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DESIGN OF CLOSED LOOP CONTROLS FOR A SEVEN-STAND HOT STRIP ROLLING MILL

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SUMMARY

A hot strip rolling mill is a complex system which requires sophisticated regulations in order to obtain a constant thickness of the strip at the exit of the mill (the screw positions and the roll speeds are the control variables). Here we present new regulations which take in account the temperature measurements at the exit of the roughing mill. The preset values of the control variables are computed before the milling (feed-forward) These values are modified during the milling by a feedback based upon the forces measurements. This type of system which has the same structure as an Automatic Gauge Control (AGC) is easy to implement on the process.

INTRODUCTION

A great amount of work has been devoted to the study of hot strip rolling mills. This is mainly due to the complexity of the system which requires sophisticated regulation and control devices. Furthermore the physical analysis of the various physical phenomena involved in the rolling process is quite complex and modelling is in itself a difficult problem.

In previous paper we have presented some models 1, 2, 3, taking in account most of the main physical knowledge of the process such as thermal behaviour, elasticity, etc.

This paper is founded on the control problem of a seven-stand hot rolling mill. The main result concerns the calculation of a new AGC (Automatic Gage Control) which takes in account temperature measurements at the last stand of the roughing mill. This is a combination of the so-called "feed forward" control and feedback control. After some calculations which can be done before the rolling it is possible to obtain an estimation of the actual temperature of the strip in the finishing mill.

The second main idea is to remark that to obtain a good flatness of the strip one must avoid great variations of screw positions for the last stand. As a consequence the thickness at the inlet of the last stand must not be constant. On contrary we must compute a thickness at the outlet of the sixth stand such that by keeping a screw position constant for the last stand the desired thickness is obtained.

Finally it is necessary to obtain an AGC which is simple to implement on line on the process. This is the last part of the study presented here. Basically this AGC uses information both on estimation of the temperature and on near optimal rolling force (which is precomputed) to get the actual screw position.

The paper is organized in five parts :

- a brief description of the simulation model (SM)
- general principles of the proposed regulators
- feedforward computations
- feedback controller (AGC)
- results.

I. THE SIMULATION MODEL

In order to have a good basis to check the validity of the proposed controllers it is necessary to have a good model for simulation of the mill. Construction of such a model is presented in details in previous papers 1,2.

Here we just recall the basic features of the model (SM) used for simulation of a seven-stand mill. Hereafter we will use the following notations :

F_i : milling force (stand number i)

F_i^* : open-loop optimized milling force (stand number i)

$\tilde{F}_i$: updated optimized milling force (stand number i)

h_i : outlet thickness (stand number i)

h_i^* : open-loop optimized outlet thickness (stand number i)

h'_i : inlet thickness (stand number i)

h'^*_i : open-loop optimized inlet thickness (stand number i)

S_i : screw position (stand number i)

S_i^* : open-loop optimized screw position (stand number i)

S_i^R : preset value of screw position (stand number i)

T_i : strip temperature (stand number i)

$\hat{T}_i$: open-loop estimated strip temperature (stand number i)

$\tilde{T}_i$: updated estimated strip temperature (stand number i)

T_{RM} : strip temperature at the exit of the roughing mill

V_i : roll speed (stand number i)

δ_{i+1} : transfer time between stand i and stand i+1

For each stand we have 3 equations governing

- the thickness at the neutral angle,
- the milling force,
- the elastic deformation of the stand.

In the interstand there are 4 basic equations governing

- the conservation of mass,
- the position of the looper,
- the creep of the strip,
- the variation of width and thickness.

Furthermore a partial differential equation governing the evolution of the temperature along the strip must be added.

The figure 1 gives a result of simulation and comparizon with measurements of the thickness of the strip at the exit of the mill.

IHICKNESS (MM)

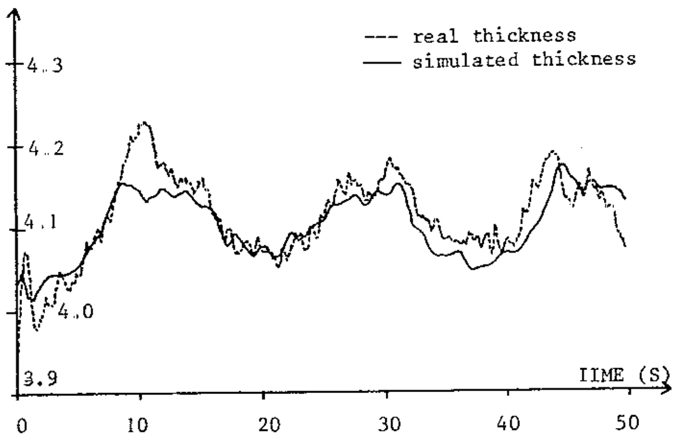


Figure 1 : Comparizon between the exit thickness obtained by the simulation and the real exit thickness

2. OVERVIEW OF IHE REGULAIION PROBLEM

Ihe general diagram of the actual mill under study is given on Figure 2.

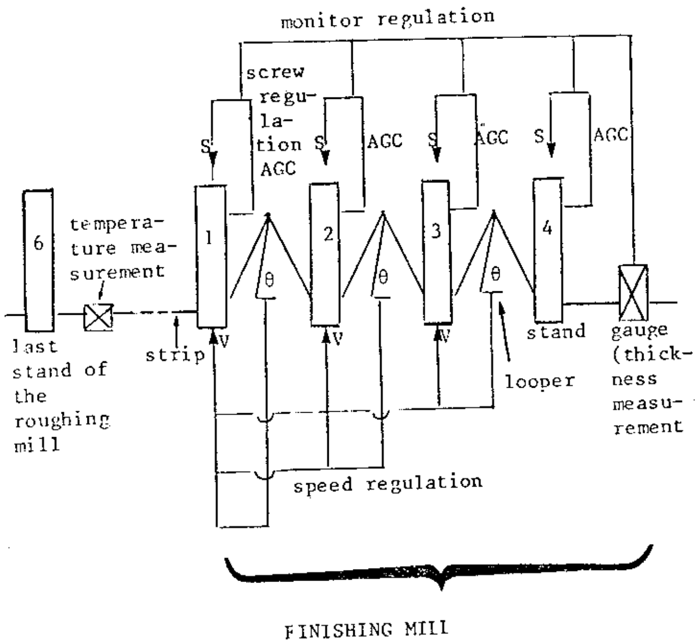


Figure 2 : General diagram of the mill with regulations (only 4 stands of the finishing mill have been drawed)

Measurements

The classical measuraments on this type of mill are :

- the surface temperature of the strip at the exit of the roughing mill $T_{RM}(t)$,
- une position of loopers,
- the milling forces (F_i),
- the thickness of the strip at the exit of the mill (h_7).

Control Variables

They are essentially for each stand :

- the screw position (S_i),
- the rolls speed (V_i).

Existing Regulators

On most plants they are of three types :

- the automatic gauge control (AGC) which compensates the elastic deformation of the stand by measuring the milling force,
- the automatic control of the speed which uses the looper angle measurements,
- the monitor which compensates the error on the exit thickness.

The Open-Loop Control Problem

It is now clear that the unused measurement is the temperature distribution T_{RM}. Thus by using the model of thermal behaviour of the strip between the roughing and finishing mill it is possible to estimate the temperature distribution of the strip during the milling process. This is the first step.

This estimation of temperature may be considered for two purposes :

a) this is a given data which permits an open-loop optimization of the thickness,

b) this allows to design some a priori feedback laws which replace the actual AGC.

The open-loop optimization has been performed by acting on screw position S_i and rolls speed V_i in order to minimize the following peformance index :

$$J = \int_0^T |h_7(t) - h_7^R|^2 \, dt \qquad (1)$$

which takes into account the desired thickness h_7^R (for more details we refer to 1, 2, 3).

As a result of this optimization, it is possible to notice that :

- the roll speed regulators have no influence on the exit thickness (they merely ensures coherency between the speeds of stands),

- the variations of screw positions in the last stand are large and this must be avoided in order to get a good flatness of the strip.

Thus it is only necessary to compute the screw positions of stands 1 to 6 to optimize the thickness, the screw position of the last stand being constant.

This open loop optimization is quite unsatisfactory for at least one reason :

the computing time is too long for an on line optimization (even if we use a very simplified model).

The natural next step consists in designing a closed-loop control system which uses the a priori information on temperature. This is presented in the next section.

3. FEEDFORWARD

The important observation we made by using the simulation model is that the thickness variations of the strip around the desired thickness has practically no effect on the temperature distribution in the mill. So, we may consider that the temperature is independent of the screw positions. Then the temperature distribution remains basically a function of the roll speeds.

Now the main steps for calculation of the feedforward controls are described.

STEP 1

Under this assumption the temperature distribution in the mill is computed by using the thermic model of the SM on the basis of the preset values of thickness and rolls speeds. The estimation of the actual temperature distribution will be made by measuring the rolls speeds during the milling. In the same time we calculate the interstand transfer time which is the transfer time of a slice of the strip from one stand to the next one.

Once we have the temperature distribution and the interstand transfer time, we can calculate the thickness of the strip in the mill.

STEP 2

The second step consists in calculating the input thickness of the last stand. This is merely done by inverting a system of 3 non linear equations where the desired thickness h_7^R is fixed ; this gives $h_7'^*(t)$ and $h_6^*(t)$ (there is a simple delay between these two values).

Obviously there is an infinite number of possibilities to choose the screw positions in order to get the desired result h_6^*. So we have introduced an additional relation (which corresponds to a weighting of the reduction of thickness among all the six stands) :

$$S_i^*(t) = \frac{S_i^R}{S_1^R} S_1^*(t_1) \qquad i = 2, \ldots, 6 \qquad (2)$$

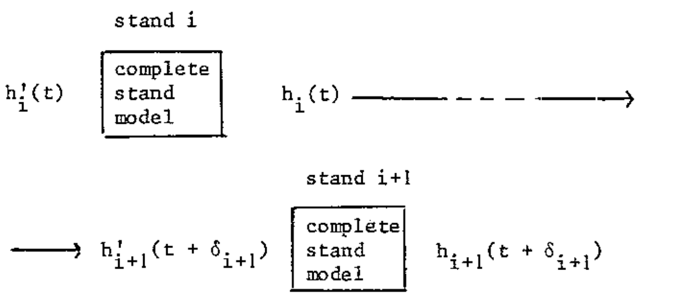
with $t_1 = t - \sum_{j=2}^{i} \delta_j$

δ_j transfer time in the interstand (j-1) - j

S_i^R preset screw position of stand i

$S_i^*(t)$ optimal screw position.

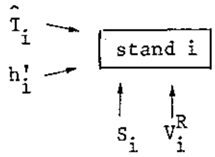
For a slice of the strip we have the following picture :



with $h_{i+1}'(t + \delta_{i+1}) = h_i(t)$ (3)

where δ_{i+1} is the interstand transfer time and h' and h are respectively the inlet and the outlet thickness of a stand.

For a stand we have the following diagram :



$h_i = f_i(h_i', S_i)$ (4)

$\hat{T}_i$ is the temperature obtained at step 1

V_i^R preset roll speed

Thus we can derive $h_6(t) = f_6(h_6', S_6) = \ldots = F(S_1)$ by means of equations (2), (3) and (4).

We solve $F(S_1) = h_6^*(t)$ by the help of an iterative Newton method and we obtain S_i^*, $i = 1, \ldots, 6$. It must be noticed that in fact the functions f_i and F are not explicit and the calculations are quite complicated (we refer to 1, 2, 3 for detailed equations).

STEP 3

If we compare the obtained optimal screw positions with the temperature distribution it turns out that there exists an affine relationship between these two variables for each stand :

$$S_i^*(t) = a_i \hat{T}_i(t) + b_i \qquad i = 1, \ldots, 6 \qquad (5)$$

It must be noticed that this relation is by no means an a priori assumption and simplification of the simulation model of the mill but is the result of our optimization : we can say that at the optimum some relationship become very simple.

Then to obtain, on line, the values of the optimal screw positions we have to calculate the 12 values $\{a_i, b_i\}_{i=1}^6$ (steps 1, 2, 3) and to estimate the actual values of temperature distribution.

4. FEEDBACK

We have seen that to obtain on line the optimal screw positions, we must have a good estimation $\tilde{T}$ of the actual temperature T. We noticed previously that we can have a good estimation of T by means of the a priori temperature $\hat{T}$ and the actual rool speeds. Then, we obtain $\tilde{T}$ from $\hat{T}$ by roll speeds measurements during the milling process.

Actually it is possible to improve the AGC by taking in account a possible error between the estimated temperature $\tilde{T}$ and its actual value T. Unfortunately there is no direct measurement of T. So we have to use another measurement which is the milling force. We have the following equation giving the exit thickness h_i :

$$h_i = S_i + C(F_i) \qquad i = 1, \ldots, 7 \qquad (6)$$

with S_i screw position

F_i milling force

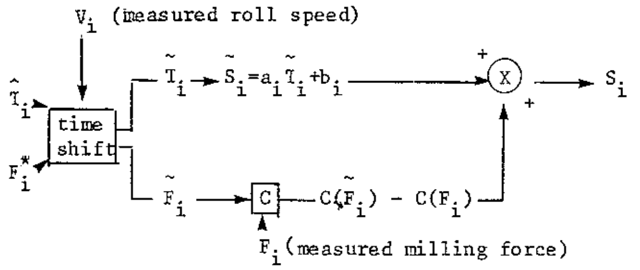
C( ) elastic deformation of the stand

$$\left(C(F_i) = \frac{1}{a1_i}\left(F_i + a_2\left(1 - e^{a_3 F_i}\right)\right)\right)$$

In the feedforward operations, we calculate ($\hat{T}_i(t)$,

$F_i^*(t)$, a_i, b_i) i = 1, ..., 6 as functions of the preset roll speed values where $F_i^*(t)$ is the optimized milling force corresponding to $h_i^*(t)$ (= $a_i\ \hat{T}_i(t)+b_i+C(F_i^*(t))$) which is the optimized thickness of each stand. Obtaining the estimation $\tilde{T}$ from $\hat{T}$ is nothing but a time shift thus we can also obtain $\tilde{F}$ which is the actual value of the milling force which should be obtained on the mill.

Thus we have the following diagram for the regulation of stand i :



In conclusion, the originality of this AGC lies in two facts :

- it uses a new measurement : the temperature at the exit of the roughing mill,
- its aim is <u>not</u> to keep a constant value of the exit thickness of each stand but on contrary to follow a given optimized profile of thickness during the milling.

5. RESULTS

The complete simulation of the milling of a real coil is presented here. The desired thickness is 4.09 mm. The milling time is 64 seconds decomposed in 640 steps of 0.1 second for the simulation.

The computer used is a HB 68. The total computation time for the feedforward is 80 seconds : 45 seconds for computing the temperature $\hat{T}$ and 35 seconds for computing the coefficients a_i and b_i. These running times have a magnitude equivalent to the transfer time between roughing and finishing mills (about 40 seconds). But we have not yet optimized and simplified the present calculations.

We have compared the exit thickness of the mill for simulations with the old and the new regulation by calculating

$$F = \sqrt{\frac{1}{T}\int_0^T (h_7^i(t) - h_7^R)^2\, dt}$$

where h_7^R is the desired exit thickness ; we have :

- old regulation F = .039 mm
- new regulation F = .010 mm

The exit thickness are compared on figure 3 and the milling forces of the last stand on figure 4. We can see that the milling force is quite regular, satisfying the flatness criterion.

A result with a very bad a priori estimation of the temperature is also presented. Figure 5 shows the difference between the temperatures at the exit of the roughing mill (time shift of 4 seconds). Figure 6 shows the corresponding thicknesses at the exit of the mill. We can see that in spite of the bad estimation of the temperature, the thickness is optimized by the means of the feedback.

But to impose our regulator, an on-line real-time identification of the temperature is necessary.

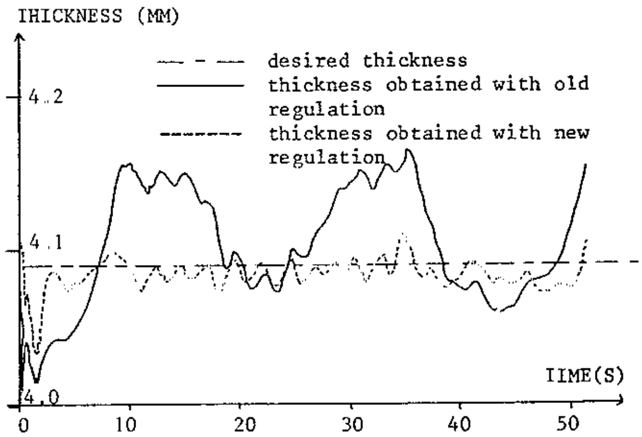


Figure 3 : Comparizon between the exit thickness obtained by the simulation with old and new regulation

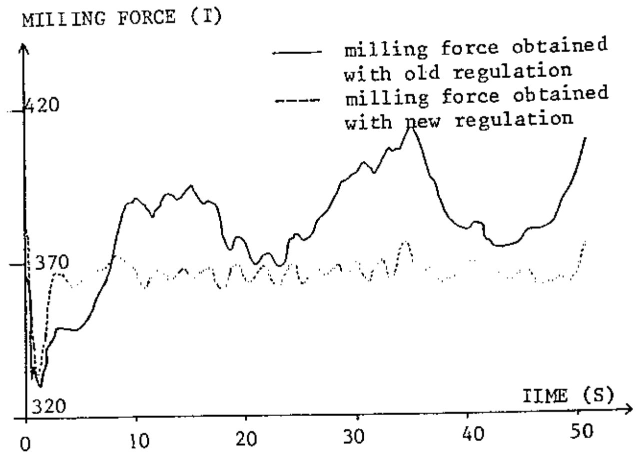


Figure 4 : Comparizon between the milling force of the seventh stand obtained by the simulation with old and new regulation

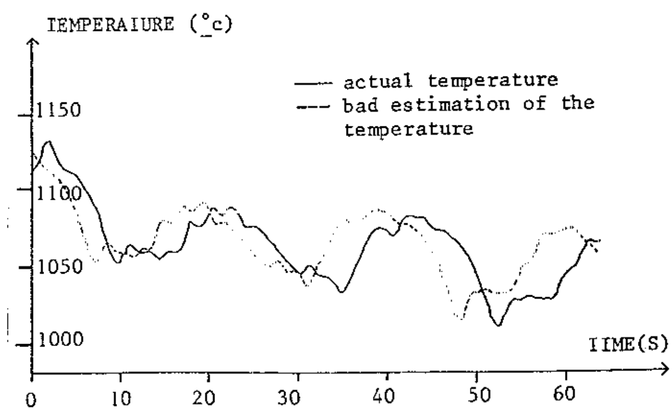


Figure 5 : Comparizon between a bad a priori estimation of the temperature and the actual temperature at the entry of the mill.

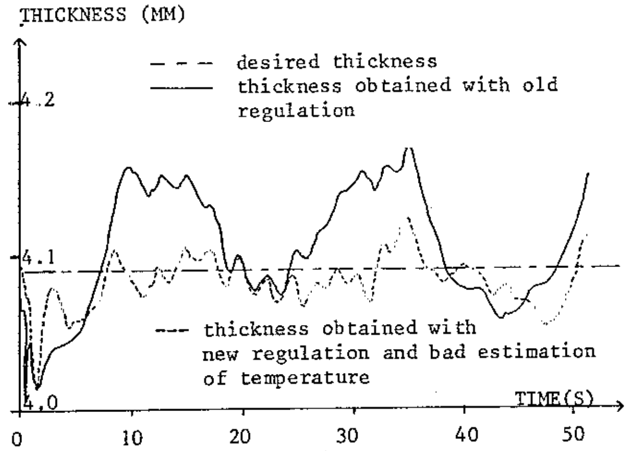


Figure 6 : Comparizon between the exit thickness obtained by the simulation with the old regulation and the one obtained by the simulation with the new regulation with a bad estimate of the temperature.

CONCLUSION

The results obtained are quite satisfactory but difficulties still remain to apply the presented regulation to the real milling process. First we have to reduce the computing time of the feedforward to permit its computation within the time limit we have. Furthermore the problem of implementation in the factory with the industrial environment and the filtering of measurements, for instance, remains to be solved.

However it seems realistic to envisage the use of the regulation presented here on the mill and solution of this problem is in progress.

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