applies to the maximum flow rate in the high-pressure circuit at the maximum travelling speed of the combine harvester. With declining travelling speed and, consequently, also the flow rate in the high-pressure circuit, the losses in this circuit would also decline.

Calculations presented in this article will be used for comparison with the real values which will be measured in the future.

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