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SELF-TUNING FUZZY CONTROL OF A ROTARY DRYER

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Abstract: Drying, especially rotary drying is without doubt one of the oldest and most common unit operations in industries. It is a very complex non-linear process including the movement of solids in addition to thermal drying. This means that both the modelling and control of a rotary dryer is difficult with conventional methods. The aim of this research was to improve dryer control by developing control systems based on self-tuning PID-type fuzzy logic controllers. The behaviour of the control systems has been tested with simulations based on the model of a pilot plant dryer located in the Control Engineering Laboratory at the University of Oulu. The control results have been compared achieved with a conventional PID controller. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Fuzzy logic is particularly suitable for process control if no model exists for the process or it is too complicated to handle or highly non-linear and sensitive in the operation region. As conventional control methods are in most cases inadequate for complex industrial processes such as rotary dryers, fuzzy logic control (FLC) is one of the promising control approaches for the dryer. It utilises experience, knowledge and historical data, which are readily available due to that rotary drying is one of the oldest and common processes in industries.

Because rotary drying is highly non-linear with long delay time, its control is difficult with conventional methods. As conventional control schemes are linear, a controller can only be tuned to give good performance at a particular operating point or for a limited period of time. FLCs are non-linear and so they can be designed to cope with a certain amount of non-linear process. However, such design is hard, especially if the controller must cope with non-linearity over a significant operating range of the process. Therefore there is a need for self-tuning control.

In the Control Engineering Laboratory at the University of Oulu the research concerning the modelling and control of a rotary dryer has been carried out during many years as Yliniemi (1999) has reported, the latest research focusing on the self-tuning fuzzy control. In this paper two different control systems based on self-tuning PID-type fuzzy controllers have been developed for a rotary dryer, the behaviour of which has been examined with simulations and compared with results achieved by a conventional PID controller.

1.1 Description of a rotary dryer

Large quantities of granular material with particles of 10 mm or larger that are not too fragile or heat sensitive or cause any other solids handling problems are dried in rotary dryers in the process industries. The rotary dryer is one of the most common types of industrial dryer. It is a cylindrical shell usually constructed from steel plates, slightly inclined, typically 0.3-5 m in diameter, 5-90 m in length and rotating at 1-5. It is usually operated with a negative internal pressure to prevent dust escape. Solids introduced at the upper end move towards the lower or discharge end. Depending on the arrangement for the contact between the drying air and the solids, a dryer may be classified as direct or indirect, concurrent or counter-current.

For the experimental work in this research a direct air-heated, pilot plant rotary dryer was used. The screw conveyor feeds the solid, calcite (more than 98 % $CaCO_3$), from the silo into a drum of length 3 m and diameter 0.5 m. The drum is slightly inclined horizontally and insulated to eliminate heat losses, and contains 20 spiral flights for solids transport. Two belt conveyors transfer the dried solid back into the silo for wetting. Propane gas is used as the fuel. The fan takes the flue gases to the cyclone, where dust is recovered. The dryer can operate in a concurrent or counter-current manner. The experiments were carried out in a concurrent manner, because this is usually more economical and therefore very often used for drying granular material in industry unless the solids are heat sensitive.

The dryer is connected to an instrumentation system for control experiments. In addition to measurements of temperature and flow of the solids and drying air, the input and output moisture of the solids is measured continuously by the IR-analysers. The flow of fuel and secondary air are controlled for keeping the input temperature of drying air in the desired value. The velocity of the solids is controlled by the rotational speed of the screw conveyor. It is also possible to control the delay time of the dryer by the rotational speed of the drum.

1.2 Why to apply intelligent control to a rotary dryer

The operation of rotary drying is easy and reliable, but neither energy-efficient nor environmentally friendly. Most rotary dryers, especially older ones, are still controlled partly manually, relying on the ”eye” and experience of the operator.

Deeper understanding of rotary drying is poor, because it is a very complex process that includes the movement of solids in addition to the thermal drying. As the process is highly non-linear and is dependent on time and position, mathematical modelling is very difficult and time-consuming. In general, models are rough approximations of real processes, and therefore often of questionable use. This means that the development of model-based control systems, although these are preferable to conventional ones because of the slow dynamic nature of rotary dryers, has not become very common.

Intelligent methods such as fuzzy logic combined with conventional control methods, are attractive approaches for the control of rotary dryers, because they make it possible to utilise experience, knowledge and historical data, of which a great deal is available. The aim to develop intelligent control systems for rotary dryers is to change existing rotary dryers for “smart” dryers and in this way to make dryer operation energy saving and pro-environmental.

2. DESIGN PROCEDURE OF A SELF-TUNING PID-TYPE FUZZY LOGIC CONTROLLER FOR A ROTARY DRYER

2.1 Design method by Mudi and Pal (1999,2000)

Cammarata and Yliniemi (1999) have made the literature review on methods to develop self-tuning fuzzy logic controllers for different processes. In this paper two control systems based on self-tuning PID-type fuzzy logic controllers (STFPIDC) are developed and tested. The development is based on the method by Mudi and Pal (1999,2000).

The method by Mudi and Pal has been designed for a self-tuning PI-type fuzzy controller (STFPIC). The motivation for their research came from the observation that a skilled human operator always tries to manipulate the process input i.e. controller output usually by adjusting the controller gain based on the current process states for getting the process optimally controlled. The exact manipulation strategy of a human operator is quite complex in nature and probably no mathematical model can replace it accurately. The above method is concentrated on the tuning of the output scaling factor (SF) of the controller due to its strong influence on the performance and stability of the system. The proposed controller is tuned dynamically by adjusting its output SF in each sampling instance by an updating factor α. The value of α is determined by fuzzy rules defined on e and Δe. The block diagram is shown in Figure 1.

The output scaling factor G_u of the controller is modified by a self-tuning mechanism, which is shown by the dotted line in Figure 1. The membership functions MFs for the controller inputs e and Δe and for incremental change in controller output Δu are defined in the common domain [-1,1], whereas the MFs for α are defined in the domain [0,1]. Symmetric triangles with an equal base and 50% overlap with neighbouring MFs are used.

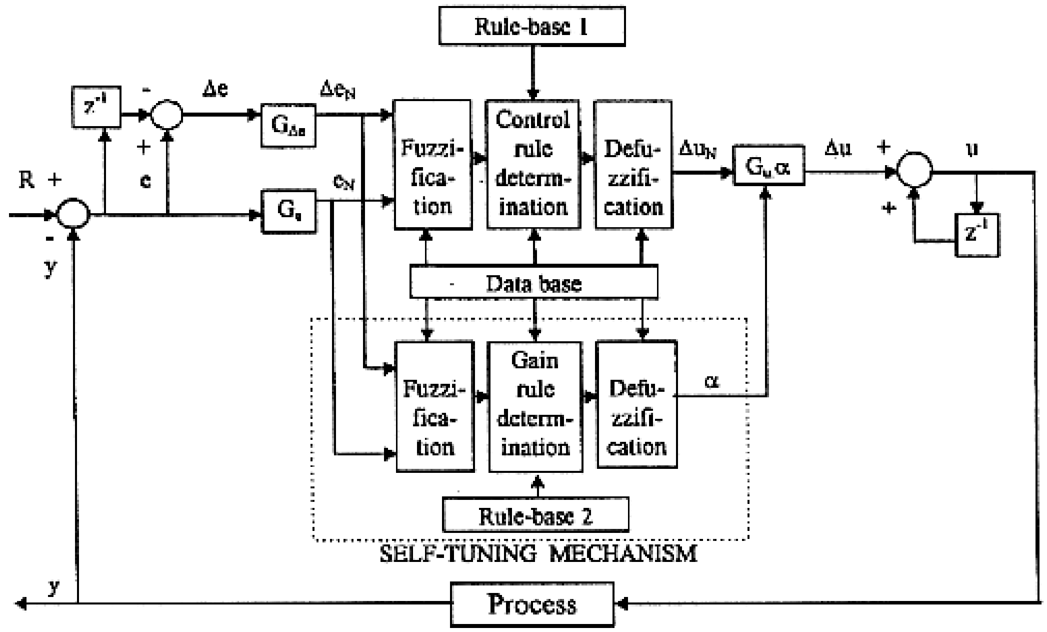

Fig. 1. STFPIC proposed by Mudi and Pal (1999).

The MFs for both normalised inputs e_N and Δe_N and output Δu_N of the controller are defined on the common domain [-1,1]. The relationships between the SFs and the input and output variables of the STFPIC are according to Figure 1:

$$e_N = G_e * e \quad (1)$$

$$\Delta e_N = G_{\Delta e} * \Delta e \quad (2)$$

$$\Delta u = \alpha * G_u * \Delta u_N \quad (3)$$

The output of the controller is obtained by

$$u(k) = u(k-1) + \Delta u(k) \quad (4)$$

In this equation k is a sampling instance and Δu is an incremental change in the controller output, which is determined by the rules being of the form:

R_{PI}: If e is E and Δe is ΔE then Δu is ΔU.

The determination of the rules for Δu in a two dimensional phase plane is based on the fact that the fuzzy logic controller drives the system into the so-called sliding mode.

The gain-updating factor α is calculated from fuzzy rules, which are of the form:

R_α: If e is E and Δe is ΔE then α is $\boldsymbol{\alpha}$.

The rule-base for α depends on the system output wanted to achieve. It is also dependent on the controller rule-base, but it is important to note that α is model independent.

The tuning procedure of the controller follows the next three steps:

Step 1: Tune the SFs of a STFPIC assuming α=1 i. e. conventional FPIC for a given process for achieving a reasonable good control performance. For doing this first, G_e is selected so that the normalised error e_N almost covers the entire domain [-1,1] for the efficient use of the rule-bases. After that the scaling factors $G_{\Delta e}$ and G_u are tuned for achieving the transient response of the system reasonable. The tuning is based on process knowledge or on the trial and error method. At the end of this step a good controller without self-tuning is resulted. This controller is the base for designing a STFPIC in Step 2.

Step 2: Set the output scaling factor (G_u) of the STFPIC nearly three times greater that that of the FPIC. This has been determined experimentally. The values of G_e and $G_{\Delta e}$ are kept same as of the FPIC obtained in Step 1. Make a small adjustment for G_u of the STFPIC. Realise almost the same rise time as in the FPIC obtained in Step 1.

Step 3. Fine tune the rules for α depending on the type of the response wanted to achieve. Several performance measures such as peak overshoot settling time, rise time, integral absolute error (IAE) and integral-of-time-multiplied absolute error (ITAE) can be used for comparing the performance of the STFPIC with the FPIC.

2.2 Design of the STFPIDC for the pilot plant dryer

The method by Mudi and Pal has been applied for the pilot plant rotary dryer, which includes the following input and output variables:

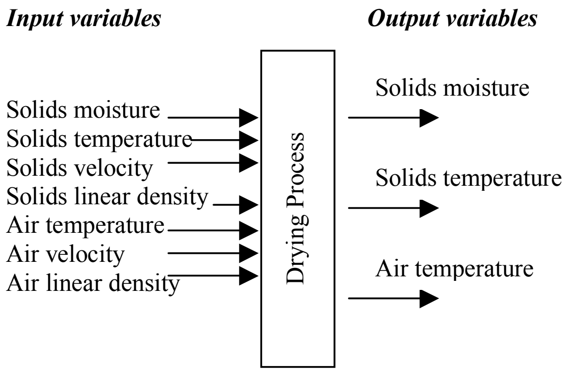

Fig. 2. Different input and output variables of the pilot plant dryer.

The centre of area method (COA) is used to transform the output of the fired rules into the crisp value. The relationships between the SFs and the input and output variables of the controller are according to the method by Mudi and Pal:

$$e_{N}=G_{e}*e \quad (5)$$

$$\Delta e_{N}=G_{\Delta e}*\Delta e \quad (6)$$

$$\Delta u=\alpha*G_{1\Delta u}*\Delta u_{N} \quad (7)$$

The equation (4) was modified to obtain a PID-type fuzzy controller

$$u=G_{2\Delta u}*\Delta u+\int \Delta u \ dt \quad (8)$$

The following tuning procedure for the self-tuning PID-type fuzzy controller is used:

Step1: Tune the SFs assuming α=1 and $G_{2\Delta u}$=0 (i.e. PI-type fuzzy controller). First, G_e should be selected as Mudi and Pal have presented in their method. Then $G_{\Delta e}$ and $G_{1\Delta u}$ are tuned to achieve a good response for the system.

Step2: Keep the values for G_e and $G_{\Delta e}$ from the previous step and tune $G_{1\Delta u}$ and $G_{2\Delta u}$ with trial and error minimising IAE and ITAE.

Step3: Keep the values for $G_{1\Delta u}$ and $G_{2\Delta u}$ and tune $G_{\Delta e}$ to minimise IAE and ITAE.

Preliminary simulations showed that the above STFPIDC gave the control performance where the values for the manipulated variable i.e. for the input temperature of drying air were too high or too low. Not either to set the limit values for the manipulated variable gave satisfactory results. Therefore the auxiliary controller was designed for resulting the velocity of the solids as the manipulated variable. The inputs of the auxiliary controller are the error and the change of error in the output moisture of solids and the output of the controller is the velocity of the solids. The structure of this auxiliary controller is a self-tuning PID fuzzy Sugeno type controller where the MFs are symmetric triangles with an equal base and 50 % overlap with neighbouring MFs. The rules for the controller output are of the form:

R_{PID}: If e is E and Δe is ΔE then Δu is ΔU

and for the gain-updating factor α

R_{α}: If e is E and Δe is ΔE then α is A,

where ΔU and A are singletons.

The relationships for the SFs and the input and output variables are the same as presented in the equations 5…8.

The above described two controller's system caused, however, interaction problems. For eliminating these problems the supervisory FLC for determining the velocity of solids was designed, where the input is the first peak value of the error in the output variable i.e. in the output moisture of solids. The controller outputs are $G_{1\Delta u}$ and $G_{2\Delta u}$. The rules arise from the simulations, where the value of the first peak is associated with the gain values $G_{1\Delta u}$ and $G_{2\Delta u}$ by minimising IAE and ITAE. The structure of the supervisory controller is presented in Figure 3 and the MFs and the rules in Tables 1 and 2.

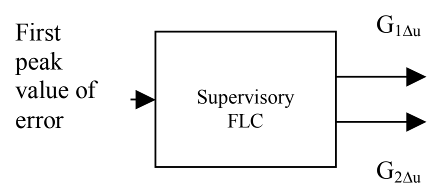

Fig. 3. Structure of the supervisory FLC for determining the velocity of solids.

Table 1 MFs of the supervisory FLC. N= negative and P=positive.

MF	Range
N7	(-0.8,-0.6,-0.576,-0.462)
N6	(-0.576,-0.462,-0.351)
N5	(-0.462,-0.351,-0.241)
N4	(-0.351,-0.241,-0.132)

N3	(-0.241,-0.132,-0.0994)
N2	(-0.132,-0.0994,-0.0665)
ZE	(-0.0665,-0.0334,0.334,0.0665)
P1	(0.00994,0.0665,0.0334)
P2	(0.0665,0.0994, 0.132)
P3	(0.0994,0.132,0.241)
P4	(0.132,0.241, 0.351)
P5	(0.241,0.351, 0.462)
P6	(0.351,0.462,0.576)
P7	(0.462,0.576, 0.6,0.8)

Table 2 Rules for the supervisory FLC.

If peak is N7 then $G_{1\Delta u}$ is 30 and $G_{2\Delta u}$ is 290
If peak is N6 then $G_{1\Delta u}$ is 24 and $G_{2\Delta u}$ is 310
If peak is N5 then $G_{1\Delta u}$ is 28 and $G_{2\Delta u}$ is 280
If peak is N4 then $G_{1\Delta u}$ is 26 and $G_{2\Delta u}$ is 170
If peak is N3 then $G_{1\Delta u}$ is 22 and $G_{2\Delta u}$ is 200
If peak is N2 then $G_{1\Delta u}$ is 23 and $G_{2\Delta u}$ is 350
If peak is N1 then $G_{1\Delta u}$ is 25 and $G_{2\Delta u}$ is 350
If peak is ZE then $G_{1\Delta u}$ is 6 and $G_{2\Delta u}$ is 350
If peak is P1 then $G_{1\Delta u}$ is 21 and $G_{2\Delta u}$ is 360
If peak is P2 then $G_{1\Delta u}$ is 26 and $G_{2\Delta u}$ is 320
If peak is P3 then $G_{1\Delta u}$ is 24 and $G_{2\Delta u}$ is 210
If peak is P4 then $G_{1\Delta u}$ is 30 and $G_{2\Delta u}$ is 270
If peak is P5 then $G_{1\Delta u}$ is 26 and $G_{2\Delta u}$ is 300
If peak is P6 then $G_{1\Delta u}$ is 24 and $G_{2\Delta u}$ is 290
If peak is P7 then $G_{1\Delta u}$ is 29 and $G_{2\Delta u}$ is 300

In this research it was also designed the control system where the above described supervisory FLC was replaced with a feedforward supervisory FLC for determining the velocity of solids. The input of this controller is the input moisture of solids and the outputs are the scaling factors $G_{1\Delta u}$ and $G_{2\Delta u}$. The controller is a FLC Sugeno type, the MFs and the rules are presented in Tables 3 and 4.

Table 3 MFs of the feedforward supervisory FLC.
N= negative and P=positive

MF	Range
N7	(-1.5,-1.1,-1.04,-0.84)
N6	(-1.04,-0.84,-0.64)
N5	(-0.84,-0.64,-0.44)
N4	(-0.64,-0.44,-0.24)
N3	(-0.44,-0.24,-0.18)
N2	(-0.24,-0.18,-0.12)
N1	(-0.18,-0.12,-0.06)
ZE	(-0.12,-0.06,0.06,0.12)
P1	(0.06,0.12,0.18)
P2	(0.12,0.18,0.24)
P3	(0.18,0.24,0.44)
P4	(0.24,0.44,0.64)
P5	(0.44,0.64,0.84)
P6	(0.64,0.84,1.04)
P7	(0.84,1.04,1.1,1.5)

Table 4 Rules for the feedforward supervisory FLC.

If $X_{s\,in}$ is N7 then $G_{1\Delta u}$ is 27 and $G_{2\Delta u}$ is 330
If $X_{s\,in}$ is N6 then $G_{1\Delta u}$ is 25 and $G_{2\Delta u}$ is 320
If $X_{s\,in}$ is N5 then $G_{1\Delta u}$ is 27 and $G_{2\Delta u}$ is 290
If $X_{s\,in}$ is N4 then $G_{1\Delta u}$ is 28 and $G_{2\Delta u}$ is 280
If $X_{s\,in}$ is N3 then $G_{1\Delta u}$ is 20 and $G_{2\Delta u}$ is 290
If $X_{s\,in}$ is N2 then $G_{1\Delta u}$ is 17 and $G_{2\Delta u}$ is 290
If $X_{s\,in}$ is N1 then $G_{1\Delta u}$ is 14 and $G_{2\Delta u}$ is 360
If $X_{s\,in}$ is ZE then $G_{1\Delta u}$ is 5 and $G_{2\Delta u}$ is 350
If $X_{s\,in}$ is P1 then $G_{1\Delta u}$ is 13 and $G_{2\Delta u}$ is 400
If $X_{s\,in}$ is P2 then $G_{1\Delta u}$ is 13 and $G_{2\Delta u}$ is 300
If $X_{s\,in}$ is P3 then $G_{1\Delta u}$ is 16 and $G_{2\Delta u}$ is 280
If $X_{s\,in}$ is P4 then $G_{1\Delta u}$ is 27 and $G_{2\Delta u}$ is 290
If $X_{s\,in}$ is P5 then $G_{1\Delta u}$ is 27 and $G_{2\Delta u}$ is 280
If $X_{s\,in}$ is P6 then $G_{1\Delta u}$ is 25 and $G_{2\Delta u}$ is 310
If $X_{s\,in}$ is P7 then $G_{1\Delta u}$ is 28 and $G_{2\Delta u}$ is 330

3. SIMULATION RESULTS

The mathematical model of the pilot plant dryer with the self-tuning PID- type fuzzy controllers has been implemented using Matlab's Simulink and Fuzzy Logic Toolbox. The simulations are carried out for step changes in the input moisture solids which is the main disturbance variable of the drying process.

The behaviour of the control systems presented in this paper was tested with simulations when a quite big step change i.e from 2.4 % to 3.4 % occurs in the input moisture of solids. The first control system (Control System 1) consists of two self-tuning PID type fuzzy controllers, one for determining the input temperature of drying air and the other for determining the velocity of solids. The latter includes the supervisory part where the input is the first peak value of the output variable and the outputs are the scaling factors $G_{1\Delta u}$ and $G_{2\Delta u}$.

The other control system (Control System 2) includes the same STFPID-controller as in the previous one for determining the input temperature of drying air, but for determining the velocity of the solids it includes the feedforward supervisory part where the input is the input moisture of solids and the outputs are the scaling factors $G_{1\Delta u}$ and $G_{2\Delta u}$.

The simulation results are compared with the results achieved by the conventional PID controller. The IAE and ITAE performance indices for comparing the results are presented in Table 5.

Table 5 Performance analysis for different control systems designed for the pilot plant dryer.

	IAE	ITAE
PID	8.61	17800
Control System 1	7.06	14500
Control System 2	6.85	13970

As the values in Table 5 show the Control System 2 gives the best control behaviour. The difference between Control System 1 and Control System 2 is not very big. However, the indices show that these control systems give clearly better control results than the conventional PID controller.

Figure 4 describes the behaviour of the conventional PID control and the STFPID control where the manipulated variables are the input temperature of drying air and the solids velocity as Figure 5 shows. The STFPID is based on the Control System 1.

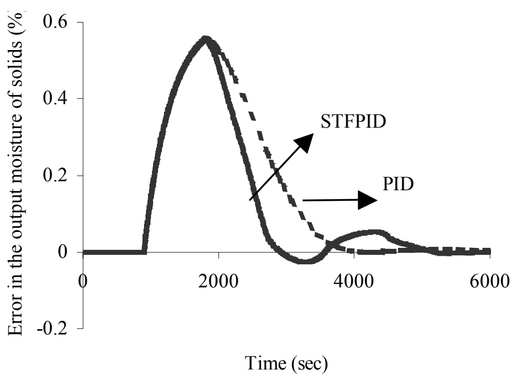

Fig. 4. Behaviour of the PID and STFPID in the control of the output moisture of solids.

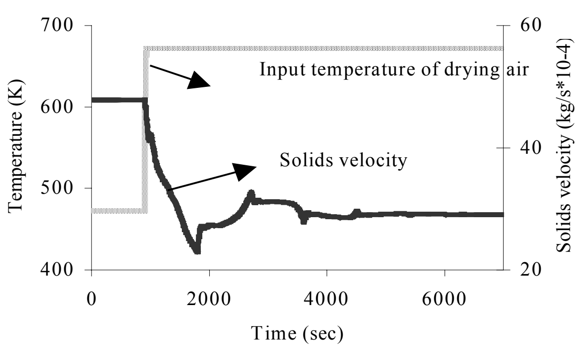

Fig. 5. Behaviour of the manipulated variables in the PID and STFPID control.

4. CONCLUSION

In this paper two different control systems based on self-tuning PID-type fuzzy logic controllers have been constructed for a rotary dryer. The first control system consists of two self-tuning PID type fuzzy controllers, one for determining the input temperature of drying air and the other one for determining the velocity of the solids: The latter STFPID controller includes the supervisory part where the first peak value of the error in the output moisture of solids is used as the input variable and as the output variables are the output scaling factors. The other control system includes the same controller as in the previous one for determining the input temperature of drying air, but for determining the velocity of solids the input moisture of solids is used as the input for the feedforward supervisory part and as the output variables are the output scaling factors.

The comparison between these different control systems was made with simulations when a step change in the input moisture of solids occurs. The simulation parameters are based on the pilot plant dryer located in the Control Engineering Laboratory at the University of Oulu. The control results have been compared with the results achieved by the traditional PID-controller. The performance indices IAE and ITAE show that both control systems including self-tuning PID-type fuzzy logic controllers give better results than the conventional PID controller.

The control systems developed in this paper will be implemented also to the pilot plant dryer for experimental research.

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