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# ROBUSTNESS EVALUATION OF SEVERAL FRACTIONAL ORDER AUTOTUNERS FOR INDUSTRIAL PROCESSES

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## ABSTRACT
*Fractional order controllers have a great potential to improve closed loop performance. However, the tuning can be sometimes overwhelming and much too complicated, especially for the non-experienced user. To facilitate a wider spread of these controllers, including industrial domains, simple tuning rules are necessary combined with a fewer process information. This has paved the way towards autotuning methods. Some tuning rules derived based on autotuning approaches are reviewed in this manuscript, in terms of robustness. The case study considered is the time delay process, widely encountered in industrial applications. Simulation results on lag and delay dominant processes are performed. The different types of autotuning methods are compared and conclusions regarding the best option are drawn.*

*Index Terms – Fractional Order Control, Autotuning Methods, Time Delay Processes, Comparative Results, Robustness.*

## INTRODUCTION
A generalization of the classical PID controller has been recently developed and extensively studied [1]. This high interest in the fractional order PID (FO-PID) controller is mainly due to its increased flexibility in the design that comes from the two extra parameters in the FO-PID controller, the fractional order of integration and differentiation [2]. Researchers have seen this flexibility as a means to increase the robustness of the controller and to ensure better closed loop performance [3], [4].

Among these advantages, recent findings suggest that a better control for time delay systems is also possible using fractional order PIDs [5]. In this manuscript, several fractional order PIDs are evaluated regarding their robustness in controlling delay and lag dominant processes described by the generalized transfer function:

$$P(s) = \frac{k}{Ts+1} e^{-Ls} \qquad (1)$$

where $P(s)$ is the process transfer function, $s$ is the Laplace variable, $k$, $T$ and $L$ are the process gain, time constant and time delay. To control these types of processes, a FO-PID will be designed with the transfer function given as:

$$C_{FO-PID}(s) = k_p \left(1 + \frac{1}{T_i s^{\lambda}} + T_d s^{\mu}\right) \qquad (2)$$

With $k_p$ - the proportional gain, $T_i$ and $T_d$ - the integral and derivative time constants and $0 < \lambda < 2$ and $0 < \mu < 2$ are the fractional orders of integration and differentiation, respectively.

Several tuning methods for the controllers in (2) have been developed and improved throughout the years. Most of them revolve around a standard set of performance specifications that refer to a certain loop gain crossover frequency and phase margin, robustness and/or the ability to reject load disturbances efficiently and cancel noise effect. Some excellent review papers that tackle various aspects regarding the tuning, implementation, advantages of fractional order controllers, as well as related topics can be found in [5]-[10]. Most of the tuning methods are based on a process model.

However, in industrial applications, determining a process model is generally tedious and time consuming. In such cases, a tuning method for fractional order controllers that requires as little process information as possible is preferred. This idea has paved the way towards the development of autotuning methods for FO-PIDs. Few direct and indirect autotuning approaches have emerged and a recent review paper discusses all of these in terms of reference tracking and disturbance rejection for a wide range of processes [11]. Nevertheless, robustness is one of the key points that is brought up when discussing the advantages of FO-PIDs. In this manuscript, some autotuning methods that have proven to be the most suitable in the control of time delay process are reviewed and compared in terms of robustness to gain and time delay variations. The autotuning methods are selected in terms of best reference tracking and disturbance rejection as resulting from [11]. The novelty of the manuscript consists in the robustness analysis of these autotuning methods.

The paper is structured into four main parts. After a short introductory section, the most efficient FO-PID autotuning methods for time delay systems are briefly presented. Section III contains the numerical results for a lag and a delay dominant process. Finally, Section IV concludes the research.

## EFFICIENT AUTOTUNING METHODS FOR FO-PIDS

### The F-MIGO indirect autotuning method

The Fractional MIGO (F-MIGO) method, derived as an extension of the $M_s$ constrained integral (MIGO) approach for PID controllers, is among the most popular, and efficient FO-PID autotuning methods for time delay processes [12]. The method is based on the constrained optimization of load disturbance ability. The sensitivity function peak is taken as a design constraint. Several benchmark processes have been considered to determine that the fractional order of the FO-PI controller depends on the relative dead time, defined as:

$$\tau = \frac{L}{T+L} \tag{3}$$

Thus, according to the dead time value $\tau$, the fractional order can be estimated and then the parameters of the FO-PI controller:

$$\lambda = \begin{cases} 1.1, & \tau \geq 0.6 \\ 1, & 0.4 \leq \tau < 0.6 \\ 0.9, & 0.1 \leq \tau < 0.4 \\ 0.7, & \tau < 0.1 \end{cases} \tag{4}$$

$$k_p = \frac{1}{k}\frac{0.2978}{\tau+0.00037} \text{ and } T_i = T\frac{0.8578}{\tau^2-3.402\tau+2.405} \tag{5}$$

*Ziegler-Nichols Method for FO-PIDs: An Indirect Method*

One of the earliest approaches regarding an autotuning method suitable for FO-PIDs consists in an extension of the standard Ziegler-Nichols method [13]. Several benchmark process similar to (1) have been considered and FO-PIDs were designed such that a set of performance specifications is met [14]. The set includes specifications regarding the gain crossover frequency, the phase margin, a high frequency value for noise and the corresponding maximum magnitude limit, as well as a low frequency value for load disturbances and the corresponding maximum magnitude. Based on tuning by minimization followed by least squares fit, tuning rules for the FO-PID controller parameters are determined as functions of the process time constant and time delay.

Two sets of tuning rules were derived to meet different performance specifications. The first set of rules is suitable for process that have $0.1 \leq T \leq 50$ and $L \leq 2$. For processes that have $0.1 \leq T \leq 50$ and $L \leq 0.5$, the second set of rules is more suitable. Detailed information and the actual tuning rules can be found in [14] or [11].

*Ziegler-Nichols Method for FO-PIDs: A Direct Method*

An extension of the modified Ziegler-Nichols tuning rules is presented also in [15]. This time, the approach uses the process critical frequency of oscillation $\omega_{cr}$ and the corresponding critical gain $k_{cr}$. Similarly to [12], the approach is suitable for designing only FO-PI controllers. The tuning rules are simple:

$$\lambda = \frac{1.11 k_{180} + 0.084}{k_{180} + 0.07} \qquad (6)$$

$$k_p = k_{cr} r_b \cos\beta + k_{cr} r_b \cot\lambda \sin\beta \text{ and } T_i = \frac{k_p}{k_i} \qquad (7)$$

With, $k_{180} = \frac{1}{k_{cr} k}$, $r_b = \frac{0.34 k_{180} + 0.03}{k_{180} + 0.52}$, $\beta = \frac{-0.92 k_{180} - 0.012}{k_{180} + 0.6}$, $k_i = \frac{-k_{cr} r_b \omega_{cr}^{\lambda}}{\sin\gamma} \sin\beta$ and $\gamma = \frac{\pi}{2}\lambda$.

The tuning rules are determined such that the ability of the controller to handle low-frequency load disturbances is maximized. Similarly to [12], the constraint refers to maximum sensitivity function of the closed loop system.

**Fractional Order Kiss Circle (FO-KC) Autotuner**

The FO-KC method is a direct autotuning method. It does not require a process model. Unlike [15], required process information refers to the magnitude, phase and phase slope at the gain crossover frequency. A single sine test at the gain crossover frequency, along with novel filtering techniques, is used to estimate the necessary process information [16], [17]. A set of three performance specifications is used. This refers to a certain loop gain crossover frequency, phase margin and is-damping. Based on these performance specifications, three nonlinear equations are obtained. The FO-PI parameters are estimated by solving the nonlinear equations. Optimization routines or graphical methods can be used [17].

A simplified version of this approach consists in using the performance specifications and defining a forbidden region circle in the Nyquist plane [18]. The loop frequency response must not enter the forbidden region. The method is iterative. For each fractional order $\lambda$, a FO-PI controller is determined and then the slope pf the loop frequency response is evaluated. The slope of the optimal FO-PI controller is determined to be the one that ensures the minimization of the slope-difference between the forbidden region border and the loop frequency response.

**Tepljakov's Indirect Autotuning Method for FO-PIDs**

An indirect autotuning method suitable for processes as indicated in (1) has been presented in [19]. First, a process mathematical model similar to (1) is determined. Then, the process critical frequency $\omega_{cr}$ and critical gain $k_{cr}$ are computed using:

$$\omega_{cr} T = -\tan(\omega_{cr} L) \qquad (8)$$

$$k_{cr} = -\frac{1 + \omega_{cr} T^2}{k(\cos(\omega_{cr} L) - \omega_{cr} T \sin(\omega_{cr} L))} \qquad (9)$$

The parameters of the FO-PID controller in (2) are estimated in two steps. First, the proportional gain, integral and derivative time constants are computed:

$$k_p = k_{cr} r_b \cos\emptyset_b,\ T_i = -\frac{T_{cr}}{\pi} \frac{\pi \cos\emptyset_b}{\sin\emptyset_b + 1} \text{ and } T_d = \alpha T_i \qquad (10)$$

with the design parameters $\alpha$, $r_b$ and $\emptyset_b$ [19]. The estimation of the fractional order of integration and differentiation is done by minimizing the integral of time multiplied with the absolute error. The loop gain and phase margins are considered as design specifications.

**NUMERICAL EXAMPLES**

Two numerical examples are considered for comparative reasons. Both are time delay processes. The first case study is a delay dominant process, while the second one is a lag dominant process. In both cases, among the autotuning methods reviewed in [11], only the ones that provided for the best closed loop performance are considered for robustness evaluation.

*The Delay Dominant Process*

The transfer function of the process is given by:

$$P(s) = \frac{1}{0.2s+1} e^{-0.4s} \qquad (11)$$

For this process, $k$=1, $L$=0.4, $T$=0.2. The critical gain is $k_{cr}$=1.5202 and the critical period of oscillation is $P_{cr}$=1.0985.

The FO-PI tuned according to the F-MIGO method described in Subsection A is given by:

$$C_{FO-PI_A}(s) = 0.45\left(1 + \frac{1}{0.30s^{1.1}}\right) \qquad (12)$$

The second set of tuning rules of the method in Subsection B is used, resulting in:

$$C_{FO-PID_B}(s) = 1.33 + \frac{1}{1.77s^{1.31}} - 0.41s^{-0.18} \qquad (13)$$

The method from Subsection C is used to determine the parameters of a FO-PI controller:

$$C_{FO-PI_C}(s) = 0.32\left(1 + \frac{1}{0.29s^{1.12}}\right) \qquad (14)$$

The FO-KC method in Section D is also used to tune a FO-PI controller:

$$C_{FO-PI_D}(s) = 0.66\left(1 + \frac{1}{0.35s^{1.19}}\right) \qquad (15)$$

Considering the nominal process model in (11), the closed loop simulation results regarding reference tracking and disturbance rejection were presented in [11] and are summarized in Table 1.

**Table 1.** Closed loop results obtained with the FO-PID controllers for the delay dominant process

| **Controller** | **Overshoot** | **Settling time** | **Disturbance rejection time** |
|---|---|---|---|
| FO-PI$_A$ | 8% | 4 | 1.5 |
| FO-PID$_B$ | 14.5% | 10.1 | 8.4 |
| FO-PI$_C$ | 8.2% | 5.8 | 2.2 |
| FO-PI$_D$ | 7.5% | 6.7 | 1.8 |

Robustness tests are carried out next. A +30% gain variation is considered first. The closed loop simulation results are indicated in Fig. 1, with results summarized in Table 2. A second test is considered where the process gain is now diminished by 30%. Due to lack of space, the simulation results are not included, only the quantitative values are given in Table 3.

**Table 2.** Closed loop results obtained with the FO-PID controllers for the delay dominant process with +30% gain variation

| **Controller** | **Overshoot** | **Settling time** | **Disturbance rejection time** |
|---|---|---|---|
| FO-PI$_A$ | 22.2% | 3.290 | 2.457 |
| FO-PID$_B$ | 18.8% | 8.838 | 8.159 |
| FO-PI$_C$ | 9.6% | 4.484 | 3.704 |
| FO-PI$_D$ | 11.6% | 5.525 | 3.233 |

**Table 3.** Closed loop results obtained with the FO-PID controllers for the delay dominant process with -30% gain variation

| Controller | Overshoot | Settling time | Disturbance rejection time |
|---|---|---|---|
| FO-$PI_A$ | 6.2% | 5.831 | 2.265 |
| FO-$PID_B$ | 15.8% | 12.194 | 8.541 |
| FO-$PI_C$ | 6.6% | 8.157 | 2.915 |
| FO-$PI_D$ | 8.2% | 8.735 | 2.783 |

Comparing these results with those in Table 1 and Table 2, it is clear that, overall, the autotuning methods in Subsection C and D provide for better robustness overall, with small overshoot and settling times that remain close to the nominal values. The third and fourth tests refer to delay variations which are prone to destabilize the closed loop system. In this case, a $\pm$30% delay variation is considered and the four controllers in (12)-(15) are compared. The closed loop simulation results are indicated in Fig. 2 and 3, while Tables 4 and 5 summarize the performance measures.

Based on Table 4 and Fig. 2, the autotuning method in Subsection A produces the best controller, both in terms of overshoot, settling time and disturbance rejection time.

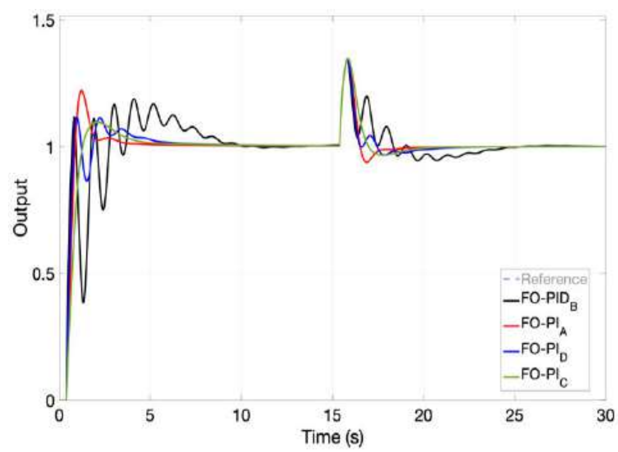


**Fig. 1.** Closed loop results obtained with the FO-PID controllers for the delay dominant process with +30% gain variation

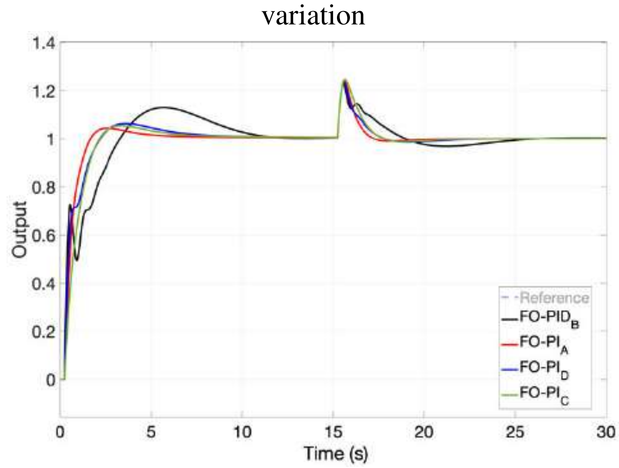


**Fig. 2.** Closed loop results obtained with the FO-PID controllers for the delay dominant process with -30% delay variation

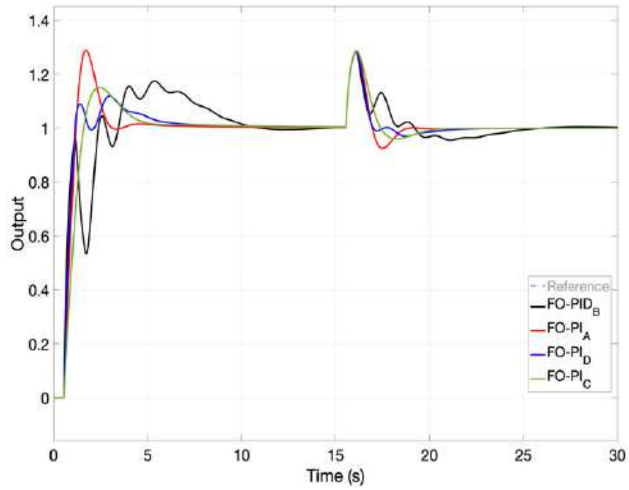


**Fig. 3.** Closed loop results obtained with the FO-PID controllers for the delay dominant process with +30% delay variation

The FO-PI controllers tuned according to Subsections C and D offer acceptable closed loop results, as well. The closed loop simulation results from Fig. 3 and Table 5 indicate that the best settling and disturbance rejection times are obtained with the FO-PI controller tuned according to the method described in Subsection A, at the expense of a very large overshoot. The smallest overshoot is obtained with the FO-PI controller in Subsection D. A comparison of the overall results obtained in Tables 4 and 5 with those from Table 1, indicate that the FO-PI controller tuned according to Subsection D is the most robust, with the smallest variation in the overshoot, settling time and disturbance rejection time. At the same time, it offers good results for the nominal case.

**Table 4.** Closed loop results obtained with the FO-PID controllers for the delay dominant process with -30% delay variation

| Controller | Overshoot | Settling time | Disturbance rejection time |
|---|---|---|---|
| FO-PI$_A$ | 4.4% | 4.489 | 1.847 |
| FO-PID$_B$ | 12.9% | 10.445 | 8.305 |
| FO-PI$_C$ | 5.4% | 6.214 | 2.309 |
| FO-PI$_D$ | 6.3% | 7.063 | 2.309 |

**Table 5.** Closed loop results obtained with the FO-PID controllers for the delay dominant process with +30% delay variation

| Controller | Overshoot | Settling time | Disturbance rejection time |
|---|---|---|---|
| FO-PI$_A$ | 29.0% | 2.879 | 3.334 |
| FO-PID$_B$ | 17.6% | 9.828 | 8.583 |
| FO-PI$_C$ | 15.2% | 4.964 | 4.325 |
| FO-PI$_D$ | 12.0% | 6.305 | 4.344 |

*The Lag Dominant Process*

The following lag dominant process is considered:

$$P(s) = \frac{2.4351}{12.5698s+1} e^{-1.0787s} \qquad (16)$$

For the process in (16), $k$=2.4315, $L$=1.0787, $T$=12.5688. The critical gain is $k_{cr}$=7.78 and the critical period of oscillation is $P_{cr}$=4.175, which can be obtained via the relay test.

The FO-PI tuned according to the F-MIGO method described in Subsection A is given by:

$$C_{FO-PI_A}(s) = 1.54\left(1 + \frac{1}{5.03s^{0.7}}\right) \quad (17)$$

The method from Subsection D is used to determine the parameters of a FO-PI controller:

$$C_{FO-PI_D}(s) = 1.09\left(1 + \frac{1}{13.74s^{1.15}}\right) \quad (18)$$

The autotuning method in Section E is used to tune a FO-PID controller:

$$C_{FO-PID_E}(s) = 1.92\left(1 + \frac{1}{0.86s^{0.8}} + 0.4s^{0.69}\right) \quad (19)$$

Considering the nominal process model in (16), the closed loop simulation results regarding reference tracking and disturbance rejection were presented in [11] and are summarized in Table 6. The results in Table 6 show that the lowest overshoot is achieved using the FO-PI tuned according to the method in Subsection D, while the fastest setting and disturbance rejection times are obtained with the FO-PID autotuned based on the method described in Subsection E.

**Table 6.** Closed loop results obtained with the FO-PID controllers for the lag dominant process

| Controller | Overshoot | Settling time | Disturbance rejection time |
|---|---|---|---|
| FO-PI$_A$ | 13% | 15.7 | 17 |
| FO-PI$_D$ | 9% | 41 | 23.5 |
| FO-PID$_E$ | 12% | 11.5 | 13.5 |

Robustness tests are carried out next. A +30% gain variation is considered first. The closed loop simulation results are indicated in Fig. 4, with results summarized in Table 7.

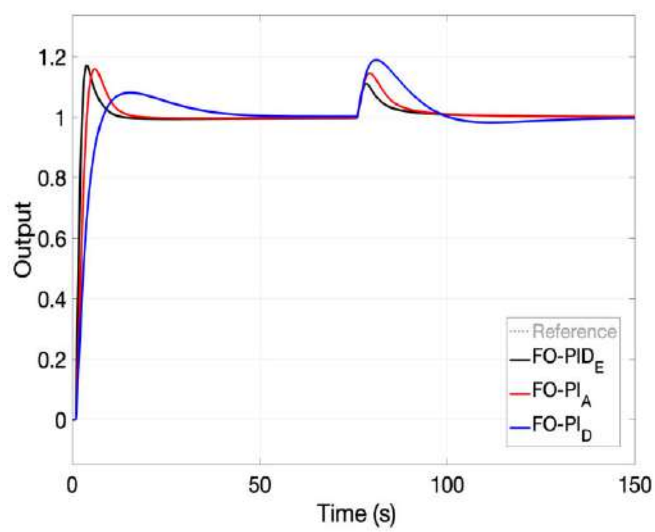


**Fig. 4.** Closed loop results obtained with the FO-PID controllers for the lag dominant process with +30% gain variation

**Table 7.** Closed loop results obtained with the FO-PID controllers for the lag dominant process with +30% gain variation

| Controller | Overshoot | Settling time | Disturbance rejection time |
|---|---|---|---|
| FO-$PI_A$ | 16.0% | 12.74 | 17.18 |
| FO-$PI_D$ | 8.1% | 35.78 | 21.65 |
| FO-$PID_E$ | 17.2% | 9.68 | 13.65 |

A -30% gain variation is also considered and the results are given in Fig. 5 and Table 8.

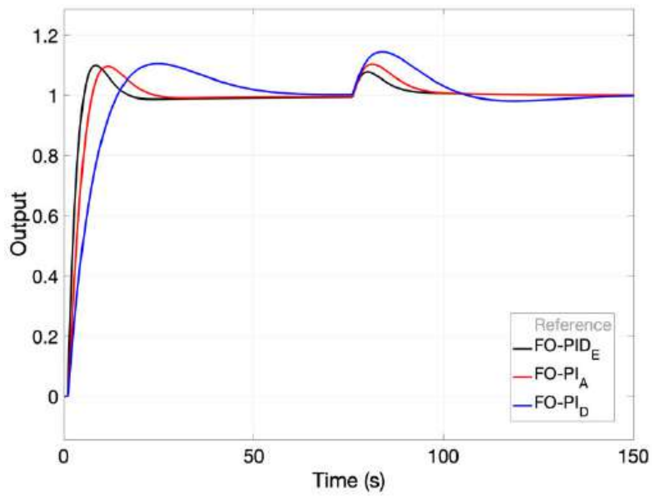


**Fig. 5.** Closed loop results obtained with the FO-PID controllers for the lag dominant process with -30% gain variation

Comparing these results with those summarized in Table 6 for the nominal case suggests that the FO-PI controller tuned according to Subsection D achieves the smallest variation in the overshoot. In terms of settling time and disturbance rejection time, the FO-PID controller is a better choice. However, note that this is to be expected since the controller exhibits derivative action, unlike the other two controllers.

**Table 8.** Closed loop results obtained with the FO-PID controllers for the lag dominant process with -30% gain variation

| Controller | Overshoot | Settling time | Disturbance rejection time |
|---|---|---|---|
| FO-$PI_A$ | 9.7% | 20.27 | 18.61 |
| FO-$PI_D$ | 10.6% | 49.78 | 26.89 |
| FO-$PID_E$ | 10.0% | 14.76 | 12.07 |

The third and fourth tests refer to delay variations which are prone to destabilize the closed loop system. In this case, a ±30% delay variation is considered and the three controllers in (17)-(19) are compared. The closed loop simulation results are indicated in Fig. 6 and 7, while Tables 9 and 10 summarize the performance measures.

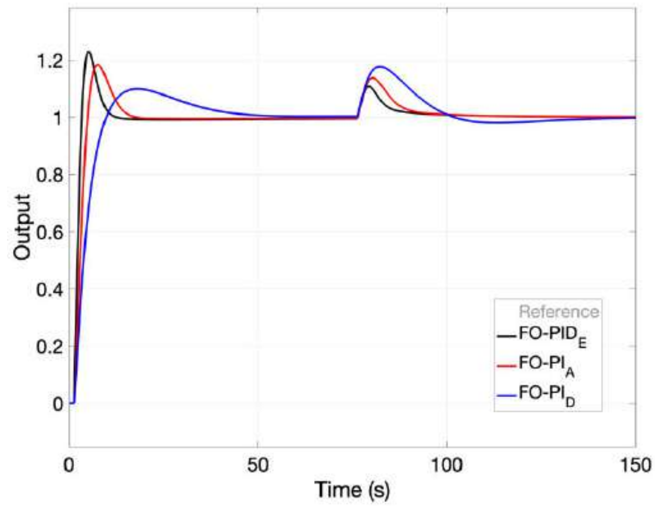


**Fig. 6.** Closed loop results obtained with the FO-PID controllers for the lag dominant process with +30% delay variation

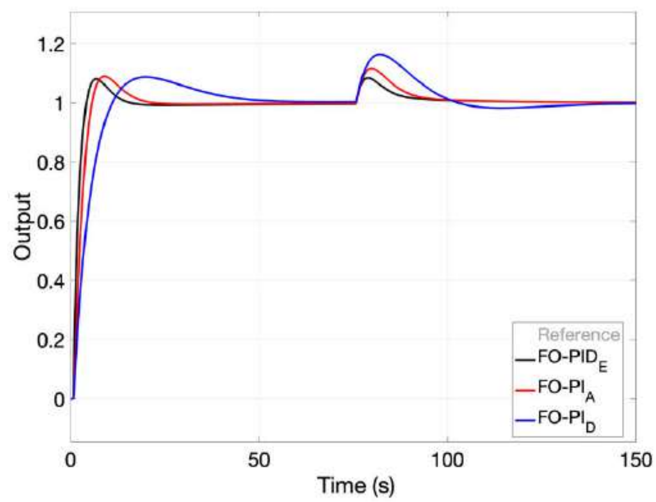


**Fig. 7.** Closed loop results obtained with the FO-PID controllers for the lag dominant process with -30% delay variation

Comparing the nominal closed loop result from Table 6 with those in Table 9 and 10 clearly shows that the most robust controller is the FO-PI tuned according to the method in Subsection D. In this case, the overshoot, settling time, as well as disturbance rejection time are maintained close to the nominal values despite delay variations. A large increase in the overshoot for the other two fractional order controllers occurs when +30% delay variation is considered. Note that in case of settling time or disturbance rejection time, the FO-PID tuned using the method from Subsection E manages to achieve the minimum values.

**Table 9.** Closed loop results obtained with the FO-PID controllers for the lag dominant process with +30% delay variation

| Controller | Overshoot | Settling time | Disturbance rejection time |
|---|---|---|---|
| FO-PI$_A$ | 18.4% | 14.553 | 16.330 |
| FO-PI$_D$ | 9.9% | 40.153 | 23.310 |
| FO-PID$_E$ | 23.0% | 10.256 | 12.811 |

**Table 10.** Closed loop results obtained with the FO-PID controllers for the lag dominant process with -30% delay variation

| Controller | Overshoot | Settling time | Disturbance rejection time |
|---|---|---|---|
| FO-$PI_A$ | 8.9% | 16.639 | 17.659 |
| FO-$PI_D$ | 8.7% | 41.608 | 23.710 |
| FO-$PID_E$ | 8.1% | 12.363 | 13.830 |

For lag dominant systems, the most robust controller is the FO-PI tuned using the method described in Subsection D. This maintains an almost constant and low overshoot despite significant variation in the process gain or time delay. On the other hand, it achieves a large settling time. A smaller settling time is possible, but it will lead to an increase in the overshoot and less robustness. Fig. 4-7 also show that, even though less robust, the FO-PID tuned using the approach in Subsection E is able to achieve small settling and disturbance rejection times.

## CONCLUSIONS

Tuning controllers without a process model can speed up and ease the entire design procedure. In the case of fractional order controllers any simplification in the design is desirable, since the overall tuning of these complex controllers can turn out to be a tedious and time-consuming task.

Several autotuning methods for fractional order controllers have been developed over the past 15 years. Most require simple experimentally obtained information such as estimation of process gain, time constant, time delay, critical gain, critical frequency/period of oscillation, magnitude, phase or phase slope at a specific frequency. Based on these, tuning rules have been designed for different types of processes.

In this manuscript, the most suitable autotuning methods of fractional order controllers for time delay processes are reviewed in terms of robustness to gain and delay variations. The autotuning methods considered in this manuscript are selected according to some recent research regarding their performance in terms of reference tracking and disturbance rejection.

Only time delay processes are considered in the comparison. Simulation results for both lag and delay dominant processes are performed. The closed loop results indicate that some of the fractional order controllers are more robust than others, while some autotuning methods should be preferred depending on the process type and performance criteria. Further research on this topic should include discussions regarding the control effort, as well as experimental validation on time delay processes.

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