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APPLICATION OF A BILINEAR PID COMPENSATOR TO AN INDUSTRIAL FURNACE

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Abstract: PID controllers are widely used in many industries and provide acceptable performances with no specific requirement for mathematical knowledge of the plant. However, these controllers, which are tuned for one operating point, are based on the assumption that local linearity holds for the plant to be controlled. When considering operation over a range, the assumption on local linearity may become invalid, and it is at this juncture that the notion of bilinearisation is raised as providing a way forward. Application of a bilinear control strategy to a high-temperature industrial furnace is described and the results in terms of improved performance are presented. *Copyright © 2002 IFAC*

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1. INTRODUCTION

During the last decade, the Control Theory and Applications Centre (CTAC) of Coventry University has been involved, in collaboration with industry, in designing new control strategies to improve the temperature control of high temperature gas-fired industrial furnaces.

As all-practical systems exhibit nonlinear behaviour, the required system performance, when use is made of a standard PID controller (Aström and Hägglund, 1995) with fixed gains, is reduced; especially when the controller operates over a region about the point of tuning. One solution to alleviate this problem is to continually retune the PID parameters over the operating range (i.e. gain scheduling). The other is to detune the PID controller to enable a wider range of operation. In practice, because of constraints on time, availability of personnel and running costs of plant, the latter solution is mostly adopted, despite the fact that the plant operates sub-optimally.

A three-term PID controller, which is routinely used to control the furnace temperature, provides satisfactory performance, when operated about the point of tuning, i.e. where local linearity holds. Via feedback of the system output the standard PID controller has the ability to eliminate steady state offsets through integral action and it can also ‘anticipate’ the future through its derivative action. In continuous form, the PID algorithm may be expressed as:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt} \right) \tag{1}$$

The bilinear controller, which has been developed for use on high temperature furnaces, and described in this paper, is considered to offer a realistic compromise between the standard PID controller and other rather more complex alternatives, which have similarly been proposed by academic research groups over the last decade.

2. THE BILNEAR APPROACH

2.1 Characteristics of a bilinear system.

Within the classes of nonlinear systems, bilinear systems represent a sub-class which are defined to be linear in both state and control, with the nonlinearity (bilinearity) occurring as a product between state and control (Mohler, 1973). The state-space representation of a continuous single-input single-output (SISO) bilinear system is given by:

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{b}u(t) + u(t)\boldsymbol{N}\boldsymbol{x}(t) \\ y(t) = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x}(t) \end{cases} \quad (2)$$

where $\boldsymbol{x} \in \Re^n$ is a vector of state variables and u, $y \in \Re$ are the control input and process output variables, respectively. $\boldsymbol{A}$ is the nxn matrix of real constants, $\boldsymbol{b}$ is the nx1 vector of real constants, $\boldsymbol{N}$ is the nxn matrix of real constants, comprising the bilinear coefficients, and $\boldsymbol{c}$ is the nx1 output vector of real constants (Dunoyer, *et al.*, 1998).

For any bilinear system of the form (2), the steady state output Y_{ss}, corresponding to a steady state input U_{ss} is given by:

$$Y_{ss} = \frac{b_0 U_{ss}}{a_0 - \eta_0 U_{ss}} \quad (3)$$

The steady-state characteristics for the three different cases of the bilinear term are illustrated in Fig. 1 (Dunoyer, 1996). When the bilinear term is null, it corresponds to a linear system. The curve with a positive bilinear term corresponds to an exothermic reaction, typical of that found in a chemical process. A negative term corresponds to many practical engineering systems (including high temperature furnaces), i.e. a decrease in gain as the input increases.

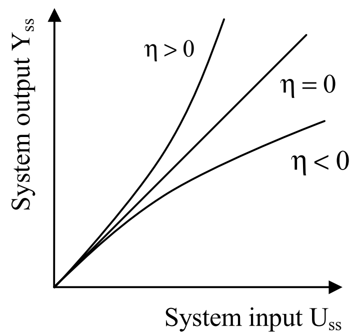


Fig. 1. Steady-state input/output characteristics of a bilinear system.

Should a system exhibit bilinear characteristics of the form given in Eqns. 2 and 3, then it is pertinent to consider adopting a bilinear systems modelling and control approach.

2.2 The bilinear PID controller (BPID).

The BPID, which has been developed in recent years to improve performance in terms of temperature control of gas-fired furnaces, can be presented as a combination of a standard linear PID controller and a bilinear compensator (Fig. 2). The resulting scheme is known as the BPID. The bilinear compensator is of the form $K / (1+ \eta y)$ where K is a constant relating to the nominal operating point, η is a tuneable bilinear term and y is the process output.

As such, the BPID results in a four-term controller, which contains the existing three-term PID controller and an additional bilinear term (Minihan, *et al*, 1999).

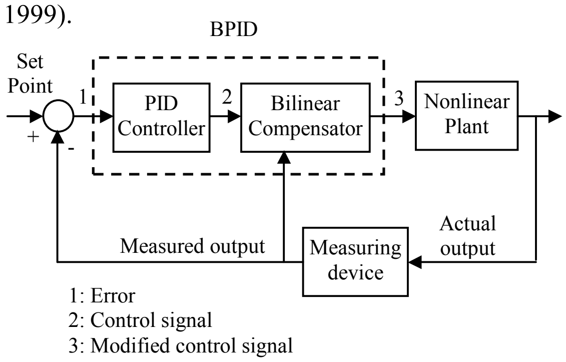


Fig. 2. Illustrating the configuration of the bilinear PID controller (BPID) implemented with the process.

The PID parameters can be tuned by making use of standard commercial packages or experienced plant engineers. The bilinear term may be obtained using methods similar to those developed for autotuning existing 3-term controllers. The method preferred here is one based on a least squares fit to measured plant data. Hence, with a minimum knowledge of the plant, use of the BPID can provide improved overall plant performance (Minihan, 2001). In practice, it is found that even an approximate value of the bilinear term gives rise to improvements.

Whereas linearisation holds at a point, bilinearisation holds over a predefined range; this is considered to be highly beneficial when dealing with practical industrial systems.

3. DESCRIPTION OF THE PROCESS

The process, under consideration, is a continuously operated gas-fired industrial furnace, based at AvestaPolarit Ltd, Sheffield, UK. Trials have been carried out on the individual zones of the furnace, which forms part of an annealing line, used to process stainless steel strip. The annealing line, illustrated in Fig. 3, is composed of three physically separated furnaces, each of which is subdivided into three zones.

The single-side fired furnaces have been designed to allow high rates of gas circulation, and each zone has its own temperature set point and control loop. To reach the required temperature, each of the Zones 1-7 use three pairs of regenerative burners in which each pair switches over a ninety second firing cycle, i.e. one (burner) fires whilst the second (regenerator) exhausts waste combustion gases, and stores the wasted heat in a ceramic chamber.

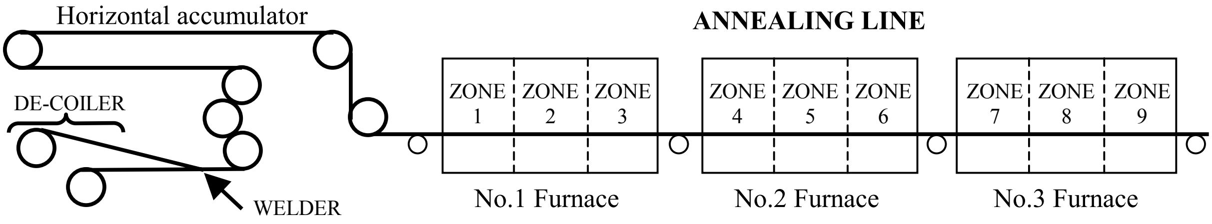


Fig. 3. Schematic of the Avesta Polarit annealing line.

Regenerative burner technology allows a gas saving of 30-50% (Disdell, 1995) by making use of the stored heat to pre-heat the air/gas mixture after the changeover. Although this technique is efficient, it does give rise to an undesirable oscillation in zone temperature. The burners, positioned within No.2 Furnace, as illustrated in Fig. 4, are fired sequentially, i.e. Pair 1, Pair 2, … Pair 9 at a ten-second interval over a 180-second cycle.

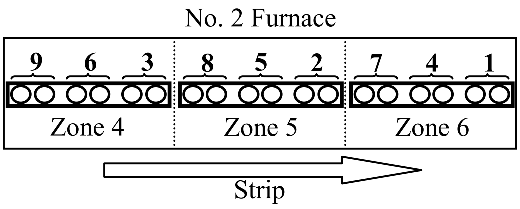


Fig. 4. Schematic of No. 2 Furnace illustrating arrangement of burners.

The temperature inside the furnace is measured by a thermocouple set in the middle of each zone and sampled every 125 milliseconds. This measuring device is influenced by the firing of the central burners (e.g. Pair 6 in Zone 4) so that the measured temperature exhibits an oscillation having a 180-second period. Another oscillatory mode of 30 seconds is present as a consequence of the firing of the adjacent burner pairs (i.e. Pair 3 and Pair 9), as the switch over of the pair of burners appears every 30 seconds in each zone.

Zones 8 and 9 make use of recuperative burners, which are less efficient and require the use of more gas to maintain the set point temperature. Control of the each furnace is carried out by a Eurotherm T640 control system, with each zone having its own control loop. The temperature is effected by regulating the speed of an air fan, and subsequently the gas flow, to obtain the desired air/gas ratio.

4. ON-SITE TRIALS

From January 2001, the bilinear trials have been carried out at AvestaPolarit Ltd, Sheffield, over a period of 6 months. The time for a steel strip to pass through the furnace is around 30 minutes. During this period, the next coil is butt-welded and uncoiled then it moves into the furnace.

The temperature control of each zone depends on the speed of the line, the quality, the thickness and the properties of each steel strip. The potential improvement arising from use of the BPID is assessed by considering trials involving overall performance in terms of set point tracking (Martineau, *et al*, 2001a; Martineau, *et al*, 2001b) and gas usage.

4.1 Control performance.

The bilinear strategy has been downloaded into the existing Eurotherm T640 controllers on Furnaces No.2 and 3. (The strategy will be downloaded to Furnace No.1 at a later date.) To compare the performance of the BPID with that of the PID, it was decided to run the BPID for half of the strip treatment and then switch to PID. This method allows a straightforward comparison between both strategies when operated on identical strips.

Fig. 5 presents the control signal for two different strips (A and B) in Zone 5. From Fig. 5, it can be observed that the mean value of the control signal is reduced whenever the BPID is active. The variance of the signal is also reduced. Similar results have been observed on the other zones in Furnaces No.2 and 3 when the BPID is active. The temperature output of Zone 5 is not presented here because no visible differences with the PID controller have been observed.

Tables 1 and 2 present data corresponding to three different steel strips for both PID and BPID control strategies. When the BPID is used, the average deviation from the set point is reduced, i.e. set point tracking is marginally better with the bilinear strategy. Furthermore, as outlined in Fig. 5, the mean level of the control signal is reduced when use is made of the BPID, indicating a reduction in fuel usage. This improvement is recorded in Table1.

Table 1. Comparison of the average set point, the average deviation from set point and the average control signal for three test steel strips in Zone 5

	BPID			PID		
	Average Set Point (°C)	Average Deviation from Set Point (°C)	Average Control Signal (%)	Average Set Point (°C)	Average Deviation from Set Point (°C)	Average Control Signal (%)
Strip 1	1124.4	1.68	70.27	1124.3	1.8533	70.66
Strip 2	1124.2	1.20	79.09	1124	1.9600	80.47
Strip 3	1120.9	1.38	71.24	1121.1	1.4800	71.40

The standard deviation of the control signal is also reduced when the BPID is active. This is recorded in Table 2. Similar improvements have also been observed in Zones 4 and 6.

Table 2. Comparison of the standard deviation of the control signal in Zone 5

	BPID	PID	% Reduction
	Standard Deviation	Standard Deviation	
Strip 1	1.3405	1.3681	2.8
Strip 2	1.2076	1.3519	10.17
Strip 3	1.1960	1.2227	2.2

The analyses of the results provide evidence of the benefits of combining a bilinear compensator with a standard PID controller. To quantify the benefit of the reduced mean value of the control signal, further trials were carried out to confirm the reduction in the consumption of gas under BPID control. (Note that new trials were required because originally gas consumption readings were not taken.)

4.2 Gas consumption.

To provide quantifiable evidence regarding the performance of the BPID, a study on the usage of gas was carried out during June and July 2001. A selection of trials focusing on gas consumption is presented and evaluated here. Note that the temperature control in each zone of the annealing line is influenced by a number of factors, e.g. the required set point temperature, the thickness, quality and required properties of each steel strip. All of these factors need to be taken into account to analyse the gas consumption readings.

To compare the use of gas under the PID and BPID control strategies, the furnace was operated with the standard PID controller during a certain period of time (usually 2-3 hours) and then switched to the bilinear scheme. The gas readings were recorded every 15 minutes. This allows a direct comparison between both control strategies.

Table 3 presents the volume of steel processed per minute and the gas consumed per unit volume of steel. N* and B* correspond to the time period (15 minutes) under normal PID and bilinear PID, respectively. By comparing the gas consumed per cubic meter of steel for the three furnaces, a reduction in the gas usage can be observed for the same volume of steel processed per minute when use is made of the BPID. However, as the control performance depends on a number of different factors, a closer examination was carried out for the periods N6 and B1, and N3 and B3, where the volume of steel processed is similar, see Table 3. (A similar examination could have been carried out on N1 and B7.)

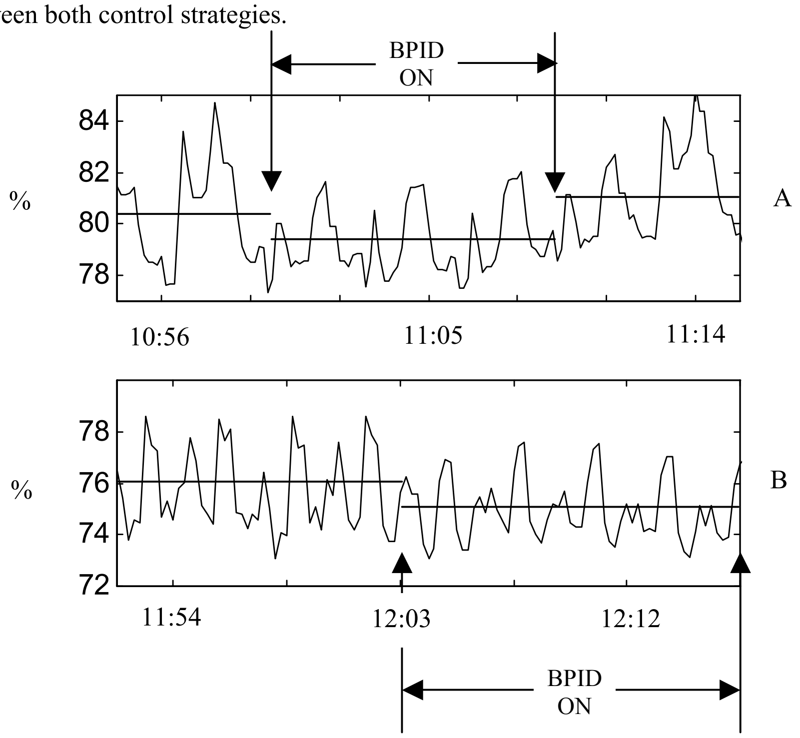
To analyse the results, the average temperature set points of the zones within Furnaces No.2 and 3 are displayed in Table 4. The width and the gauge of the steel strip and the line speeds are presented in Table 5.

Table 4 Average set point temperature

	Furnace No.2			Furnace No.3		
Period	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
N6	1053	1105	1137	1114	1109	1097
B1	1074	1110	1140	1131	1108	1102
N3	1055	1103	1129	1112	1104	1104
B3	1049	1103	1139	1111	1095	1090

Table 5 Characteristics of the steel strip processed

Period	Strip width (m)	Strip gauge (m)	Line speed (m/min)
N6	1.554	0.00391	24.5
B1	1.295	0.00511	22.3
N3	1.549	0.00592	15.0
B3	1.554	0.00325	27.0



The traces in Fig. 5 present the control signal for Zone 5 for two different steel strips. The BPID is only active during half of the treatment.
The control signal relates to the gas flow, which is required to maintain set point temperature.
When the BPID is active, the reduction in the mean value of the control signal can be observed

Fig. 5. Control signal in % indicating periods of BPID operation.

Table 3. Volume of steel processed per minute and gas consumed per cubic meter of steel for the different furnaces and periods

Period	Volume of steel processed per minute (m^3 steel/min)	Gas consumed per cubic meter of steel for Furnace No.1 (m^3 gas/m^3 steel)	Gas consumed per cubic meter of steel for Furnace No.2 (m^3 gas/m^3 steel)	Gas consumed per cubic meter of steel for Furnace No.3 (m^3 gas/m^3 steel)
N1	0.1203	135.25	104.65	66.75
N2	0.0958	158.66	123.49	77.24
N3	0.1381	114.41	80.24	51.40
N4	0.1494	105.31	78.09	46.20
N5	0.1908	78.97	59.17	34.00
N6	0.1490	98.88	78.17	43.70
N7	0.1378	84.18	67.95	36.30
B1	0.1477	62.29	52.81	28.23
B2	0.1192	104.61	74.92	38.00
B3	0.1367	79.01	62.56	45.30
B4	0.1328	113.45	80.60	46.20
B5	0.1198	121.31	86.51	42.10
B6	0.1248	116.45	83.20	39.00
B7	0.1204	117.94	84.98	38.70

By comparing periods N6 and B1, it can be observed from Table 3 that the furnaces use less gas when the BPID is active. The volume processed is quite similar; 0.1490 m^3/min for the PID controller and 0.1477 m^3/min for the BPID controller. The characteristics of the steel strip and the required set point temperatures are very close. This similarity allows a fair comparison to be made between these two periods.

Periods N3 and B3 are under consideration because whilst the volume of steel processed per unit time is comparable, the line speed is significantly different. For the case considered, the annealing line runs approximately two times faster under the BPID control strategy in order to ensure consistency in terms of mass flow rate of steel product and to account for any difference in steel. Again it is clear from Table 3 that less gas is used in period B3 that in N3, indicating the benefit of the bilinear controller (e.g., 45.3 m^3 gas/m^3 steel and 51.4 m^3 gas/ m^3 steel for BPID and PID controller, respectively).

Having examined two isolated cases (N6, B1) and (N3, B3) attention is now focused towards the long-term performance. It is useful to consider the volume of steel processed under the two different control strategies. This together with the total gas usage over the two periods N and B are given in Table 6.

The total volume of steel processed per minute and the gas consumed per cubic meter of steel for the 3 furnaces correspond to the sum of the values for each controller over the 7 periods given in Table 3. Because each period is 15 minutes, the total volume of steel processed in each case (i.e. N1 to N7 and B1 to B7) is 14.72 m^3/7 periods and 13.52 m^3/7 periods for the PID and BPID control strategies, respectively, see Table 6. This gives an average per period volume of steel of 2.1 m^3 and 1.93 m^3 for the two schemes. The average gas consumed for the PID on all furnaces is 82.05 m^3 gas/m^3 steel and for the BPID 72.29 m^3 gas/m^3 steel.

- With the standard PID controller, 2.1 m^3 of steel is processed per period with a consumption of 172.55 m^3 gas (82.05 m^3 gas/m^3 steel * 2.1 m^3 steel/period).
- With the BPID controller, 1.93 m^3 of steel is processed per period with a consumption of 139.67m^3 gas (72.29 m^3 gas/m^3 steel * 1.93 m^3 steel/period).

Due to the fact that the PID processes more steel in this case, it is necessary to normalise the results, such that 1.93m^3 of steel under PID control would use 158.58 m^3 gas; this corresponds to the same volume of steel processed for both strategies. This comparison indicates a significant reduction in gas consumption for this set of trials. On average, use of BPID has been found to give rise to a reduction of approximately 3% fuel savings over a number of similar trials.

Table 6. Total and average volume of steel processed per minute and gas consumed per cubic meter of steel for the different furnaces over the PID and BPID control periods.

Period		Volume of steel processed	Gas consumed for Furnace No.1	Gas consumed for Furnace No.2	Gas consumed for Furnace No.3
PID control period	Total	14.72 m^3 /7 periods	775.66 m^3 /7 periods	591.76 m^3 /7 periods	355.59 m^3 /7 periods
	Average	2.1 m^3 /period	110.81 m^3 /period	84.54 m^3 /period	50.80 m^3 /period
BPID control period	Total	13.52 m^3 /7 periods	715.06 m^3 /7 periods	525.58 m^3 /7 periods	277.53 m^3 /7 periods
	Average	1.93 m^3 /period	102.15 m^3 /period	75.83 m^3 /period	39.65 m^3 /period

5. CONCLUSION

This paper has presented the benefits of combining a bilinear compensator and a PID control strategy. The resulting bilinear controller has been applied to a continuously operated multi-zone furnace at AvestaPolarit Ltd, Sheffield, UK. Two different studies have been carried out to evaluate the performance of the bilinear PID controller. From the first study, significant improvements in the control of zone temperatures have been observed leading to a reduction in the mean value of the control signal as well as a smoother control action having a lower variance.

Furthermore trials have confirmed fiscal improvements in terms of reduced gas usage. The results present a reduction in the use of gas when applying the BPID controller compared to the standard PID controller for similar steel characteristics.

This successful application demonstrates the potential benefit of the BPID by reducing the gas consumption, hence costs. The BPID may be regarded as a natural extension to the standard PID controller. The BPID, which can be easily implemented and tuned, provides adaptivity, through an assumed nonlinear controller model structure, with robustness being provided by the existing three-term PID controller. In practice, the compensator may be cascaded with an existing PID as a retrofit device, or integrated within a standard PID to form a BPID scheme.

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