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EXAMINATION OF LOAD EFFECTS OF AN ALTERNATING CURRENT SYNCHRONOUS HYDRAULIC DRIVE

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Abstract
Alternating current hydraulic systems can be divided into two large groups based on the electrical analogy: synchronous alternating current hydraulic drives and asynchronous alternating current hydraulic drives. The three main building units of alternating current systems are a hydromotor, a hydrogenerator and a phase space connecting the two main units. The relative angular position of the hydrogenerator and the hydromotor is changed by the loads occurring during operation. In this article I would like to present the load effects.

Keywords: *alternating current hydraulic drive, load, hydrogenerator, hydromotor*

1. Introduction

The energy transfer at the hydraulic drives can be solving with direct current hydraulic drives and alternating current hydraulic drives (Constantinescu, 1922; Constantinescu, 1959). At the direct current hydraulic drives, the operating fluid flow in one way besides the alternating current hydraulic drives where it alternating periodically between a hydrogenerator and a hydromotor. The alternating current hydraulic drives have two types. The alternating current synchronous drive, and the alternating current asynchronous drive. The alternating current hydraulic drives have two main units: an alternating current hydrogenerator and an alternating current hydromtor (Fekete, 2014).

In the case of alternating current hydraulic drives (Fekete, 2014; Lukács et al., 2006; Petrescu et al., 2017; Fekete, 2017; Kröell et al., 1988), when the hydrogenerator is driven, the hydromotor starts with a slight delay, even when idling. This phenomenon is called the load angle. This is because loads occur even when idling, for which the torque required for starting must be built up, which can develop as the pressure increases. The greater the load, the greater the angular deviation between the axes of the hydrogenerator and the hydromotor. In this experiment, the load module was solved with a hydraulic pump in such a way that I increased the load with the help of a throttle valve. In this article, I would like to examine the effects of the load on the system.

2. Load of the hydromotor

As a result of the load module attached to the output shaft of the hydromotor, I had to examine the forces acting on the phase pistons of the hydromotor and the torque of the resulting forces. The shaft of the hydromotor is loaded with torque. It is necessary to determine the torque exerted by the forces acting on the phase pistons of the hydraulic motor. This torque balances the load torque. I performed the calculation based on *Figure 1* (Fekete, 2022; Fekete, 2023).

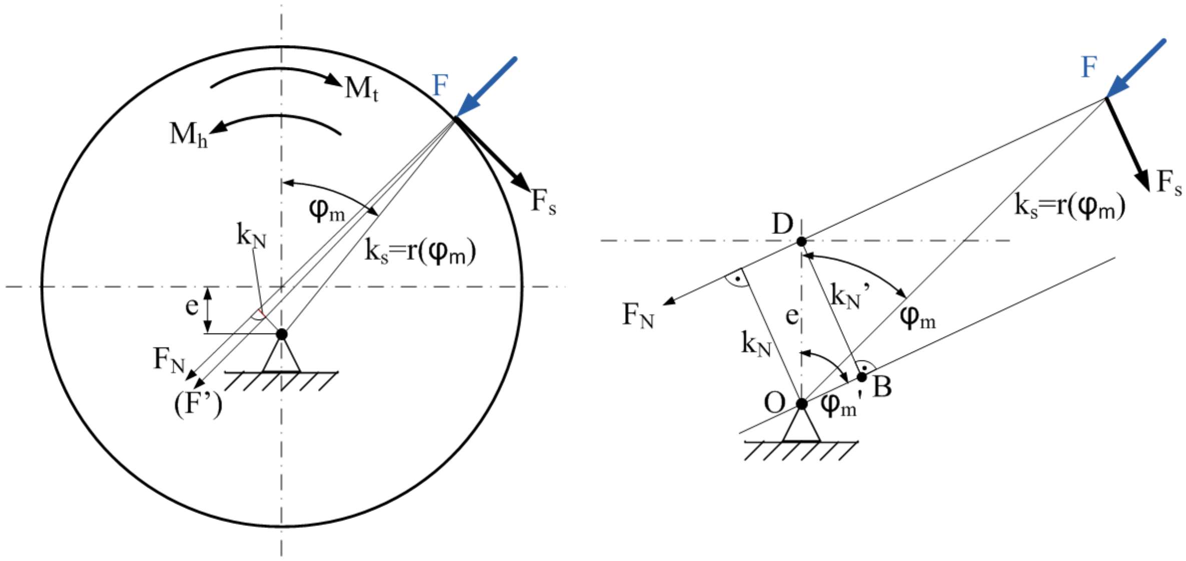

Figure 1. *The force system of the shaft load of the motor unit in the case of a phase piston* (Fekete, 2023)

Based on *Figure 1*, the driving torque can be written:

$$M_h = F_N k_N - F_S k_S, \tag{1}$$

where

- F_S: friction force,
- F_N: normal force.

In practice in hydraulic equipment:

$$F_N >> F_S \tag{2}$$

for that reason

$$F_N \approx F \tag{3}$$

and (if $k_N \equiv k_N'$ és $\varphi_m \approx \varphi_m'$) in case of ODB triangle (Lukács, 2023)

$$\sin\varphi_m = \frac{k_N}{e} \to k_N' = e\sin\varphi_m' \tag{4}$$

With the previously established approximations, the phase pistons in direct contact with the eccentric of the hydraulic motor produce a resulting driving torque M_h on the shaft of the motor unit. The kinematic model is shown on *Figure 2*. (Fekete, 2022)

Figure 2 shows the moment of the start-up phase, when the driving torque created because of the phase pressures acting on the phase pistons of the hydromotor unit due to the rotation of the eccentric disk of the generator unit, balances with the load torque ($M_h = M_t$), and the shaft of the hydromotor unit moves.

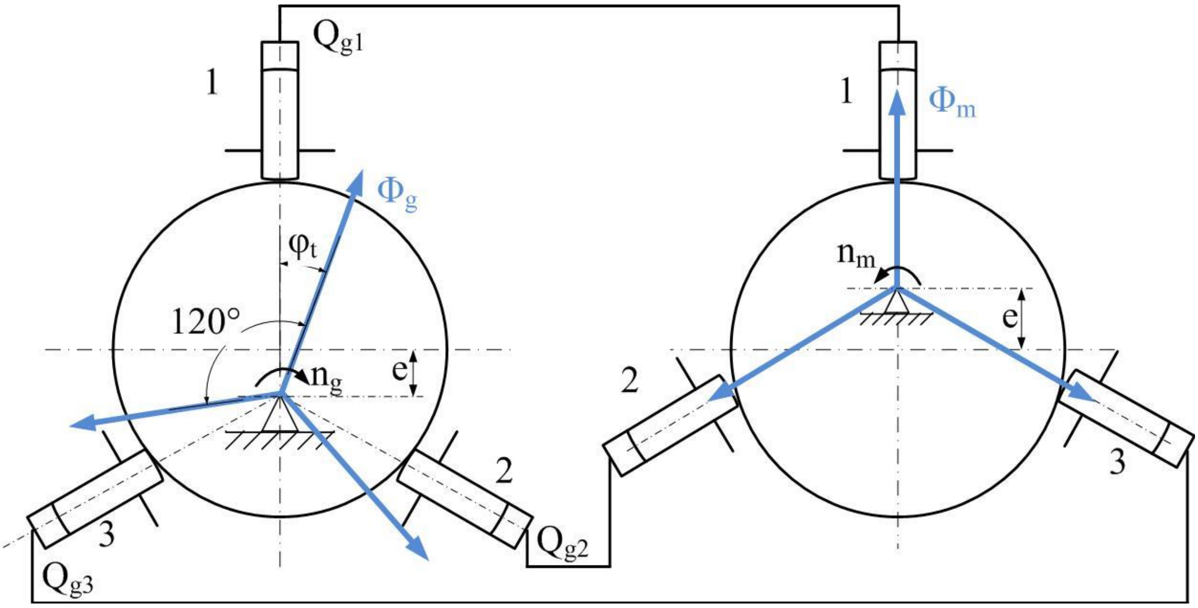

Figure 2. *Creation of resultant M_h driving torque* (Fekete, 2023)

The resulting M_h driving torque can thus be determined with the following relationship:

$$M_h = \sum_{i=1}^{3} F_{Ni} k_{Ni} \tag{5}$$

The angle required to start the hydromotor unit is called the load angle φ_t corresponding to the load torque. This phenomenon occurs because, due to load, the synchronous position of the hydrogenerator and the hydromotor ceases.

Based on *Figure 2*, on the axis of the hydromotor unit (described in detail based on *equation 5*):

$$M_h = F_1 k_1 + F_2 k_2 + F_3 k_3 \tag{6}$$

a driving torque occurs. The source of the F_1, F_2 and F_3 forces are the phase pressures occurring in the phase space. The phase pressures can be determined from the capacitive fluid flows occurring in the phase spaces.

As a result of the resulting M_h driving torque, a pressure increase occurs in the phase lines (one or two). The degree of pressure increase depends on the size of the load, because the greater the load, the greater the driving torque the phase pistons have to exert on the hydromotor shaft.

The fluid flows of the generator unit (Fekete, 2023):

$$Q_{gi} = A\frac{dx_i}{dt} = Ae\omega_g \sin\left((i-1)(\omega_g t - \frac{2\pi}{3})\right),\ i = 1...3 \tag{7}$$

where

- i: number of phases.

As a result of the load, the synchronous position of the generator and motor units is lost. The eccentric disk of the motor unit lags behind the eccentric disk of the generator unit by the φ_t load angle value t. As a result, the relation:

$$\Delta s_{gi} + \Delta s_{mi} = \Delta s_{Ci} \text{,} \tag{8}$$

where

- Δs_{gi} : the displacement of the pistons of the hydrogenerator compared to the basic position, and
- Δs_{mi} : the displacement of the pistons of the hydromotor compared to the basic position,

it will be shaped. Capacitive fluid flows accumulate $\Delta s_{Ci} A$ (where A, area of cross section) hydraulic charges in the phase spaces. The capacitive pressure change of the phase spaces from the hydraulic charges based on the hydraulic Hook's law:

$$\Delta p_{Ci} = -\frac{A \Delta x_{Ci}}{V_0} E = -\frac{A \Delta x_{Ci}}{C_H} \tag{9}$$

where

- Δx_{Ci} : change of the capacitive component of the hydraulic resistance,
- V_0 : starting volume of phase space,
- C_H: hydraulic capacitive resistance.

In case of load, the sum of the fluid flows in the phase spaces of the generator and motor units is not zero. The difference between the generator and motor fluid flows is the capacitive fluid flow, from which the pressure of the phase space can be determined:

$$Q_{Ci} = Q_{gi} + Q_{mi} \tag{10}$$

where

$$Q_{mi} = \frac{d}{d\varphi} Ae \left[1 - \cos\left(\varphi_{gi} - \varphi_t \right) \right] \tag{11}$$

Substituting into (11) and arranging it for capacitive fluid flows:

$$Q_{Ci} = Ae \left[\sin\varphi_{gi} + \sin\left(\varphi_{gi} - \varphi_t \right) \right] \tag{12}$$

occurs. The result of the two components of the relationship can be determined. Transforming the relation from which the capacitive fluid flow is obtained by the method of equal coefficients by a linear combination of the sine and cosine functions:

$$\left. \begin{aligned} & Ae \sin\varphi_{gi} \left(1 - \cos\varphi_t \right) + Ae \cos\varphi_{gi} \sin\varphi_t = a \sin\left(\varphi_{gi} + \psi \right) \\ & Q_{Ci} = a \sin\left(\varphi_{gi} + \psi \right) \end{aligned} \right\} \tag{13}$$

into (13) the resulting amplitude:

$$a = \sqrt{\left\{\left[Ae\left(1-\cos\varphi_t\right)\right]^2 + \left[Ae\sin\varphi_t\right]^2\right\}} = 1{,}41Ae\sqrt{1-\cos\varphi_t} \tag{14}$$

and the phase angle:

$$tg\psi = \frac{\sin\varphi_t}{1-\cos\varphi_t} \tag{15}$$

can be determined.

The capacitive pressure changes in each phase space can be determined from (14):

$$\Delta p_i = -\frac{1}{C_H}\int \omega_g a \sin\left(\omega_g t + \psi - (i-1)\frac{2\pi}{3}\right)dt,\ i = 1...3 \tag{16}$$

The phase pressures cannot be below zero. Therefore, the pressure changes must be superimposed on such constant pressures that the phase pressure cannot be a value lower than zero (the phase spaces must be pre-tensioned so that in case of displacement of the phase pistons of the hydrogenerator, it is able to force the phase pistons of the hydromotor to move). Knowing the phase pressures and the torque arms, the driving torque can be calculated.

$$p_{ci} = \frac{a}{2}\left[1+\cos\left(\varphi_g + \psi - (i-1)\frac{2\pi}{3}\right)\right], i = 1...3 \tag{17}$$

and

$$k_i = -e\sin\left(\varphi_m + (i-1)\frac{2\pi}{3}\right), i = 1...3 \tag{18}$$

Knowing *equations (17)* and *(18)*, the driving torque can be determined:

$$M_h = Ap_{C1}k_1 + Ap_{C2}k_2 + Ap_{C3}k_3 \tag{19}$$

After arranging the substitutions, for the theoretical drive torque of the three-phase synchronous system alternating current hydraulic drive:

$$M_h = 1{,}5\frac{Aae}{C_H}\sin\left(\varphi_t + \psi\right) \tag{20}$$

a connection occurs.

Due to the various losses, the actual driving torque is:

$$M_h = k_v 1{,}5\frac{Aae}{C_H}\sin\left(\varphi_t + \psi\right) \tag{21}$$

where $k_v = 0.7\sim0.8$ (Lukács et. Al., 2006).

In this context, the load angle φ_t is a function of the load. It can be determined from the $M(\varphi_t)$ diagram of the φ_t drive. To determine the $M(\varphi_t)$ diagram, the torque equation must be written on the axis of the motor unit in synchronous position (just starting), knowing that the motor unit is stationary, therefore, there is no liquid flow at this moment, so the generator liquid flow ($Q_{gi} = Q_{Ci}$) is a pure capacitive current, ($\varphi = \varphi_t$) angular rotation is the value of the load angle φ_t. The value of the torque arm k_1 is zero, with $k_2 = -k_3$.

Taking the above into account, the starting torque is:

$$M_i = Ap_{\max}\left\{\left[1+\cos\left(\varphi_t - \frac{2\pi}{3}\right)\right]k_2 - \left[1+\cos\left(\varphi_t - \frac{4\pi}{3}\right)\right]k_2\right\} \tag{22}$$

After substitutions of arrangements,

$$M_i = 1{,}3Ap_{\max}e\sin\varphi_t \cdot \tag{23}$$

The function of the load torque versus load angle can be seen in *Figure 3*.

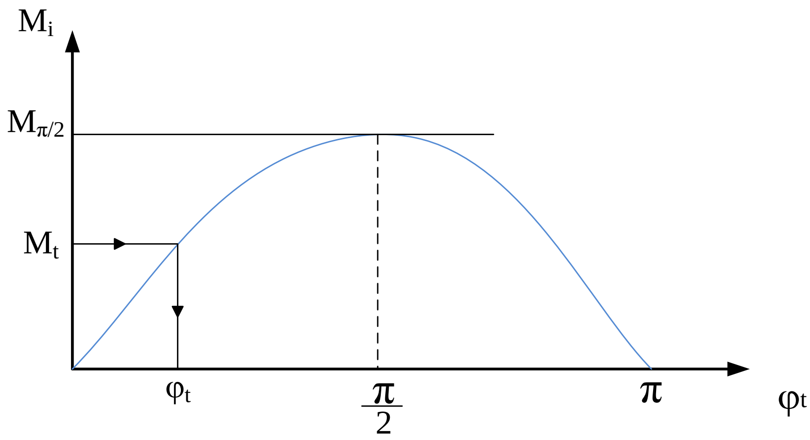

Figure 3. *The function of starting torque* (Fekete, 2023)

In aware of the load torque, φ_t can be determined. If $\varphi_t > \varphi_{t\_krit}$, (where φ_{t_krit}: the maximum load angle) the drive falls out of synchronization and the axis of the motor unit stops or rotates back and forth with a slight angular rotation. By reducing the load, the synchronous position can be restored, when the shaft of the hydromotor picks up the speed of the hydrogenerator. The load angle, taking into account the losses, can be approximately determined from the following relationship:

$$M_i \approx \frac{(Ae)^2}{C_H}\sin\varphi_t \tag{24}$$

3. Summary

In the case of a synchronous alternating current hydraulic drive, loads also occur when idling. The system must overcome the extra loads resulting from normal operation, but if it is no longer able to do so, it falls out of sync. This is a typical feature of these drives. If this happens, the system must be restarted, and the extra load must be removed.

The appearance of leakage loss between the pistons and the cylinder can be considered a disadvantage of the system I implemented. This could be eliminated by using a membrane instead of the current pistons, which would offer a solution to the leakage loss from the leak. The biggest disadvantage of the diaphragm is that it cannot move as much (permanent deformation, without damage) as the piston.

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