Automatic control of roadheader cutting head speed and load torque

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Abstract. Roadheaders are nowadays using both in mining engineering and in civil engineering (tunnelling). They often operate in hard rocks, so it is very important to optimize their performance by the full use of their power in different operating conditions. The coal seams are opened deeper and due to rock compactness and their uniaxial stress compression there increases serious problems with power demand and machine wear. The angular speed of cutting head should be adjusted to the rock hardness (the harder is the rock, the lower should be the speed). Nowadays, most of the produced roadheaders have constant speed driven cutting heads. In these cases, sometimes the rock cutting process is performed in conditions far from optimum. The paper presents a concept of the cutting head speed control system and selected results of research performed on laboratory stand equipped with a special R-130 roadheader with an inverter-fed cutting head drive. The closed-loop speed control is accomplished with a PI-controller. Optimum settings of this controller have been calculated using the model in the loop simulation and ITAE (Integral of Time multiplied by an Absolute value of Error) criterion. This criterion is widely used in electric drive technology. The application of the ITAE criterion for the selection of PI controller parameters usually provides a short settling time and an acceptable overshoot value. Results of the experiment show that the system is capable to maintain demanded speed and to follow commands from the master load controller. The drive operation parameters (motor power utilization and frequency of momentary overloads) are much better with automatic control of inverter frequency than with constant frequency drive operation. It should result in lowering power consumption and knife wear intensity.

1. Introduction

Roadheaders are currently the most frequently used mining machines used to excavate underground corridors. They operate in coal and other rocks of varying strength. The cutting load torque significantly depends on the compactness and mechanical strength of the rock and on the pressure to which the rock is subjected by the rock mass above. Currently, the mining depth of coal seams is increasing, hence the mining of coal and increasingly harder surrounding rocks is creating more and more difficult working conditions for the drive system of the cutting head. In this context, significant problems with power demand and wear of knives mounted on the cutting head begin to appear. Therefore it is very important to optimize roadheader performance by the full and efficient use of its power in different operating conditions. The cutting advance rate depends on the penetration per cut and the rotational speed. Cutting head rotational speed and torque determine the power transmitted to the head. Too high rotational speed of the cutting head (for a given transverse or vertical boom movement) leads to excessive rock fragmentation. This again is associated with too much power consumption, too much wear of cutting knives and too high vibration level. If the rotational speed of the cutting head is too low (in relation to
the current rock strength parameters), this significantly limits the speed of the transverse movement of the boom and thus reduces the overall performance of the roadheader. The installed power is not used efficiently and the advance rate of excavated corridor is too low. Currently, the majority of the produced roadheaders is equipped with constant speed driven cutterheads, as this is the simplest and the most robust and reliable type of electrical drive in harsh mining environmental conditions. But in these cases, the rock cutting process is sometimes performed in conditions far from optimum. The rock cutting process is very complex because the cutting torque is the sum of the torques generated by the individual knives. Moreover, the rock cutting process is stochastic (in fact, the sum of a large number of stochastic processes), because, with the movement of the knife, the tension increases until the given rock fraction is detached from the rest of the rock. Therefore, research has been undertaken to develop a control system for an experimental roadheader equipped with a cutting head drive powered by a frequency converter.

2. Structure of the control system
Since the rock cutting process is as complex as described in the introduction, the control system supervising and regulating the operation of the roadheader has been separated into three parts connected in series:

- Cutting speed generator, setting the optimal cutting speed incrementally. The speed is gradually reduced if such negative phenomena occur as too high average torque value or too many momentary overloads. If there are no such temporary overloads and if the average load torque is below the rated value, the cutting speed is gradually increased. More detailed description can be found in [1][2].

- Speed controller, determining the frequency of the inverter output voltage based on the error signal (the difference between the set and actual rotational speed of the cutting head)

- Internal frequency converter control system ensuring (due to the very low thermal inertia of the semiconductor valves) overload protection of the inverter. This protection is realized by a very fast reduction of voltage and frequency value in case of exceeding the rated current of the converter twice. At the same time, in order to reduce dynamic overloads at the drive input, a speed frequency change limiter is applied, preventing rapid frequency changes that may cause the critical motor slip value to be exceeded.

The first controller operates on the torque data, gathered during one full rotation cycle on the cutting head, so it can be more than 1 s. The second and the third controllers operate with a much shorter sampling period (4ms or even less than 1ms). They operate on different input signals (respectively torque, speed and current) so the whole control system can be presented as a set of three cascaded feedback loops as depicted in Figure 1. The main topic of this paper is an analysis and setting of the second (cutting head rotational speed) loop, as it is responsible for the fast and stable following the reference signal for the first (load torque) controller.
Figure 1. Block diagram of the roadheader with the cutting head speed and load torque control system

3. Cutting head speed controller
The speed controller should provide close following the reference signal with no static error, no oscillations and no overshoot. These oscillations and overshoots could cause overload to the mechanical part of the drive. So, it was chosen to be a simple proportional-integral (PI) controller. A derivative part was omitted because of noise in the input signal. Optimal values of the proportional $K_p$ and integral $K_i$ gains of the controller have been selected on the basis of the simulation of the linearized model of the controlled system (inverter-fed induction motor). Model linearization – around the rated operating point – significantly increased the simulation speed, still capturing the most important dynamical features of the original system.

Figure 2. Block diagram of the analyzed model of roadheader cutting head drive control system with reference signal input and load torque disturbance input

The block diagram of the model used for controller tuning and numerical simulation has been presented in figure 2. Much more complex (and therefore much more computationally intensive) models
of electrical and mechanical subsystems have been described in detail in [3]. An incremental encoder has been used to measure rotational speed of the motor in the control system. The encoder has been modelled as an operator transfer function of proportional element with time delay $T_{ZOH}$. Two values of delay time have been considered in the simulations – 1 and 4 ms. Preliminary settings of the cutting head speed controller could have been selected by analytical methods, but the fine tuning was done by simulation methods, as they allowed the evaluation of the system operation in the presence of real disturbances (from the waveforms recorded on the test stand and then mapped with the ARMA model). The Integral of Time multiplied by an Absolute value of Error (ITAE):

$$I_{ITAE} = \int_0^\infty (t \cdot |e|) dt$$

(1)

was adopted as the criterion for assessing the performance of the cutting head rotational speed control system. This criterion is widely used in electrical drive technology. Due to the purpose of control associated with the need for relatively frequent changes in the setpoint of the angular speed of the motor, it is important that the settling time is as short as possible, with a minimum control error. But these requirements are difficult to fulfill simultaneously. Criterion (1) in the situation of optimization of the control system with a second order object gives relatively small overshoot with a short time of reaching the new set point for the first time [4]. We have also extensively tested other widely used in automatic control theory criteria as Integral of Absolute Error (IAE):

$$I_{IAE} = \int_0^\infty |e| dt$$

(2)

Integral of Squared Error (ISE):

$$I_{ISE} = \int_0^\infty e^2 dt$$

(3)

Integral of Time and Squared Error (ITSE)

$$I_{ITSE} = \int_0^\infty (t \cdot e^2) dt$$

(4)

and Integral of the Squared Time and Absolute Error (ISTAE).

$$I_{ISTAE} = \int_0^\infty (t^2 \cdot |e|) dt$$

(5)

As the PI controller has two tunable parameters (gains $k_p$ and $k_i$) it is possible to present simulation results in the form of 3-D diagram. Simulation results with the chosen optimum point have been presented for all the criteria described above in Figure 3. It can be seen that these criteria give us somewhat similar values for the optimum gains, but it was the ITAE criterion which gave us the best quality of transient waveforms, and the minimum point of $k_p$, $k_i$ parameters was the most obvious.
Figure 3. Simulation results and selected (red dots) optimum points \((k_p, k_I)\) for different control system performance criteria a) IAE criterion, b) ISE criterion, c) ITSE criterion, d) ISTAE criterion, e) ITAE criterion

As the speed sensor (in our case – an incremental encoder) dynamical parameters can have a significant influence on closed-loop overall system performance and controller tuning, the simulation tuning have been performed for two values of the encoder sampling time (1ms and 4ms). The final results \(k_P\) and \(k_I\) controller gains)) of the PI controller tuning according to five optimization criteria (1) - (5) have been presented in Table 1. As can be seen from Table 2, the optimized controller gain values according to different integral criteria are quite close to each other.
Table 1. Proportional and integral gain values of the PI controller tuned by a simulation experiment according to different integral criteria

| L.p. | $I_{IAE}$ | $I_{ISE}$ | $I_{ITAE}$ | $I_{ISTAE}$ | $I_{ITSE}$ | $T_{ZOHI}$ (ms) |
|------|-----------|-----------|-----------|-------------|-------------|----------------|
|      | $k_p$    | $k_I$    | $k_p$    | $k_I$       | $k_p$      | $k_I$         | $k_p$ | $k_I$ |
| 1    | 0.045    | 6.5      | 0.011    | 6.1         | 0.011      | 5.5           | 0.015 | 5.4 | 1   |
| 2    | 0.080    | 6.5      | 0.011    | 6.0         | 0.011      | 5.5           | 0.015 | 5.4 | 4   |

4. Results of the laboratory tests

The choice of the structure of the automatic control system and the settings of the P and PI controllers used in it was made using the M-i-L (Model-in-the-loop) method described above. The evaluation of the dynamic properties of this control system implementation (using a cRIO-9074 controller), was carried out during simulation tests using the H-i-L (Hardware-in-the-loop) method [5]. Designed cutting head rotational speed control system has been therefore implemented into an experimental Famur R-130 roadheader with 132kW induction motor powered from the TWERD frequency converter. Laboratory tests have been carried out in the technological hall of the Faculty of Mining, Safety Engineering and Industrial Automation at the Silesian University of Technology by cutting a specially prepared multilayered concrete block. Different mixtures of cement and sand map different rock types appearing in mining practice. Photography of the laboratory roadheader cutting this multilayered concrete block has been presented in figure 4. And an example waveform recorded during laboratory tests in figure 5.

Figure 4. R-130 roadheader cutting specially prepared multilayered concrete block during laboratory experiments in the technology hall of the Faculty of Mining, Safety Engineering and Industrial Automation at the SUT.
Figure 5. Example waveforms of load torque (upper plot) and speed (lower plot) recorded during laboratory experiments

Alternating white and light grey bars in figure 5 present consecutive rotations of the cutting drums. So, it can be clearly seen that the new value of the reference speed is calculated and updated after each rotation cycle. Other results of the laboratory tests (concerning e.g. power consumption) have been presented in [6].

5. Conclusions

Laboratory stand experiments proved that the control system structure and tuned controller parameters provide stable operation in different work conditions and performance much better than for manual boom control with non-controlled cutting head drive. The control task is quite difficult because of the very rapid momentary variations of the cutting torque. In the outermost feedback loop, they are somehow averaged (for further calculations of the reference speed) within one full rotation cycle, but these short torque pulses significantly affect the inner feedback loops (speed and current control). Because of the inverter high thermal sensitivity even to short overloads, the rated power and rated current of the inverter must be greater than resulting from the motor parameters. Also, the internal frequency rate limiter on the input of the frequency converter has a deep impact on overall system dynamics and must be included in modelling, tuning and analysis of the roadheader model. Closed-loop speed cutting head speed control system stabilizing speed under significant load torque variations and closely following the commands from the reference speed generator can be one of the few interacting control systems for new roadheaders designed as mechatronic devices [7].

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