Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 10, No. 4, December 2022, pp. 849~857
ISSN: 2089-3272, DOI: 10.52549/ijeei.v10i4.4034

Novel Robust Control Using a Fractional Adaptive PID Regulator for an Unstable System

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Article Info

Article history:

Received Jul 30, 2022
Revised Oct 29, 2022
Accepted Nov 14, 2022

Keywords:

Fractional systems,
Control theory
Fractional PID controller
Robustness analysis
Stability

ABSTRACT

Recent advances in fractional order calculus led to the improvement of control theory and resulted in the potential use of a fractional adaptive proportional integral derivative (FAPID) controller in advanced academic and industrial applications as compared to the conventional adaptive PID (APID) controller. Basically, a fractional order adaptive PID controller is an improved version of a classical integer order adaptive PID controller that outperformed its classical counterpart. In the case of a closed loop system, a minor change would result in overall system instability. An efficient PID controller can be used to control the response of such a system. Among various parameters of an instable system, the speed of the system is an important parameter to be controlled efficiently. The current research work presents the speed control mechanism for an uncertain, instable system by using a fractional-order adaptive PID controller. To validate the arguments, the effectiveness and robustness of the proposed fractional order adaptive PID controller have been studied in comparison to the classical adaptive PID controller using the criterion of quadratic error. Simulation findings and comparisons demonstrated that the proposed controller has superior control performance and outstanding robustness in terms of percentage overshoot, settling time, rising time, and disturbance rejection.

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1. INTRODUCTION

From the beginning of 19th century, the notion of using fractional order operator has been introduced in control theory [1]. Literature suggests that Liouville, Riemann, and Holmgren have presented the pioneer study in this context [1, 2]. The applications of fractional order differentiation have attracted the attention of researchers from a variety of science disciplines, especially in the fields of applied sciences [3, 4]. Numerous studies regarding feasible applications of fractional order differentiation in the field of engineering and technology have also been reported earlier [4,5].

The effect of instable systems can be controlled by adopting various practical methods such as an adaptive fractional-order switching-type control method, an adaptive fuzzy sliding-mode control method synchronization control method [6]. Among all these methods, the fractional order control system is the most reliable system being studied since last two decades [7,8].

In [9,10], Oustaloup and his co-workers proposed the robust feedback control by using phase constant property of Bode's transfer function against the variations in gain of the controller. The robustness is one of the main factors being studied extensively in the last decade because of the fact that robustness plays an important role in defining the practical viability of fractional order controllers against different noises and perturbations. The role of robust feedback control has very much importance in non-volatile fractional order systems [11-13]. A fractional-order controller for stabilizing an unstable open loop is proposed in [14-16]. In [17], adaptive fractional PID controller based on neural network is proposed. In [5,11,17,18], an adaptive fractional PID controller was investigated.

This work's primary contribution is using of novel fractional adaptive PID controller (FAPID) approach in order to reduce noise effect by introducing a fractional order integrator in the the conventional adaptive PID controller.The present work emphasizes on the improvement of classical feedback adaptive PID controller (APID) by implementing a fractional approach specifically, the introduction of fractional order integrator to control the noise effects. The manuscript is organized as; first we have discussed the fundamentals of a fractional order system followed by the study of algorithms for a fractional adaptive PID controller. Afterwards, the results obtained from simulation data are presented and lastly, the conclusions along with future perspectives of the study are given.

2. FRACTIONAL ORDER SYSTEMS

2.1. Fractional calculus

It is well-known that calculus is used to generalize the derivation or integration of various functions. However, a subfield of calculus is called fractional calculus, which normally uses non-integer order for the generalization of derivatives or integrals of a function. For instance, fractional calculus would help to evaluate n-fold integrals like $(d^q y/dt^q)$, where n represents the fractional, irrational or complex part. For purely fractional-order systems, n would be considered as fraction. It is worth mentioning that the real-world applications of fractional calculus grow rapidly owing to the fact that these mathematical aspects would help to express a system more precisely when compared with conventional classical methods. Factually, the real objects are found generally fractional, although fractionally is observed to be very low for most of them. The lack of solutions for fractional differential equations is one of the main reasons to study integer-order models. To date, many studies are available regarding the use of fractional calculus in many practical applications e.g. in controllers, capacitors, control theory and circuit analysis [19-21].

For differentiation and integration, a generalized fundamental operator being used is given as;

$$\mathrm{a}D_t^{\alpha} = \begin{cases} \frac{d^{\alpha}}{dt^{\alpha}} & , R(\alpha) > 0 \\ 1 & , R(\alpha) = 0 \\ \int_a^t (d\tau)^{-\alpha} & , R(\alpha) < 0 \end{cases} \tag{1}$$

Where, 'a' represents the lower limit of integration, 'T' represents the upper limit of integration, 'α' represents the order of fractional operator ($\alpha \in R$) and '$R(\alpha)$'represents the real part of α.

Since 19th century, the focus has been shifted towards development of fractional-order theory for derivatives. Amongst various definitions of fractional order derivative, the *Grünwald-Letnikov definition* is widely accepted one because of its suitability for control algorithms [22-24]. The Riemann-Liouville definition is the second most important definition of fractional order derivative being used.The Grünwald-Letnikov definition can be expressed mathematically as;

$$D^{\alpha} f(t) = \lim_{h \to 0} h^{-\alpha} \sum_{j=0}^{k} (-1)^j \binom{\alpha}{j} f(kh - jh) \tag{2}$$

Here, 'h' is the step time and the coefficients given in above relation can be evaluated from the expression given below;

$$\omega_j^{(\alpha)} = \binom{\alpha}{j} = \frac{\Gamma(\alpha+1)}{\Gamma(j+1)\Gamma(\alpha-j+1)}$$

The Riemann-Liouville definition can be expressed mathematically as:

$$f(t) = \frac{d^n}{dt^n} \int_0^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau \tag{3}$$

It is worth mentioning that as far as the problems of real-world applications are concerned, specifically applications from the field of physical and engineering sciences, the Riemann-Liouville and Grünwald-Letnikov definitions are taken as equivalent [6,25-28].

2.2. Approximation methods FOTF:

Literature suggested that there are several approximations are available for fractional order transfer functions (FOTF). All the available approximations demonstrate some advantages over the others in the context of a few characteristics. It is a bit difficult to say which approximation would deliver the best results. There are several characteristics that would decide the relative merits of any approximation, such as differentiation order, frequency behavior, time responses… etc. Several approximations are discussed here with respect to their comparative analysis with others. The available approximations belong to two different domains i.e. frequency and time domains which are specified as s-domain and z-domain, respectively. The approximations in frequency and time domains are also termed as continuous and discrete approximations.

2.2.1. Oustaloup approximation method

The Oustaloup pmethod is based on the function approximation from as;

$$G_f(s) = S^{\alpha} \qquad ,\alpha \in R^+ \tag{4}$$

By taking into account the rational function [29,30];

$$G_f(s) = K\prod_{k=1}^{N}\frac{s+w_k'}{s+w_k} \tag{5}$$

However, gain , zeros, and poles can be evaluated as:

$K = w_h^{\gamma}$, $w_k = w_b . w_u^{(2k-1+\gamma)/N}$, $w_k' = w_b . w_u^{(2k-1-\gamma)/N}$

Where $w_u$represents the unity gain in frequency and the central frequency in a geometrically distributed frequency band. Let,$w_u = \sqrt{w_h w_b}$, where w_h and $w_b$represent the upper and lower frequencies, respectively. γ and N are the orders of derivative and filter, respectively.

2.2.2. Charef 's transfer approximation method: SingularityFunction

The Charef 's transfer method is based on approximation of the function [11] :

$$G_f(s) = S^{\alpha} \qquad ,\alpha \in R^+$$

These processes in the frequency domain can be described by an approximation in the Laplace domain such as :

$$G_f(s) = s^{\alpha} \approx \left(1+\frac{s}{p_T}\right) \approx \frac{\prod_{i=0}^{N}(1+\frac{s}{P_i})}{\prod_{i=0}^{N-1}(1+\frac{s}{Z_i})} \tag{6}$$

Where $P_i = (ab)^i . P_0$, $i = 1,2,3,\dots,N$

$Z_i = (ab)^i . a . P_0$, $i = 2,3,\dots,N-1$ and $P_0 = P_T . 10^{\frac{e_P}{20\beta}}, \alpha = 10^{\frac{e_P}{10(1-\beta)}}$, $b = 10^{\frac{e_P}{10\beta}}$, $\beta = \frac{\log(a)}{\log(a.b)}$

2.3. The Fractionalized Integrator

The analysis of fractionalized integrator in the frequency domain is discussed below, keeping in view the applications of a fractional integrator regarding transfer functions of a feedback control system as specified in equation (1). Figure 1 shows the Laplace transform of a fractionalized integrator in order to depict the effectiveness of this method.

The integral operator $1/s$ is fractionalized in this case.

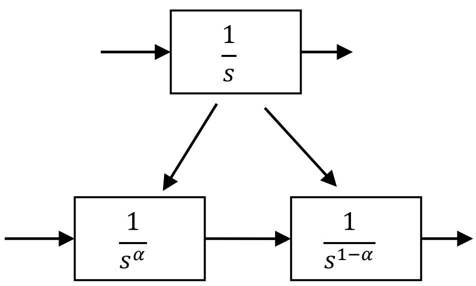


Figure 1. Proposed fractionalized integrator

The Fractionalized integrator is given by the folowing equation:

$$\frac{1}{s} = \frac{1}{s^{\alpha}}\frac{1}{s^{(1-\alpha)}} \tag{7}$$

here, 'α' is a real number i.e.,$0 < \alpha < 1$.

The Oustaloup and Charef approximation methods were used comparatively in the frequency domain between $\frac{1}{s}$ and the product of $\frac{1}{s^{\alpha}}$ and $\frac{1}{s^{1-\alpha}}$ as shown in Figure 2.

Bode's diagram of the original integrator depicts that the Charef approximation approach is better when compared with the Oustaloup approximation. For a particular interval of frequency, the product of filters resulted in a satisfactory approximation of the integral operator. As α is a real number abd if we take a fractional value of $\alpha = 0.4$ for example, we can get an approximated values between $\omega b = 0.1 rad/sec$, $\omega h = 1000 rad/sec$, $\delta = 1.5 d\beta$ by using the singularity approximation method.

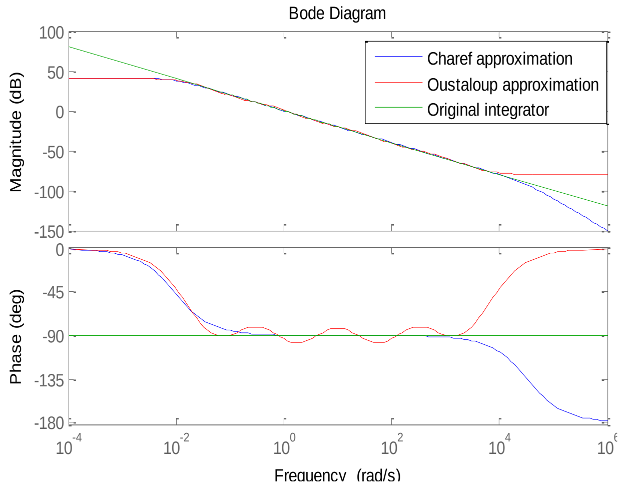


Figure 2. Frequency domain comparison of the Oustaloup and Charef approximations methods

3. CONTROL STRATEGY DESIGN

3.1 Integer adaptive PID Controller

The integer adaptive feedback control law is given by the equation 5, [30]:

$$u(t) = -k_c[k_1(t)e(t) + I\{k_2(t)e(t)\} + D(k_3(t)e(t))] \quad (8)$$

Where:

$$k_1(t) = k_p(t) + \alpha_1 k_i(t) + \alpha_3 k_d(t)$$

$$k_2(t) = \alpha_2 k_i(t)$$

$$k_3(t) = \alpha_4 k_i(t)$$

$$k_p(t) = e^2(t)$$

$$k_i(t) = I\{e^2(t)\}$$

$$k_d(t) = D\{e^2(t)\}$$

$$e(t) = y(t) - r(t)$$

Where k_c, α_1 and α_2 are positive constants.

A simple control system is shown in Figure 3. It is expected that the integral term in the controller (Equation 8) will help to eliminate the effects of constant disturbance in a closed-loop system without destroying its stability [25].

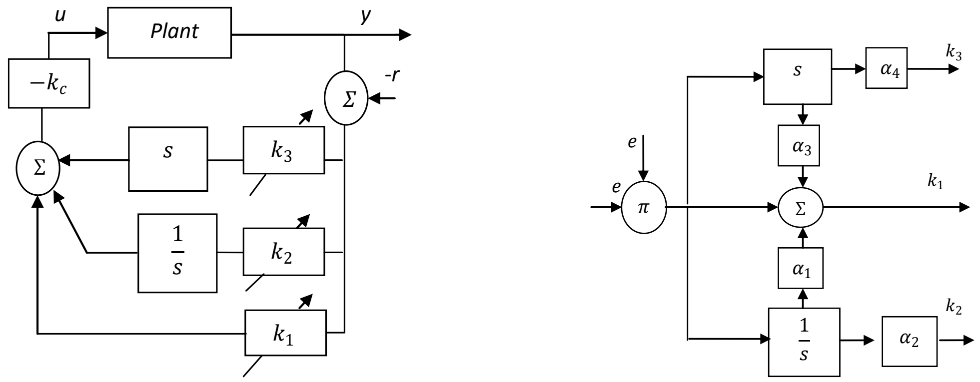


Figure 3. Classical Adaptive PID Control System

3.2 Fractional adaptive PI$^\lambda$D$^\mu$ Controller

The control law of Fractional adaptive feedback is given as;

$$u(t) = -k_c\left[k_1(t)\, e(t) + I^\lambda\{k_2(t)e(t)\} + D^\mu(k_3(t)e(t))\right] \quad (9)$$

Where: $k_1(t) = k_p(t) + \alpha_1 k_i(t) + \alpha_3 k_d(t)$

$k_2(t) = \alpha_2 k_i(t)$
$k_3(t) = \alpha_4 k_i(t)$
$k_p(t) = e^2(t)$
$k_i(t) = I^\lambda\{e^2(t)\}$
$k_d(t) = D^\mu\{e^2(t)\}$
$e(t) = y(t) - r(t)$

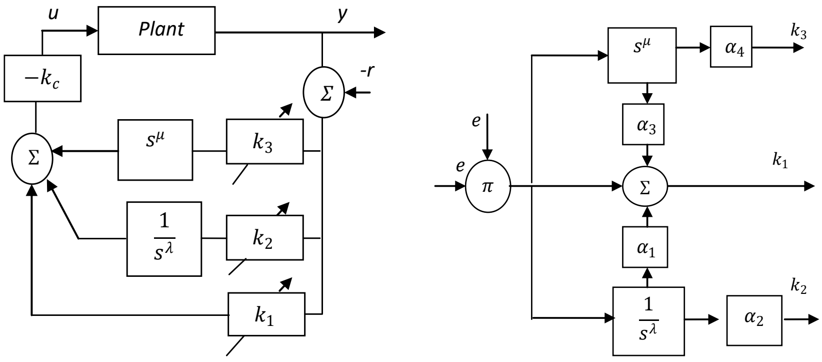


Figure 4. Fractional Adaptive PID Control System

4. RESULTS AND DISCUSSION

Remark 1: By applying the proposed adaptive controller with $e(t) = y(t) - r(t)$ instead of $y(t)$ can resolve the step reference tracking problem. The closed-loop system now becomes stable and satisfies the following limit;

$\lim_{t\to\infty} y(t) = r$, where r is a constant.

Remark 2: The tuning parameters $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and k_c will have an impact on the system's transient -term performance but not on the cost of stability of the system.

To accelerate the response, a large value of k_c can be taken although it requires bit higher input values. The α_1 and α_3 in the proportional process, α_4 in derivation and α_2 in integration process would definitely improve the rise time and offset removing without any requirement of higher initial input values.
However, the tuning of the system is application-dependent and needs more investigation regarding its practical viability.

An example from the literature is taken to validate the proposed robustness of proposed fractional adaptive controller [30]:

$$\begin{cases} \dot{x(t)} = Ax(t) + Bu(t) + d \\ y(t) = C\,x(t) \end{cases} \tag{10}$$

Where d is a constant perturbation vector and:

$$A = \begin{bmatrix} -3 & 0 & 0 \\ 1 & 2 & -1.414 \\ 0 & 1.414 & 0 \end{bmatrix}, b = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad c = [1 \quad 5 \quad 0], \quad d = [0.5 \quad 0.5 \quad 0.8]^T$$

By using the initial parameters as, $k_c = 5, \alpha_1 = 3000, \alpha_2 = 5000$, μ=0.5 and $\lambda = 0.3$, the simulation response is depicted in Figure 5.

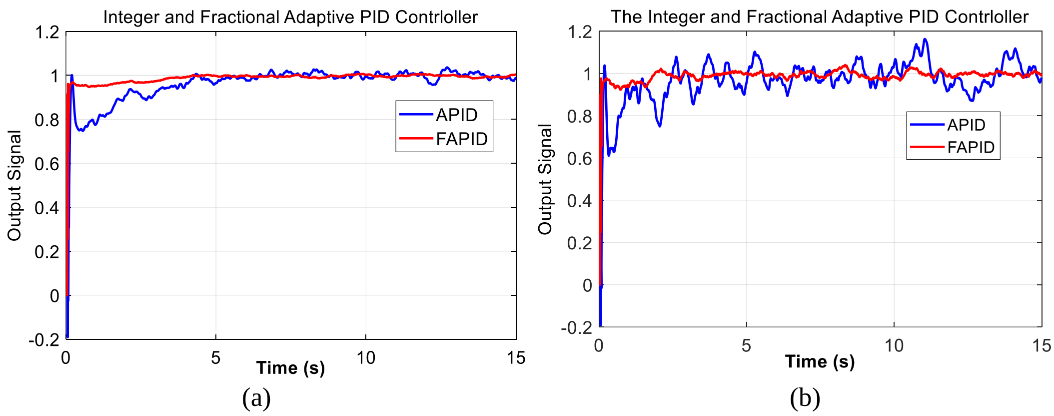
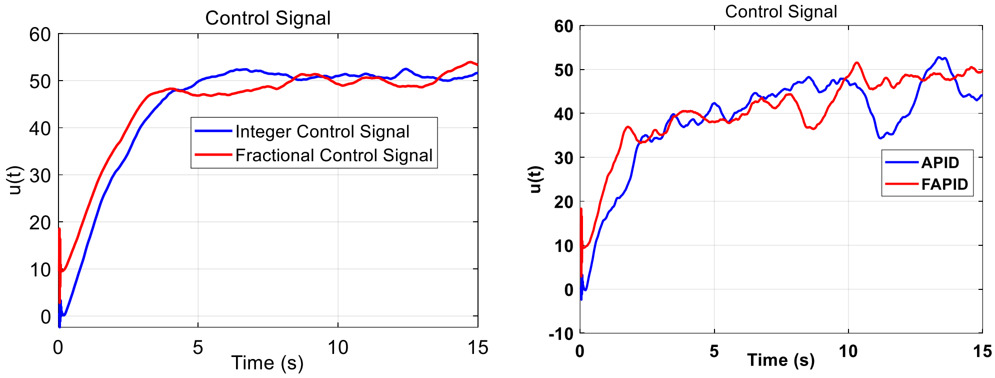


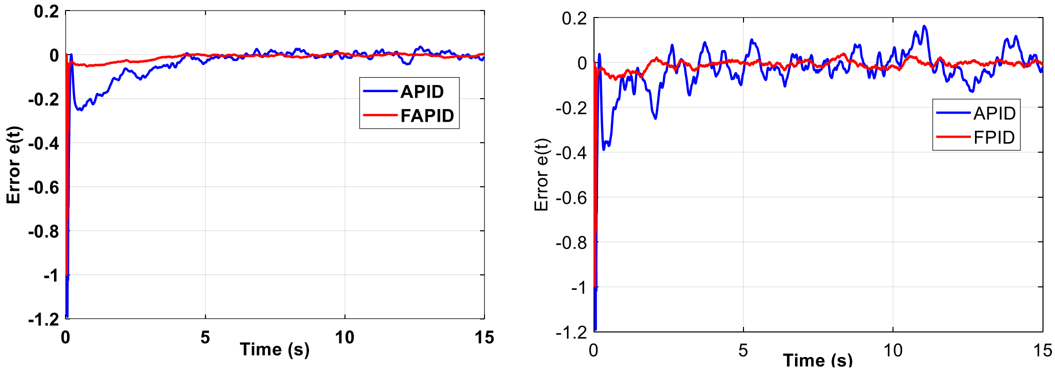
Figure 5. Comparison of the output for APID and FAPID with random output noise of :
(a) 5% of the reference signal amplitude and (b) 15 % of the reference signal amplitude

Figure 6 and 7 show the control signal and the error signal for a conventional and fractional order adaptive PID controller.



(a) (b)

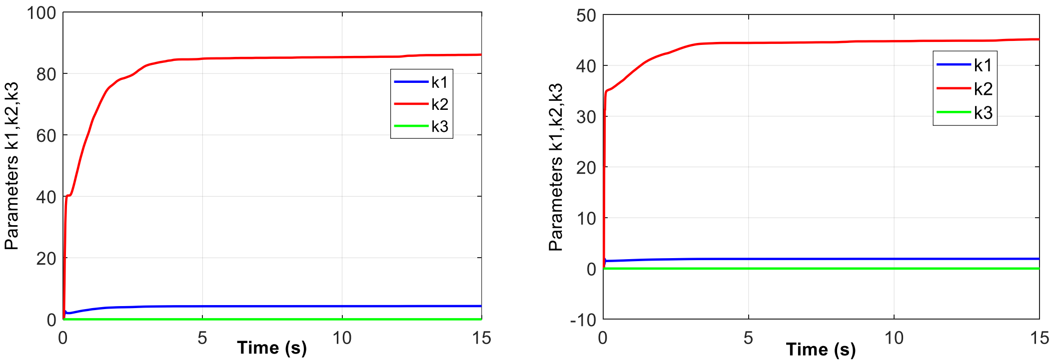
Figure 6. The Control signal for APID and FAPID with random output noise of :
(a) 5% of the reference signal amplitude and (b) 15 % of the reference signal amplitude



(a) (b)

Figure 7. The Error signal for of APID and FAPID with random output noise of :
(a) 5% of the reference signal amplitude and (b) 15 % of the reference signal amplitude

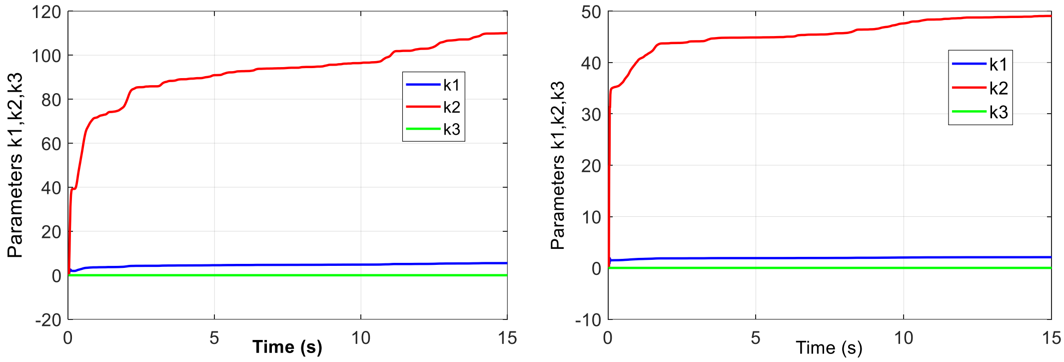
Figure 8 shows the evolutions of the k_1, k_2 and k_3 parameters with random output noise of 5% of the reference signal amplitude: (a) APID and (b) FAPID.



(a) (b)

Figure 8. Evolutions of k_1, k_2, k_3 parameters with random output noise of :
5% of the reference signal amplitude using: (a) APID and (b) FAPID

Figure 9 shows the evolutions of the k_1, k_2 and k_3 parameters with random output noise of 15% of the reference signal amplitude: (a) APID and (b) FAPID.



(a) (b)

Figure 9. Evolutions of k_1, k_2, k_3 parameters with random output noise of : 15% of the reference signal amplitude using: (a) APID and (b) FAPID

We remark that the fractional order adaptive PID controller has superior control performance and outstanding robustness in terms of percentage overshoot, settling time, rising time, and disturbance rejection compared with the integer order adaptive PID controller.

5. ROBUSTNESS ANALYSIS

A quadratic error criterion J was defined to evaluate the performance of proposed control system as;

$$J_{\infty} = \int_{t1}^{tf} (U_R(t) - Y(t))^2 dt \quad (11)$$

The noise reduction (Nr) percentage is given by:

$$N_r[\%] = \frac{min(J_{FAPID})}{J_{APID}} X100 \quad (12)$$

The criterion for quadratic error with random output noise of 5% with $\mu = 0.5$ and $\mu = 0.7$ are given in Table 1 and 2, respectively.

Table 1. The Criterion of quadratic error using random output noise of 5% with $\mu = 0.5$

	FPID ($\mu = 0.5$)									APID ($\mu = 1$)
λ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
J	**2.3**	2.5	**2.3**	2.8	2.6	2.4	2.7	**2.3**	**2.3**	6.2

Table 2. The Criterion of quadratic error using random output noise of 5% with $\mu = 0.7$.

	FPID ($\mu = 0.7$)									APID ($\mu = 1$)
λ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
J	3.5	3.4	3.7	3.6	**3.2**	3.4	3.7	**3.2**	3.3	6.2

The criterion for quadratic error with random output noise of 15% with $\mu = 0.5$ and $\mu = 0.7$ are given in Table 3 and 4, respectively.

Table 3. The Criterion of quadratic error for random output noise of 15 % with μ=0.5

	FPID ($\mu = 0.5$)									APID ($\mu = 1$)
λ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
J	4.6	4.5	**4.3**	4.9	4.7	5.1	4.7	**4.3**	4.5	9.8

Table 4. The Criterion of quadratic error for random output noise of 15% with $\mu = 0.7$

	FPID ($\mu = 0.7$)									APID ($\mu = 1$)
λ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
J	5.4	**5.3**	5.7	**5.3**	**5.3**	5.8	5.5	**5.3**	5.4	9.8

From Table 1−4, the nosie reductions (using Eq.12) are: 37.09%, 51.61%, 43.87%, and 54.08 respectively. It is observed that a fractional-order adaptive PID controller is able to reduce the noise effects between (37% to 54%) as compared to an integer-order adaptive PID controller.

6. CONCLUSION

In summary, a new comparison approach using Oustaloup and Charef approximations with a fractionalized integrator has been proposed to enhance the control of a closed-loop system. Furthermore, both fractional and integer PID controllers have been studied comparatively on the basis of reduction in noise and robustness of the control system. Simulation results show that the fractional-order adaptive PID controller is able to reduce the noise effects by up to 54% as compared to the integer-order adaptive PID controller. It is suggested that the proposed robustness of the system should be generalized in the future for other adaptive and non-adaptive control systems.

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