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Software sensor as distributed parameter system for the control of secondary cooling in the continuous casting of steel

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Abstract: Sophisticated numerical models are created nowadays for the continuous casting of steel, partly thanks to the rapid development of information technology. These models are based on the numerical solutions of nonlinear partial differential equations describing the dynamics of modelled phenomena. Such distributed parameter numerical models used as "software sensors" offer the possibility to control the secondary cooling process. However, in current engineering practice the control synthesis is solved by lumped parameter systems approach. This paper shows how to solve the control synthesis problem based on distributed parameter system approach, using widely available software products for numerical modelling of continuous casting of steel combined with algorithms for control of lumped and distributed parameter systems.

Keywords: software sensor, continuous casting of steel, distributed parameter system, dynamics decomposition, control design, approximation problem, constrained model predictive control.

1. INTRODUCTION

Continuous casting of steel is one of the fundamental technologies of our industrialized civilization. More than 1.5 billion tonnes of semi-finished products are being cast annually by this technology alone. The intrinsic feature of this technology is a successive cooling of the molten steel in several cooling zones, aiming to ensure an optimized solidification process. Sophisticated mathematical models are used to optimize the solidification process, which are a part of commercially available virtual software environments based on the solution of nonlinear partial differential equations. This modelling approach provides a possibility not only for off-line process optimization but also for on-line control of such complex industrial processes.

Because of long-term development and industrial experience, various steady state operational modes were established for particular continuous casting technology, yielding optimized values of relevant process parameters. Each of these optimized operational modes corresponds to the optimal temperature field in the casting strand. Deviations from the optimized process parameters cause the temperature profile to change as well, which of course has an adverse effect on the solidification process.

The operation of the continuous casting machine (caster in short) in different steady state operational modes means, that from the viewpoint of control and process engineering these phenomena occur in the linearized neighborhood of steady state operational modes, or respectively, in between the transients of the given steady state operational modes. The structural layout of casters enables direct action of the cooling subsystem on the temperature field of the casting strand $YN(\boldsymbol{x},t)$ in the secondary cooling zone (SCZ, see Fig. 1) by changes in the flow rates of the cooling medium $\bar{U}N(k)=\{UN_i(k)\}_i$. Therefore, given control task in the linearized neighbourhood of a given steady state $\bar{U}N(\infty)=\{UN_i(\infty)\}_i\,/\,YN(\boldsymbol{x},\infty)$ can be solved by means of inputs $\breve{\bar{U}}N(k)=\bar{U}N(\infty)+\breve{\bar{U}}(k)$, Fig. 2.

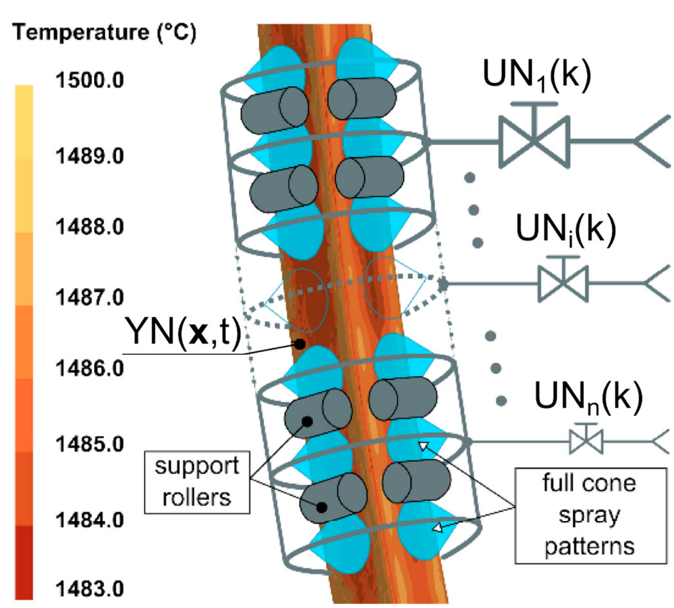

Fig. 1 Surface temperature field of the casting strand in the secondary cooling zone with controlled flow rates.

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Unfortunately, the measurement of surface temperature field of a casting strand is very challenging and almost impossible in practice due to the harsh working conditions in the secondary cooling zone. For this, numerical models can be recommended as "software sensors" for process control purposes. This means that the control synthesis is solved in a parallel control feedback loop, where the distributed parameter mathematical model (DMM) of the temperature field is considered as the controlled plant, thus effectively serving the purpose as a software sensor. The changes of process parameters corresponding to given optimal operational modes are supplied into this control system with software sensor (CSS). The resulting temperature field changes are then eliminated by using appropriate inputs $\breve{U}(k)$, generated by controllers (C) in the control loop. At the same time, these signals – representing cooling flow rates – are synchronously supplied as $\breve{UN}(k) = \bar{UN}(\infty) + \breve{U}(k)$ into the SCZ, eliminating deviations in the temperature field of the strand.

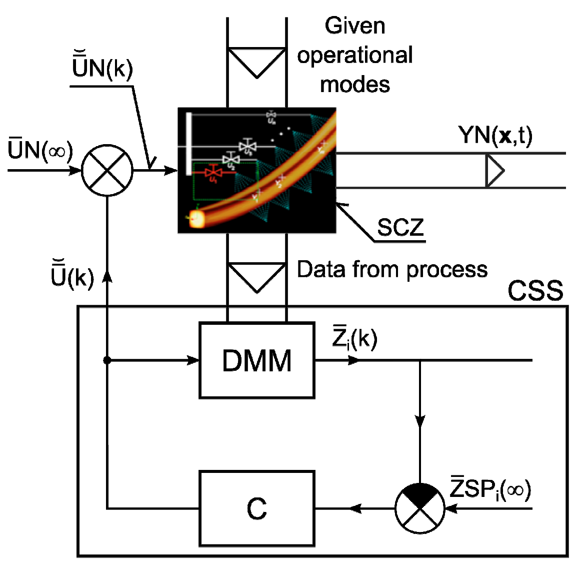

Fig. 2 Control of secondary cooling system – control system with built-in software sensor.

Generally, we can say that the numerical models of strand temperature field are in fact distributed parameter systems. However, current engineering practice considers lumped parameter concepts for control synthesis (Petrus et. al., 2010, Bouhouche et. al., 2008, Klimeš and Štětina, 2014, Mauder et. al., 2015,…). Based on different simplifying assumptions, just a few lumped quantities are assigned to the distributed quantities on the output of the controlled system $\bar{Z}_i(k)$. Often, a temperature field of the casting strand in secondary cooling zone with the corresponding length of 12 – 15 m is represented by a mere 6 – 7 lumped values. However, it is expected that the minimization of control error on the lumped parameter level between $\bar{Z}_i(k)$ and the set--point $\bar{ZSP}_i(k)$ ensures the minimization of the control error on the distributed parameter level as well, guaranteeing a minimal set-point error in the temperature field of the strand.

In this paper, we present a control synthesis for the secondary cooling zone of a continuous casting machine based on distributed parameter systems control (Hulkó et. al., 2003--2014, Lipár, Noga and Hulkó, 2013). We employ the ProCAST modelling suite (ProCAST-ESI Group Paris, 2014) in combination with MATLAB & Simulink (MATLAB & SIMULINK, 2014) and the Distributed Parameter Systems Blockset for Simulink (DPS Blockset) (Hulkó et. al., 2003-2014) to solve a demonstration benchmark example. The numerical simulation of the temperature field in the casting strand ran as a co-simulation, meaning that the computation and data exchange between MATLAB & Simulink and ProCAST has been synchronized.

2. SOFTWARE SENSOR AS A DISTRIBUTED PARAMETER SYSTEM

The temperature field dynamics in a casting strand in secondary cooling zone can be described by nonlinear partial differential equations. In the linearized neighbourhood of the chosen steady state operational mode, let us consider the unit step changes in cooling medium flow rates $\{U_i(t)\}_i$. This way we obtain the discrete distributed parameter transient characteristics $\{\mathcal{H}H_i(\boldsymbol{x},k)\}_i$ sampled with a unit period. Then the impulse characteristics $\{\mathcal{G}H_i(\boldsymbol{x},k) = \mathcal{H}H_i(\boldsymbol{x},k) - \mathcal{H}H_i(\boldsymbol{x},k-1)\}_i$ are obtained simply by subtracting the time-shifted distributed parameter transient characteristics. The discrete convolution model of the output variable $Y(\boldsymbol{x},k)$, representing the linearized part of nonlinear plant dynamics with output $YN(\boldsymbol{x},t)$ and particular outputs $\{Y_i(\boldsymbol{x},k)\}_i$ can be then defined as

$$Y(\boldsymbol{x},k) = \sum_{i=1}^{n} Y_i(\boldsymbol{x},k) = \sum_{i=1}^{n}\sum_{q=0}^{k} \mathcal{G}H_i(\boldsymbol{x},k-q)U_i(q) \tag{1}$$

Similarly, such convolution models can be used for the modelling of other relevant process parameters that affect the temperature field of the casting strand. These models represent the dynamics of a software sensor for control design purposes, being a discrete lumped input and distributed parameter output system with zero order hold units – HLDS.

Let us now choose points $\{\boldsymbol{x}_i\}_i$ on the definition domain of a controlled system, where the distributed parameter transient characteristics in steady state $\{\mathcal{H}H_i(\boldsymbol{x}_i,\infty)\}_i$ reach their maxima. We can compute the so-called reduced characteristics in steady state as follows:

$$\{\mathcal{H}HR_i(\boldsymbol{x},\infty) = \mathcal{H}H_i(\boldsymbol{x},\infty) / \mathcal{H}H_i(\boldsymbol{x}_i,\infty)\}_i \tag{2}$$

for $\{\mathcal{H}H_i(\boldsymbol{x}_i,\infty) \neq 0\}_i$.