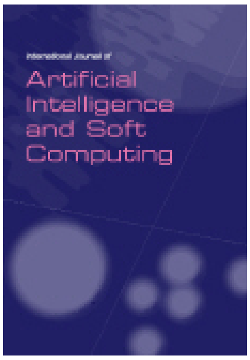

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Improved moth flame optimisation succored FOPID controller of integrated industrial processes with delay time

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Abstract: The control of industrial process in the presence of delay time is a demanding benchmark control issue. The conventional feedback controllers and tuning approaches do not provide the controller with enough robustness to prevent delay time. Using a conventional control scheme is ineffective, and so the fractional order proportional integral derivative controller (FOPIDC) is preferred. This paper focuses an efficient optimisation control for industrial processes with delay time. The proposed technique is the execution of the improved moth flame optimisation (IMFO) scheme. This paper concentrated on three main contributions to the optimal tuning of the parameters of the FOPID controller, such as crow search optimisation (CSO) control, whale algorithm optimisation (WAO) and the proposed IMFO control. The performances of the methods are evaluated based on transient responses, convergence rate and bode plot-based stability analysis to demonstrate the effectiveness of the proposed IMFO technique in enhanced system operation.

Keywords: delay time; tuning of FOPID; IMFO algorithm; crow search optimisation; CSO; algorithm; whale algorithm optimisation; WAO algorithm.

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1 Introduction

The philosophy of fractional order PID (FOPID) controller was taught by Podlubny (1999). In control systems, in order to get more accurate models fractional calculus is used, new control policies are developed and improves the performance of the system. The control action applied to the computed process variable in industrial processes that incorporate delay time (DT) will only be transferred to the controlled variable after the DT (Badri and Tavazoei, 2013). The technical description of the DT is the interval of time between the commencement of the response of the measured process variable and the controller output signal. Modern industrial systems are more complicated and more than 90% are managed by proportional integral (PI) or proportional integral derivative (PID) controllers, 80% of which are not tuned properly (Das et al., 2012). The performance of a traditional PID controller that has been fine-tuned directly suffers, especially when the DT exceeds the dominant process time constant (Bingul and Karahan, 2018). The DT is caused by the time needed for the transit and propagation of system constraints including energy, mass, and information (Gozde and Taplamacioglu, 2011). The DT complicates the analysis of the control system in addition to causing the coup of the target. Pruning the controller gain is necessary to maintain stability, however this causes slow reactions. The stability problems are made worse by the resulting unbounded phase angle (Hamamci et al., 2008). The phase shift is purportedly proportional to frequency, with the proportionality constant being determined by the DT. The phase margin is noticeably reduced in the Bode plot, despite the fact that the amplitude characteristics and Gain crossover frequency are unaffected by the DT. (Podlubny, 1999; Mirjalili and Lewis, 2016) explored FOPID controller and modelling. In control systems, in order to get more accurate models fractional calculus is used, new control policies are developed and improves the performance of the system. Process control will make use of fractional calculus in order to improve modelling accuracy and resilience. The FOPID's superiority has been supported in a number of examples (Mirjalili, 2015). The most generalised variation of the traditional PID controller is the FOPID controller. There are two components: an integrator and a differentiator with the orders and, respectively. The more adjustable factors there are, the more stabilising knowledge and freedom there is for tuning (Mosaad et al., 2019). The FOPID's key advantages over its rival are structural simplicity, increased disturbance rejection, better set point tracking, confronting of system uncertainties, etc. The analytical methods are not advised for tuning FOPID controllers due to the unfavourable results. The FOPID has been tuned using a number of different techniques (Padula and Visioli, 2011). Using the model reduction method and the optimisation method, Das et al. modelled the FOPID controller in 2011. They focused on higher-order systems. An Artificial Bee Colony (ABC) algorithm-tuned PID controller has been put out by Godze and Taplamacioglu (2011). In 2015, Mirjalili exploited the moth's navigation property in high performance computing to build processes. IMFO is a meta-heuristic algorithm that is more adjustable, simple, and easy to create than other meta-heuristic algorithms. MFO can be used to tackle a wide range of problems in a variety of applications. Moths are microscopic insects that live in polar environments and have dust-like scales on their wings, body, and legs. In comparison to butterflies, moths have wider bodies and a blander colour. In this paper, the IMFO technique is employed for tuning the PID and FOPID controller parameters. The effectiveness of IMFO is proved through the comprehensive comparison with the WAO and CSO optimisation methods. The rest of the paper is systematised as follows. Section 2 states the theory of controllers and the key of used IMFO. Section 3 embraces the execution of and analysis using the simulation results attained in MATLAB/SIMULINK with exhaustive discussions. Finally, Section 4 concludes the paper.

2 Controllers and IMFO

As previously stated, PID controllers constitute the majority of the feedback controllers utilised in industrial processes. Peak overshoot, rising time, steady-state error, and settling time are some of the time domain specifications (TDSs) that the controller is tuned to enhance.

2.1 Proportional integral derivative controllers

Similarity with design specifications is necessary for the control of modern industrial processes. There are more than one ways to achieve this. Evidently, industrial automation necessitates uncomplicated control, basic implementation, cost-effectiveness, adequate resilience, etc. For many applications, the pure PID controllers are utilised most frequently. The following is the given TF GPID(s) for a traditional PID controller.

$$GPID(s) = \frac{u(s)}{E(s)} = k_p + \frac{K_i}{s} + k_d s \tag{1}$$

where K_p, K_i and K_d are the proportional, integral and derivative constants, accordingly.

2.2 Fractional order PID controller

The FOPID controller is a classical PID controller that employs fractional calculus. For many decades, PID controllers were frequently utilised in industry for process control applications. Their strength is in their design simplification and superior performance, like minimal overshoot and settling time Because PID controllers are so important, continuous efforts are made to enhance their quality and reliability. In the field of automatic control, FO controllers, a generalisation of classical integer order controllers, would result in more accurate and stable control performances. Though it is true that fractional order models need FO controllers for optimal performance, in most cases, FO controllers are most often used on conventional linear or nonlinear dynamics to improve system control performance. In automatic industrial applications, the FOPID controller with non-integer derivation and integration is very useful to enhance control system performance. These remarkable features gained the attention of researchers and practicing experts, who tries to address the DT challenge. The DT renders traditional ways of evaluating phase and amplitude margins, as well as robustness, ineffective. The Laplace transform of the FOPID controller offered below.

$$C(s) = K_p + \frac{K_I}{s^{\lambda}} + K_d s^{\mu} \tag{2}$$

where λ and μ indicates the order corresponding to the integrator and differentiator, accordingly.

2.3 Improved moth flame optimisation

An improved moth flame optimisation (IMFO) algorithm is employed to enhance the moth's global exploration ability. The basic concept is based on the night time activities of moths. Moths are little insects that resemble butterflies in appearance. Moths fly at night by keeping their angles aligned with the direction of the moon. The IMFO is a powerful mechanism for determining the best solution. The essential truth about moths is their unique night time navigation habits. The moths are fluttering in the direction of the moonlight. The moths are flying in a straight line for a long distance. The IMFO is mostly based on the MFO concept, with the track of moths in original spirals surrounding the flame being modified. The IMFO steps are as follows

Step 1 Initialise the parameters-initialise the input parameters such as k_p, k_i k_d, λ and μ of FOPID controller, population size, and maximum number of iteration.

Step 2 Random selection of control parameters-the controller parameters k_p, k_i k_d, λ and μ are randomly generated using equation (3).

$$x_i = \left\lfloor k_p^1 k_i^1 k_d^1 \lambda^1 \mu^1 \quad k_p^2 k_i^2 k_d^2 \lambda^2 \mu^2 \quad \ldots\ldots k_p^n k_i^n k_d^n \lambda^n \mu^n \right\rfloor \tag{3}$$

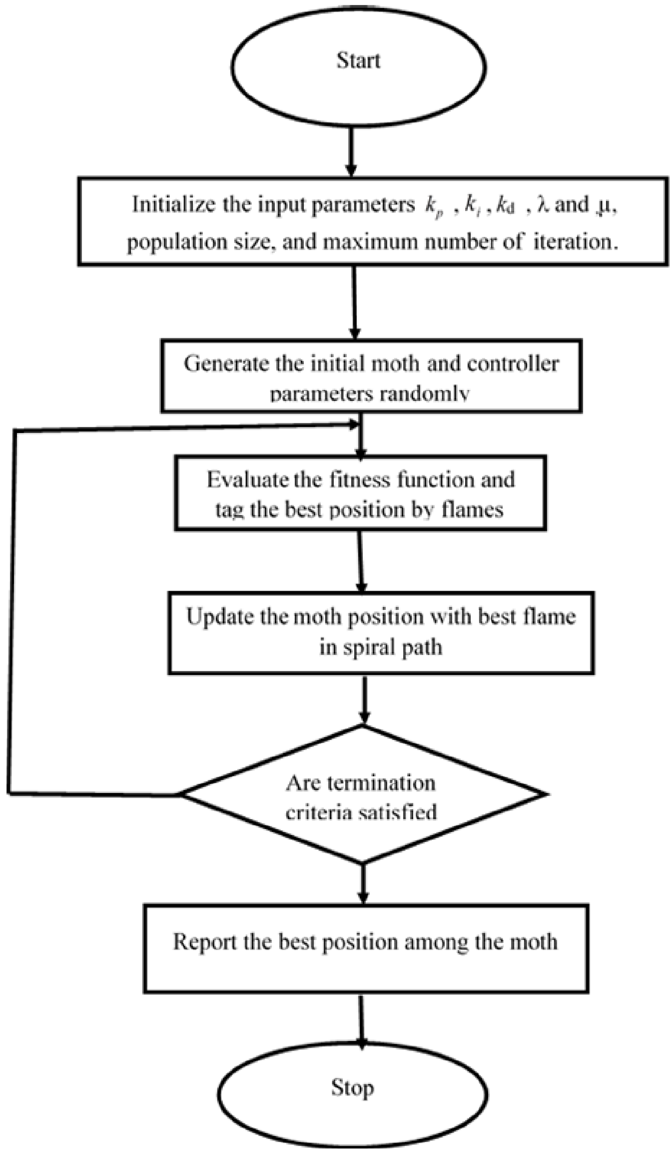
Step 3 Objective function calculation: the objective function is applied to search space. The fitness function evaluation equation is presented below.

$$F = \min \ \{ITAE\} \tag{4}$$

where *ITAE* represents integral time absolute error, which can be calculated using equation (5)

$$ITAE = \left(W_r^* - W_r\right)^2 \tag{5}$$

Figure 1 Flow chart of IMFO



Step 4 Updating the position: the moth's location is updated in terms of the best flame.

$$x_i^j = x_{\min}^j + rand[0,1]\left(x_{\max}^j - x_{\min}^j\right) \tag{6}$$

where $j = (1, 2, 3...n)$

X_{ij} – denote the neighbourhood solution.

Step 6 Check the iteration: if the iteration limitation has been reached, proceed to termination; otherwise, adjust the iteration number and return to Step 2 to develop the control parameters again.

Step 7 Termination: when the maximum number of iterations has been achieved, the moth may have found an effective flame in the search space, which is the best solution to the problem. As a result, once the maximum iteration has been reached, the optimal gain values of the FOPID controller parameters have been found.

2.4 Controller performance measure

To minimise the error signal for better responsiveness, the objective function or controller performance measurements are applied. Different performance metrics, such as integral absolute error (IAE), integral time-weighted-absolute error (ITAE), integral square error (ISE), integral time square error (ITSE), etc., are frequently employed for controllers. In the proposed method the used performance measures are ITAE. The ITAE performance metric enhance the absolute error and settling time, which are not consummate by others. In the closed loop response of the system, the minimisation of ITAE results in minimal overshoot and oscillation. These system appearances for the controller parameter through informative time-domain specifications and time integral performance measure. The mathematical expression of ITAE is represented in the equation (7)

$$J = \int_0^\infty t\,|\,e(t)\,|\,dt \tag{7}$$

The above system is subjected to some industrial test bench model .Simulation studies are carried for the below processes.

3 Simulation result and discussion

The simulation results used to verify the efficacy of the suggested industrial processes with DT based on the FOPIDC adjusted by IMFO algorithm are presented in this section. The IMFO-FOPIDC parameters are chosen in this proposed strategy for regulating the industrial processes

- Case study 1: Consider the third-order process with DT described in Das et al. (2011), in which the authors applied the model reduction method to formulate FOPIDC. The third-order DT system equation (8) is shown below.

$$P_2(S) = \frac{9e^{-s}}{(s+1)(s^2+2s+9)} \tag{8}$$

  The lower limit and upper limit are set, 0≤ $K_p \le 2.5$, $0 \le K_i \le 1.5$, $0 \le K_d \le 2.5$, $2 \le \lambda$, $\mu \le 1$. During the design of WAO-FOPIDC for third-order process with DT, the following parameter settings are as SA = 50, a maximum count of iterations = 100.

- Case study 2: Consider the fourth order DT process described in Das et al. (2011). The equation (9) for fourth-order DT process is shown below.

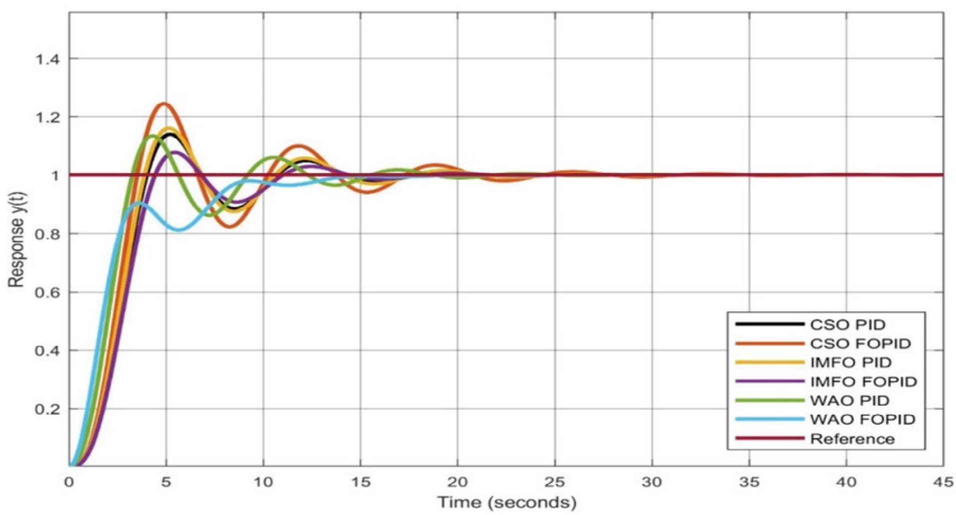
$$P_3(S) = \frac{e^{-s}}{(s+1)^4} \tag{9}$$

The parameter settings are as follows: SA = 50, maximum count of iterations = 100.

3.1 Comparative response of case study 1 with DT

It focuses on the simulation results and comparative performances of CSO-PID, CSO-FOPID, IMFO-PID, IMFO-FOPID, WAO-PID and WAO-FOPID controllers, both in the absence and presence of disturbances. Figure 2 shows the comparative response of case study 1 with optimisation of PID and FOPID controllers in the absence of disturbance and in the presence of disturbances; they are shown in Figure 3.

Figure 2 Comparative response of case study 1 with optimisation in the absence of disturbance (see online version for colours)



3.2 Simulation results of set point tracking performance for process 2

Set point tracking performance for case study 1 was performed.

Table 1 Time domain specifications for process 2

Controller		*CSO-PID*	*CSO-FOPID*	*IMFO-PID*	*IMFO-FOPID*	*WAO-PID*	*WAO-FOPID*
Time domain	Rise time (sec)	1.030	1.028	1.058	1.028	1.046	1.02
	Settling time (sec)	36.726	26.958	26.160	15.080	18.414	12.073
	Peak time (sec)	5.1	5	5	4.9	4.2	2.5
	Over shoot (%)	11.882	10.107	9.553	8.567	11.331	9.331

The initial operating point was reference magnitude and the designed controller was able to achieve the set point. Later, at time t = 25 sec, the operating point was changed to 0.5 magnitude, as shown in Figure 4.

Figure 3 Comparative response of case study 2 with optimisation in the presence of disturbance of 0.4 magnitude at t = 25 sec (see online version for colours)

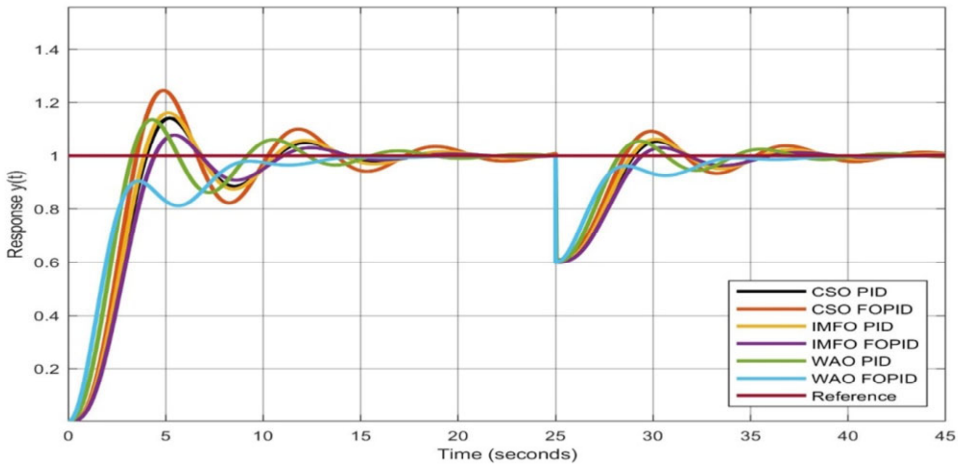
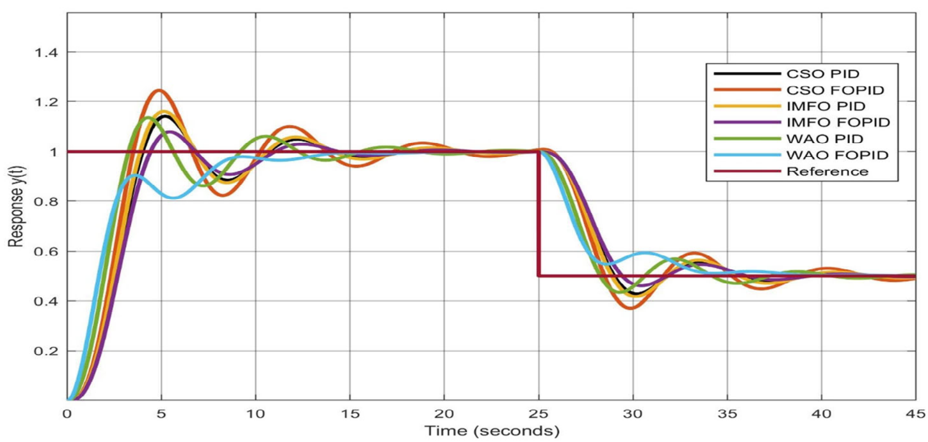


Figure 4 Simulation results of set point tracking performance for case study 1 (see online version for colours)



3.3 Simulation results of bode plot based stability analysis for case study 1

It focuses on the simulation results of bode plot based stability analysis for case study 1 with IMFO optimisation using PID and FOPID controllers. The bode plot is shown in Figures 5 and 6.

Figure 5 Bode diagram for case study 1 with delay time using IMFO-FOPID controller (see online version for colours)

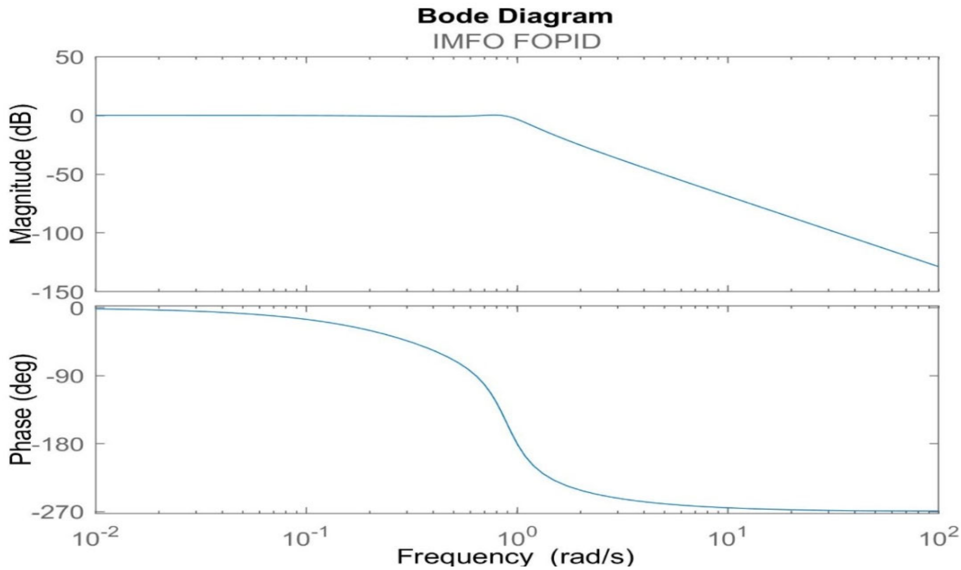
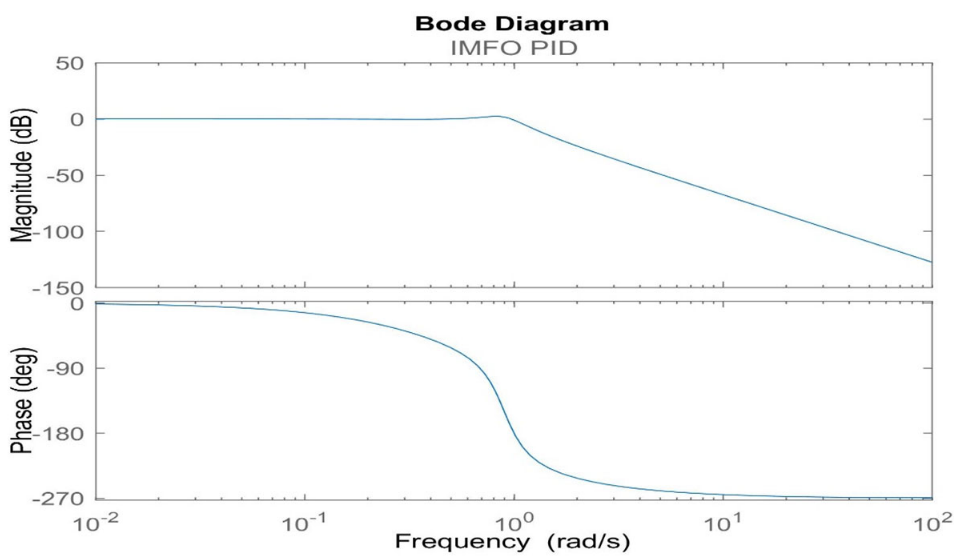


Figure 6 Bode diagram for case study 1 with delay time using IMFO-PID controller (see online version for colours)



The frequency response characteristics of the IMFO tuned PID and FOPID for case study 2 are considered by considering bode plot analysis. In Table 2, the bandwidth, phase margin, gain margin, and peak gain are given for the IMFO tuned PID and FOPID controllers. Furthermore, the obtained values are compared with the PID and FOPID controllers optimised by the CSO and WAO algorithms. It has been observed from the bode plot that the proposed IMFO-FOPID controller exhibits the maximum phase margin, gain margin, and minimum bandwidth. Thus, the bode analysis of the proposed IMFO tuned FOPID controller for case study 1 gives a stable frequency response.

Table 2 Frequency domain specifications for case study 1

Controller		*CSO-PID*	*CSO-FOPID*	*IMFO-PID*	*IMFO-FOPID*	*WAO-PID*	*WAO-FOPID*
Frequency domain	Peak margin (dB)	1.56	1.42	1.51	1.45	0.469	0.52
	Gain margin (dB)	37.6	38.3	37.8	38.9	38.2	41
	Phase margin (degree)	176	179	177	180	178	180
	Bandwidth (rad/sec)	7.8	7.2	7.6	6.8	7.2	6.4

Note: Fitness comparison in case study 1.

Figure 7 Fitness comparisons in case study 1 (see online version for colours)

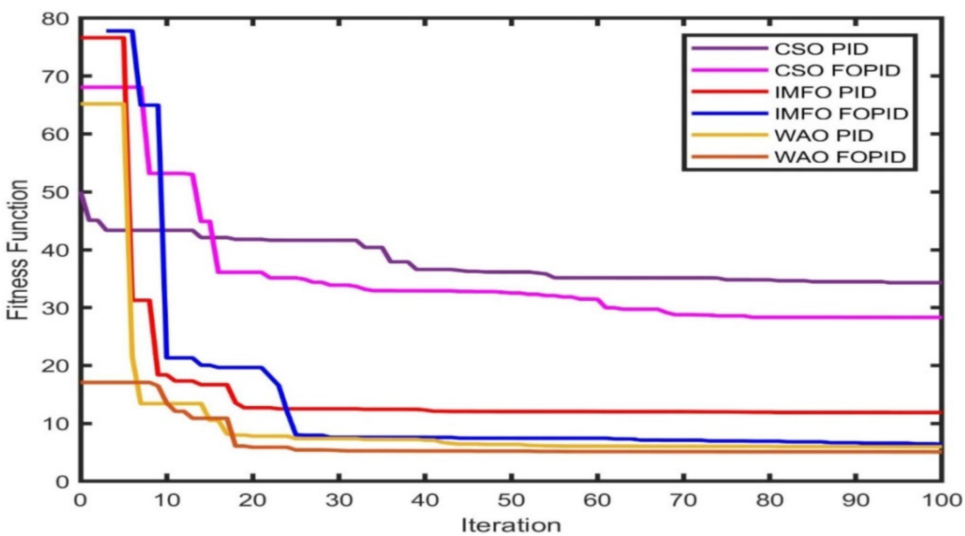


Figure 7 depicts the fitness comparison of IMFO-FOPID and other existing methods. Compared to the CSO and WAO, the fitness range of IMFO-FOPID is better and maintained at 6.8 after 20 iterations. The fitness function is computed in the proposed IMFO-FOPID, based on the ITAE in the higher order process with dead time.

3.4 Case study 2: comparative response of case study 2 with DT

It focuses on the simulation results and comparative performances of CSO-PID, CSO-FOPID, IMFO-PID, IMFO-FOPID, WAO-PID, and WAO-FOPID Controllers, both in the absence and presence of disturbances. Figure 8 shows the comparative response of case study 2 with optimisation of PID and FOPID controllers in the absence of disturbance, and in the presence of disturbances, they are shown in Figure 9.

Figure 8 Comparative response of case study 2 with optimisation in the absence of disturbance (see online version for colours)

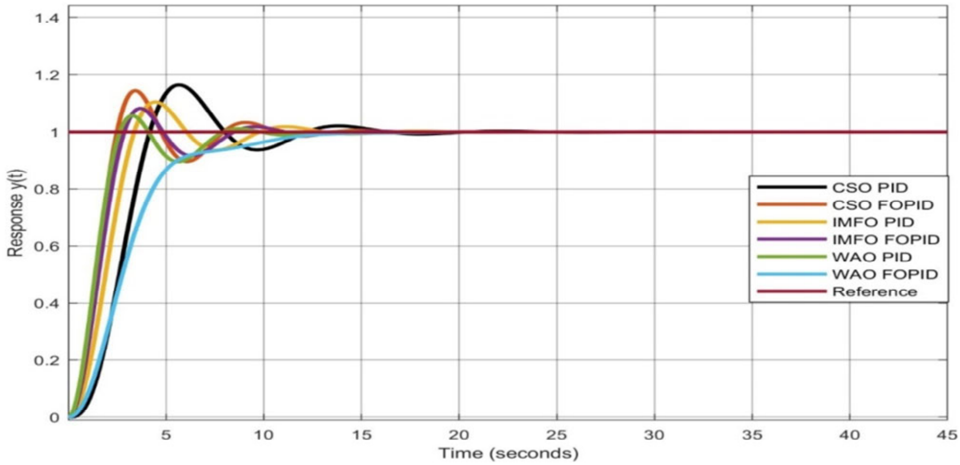
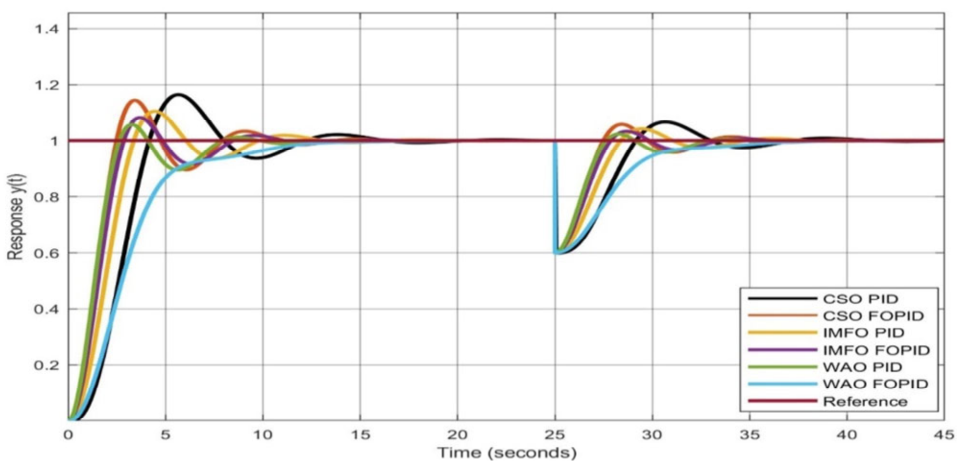


Figure 9 Comparative response of case study 2 with optimisation in the presence of disturbance of 0.4 magnitude at t = 25 sec (see online version for colours)



Set point tracking performance for case study 2 was performed.

Table 3 Time domain specifications for case study 2

Controller		*CSO-PID*	*CSO-FOPID*	*IMFO-PID*	*IMFO-FOPID*	*WAO-PID*	*WAO-FOPID*
Time domain	Rise time (sec)	3.03	2.03	1.09	1.05	1.03	1.02
	Settling time (sec)	18.08	16.78	16.06	13.06	15.21	14.07
	Peak time (sec)	6	4	4.8	4.1	2.5	5
	Over shoot (%)	12.78	11.57	19.5	12.96	5.32	4.23

The initial operating point was reference magnitude and the designed controller was able to achieve the set point. Later, at time t = 25 sec, the operating point was changed to 0.5 magnitude, as shown in Figure 10.

Figure 10 Simulation results of set point tracking performance for case study 2 (see online version for colours)

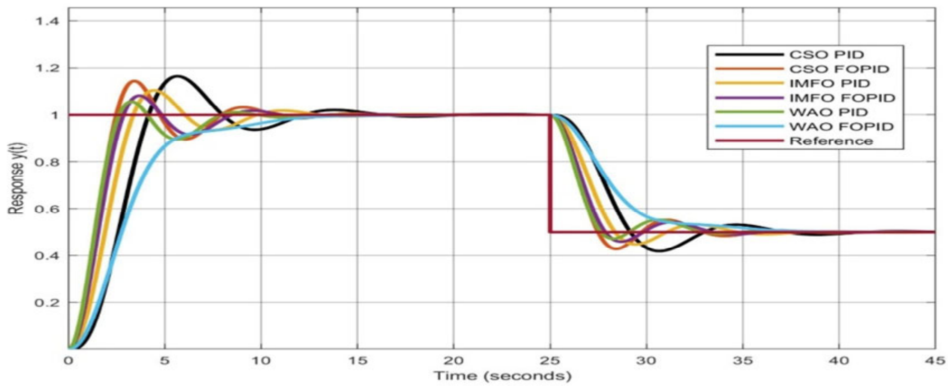
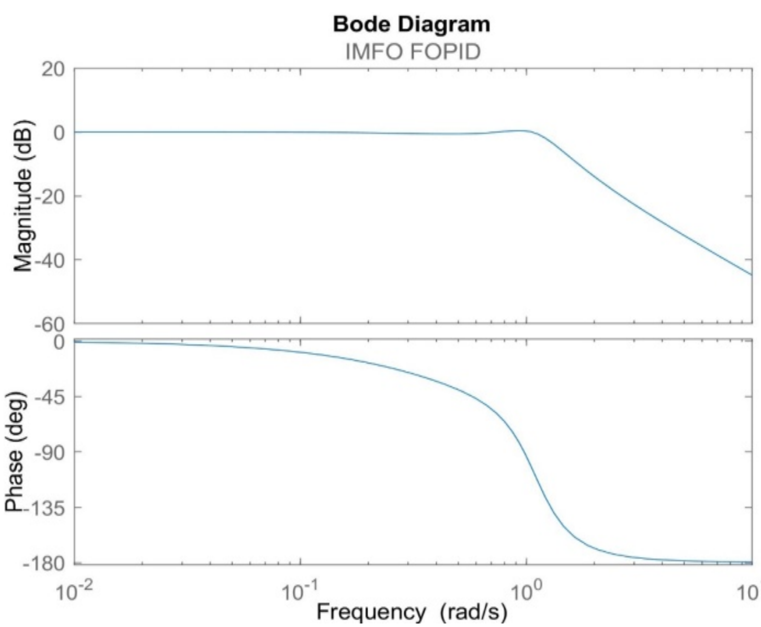


Figure 11 Bode diagram for casestudy2 with delay time using IMFO-FOPID controller (see online version for colours)



The frequency response characteristics of the IMFO tuned PID and FOPID for the case study 2 by considering the bode plot. In Table 4, the bandwidth, phase margin, gain margin, and peak gain are given for the WAO tuned PID and FOPID controllers. Furthermore, the obtained values are compared with the PID and FOPID controllers optimised by the CSO and IMFO algorithms. It has been observed from the bode plot that the proposed IMFO-FOPID controller exhibits the maximum phase margin, gain margin, and minimum bandwidth. Thus, the bode analysis of the proposed IMFO tuned FOPID controller gives a stable frequency response.

Table 4 Frequency domain specifications for case study 2

Controller		*CSO-PID*	*CSO-FOPID*	*IMFO-PID*	*IMFO-FOPID*	*WAO-PID*	*WAO-FOPID*
Frequency domain	Peak margin (dB)	1.36	1.32	1.41	0.35	0.64	0.42
	Gain margin (dB)	36.6	37.3	39.8	40.9	37.2	40.2
	Phase margin (degree)	177	179	176	179	176	178
	Bandwidth (rad/sec)	7.2	6.8	7.4	7.5	7.1	6.2

Figure 12 Fitness comparisons in process 2 (see online version for colours)

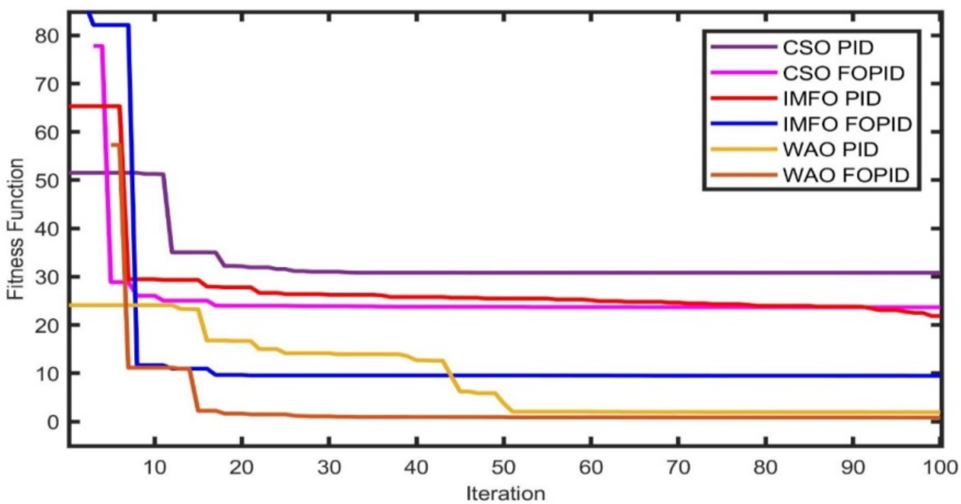


Figure 12 shows the fitness comparison of IMFO-FOPID and other existing methods. Compared to the CSO and IMFO, the fitness range of IMFO-FOPID is better and maintained at 0.18 after 15 iterations.

4 Conclusions

In this paper, optimal tuning of the FOPID controller using meta-heuristic algorithms such as crow search optimisation (CSO), IMFO and whale algorithm optimisation (WAO) for industrial processes with DT is evaluated using simulation. The comprehensive contemplation observed that many industrial processes include the DT resulting from the process time and the accumulation of time lags. For such processes, the traditional PID controller causes a rise in the loop variability due to these time lags, which produces high overshoot and takes more time in order to attain the desired output. However, the employment of the fractional calculus can able to improve the performance of the traditional PID controllers. That is, the fractional order controller, which incorporates the fractional (non-integer) differentiation and integration orders. This thesis examined two different processes with DT and the IMFO based tuning of the FOPID controller was also established. Minimisation of the ITAE has been the objective function. The performance of the IMFO tuned FOPID controller for the two different processes has been evaluated on the MATLAB/Simulink platform using the FOMCON toolbox. The efficacy of the IMFO tuning has been confirmed by a comprehensive result comparison of IMFO tuning with CSO and WAO algorithm based tuning methods. The major study approaches have been bode diagram based stability analysis and evaluation of TDSs .The IMFO requires lease time for the optimisation and best frequency response. The IMFO tuned FOPID controller minimises the peak overshoot by 86% and 78%, respectively, when compared to the CSO-FOPID and WAO-FOPID controllers in the case study 2.

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