Adaptive identification method for simulation and control of glass melting process

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Introduction

Vast majority of industrial applications operate based on PID controllers. This type of controller is widely used due to its simplicity and reliability. Unfortunately industrial practice shows that PID controller parameters are often badly tuned.

There are many methods of tuning PID controllers. Many of them requires the system model identification. This procedure is rarely performed in practice and some plant operators do not have even the simplest model of the process. Moreover, performing active identification experiments is also impossible.

This problem was the main motivation of developing described adaptive on-line identification procedure. Obtained linear model should allow to simulate the current process dynamics, e.g. for PID controllers tuning.
Ideal forehearth control system should fulfill two main tasks:
• Defining optimal set point temperatures in each forehearth zone depending on the current conditions.
• Ensuring optimal transition between two forehearth operating points.
Identification method overview

Identification procedure can be divided into two steps:
- SISO models identification with the use of Modulating Functions Method.
- Strejc model identification based on simulated system step response.
Modulating Functions Method [2], [3]

Linear Time-Invariant MISO system can be described by the differential equation.

\[ \sum_{i=0}^{n} a_i y^{(i)}(t) = \sum_{k=1}^{K} \sum_{j=0}^{m_k} b_{kj} u_k^{(j)}(t) \]

MFM assumes the use of function inner product with the modulating function \( \phi(t) \).

\[ y_i(t) = \int_{0}^{h} y(t - \tau) \cdot \phi^{(i)}(\tau) d\tau \]

\[ u_{kj}(t) = \int_{0}^{h} u_k(t - \tau) \cdot \phi^{(j)}(\tau) d\tau \]

Function \( \phi(t) \) should be of class \( C^{n-1} \) and has compact support. The function and their derivatives should be given given on the interval \([0,h] \).

\[ \phi(0) = \ldots = \phi^{(n-1)}(0) = \phi^{(n)}(0) = 0 \]

\[ \phi(h) = \ldots = \phi^{(n-1)}(h) = \phi^{(n)}(h) = 0 \]
Modulating Functions Method

After the transformation the algebraic equation can be obtained.

\[
\sum_{i=0}^{n} a_i y_i(t) = \sum_{k=1}^{K} \sum_{j=0}^{m_k} b_{kj} u_{kj}(t) + \varepsilon(t)
\]

The term \( \varepsilon(t) \) represents a difference resulting from signal noises and modelling errors.

\[
\varepsilon(t) = c^T \theta = \begin{bmatrix} y_0(t), \ldots, y_n(t), -u_{10}(t), \ldots, -u_{1m_1}(t), \ldots, -u_{K0}(t), \ldots, -u_{Km_K}(t) \end{bmatrix}
\]

Square error value can be treated as a performance index.

\[
\min J^2 = \min \| \varepsilon(t) \|^2_{L^2[t_0+h,T]} = \min \| c^T(t) \theta \|^2_{L^2} = \min \theta^T \langle c(t), c^T(t) \rangle \theta = \theta^T G \theta
\]

The task can be solved with the use of Lagrange multiplier technique assuming constraint vector \( \eta \), such that \( \eta^T \phi = 1 \).

\[
L = \theta^T G \theta + \lambda (\eta^T \theta - 1) \quad \Rightarrow \quad \theta_o = \frac{G^{-1} \eta}{\eta^T G^{-1} \eta}
\]
Modulating Functions Method

Matrix $G$ is composed of system inputs and outputs inner products.

\[
G = \begin{bmatrix}
\langle y_0, y_0 \rangle & \cdots & \langle y_0, y_n \rangle \\
\vdots & \ddots & \vdots \\
\langle y_n, y_0 \rangle & \cdots & \langle y_n, y_n \rangle \\
\end{bmatrix} \\
\begin{bmatrix}
-\langle u_{10}, y_0 \rangle & \cdots & -\langle u_{10}, y_n \rangle \\
\vdots & \ddots & \vdots \\
-\langle u_{1m_1}, y_0 \rangle & \cdots & -\langle u_{1m_1}, y_n \rangle \\
\vdots & \ddots & \vdots \\
-\langle u_{K0}, y_0 \rangle & \cdots & -\langle u_{K0}, y_n \rangle \\
\vdots & \ddots & \vdots \\
-\langle u_{Km_K}, y_0 \rangle & \cdots & -\langle u_{Km_K}, y_n \rangle \\
\end{bmatrix}
\]

\[
= \begin{bmatrix}
\langle u_{10}, u_{10} \rangle & \cdots & \langle u_{10}, u_{1m_1} \rangle & \cdots & \langle u_{10}, u_{K0} \rangle & \cdots & \langle u_{10}, u_{Km_K} \rangle \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\langle u_{1m_1}, u_{10} \rangle & \cdots & \langle u_{1m_1}, u_{1m_1} \rangle & \cdots & \langle u_{1m_1}, u_{K0} \rangle & \cdots & \langle u_{1m_1}, u_{Km_K} \rangle \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\langle u_{K0}, u_{10} \rangle & \cdots & \langle u_{K0}, u_{1m_1} \rangle & \cdots & \langle u_{K0}, u_{K0} \rangle & \cdots & \langle u_{K0}, u_{Km_K} \rangle \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\langle u_{Km_K}, u_{10} \rangle & \cdots & \langle u_{Km_K}, u_{1m_1} \rangle & \cdots & \langle u_{Km_K}, u_{K0} \rangle & \cdots & \langle u_{Km_K}, u_{Km_K} \rangle \\
\end{bmatrix}
\]
Described identification method can be successfully used for linear systems with time-invariant parameters. Analysed process is nonlinear and identified models parameters can vary in a wide range. That is why, adaptive identification procedure was developed based on the MFM. Individual SISO systems parameters can be changed during the identification procedure.
Adaptive identification procedure

1. **Find operating point and perform system linearization**
   - Perform MISO model identification
   - Save current model parameters

2. **Simulate identified system output for last interval using current model**
   - **Difference between simulated model output and system output is less than prescribed threshold value**
     - Do not change current model parameters
     - **Perform SISO models identification**
       - Find the best set of models
       - Update current model parameters
   - **No**
     - Perform SISO models identification
     - Find the best set of models
     - Update current model parameters

For each time interval.
Strejc model identification [1]

Developed in [1] double point identification procedure for the Strejc model is based on the assumption that the normalised step response of the identified system should be equal to the normalised step response of the Strejc model in two points. The first one is the inflection point \( h(t_0) \) at \( t_0 \) and the second point is arbitrary chosen e.g. \( T_{90} \), where \( h(T_{90}) = 0.9 \).

Step response for Strejc model without delay \( G(s) \) is given as \( h(t) \).

\[
G(s) = \frac{k}{(Ts + 1)^n} \quad h(t) = k \left[ 1 - e^{-\frac{t}{\tau}} \sum_{i=0}^{n-1} \left( \frac{t}{T} \right)^i \frac{1}{i!} \right]
\]

The inflection point can be calculated from the below condition.

\[
\ddot{h}(t) = \frac{k \cdot t^{n-2}}{(n-1)! \cdot T^n} \left[ 1 - \frac{t}{(n-1) \cdot T} \right] e^{-\frac{t}{\tau}} = 0
\]

Based on an active experiment with unknown system, from its step response one can find two moments of time \( t_{0n} \) and \( T_{90} \) for known output values \( h(t_{0n}) \) and \( h(T_{90}) \) for different ranks \( n \) of the Strejc model. Based on these times and formulas [1] one can find parameters \( T_n \) and \( \tau_n \) of different Strejc models with suitable time delay (as in Table.)
## Strejć model identification

![Graph showing the Strejć model identification](https://via.placeholder.com/150)

### Parameter Table

| n | $h_{0n}$   | $T_n$              | $\tau_n$               |
|---|------------|--------------------|------------------------|
| 2 | 0.2646211 | $0.34605 \cdot (T_{90} - t_{02})$ | $1.34605 \cdot t_{02} - 0.34605 \cdot T_{90}$ |
| 3 | 0.3233236 | $0.30099 \cdot (T_{90} - t_{03})$ | $1.60199 \cdot t_{03} - 0.60199 \cdot T_{90}$ |
| 4 | 0.3527681 | $0.27168 \cdot (T_{90} - t_{04})$ | $1.81504 \cdot t_{04} - 0.81504 \cdot T_{90}$ |
| 5 | 0.371163  | $0.25040 \cdot (T_{90} - t_{05})$ | $2.00160 \cdot t_{05} - 1.00160 \cdot T_{90}$ |
Identification results

Comparison of measurements with simulation results

Temperature [°C]

Simulation time [s]

- Simulated temperature
- Measured temperature
- Temperature set point
- Simulated temperature-Strejc model
- Interval boundaries
Identification results

Identification results for both models (SISO\(_1\) – mixture pressure, SISO\(_2\) – previous zone temperature) are presented in tables. Both transfer functions have the fourth order.

### SISO\(_1\) parameters

| Intervals | \(a_{10}\)  | \(a_{11}\)  | \(a_{12}\)  | \(a_{13}\)  | \(a_{14}\)  | \(b_{10}\)  |
|-----------|--------------|--------------|--------------|--------------|--------------|--------------|
| 1-11      | 5.8e-4       | 4.6e-3       | 7.7e-2       | 8.6e-2       | 8.3e-1       | 1.8e-4       |
| 12-17     | 6.8e-5       | 4.1e-3       | 7.8e-2       | 8.3e-2       | 8.4e-1       | 1.2e-4       |
| 18        | 1.1e-5       | 1.8e-3       | 8.2e-2       | 6.2e-2       | 8.5e-2       | 3.2e-5       |

### SISO\(_2\) parameters

| Intervals | \(a_{20}\)  | \(a_{21}\)  | \(a_{22}\)  | \(a_{23}\)  | \(a_{24}\)  | \(b_{20}\)  |
|-----------|--------------|--------------|--------------|--------------|--------------|--------------|
| 1-10      | 5.8e-4       | 4.6e-3       | 7.7e-2       | 8.6e-2       | 8.3e-1       | 6.2e-5       |
| 11-18     | 1.9e-5       | 4.9e-3       | 7.7e-2       | 8.1e-2       | 8.4e-1       | 1.9e-5       |

Parameters for the 2\(^{nd}\) order Strejc model are presented below.

| Intervals | 2\(^{nd}\) order Strejc model parameter |
|-----------|----------------------------------------|
|           | \(k\)  | \(T\)  | \(T\)  |
| 1-11      | 3.142  | 41.525 | 10.474 |
| 12-17     | 1.718  | 28.03  | 19.97  |
| 18        | 3.073  | 86.85  | 16.14  |
PI controller tuning

In the Siemens SIPART controllers, PID tuning procedures are based on the rules from [5].

\[
K_p = \frac{1}{4k} \frac{n+2}{n-1}, \quad T_i = \frac{T}{3} (n+2), \quad R(s) = K_p \left(1 + \frac{1}{T_n s}\right)
\]

The same rules were used in this research for the obtained Strejc models.

| Intervals | PID parameters |
|-----------|----------------|
|           | $K_p$ | $T_i$ |
| 1-11      | 0.31826 | 55.36 |
| 12-17     | 0.5821  | 37.373 |
| 18        | 0.3254  | 115.8 |
PI controller tuning

Simulation for tuned PID controller parameters

Temperature [°C]

Simulation time [s]

Simulated temperature
Temperature set point
Conclusions

• Performed experiments proved that both types of models are sufficient to accurately simulate molten glass temperature changes in the single forehearth zone.

• Obtained models can successfully be used for PID controller tuning.

• In the future work, the created identification procedure can be used in more advanced algorithms, such as control with feed forward or predictive control.
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