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# OPTIMIZATION OF VALVE MANIFOLD TIMING SEQUENCE USING DIFFERENTIAL EVOLUTION ALGORITHM

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**Abstract:** *The present article deals with time optimization of the valve manifold by differential evolution algorithm. The adjustable valve manifold is a part of the experimental energy regeneration circuit for heavy vehicles with hydrostatic drive. The optimization process is based on a numerical model of the experimental rig, which is a scaled model of the real hydrostatic drive of the heavy vehicle.*

**Keywords: Differential evolution algorithm, Optimization, energy regeneration, Efficiency.**

## 1. Introduction

Reduction of vehicle fuel consumption is nowadays a significant technical problem in many heavy vehicle categories, e.g. construction vehicles described by Baseley et al. (2007). Recently, Brno University of Technology and Bosch Rexroth Company have been collaborating on the device for energy regeneration for heavy vehicles equipped with a hydrostatic drive. An experimental rig was assembled to simulate the hydrostatic drive of the real vehicle in a particular scale (Nevrlý et al., 2013). A correct operation of suggested device depends on the valve manifold which selects between the normal operation and the energy regeneration. Therefore a certain degree of optimization of the process is required to achieve high efficiency of device operation. This article deals with time optimization of the valve manifold by differential evolution algorithm. The acceleration mode of the experimental rig with energy regeneration is the subject of the optimization process.

## 2. Experimental Rig and its Simulation Model

Fig. 1a shows a simplified hydraulic circuit of the experimental rig. There are depicted all the valves (V1 to V6) in the valve manifold; its time sequence setting is the subject of the proposed optimization.

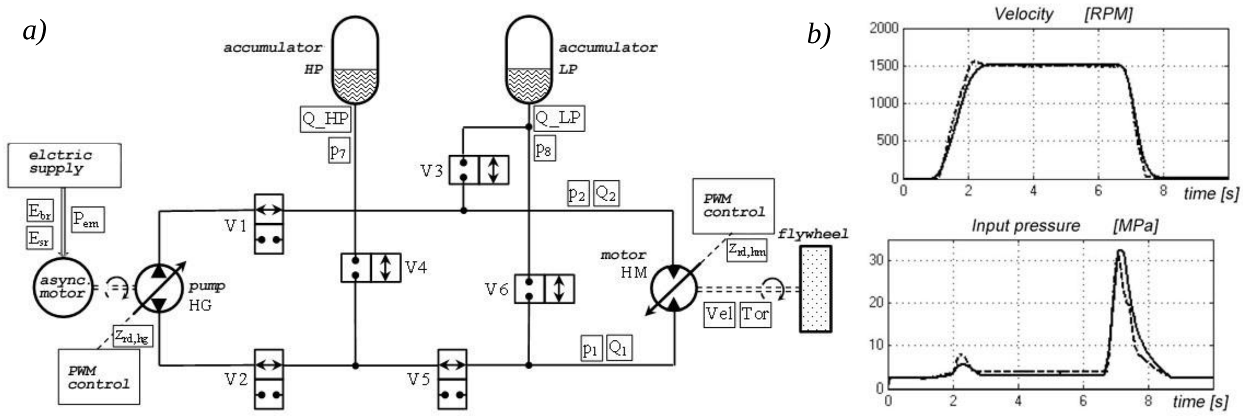


*Fig. 1: a) Experimental rig diagram; b) Time response of selected quantities for the model verification.*

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A simulation model of the rig was assembled in the Matlab/Simulink/SimHydraulics. It was verified by comparison of the results obtained by simulation and by measurement on the experimental rig in various operational modes. Time responses of the selected physical quantities depicted in Fig. 1b confirm a good agreement between the simulated and measured results. Thus the suggested simulation model is suitable for the optimization of valve timing.

## 3. Optimization of the Valve Control Signal Timing for *Accel* and *SetRPM* Mode Transitions

The experimental rig is capable to simulate the same operational modes as those found a real vehicle. The operational mode, which simulates the hydrostatic drive, is called *SetRPM*. It is possible to change the settings of the throttle which controls output revolutions of the hydraulic motor. Another operational mode called *Decel* simulates braking with active energy regeneration where the energy of braking is stored into the high pressure accumulator. The operational mode called *Accel* simulates acceleration of the experimental rig with active energy regeneration which utilizes previously stored energy. The article deals with the optimization of the acceleration process with energy regeneration; therefore transitions between *SetRPM* and *Accel* are considered. This operational mode is the most significant regarding the highest possible efficiency to be achieved.

### 3.1. Working cycle

The *SetRPM* mode with a zero throttle is the initial state of simulation. After 0.5 *s*, it is switched to the *Accel* mode with 51% throttle which is approx. 1 500 RPM of the motor. There are only two valves in the manifold switched (namely V4 and V6) within this transition, the other valves remain in the initial state. The accumulator becomes discharged after 1 *s*, therefore *Accel* switches back to *SetRPM* mode with the throttle remaining at 51%. This time, valves V4, V5 and V6 are switched if it is required.

### 3.2. Control signal timing

The timing vector is defined as follows:

$$\boldsymbol{t}_{R1,R2} = \left(t_{R1,R2,V1}, t_{R1,R2,V2}, \dots, t_{R1,R2,V6}\right) \tag{1}$$

Where $R1$ represents the initial operational mode and $R2$ is the mode to which the experimental rig is switched. Elements of the vector $\mathbf{t}_{\mathrm{R1,R2}}$ determine a time delay of the valve control signal in milliseconds. The time delay is calculated from the moment of change of the operational mode from $R1$ to $R2$.

### 3.3. Purpose function

Maximum efficiency of the system is required providing:

$$\eta = \frac{E_2}{E_1} \tag{2}$$

where kinetic energy $E_2$ of the flywheel is determined by angular velocity and moment of inertia:

$$E_2 = \int_0^{t_{max}} P_2(t)dt \tag{3}$$

$$P_2(t) = \frac{d\left(\frac{1}{2}I\omega^2\right)}{dt} \tag{4}$$

and $E_1$ is energy consumption of the electromotor driving the test rig. This energy is replaced by energy $E_0$ for the optimization purposes. $E_0$ is defined as an integral of the true input power of the electromotor $P_{em}$ decreased of true input power of the steady state $P_{st}$ (losses):

$$E_0 = \int_0^{t_{max}} (P_{em}(t) - P_{st}(t))dt \tag{5}$$

$$P_{st}(t) = P_{st1} + \omega(t)\frac{P_{st2} - P_{st1}}{\omega_{st2} - \omega_{st1}} \tag{6}$$

where $P_{st1}$ and $P_{st2}$ are true input power values of the electromotor in steady states before and after the experiment. In similar way, $\omega_{st1}$ and $\omega_{st2}$ are values of the flywheel angular velocity before and after the experiment.

The purpose function formula based on equations (3, 5) is:

$$f = k_p \frac{E_2}{E_0} \tag{7}$$

Some penalization is needed of non-feasible solutions. The criterion of the solution feasibility is met when there is zero flow $Q_{\text{saf}}(\text{t})$ through the safety valves. Therefore coefficient $k_{\text{p}}$ is introduced.

$$k_p = \begin{cases} 1, & Q_{saf}(t) = 0, t \in \langle 0;\ t_{max} \rangle \\ 0, & other\ cases \end{cases} \tag{8}$$

The time of the experiment is expressed by interval $\langle 0;\ \text{t}_{\text{max}} \rangle$.

### 3.4. Description of optimization algorithm

The algorithm of differential evolution (Price and Storn, cited 2013) was used for optimization of time vectors $\text{t}_{\text{SetRPM,Accel}}$ and $\text{t}_{\text{Accel,SetRPM}}$ and their elements. It is a stochastic population based optimization algorithm. The algorithm works over a set of candidate solution vectors $P_{\text{g}}$, where g represents a number of iteration. New elements of the solution vector group $P_{\text{g+1}}$ are obtained from $N$ vectors from previous solution $P_{\text{g}}$ by the following method:

1. Assembly of the noise vector (Wang and Jiang, 2009):
$$v_{i,g+1} = x_{i,g} + F(x_{rand1,g} - x_{rand2,g}) \tag{9}$$
where $i = 1..N$, $x_{\text{i,g}}$ is base vector, $x_{\text{rand1,g}}$ and $x_{\text{rand2,g}}$ are random vectors selected from $P_{\text{g}}$. The amplification factor $F$ affects the rate of convergence.
2. Assembly of the trial vector $\text{u}_{\text{i,g+1}}$ with regarding that the elements of the vector $v_{\text{i,g+1}}$ should be swapped with corresponding elements of the vector $x_{\text{i,g}}$ with probability $P_{\text{c}}$.
3. Calculation of the purpose function $f(\text{u}_{\text{i,g+1}})$.
4. Vector with the highest value of the purpose function is selected from $x_{\text{i,g}}$ and $u_{\text{i,g+1}}$. The selected vector is placed into a group of new solution vectors.

The algorithm was implemented on .NET platform. An assessment of quality of the optimization output (calculation of the criterion value) was conducted with verified simulation model in Matlab/Simulink. The group of solutions contained 150 solution vectors. The terminal condition of the process was a zero increase of the purpose function value after 50 iterations. The $F$ factor has a constant value of 0.5 during the entire solution process.

## 4. Results

At first, a simulation was conducted of the efficiency of pure hydrostatic drive in acceleration according to the working cycle. Only the *SetRPM* operational mode is used. Thus all valves remain in the initial state and no time vector is needed. The energy consumption of the electromotor is $E_1 \cong 25.85\ kJ$ and kinetic energy of the flywheel is $E_2 \cong 7.68\ kJ$. Overall efficiency of the cycle obtained according to the equation (2) is $\eta = 29.75\%$.

Subsequently the working cycle with active energy regeneration was simulated. Provided there is no particular timing of the valve control signals, thus

$$\boldsymbol{t}_{SetRPM,Accel} = (0, 0, 0, 0, 0, 0), \boldsymbol{t}_{Accel,SetRPM} = (0, 0, 0, 0, 0, 0)$$

the energy consumption of the electromotor is $E_1 \cong 20.39\ kJ$ and obtained kinetic energy of the flywheel is $E_2 \cong 7.72\ kJ$. Overall efficiency is $\eta = 37.88\%$. Therefore the energy regeneration system is capable to increase the overall efficiency of the hydrostatic drive by 8.13%. The efficiency of driveline can be further improved by the optimization of the energy regeneration process.

Introducing optimized time vectors

$$\boldsymbol{t}_{SetRPM,Accel} = (0, 0, 0, 160, 0, 20), \boldsymbol{t}_{Accel,SetRPM} = (0, 0, 0, 60, 200, 80)$$

we can obtain the electromotor energy consumption $E_1 \cong 19.203\,kJ$ and flywheel kinetic energy $E_2 \cong 7.735\,kJ$. The overall efficiency is $\eta = 40.28\%$. Optimization of the process yields another 2.4% increase in the efficiency according to the operational conditions used.

A comparison of simulated results is shown in Fig. 2. There are time responses of the electromotor true power and time response of the velocity.

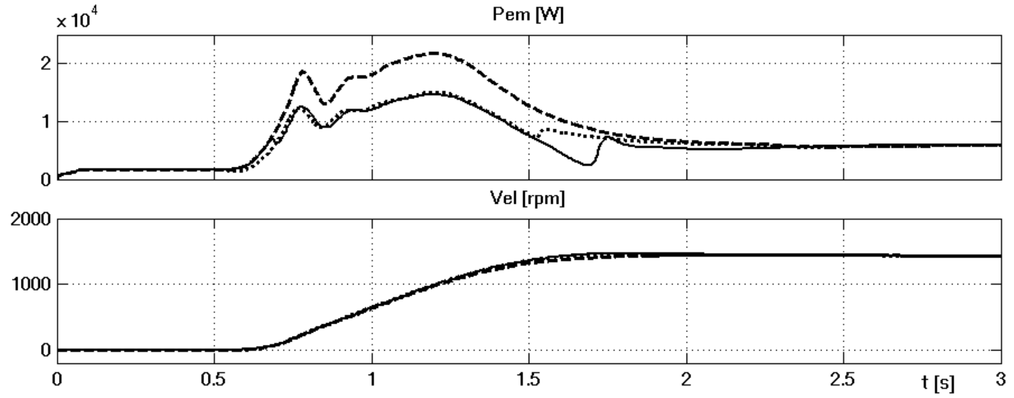


*Fig. 2: Time response of selected simulated quantities. Hydrostatic drive mode – dashed; Energy regeneration active – dotted; Energy regeneration active and optimized – full.*

## 5. Conclusions

The optimization of the selected operational mode with differential evolution algorithm results in 10.5% increase in the overall efficiency of the system in contrast to a non-optimized system. Another process which requires a similar optimization is the *Decel* operational mode where a pressure accumulator is charged with the energy of braking. The volume of the pressure accumulator should also be optimized. Considering the aforementioned optimization, there is a good possibility to achieve up to 16% increase in simulated efficiency of the drive with energy regeneration in comparison to the pure hydrostatic drive. Subsequently, simulated results should be verified by experiments on a testing rig. It is expected that the experimentally obtained efficiency of the system should be a maximum of 3% lower due to some minor simplifications of the mathematical model.


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