Prototype hybrid power transmission for city bus

Zbigniew Pawelski*

* Vehicle Research Institute Technical University of Łódź, Poland
pawelski@p.lodz.pl

Abstract – **Work on the construction of a hybrid drive for a city bus has led to a solution in which hydropneumatic energy accumulators and a variable-speed transmission with a parallel power flow are used. In the controllable part of the variable-speed transmission there is a hydrostatic transmission operating in four quarters of the power field, owing to which it is possible to transfer energy to and from the vehicle wheels through the variable-speed transmission. A change in the direction of an energy flow results in a change in the value of pressure in the operating conduits of the hydrostatic transmission from suction to force. The hydropneumatic accumulators were connected to the operating system by means of a system of logic valves controlling the flow and pressure, irrespective of the fact which operating conduit is a pressure conduit at a given moment.**

In a series connection the same power flows through all the elements of the system, while the efficiency and the range of ratios of the whole drive system is equal to the product of the efficiency or the range, respectively, of particular elements. In this connection it is possible to increase the range by means of adding a reducer, whereas an increase in the efficiency can be obtained in the same way only in the case of shifting the operating parameters of a variable-speed transmission to a more favourable area.

In the parallel connection, where the power transmitted branches off, a variable-speed transmission transmits part of the power and has a different range of ratio than the whole drive system. Besides, the transmission transmits smaller power but has smaller dimensions and weight. Consequently, the drive system obtained can have better properties in every respect than the variable-speed transmission constituting its element, if it were to transmit the whole power. In many cases it is the only acceptable solution, eg for a city bus. In addition, parallel systems allow a variable-speed transmission to be combined into systems of a variable structure, which will yield properties satisfying the requirements resulting from their use in vehicles. It has the following advantages:

- it allows the operation field of the engine to be limited, irrespective of the load to the segment or point in the area of the maximum efficiency; this depends on the dynamic structure of the gear box assumed,
- with the efficiency of the gear box reduced by several per cent, compared with the conventional system, this system guarantees a high average efficiency of the engine, thereby reducing the consumption of fuel in city traffic,
- it ensures a smooth change in the speed and direction of motion (driving backwards and forwards),

- it enables the vehicle to move at any slow speed, also during changes in resistance to motion, eg with considerable terrain ruggedness,
- it has small dimensions and weight in relation to the power transmitted; for mechanical and hydrostatic transmissions the unitary weight ranges between 1.0 and 2.4 kg/kW,
- it allows the vehicle to be braked with 'any intensity' until it comes to a complete halt; the power of a variable-speed transmission limits the maximum delay.

These features depend on a number of properties of a variable-speed transmission, which can be determined by considering the conditions of its interaction with a vehicle. Of existing variable-speed transmissions, the hydrostatic transmission and the friction gear manifest these features to the largest extent.

Considering the manner of connection of a variable-speed transmission (SG) to a mechanical transmission (MG), three basic system types can be identified:

- with the connection of variable-speed transmission (SG) to a mechanical transmission (MG) by means of a constant transmission at its input,
- with the connection of variable-speed transmission (SG) to a mechanical transmission (MG) by means of a constant transmission at its output,
- with an internal connection.

The relationships for the operation parameters in these three solutions, with the drive from one energy source, as well as the curves of the corresponding characteristics are shown in Fig.1 [1,3]. In the case of the drive from two or more sources, a modification - consisting in the introduction of a limitation resulting from the permissible operation parameters of variable-speed transmission (SG) - is necessary, e.g. the maximum pressure in the hydrostatic transmission.

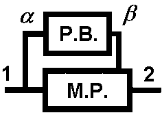
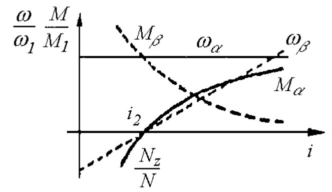
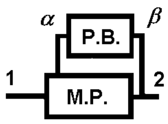
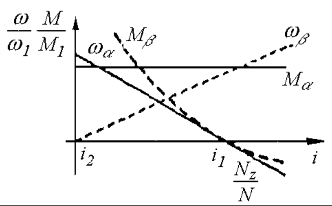
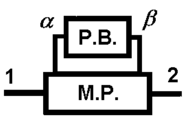
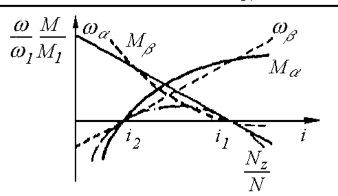
	Structural diagram	Charakterystics of wad	Operating parameters	
Connection at the input			$0 < i_2 = \frac{B}{D} < i_1 = \infty$ $\frac{\omega_\alpha}{\omega_1} = k_\alpha$ $\frac{M_\alpha}{M_1} = \frac{1}{k_\alpha}(1-\frac{i_2}{i})$	$\frac{N_z}{N} = 1-\frac{i_2}{i}$ $\frac{\omega_\beta}{\omega_1} = k_\beta(i-i_2)$ $\frac{M_\beta}{M_1} = \frac{1}{k_\beta}\frac{1}{i}$
Connection at the output			$0 = i_2 < i_1 = \frac{A}{C} < \infty$ $\frac{\omega_\alpha}{\omega_1} = k_\alpha(1-\frac{i}{i_1})$ $\frac{M_\alpha}{M_1} = \frac{1}{k_\alpha}$	$\frac{N_z}{N} = 1-\frac{i}{i_1}$ $\frac{\omega_\beta}{\omega_1} = k_\beta\frac{i}{i_1}$ $\frac{M_\beta}{M_1} = \frac{1}{k_\beta}(\frac{i_1}{i}-1)$
Internal connection			$0 < i_2 = \frac{B}{D} < i_1 = \frac{A}{C} < \infty$ $\frac{\omega_\alpha}{\omega_1} = k_\alpha\frac{i_1-i}{i_1-i_2}$ $\frac{M_\alpha}{M_1} = \frac{1}{k_\alpha}\frac{i-i_2}{i}$	$\frac{N_z}{N} = \frac{(i_1-i)(i-i_2)}{i\,(i_1-i_2)}$ $\frac{\omega_\beta}{\omega_1} = k_\beta\frac{i-i_2}{i_1-i_2}$ $\frac{M_\beta}{M_1} = \frac{1}{k_\beta}\frac{i_1-i}{i}$

Fig.1. Types of connections of a variable-speed transmission in the power transmission system with a parallel power flow

Work on the construction of the hybrid drive in a city bus has led to the solution shown in Fig.2. The main units are: hydropneumatic energy accumulators and a three-range variable-speed transmission with a parallel power flow. The latter consists of: a planetary transmission with three simple series I, II, III, two clutches A and B which change over the ranges of ratio, a hydrostatic transmission with two machines a and b, and several toothed gears of constant axes. A change in the ratio in the hydromechanical variable-speed transmission is brought about by a change in the ratio in the hydrostatic transmission. The following configurations are possible: in range I - the connection of the hydrostatic transmission to the remaining part of the parallel system by means of a constant transmission at the output, and in ranges II and III - with the internal connection [1,3]. The method of connection of the hydrostatic branch to the mechanical one affects curves of the basic parameters, Fig.2, and the algorithm of operation of the control system.

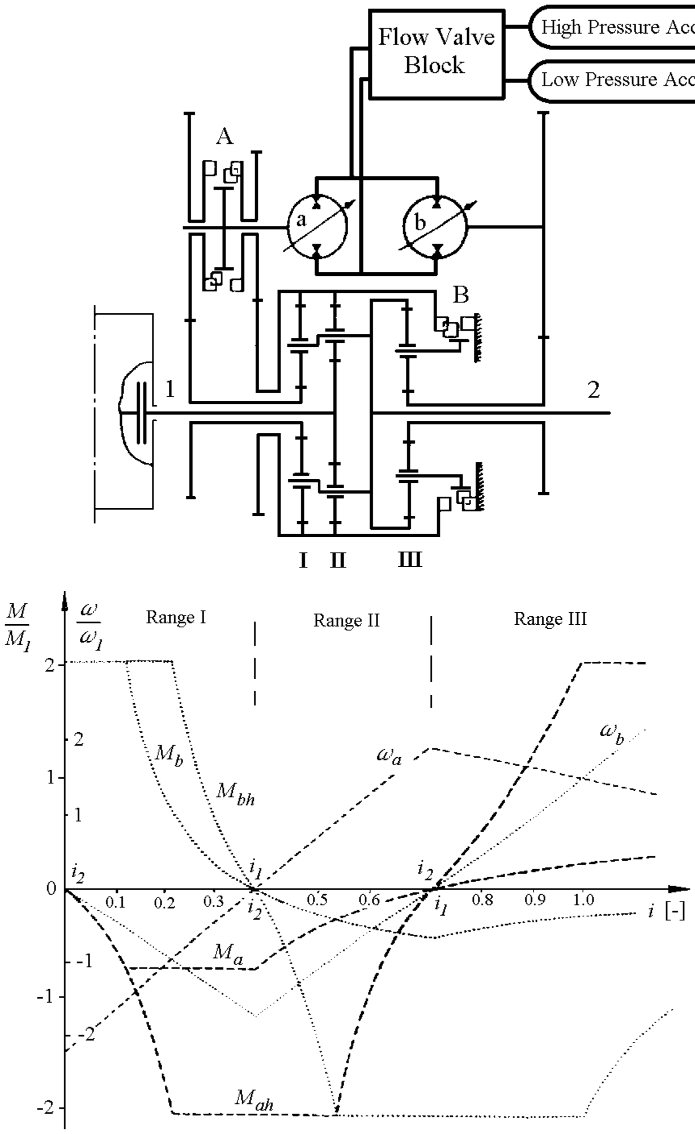


Fig.2. The schematic diagram of the power transmission system and curre's courses of the basic parameters of the hydrostatic transmission

A schematic diagram of the hydrostatic transmission with an arbitrary, variable direction of the flowing power is shown in Fig.3. Multi-piston, axial units operating alternately as a pump and an engine are intended as hydrostatic machines. The specific efficiency (absorbing power) of these machines is regulated by changing the deflection angle of the disk by means of a control mechanism made up of servomotor (2) and servovalve (1). Pump 'a' and engine 'b' are connected by means of two conduits (7), operating alternately as high- and low-pressure conduits depending on the function of hydrostatic machines a and b [4]. Supply pump (12) serves the purpose of leakage makeup and forcing an exchange of oil, and is - at the same time - the source of power for the control circuit.

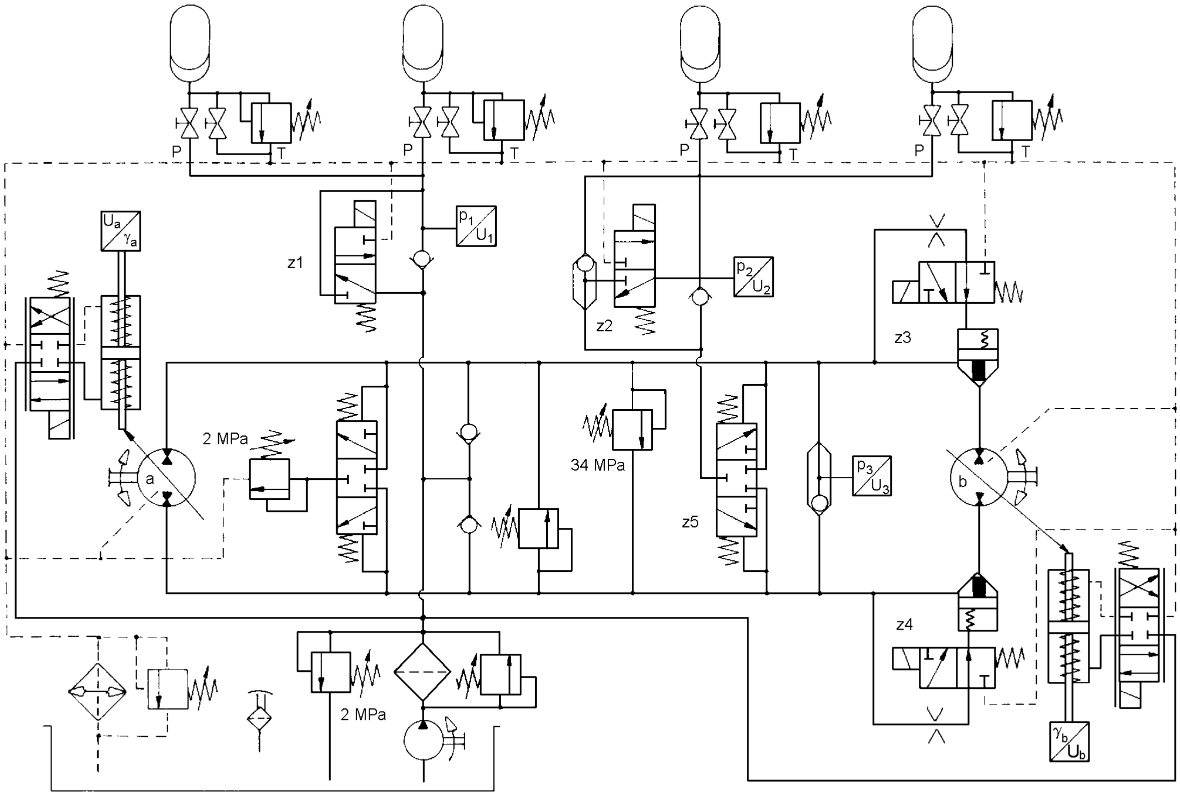


Fig.3. The schematic diagram of the hydrostatic system for the prototype variable-speed transmission and hydropneumatic energy accumulators

Valves (z1-z5) enable the hydrostatic transmission to interact with hydropneumatic energy accumulators of high (4) and low (3) pressure in all the phases of motion of the hydrostatic transmission.

Valve (z1) operates in the tensionless condition as a non-return valve with the flow direction from the low-pressure part of the system to the accumulator. When the control current is switched on, the flow in both directions is possible, and only then drawing the oil from the accumulator is possible. The accumulator is continuously charged, irrespective of the position of valve (z1): through the non-return valve when switched-off and through the logic valve when switched-on.

Valve (z2) operates in the tensionless condition as a non-return valve with the flow direction from the accumulators of high-pressure to the hydrostatic transmission. When the control current is switched on, the flow in two directions through the logic valve is possible.

Valves (z3) and (z4) operate in the tensionless state as non-return valves with the flow direction from the hydrostatic engine ‘b’ to the system. Switching the control current allows a ‘free’ flow in both directions and then the motion of hydrostatic engine ‘b’ is rendered possible. The tensionless state is equivalent to a standstill of the vehicle, for the energy cannot be transmitted to hydrostatic engine ‘b’.

Valve (z5) allows the automatic connection of the high-pressure accumulators to the operating conduit which at a given moment is a force conduit, simultaneously cutting off the suction conduit.

It results from an analysis of equations describing the dynamics of particular units that the above drive system is a multi-dimensional object of control. Variable resistance to motion of vehicle M_2 is a signal that interferes with the correct operation of the system. The disturbance of a nearly constant value is moment M_3 of resistance to motion of the hydromechanical gear box. A schematic diagram of the hybrid drive as an object of regulation, with the signals marked, is shown in Fig.4. Currents i_a and i_b of the coils of both servo-distributors and moment M_1 of the combustion engine are signals that control this object. By controlling currents i_a and i_b the deflection angles of hydrostatic machine disks are regulated, thereby regulating both the torques and the angular velocities of the shafts of these machines. The angular velocity ω_2 of the output shaft and the pressure p in the high-pressure accumulator are basic output quantities subject to regulation. The above concept of control is characterized by two separate governors, RI and RII.

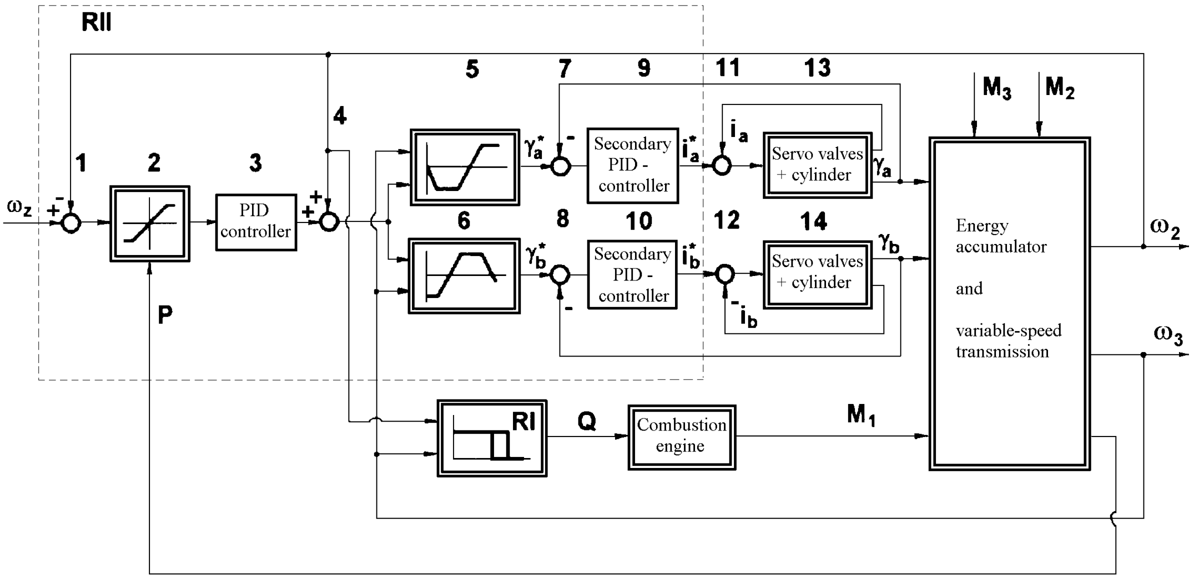


Fig.4. The hybrid drive as a complete circuit of regulation

Governor RI is intended to cyclically control the operation of the combustion engine so that the energy accumulated in the accumulator is within the assumed limits. The assumption of a certain interval for the energy accumulated is equivalent to assuming an appropriate interval for the value of the parameter defining the energy, e.g. the pressure p. The simplest method of obtaining a signal to control the engine is to use a comparator with hysteresis [3].

Governor RII eliminates differences between the speed set by the driver and the actual speed of the vehicle. In summing node (1) the angular velocities ω_z and ω_2 are compared. The deviation signal is subject to the limitation in non-linear block (2). The limitation results, among other things, from the maximum pressure in the hydrostatic transmission. Block (3) is a governor of PID type. In adder (3) this signal is added to the signal of the current angular velocity ω_2. The sum obtained is transmitted to non-linear blocks (5) and (6) whose task is to generate the signals of settings γ_a* and γ_b* of disks of both hydrostatic machines. A kinematic analysis of the parallel system shows that the values of the angles γ_a* and γ_b* are functions of the constant parameters of toothed gears in the mechanical branch and of the variable angular velocity ω_2 and pressure p. In nodes (7) and (8) the signals γ_a* and γ_b* of the required positions of the disks are compared with the signals γ_a and γ_b corresponding to the current positions. The errors of positions of the disks made are transferred to governors (9) and (10) which allow the deviations of the disk positions to be eliminated quickly. In turn, in nodes (11) and (12) signals of the required currents of the servo-distributor coils i_a* and i_b* are compared with their instantaneous values i_a and i_b . The differences in the values of these currents are input signals of elements (13) and (14). The dynamics of the secondary governor and servovalve is higher by four orders of magnitude than that for the primary drive system. Thus, this part of the control circuit behaves as an element proportional to the remaining 'slow-changing, inertial' part of the drive system. Thus, governors (9) and (10) are governors of P type [4].

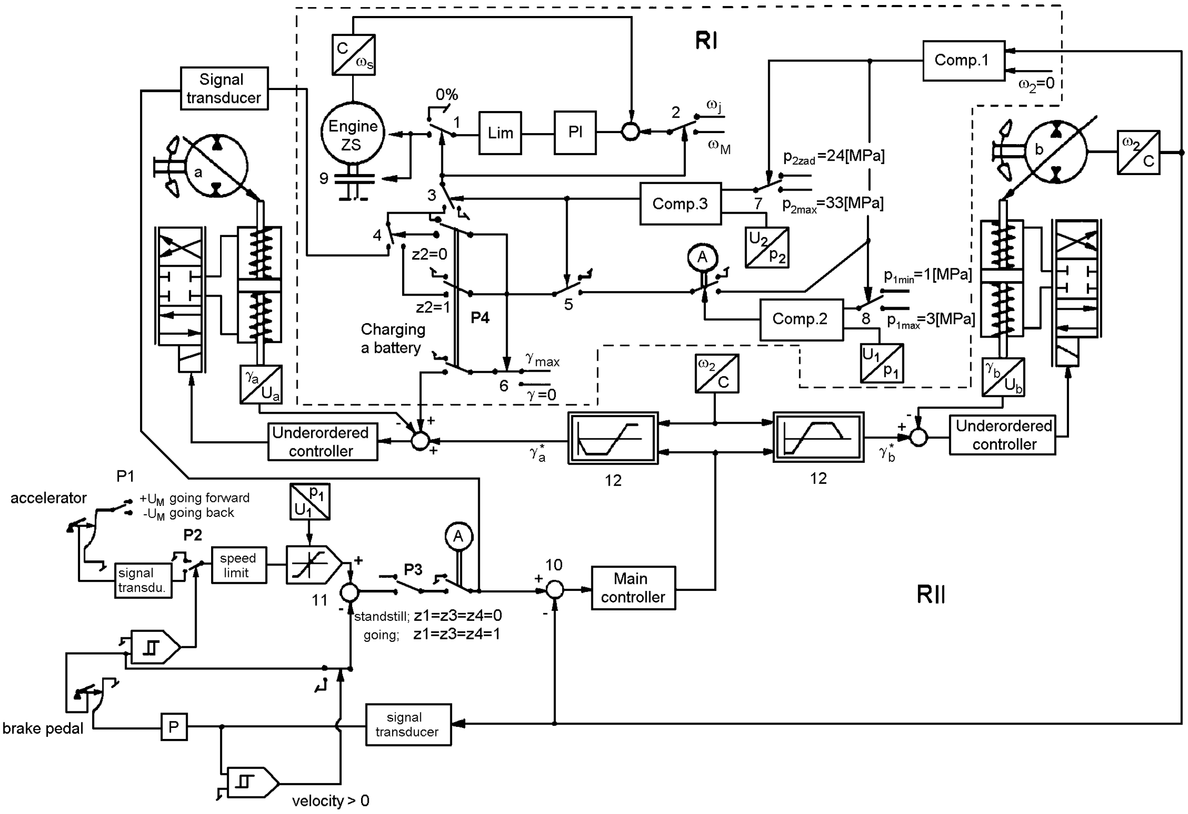


Fig.5. The schematic diagram of the control system for the prototype variable-speed transmission and hydropneumatic energy accumulators

The microprocessor control system, Fig.5, for the following operating conditions to be obtained:

I. Standstill

1. The control system switched off. No tasks are performed in the system. The bus is parked in a bus depot or at a terminus.
2. The control system switched on. Direct current is supplied to the functional switches and governors. The valves controlling the oil flow are closed; z1=z2=z3=z4=0.
3. Charging the accumulators while parking. The charging pump connected to the combustion engine by means of a constant-ratio transmission, always pumps the oil to the low-pressure accumulators through non-return valve (z1), when the engine is running. In the comparator, comp (1) the selection of the maximum pressure values in the accumulators is made. During the vehicle standstill (ω_2=0) these values are p_1=3 MPa and p_2=33 MPa; while driving: p_1=1 MPa and p_2=24 MPa, respectively. Until the pressure in the low-pressure accumulator reaches a value of 3 MPa, the comparator, comp (2) will not switch on switch A, thereby the control system is disconnected. The charging of the high-pressure accumulator can take place when switch P4 is in the position z2=1. Then, a signal from the comparator, comp (1), through the switches: A, 5, P4, 4 and 3 engages clutch (9) and sets the angular velocity $\omega_s=\omega_M$ in the combustion engine governor and switches on switch (6), while the deflection angle of the disk $\gamma_{max}=18^o$ is given to the secondary governor of

hydrostatic machine ‘a’. When the value of p_{2max}=33 MPa is reached in the high-pressure accumulator, the comparator, comp (3), disconnects the system. In the combustion engine governor the signal controlling switch (1) is turned off, and the angular velocity $\omega_s=\omega_j$ is set, whereas the value of $\gamma=0$ is conveyed through switch (6) to the deflection circuit of the disk.

4. During a standstill, when switch (P4) of governor RI is switched over from the ‘accumulator charging’ position, the system charges only the low-pressure accumulators. When the value of 3 MPa is reached, switch A is turned on and a signal from the comparator, comp (1) is sent to switch (P4), and a signal from the set signal processing system in governor RII can be given to adder (10).

II. Driving

1. The vehicle is powered by a combustion engine only (‘conventional drive’). Switch (P3) is in the z1=z3=z4=1position, while switch (P4) in z2=0. When valve (z1) is turned-on, it is possible to make up leakage in the hydrostatic circuit by means of the low-pressure accumulators and the charging pump, to the value p_{1min}=1 MPa. A signal of the set speed of the vehicle is worked out in the unit of control of signals, where a signal from the accelerator is sent to the matching element in which it is changed into a standard internal signal of the governor. The value of this signal depends on the degree of the accelerator pedal and switch (P1) position. It can assume positive values with the ‘driving forwards’ position or negative values with the ‘driving backwards’ position. The signal of the set speed is then sent through switch (P2) to the acceleration speed limiting block. The position of (P2) depends on the value of the signal from the system: the sensor of the speed ω_2, the matching element, the reversing amplifier, the brake pedal potentiometer. The signal thus shaped is sent to adder (11), in which it is added to the signal from the brake pedal potentiometer. One of these signals is always equal to zero. The first of these governors, on the basis of the set and actual speed, works out the signal of the set position of the servovalves that deflect the disk in hydrostatic machine ‘a’ or ‘b’, whereas the second one works out the signal controlling the servovalve. The signal of the set speed, through the matching system and switch (4), is also conveyed to the combustion engine governor, in which the angular velocity $\omega_s=\omega_M$ is set. In this way, it is possible to transfer the energy from the ZS engine, through the hydrostatic transmission a, b, to the vehicle wheels without the participation of the energy accumulated in the high-pressure accumulator.
2. Hybrid drive. The connections in the control systems are the same as described above, and switch (P4) is turned on. The phases of operations proceed here as in sections I.3 and II.1; if the pressure in the high-pressure accumulator is p_2>24 MPa, only secondary, accumulated energy will be used for the motion of the vehicle. Below the set value of the pressure, the comparator, comp (3) will turn on switches (3) and (5) and send the signal to the engine governor, thereby allowing the interaction of two sources of energy: primary - the combustion engine, and secondary - the high-pressure accumulator.. While braking there will be a reverse flow of energy - from the vehicle wheels, through hydrostatic machine ‘b’, which then starts functioning as a pump, to the high-pressure accumulator; the energy will accumulate in the accumulator as a result of the operation of governor RII.

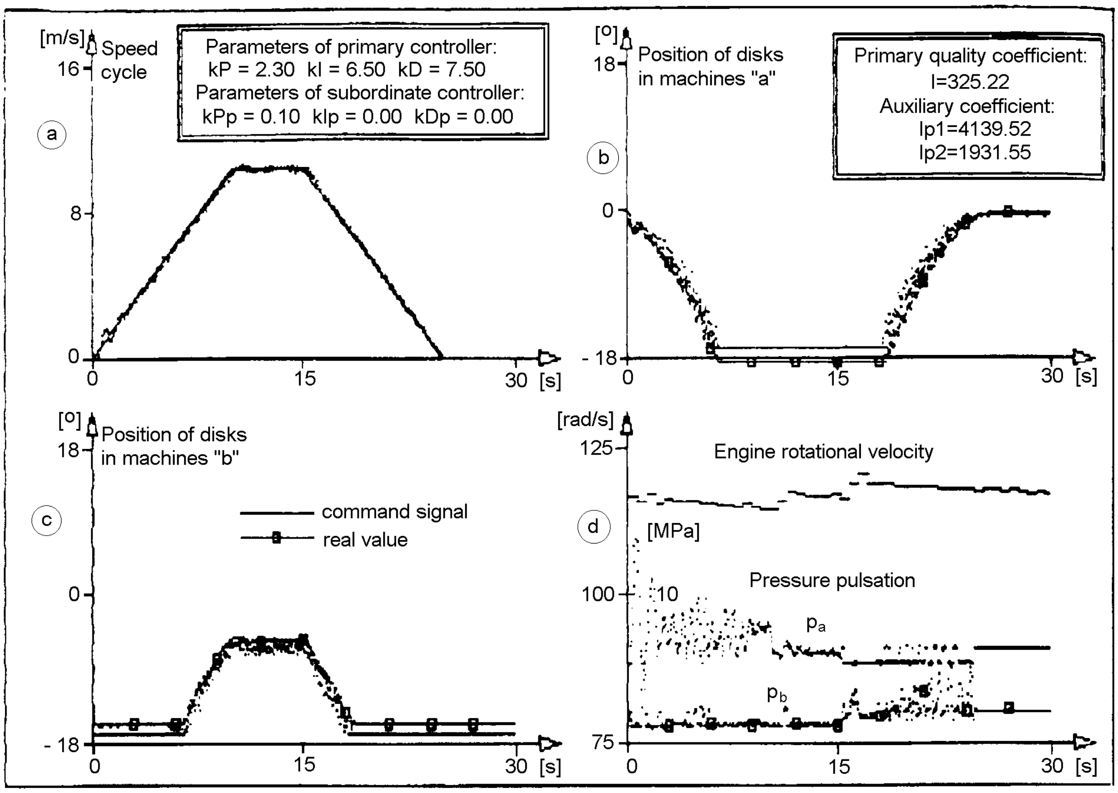
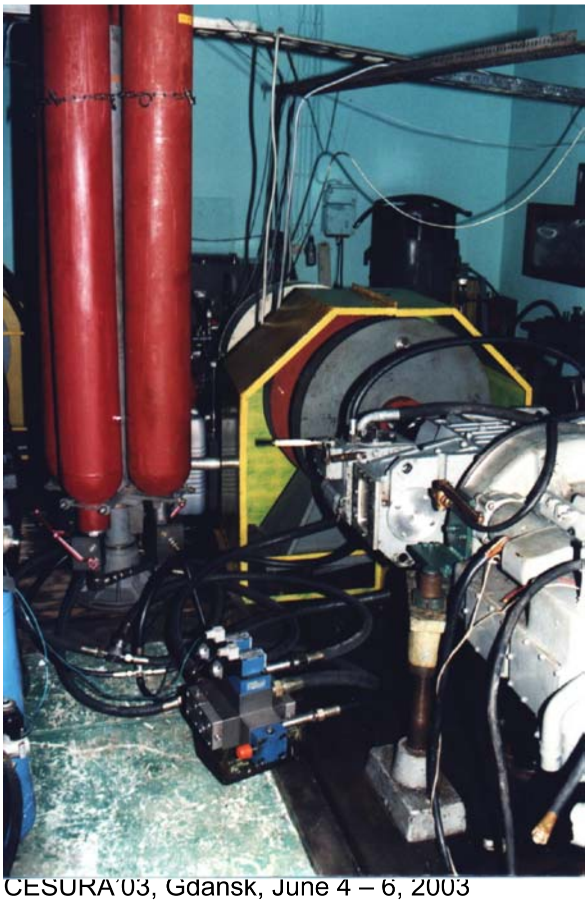


Fig. 6. Example curves of selected theoretical and actual parameters from the investigations of governor ‘3’: I) the vehicle speed, II) the angle of deflection of the disk in a hydrostatic machine ‘a’, III) the angle of deflection of the disk in hydrostatic machine ‘b’, IV) the angular velocity of the combustion engine, pressure at the outlet of machine ‘a’, pressure at the outlet of machine ‘b’.



Fot.1. Station researches place of prototype, hybrid

power transmission system

Conclusions

The construction of the variable-speed transmission gear-box and the type of the energy accumulator have an effect on the realization of control of the transmission through control of the hydrostatic transmission. The introduction of a variable-speed transmission will reduce fuel consumption by approx. 12÷16%, and supplementing the transmission with a set of energy accumulators will result in a further decrease by 14÷18%. In view of the functioning of a hybrid drive, an essential problem is the manner of cooperation of energy sources: the primary - from the combustion engine, and the secondary - from the energy accumulator. The conception of such cooperation, verified experimentally, allowing the realization of any cycle of driving in the city bus been presented. In principle, the combustion engine performs the function of the unit equalizing the energy balance.

References

[1] Kowalski S.: Multirange hydromechanical transmissions. Warsaw University of Technology, Institute of Vehicles Papers, Nr 1, 1993.
[2] Der Hydraulik Trainer. Band 1-6. Mannesmann Rexroth Gmbh, Lohr am Main.
[3] Pawelski Z.: Napęd hybrydowy dla autobusu miejskiego. Wydawnictwo Politechniki Łódzkiej, Monografia nr 890, 1996.
[4] Pawelski Z.: Studies of the Speed Governor for a Variable-Speed Transmission with a Parallel Power Flow. ISATA'98, Paper Nr.98AE009.