THE STUDY OF HYDRODYNAMIC SYSTEMS USED IN RAIL TRANSPORT

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Abstract: As the main energy source, diesel locomotives have a diesel combustion engine coupled to the driving wheels through a power transmission system; three systems have been developed so far: diesel-electric, diesel-hydraulic and diesel-mechanic, the first two being the most utilised due to their characteristics and specific performances.

The diesel-hydraulic locomotive uses a fluidic system to transmit the power from diesel engine to motor wheels: the system ensures power transmission through hydraulic machines combined with one mechanical transmission with gears, and that is why the system is also called hydromechanics transmission. This paper aims to address issues related to hydraulic power systems specific to diesel-hydraulic locomotives march.

Key-words: rail transport, locomotives, hydraulic powers

1. INTRODUCTION

The mobility of the national rail rolling stock is ensured by electric as well as diesel locomotives, while the steam powered ones are used only for leisure purposes.

The fluid power systems used by trains are divided into hydraulic type systems (using liquid) as well as pneumatic type ones (using either compressed air or other gases) and they are used either to power a series of execution elements (machineries) or for lubrication. Considering the fluid power systems, the pressure operating environment is used to power the engines which move the mechanical parts.

The main energy source of diesel locomotives is a thermal diesel engine which is connected to the main wheels by a power transmission system; three categories of this kind of system have been developed: diesel-electric, diesel-hydraulic and diesel-mechanical, the first two being mainly used due to their characteristics and superior performances.

Considering the case of diesel-hydraulic locomotives, the hydraulic systems

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ensure the transmission of power from the diesel engine to the driving wheels of the locomotive through a series of hydraulic machineries combined with mechanical sprockets transmission, also called hydro-mechanical transmissions: the hydraulic transmissions, their active components, may be divided into hydrostatic and hydrodynamic, the second ones being used more frequently.

There also are hydrostatic systems specific to all types of locomotives, used to power auxiliary installations which are important for the operation of the locomotive as well as of the entire train.

2. GENERALITIES ON THE HYDRODYNAMIC TRANSMISSIONS

The hydraulic power may be defined as a system which through the use of a hydraulic environment transmits the mechanical energy from an actuator element to a driven one.

According to the block diagram presented in Figure 1, the hydraulic power systems used comprise the energy transmission parts *T* from the energy source *SE* to the operating part *OL* and from the command and regulation equipment establishing the operation of the system: run-up, shutdown, reversing the operation of the system, speed and load regulation, etc.

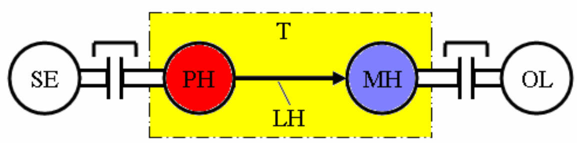

Fig. 1. The basic diagram of hydraulic operation

The parts ensuring the transmission of the hydraulic power comprise the hydraulic pump *PH* and the hydraulic motor *MH*. The connection *LH* between the pump and the motor has a purely hydraulic characteristic and it is realised by an under pressure flow of liquid. The Energy source *SE* of the hydraulic system is an internal combustion or pneumatic electric motor which drives the hydraulic generator by a mechanical connection; the operation system *OL*, mechanically connected to the motor, may have – depending on the type of motor – either a linear or a circular movement.

The hydraulic pump *PH* transforms the mechanical energy of the driving element (the energy source) *SE* into energy provided by the flow of liquid.

The hydraulic motor *MH* realises the conversion of hydraulic energy into mechanical energy which is then sent to the driven element (the operation system) *OL*.

Hydrodynamic transmissions keep to the above mentioned principles and they are systems composed of two hydraulic turbo-machines used for the transmission of mechanical power: this kind of transmission comprises in the same casing a hydrodynamic pump rotor as well as a hydraulic turbine rotor [1], [2].

This kind of transmission allows the continuous change, within certain limits, of the speed and torque through the variation of the volume of the flow and the hydraulic charge of the turbine.

According to their function, hydraulic transmissions are divided into:

- hydrodynamic couplings (clutch);
- hydrodynamic converters (torque amplifiers);
- hydrodynamic brakes.

The hydrodynamic coupling allows the elastic coupling of axles *SE* (the actuating axle of the pump) and *OL* (the output axle powered by the turbine), with speed ratio variable within large limits $\left(\frac{n_{OL}}{n_{SE}} = \frac{n_2}{n_1} \neq \text{ct}\right)$, but keeping the torque constant ($M_{OL} = M_{SE} \Leftrightarrow M_2 = M_1$). In normal operation conditions, the $M_2 = f(n_2)$ characteristic of the secondary axle is different of the $M_1 = f(n_1)$ of the main axle by the existence of a slight slip (relative speed variation).

The hydrodynamic converter largely changes the torque transmitted between the main and the secondary axle: as speed n_2 of the axle of the turbine decreases following a demand of an increased torque, it ads the torque to that of the main axle M_1. The $M_2 = f(n_2)$ characteristic of the secondary axle is similar to that of a variable speed electric motor.

The hydrodynamic break acts as a hydrodynamic coupler with the secondary axle blocked. The $M = f(n)$ characteristic is increasing, not being able though to block the main axle.

Figure 2 represents a first alternative of the hydrodynamic transmission: motor 1 drives the hydrodynamic pump 2 which through the pipe 3, hydraulically supplies turbine 4 which then powers the operation system actuated by axle 6 (driving wheels, a ship propeller etc.). Considering that the hydraulic losses through the connection pipes of the hydraulic machineries are important, a more compact solution 5 has been chosen: therefore, the hydraulic circuit was concentrated in the same case with the rotors of the two machines.

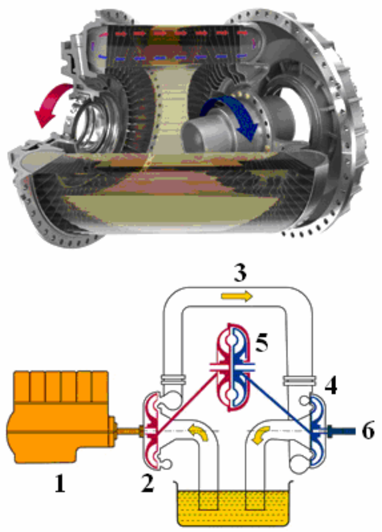

Fig.2. The genesis of the hydrodynamic transmission [3]

The hydrodynamic systems for movement transmission transform therefore the mechanical energy of the source in kinetic energy of a liquid flowing in an enclosed volume at relatively low pressure (p = 3 – 5 N/cm^2) and high speeds (v = 20 – 30 m/s) between a pump and a turbine the later one transforming it again in mechanical energy useful to the destination. The volume or the operation area of the liquid is toroidal the transversal section of the torus being divided between the mobile and static elements: the mobile parts are pumps (inputs) and turbines (outputs) while the static ones – reaction members (stators). All the elements are installed in one single case with sealing areas, mobile and static parts foreseen with different form blades.

In a hydrodynamic transmission elementary cell pump-turbine-stator (*P*-*T*-*S*) (figures 3 and 4), the kinetic energy of the pump *P* found in movement with the angular speed ω_P is transferred to the operating liquid *L*, which due to the centrifugal force is involved along the toroidal surface towards the exterior, hitting the blades of the turbine *T* descending along the toroidal surface towards the interior radius of the torus transferring the energy to the turbine which will rotate with an angular speed ω_T.

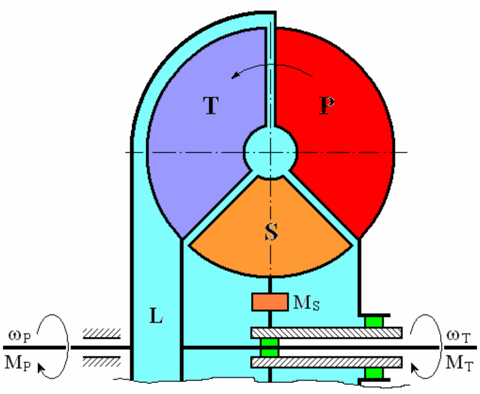

Fig. 3. Hydrodynamic transmission: elementary cell

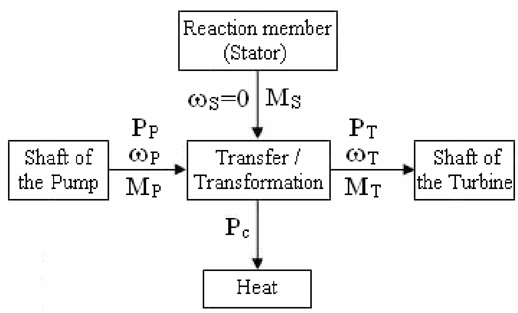

Fig. 4. Basic diagram of the elementary cell P-T-S

The liquid will flow from the blades of the turbine onto the stator *S* modifying its trajectory and gives it an additional momentum therefore the momentum of the turbine is given by the sum of the momentum of the pump and respectively that of the stator:

$$M_T = M_P + M_S \,. \tag{1}$$

Considering the lack of the stator *S* or its rigid connection to the pump *P* or turbine *T*, $M_S = 0$, the cell becomes *P*-*T*, and

$$M_T = M_P \,. \tag{2}$$

In the first case the hydrodynamic transmissions amplify the input momentum, therefore being called *hydrodynamic torque amplifier,* $M_T / M_P > 1$, while in the second case they preserve the input momentum $M_T / M_P = 1$, being therefore called *hydrodynamic clutches* (*hydraulic couplings*).

The hydraulic coupling is the particular case of hydrodynamic transmission system which lacks the stator and realises the transmission of the momentum from the source to the operating element according to relation (2).

From a kinematical point of view, the hydraulic coupling is characterised by the transmission ratio *i*, which connects the output angular speeds ω_T as well as the input ones ω_P:

$$\omega_T = i \cdot \omega_P\,; \tag{3}$$

the transmission ration defines as well the slip of the connection, respectively the lag of the turbine *T* in relation to the pump *P* following the load of the operation machine:

$$a = 1 - i\,. \tag{4}$$

According to the structure presented in Figure 5, the hydraulic coupling transfers the kinetic energy of the source to the operation machine through a successive conversion of mechanical-hydraulic-mechanical energy. Considering the hydraulic domain of the conversion, due to the friction of liquid molecule and the interior surfaces of the pump and turbine, internal losses appear as heat, the hydraulic coupling being characterised as well by the effective power η_C which may be mathematically expressed according power (5) or slip (6):

$$\eta_C = \frac{P_T}{P_P} = \frac{P_T}{P_T + P_c} = 1 - \frac{P_c}{P_P}\,, \tag{5}$$

respectively

$$\eta_C = \frac{P_T}{P_P} = \frac{M_T \cdot \omega_T}{M_P \cdot \omega_P} = \frac{n_T}{n_P} = i = 1 - a\,; \tag{6}$$

in expressions, P_P, P_T and P_c are input, output powers as well as the one lost through thermal dissipation at the coupling (the indexes *P*, *T* and *c* are related to the pump, turbine and heat).

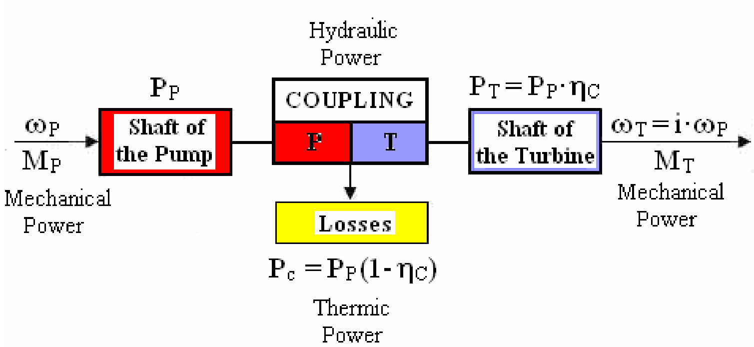

Fig. 5. Block diagram of the hydraulic coupling

The hydrodynamic converter (torque amplifiers) or the stator hydrodynamic transmissions represent the most complex solution for the centrifugal hydraulic power systems. As well as in the case of hydraulic couplings, they ensure the transmission of movement from a pump actuated by the angular speed ω_P and the torque M_P to a turbine rotating at an angular speed ω_T developing the momentum M_T , their characteristic being the fact that they amplify the output momentum due to the insertion of a stator between the two main rotors.

Besides the two measures characteristic to hydraulic couplings, namely the transmission ration

$$i = n_T / n_P \tag{7}$$

and slip (relation 4), another characteristic of the hydrodynamic torque amplifiers is the coefficient of amplification *A*, defined by the following expression:

$$A = M_T / M_P . \tag{8}$$

The difference between the fluid couplings and the hydrodynamic converters is not composed only by the existence of the stator but also by the form of the blades as well: if the radial blades are rectilinear at the connection, the ones at the amplifiers are curved. The balance of the momentum established at the fluid couplings modifies due to the introduction of the stator, developing therefore an additional momentum. The curvature of the blades determines a more complex trajectory of the operation liquid, resulting in an increase of its kinetic energy. Thus, considering the fluid coupling, the hydrodynamic torque amplifier, with the same energy consumption, will have a larger output momentum (relation 1).

The effective power η_{Ac} of the hydrodynamic connection amplifier is given by the power ratio of the turbine and the pump:

$$\eta_{Ac} = \frac{P_T}{P_P} = \frac{M_T \cdot \omega_T}{M_P \cdot \omega_P} = 1 - \frac{\Delta P_{Ac}}{P_P} = A \cdot i \tag{9}$$

where ΔP_{Ac} are the energy losses due to liquid particles friction and collision and the mechanical friction o f the bearings.

3. HYDRODYNAMIC TRANSMISSIONS FOR THE MOVEMENT OF LOCOMOTIVES

These systems, ensuring the transmission of power from the diesel engine to the driving wheels of the locomotives using hydraulic systems combined with mechanical transmissions, operate through the variation of kinetic energy of the liquid generated by its acceleration by a pump operated by the diesel engine and the deceleration of the same mass of liquid inside a turbine connected to the actuated axle. Oil is exclusively used as operational liquid, due to its lubrication functions of the mechanical gear box with which the hydrodynamic transmission configures the hydro-mechanical system.

The hydro-mechanical transmission has to meet the following conditions in order for the diesel engine to power the driving wheels:

- The energy losses should be as little as possible;
- The tractive force should change from zero to maximum uniformly;
- The variation of the tractive force should be ensured according to the relation:

$$\frac{F_{\max}}{F_{\min}} = \frac{v_{\min} \cdot \eta_m}{v_{\max} \cdot \eta_M} \tag{10}$$

where: F_{max} is the tractive force of the locomotive at maximum speed, $F_{\min}$ – the tractive force at the lowest continuous speed, v_{min} – the minimum admissible speed of the locomotive, v_{max} – the maximum designed speed, η_m and η_M – the effective power of the transmission at the respective speeds;

- the sense of rotation of the secondary axel of the transmission system has to be changeable in order to change the moving direction;
- the weight and size of the transmission system have to be reduced, while its power density should be increased.

The torque hydrodynamic amplifiers of diesel drive vehicles should ensure a constant power operation of the motor, independent of the operation conditions of the actuated axel. These are recommended therefore for the ignition, the torque M_T being in indirect proportion to the speed n_T of the axel of the turbine, this being higher at the ignition compared to the torque M_P of the axle of the pump (when $n_T \to 0$, $M_T = (4 - 5)\ M_P$); the efficient power, with a parabolic form, has a maximum of 0.85 when the speed of the turbine evolves within the range $(0.4 - 0.6) \cdot n_n$, (n_n - nominal speed) the mentioned values corresponding to the integral filling of the transformer. If the torque amplifier is partially filled with oil then the output momentum M_T decreases, while the torque M_P which may be transmitted decreases as well.

Hydraulic couplings are recommended for cruising speed when the torques of the turbine and motor are almost equal.

Neither the converter nor the hydraulic coupling corresponds to the conditions required by the use of diesel locomotives: only by combining them with a gear box or by a combination of converters respectively that of a converter and of a fluid coupling (Figure 6), the corresponding

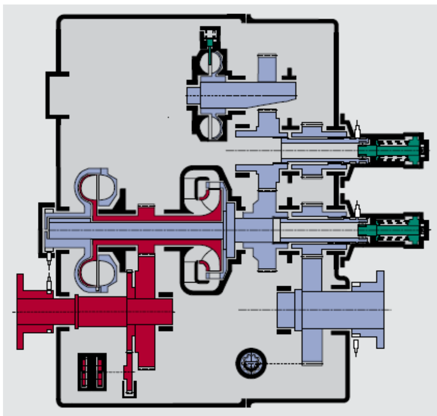

Fig. 6. T311bre Voith Transmission, with hydraulic connection and torque amplifier: red – primary components (actuated by the motor); blue – secondary components (connected to the driving wheels); black – stationary components [3]

characteristics for the use of diesel traction are obtained. Considering the constant power of the diesel engine to actuate the hydraulic transmission, it is implied that the ignition is ensured by a torque amplifier and the cruising regime by another amplifier or by a hydraulic coupling.

4. CONCLUSIONS

If the constant power of the diesel engine for the operation of the hydro-mechanical transmission of locomotives is considered, then it is imposed for the ignition to be ensured by a torque amplifier, being able to maintain the cruising speed either by hydraulic coupling or by a low level torque amplifier.

When igniting and at low speeds, namely for the operation with a converter, the speed of the pump and therefore of the diesel engine is constant, while the torque of the turbine is $M_T = (4.5\ldots5)\ M_P$. Around the considered value of 0.65 of the speed of the turbine out of its nominal speed, it is recommended to operate with a low level torque amplifier or by the hydraulic coupling the momentum stays constant, while the speed may reach the nominal value of the diesel engine.

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