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Improving disturbance rejection of PID controllers by means of the magnitude optimum method

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ABSTRACT

The magnitude optimum (MO) method provides a relatively fast and non-oscillatory closed-loop tracking response for a large class of process models frequently encountered in the process and chemical industries. However, the deficiency of the method is poor disturbance rejection performance of some processes. In this paper, disturbance rejection performance of the PID controller is improved by applying the"disturbance rejection magnitude optimum" (DRMO) optimisation method, while the tracking performance has been improved by a set-point weighting and set-point filtering PID controller structure. The DRMO tuning method requires numerical optimisation for the calculation of PID controller parameters. The method was applied to two different 2-degrees-of-freedom PID controllers and has been tested on several different representatives of process models and one laboratory set-up. A comparison with some other tuning methods has shown that the proposed tuning method, with a set-point filtering PID controller, is quite efficient in improving disturbance rejection performance, while retaining tracking performance comparable with the original MO method.

1. Introduction

Tuning of PID controllers has been attracting interest for six decades. Numerous methods suggested so far try to accomplish the task by making use of different representations of the essential aspects of the process behaviour.

Today, the most often applied tuning rules for PID controllers are those based either on the measurement of the process step response or on the detection of a particular point on the Nyquist curve of the process (usually one related to the ultimate magnitude and frequency of the process by using relay excitation [1–3]). These methods are relatively simple to perform, but the information they make use of is frequently insufficient. Basically they rely only on measured lag and rise times or ultimate amplitude and frequency.

Apart from standard tuning rules, such as Ziegler–Nichols, Cohen–Coon or Chien–Hrones–Reswick rules, more sophisticated tuning approaches have been suggested. They are usually based on more demanding process identification algorithms or tuning procedures, like non-convex optimisation, gain and phase specification, IMC controller design, identification of multiple points in frequency domain or genetic algorithms [4–6,2,7,3].

One representative is the magnitude optimum method (MO) [8–12]. The MO method is very demanding, since it requires the reliable estimation of quite a large number of process parameters even for simpler controller structures (like a PID controller). This is one of the main reasons the method was mainly used in mechanical systems, which parameters can be reliably estimated.

Recently, the efficiency of the MO method has been improved by using a nonparametric approach in time domain instead of using explicit parametric identification of the process. The improved method is based on multiple integrations of process input and output signals and is hence called the magnitude optimum multiple integration (MOMI) method [11]. The proposed approach uses information from a relatively simple experiment in the time domain while retaining all the advantages of the MO method. This was an important step in making the MO method more applicable for wider spectrum of processes in practice, especially in the process and chemical industries [13]. The deficiency of the MO method (and consequently the MOMI method) is that it is designed exclusively for improving tracking performance. In some cases this may lead to poor attenuation of load disturbances [1].

Recently, the so-called disturbance-rejection MO (DRMO) method [14] has been developed and applied to the PI controller structure. The results were encouraging, since the disturbance rejection performance has been greatly improved for some processes.

However, the DRMO criterion is not limited only to the PI controllers. The aim of this paper is to apply it to the PID controllers.

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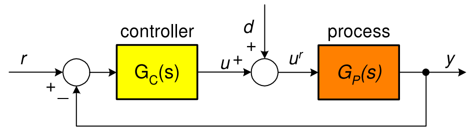

Fig. 1. Typical closed-loop configuration using a 1-DOF controller.

However, since the structure of the PID controller is more complex, numerical optimisation is required for calculation of the PID controller parameters.

The new tuning rules are applied to a two-degrees-of-freedom (2-DOF) PID controller, by means of set-point weighting and set-point filtering, in order to improve tracking performance.

The paper is set out as follows. Section 2 describes the original MO tuning method for the PID controllers. The method is illustrated in four process models. Section 3 provides a derivation of DRMO tuning rules for the PID controller. The results are illustrated on the same process models. The set-point weighting and set-point filtering are introduced in Section 4. The DRMO method with a filtered PID controller is compared with some other PID tuning methods and tested on one laboratory set-up in Section 5. Conclusions are then provided.

2. Magnitude optimum criterion

Fig. 1 shows the process in a closed-loop configuration with a 1-DOF controller, where signals r and d represent a set-point (reference) and an input disturbance, respectively.

The magnitude optimum (MO) design objective is to maintain the closed-loop magnitude (amplitude) as flat and as close to unity over as wide a frequency range as possible [1,12].

For a typical closed-loop transfer function:

$$G_{CL}(s) = \frac{Y(s)}{R(s)} = \frac{1 + sf_1 + s^2 f_2 + \cdots}{1 + se_1 + s^2 e_2 + \cdots}, \tag{1}$$

the MO criterion is achieved by satisfying the following set of equations [15,14]:

$$\sum_{i=0}^{2k} (-1)^{i+k} (e_i e_{2k-i} - f_i f_{2k-i}) = 0; \quad k = 1, 2, \ldots, k_{\max}, \tag{2}$$

where $e_0 = f_0 = 1$ and $k_{\max}$ represents the number of controller parameters.

Let us now calculate parameters of the PID controller, which can be described by the following transfer function:

$$G_C(s) = \left[K_P + \frac{K_i}{s} + sK_d\right] \frac{1}{1 + sT_f} = K_P \left(1 + \frac{1}{sT_i} + sT_d\right) \frac{1}{1 + sT_f}, \tag{3}$$

where K_P, K_i, K_d, T_i, T_d, and T_f are proportional gain, integral gain, derivative gain, integral time constant, derivative time constant and filter time constant, respectively. Note that the filter is applied to all controller terms, instead of only to derivative term, since such a configuration significantly simplifies the calculation of controller parameters (the filter can be considered as a part of a controlled process) [16].

The process is given by the following rational transfer function

$$G_P(s) = K_{PR} \frac{1 + b_1 s + b_2 s^2 + \cdots + b_m s^m}{1 + a_1 s + a_2 s^2 + \cdots + a_n s^n} \mathrm{e}^{-sT_{\mathrm{del}}}. \tag{4}$$

By applying expressions (3) and (4) into expression (1) and by solving Eq. (2) for $k = 1, 2$ and 3, the following PID controller parameters are obtained [10,11,17]:

$$\begin{bmatrix} K_i \\ K \\ K_d \end{bmatrix} = \begin{bmatrix} -A_1 & A_0 & 0 \\ -A_3 & A_2 & -A_1 \\ -A_5 & A_4 & -A_3 \end{bmatrix}^{-1} \begin{bmatrix} -0.5 \\ 0 \\ 0 \end{bmatrix}, \tag{5}$$

where symbols A_0 to A_5 represent the so-called "characteristic areas" of the process [11,17]:

$$\begin{aligned} A_0 &= K_{PR} \\ A_1 &= K_{PR}(a_1 - b_1 + T_{\mathrm{del}}) \\ A_2 &= K_{PR}\left[b_2 - a_2 - T_{\mathrm{del}} b_1 + \frac{T_{\mathrm{del}}^2}{2!}\right] + A_1 a_1 \\ &\vdots \\ A_k &= K_{PR}\left((-1)^{k+1}(a_k - b_k) + \sum_{i=1}^{k} (-1)^{k+i} \frac{T_{\mathrm{del}}^i b_{k-i}}{i!}\right) \\ &\quad + \sum_{i=1}^{k-1} (-1)^{k+i-1} A_i a_{k-i}. \end{aligned} \tag{6}$$

Note that area A_0 equals the steady-state gain of the process.

The name "characteristic areas" is associated with the fact that they can also be calculated from a non-parametric process model in the time-domain by changing the steady-state of the process and performing multiple integrations of the process input ($u(t)$) and output ($y(t)$) signals [10,11,17].

Note that the process transfer function can be expressed as areas by using the following infinite-order expression [18]:

$$G_P(s) = 1 - A_1 s + A_2 s^2 - A_3 s^3 + A_4 s^4 - \cdots. \tag{7}$$

The expression is non-physical, but gives an accurate description of the process in the frequency domain. For finite-order expression (7), the process is well described at lower-frequencies only.

2.1. Example

The MOMI method will be demonstrated on four different process models. The process models chosen are:

$$\begin{aligned} G_{P_1}(s) &= \frac{1}{(1+9s)(1+s)} \\ G_{P_2}(s) &= \frac{1+s}{(1+8s)(1+1.5s)^2} \\ G_{P_3}(s) &= \frac{1-2s}{(1+4s)^2} \\ G_{P_4}(s) &= \frac{\mathrm{e}^{-2s}}{(1+s)^8}. \end{aligned} \tag{8}$$

They are selected in order to cover a wider selection of process models from lower-order processes to higher order ones.

Since the filter of the PID controller (3) can be considered as a part of the process, it should be added to the mentioned process models when calculating the PID controller parameters. The chosen filter transfer function is:

$$G_{FC}(s) = \frac{1}{1 + 0.5s}. \tag{9}$$

The characteristic areas A_0 to A_5 for all four process models (8) including filter (9) are obtained from expression (6). The calculated areas are given in Table 1 and the PID controller parameters (5) are shown in Table 2.

Fig. 2 (solid lines) shows the closed-loop responses ($y_{CLR}(t)$) of the chosen process models on set-point change ($r = 1$ at $t = 0$ s), and Fig. 3 (solid lines) shows the closed-loop response