

Analysis of regulation indicators in schemes with subordinate regulation and modal control of electric drive of feeding mill for cold rolling tube

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Abstract. The article is devoted to the issue of selection of the preferred structure of a positional electric drive of the feeding mill for a cold rolling tube by the criterion of minimum feed overshoot and, as a consequence, minimum polythickness of the tube. The cut-off frequency limit of a torque control loop is determined as 200 rad/s, for which the subordinate regulation is optimal. If the value of this parameter is high, then the modal control is preferred. This article consists of recommendations how to choose an actual control system according to processing speed opportunities of an electric drive torque control loop.

1. Introduction

The production of a thin and ultra-thin tube with minimal polythickness is demanded in the nuclear, automotive and helicopter industries. Tubes with an ultra-thin wall and a high quality of the surface can be produced by cold rolling mills (CRM), the workpiece is reduced by 75-85%, and the strength of tubes is significantly higher in comparison with the products produced by hot rolling. Improving the quality of cold rolling mills will reduce the percentage of rejection of expensive tubes and will have economic impact.

Analysis of the work of cold rolling mills has shown that “the weakest” unit in the technological process is the feeding mechanism, to which the stringest requirements for velocity and accuracy of position control, over-torque and operating conditions are applied.

2. Research method

2.1 Materials and methods

Traditionally, the positional electrical drive control system is made according to the structure of the subordinate regulation and includes the position control loop in addition to the torque and speed control loop. The mechanical part of the movable object of the tube feeding mechanism, which is providing the required accuracy in the correct electric drive mathematical model, must be presented in the form of a two-mass system, in which the first “mass” includes a rotating part of the motor and a bevel gear speed reducer, and the second “mass” has a moving tube (the screw-gear is an elastic element connecting these masses). In this case, there is additional internal loop 2, (Figure 1).



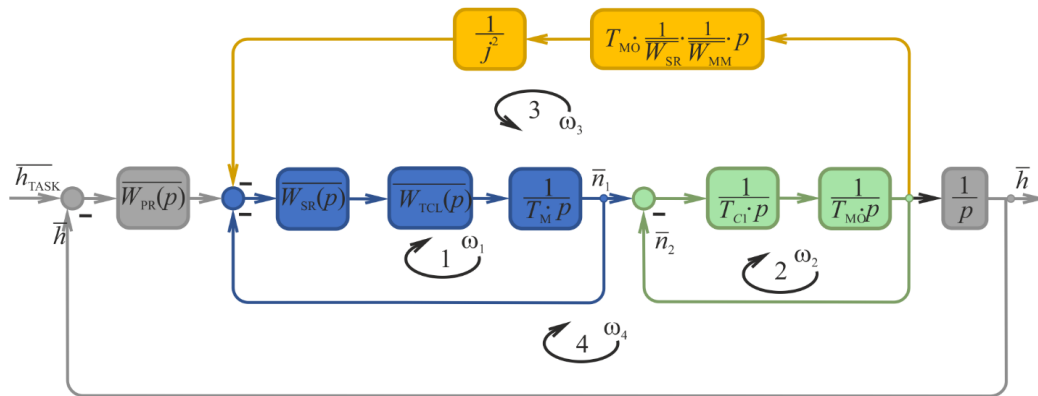


Figure 1. A simplified block diagram of the electric drive

It is practically impossible to provide the required accuracy by simple methods in complex systems, described by the third- and higher order differential equations. In this instance, an alternative method is chosen, which allows reducing the steady-state error; this is the use of structures with modal control. The essence of this method can be summarized as follows.

In the system, shown in Figure 1, the feedback is introduced in each of the variables of the direct channel (Figure 2). Therefore, there are four control loops: torque T , motor shaft speed n_1 , elastic torque TE and speed of sliding member n_2 . The setting begins with the torque loop, making it at the highest speed, selecting the appropriate value of factor K_1 . Further, one may obtain the response time of this loop $T_2 = (2 \dots 4) T_1$ by varying the value of the feedback factor of motor shaft speed loop K_2 . The setting of all subsequent loops is made in a similar way. Finally, the system will be obtained and the response time of each subsequent "external" loop will be 2 to 4 times more. Cross-connection can be considered in two ways: either lead to an adder located at the output of the position regulator according to the transfer rule, or can be discarded.

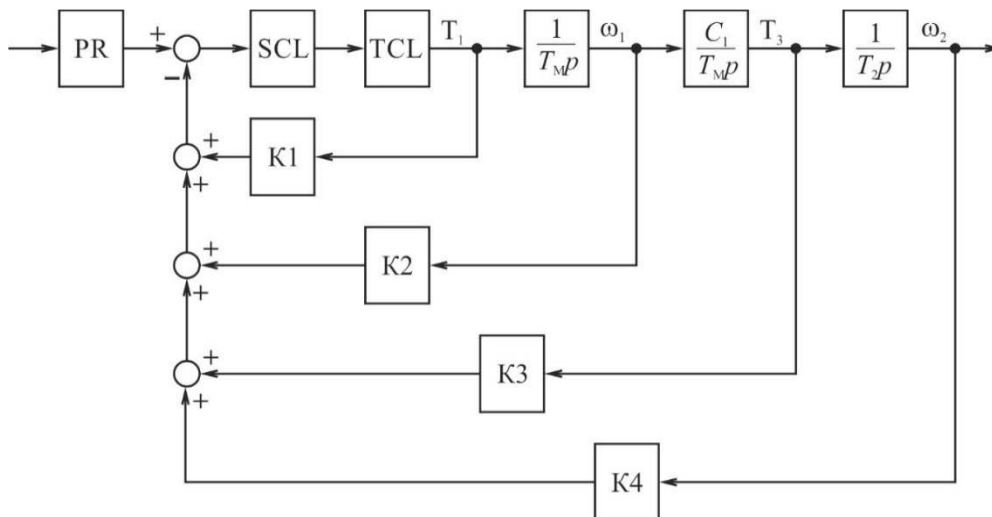


Figure 2. A structure of modal control

This control system makes it possible to achieve a high dynamic index. However, because of the great number of feedbacks, one requires the great number of sensors, which make it significantly more costly. It is agreed to use observers (digital twins) to solve this problem. These devices calculate in the real-time mode the drive variable on one or more signals available for the measurement. Considering the development of modern microprocessor technologies, the implementation of these devices is not a particularly difficult task. The observer usually is covered in feedback by the position (Figure 3) to

increase the accuracy of the calculation.

A distinctive feature of the diagram is the structure selection of the position regulator in a function of derivative of elastic torque by time. This solution simplifies the transfer function of the regulator itself.

This approach is an effective way to achieve a high dynamic index in complex control systems [1]. The setting of this system begins with the internal control loop – (torque control loop) - and it is fulfilled by selecting the gain factor K1. As a result, the maximum possible velocity can be obtained at a minimum process variability.

Then the setting of motor speed loop ω_1 is made by changing the gain factor K2 of the feedback channel. The cut-off frequency of this loop is reduced 2 to 4 times, because the integrator with response time T_m is added in the loop.

When setting loop 2, this brings up the question of considering local feedbacks caused by intrinsic nature of the unchangeable part of the system, for example, the cross-connection by the elastic torque. This will be considered during the setting up of the next loop, transferring the effect of T1 to the input of the SR regulator. Likewise, the setting of the following control loops is made with feedbacks by the state variables T2 and n_2 , which is carried out by choosing the values of gain factors K3 and K4.

2.2 Modal regulator setting

Let us make the settings of modal regulators by the algorithm suggested and described in detail by Professor Y.S. Usynin in [1].

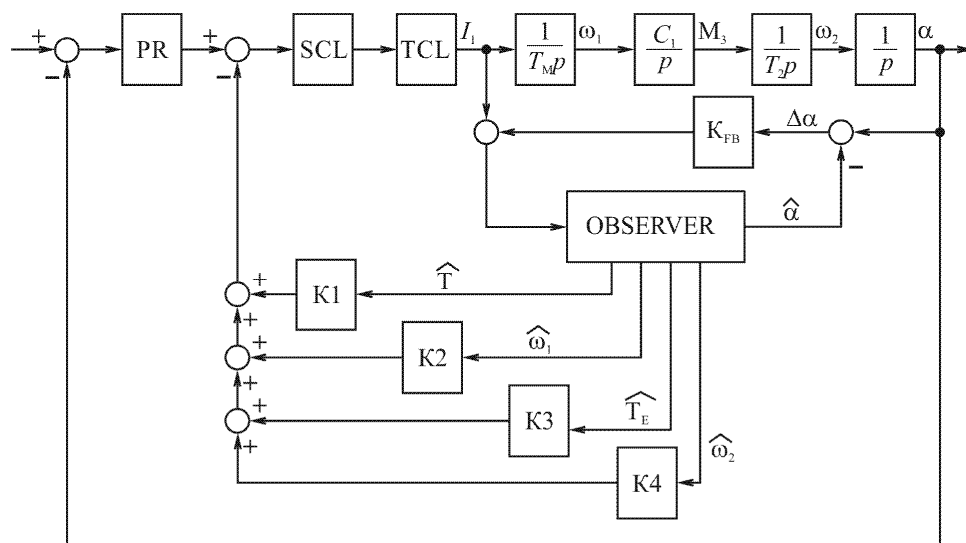


Figure 3. A block diagram of modal control of the feed drive

It can be obtained in real systems; the response time of the torque control loop will be $T_r = 0.005$ s; $T_m = 0.04$ s – electromechanical response time of the motor; $T_t = 0.01$ s - time constant of the unit, considering the elasticity of the screw-gear; $T_{mm} = 0.1$ s - electromechanical time constant of the movable mechanism; SCL (Speed Control Loop) = 50 – the gain factor of the SR regulator. Feedback by torque is not considered during the setting of the modal controller, because cutoff frequency ω_3 (Figure 4) is much smaller than cutoff frequency ω_2 in the modal control structure.

The necessity to enter the feedback of this loop is useless; therefore, the TP response time is small. In other words, the transfer function of the torque control loop is approximated by an aperiodic link of the first rank, then:

$$W_1 = k_{SR} W_{MM} = \frac{50}{1 + 0.005p}.$$

The next is loop 2 tuning with the feedback by the ω_1 speed so that the cut-off frequency of this

loop was nearly $\omega_2 \approx 200$ rps. The transfer function of the direct channel in loop 2 is approximated by the expression:

$$W_1 W_d = \frac{50}{0.5p(1 + 0.005p)}.$$

After coverage links of the direct channel by the feedback with the amplification factor k_2 , the transfer function of closed loop 2 can be approximated by the expression:

$$W_2 = \frac{1}{k_2(1 + T_2p)(1 + T_Mp)} = \frac{1}{50(1 + 0.005p)(1 + 0.5p)},$$

where $k_2 = 50$, $T_2 = 1/\omega_2 = 0.005$ s.

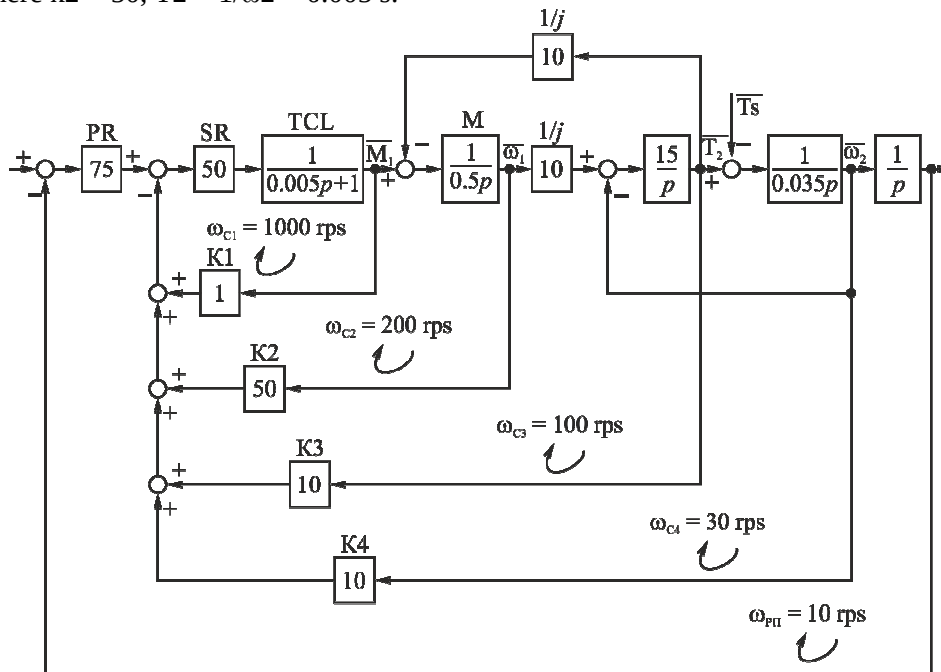


Figure 4. Modal regulator setting

During the next control loop 3 setting with the feedback by the moment of elasticity into its direct channel consistently with loop 2 closed by ω_1 , the integrating link is activated, taking into account the elasticity of the screw gear. It follows that the cut-off frequency ω_3 of this loop, compared with the previous one, should be reduced 2...4 times.

Let us choose:

$$\omega_3 = \frac{\omega_2}{2 \dots 4} = \frac{200}{2 \dots 4} = 100 \text{ rps}.$$

Then, similarly:

$$W_3 = \frac{1}{k_3(1 + T_3p)(1 + T_2p)} = \frac{1}{10(1 + 0.01p)(1 + 0.005p)},$$

where $k_3 = 10$, $T_3 = 1/\omega_3 = 0.01$ s.

The fourth loop adjustment. The movable object MO integrator is activated here consistently with loop 3. Cut-off frequency is:

$$\omega_4 = \frac{\omega_3}{2 \dots 4} = \frac{100}{2 \dots 4} = 30 \text{ rps}.$$

An approximated transfer function would be as follows:

$$W_4 = \frac{1}{k_4(1 + T_4 p)(1 + T_3 p)} = \frac{1}{10(1 + 0.03 p)(1 + 0.01 p)},$$

where $k_4 = 10$, $T_4 = 1/\omega_4 = 0.03$ s.

Thus, it is a system with previously adjusted controller parameters.

Based on limits of torque control loop performance, during the setting of the modal control system, its transfer function was approximated by an aperiodic link of the first rank with a response time $T_{TCL}=0.005$ s, corresponding to real time values of the transient process in the torque loop system with DTC-control.

An internal loop was installed by a criterion of maximum velocity (Figure 4) cut-off frequency was $\omega_{CI} = 1000$ rps. Each additional external loop was installed by concept $T_n = (2 \dots 4) T_{(n-1)}$. Cut-off frequencies of each loop are shown in Figure 4.

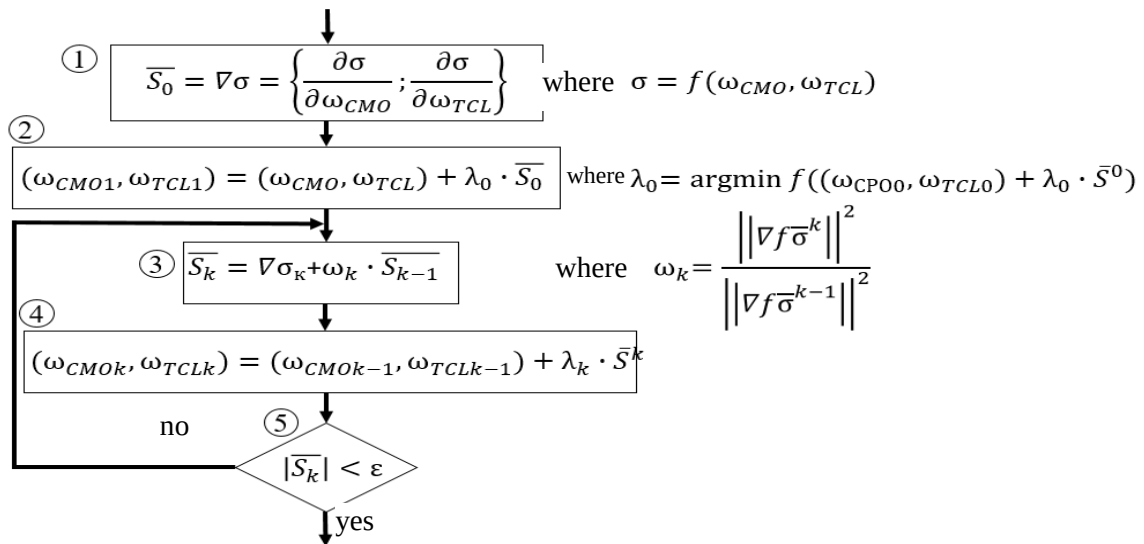


Figure 5. Critical points of the search algorithm

2.3 The comparison of the multi-loop system of subordinate regulation and the modal control system.

The measurement comparison in schemes with subordinate regulation and modal control while changing cut-off frequency of loop control's "unchanging part" (loop 2) and torque control loop should be made.

The multi-loop scheme of subordinate regulation with the external loop of movable object h position's regulation and a multi-loop scheme with the modal controller, in which intermediate variables calculated in the observer were chosen for comparison. In the initial scheme, the following were taken: cut-off frequency TCL (Torque Control Loop) $\omega_{TCL}=1500$ rps, rates $\omega_1=200$ rps and "unchanging part" loop II, $\omega_C=20$ rps. In these structures, overshoot value σ was registered during the cut-off frequency of TCL (Torque Control Loop) ω_{TCL} and "unchanging part" II ω_{CMO} was changed. Critical points were defined in order to clarify dependences by the Fletcher-Reeves gradient method. This method is a modification of the steepest descent method and differs by quick convergence. The calculation method, which was used for the power drive system of the mathematic model with a modal control, is shown in Figure 5.

The estimation of a steepest descend direction by a gradient of function $\sigma=f(\omega_{CMO}, \omega_{TCL})$ is in the first block. In the 2nd block from the very beginning, the decision vector step is calculated by a minimization of a λ coefficient. The next point variables are defined considering this very step. The 3rd block includes a selection of a new descent direction, considering previous $S_{(k-1)}$, while the ω_k

parameter based on Hessian matrix values, calculated for $k-1$ and k stages. The calculation ends when S_k is less than the tolerance. Calculated points enable one to clarify curves in the area of these points.

3. Results and analysis

Clarified dependences (surfaces) of the overshoot value for the subordinate regulation structure (surface 1) and modal control (surface 2) are shown in Figure 6. Surface 1 consists of feebly marked minimum. An overshoot value reduces both ω_{CMO} and ω_{TCL} raising frequency as shown in Figure 6. As illustrated in Figure 6, second mass influence onto stability conditions can be ignored by $\omega_{CMO} > 50$ rps frequencies. The system can be determined as a single-mass system in this area, and control factors are practically the same as in the modal control structure, during subordinate scheme setting. Surface 2 is a continuously decreasing function and depends weakly on a cut-off frequency. Surface 1 was placed below surface 2 in the frequency range from 0 to 200 rps and was decreasing more quickly, so the external loop setting conditions (by varying speed, elastic torque) worsened sharply with decreasing cut-off frequency ω_{KPM} . In this area, modal control systems are worse in indexes than a structure with subordinated regulation.

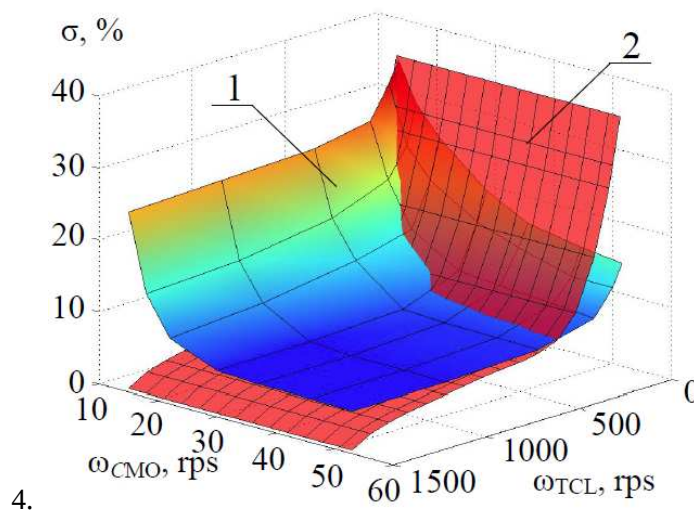


Figure 6. The overshoot dependence in a position loop on TCL cut-off frequency I ω_{TCL} and loop cut-off frequency II ω_{CMO} in schemes with subordinate control (1) and modal control (2).

4. Conclusion

In the course of the study, the authors of the paper has come to the following conclusion. The preferred structure of the positional electric drive of the feeding mill for cold rolling tube was selected according to the criterion of minimum feed overshoot. Thus, the minimum polythickness of tube has been identified. During the cut-off frequency limit of a torque control loop has been determined. For this value, the subordinate regulation is optimal. If the value of this parameter is high, then the modal control is preferred. The recommendations on how to choose an actual control system according to processing speed opportunities of an electric drive torque control loop have been given.

5. Acknowledgments

The work was supported by Act 211 of the Government of the Russian Federation, contract № 02.A03.21.0011

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