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Adaptive Repetitive Control for Periodic Disturbance Rejection with Unknown Period

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ABSTRACT

In this paper, an adaptive repetitive controller (ARC) is proposed to reject periodic disturbance with an unknown period. First, a repetitive controller is designed when the disturbance period is known. In this case, the RC time delay is equal to the period of disturbance. Then, the closed-loop system with the RC controller is analyzed and the effect of RC gain, k, is studied analytically. It is shown that by increasing k, the steady-state error is reduced. It is dependent on the speed of the response convergence. Secondly, an adaptive fast Fourier transform (AFFT) algorithm is proposed to extract the accurate period of disturbance adaptively. Simulation results show that the period is converged to its true value even though varying the period. Also, simulation results about the effect of controller gain are in good agreement with analytical results. Finally, it is shown that the proposed method can decrease the amplitude and energy of output signal significantly.

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I. Introduction

In control systems, the presence of disturbances is inevitable, so disturbance rejection is an important subject in the control theory [1]. In fact, the first motive for feedback control is to reject (attenuate) the effect of disturbances.

Disturbances are usually considered as a step type. Proportional-integral-derivative (PID) controller is a conventional approach for step disturbance rejection. This use of PID is based on the internal model principle (IMP) [2], [3]. On the other hand, in many applications, disturbances are not of step type, such as optical and magnetic disk drives, robot manipulators, and torque ripples in harmonic drives [4]. All approaches based on the PID controller are not useful for periodic disturbance rejection [3]. Therefore, we need an approach to attenuating periodic disturbances.

The idea is to estimate periodic disturbances and then to reject them. The quality of disturbance rejection depends on the estimation of characteristics of a periodic signal. Amplitude and frequency of periodic disturbances are often unknown and they must be estimated. Several adaptive algorithms have been developed to provide an estimation of the characteristics of a periodic signal and exact disturbance rejection.

In [5], two adaptive algorithms, called direct and indirect, were proposed for rejecting periodic disturbances with an unknown period. In the direct adaptive control approach, frequency estimation and disturbance cancellation are performed simultaneously. It is quite nonlinear. An indirect scheme is

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such that plant estimates are used in an inner control loop as if they were the exact plant parameters.
Another useful algorithm, which has been proposed for period estimation and disturbance rejection, was adaptive notch filter (ANF) that has been used in many works like [6], [7].
ANF is a useful technique to estimate unknown frequencies and has a relatively simple structure but the approach is nonlinear for both continuous-time (CT) and discrete-time (DT) dynamical systems. The main algorithm is an adaptive notch filter developed in Regalia [8] that is designed to eliminate the periodic components from a measured signal.
The extended Kalman filter (EKF)-based period estimation methods [9], [10] constitute another group of advanced period estimation algorithms. Intelligent-based approaches such as fuzzy algorithms have also been proposed for tracking/rejecting goals [11], [12].
There are some disadvantages in previous works. They are model-based and the structure of plant and disturbance are needed to be known. They require appropriate models of plant and disturbances, and their computational procedures are complicated. The system response in these approaches is also highly nonlinear.
Repetitive control has been proven to be a highly effective and efficient way of rejecting periodic signals [13] and has been used widely in practical applications such as (PWM) inverters [14], DC motors, mechanical systems, uninterruptible power supplies (UPS), and so on [15].
Based on [16], any periodic signal can be regarded as the output of an autonomous system model $1/1-e^{-Ts}$, an infinite-dimensional model. A controller including the internal model $1/1-e^{-Ts}$ is called a *repetitive controller* (RC, or *repetitive control*), and a system including such a controller is referred to as an RC system. The basic idea of RC stems from the cancelation viewpoint on the IMP.
It has a simple structure and is formed from a delayed loop. It does not need to estimate the amplitude of the signal.
The main factor in RC analysis is the accurate choice of time delay which should be determined based on the period of the signal. In other words, the RC problem is that the period should be known exactly. As its first contribution, this paper resolves this problem by presenting an adaptive approach.
RC design mainly involves two parts: the first part is determining the delay of the system and the second is analyzing the effects of parameter k (controller gain).
In many related works, the delay of RC and the period of disturbance have been studied but very little attention has been paid to parameter k. It is due to the fact that the nature of an RC system is a kind of neutral time-delay system [17]. Therefore, its analytical study is very complicated and it has been subject to very little analytical analysis [18].
This paper proposes a simple approach for RC analysis. Delay is approximated by 2nd order of Pade approximation. Therefore, the system is simplified. System equations in the presence of periodic disturbance and RC controller are determined. After simplifying, the dependence of the output parameters to the RC parameters (gain and period) is determined and clarified in Section III. It should be mentioned that the delay, in this case, is assumed to be known and equal to the disturbance period.
In the next step, the delay is considered unknown. Then, the period of disturbance is estimated by a novel adaptive approach and it is considered as the adaptive delay.
The paper is organized as follows. The main problem is described in Section II. Section III is devoted to the analysis of RC and the dependence of output response to the RC parameters. The AFFT algorithm is proposed in Section IV. The simulation is done in Section V. Three different scenarios are considered and the quality of the proposed approach is compared with some other well-recognized methods in Section V and finally, the results are summarized in the Conclusion Section.

II. Problem Statement and Assumptions

In this section, the system is considered in the presence of an RC controller. The basic structure for RC is shown in Fig. 1. It has a delayed loop in a structure that can produce a periodic signal with the following transfer function

$$C(s)=\frac{k}{1-e^{-Ts}} \quad (1)$$

where T is the delay of the repetitive controller and k is the controller gain.

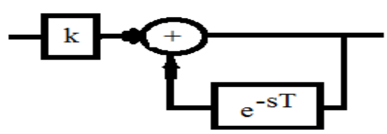

Fig. 1. The simple structure of the repetitive control [19].

For the sake of the analysis of RC as the main work, Fig. 1 can be put in Fig. 2 as a general structure for the RC system.

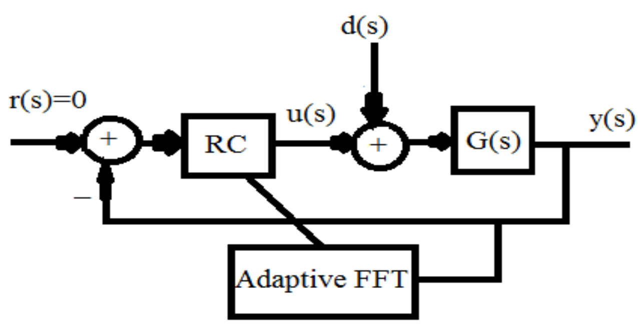

Fig. 2. The configuration of the proposed approach.

In a disturbance rejection problem, it is assumed that there is no reference input (pure disturbance rejection problem) [5], and $G(s)$, the control plant, is stable. It is also assumed that the system cannot filter the periodic disturbance. In other words, the disturbance frequency is much lower than the cut-off frequency of the plant. The output of the system can be described by

$$y(s) = G(s)(s)u(s) + G(s)d(s) \tag{2}$$

where $d(s)$, $u(s)$ and $y(s)$ denote the periodic disturbance, RC controller output, and output response of the system, respectively.

Based on Fig. 1 and Fig. 2, it can be drawn that

$$u(t) = u(t)(t-T) - ky(t) \tag{3}$$

which can be written as

$$u(s)\left(1-e^{-Ts}\right) = -k\left(y(s)\right) \tag{4}$$

Therefore, by substituting Eq. (4) in Eq. (2), it can be written as

$$y(s) = \frac{-ky(s)}{1-e^{-Ts}} G(s) + G(s)d(s) \tag{5}$$

The disturbance is assumed to be a periodic signal, so that

$$d(t) = g\sin(\omega t) \tag{6}$$

where g is the amplitude [20] and $\omega = 2\pi/T$, both of which are assumed to be unknown.

The contribution that can be mentioned here is that in works like [20], the amplitude should be estimated or known but in the proposed approach, it is unknown and no limitation is applied to it. In Section III, it can be seen that the amplitude has no effect on the output response. This point is also shown in the simulation results.

The main problem is the disturbance rejection so that the energy ratio of the output signal to that of the disturbance in a closed-loop system is sufficiently small. In other words, it is important to determine the controller output so that the output signal is sufficiently decreased. Therefore, the main aim is to design an adaptive RC controller to achieve the convergence of the closed-loop system to zero as $t \to \infty$ despite the unknown sinusoidal disturbance.

This method has advantages over the existing ones.

1) The rejecting performance is improved by choosing a suitable value for the gain of the repetitive controller.
2) The configuration is very simple and easy to implement.
3) The method is converging faster and more accurately than the PID and Bodson's algorithm.

The proposed approach is described in Section III.

III. Analysis of RC

It is assumed here that the period of the signal is constant and known. The disturbance is in the form of Eq. (6). Now, Eq. (5) can be rewritten as

$$y(s) = \frac{-ky(s)}{1-e^{-Ts}} G(s) + \frac{g}{s^2+\omega^2} G(s) \tag{7}$$

It is worthy to note that when the plant is a full pass filter, the worst case happens. So, G is considered unity. This is the complete case for attenuating disturbance because it involves all frequencies. In any case, Eq. (7) can be simplified as

$$y(s)\left(1+\frac{k}{1-e^{-Ts}}\right) = \frac{g}{s^2+\omega^2} \tag{8}$$

Now the problem is approximating the delay term. As the delay term is in the denominator and it complicates Eq. (7), the Pade approximation is used for simplicity.

It can be approximated by an equation like that in [21] and [15], but the following relationship is used based on the 2nd order of the Pade approximation.

$$1-e^{-Ts} \approx \frac{Ts}{1+\frac{T}{2}s+\left(\frac{T}{2}s\right)^2} \tag{9}$$

The higher order powers can also be added for more accuracy, but they are dismissed due to the simplicity of the results.

By substituting Eq. (9) in Eq. (8), the following relationship is obtained.

$$y(s)\left(1+k\frac{T^2s^2+2Ts+4}{4Ts}\right) = \frac{1}{s^2+\omega^2} \tag{10}$$

which can be more simplified as

$$y(s) = \frac{\frac{4g}{kT}s}{\left(s^2+\omega^2\right)\left(s^2+\frac{2}{kT}(2+k)s+\frac{4}{T^2}\right)} \tag{11}$$

Let's define,

$$\alpha = \frac{2}{kT}(2+k) \tag{12}$$

$$\omega' = \sqrt{\frac{4}{T^2} - \frac{1}{(kT)^2}(2+k)^2} \tag{13}$$

where ω' is the frequency that will be filtered.

Now Eq. (11) can be transformed into

$$y(s) = \frac{A_1 s + B_1}{\left(s^2+\omega^2\right)} + \frac{A_2 s + B_2}{\left(s+\frac{\alpha}{2}\right)^2 + \omega'^2} \tag{14}$$

Equivalently, in the time domain, Eq. (14) can be written as

$$y(t) = A_1\cos(\omega t) + \frac{B_1}{\omega}\sin(\omega t) + A_2 e^{-\frac{\alpha}{2}t}\cos(\omega' t) + \frac{B_2}{\omega'} e^{-\frac{\alpha}{2}t}\sin(\omega' t) \tag{15}$$

It is clear that in the steady-state, A_2 and B_2 exponentially tend to zero and it is enough just to know A_1 and B_1 .

By unifying Eq. (11) and Eq. (14), and simplifying α and ω'^2 , the final results are obtained as follows:

$$\begin{cases} A_1 = \dfrac{-T}{k\left(\pi^2-1\right)} \\ A_2 = \dfrac{T^3}{\left(\pi^2-1\right)} \\ B_1 = 0, \\ B_2 = 0, \end{cases} \tag{16}$$

Now Eq. (15) can be rewritten as

$$y(t)=\frac{-T}{k\left(\pi^2-1\right)}\cos(\omega t)+\frac{T^3}{\left(\pi^2-1\right)}e^{-\frac{\alpha}{2}t}\cos(\omega' t) \qquad (17)$$

Based on Eq. (15), for any positive k, the value of α is positive. Therefore, the second part of Eq. (13) tends to zero as $t\to\infty$.

Therefore, the steady-state of y is as

$$y_{ss}(t)=\frac{-T}{k\left(\pi^2-1\right)}\cos(\omega t) \qquad (18)$$

The maximum value of amplitude in the steady-state is A_1 and the other coefficients have no effect. k can also affect A_1. It is seen that with the increase in k, A_1 moves to zero. In other words, it is related to $-20\log k$. If k is 10 times bigger, the output decreases as much as $-20dB$.

For the higher values of T, or low frequencies, k should be selected higher to get the desired result.

The rate of damping is equal to $\frac{\alpha}{2}$. On the other hand, k is dependent on α. Therefore, the system response becomes convergent (Eq. (15)). In fact, k does not affect the convergence and it just can change (increase/decrease) the speed of it. Based on Eq. (12) and Eq. (16), the damping rate is dependent on α. It has a value between $\frac{2}{T}$ and $\frac{4}{kT}$.

IV. Adaptive FFT

FFT decomposes a digitized waveform into a series of sinusoidal components and allocates a proportion of the total power [22]. The classical Fourier analysis estimates the frequencies and the amplitudes of a periodic signal provided that the signal can be stored and processed off-line [23].

This paper uses an adaptive FFT which has basically been presented to find the frequency components of a signal specially mixed with a noisy time-domain signal [24]. For one unknown period, the FFT has a very good performance. For the adaptive case, the condition is difficult. In this case, adaptive FFT is needed. The classical Fourier analysis has been a potential solution for period estimation [25], but in this paper, adaptive FFT is needed and the classical FFT is improved.

In previous adaptive FFT methods such as [26] and [27], the algorithm is used only at the beginning of the estimation process. Once the desired results of the estimation are obtained, it is stopped.

It was due to the fact that the disturbance is considered a constant value, but adaptive FFT is used in this study and the adaptive FFT gets the output data adaptive and estimates the frequency and period of disturbance simultaneously because we want to know the accurate period even if the disturbance changes during the process. To this end, the adaptive FFT algorithm is written in the following procedure.

Design Algorithm:

The steps of this algorithm are as follows:

1. Let us define the vector φ_k as
$\varphi_k=[y(kT_S),y((k-1)T_S),((k-2)T_S),\ldots,((k-L)T_S)]$.
2. Regular FFT is applied to this vector to calculate the amplitude of each frequency.
3. The maximum value for the amplitude is determined, i.e., $A_k=\max(A)$.
4. If $f_{\min}<f_k\le f_{\max}$, the relevant frequency of A_k is determined, i.e., $f_k=f(A_k)$, otherwise, $f_k=f_0$.
5. The period of disturbance is calculated as
$T_k=\frac{1}{|f_k|+\varepsilon}$.
6. : Go to step 1 at the next sampling time.

Notes:

The frequency limitation should be known. In the algorithm, it is as $f_{\min}<f_k\le f_{\max}$.

In other words, both a lower bound $T_{\min}$ and an upper bound $T_{\max}$ are known for the period T.

T_s should be chosen 10 times bigger than this limitation.

The length of L is chosen by trial and error. Here, the 600 last samples are considered.

We know that the methods based on FFT generally require many data samples for an accurate estimation [28], so in this study, 600 data samples are gathered and then the estimation algorithm is applied. In other words, after LT_S seconds, the algorithm is applied. A very small value is used for ε which is 0.001 here.

In the next section, the effectiveness of the approach is illustrated in a simulation example.

V. Simulation Results and Discussion

In this section, the performance of our adaptive algorithm is examined via simulation in three scenarios. At first, the period of disturbance is assumed to be known but the amplitude is unknown. In the second scenario, the period of disturbance is unknown and it is estimated. For the numerical statement of the proposed approach, the energy ratio of the output signal to that of the disturbance is also calculated.

As we know, the power and energy formulas for a continuous real signal are as below:

$$P_y=\lim_{\tau\to\infty}\frac{1}{\tau}\int_0^{\tau}y^2(t)dt\ ,\quad E_y=\int_0^{\tau}y^2(t)dt$$

where y represents the output.

In the third part, the disturbance is time-varying. Finally, the comparison is done. It is worthy to note that the time is constant for all simulation, (One second) except for the first scenario which is considered 10 seconds due to the period of disturbance ($T = 1s$) and for better representation of the output.

We will compare our algorithm with other algorithms and methods for disturbance rejection. Therefore, we consider a situation in which $G(s) = \frac{100}{s+100}$ like [29]. Disturbance for scenarios 1 and 2 is $d = \sin(2\pi t)$, but it varies for scenario 3. The period is 1 s and the frequency is 1 Hz. The proposed analysis involves three scenarios.

Scenario1:

The period is assumed to be known and the RC performance is studied. Based on the results in Section III, the gain *k* can make output become zero. In other words, the parameter A_1 in Eq. (18) determines the steady-state response and the other coefficients have little effects. Fig. 3 refers to this point which is the first part of our analysis.

As the value of the amplitude is optional, for disturbance $d = 10\sin(2\pi t)$, the results are repeated which is shown in Fig. 4. It is clear that the quality of the response does not change and there is no need to limit the amplitude and to estimate it. In fact, the amplitude of the response is just multiplied by the amplitude of the disturbance, and the totality of the output response is similar to Fig.3.

Given the analysis in Section III, the system output does not become accurately zero because it was shown that there is a steady-state value which is negligible but not zero (Eq. (18)). It is seen that by greater values for *k*, the output is about 0.1 which becomes more than -20*dB* attenuation.

Based on Eq. (15)-(16), k does not affect the convergence and it can change (increase/decrease) just the speed of convergence (Fig. 3).

Scenario 2:

Here, the adaptive period estimation is simulated. Based on the analysis in scenario 1, to get better and more challenging results, a small value is considered for *k*. It is assumed 0.5 in the next two scenarios.

Adaptive repetitive control alongside FFT period spectrum estimation can distinguish the disturbance period and attenuate the disturbance with good accuracy which is shown in Fig. 5. It is evident that output system response is almost between ± 0.1 which is about -20*dB* attenuation.

Period identification is another main subject that is done and the result is depicted in Fig. 6. However, undesired steps is seen in the identified period, but the period is estimated with very good accuracy (period should be 1 second which is 1.024 seconds here).

Another subject in this scenario is the energy ratio of the output signal to that of the disturbance. By simulation, it is seen that the energy of the output signal in the presence of ARC and adaptive FFT is 0.8933 and the energy of the disturbance becomes 95.0. The ratio is less than 0.01, which is a great attenuation. The input signal energy is also 40.6148.

Scenario 3:

As noted in previous sections, for adaptive estimation, the disturbance is not constant. Therefore, a time-varying disturbance is considered as

$$d = \sin(\omega t), \begin{cases} \omega = 2\pi\ , & t < 1s \\ \omega = 3\pi\ , & t > 1s \end{cases}$$

The result is shown in Fig. 7. ARC can attenuate both of disturbances with very good performance. The route of the estimated period, in this case, is shown in Fig. 8.

According to these figures, once the algorithm is engaged, it can estimate the accurate period in a fraction of a second. Period identification is desirable. The real values are 1 and 0.67 seconds which become about 1.024 and 0.68 seconds, respectively. Again there are undesired steps in the identified period which is due to the fact that when the estimated period approaches the true one, the output function will make the estimation of the exact period almost impossible. Therefore, in an adaptive operation, there will be a bias in the estimated period caused by the need to have a certain level of the measured output to carry on the estimation [29]. It is expected to be improved in the next papers.

Comparisons

In order to demonstrate the behavior of the method and compare our algorithm with Bodson's algorithms, the plant model $G(s) = \frac{100}{s+100}$ and disturbance $d = \sin(100t)$ are used [29].

The results of the simulation are shown in Figs. 9 and 10. From the figures, we can see that both algorithms provide good disturbance rejection, but the proposed approach attenuates the periodic disturbance to a great extent. Our algorithm also provides very better identification (Fig. 10). Bodson's algorithm is converged to correct value after 1 second but our proposed algorithm is converged immediately to the accurate value. There exists a larger overshoot in the identified frequency with Bodson's approach. Moreover, in Bodson's algorithm, the magnitude of the transfer function of the plant at the identified frequency is explicitly required in order to implement it. Thus, if the plants are complicated, the algorithm may be complicated.

It can be seen that the frequency identifications of Bodson's approach have bigger errors and the plant output of the approach has less attenuation of the disturbance than that of the proposed approach.

Although it is proven that RC has superiority over other control methods like PID, optimization, etc. [16], the comparison with the PID controller is done here for better understanding of the proposed approach performance.

Here, autotuning coefficients for PID are considered as $P = I = D = 1,\ N = 0.1$.

Based on Fig. 8, the performance of the disturbance rejection is very lower than that of ARC. There are many distortions and after 1 second, no complete rejection is seen. PID also cannot distinguish the period of disturbance and cannot be a good choice for unknown disturbance rejection cases.

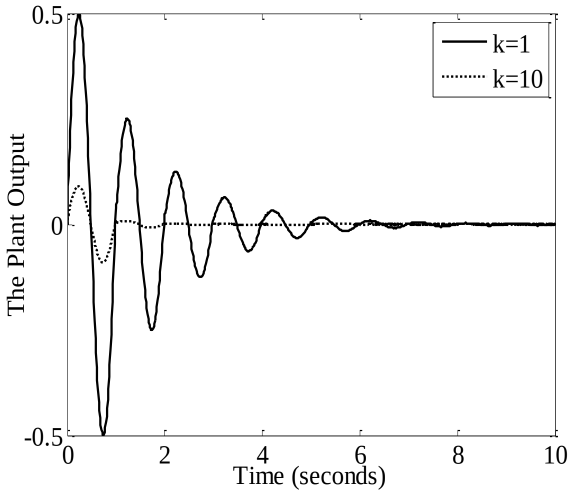

Fig.3. Disturbance rejection for different values of *k*.

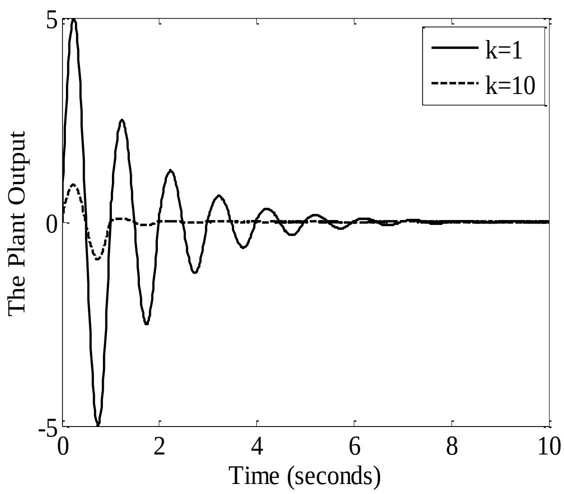

Fig. 4. Disturbance rejection for the previous case by new disturbance amplitude.

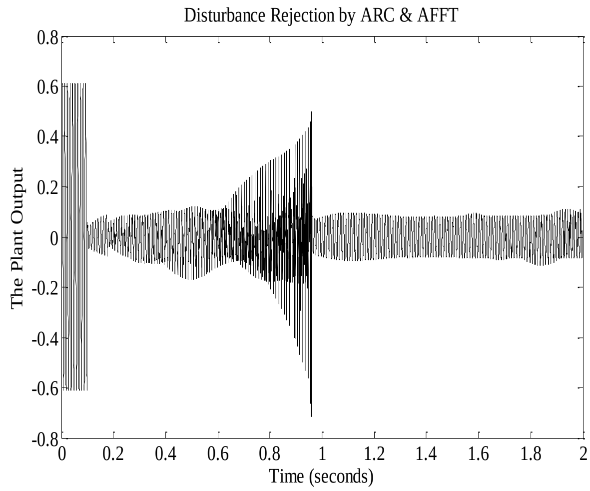

Fig. 5. Disturbance rejection for scenario 2.

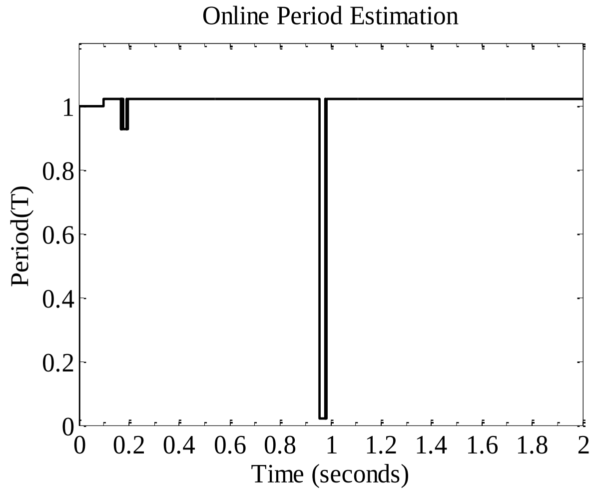

Fig. 6. Adaptive period estimation for scenario 2.

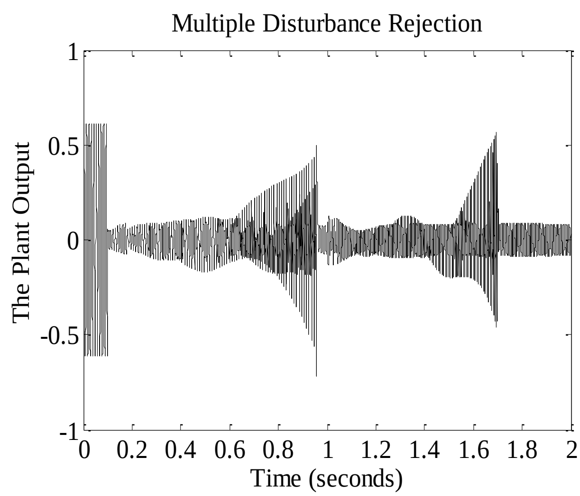

Fig. 7. Time-varying periodic disturbance rejection by the ARC system and adaptive FFT algorithm.

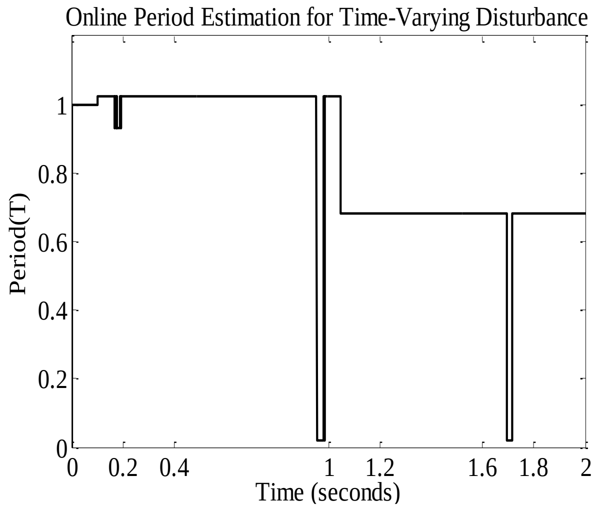

Fig. 8. Adaptive period estimation of two different periodic disturbances.

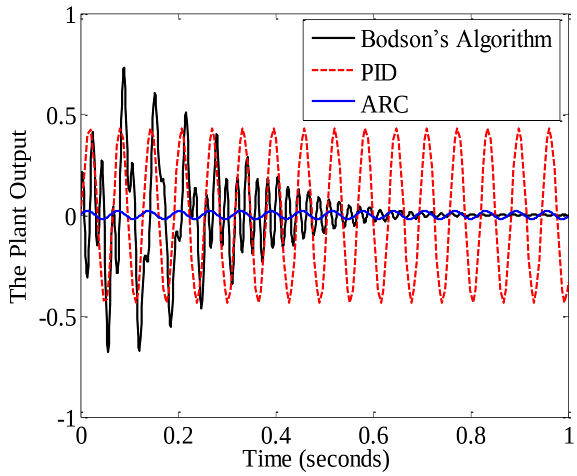

Fig. 9. The plant outputs using three different approaches.

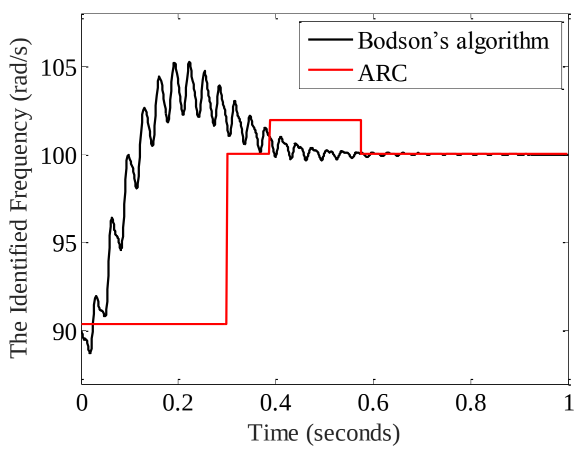

Fig. 10. The frequency estimation by Bodson's algorithm and the proposed approach

VI. Conclusion

In this paper, a mathematical analysis was done on an RC closed-loop system. Due to the delay loop in the RC structure, for simplicity, the Pade approximation was used. In the worst case, the plant was considered unity as a full pass filter.

When the period is known, the effect of RC gain and the conditions of the output system response were studied analytically. The performance was very good. It was shown that there is no need to make limitation on the amplitude of periodic disturbance. In other words, if the amplitude varies, the steady-state response which depends on RC gain decreases and the disturbance is rejected. The steady-state response was proportional to $-20\log k$. It was shown that the output system response is almost between ± 0.1 which is about -20dB attenuation. A novelty of this paper was adaptive FFT algorithm. An adaptive FFT algorithm was proposed for periodic disturbance rejection in different known and unknown and time-varying scenarios, and the period estimation was done accordingly.

The ability of this algorithm to identify the frequency of periodic disturbances and to reject periodic disturbances was shown in simulations and that it can indeed identify the frequency of the given periodic disturbance and cancel this disturbance.

However, to achieve better and more accurate results, the algorithm should be improved. This point and the disturbance rejection in the presence of noise and uncertainty need further studies. They are postponed to next works hopefully.

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