MATERIAL TRACKING WITH DYNAMIC TORQUE ADAPTATION FOR TENSION CONTROL IN WIRE ROD MILL

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Abstract. *Material tracking is an important part of the automation control system which has a major impact on the product quality. This paper addresses a stand load identification in wire rod mill as a new algorithm added to existing control system. Tension control approaches are described and a modification of existing tracking system is proposed in order to eliminate tracking faults. Proposed method is based on dynamic torque calculation and its performance was experimentally verified on the industrial wire rod mill. Experimental results show significant reduction of the errors.*

Keywords

Dynamic torque, material tracking, tension control, wire rod.

1. Introduction

Wire Rod Mill (WRM) usually consists of roughing, intermediate and finishing mill. Each mill consists of several Stands (STD) [1] and [2] and each stand is driven individually by electrical motors supplied from power converters. Typically, one quadrant or four quadrant controlled DC machines are used. To maintain a stable and high quality rolling process, it is required to control the speed of the stands according to the tension conditions between the stands. Speed ratios between these stands must remain constant to maintain stable material flow. If there is a change in a gap between rolls, it causes a deviation in rolling parameters, what can increase or decrease interstand tension [3]. The tension between stands has a great influence on the properties of the workpiece produced in the mill.

Wire rod rolling is a periodical process. The workpieces pass through roll stands sequentially and one workpiece follows another. For that reason, material tracking system is one of the most important parts of the WRM control structure. It manages the tension control and it is used also for cobble identification. Material tracking function provides accurate information of the workpiece head and tail end positions in the mill. This is a fundamental requirement for automatic control sequence, data collecting systems, main and auxiliary drives and services. Even more, the speed reference distribution, automatic loop control, minimum tension control and automatic cutting of the flying shears are based on precise material tracking.

Following sources of feedback signals are usually used in WRM [10] and [11]:

- *Hot Metal Detector (HMD)* - the most commonly used sensor in the mill lines, it uses infra-red radiation emitted by hot materials which is received by an optical system in the sensor,
- *Loop scanner* - used in the automatic loop control, optically scans the field to be controlled and does not need any optical adjustments,
- *Stand threading signal* - generated from the peak torque detector in the drive or PLC unit.

Obviously, installation of the first two sensor systems results in additional costs.

While the end of the workpiece passes through the roll, the tension of the bar suddenly turns to zero and size of the bar changes [4]. The changes in cross-sectional area along the workpiece can lead to the cobble in the intermediate and finishing mill. Massive tension can cause total unloading of the stand that consequently leads to the cobble due to the failure of interstand tension control. On the other side, no tension

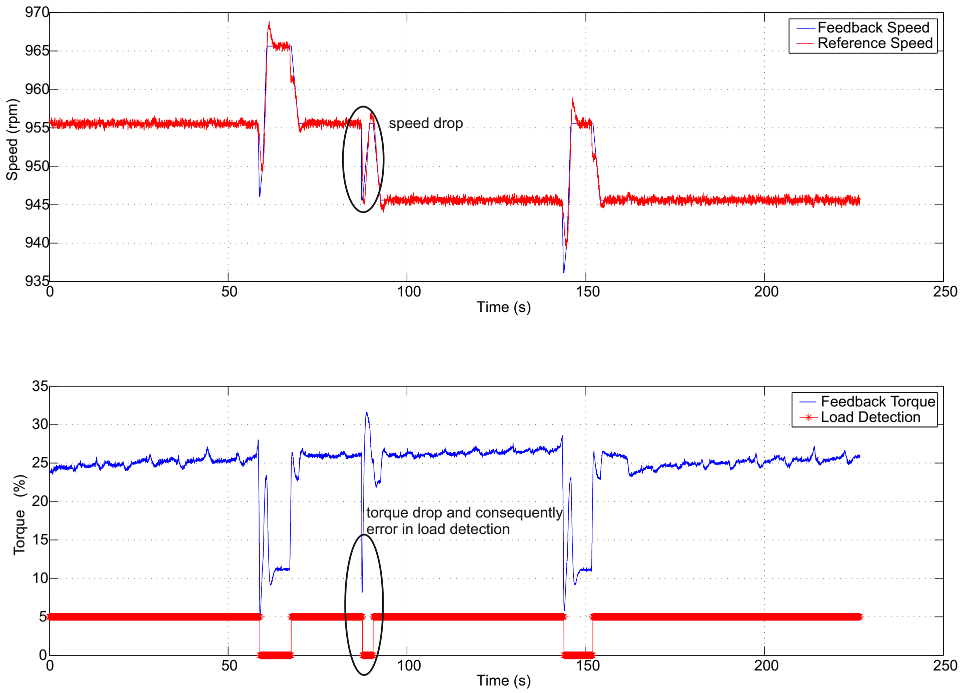


Fig. 1: Material tracking fault due to the raped machine speed decrease.

means loopering of the material between the stands, that also leads to cobble in the mill [6].

All these deviations have a big impact on product quality. Even more, these deviations increase amount of the time spent by engineers for the mill maintenance.

2. Problem Formulation

In case there is no sensor for tracking of the workpiece, motor torque and speed are used to track the material. Load Detection (LD) signal is a control signal indicating that the stand is under load i.e. the workpiece has been rolled by stand. If the actual torque value exceeds LD signal level, head position of the workpiece is traced. When workpiece leaves the stand, motor torque decreases and workpiece tail end is detected. However, WRM is highly dynamic system consisting of drives and processing material coupled together. While the mill speed is decreased rapidly, motor torque can decrease close to the zero, even though it is fully loaded. On the other side, if the mill speed is increased rapidly, motor torque increases and, under certain conditions, it can exceed LD signal level. This situation is shown in Fig. 1 and, obviously, it causes significant errors. It can be observed in Fig. 1 that 3 workpieces have been rolled. During the rolling of the 2^{nd} workpiece (since $t = 60$ s to $t = 140$ s), LD signal is active, but the speed change in $t = 85$ s coming from superior control results in torque drop. Torque value had dropped under LD level, therefore, LD signal became inactive, although the stand was fully loaded. This phenomenon leads to faulty tension control with consequent cobble. In order to eliminate this problem, a modification of the classical tension control has been proposed, as shown in Section 5.

Total motor torque T of each stand can be expressed as [6], [15]:

$$T = T_0 + T_d + T_r + T_p + T_{ft} + T_{bt}, \tag{1}$$

where:

- T_0 is friction torque,
- T_d is dynamic torque,
- T_r is rolling torque,
- T_p is torque from pins friction during the rolling,
- T_{ft} is forward tension torque,
- T_{bt} is backward tension torque.

For a period of a free rolling, when there is no billet in the stand, only T_0 and T_d act on motor shaft. T_0 depends on actual motor speed and friction conditions and T_d is given as:

$$T_d = J\frac{\mathrm{d}\omega}{\mathrm{d}t}, \tag{2}$$

where J is a total stand inertia and ω is motor speed of given stand [10]. Inertia of each stand depends on invariable factors, such as gearboxes or motor shafts, and variable factors, which are working roll parameters. Mass and size of the roll varies according to pass schedule and roll wear. However these changes, compared to the total inertia of the stand, are small enough to be neglected.

During the rolling, additive torque components T_r, T_p, T_{ft} and T_{bt} act on the motor shaft. These components are closely related and depend on many rolling parameters and rolling and tension forces, which influence the stand. For example, rolling torque T_r is given by [1]:

$$T_r = 4 \int_0^{L_r} b\sigma_y (L_r - x)\mathrm{d}x, \tag{3}$$

where b is a width of approximated workpiece-roll surface area, σ_y is a stress component in vertical direction and L_r is a roll-bite length. Torque from pins' friction during the rolling T_p is:

$$T_p = \frac{1}{2} F_r f_p D_p, \tag{4}$$

where F_r is a rolling force [1], f_p is a friction coefficient of the pins and D_p is a diameter of the pins. Forward and backward tension torque, T_{ft} and T_{bt}, are given by [1]:

$$T_{ft} = \frac{1}{2} D_{ef} A_f \sigma_f, \tag{5}$$

$$T_{bt} = \frac{1}{2} D_{ef} A_b \sigma_b, \tag{6}$$

where D_{ef} is an effective diameter of the rolls, A_b and A_f is a workpiece cross-sectional area in front and back of the roll-bite lenght, respectively; and σ_f and σ_b is a front and back axial stress, respectively [12].

There is no tension force measurement in the mill and so the components of the motor torque cannot be identified separately. Estimation of all these components requires knowledge of many rolling parameters, which are varying during the rolling process. Therefore, components T_r, T_p, T_{ft} and T_{bt} will be used only as one lumped variable for further calculations. It is important to note, that the torque acting on the motor shaft consists of these parts:

- rolling part T_r, T_p, T_{ft}, T_{bt},
- free running part T_0, T_d.

Tracking system has to securely identify the time interval, in which the stand is under rolling load. When compared to the torque of rolling part, T_0 is quite small, so it is neglected in Eq. (7). Hence, by calculation of dynamic torque T_d in each time of rolling sequence and consequently by subtracting it from the motor torque feedback, free running part is excluded from the total motor torque and only rolling part remains. This is the way how to securely indicate total rolling load. Load torque T_{load} is then given by:

$$T_{load} = T_{fbk} - J\frac{\Delta\omega}{\Delta t}, \tag{7}$$

where T_{fbk} is actual motor torque feedback and $\Delta\omega$ is the change of angular speed during defined time interval Δt. Note, that the value of T_0 in Eq. (7) is neglected, but it has to be identified for the calculation of inertia.

3. Tension Control

In high-speed WRM with fixed speed ratios between the stands, interstand tensions are used to obtain stable rolling conditions [5]. Traditional tension control systems are based on the *minimum tension control* for roughing mill, the *loop control* for intermediate mill and the *tension rolling* for finishing mill.

3.1. Roughing Mill

Since it is not possible to control the loop between the stands due to big dimensions of the workpiece in roughing mill, a looperless control scheme has to be used. So called *minimum tension control* assumes that the workpiece dimension and material temperature profile remain constant along the whole workpiece. Motor torque feedback during the time interval with and without interaction of the workpiece with the stand is used as a tension indicator [6], [8] and [9]. Recent approach is to use *Interstand Dimension Control* (IDC) with the complex system of workpiece cross-sectional area measurements in the interstand area. U-Gauge sensors measure dimensions and IDC control system is used to automatically adjust the gap set–up and speed [7]. WRM described in this paper has a conventional sensorless control system with the minimum tension control. Tension free rolling conditions of i-th stand STD_i are represented by the time interval, when the workpiece is rolled by STD_i but does not reach following stand yet. Once the workpiece enters stand STD_{i+1}, motor torque of STD_i is affected by the tension between STD_i and STD_{i+1} and tension control turns on. To control the intervals, the knowledge of actual front and tail end position of workpiece in the mill is required.

3.2. Intermediate Mill

To keep the constant material flow in the intermediate mill, the loopers are installed between the stands. Looper consists of a roller mounted on a pivoted arm that is initially lowered below the mill pass line. The pivoted arm is raised after the head of the workpiece enters the stand. This causes a deflection of the workpiece and a small loop is formed. Loop scanner measures loop height. The speed of a given stand is then adjusted to maintain the loop height on desired value [1]. When workpiece leaves the stand, pivot arm is lowered and loop height is decreased. Recent approach is to use IDC, where, as in the roughing mill, U-gauge sensors measure dimensions and IDC system is used to automatically adjust roll gap and speed [7]. WRM under experiment has a conventional looper control scheme without IDC.

3.3. Finishing Mill

Configuration of the finishing mill is different from the previous ones. To meet the demand for increased production rates, the rolling speed must be drastically increased. Exit material speed can reach more than 100 m·s^{-1}; therefore the conventional loop control cannot be used. Stands are equipped with changeable roll rings and there is no space for a measuring sensor or device, so measurement of any quantity in the finishing block is hardly possible. Rolling speed of each stand is determined by gear ratio and working diameter of the roll ring.

Since there is no possibility to change the speed ratios between the stands, roll rings of the finishing block usually creates so-called roll rings families, which have to be used for each individual pass design. Pass schedule is designed to maintain a tension between each two consequent stands to prevent the loopering [1] and [2]. WRM under experiment has a conventional block with the ten stands coupled by gearboxes and driven by one DC motor. Loop control is used only between the last stand of the intermediate mill and first stand of this block. Recent approach is to equip each stand with a maller motor instead of a complex gearing with one large motor.

4. Parameter Identification

4.1. Identification of Friction

The value of load torque friction component T_0 has to be identified at first in order to calculate inertia of each stand. T_0 is determined as a speed-depended polynomial function. The function was obtained using the MATLAB Curve Fitting Toolbox using the data recorded during motor acceleration with slow speed reference ramp in order to suppress the effect of dynamic torque. This measurement is shown in Fig. 2, where actual torque and speed feedback during the slow speed ramp up (approx. 100 s), free running and slow speed ramp down is shown for stand *STD16*. The relation between speed and torque and the approximation by the 4$^{\text{th}}$ degree polynomial equation is shown in Fig. 3, where *original* line shows measured motor torque during acceleration, free running and deceleration, *middle* line shows the difference between acceleration and deceleration torque and *approximated* line shows the result of the approximation of the *middle* line with MATLAB.

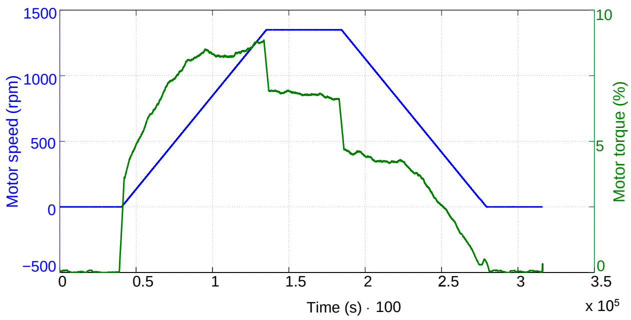


Fig. 2: Measurement for the identification of friction torque.

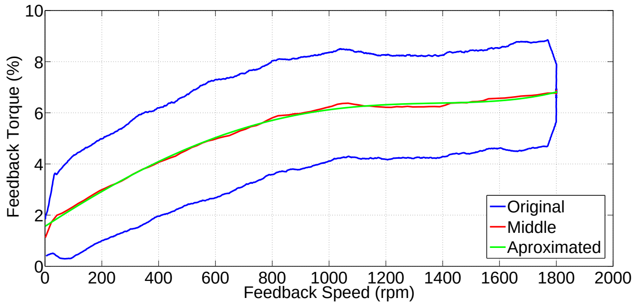


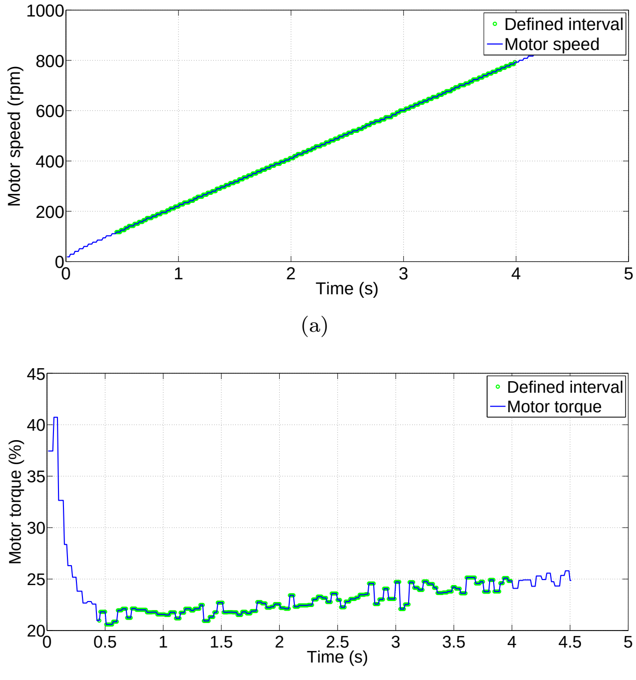
Fig. 3: Friction torque as a function of actual speed.

4.2. Identification of Inertia

Identification of the total stand inertia is shown in Fig. 4. Motor was accelerated to the maximum speed and actual speed and torque were recorded. Green line shows the interval used for further calculations. Partial calculation of J for each measured time interval Δt was performed according to:

$$J = (T - T_0)\frac{\Delta t}{\Delta \omega}, \tag{8}$$

where $\Delta\omega$ is the speed difference during each time interval, T is actual motor torque and T_0 is friction torque given by polynomial function. Total stand inertia is then estimated as the average value of partial inertia calculations. The results of these calculations of inertia are shown in Fig. 5. It shows the difference between the inertia calculated exactly as in Eq. (8) and the inertia calculated as in Eq. (8)but for $T_0 = 0$. It can be observed, that the difference is considerable and



(a)

(b)

Fig. 4: Identification of total inertia - the 1st method.

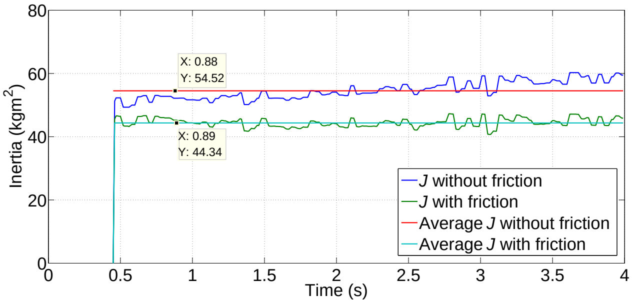
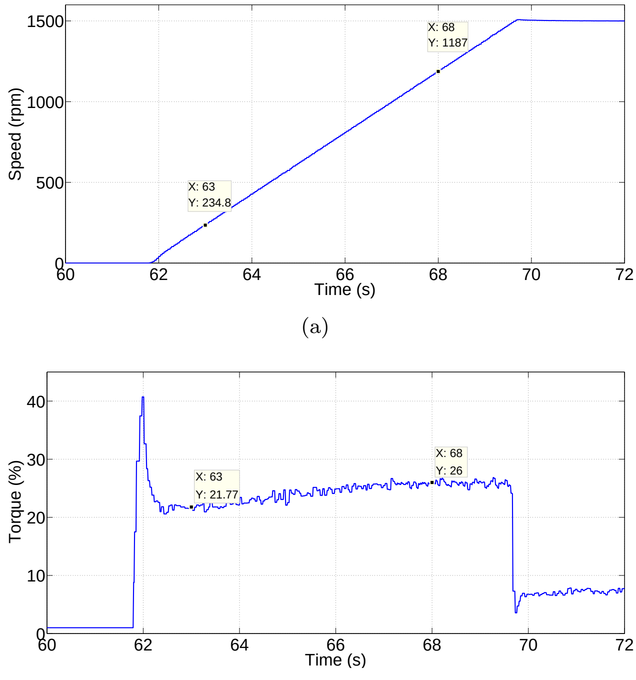


Fig. 5: Partial calculations of J in *STD16*.



(a)

(b)

Fig. 6: Identification of J - the 2nd method.

so friction torque always has to be identified for inertia calculations.

Much faster estimation of inertia with less computational burden can be obtained during the acceleration of the motor without any additional measurement. If the average value of friction torque in steady state is used (e.g. T_0 is approximately 7 % for 1500 rpm in Fig. 6, J can be calculated again with Eq. (8). The measurement points are shown in Fig. 6. $\Delta\omega$ and Δt are given:

$$\Delta\omega = \omega_2 - \omega_1, \tag{9}$$

$$\Delta t = t_2 - t_1. \tag{10}$$

In this case, T is an average value of motor torque during acceleration within time interval $t_1 - t_0$. The difference between values of inertia calculated by the 1st and by the 2nd approach is less than 1 %. Hence, the 2nd method was used to calculate the inertias for all stands. These values are shown in Tab. 1. They need to be calculated in order to implement the dynamic torque adaptation algorithm described in the next section.

Tab. 1: Inertia values of the individual WRM stands.

Stand	STD01	STD02	STD03	STD04
J (kg·m^2)	8.97	21.87	10.41	22.67
Stand	STD05	STD06	STD09	STD10
J (kg·m^2)	18.49	29.97	19.47	26.27
Stand	STD11	STD12	STD13	STD14
J (kg·m^2)	20.81	28.74	19.97	35.16
Stand	STD15	STD16	FBLCK	
J (kg·m^2)	23.39	41.13	1960.66	

5. DTA Algorithm

The algorithm of Dynamic Torque Adaptation (DTA) was implemented into existing control system based on Siemens S7 400 Programmable Logic Controller (PLC). Cycle interrupt time for proposed algorithm is 10 ms. There is no need for modification of the existing hardware, the solution is purely based on the software modification. DTA algorithm is shown in Fig. 7. The aim of the algorithm is to to calculate the value of T_{load}, which is used for stand load identification, where:

- *cycle time* is PLC cyclic interrupt time interval,
- *speed FBK* $(t-1)$ is motor speed feedback from the previous cycle,

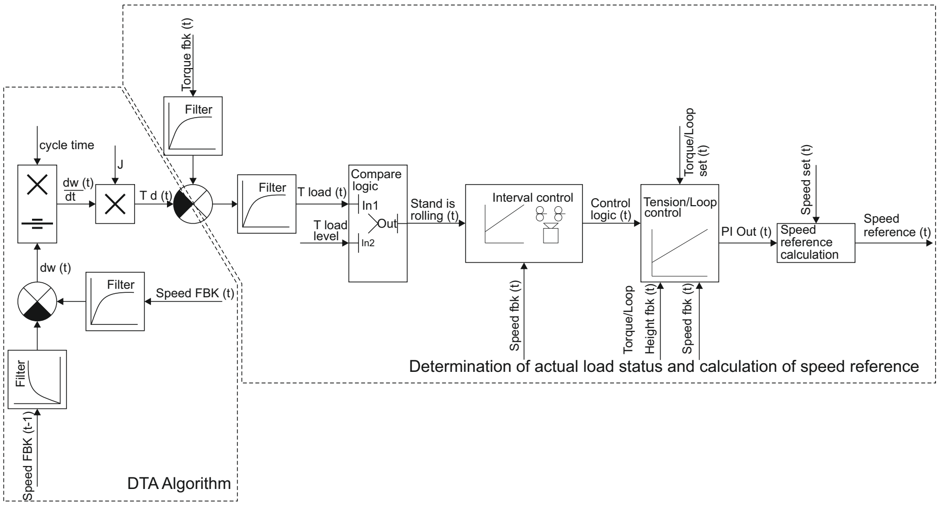


Fig. 7: Speed reference control chain for one stand with determination of actual load status and DTA algorithm implementation.

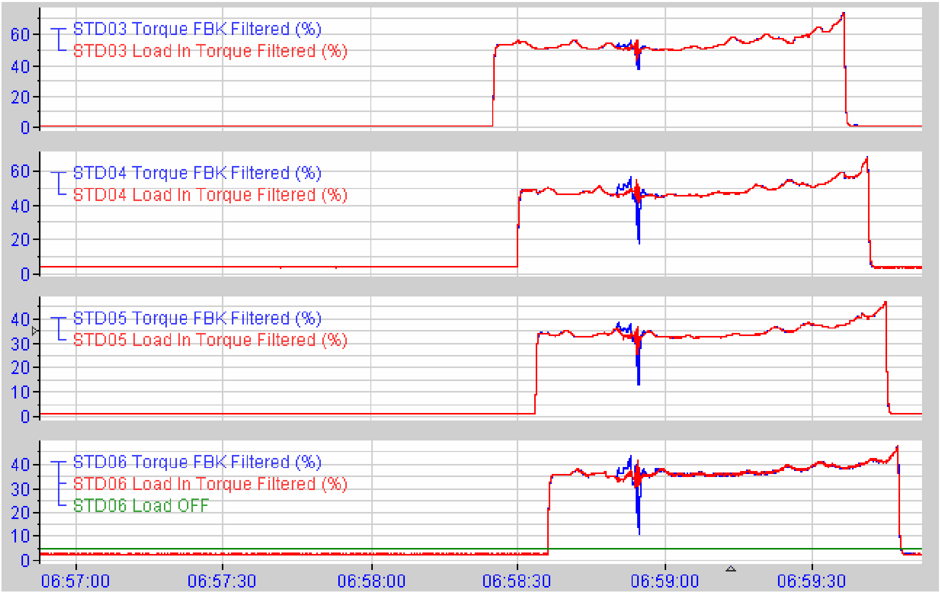


Fig. 8: Experimental results of the WRM control after the implementation of DTA algorithm.

- *speed FBK* (t) is motor speed feedback of the actual cycle,
- J is total stand inertia, as given by Tab. 1,
- $T(t)$ is motor torque feedback,
- T_{load_level} is a torque decision-making level for identification of rolling (LD signal).

Actual motor torque and actual motor speed are obtained from the drive converter via Profibus network. Calculated dynamic torque is subtracted from filtered actual torque, what gives T_{load} value. This value is compared with LD signal level in order to obtain logical signal showing that stand is under load. The logic for auxiliary devices (shears, loopers, cooling) is calculated in *Interval control* block. One of its outputs presents the control logic signal for *Tension/Loop control* block. Here, the tension control or the loop control is executed: the tension control for roughing mill and the loop control for intermediate and finishing mill. Output of this controller is led into *Speed reference calculation* block. Reference speed calculation, together with the speed components from other drives and basic speed from the pass schedule, is executed here. Drive speed is controlled in closed loop and encoder is used for motor speed measurement. If the speed feedback is noised, it is necessary to use filtered speed signal, otherwise it would result in the ripple of actual torque, which then cannot be used for the torque level comparison. The ripple effect was significant especially for the Finishing Block (FBLCK) torque calculation, since its inertia is much higher when compared to other stands.

Detailed description of the speed control chain is beyond the scope of this paper. If necessary, it can be found in [13] or [16].

Experimental results of DTA algorithm implementation are shown in Fig. 8. The blue lines are the actual torque values T_{fbk} of individual stands (STD03 - STD04 - STD05 - STD06) and the red lines are the values of total filtered load torque T_{load} obtained by DTA algorithm.

The time responses show values during the rolling of one workpiece. Rolling started in t = 06 h 58 m 26 s. Rapid speed changes occurred in t = 06 h 58 m 50 s due to the control signal from intermediate mill. These speed changes cause torque droop, which is clearly visible on the value of T_{fbk} of STD06. This torque droop is very close to the LD level value (green line). However, the tension control uses values of T_{load} instead of T_{fbk}. The value calculated by DTA is invariant to the speed changes and so it is preferable for LD. All these measurements were obtained by *ibaAnalyzer* [14] during full rolling operation with high dynamic speed changes.

6. Conclusion

The stand rolling load identification in wire rod rolling was analysed in this paper. Load identification was improved by dynamic torque adaptation. With the calculation of the dynamic part of the motor torque, which is subsequently excluded from the motor torque feedback, the effect of rapid speed change to the stand load identification is suppressed. Functional description of the algorithm, the procedure of rolling parameters identification, the measurements and the final implementation to the control system was described in detail. Experimental results measured in real rolling mill demonstrate applicability and correctness of the proposed technique.

Moreover, the results of the dynamic torque adaptation algorithm have some other benefits. In conventional tension controllers, the motor torque actual value obtained from the converter is used for the tension controller. With DTA algorithm, the load torque value is available as a new process value for the tension controller independently, without the dynamic and the friction components, and so it can be used for further tension control quality improvement. However, this issue has not been investigated in the paper and it may be a subject of further research.

DTA algorithm was successfully implemented in Slovakia Steel Mills company in Slovakia. There were circa 3 tracking faults per 30 000 rolled billets (on average per month) before DTA implementation, sometimes with consequent cobble in the mill. After the DTA implementation, the rolling load was determined securely. At present, there are no tracking faults due to the rapid speed changes in the mill.

Acknowledgment

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