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Robust tuning of dynamic matrix controllers for first order plus dead time models

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ABSTRACT

Dynamic Matrix Control is a widely used Model Predictive Controller in industrial processes. The successful implementation of Dynamic Matrix Control in practical applications requires appropriate tuning of the controller parameters. Three different cases are considered. In the first case, a tuning formula is developed that ensures the nominal closed loop desired performance. However, this formula may fail in the presence of plant uncertainty. Therefore a lower bound for the tuning parameter is derived to secure the robust stability of the uncertain first order plus dead time plant. Finally, a tuning boundary is derived which gives the lower and upper permissible bounds for the tuning parameter that guarantee the robust performance of the uncertain first order plus dead time plant. The tuning procedure is based on the application of Analysis of Variance, curve fitting and nonlinear regression analysis. The derived results are validated via simulation studies and some experimental results.

1. Introduction

Model Predictive Control (MPC) strategies have been successfully employed in a wide range of real industrial applications [1–3]. It is shown in [4], that linear MPC as a modern advanced control methodology improves both the energy conservation and productive capacity in industrial and chemical processes. Dynamic Matrix Control (DMC) as one of the first commercial implementations of MPC is extensively used in many chemical and petrochemical processes [5]. This is due to the simple structure of the controller and the minimum required plant information. Many open loop stable processes can be effectively modeled by Finite Step Response (FSR) models [5]. DMC uses the FSR information which is easily obtained by open loop step tests. Two key DMC elements are a FRS based prediction model and an objective function [6]. It is desired that the future plant output on a specified finite horizon follow a desired reference trajectory and simultaneously the control effort is minimized.

DMC has many tuning parameters such as the prediction horizon, the control horizon, the model horizon, and the penalty weights in the objective function, the reference trajectory time constant and the sampling time. Note that the successful implementation of DMC in practical applications requires a proper tuning of the controller parameters. The issue of MPC tuning is addressed in many research papers [7,8].

In Lee and Yu [9], a tuning method to obtain robust performance is proposed based on state estimation and sensitivity functions analysis. A case dependent method for MPC tuning, called the response surface tuning is proposed for a pressure

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tank system in [10]. An on-line tuning strategy is presented in [11] for DMC, based on a constrained least square optimization that tunes parameters to satisfy a predefined closed loop time domain performance. Trierweiler and Farina [12] used the Robust Performance Number (RPN) to develop a MPC tuning procedure for multivariable and non minimum phase plants. An extension of the modified GPC algorithm and a tuning strategy is developed in [13]. Garriga and Soroush [14] used MATHEMATICA to present an analytical study of the effects of various MPC tunable parameters on the location of closed-loop eigenvalues. This idea leads to complicated formulations not straightforwardly applicable to tune the parameters for desired performance. Two methods for selecting the MPC weight matrices are derived by Cairano and Bemporad [15] that use a state space MPC approach, multivariable controllers are also considered and Linear Matrix Inequality (LMI) solves the inverse problem of controller matching which numerically tunes the weight matrices. Shah and Engell [16] provided a tuning procedure to achieve desired closed loop performance. The penalty weights and control horizon of GPC are tuned by using convex optimization. However, it is noted that the control horizon must be one; otherwise the optimization problem would no longer be solved using the convex optimization. Recently, a robust analysis and tuning for GPC in two-degree-of-freedom configuration is proposed in [17]. Note that, none of the above mentioned papers provide a tuning formula. Shridhar and Cooper [18] derived a closed form equation for all the DMC parameters based on the FOPDT model approximation of the real plant. Among these tuning parameters, the move suppression coefficient, λ (defined later) is the most effective parameter [18] and the equation given for λ is to avoid singularity calculation in the control signal and closed loop performance is not considered. An analytical formulation for DMC tuning using gain and dead time of the plant based on some practical approaches is presented in [19], but the weight factor of control effort is not normalized that can lead to difficulties as shown in [18]. Analysis of Variance (ANOVA) is used in [20] to develop an analytical equation for λ. Unfortunately, there are severe deficiencies associated with the derived formulae [21,22]. The ANOVA technique is used for tuning GPC parameters in the case of Second Order plus Dead Time (SOPDT) models in [23], and a new analytical equation for λ is obtained. An analytical tuning equation for DMC tuning parameter λ is developed by Bagheri and Khaki-Sedigh [21,22]. It is based on the application of ANOVA and nonlinear regression analysis for FOPDT process models and provides closed form tuning equations for the nominal performance and disturbance rejection of DMC. Recently, Bagheri and Sedigh [24] developed an analytical MPC tuning methodology for FOPDT models to ensure nominal desired performance of closed loop system. Also, achievable performance is addressed. This tuning strategy is extended to unstable plants with fractional dead times in [25] and also for multivariable plants in [26]. Note that, in Bagheri and Khaki-Sedigh [21,22,24–26] only nominal FOPDT model is considered to achieve tuning equations. In this paper, the idea in Bagheri and Sedigh [21,22] is extended to handle the uncertain FOPDT systems. A tuning equation and inequalities are derived for DMC. The focus is on tuning the parameter λ, and three formulations are proposed. First, the nominal model without uncertainty is considered and the objective would be the desired nominal closed loop performance. This performance is the ratio of the closed loop to the open loop settling times. Then, robust stability is the tuning objective for an uncertain FOPDT model with structured uncertainty which gives a lower band of the tuning parameter λ. Finally, the robust performance of an uncertain FOPDT model is considered that results in a lower and upper bound for λ. In the first stage, a bank of nominal FOPDT models with different performance parameters is defined. In the case of uncertainty, a bank of uncertainties is defined and simulated to test the effect of different model parameters, uncertainties and stability/performance parameter on the tuning parameter λ. In the second stage, ANOVA is performed on these data to determine the effectiveness of the parameters on the tuning parameter. Note that, there are several parameters that affect the tuning parameter λ and ANOVA is an appropriate tool to provide information about the relative effect of the various parameters on the tuning parameter. Finally, curve fitting and nonlinear regression techniques are employed to obtain a closed form tuning equation for λ.

In the following section, the preliminary materials on DMC and the previous DMC tuning methods that lead to closed form formulations are briefly studied. In Section 3, the procedure for the proposed tuning method is given. Finally, experimental results are given in Section 4.

2. Preliminary materials

2.1. Dynamic Matrix Control (DMC)

DMC is a widely used industrial MPC method which was developed in the early 1970s and is a practical control system design, particularly in the oil and petrochemical industries [2]. In this section, Single Input–Single Output (SISO) formulation of the DMC is briefly reviewed.

In the open loop stable plants with slow and simple dynamics such as the petrochemical processes, FSR models can sufficiently capture the process dynamics [5], which are readily employed by DMC. Assume that $y(t)$ is the process output, $u(t)$ is the control signal and $\Delta u(t) = u(t) - u(t-1)$ is the control effort. Then, the system step response can be described as follows

$$y(t) = \sum_{i=1}^{\infty} g_i \Delta u(t-i), \tag{1}$$

where g_i are the sampled step responses. The output prediction values along the finite horizon will be as

$$\hat{y}(t+k|t) = \sum_{i=1}^{k} g_i \Delta u(t+k-i) + f(t+k), \tag{2}$$