Control System for Hydrostatic Transmission of Railcar M27

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Abstract — **The paper describes functions of a control system for hydrostatic transmission for the reconstructed railcar M27 which is used for transport of passengers on a narrow gauge railway near Jindřichův Hradec, Czech Republic. Software for this control system was developed at the University of Pardubice.**

Keywords: rail vehicle, control system, hydrostatic transmission, tractive effort, JHMD, M27, MUV 74.1.

I. INTRODUCTION

Jindřichohradecké místní dráhy a.s. (JHMD) company provides regular railway service on a narrow gauge railway between Jindřichův Hradec and Obrataň in the Czech Republic. During the year 2012 the JHMD decided to start reconstruction of four railcars of type M27 (805.9). Originally the M27 was manufactured in Romania in the middle of 80's. TABLE I summarizes technical parameters of the original railcar M27 (805.9).

TABLE I.
TYPE SIZES FOR CAMERA-READY PAPERS

Gauge	750 mm
Length	15 920 mm
Weight	24,5 t
Wheelset arrangement	B' 2'
Maximum towing capacity	57 kN
Engine type	Raba-MAN D2156HM6U
Engine output	141 kW
Transmission	Hydrodynamic
Maximum speed	60 km/h

The reconstructed railcar M27 has completely new design, engine, new hydrostatic transmission, wheelset arrangement, control system, interior, air conditioning, lights etc. Main frame and bogies are almost the same as on the original M27.

Fig. 1. Reconstructed railcar M27

A hydrostatic transmission is used instead of the original hydrodynamic transmission. The control system for the hydrostatic transmission used in the reconstructed vehicle was developed at the University of Pardubice/DFJP-KEEZ and at first it has been succesfully used on special rail vehicles MUV 74.1 by CZ Loko company during the years 2012 and 2013.

TABLE II summarizes technical parameters of the M27 after reconstruction.

TABLE II.
TYPE SIZES FOR CAMERA-READY PAPERS

Gauge	750 mm
Length	15 920 mm
Weight	24,5 t
Wheelset arrangement	B' B'
Maximum towing capacity	24 kN
Engine type	Tedom 242R6VHTA26
Engine output	242 kW
Transmission	Hydrostatic (Parker) 2x hydraulic pump PV270 2x hydraulic motor F12-250
Maximum speed	60 km/h

II. WHEELSET ARRANGEMENT

There are two bogies and two independent hydraulic circuits, one for each bogie. It allows to continue driving if one circuit fails. Each circuit consists of an axial piston pump with variable displacement (Fig. 2, pos. 3) and a hydraulic motor with constant displacement (Fig. 2, pos. 4 and 5). A cardan shaft is used to couple wheels with the hydromotor. Both hydraulic pumps are connected directly to the engine output shaft.

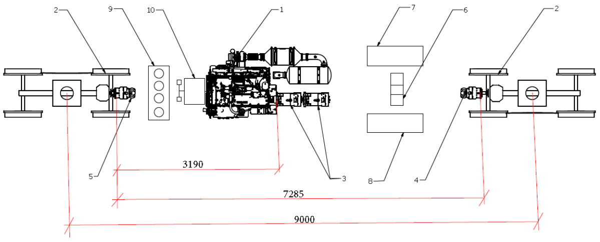

Fig. 2. Wheelset arrangement

III. HYDROSTATIC TRANSMISSION

A. Overview

Hydrostatic transmission is commonly used in off-highway vehicles. In locomotion applications it is commonly used for propeling of auxiliary devices such as fans. Due to its benefits it is also succesfully used in traction drives especially on low power shunting locomotives and special maintenance vehicles like tampers.

Benefits of the hydrostatic transmission are high power density (easy installation to vehicle where only a small room is available) and continuous transfer ratio that allows to achieve the prescribed speed-tractive-effort curve and utilizes engine power well.

Disadvantages are lower efficiency, possible oil leaks, sensitivity to oil cleanness and increased demands and costs for maintenance compared with modern electric drives.

Basic structure of one hydraulic circuit (one bogie) of the M27 vehicle is in Fig. 3.

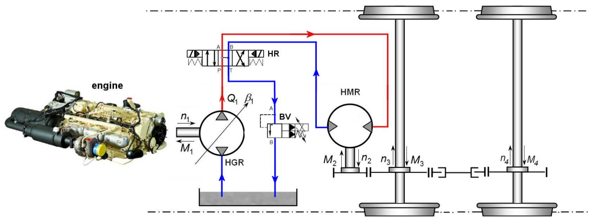

Fig. 3. Diagram of one hydraulic circuit

The open hydraulic circuit consists of the axial piston pump (HGR) Parker PV270 acting as a source of oil flow, hydraulic motor (HMR) Parker F12-250 with constant displacement, directional control valve (HR) and brake valve (BV). The bypass valve is connected parallel to the brake valve (not shown in Fig. 3) for lowering pressure losses of the brake valve if it is open.

The tractive effort depends on the oil pressure on the pump output . Therefore the oil pressure is the main controlled variable. The oil flow rate and vehicle speed are dependent variables. The oil pressure is controlled by the pump displacement, which is represented by the dimensionless quantity β, according to the control law

$$\beta = \frac{V_g}{V_{g\max}} \tag{1}$$

where $V_{g\max}$ is the nominal displacement [cm^3] and V_g is the actual displacement [cm^3].

The theoretic oil flow rate in [m^3/s] is:

$$Q = \frac{V_{g\max}}{2\pi} \cdot \omega \cdot \beta \tag{2}$$

where ω is the angular speed of the pump or motor.

The theoretic torque (input in the case of pump or output in the case of motor):

$$M = \frac{V_{g\max}}{2\pi} \cdot p \cdot \beta \tag{3}$$

where p is the differential pressure across the pump or motor.

The theoretic power (input in the case of pump or output in the case of motor):

$$P = M \cdot \omega = Q \cdot p \tag{4}$$

All above mentioned equations are theoretic, i.e. efficiency is not included. Maximum pressure used on the M27 is 330 bar, the oil flow rate for maximum velocity 60 km/h is 367 litres per minute.

In the first proposals the proportional brake valve should have been used for hydraulic braking but in the final version the hydraulic braking is not implemented. Instead of it the brake valve with its bypass valve are fully opened during normal operation to avoid pressure losses. If the driving direction is not set (the direction control valve is disengaged and is in the central position) the brake valve is activated and its bypass valve deactivated to ensure minimum pressure for a proper operation of the pump. This minimum pressure is about 20 bar.

Control law

The hydrostatic transmission is controlled according to the ideal tractive effort curve of the vehicle.

In Fig. 4 you can see fundamental control characteristic of the hydrostatic transmission equipped with the pump and motor, both with variable displacement.

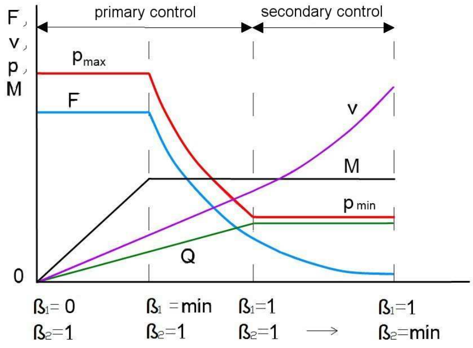

Fig. 4. Control characteristic of HS transmission

The motors used in the M27 have constant displacement ($\beta_2 = 1$) therefore the part named “secondary control” in Fig. 4 does not exist, the control range is restricted to the pump operation only (primary control).

In the region of constant power (from β_1 = min to $\beta_1 = 1$) the engine load torque M is kept constant (5).

$$\begin{aligned} M_{1\mathrm{T}} &= \frac{V_{\mathrm{gmaxHG}}}{2\pi} \cdot p_{\min} = \frac{V_{\mathrm{gmaxHG}}}{2\pi} \cdot p_{\max} \cdot \beta_{1\min} = \\ &= \frac{V_{\mathrm{gmaxHG}}}{2\pi} \cdot p \cdot \beta_1 = const. \end{aligned} \tag{5}$$

The pump is commanded with the desired pressure *p* according to the desired tractive effort. Quantities β_1, flow *Q* and vehicle speed *v* result from actual situation (running resistance). The rngine speed (not shown in Fig. 4) is commanded according to the desired tractive power. Speed for the desired power is a compromise between engine manufacturer requirements and minimum brake specific consumption.

In the region of the constant tractive effort, the pressure is set according to the desired tractive effort (330 bar maximum), the engine load is proportional to the actual pump displacement.

The vehicle velocity is directly proportional to the actual pump displacement (β_1). The transmission ratio is continuously changing (6).

$$i_T = \frac{n_{2T}}{n_1} = \frac{V_{g\max HG}}{V_{g\max HM}} \cdot \frac{\beta_1}{\beta_2} \qquad (6)$$

The subscript *T* stands for "theoretic", i.e. efficiencies are not included, n_1 is the pump (engine) speed and n_{2t} motor speed (theoretic).

In Fig. 5 you can see the tractive effort curve of the reconstructed railcar M27 including grade resistance curves.

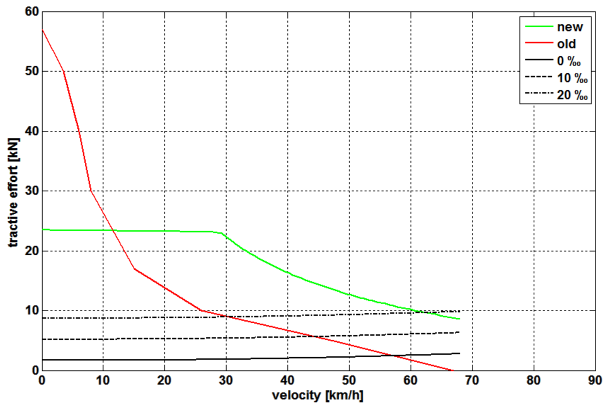

Fig. 5. Tractive effort curve of M27 after reconstruction (new) compared with tractive effort of M27 before reconstruction (old)

Absence of motors with variable displacement reduces the dynamic control range and shortens the constant power region to lower velocities (see Fig. 6).

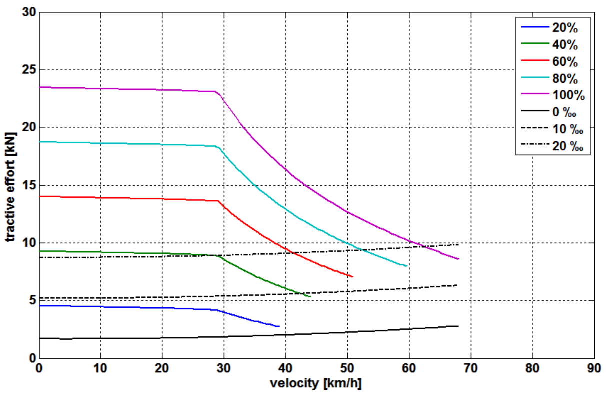

Fig. 6. Partial tractive effort curves of M27 after reconstruction

To achieve the desired vehicle velocity while running resistance is low can be uneconomical because the oil flow and therefore the engine speed is high but the engine load is low due to low running resistance (curves don't intersect).

Fortunately the JHMD's railway is situated to a hilly country so the aforementioned disadvantage can be avoided. The motors with variable displacement of the used size and for a reasonable price were not available for this vehicle.

B. Control structure

A simplified control structure is shown in Fig. 7.

Driver sets a desired tractive power. The desired power is evenly distributed across both hydraulic circuits (bogies). The traction control is not implemented. In the case of one circuit malfunction the broken circuit is commanded to zero desired power and the circuit is disabled.

The desired power is ramped and goes to the tractive power limiter that limits the desired tractive power in all circuits proportionally if the engine load is above a specified value.

The actual engine load at current speed is received from the engine ECU via CAN bus. Next a desired load torque M_{1t}* is computed from the desired tractive power and engine speed n_1*. The M_{1t}* is then converted to the desired pressure p* with the help of equation (5). Actual β_1 is sensed by the LVDT sensor inside of the pump. These computations are done for each hydraulic circuit. The desired speed of the engine is computed according to the desired tractive power including defined constant margin for accessory loads that can switch randomly on and off.

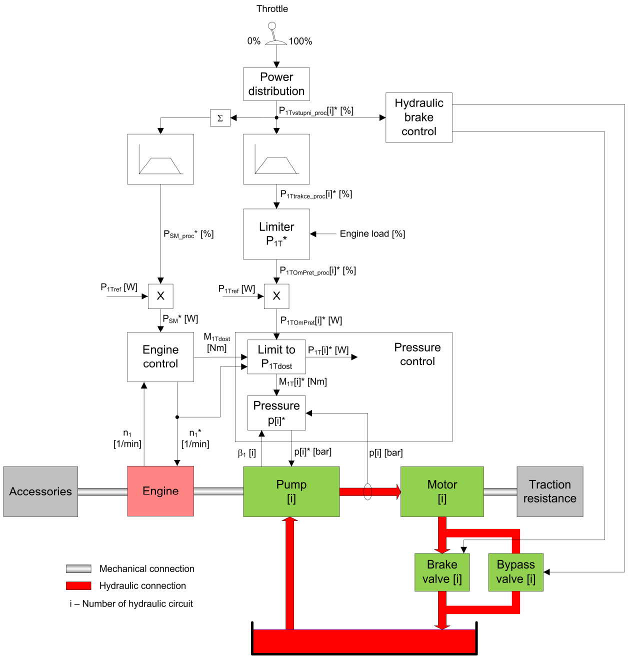

Fig. 7. Control structure

Due to the used control principle the available engine power at current speed is utilized only in the region of the constant tractive power, not in region of the constant tractive force. This is due to fact that driver commands the desired power not desired force, i.e. the engine speed is set directly according to the throttle position regardless of the fact if the engine would be loaded with this power or not.

The brake valve and its bypass valve are fully opened during normal drive to minimize power losses in the system.

C. Coasting

If coasting is commanded by driver or by external logic then the direction control valves in both circuits are disengaged and oil can freely flow from the output port to the input port of both motors. The motors act in this situation as pumps. The desired power is set to zero but the desired pressure is not zero, instead of it 20 bar is commanded. The minimum pressure 20 bar is needed for a proper pump operation. Without this pressure pump it is not possible to close the pump to almost zero displacement. Almost no oil flow from the pump is generated during coasting, the engine is unloaded. The minimum pressure is maintained by actuation of the brake valve, bypass valve is closed. Engine idles during coasting.

Special care must be taken during a return phase from coasting back to pulling when the vehicle is moving. In the beginning of this phase the pumps generate only small flow because the desired power and therefore the engine speed is low but the motors generate flow that depends on the vehicle speed. At the maximum vehicle speed this flow could be twice as flow generated by the pumps. To prevent big flow difference, that motor would have to suck via leakage line from tank, the direction control valve in each circuit is not engaged immediately but after the flow difference decreases under a defined threshold (50 litres per minute). Big flow difference should cause negative pressure in the motor leakage line and cavitation could occur.

The same principle is used during "small" coasting while driver commands low power but the vehicle still keeps its velocity. In this situation again a flow difference between the pump and motor exists. If this difference is greater then the defined threshold (150 litres per minute) then the direction valves are disengaged to prevent negative pressure in the motor leakage lines.

There are a few differences compared with "big" coasting. During "small" coasting the desired pressure stays at the level according to the desired power, engine speed also the brake valves and bypass valves are fully opened as during normal operation. Return from the"small" coasting back to pulling is automatic and occurs if the vehicle slows enough down causing reaching of the flow rate difference threshold for engaging of the direction valves.

IV. HARDWARE COMPONENTS

The control system performs only functions closely related to the hydrostatic transmission. All other functions like the engine starting, lighting, information system, doors are controlled by their autonomous control systems.

The throttle is an analog type (4-20 mA output) with latch in the bottom position (coasting demand). The external switching logic for blocking traction power is connected to the input named "coasting switch". Reaction of the hydraulic system on the coasting demand is following. Power is set to zero and the direction valves are disengaged. Oil can flow freely through the hydraulic motors, the vehicle is coasting.

The TEDOM engine is controlled in a speed loop, communication runs over the J1939 protocol. The state of engine is displayed on a small color diagnostic display placed on the driver's desk. State of the hydraulic drive would be also displayed on the same display in a future.

An ethernet port on the RRCPU is used for debugging purposes and for firmware and application software download to the RRCPU.

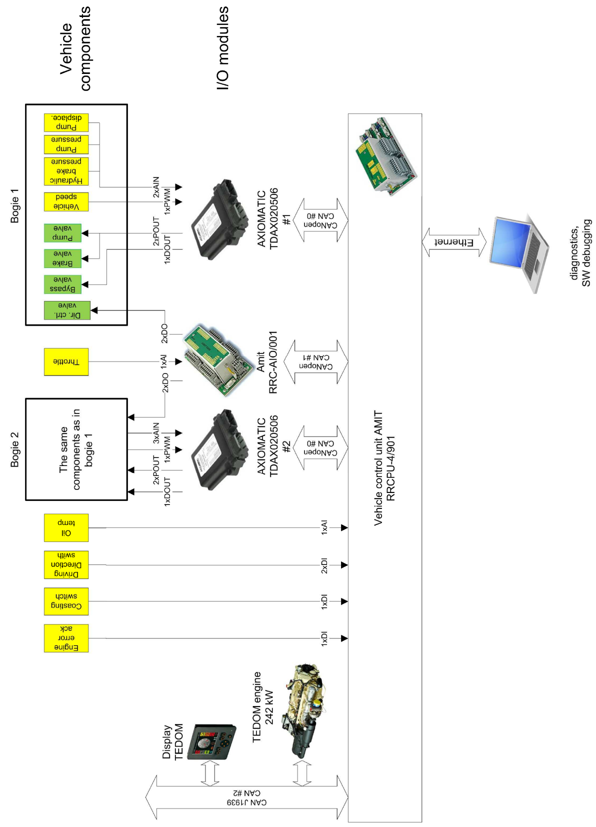

Fig. 8. HW architecture

V. SOFTWARE DEVELOPMENT

Main functions of the application SW are following:

- Control of the hydrostatic transmission
- Control of the engine speed
- On board diagnostic of components

The application software for the vehicle control unit RRCPU is developed in compliance with legislative norm EN 50128 [2] and with MISRA coding standard. The vehicle computer firmware itself meets requirements for safety integrity level 0. The application SW is written in the C++ language. The application SW uses TROL library by AMiT for access to the CANopen buses, I/O and other functions in the vehicle control unit RRCPU. Special applications TrolDatGen and TrolView developed by AMiT are used for setting up a project and real-time application debugging including data logging, displaying data in charts, using alarms for detection mechanism of faults and so on.

The SAE J939 communication stack for communication with the engine was developed on the KEEZ department because this type of protocol was not supported by the TROL library.

Safety functions are secured outside of the application SW using the HW relay logic. It sends a signal to the "coasting switch" input on the RRCPU if it is needed and also mechanically interrupts digital outputs of the RRC-AIO module for disengaging of the direction valves in all hydraulic circuits. The result is disengaging of power and vehicle switches to coasting.

The safety relay circuit guards following:

- Air pressure in brake system (drop in pressure results in disengaging of power).
- If vehicle doors are closed.
- Actual position of the hydraulic direction control valves (has to be same as commanded position).
- Oil temperature and oil level in tank.

Integration testing on the first and second vehicle takes place in these days. After its completion a final validation tests will be performed. The vehicle will then be prepared for the approval procedure.

VI. MEASUREMENTS

In Fig. 9 there are shown main quantities of the hydrostatic propulsion that were acquired during the vehicle acceleration from zero velocity at 100 % throttle. Measurements were taken on the real vehicle M27.002.

At the beginning the vehicle stays at zero velocity, engines idle at 800 rpm, the direction valves are disengaged (outputs of both pumps are connected with an oil tank through the brake valves), the brake valves are activated and create approx. 20 bar pressure (pump 1 and 2 actual pressures are approx. 20 bar in Fig. 9) in order to close both pumps (beta of both pumps is approx. zero in Fig. 9).

Driver sets 100 % throttle at the 25th second, i.e. maximum tractive effort. Signal from the throttle is ramped. The direction valves for switching forward direction are activated, oil can flow from now from pumps to motors. Pressure ramps up to maximum value 330 bar. The vehicle begins to move. The pump displacements and flow rates increase which results in a vehicle velocity increase. Pressure is still held on the maximum value.

The engine load increases as well. The engine load represents engine torque at a current engine speed. This part of figure corresponds to a constant tractive effort region in the tractive effort curve.

The engine speed is set to the value corresponding to 100 % power demand even if the actual power taken from the engine in the constant tractive effort region is just increasing with the vehicle velocity and the commanded engine speed does not correspond to 100 % power demand (engine speed is set according to the throttle position, not according to the real power needed from the engine).

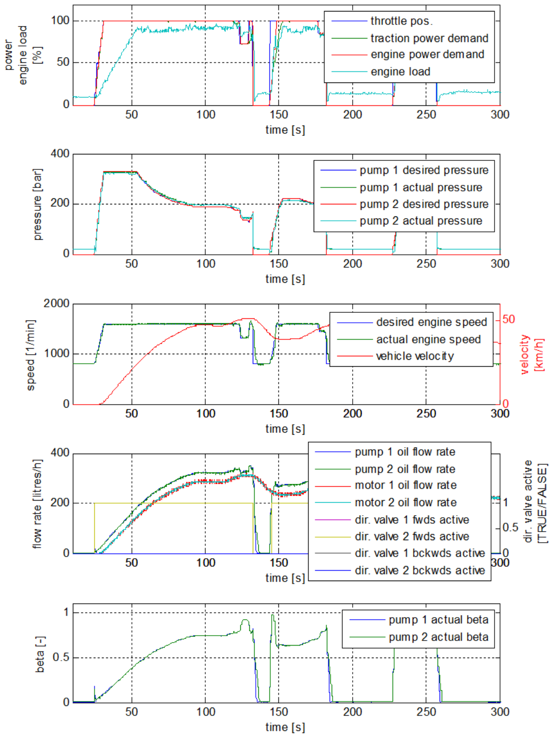

Fig. 9. Vehicle acceleration at 100 % throttle

At the 54th second the velocity reaches approx. 24 km/h. This is the point where the region of constant power begins. It corresponds with the theoretic tractive effort curves shown in Fig. 4 or Fig. 5 quite well. From this point engine further works with an optimal load at optimal speed, i.e. the engine speed is optimal for the demanded power.

The pressure demand is computed according to (5) in order to keep the engine load at a constant value approx. 95 %. As the vehicle velocity increases, the pressure and tractive effort decreases to keep the engine load constant.

At the 133th second driver commands coasting. The traction power is set to zero, i.e. the pressure demands are zero, the engine goes to idle, the direction valves are disengaged, outputs and inputs of the motors are connected through the direction control valves. It enables free oil flow through the motors. The pumps are closed because the brake valves are activated. The vehicle is coasting.

At the 143th second driver commands full throttle again while the vehicle is moving. The drive goes from coasting to pulling in the same way as at the beginning. The only difference is a later activation of the direction valves. The valves are engaged at the moment when difference between the pump flow rate and motor flow rate in each circuit reduces below the defined threshold (50 litres/h). It enables fluent transition without oscillation.

VII. CONCLUSION

Main functions of the control system for the hydrostatic transmission of the rail vehicle M27 were described in the paper. In these days integration tests are performed. Results from the first measurements on the real vehicle match theoretical assumptions. It was observed that the hydraulic pumps come from manufacturer with a large deviation in the minimum pressure setting that influences a pump controllability in coasting. Therefore it requires an additional finer setting on each produced vehicle. But overall system behaves as expected.

ACKNOWLEDGMENT

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