Robust optimization-based multi-loop PID controller tuning:
A new tool and an industrial example

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Abstract: Modern process plants are highly integrated and as a result, decentralized PID control loops are often strongly interactive. The currently used sequential tuning approach is not only time consuming, but does also not achieve optimal performance of the inherently multivariable control system. This paper describes a method and a software tool which allows a control engineer to calculate optimal PID controller settings for multiloop systems. It is based on the identification of a state space model of the multivariable system, and it uses constrained nonlinear optimization techniques to find the controller parameters. The solution is tailored to the specific control system and PID algorithm to be used. The methodology has been successfully applied in several industrial advanced control projects. The tuning results which have been achieved for interacting PID control loops in the stabilizing section of an industrial Gasoline Treatment Unit at SABIC Petrochemicals are presented.

Keywords: PID controller tuning, multi-loop control, decentralized control system design, nonlinear optimization, genetic algorithm, multivariable system identification.

1. INTRODUCTION

One of the most important challenges facing the process industry today is optimizing the operation of complex units, without compromising the safety and integrity of the process equipment. Process complexity has increased significantly over the past two decades due to increased level of heat integration and use of recycle streams. In addition, the need for increased process flexibility to deal with changing raw materials and alternate energy sources, as well as the need to adapt quickly to fluctuating throughput and quality targets, often means that the process dynamics will vary significantly over time and with operating point. The basic control layer of process plants almost always consists of a large number of decentralized SISO PID controllers, although this approach is intrinsically inadequate for multivariable processes. Due to the situation described above, the interactions between these controllers are becoming more important, and tuning these control loops for good performance and adequate robustness is a challenging task.

The industrial practice of PID controller tuning is still dominated by manual trial-and-error tuning. If tuning rules are used at all, it's the "classical" ones like Ziegler-Nichols or Chien-Hrones-Reswick which are based on simplified first order plus dead time (FOPDT) process models and do not consider stability robustness issues, therefore often being not adequate in modern process units with more complex dynamics and nonlinearity. In addition, many tuning rules assume that all PID controller equations work as described in the textbooks, when in fact there is substantial variation between the different vendors. In contrast, different PID controller structures result due to use of either the parallel or the serial form, using the control error or the PV by the Proportional (P) and Derivative (D) terms, and many other quirks like alternative implementations of the derivative filters. Tuning SISO PID controllers in a multivariable environment is usually done in a time-consuming sequential and iterative way, starting with the most important loops, and heuristic detuning in case the interactions are significant.

For a long time, vendors of automation systems such as Distributed Control Systems (DCS) and Programmable Logic Controllers (PLC) have been offering PID self-tuning functionality (tuning on demand). Unfortunately, they have only found limited application. This is also true for model based PID controller tuning software provided by the same or third-party vendors. Moreover, in most cases these tools are restricted to single loop tuning applications, and do not support multi-loop tuning (Li et al., 2006, Espinosa Oviedo et al., 2006 and Zhu, 2004).

The design of interacting PID controllers in a multivariable environment is not a new topic in the process control literature. At least three research directions can be identified: (1) reduction of controller interactions by proper MV-CV pairing, (2) design of decoupling networks and (3) consideration of MIMO interactions in decentralized controller tuning. In this paper, only the third direction is relevant. Several methods have been developed, Luyben's

BLT method being the most popular one (Monica et al., 1988). Here, the individual PI loops are first tuned by the Ziegler-Nichols rules independently. Then, a detuning factor is calculated which assures a certain stability margin for the controlled MIMO system. All individual controller gains are divided by this factor, and the reset times are multiplied by it. The price to be paid for the reduced interaction is a more sluggish behaviour of PI loops. Other methods include the sequential loop closing approach (Hovd and Skogestad, 1994), the independent design method (Hovd and Skogestad, 1993) and the multivariable generalization of the relay-feedback self-tuning method (Halevi et al. 1997). For a discussion of these methods the reader is referred to (Chen and Seborg, 2003).

This paper introduces a new method and a software tool "AptiTune™" for the calculation of optimum PID controller settings in a multivariable system (multivariable loop tuning). The method consists of several steps. First, a set of Finite Impulse Response (FIR) models of the open-loop MIMO plant is being identified and approximated by a reduced-order state space model. In a second step, optimal parameters for the decentralized PID controllers are calculated using constrained optimization. Finally, the setpoint tracking, disturbance rejection and noise attenuation behaviour of the controlled system is simulated.

It was the aim of the development to come up with a software tool which is based on recent identification and control developments, but which does not require in-depth knowledge of identification and control theory by the average user. Furthermore, the optimization solution is tailored to the specific target automation system, e.g. the particular DCS or PLC which is used for control purposes.

The remainder of the paper is organized as follows: In section 2, the identification and optimal tuning methods will be described together with the "AptiTune™" software tool. Section 3 presents some results of multiloop tuning in the stabilizer section of an industrial Gasoline Treatment Unit (GTU). The retuning of the PID controllers was one of the first steps of an advanced control project, which also included the design and commisioning of an MPC controller.

2. METHOD AND TOOL FOR MULTILOOP TUNING

2.1 Identification of the MIMO process model

The first step of model based multiloop tuning is to develop a dynamic model of the multivariable process with n inputs and n outputs, the outputs (u_i) and process variables (y_i) of the PID controllers shown in Fig. 1.

Our preferred approach is to switch all PID controllers to be tuned into manual mode whenever possible and to perform a series of output steps of different duration and amplitude. According to our experience, four to six steps with duration varying between 10% and 100% of the desired closed-loop settling time are usually sufficient. If a test signal generator is available, PRBS (pseudo-random binary sequence) or GBN
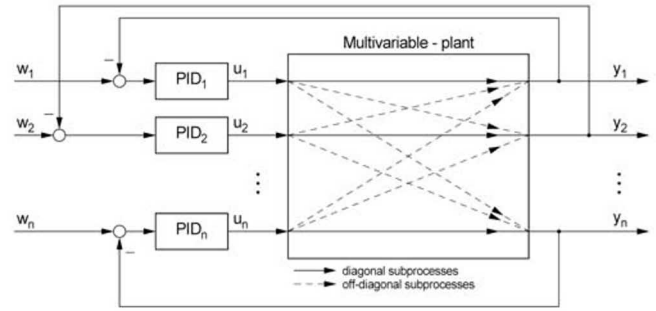

Fig. 1: Decentralized multiloop PID control system

(generalized binary noise), then an automated test may be used as an alternative. Both types of plant tests can be performed in sequential or in time-saving simultanous mode.

If one or more PID controllers cannot be switched to manual mode, then the loop can be kept in automatic mode and multiple setpoint steps can be made. The Projection Method described in (Forsell and Ljung, 2000) can then be used.

After pre-processing the raw test data (detection/rejection of outliers, filtering, decimation, cutting out periods of bad data etc.), the parameters of a MIMO FIR model

$$\vec{g}_{ij} = \left[g_{ij}(0), g_{ij}(1), g_{ij}(2), \ldots, g_{ij}(n_M) \right] \qquad i, j = 1 \ldots n \quad (1)$$

are estimated by least squares regression. The user should specify a-priori knowledge such as zero gain, known dead time or integrating behaviour of subprocesses. Although FIR models are estimated, the results are presented as Finite Step Response (FSR) models for easier visualization and understanding. The "AptiTune™" software tool also supports the import of FSR models created by identification tools from MPC packages, but also allows the user to specify a transfer function matrix.

In the next step, the MIMO FIR model is approximated by a linear state-space model of the form

$$\dot{x}(t) = A\,x(t) + B\,u(t)$$
$$y(t) = C\,x(t) \qquad\qquad (2)$$

This approximation is not based on the raw or preprocessed plant test data, but on a model-to-model fit. To remove noise and cycles from the FIR model, it can first be smoothed using a central average filter. The state-space model is constructed using the singular value decomposition (SVD) model reduction technique (Maciejowski, 1989). While creating the state-space model, the diagonal model curves are given more preference than the off-diagonal models. As a result, diagonal models normally have higher order than the off-diagonal ones and consequently fit the original FIR model curves more accurately. The step responses calculated based on the stat-space models are graphically displayed.

If it is possible to do a closed-loop step test (or if historical data contain a clear SP step), a practical way of validating the process model is to simulate the closed loop behaviour of the control system with the actual PID controller parameters