Successful Industrial Application of Advanced Control Theory to a Chemical Process

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Abstract

This paper reports the experiences and results of a project aimed at designing an automatic control scheme for titanium dioxide rotary kilns. The process was studied by way of computer simulations, both steady-state and dynamic, from which a low order model was derived by matching the input-output frequency responses. Use of LQG theory then led to the conclusion that the kiln can be considered as a single-input, single-output process. Plant trials and simulation studies finally led to the adoption of a control scheme incorporating a self-tuning regulator in a feedback loop around a kiln controlled by a discrete regulator designed on minimum-variance principles. This scheme has been in use for three years and resulted in great improvement in control performance. Long term industrial results are presented. Practical considerations concerning implementation and acceptance by plant personnel are given.

I. Introduction

This paper summarizes the experiences and results of a six-year project whose purpose was to provide an automatic control scheme for a TiO₂ rotary kiln. This project, a good example of cooperation between a university (McGill) and an industrial firm (Tioxide SA France), was initiated in 1974 when G. A. Dumont came to McGill to work towards his PhD. under the supervision of Prof. P. R. Belanger. The history of this project can be divided into four main periods: (1) Steady-state and Dynamic Simulation Studies; (2) Control System Design and Simulation Trials; (3) Plant Trials, inclusion of the self-tuning regulator; and (4) Further tuning, commissioning, plant personnel training towards full on-line control. Full time presence of one of the authors in the plant.

The purpose of this paper is not to give technical details that have been presented in previous publications [1–3], but rather to depict the general methodology and insist on the points that are believed essential for the success of such a work. Human factors are considered to be crucial. The paper is organized as follows: in Section II the process is described; simulation results and control system design are presented in Section III; Section IV describes the results of plant trials; finally, Section V presents the long-term industrial experience.

II. Description of the Process

Titanium dioxide (TiO₂) is a substance used as a pigment or whitener in paints, textiles, plastics and other products. The raw material is mostly available in a crystalline form known as Anatase, while the other crystalline form Rutile has the most valuable pigmentary properties. Most TiO₂ pigment is produced by the sulphate process in which a critical step is the calcination in a rotary kiln of a hydrous precipitate of titanium oxide, during which transformation of anatase to rutile occurs, accompanied by a crystal growth.

The kiln, fed with a slurry, can be divided in three parts: (a) the drying zone where the water is evaporated, (b) the heating zone where the solid temperature increases rapidly until it reaches the point where rutilization is initiated, and (c) the rutilization zone where the crucial endothermic crystalline reaction occurs.

The kiln is heated from a chamber located at the end of the kiln, by combustion of a fuel and a strong forced gas flow, moving counter-current to the material (Figure 1). Because of constraints on pigmentary properties, lower and higher acceptable limits on rutile percentage are fixed. The control objective is to keep the rutile percentage within these specifications.
Two different types of perturbations affect the process: (1) slow variations of small amplitude, mainly due to feed rate and feed moisture variations, and (2) sudden disturbances causing large changes in rutile percentage. Those disturbances are difficult to explain and are a major cause of product degrading.

The measurements available are: the combustion chamber gas temperature, the temperature of the hot material and the cold gas temperature. The rutile percentage at the cooler discharge is measured by x-ray diffraction. This cannot be performed on-line. The manipulated variables are: the fuel rate, the primary air flow rate, the secondary air flow rate. When controlled manually, from hot material temperature, the percentage of production within specifications obtained is rather poor.

III. Simulation Studies and Control Design

The purpose of the simulation studies was two-fold; first it was to provide a better understanding of TiO₂ calcination and to guide the choice of measurements used for control and, secondly it was to give a dynamic model eventually to be used for control design.

Steady-state simulation

The basic result yielded by the steady-state simulation is the set of profiles along the kiln. It shows that the crucial reaction is taking place in the very few last meters of the kiln. However, the most important result was obtained by a sensitivity analysis. It showed that the rutile percentage is very sensitive to a change in the energy of activation of the reaction whereas the temperatures are practically not affected, probably due to the endothermic nature of the reaction. This appears to explain the phenomenon, often observed, where the rutile percentage drops dramatically without temperature change. Thus, the utilization zone temperature fails to respond to the main disturbance and is de facto useless in controlling the rutile percentage.

Dynamic simulation

A dynamic model was then written by linearization about the steady-state solution, generating a set of linear, time-invariant partial differential equations with space-dependent coefficients. A lumped-model approximation was then used to compute the frequency responses between the output and input variables (both manipulated and disturbance). These were then matched with rational transfer functions with time delay. The perturbations were then characterized as random processes. The energy of activation not being accessible, this perturbation was modelled as a disturbance on the rutile percentage, from data obtained for a highly perturbed period. This showed that it can be represented by a first-order Gauss-Markov process.

Feed-rate and feed-moisture perturbations were reasonably approximated by Wiener processes.

Control design

From the results of the dynamic simulation, a discrete time, state-space realization was written. The steady-state solution of the regulator problem then shows that the output covariance is only slightly affected by changes in weighing matrices, indicating that this is a near minimum-variance control law. Also, the Kalman filtering problem shows that the use of temperature measurements in the states estimation scheme would bring only a marginal improvement. This leads to consider the kiln, as far as rutile percentage control is concerned, as a single-input (the fuel rate), single-output (the rutile percentage) process. For such a process, Åström’s minimum-variance controller can be used [4], i.e. for the kiln:

\[ u(k) = b_1u(k-1) + b_2u(k-2) - a_1y(k) - a_2y(k-1) - a_3y(k-2) \]  

where:  
- \( u \) is the fuel rate  
- \( y \) is the rutile percentage

The simplicity of this control law is due to the first-order process transfer function and the simple noise structure [2].

IV. Plant Trials—Self-Tuning Regulator

Minimum variance control law (MVC)

During plant trials, the control algorithm was implemented on a simple programmable pocket calculator. The calculator was simply protected from the very dusty environment by a transparent plastic bag and performed without problems during the entire six-week trial period. The control law (1) with the coefficients issued directly from the simulation was applied to kiln #1 and performed much better than any previous control method, raising the percentage of production within specifications by 30%.

This minimum-variance control out-performs the previous control methods, but is not optimal and seems to need periodical retuning. This is why a self-tuning regulator was inserted in the scheme.

Self-tuning regulator (STR)

The self-tuning regulator was introduced in 1973 [5] and has since become the most widely used adaptive control scheme.

Using the model (1), the standard self-tuning method would proceed to the design of a five-parameter algorithm. However, another structure was chosen, consisting of placing the STR around the controlled plant. This solution presents three advantages: (1) the MVC can be used as back-up in case of STR stability problems, (2) the controlled system is tunable with only two parameters, and (3) the MVC contains an integrator, thus solving the problem of steady-state offset.

This represents a good compromise between the use of a priori knowledge of the process and the use of on-line estimation. Thus, the fixed MVC takes most of the
control action, while the STC takes care of modelling errors. Also, with the "classical" STC configuration, during a period of unperturbed process operation, when the process output is near a white noise, the STC will tend to a zero gain regulator. Then, should a perturbation happen, the STC, even with a forgetting factor less than unity, will not take a proper control action until its parameters have moved to a different set of values. With the configuration used here, the STC will have the same behaviour but the MVC, with its non-zero parameters will be able to take at least a reasonable fraction of the necessary control action, while the STC slowly reacts to the perturbation.

Figure 2 depicts the subsequent control structure. Due to this unorthodox application, the satisfactory asymptotic behaviour had to be checked using the Ljung equations. It was found that when the minimum-variance controller is optimal, the optimality of the system is preserved, i.e., the self-tuning regulator does not take any control action. Also, the performance and stability of this structure were analyzed for a range of values of process gain and delay [3]. This structure appears to provide a very robust controller.

Plant trials showed that the self-tuning control raised the in-specifications production fraction by another 15%. It also proved capable of controlling the kiln during a grade change, transient period during which the dynamic behaviour of the kiln undergoes drastic changes, reducing the out-of-specification period from 12 hours to 2-3 hours.

V. Long-Term Industrial Experience

Benefits of the control system

This control scheme has been in use continuously for about three years. Figure 3 depicts the dramatic evolution of the in-specification production since 1973. The table below summarizes the improvements brought by the computer control method:

<table>
<thead>
<tr>
<th></th>
<th>Improvement 1979/1973</th>
</tr>
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<tbody>
<tr>
<td>Kiln throughput rate</td>
<td>+15%</td>
</tr>
<tr>
<td>In-Spec' production</td>
<td>+49%</td>
</tr>
<tr>
<td>'Off-Spec' low</td>
<td>4 times less</td>
</tr>
<tr>
<td>'Off-Spec' high</td>
<td>6 times less</td>
</tr>
</tbody>
</table>

The reduction in under- and over-calcined pigment production has a tremendous economic effect, since off-spec pigment needs special treatment. Moreover, this control method allowed a 15% increase in the kiln throughput, compared to 1973 at which time the kilns were thought to have reached their limit capacity. More throughput can be expected in the future.

This scheme also permits the control of two kilns by a single operator located in the plant, whereas the manual control method needed two operators, one in the plant and the other in the control laboratory. No major difficulties were encountered during the commissioning and implementation of this control system. This may be due to the fact that this project did not require the use of any sensor new to the plant personnel, the rutile percentage being measured by a standard x-ray diffractometer. In this respect, the uselessness of temperature measurements, shown by simulation certainly was a major factor for the success of this project. Also, the fact that the system essentially consists of one control loop contributed to the ease of implementation and commissioning. Only usual tuning problems were encountered with new product grades. They were however quickly solved.

The control scheme is implemented on a small-size microcomputer. During the commissioning period, and thanks to the relative slow process dynamics, the implementation was not fully on-line automatic, the operator having to act as interface between the plant and the microcomputer. Further minor developments required to go to a truly on-line control scheme are now being considered by the company.
Long-term behaviour of the self-tuning regulator

The long-term operation of the self-tuning regulator can give rise to some problems. After several weeks of satisfactory operation, the self-tuning regulator can create systems oscillations. It seems that the kiln behaviour undergoes dramatic and sudden changes of dynamics that the estimator, even with a forgetting factor less than unity, cannot track, after several weeks of steady performance. The origin of these rapid changes in process dynamics is yet to be found, but is probably associated with some characteristic of the raw material. The solution adopted is to "crank up" or reinitialize the co-variance matrix to a higher value, it then takes 6 to 8 sampling periods for the self-tuning controller to converge to a new set of coefficients and perform a better control. Another phenomenon, although very seldom observed in this case, is a blow-up of the parameters estimates when working with a forgetting factor less than one. However, this generally happens with processes that are not very noisy, which is not the case of the TiO₂ kiln. For a detailed description of various problems associated with the P-matrix and their solutions, the reader is referred to Åström in [6].

A solution to both problems might be the variable forgetting factor introduced by Fortescue et al. [7], which will be tried in the near future. This approach virtually allows a time-varying drift rate for the parameters.

Human factors

Very often in such a project, human factors are a major cause of failure, e.g., the transfer of technology to the plant cannot be adequately performed, due to the lack of on-site control expertise; or psychological barriers may lead to the non-acceptance of the system by the plant personnel.

In the case of this project, one of the authors (G. A. Dumont) was present in the plant to commission the control system and to ensure the proper transfer of know-how. In particular, a lot of experience with long-term behaviour of the self-tuning regulator was obtained. In order to increase the confidence in the control system of all the personnel involved in this project, many training and information seminars dealing with the fundamental as well as the practical aspects of the algorithms were held. The important results of the simulation as well as the fundamental concepts behind the minimum-variance controllers and the self-tuning regulator were emphasized. These sessions prove that a priori complex concepts can be simply explained to persons without control background. Operators and foremen were taught to notice when to reinitialize the P-matrix, and so far their reaction has been rather satisfactory.

The technical staff and management of this plant is characterized by a fairly high level of scientific education, that may explain their receptiveness and keenness on the project. It is worthy to note that there was a general awareness of the crucial role played by the control algorithms in the performance of the system. They were not viewed as black boxes and there was an eagerness to become familiar with all the concepts involved, even though no staff member had a background in control engineering.

VI. Conclusions

This work showed that first-principles modelling and computer simulations provide very powerful tools in the preliminary stage of a project. In this case, they allowed the design of a very simple, yet very performant control scheme and minimized the amount of tuning during the plant trials, thus increasing the staff confidence in the algorithms. It was also shown that concepts like self-tuning regulators can be explained to noncontrol experts and implemented on a permanent basis in an industrial environment, without the need for a control expert after the commissioning period. However, the presence in the plant of one of the authors is believed to have been essential. Another positive point is that the personnel grasped the importance of control algorithm design and the underlying concepts. It must be noted that this project would not have been successful without the complete cooperation of the plant personnel.

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REFERENCES

Guy A. Dumont (M’78) was born in Calais, France on November 3, 1951. He received the Diplome d’Ingénieur from the Ecole Nationale Superieure d’Arts et Metiers, Paris, in 1973, and the Ph.D. degree in electrical engineering from McGill University, Montreal, P.Q. Canada in 1977. He worked for Tioxide S.A., Calais, France first from 1973 to 1974 as a project engineer and then from 1977 to 1979 as a Process R & D Engineer. In 1979 he joined the Pulp and Paper Research Institute of Canada, Pointe Claire, PQ, Canada where he is involved in applications of advanced control theory to pulp and paper processes. His present interests are in stochastic and adaptive control; process modeling and identification, and industrial applications.

Pierre R. Belanger was born in Montreal. He received the B.Eng. from McGill University in 1959, and the S.M. and Ph.D. degrees, both in Electrical Engineering, from M.I.T. in 1961 and 1964, respectively. After a two-year period with the Foxboro Company, he joined McGill in 1967 and has been there since that time. He is currently a Professor in Electrical Engineering and Chairman of the department. He is currently Vice President (Finance and Administration) of the IEEE Control Systems Society.

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ment and support funds of the Navy’s research and development appropriation, established the Navy’s RDT&E military construction program, and sponsored certain technical programs carried out by the Laboratories. From 1967 to 1968 he was Research and Engineering Consultant to Commander-in-Chief, Pacific. From 1965 to 1967 he served as Special Assistant (Electronics) to the Assistant Secretary of the Navy (Research and Development). From 1958 to 1965 he was with Scientific Engineering Institute, a small nonprofit research organization in Boston, Massachusetts. From 1953 to 1958 he was with the Control Systems Laboratory, University of Illinois.

He received his B.A. with honors in physics and did his graduate work in nuclear physics at the University of Illinois, receiving his M.S. in 1949 and his Ph.D. in 1953 from the University of Illinois.