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Abstract

An online estimation method for single-input single-output (SISO)-type stable systems is discussed based on frequency transformation technique. Reported method based on fast Fourier transform (FFT) is an off-line identification method means the controller is required to remove from the closed loop at the time of autotuning test. So the modified method is suggested for online identification and has been tested on several systems to show the effectiveness of the method. A relay with hysteresis in parallel with proportional–integral (PI) controller induces stationary oscillation cycle whose frequency and amplitude are used for system identification. We consider the development of a non-iterative approach with less computational efforts and a reasonable amount of data. A simulation study is given to illustrate the potential advantage of the presented method.

Keywords (separated by '-') SISO - FFT - System identification - Relay experiment

Chapter 14
Online Frequency Domain Identification Method for Stable Systems

Priti Kshatriy and Utkal Mehta

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Abstract An online estimation method for single-input single-output (SISO)-type stable systems is discussed based on frequency transformation technique. Reported method based on fast Fourier transform (FFT) is an off-line identification method means the controller is required to remove from the closed loop at the time of autotuning test. So the modified method is suggested for online identification and has been tested on several systems to show the effectiveness of the method. A relay with hysteresis in parallel with proportional–integral (PI) controller induces stationary oscillation cycle whose frequency and amplitude are used for system identification. We consider the development of a non-iterative approach with less computational efforts and a reasonable amount of data. A simulation study is given to illustrate the potential advantage of the presented method.

Keywords SISO · FFT · System identification · Relay experiment

14.1 Introduction

It is desirable to know the system before it is manipulated for control purposes. To estimate the system behavior, a relay experiment is probably most successfully used in the process industry [1]. Various methodologies on the relay test are reported and summarized in [1–3]. Some of the distinct advantages of the relay tuning are as follows: (i) It identifies system information around the important frequency, the ultimate frequency (the frequency where the phase angle is π), (ii) it is a closed-loop

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test; therefore, the system will not drift away from the nominal operating point, and (iii) for systems with a long time constant, it is a more time-efficient method than conventional step or pulse testing. The experimental time is roughly equal to two to four times the ultimate period. Despite this method has been subject of much interest in recent years and also has been field tested in a wide range of applications, basically, this technique is an off-line testing; i.e., some information is extracted after removing the controller from the loop. It has been noted [2, 4] that off-line testing may affect the operational process regulation which may not be acceptable for certain critical applications. Indeed, in certain key process, control areas such as vacuum control and environment control may be too expensive or dangerous for the control loop to be broken for tuning purposes.

A recent survey shows that the ratio of applications of proportional–integral–derivative (PID) control, conventional advanced control (feed forward, override, valve position control, gain-scheduled PID, etc.), and model predictive control is about 100:10:1 [5]. An important feature of this controller is that it does not require a precise analytical model of the system that is being controlled. For this reason, PID controllers have been widely used in robotics, automation, system control, manufacturing, transportation, and interestingly in real-time multitasking applications [6]. However, the parameters of controller must be tuned according to the nature of the system. In practice, it has been shown that the PID gains are often tuned using experiences or trial and error methods. Again, due to varying nature of the system and environment, the performance of the closed-loop system is always deteriorated. It is important to re-tune the controller to regain the desired performance.

One of the simplest and most robust autotuning techniques for system controllers is a relay autotuning test. Many modified methods [2, 7–13] based on relay experiments are reported to rectify demerits in the original conventional method of relay feedback test. Most methods are discussed to estimate the system dynamics online, and then, based on estimated data, the new controller setting is suggested to improve the closed-loop performances. Again, some refinements to the original relay feedback method have been undertaken in identifying multiple points on the system frequency response. Based on the frequency domain describing function approach, many methods have been reported [1, 3] with improved accuracy to estimate process transfer function models. However, these approximate DF methods are basically iterative and also required some suitable initial guesses. A systematic time domain analysis was presented in [11] for identifying process dynamics with first-order model. In this approach, a relay is connected in series with a controller to tune the controller online. Other identification method has been reported, using fast Fourier transform (FFT), is very useful for process response identification [4, 14]. In this method, process input and output responses are obtained first from a single relay feedback test. The logged limit cycle oscillation is decomposed into the transient parts and the stationary cycle parts. Then, these parts are transformed to their frequency responses using the FFT and digital integration, respectively, to estimate the process frequency response. This method is basically an off-line since the controller is removed from the main line at the time of autotuning.

The paper is concerned with identification of single-input single-output (SISO) system based on FFT algorithm. The off-line method has some limitations as removing controller from main loop may not acceptable for some applications. To overcome this problem, an online system identification technique has been considered. A relay with hysteresis in parallel with PI controller induces stationary oscillation cycle whose frequency and amplitude are used for system identification. The system input and output are decomposed into their transient part and steady-state part, respectively. The system frequency response can be obtained by transforming transient part and steady-state part into their frequency response using FFT and digital integration, respectively. A number of examples are given to illustrate simplicity, effectiveness, and potential advantage of the online FFT-based technique.

14.2 Revisited FFT-Relay Method

Departing from the conventional relay test where the controller is replaced by the relay, the presented test is to carry out online without breaking the closed-loop control by placing the relay in parallel with the controller. Figure 14.1 shows the tuning scheme in which the relay height is increased from zero to some acceptable value when re-tuning is necessary.

Aiming to estimate the system frequency response, $G(j\omega)$ accurately without disconnecting controller from the loop (online). Let us take the controller of type PI at the time of relay test as AQ2

$$C(s) = K_p + \frac{K_i}{s} \quad (14.1)$$

where K_p and K_i are its controller gains. This structure is simple with only two parameters yet it is one of the most common and adequate ones used, especially in the process control industries. When a relay is invoked with amplitude $\pm h$ and hysteresis $\pm \varepsilon$ in parallel with the controller, a stable oscillation will result if the system has a phase lag of at least π radians.

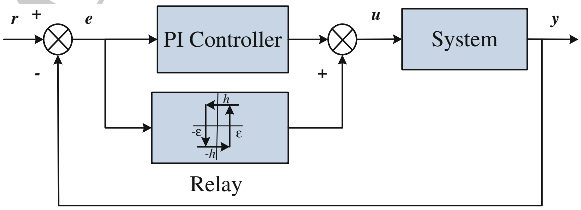


Fig. 14.1 Relay feedback structure

We want to extract the dynamic information on the given process, such as frequency response, from the measured values of $y(t)$ and $u(t)$. In the following, the method is given to compute system frequency response using the FFT [14].

Transient part and steady-state part of the system input $u(t)$ and output $y(t)$ are extracted from its time response data. By replacing transient part by steady-state part, one can obtain steady-state part of system input [14]. As we know,

$$u(t) = u_s(t) + \Delta u(t) \tag{14.2}$$

$$y(t) = y_s(t) + \Delta y(t) \tag{14.3}$$

By subtracting steady-state part u_s from system input u, transient part Δu can be obtained. Same method is applied to get steady-state part y_s and transient part Δy of system output.

For a system $G(s) = Y(s)/U(s)$, from (14.2) and (14.3)

$$G(s) = \frac{\Delta Y(s) + Y_s(s)}{\Delta U(s) + U_s(s)} \tag{14.4}$$

where

$\Delta Y(s)$ Laplace transform of transient part of $y(t)$
$\Delta U(s)$ Laplace transform of transient part of $u(t)$
$Y_s(s)$ Laplace transform of steady-state part of $y(t)$
$U_s(s)$ Laplace transform of steady-state part of $u(t)$

For the periodic part of time response, the following Lemma [15] holds. The periodic function $f(t)$ can be described as

$$f(t) = \begin{cases} f(t + T_c), & t \in [0, +\infty) \\ 0, & t \in (-\infty, 0) \end{cases} \tag{14.5}$$

where T_c is the time period of function $f(t)$.

Assume that £$\{f(t)\} = F(s)$ exists. Then, the Laplace transform of $f(t)$ is given by

$$F(s) = \frac{1}{1 - e^{-sT_c}} \int_0^{T_c} f(t) e^{-sT_c} dt \tag{14.6}$$

If we apply above theorem to (14.4), then G(s) becomes

$$G(s) = \frac{\Delta Y(s) + \frac{1}{1-e^{-sTc}} \int_0^{T_c} y_s(t) e^{-st} dt}{\Delta U(s) + \frac{1}{1-e^{-sTc}} \int_0^{T_c} u_s(t) e^{-st} dt} \tag{14.7}$$

where T_c is the period of the steady-state part of the system output obtained from the relay feedback test. If we put $s = j\omega$, (14.7) becomes

$$G(j\omega) = \frac{\Delta Y(j\omega) + \frac{1}{1-\mathrm{e}^{-j\omega Tc}}\int_0^{T_c} y_s(t)\mathrm{e}^{-j\omega t}\mathrm{d}t}{\Delta U(j\omega) + \frac{1}{1-\mathrm{e}^{-j\omega Tc}}\int_0^{T_c} u_s(t)\mathrm{e}^{-j\omega t}\mathrm{d}t} \tag{14.8}$$

Suppose that $t = T_f$ is transient period for u and y and after $t = T_f$, both Δu and Δy are approximately zero. Then, the Fourier transform of Δy is given by

$$\begin{aligned}\Delta Y(j\omega) &= \int_0^{\infty} \Delta y(t)\mathrm{e}^{-j\omega t}\mathrm{d}t \\ &\approx \int_0^{T_f} \Delta y(t)\mathrm{e}^{-j\omega t}\mathrm{d}t\end{aligned} \tag{14.9}$$

Equation (14.4) can be computed at discrete frequencies with the standard FFT algorithm, which is an efficient and reliable way for calculating DFT more quickly. Suppose that $y(kT)$, $k = 1, 2, 3, \ldots, N - 1$ are samples of $y(t)$ where T is the sampling interval and $(N - 1)T = T_f$ are formed from (14.6) and we have its FFT as

$$\begin{aligned}\mathrm{FFT}(\Delta y(kT)) &= T\sum_{k=0}^{N-1} \Delta y(kT)\mathrm{e}^{-j\omega_l kT} \\ &\approx \Delta Y(j\omega_l) \quad l = 1, 2, 3, \ldots, M\end{aligned} \tag{14.10}$$

where M is the number of frequency response points to be identified on Nyquist plot and $\omega_l = 2\pi l/(NT)$.

$Y_s(j\omega)$ in (14.8) at discrete frequency ω_l are computed using digital integral as

$$Y_s(j\omega_l) = \frac{1}{1-\mathrm{e}^{-j\omega_l Tc}}\sum_{k=0}^{Nc} y_s(kT)\mathrm{e}^{-j\omega_l kT}T \quad l = 1, 2, 3, \ldots, M \tag{14.11}$$

where ω_l and M are defined as in (14.9) and $N_c = (T_c - T)/T$. $\Delta U(j\omega_l)$ and $U_s(j\omega_l)$ can be calculated in the same way. Consequently, the system frequency response is obtained as

$$G(j\omega_l) = \frac{\Delta Y(j\omega_l) + Y_s(j\omega_l)}{\Delta U(j\omega_l) + U_s(j\omega_l)} \quad l = 1, 2, 3, \ldots, M \tag{14.12}$$

To calculate FFT of $\Delta y(kT)$ given by (14.10), we have to give value to time period T_f which can be obtained either from time response data or by $T_f = (N - 1)T$. It shows that T_f is related to frequency response points to be identified between zero frequency to phase cross over frequency ω_c on Nyquist plot. It observed from (14.11) that the frequency response points to be identified by the FFT algorithm are at the discrete frequencies 0, $\Delta\omega$, $2\Delta\omega$, $3\Delta\omega$, …, $(M - 1)\Delta\omega$, where $\Delta\omega = \omega_{l+1} - \omega_l = 2\pi/NT$. The definition of M means that $\omega_c \approx (M - 1)\Delta\omega$, thus

$$\omega_c \approx (M-1)\frac{2\pi}{NT} \tag{14.13}$$

The oscillation period can also be measured online at the time of relay test and can be estimated as

$$\omega_c \approx \frac{2\pi}{T_c} \tag{14.14}$$

From Eqs. (14.13) and (14.14)

$$N \approx (M-1)\frac{T_c}{T} \tag{14.15}$$

where M should be specified by user.

This FFT-based method gives a high accuracy to identify multiple points on frequency response from a single relay test. However, it has been found that the input and output must be recorded from the initial time to calculate the transient parts Δy and Δu accurately. Here, the initial time is defined when the relay feedback is performed to the system. Therefore, it is required for the system at the steady state before a relay feedback is applied at $t = 0$. The transient parts $\Delta y(\Delta u)$ and steady-state parts $y_s(u_s)$ are required to decompose first to determine FFT from its time response data accurately using some computational efforts.

14.3 Examples

In this section, proposed method has been applied on several systems to show robustness and accuracy of the method. The amplitude level should be sufficient to prevent false switching caused by noisy signals. It is important to keep the output oscillation amplitude in the prescribed limit as per the tolerable system variable swing and decide values for the relay heights that produce a limit cycle with acceptable amplitude level. To overcome the undesirable relay chattering caused by noisy signals, the width of the hysteresis of the relay is set to twice the standard deviation of the noise. For ease in simulation study, the relay with $h = \pm 0.1$ and $\varepsilon = \pm 0.01$ is taken although fairly low values of relay height could be used.

Example 1 Consider second-order plus dead time system

$$G(s) = \frac{1}{(s+1)(3s+1)}e^{-s} \tag{14.16}$$

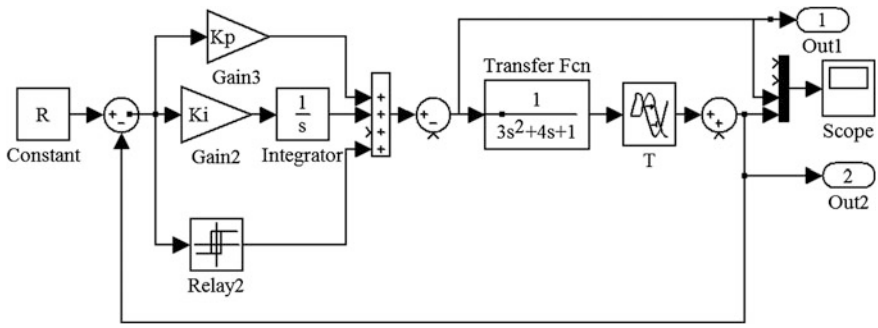
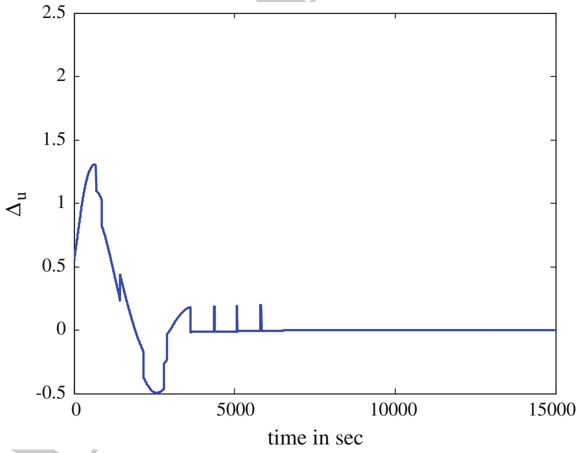


Fig. 14.2 Simulink block diagram of relay feedback applied to system

Fig. 14.3 Transient part of system input



For this system, $K_p = 0.35$, $K_i = 0.35$, $h = 0.1$, and $\varepsilon = 0.01$ have been taken. Relay feedback has been applied as shown in Fig. 14.2 from which the system input and output parameter has been extracted. The system input and output are then decomposed into their transient part (Figs. 14.3 and 14.6) and steady-state part (Figs. 14.4 and 14.5), respectively. FFT and digital integration have been applied to transient parts and steady-state parts, respectively, to obtain their frequency response. These two parts are then combined to calculate system frequency response and compared with actual frequency response. Simulation result as shown in Fig. 14.8 shows, even for reference point other than zero; this method is quite accurate (Fig. 14.7).

Example 2 Consider second-order plus dead time system

$$G(s) = \frac{1}{(s+1)^2} e^{-s} \tag{14.17}$$

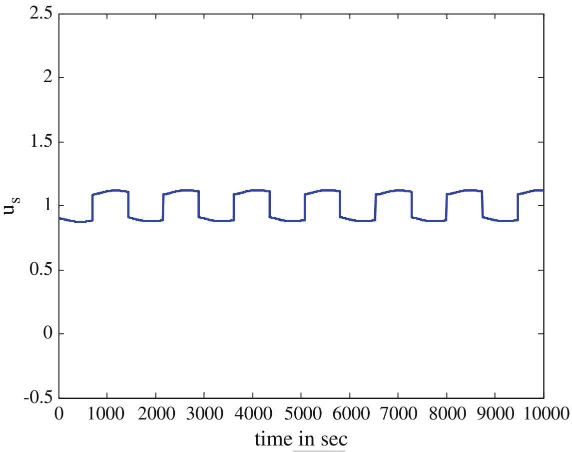


Fig. 14.4 Steady-state part of system input signal

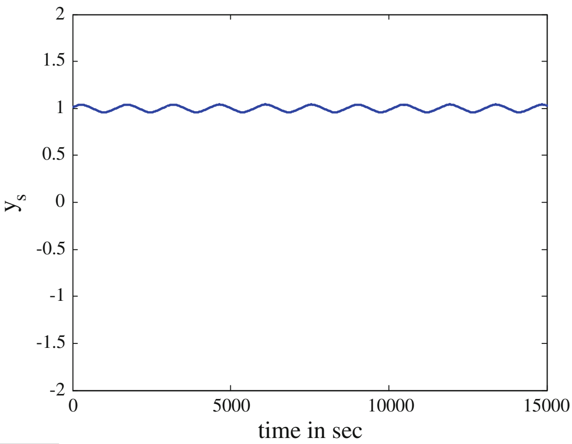


Fig. 14.5 Steady-state part of system output signal

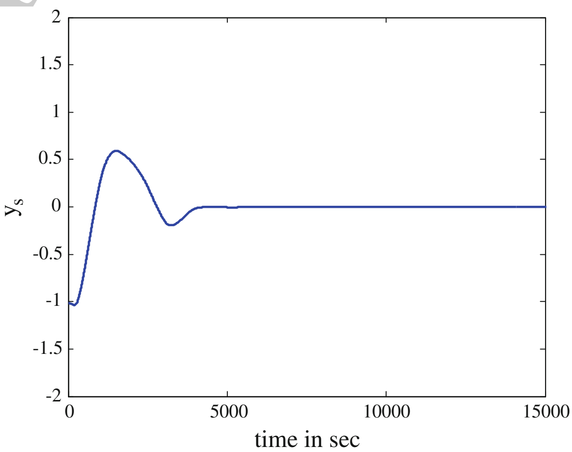


Fig. 14.6 Transient part of system output

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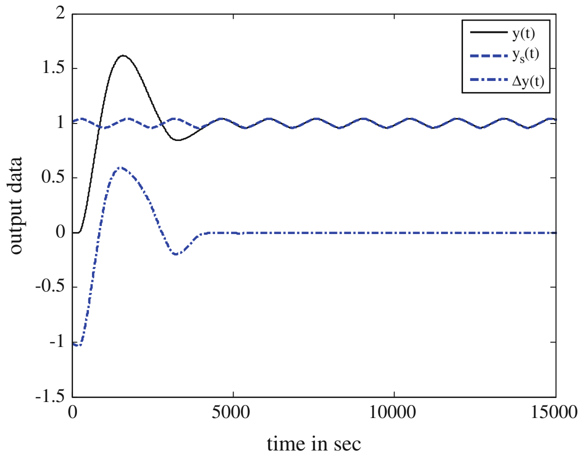


Fig. 14.7 System output signals

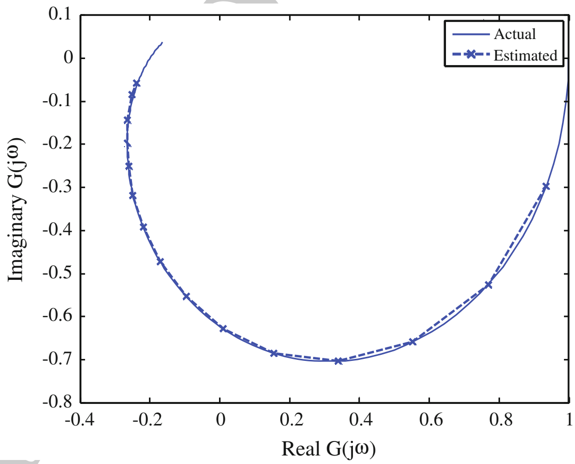


Fig. 14.8 System Nyquist plots

For this plant, Mehta and Majhi [13] have proposed controller parameter, $K_p = 0.35$, $K_i = 0.35$, $h = 0.1$, and $\varepsilon = 0.001$. With $M = 15$ and $T = 0.005$, time period $T_c = 5.41$ has been calculated manually. System input (output) is decomposed into its transient part and steady-state part as shown in Fig. 14.9 (Fig. 14.10). Using proposed methodology, multiple points on frequency response curve have been identified accurately as in Fig. 14.11. AQ4

Example 3 Consider non-minimum phase system

$$G(s) = \frac{-1.5s + 1}{(s + 1)^3} \tag{14.18}$$

Fig. 14.9 System input signals

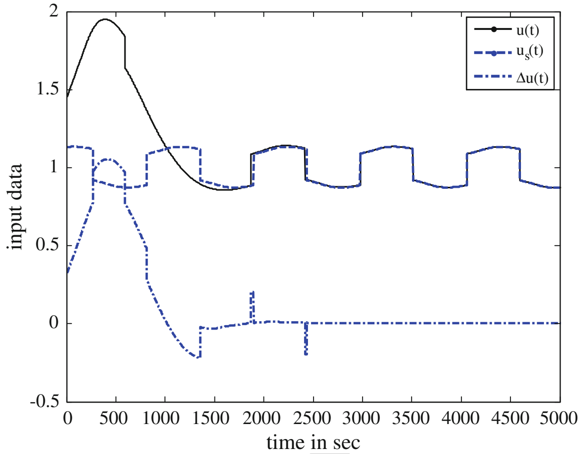


Fig. 14.10 System output signals

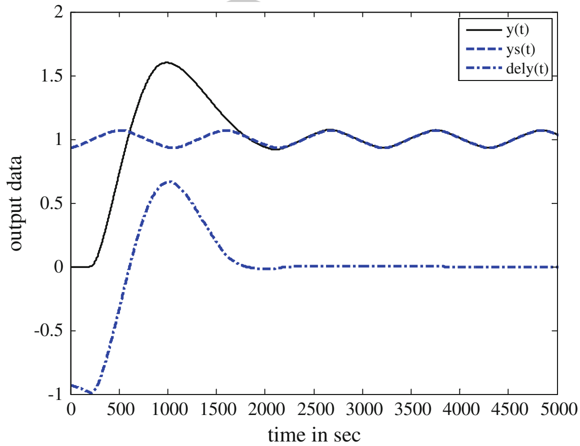
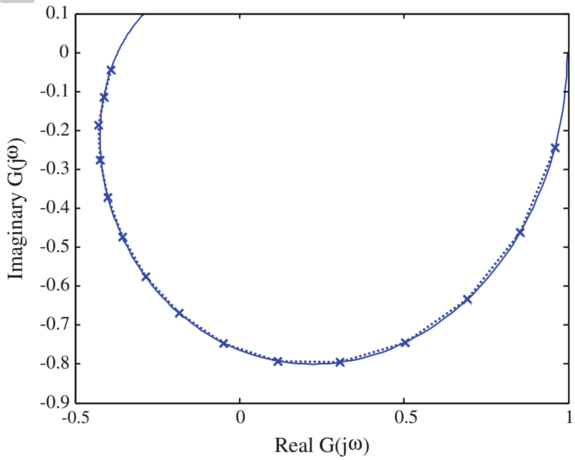


Fig. 14.11 System Nyquist plots



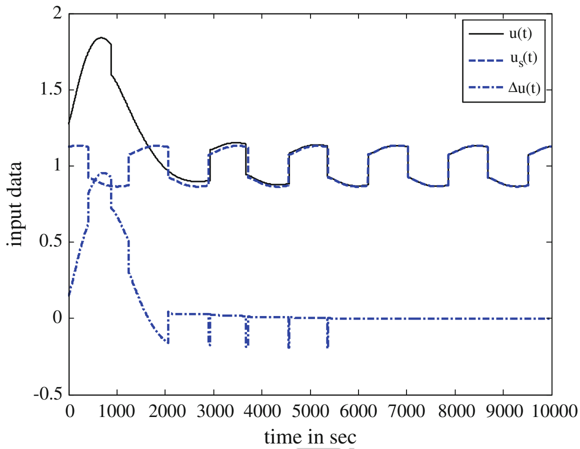


Fig. 14.12 System input signals

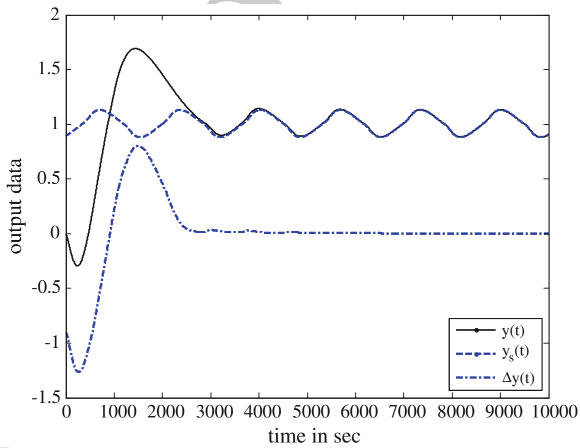


Fig. 14.13 System output signals

For this plant, Mehta and Majhi [13] have proposed controller parameter, $K_p = 0.172$, $K_i = 0.181$, $h = 0.1$, and $\varepsilon = 0.001$. With $M = 15$ and $T = 0.005$, time period $T_c = 8.31$ has been obtained. The transient part and steady-state part of system input are as shown in Fig. 14.12. Same for system output is as shown in Fig. 14.13. Estimated frequency response points in important frequency range from zero to critical frequency (i.e., $[0,\omega_c]$) is as shown in Fig. 14.14.

Example 4 Consider the very high-order system

$$G(s) = \frac{1}{(s+1)^{20}} \tag{14.19}$$

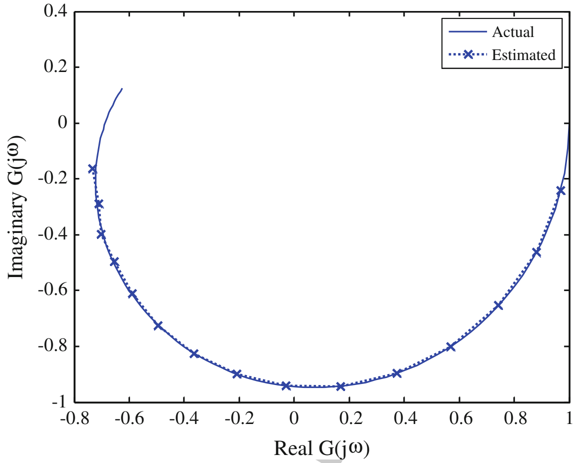


Fig. 14.14 System Nyquist plots

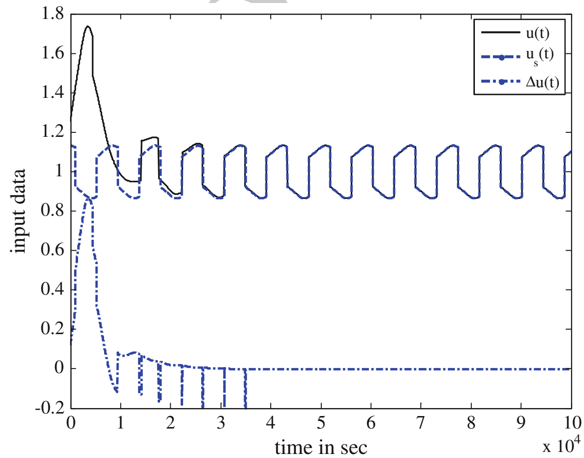


Fig. 14.15 System input signals

$K_p = 0.172$, $K_i = 0.181$, $h = 0.1$, and $\varepsilon = 0.001$ has been proposed by Majhi [15]. With $M = 15$ and $T = 0.005$, time period $T_c = 8.31$ has been calculated. The system input (output) is decomposed into transient part and steady-state part as shown in Fig. 14.15 (Fig. 14.16). DFT-based algorithm gives accurate result as shown in Fig. 14.17.

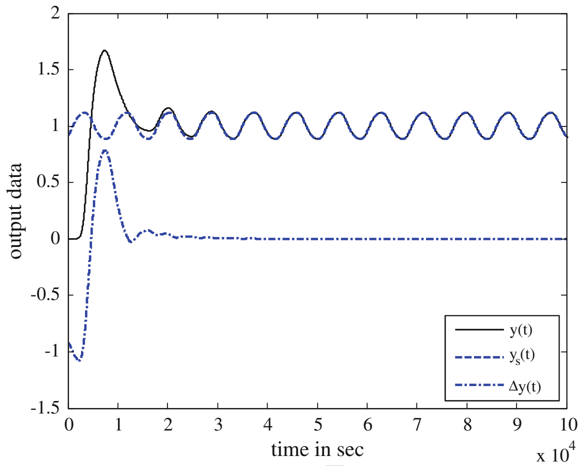


Fig. 14.16 System output signals

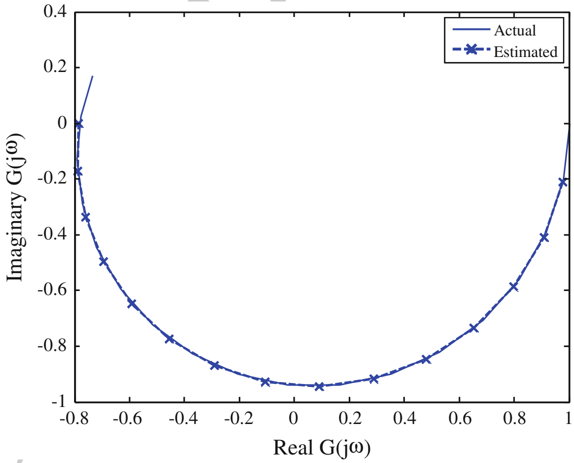


Fig. 14.17 System Nyquist plots

239 ## 14.4 Conclusions

An online technique is presented for system frequency response identification in context of the relay experiment. The method has several features. First, it can obtain multiple points on system frequency response simultaneously without breaking the closed-loop control and this increases applicability for certain critical systems. Second, this approach is robust as all measurements are made nearby setpoint value without removing the controller from the main line. Third, it can be used in the presence of a static load disturbance since the PI action is always present during the test. The estimated system frequency response is useful generally for controller design.

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Change italic to upright type	(As above)	
Change bold to non-bold type	(As above)	
Insert 'superior' character	/ through character or where required	or under character e.g. or
Insert 'inferior' character	(As above)	over character e.g.
Insert full stop	(As above)	⊙
Insert comma	(As above)	,
Insert single quotation marks	(As above)	or and/or or
Insert double quotation marks	(As above)	or and/or or
Insert hyphen	(As above)	
Start new paragraph		
No new paragraph		
Transpose		
Close up	linking characters	
Insert or substitute space between characters or words	/ through character or where required	
Reduce space between characters or words	between characters or words affected	