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Characteristic signal extracted from a continuous time signal on the aspect of frequency domain*

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Extracting characteristic signal from a continuous signal can effectively reduce the difficulty of analyzing the running states of a single-variable nonlinear system. Whether the extracted characteristic signal can accurately reflect the running states of the system is very important. In this paper, a method called automatic sampling method (ASM) for extracting characteristic signals is investigated. The complete definition is described, the effectiveness is proved theoretically, and the general formulas of the extracted characteristic signals are derived for the first time. Furthermore, typical Chua's circuit is used to accomplish a lot of experimental research on the aspect of frequency domain. The experimental results show that ASM is feasible and practical, and can automatically generate a characteristic signal with the change of the original signal.

Keywords: automatic sampling method, characteristic signal, frequency domain, system states

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1. Introduction

By monitoring the output signal of a nonlinear system, the change of the system's running state can be directly identified. In order to analyze or apply the dynamic characteristics of a system, the traditional analytical methods have been applied to many research fields. For instance, the Lyapunov exponent is used to detect weak signals[1] and prove the intra-layer synchronization of the duplex network;[2] the numerical simulation method is used to study the magnetoelastic dynamic behavior of a rotating annular thin[3] and the Hopf bifurcation control of a modified Pan-like chaotic system;[4] the bifurcation is used to study the nonlinear dynamic behavior of the PMSG[5] and external-cavity multi-quantum-well laser;[6] the Poincaré section is used to analyze the limit cycle oscillation flutter and chaotic motion of a two degree-of-freedom aeroelastic airfoil[7] and the chaos properties of the time-dependent driven Dicke model.[8] All these methods may help people predict the behavior of these systems or avoid their negative effects. However, for a single-variable nonlinear system, the traditional methods are difficult to monitor its running states. In recent years, many methods for analyzing nonlinear time series have been proposed, which can be used to analyze a single-variable nonlinear system. For instance, reference [9] used the recurrence plot (RP) and recurrence quantification analysis (RQA) method of the volume data of the lane closest to the median to analyze nonlinear time series on traffic data for incident detection; reference [10] proposed a new algorithm which can automatically select an optimum Poincaré plane for transferring the maximum information from EEG time series to a set of Poincaré samples. Although these methods can effectively detect the dynamic characteristics of the single-variable nonlinear systems, they require a lot of numerical calculations to obtain results, which makes them unable to monitor the system in real time.

In 2013 and 2015, the 45-degree line and SP methods were respectively proposed in Refs. [11] and [12], which can monitor the running states of a nonlinear system in the screen of an oscilloscope by a special way. Extracting the useful characteristic signals from a continuous signal is the key to realize these methods. However, these methods neither give a complete definition of the extraction method nor demonstrate and validate it. These shortcomings affect their further application.

Therefore, a method which can automatically obtain characteristic signal according to the complexity of the tested signal is called automatic sampling method (ASM) in this paper. It is a fast and efficient sampling method.

The structure of this paper is as followed. In Section 2, the complete definition of ASM is given, and the extracted characteristic signals still retaining the frequency characteristics of the tested signal are analyzed and proved. Then the general formulas of characteristic signals which are extracted from periodic signals and non-periodic signals are derived. In Section 3, based on the ASM, the key issue on the choice of marking time points for extracting characteristic signal is studied, and its selection method is given. In Section 4, according to the above method, a hardware circuit system for extracting characteristic signal is designed, which is used to do the verification experiments of the extracted characteristic signals from the frequency domain perspective. Finally, the conclusions are given in Section 4.

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2. ASM method

Characteristic signal is a kind of signal which can reflect the characteristic information of the tested signal. In order to ensure the applicability of the characteristic signal, it is necessary to study how to obtain different characteristic signals according to the different tested signals. Therefore, a definite method of extracting characteristic signal is given below.

Automatic sampling method (ASM): for a bounded continuous and differentiable signal $f(t)$, a horizontal straight line is selected within its boundary to intersect $f(t)$ for $\mathrm{d}f(t)/\mathrm{d}t > 0$ at $(t_i, f(t_i))$ $(i = 1,2,3,\ldots)$. Based on t_i, a tiny Δt $(\Delta t < T_{\mathrm{fmin}})$ is selected for obtain characteristic values $f(t_i + \Delta t)$ $(i = 1,2,3,\ldots)$. Then, the characteristic signal $f_{xy}(t)$ of $f(t)$ can be automatically extracted by keeping $f(t_i + \Delta t)$ from $t_i + \Delta t$ $(i = 1,2,3,\ldots)$ to $t_{i+1} + \Delta t$ $(i = 1,2,3,\ldots)$.

It should be noted that for signal $f(t)$, if M is the set of its maximum; N is the set of its minimum. Then any $y_w \in M$ $(w = 1,2,3,\ldots)$ must be greater than any $x_u \in N$ $(u = 1,2,3,\ldots)$.

Combining with Fig. 1, the working principle of ASM is analyzed and explained as follows.

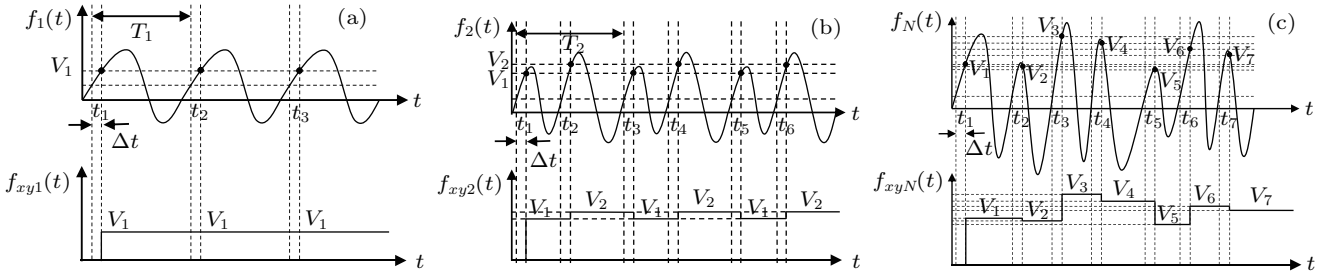


Fig. 1. The principle of ASM. (a) The signal of period 1; (b) the signal of period 2; (c) the non-period signal.

2.1. If the tested signal is a periodic signal

(a) For a continuous period 1 signal $f_1(t)$ with the period of T_1, there is

$$f_1(t) = f_1(t + nT_1), \quad (n = 1,2,3,\ldots), \tag{1}$$

and the frequency of $f_1(t)$ is $f_1 = 1/T_1$.

In order to determine t_i $(i = 1,2,3,\ldots)$, a constant C is chosen to intersect $f_1(t)$ for $\mathrm{d}f_1(t)/\mathrm{d}t > 0$. The abscissa of the intersection point is taken as t_i. t_i should satisfy

$$f_1(t_i) = f_1(t_i + nT_1) = C, \quad (i = 1,2,3,\ldots;\ n = 1,2,3,\ldots). \tag{2}$$

Since the length of section two is too long, the method for determining C and t_i will be given in the next section.

According to ASM, a Δt is selected and added as shown in Fig. 1(a). To avoid losing the characteristic information of the tested signal, Δt should satisfy

$$\Delta t < T_{\mathrm{fmin}}, \tag{3}$$

where T_{fmin} is the minimum period of the tested signal. For the period 1 signal, its minimum period is T_1.

Then the characteristic values can be extracted at $t_i + \Delta t$ respectively, as shown by the abscissa of dots in Fig. 1(a). There must be

$$f_1(t_i + \Delta t) = f_1(t_i + \Delta t + nT_1),$$
$$(i = 1,2,3,\ldots;\ n = 1,2,3,\ldots). \tag{4}$$

It can be seen from ASM and Fig. 1(a) that only one characteristic value V_1 can be extracted in every period T_1 of $f_1(t)$ and they are equal. Therefore, the characteristic signal $f_{xy}(t)$ of $f_1(t)$ looks like a continuous straight line (as shown in Fig. 1(a)) if these characteristic values are all kept for a T_1, and there is

$$f_{xy1}(t) = f_1(t_i + \Delta t + nT_1) = V_1,$$
$$(t_i + \Delta t \le t < t_{i+1} + \Delta t;\ i = 1,2,3,\ldots;\ n = 1,2,3,\ldots). \tag{5}$$

Therefore, the frequency of the characteristic signal $f_{xy1} = f_1 = 1/T_1$.

(b) For a continuous period 2 signal $f_2(t)$ with the period of T_2, there is

$$f_2(t) = f_2(t + nT_2) = \sum_{p=1}^{2} g_p(t + nT_{2p}), \quad (n = 1,2,3,\ldots), \tag{6}$$

where T_{21} is the period of $g_1(t)$ and T_{22} is the period of $g_2(t)$. The frequency of $g_1(t)$ is $f_{g1} = 1/T_{21}$; the frequency of $g_2(t)$ is $f_{g2} = 1/T_{22}$. For the period 2 signal $f_2(t)$, if $f_{g1} < f_{g2}$, then $f_{g2} = 2f_{g1}$,[13,14] namely $T_{21} = 2T_{22}$.

Because f_{g1} is the minimum frequency of $f_2(t)$, T_{21} certainly equals T_2.

Similarly, a constant C is selected to determine t_i $(i = 1,2,3,\ldots)$ for $\mathrm{d}f_2(t)/\mathrm{d}t > 0$, and it makes t_i satisfy

$$f_2(t_i) = f_2(t_i + nT_2) = \sum_{p=1}^{2} g_p(t_i + nT_{2p}) = C,$$
$$(i = 1,2,3\ldots;\ n = 1,2,3,\ldots). \tag{7}$$

Then, a Δt that satisfies Eq. (3) is selected. Finally at $t_i+\Delta t$ there are two characteristic values that can be extracted respectively in every period of $f_2(t)$, as shown in Fig. 1(b), there must be

$$f_2(t_i+\Delta t)=f_2(t_i+\Delta t+nT_2)=\sum_{p=1}^{2}g_p(t_i+\Delta t+nT_{2p}),$$
$$(i=1,2,3\ldots;\ n=1,2,3,\ldots), \tag{8}$$

and

$$f_2(t_{i+1}+\Delta t)=f_2(t_{i+1}+\Delta t+nT_2)=\sum_{p=1}^{2}g_p(t_{i+1}+\Delta t+nT_{2p}),$$
$$(i=1,2,3\ldots;\ n=1,2,3,\ldots). \tag{9}$$

Namely, the characteristic signal $f_{xy2}(t)$ of $f_2(t)$ contains two characteristic values V_1 and V_2 (as shown in Fig. 1(b))

$$f_{xy2}(t)=f_2(t_i+\Delta t+nT_2)=\begin{cases}V_1, & (t_i+\Delta t\le t<t_{i+1}+\Delta t,\ i=1,3,5,\ldots),\\ V_2, & (t_i+\Delta t\le t<t_{i+1}+\Delta t,\ i=2,4,6,\ldots),\end{cases}\quad (n=1,2,3,\ldots). \tag{10}$$

Since $f_{xy2}(t)$ is a periodic signal with the period of T_2 (as shown in Fig. 1(b)) and $T_2=T_{21}$, then the minimum frequency f_{xy21} of $f_{xy2}(t)$ is equal to f_{g1}. Furthermore, the periodic signal has harmonic wave, its harmonic frequency is an integer multiple of its fundamental frequency. Therefore, $f_{xy2}(t)$ certainly has a frequency equal to f_{g2}.

(c) For a continuous period k signal $f_k(t)$ with the period T_k , there is

$$f_k(t)=f_k(t+nT_k)=\sum_{p=1}^{k}g_{kp}(t+nT_{kp}),\quad (n=1,2,3,\ldots), \tag{11}$$

where T_{k1} is the period of $g_{k1}(t)$, T_{k2} is the period of $g_{k2}(t)$, T_{k3} is the period of $g_{k3}(t)$, …, T_{kk} is the period of $g_{kk}(t)$. Namely, $f_k(t)$ contains k frequency components f_{gk1} $(f_{gk1}=1/T_{k1})$, $f_{gk2}(f_{gk2}=1/T_{k2})$, $f_{gk3}(f_{gk3}=1/T_{k3})$, …, and $f_{gkk}(f_{gkk}=1/T_{kk})$.

Similarly, t_i which is determined by a constant C satisfies

$$f_k(t_i)=f_k(t_i+nT_k)=\sum_{p=1}^{k}g_{kp}(t_i+nT_{kp})=C,$$
$$(i=1,2,3\ldots;\ n=1,2,3,\ldots). \tag{12}$$

In a similar way, the characteristic signal $f_{xyk}(t)$ of $f_k(t)$ contains k characteristic values V_1, V_2, V_3, …, and V_k in every period of $f_k(t)$

$$f_{xyk}(t)=f_k(t_i+\Delta t+nT_k)=\begin{cases}V_1, & (t_i+\Delta t\le t<t_{i+1}+\Delta t, i=1,1+k,1+2k,\ldots),\\ V_2, & (t_i+\Delta t\le t<t_{i+1}+\Delta t, i=2,2+k,2+2k,\ldots),\\ V_3, & (t_i+\Delta t\le t<t_{i+1}+\Delta t, i=3,3+k,3+2k,\ldots),\\ \vdots & \\ V_k, & (t_i+\Delta t\le t<t_{i+1}+\Delta t, i=k,k+k,k+2k,\ldots),\end{cases}\quad (n=1,2,3,\ldots). \tag{13}$$

Similarly, the characteristic signal extracted from $f_k(t)$ certainly has k frequency components: $f_{xyk1}=f_{gk1}$, $f_{xyk2}=f_{gk2}$, $f_{xyk3}=f_{gk3}$, …, and $f_{xykk}=f_{gkk}$.

2.2. If the tested signal is a non-periodic signal

According to ASM and Fig. 1(c), the characteristic signal $f_{xyN}(t)$ with the characteristic information of the system can also be extracted from a continuous non-periodic signal $f_N(t)$ as long as the suitable marking time points t_i $(i=1,2,3,\ldots)$ and Δt are found. The characteristic signal of a non-periodic signal is

$$f_{xyN}(t)=f_N(t_i+\Delta t)$$
$$=\begin{cases}V_1, & (t_i+\Delta t\le t<t_{i+1}+\Delta t, i=1),\\ V_2, & (t_i+\Delta t\le t<t_{i+1}+\Delta t, i=2),\\ V_3, & (t_i+\Delta t\le t<t_{i+1}+\Delta t, i=3),\\ \vdots & \\ V_n, & (t_i+\Delta t\le t<t_{i+1}+\Delta t,\ i=n,\ n\to\infty).\end{cases} \tag{14}$$

As shown in Fig. 1(c), the extracted characteristic signal changes with the tested signal. Therefore, $f_{xyN}(t)$ is also a non-periodic signal.

According to the above analysis and theoretical proof, for periodic signals with T, the general formula of the characteristic signal is

$$f_{xy}(t)=f_D(t_i+\Delta t+nT)=V_q,$$
$$(t_i+\Delta t\le t<t_{i+1}+\Delta t;$$
$$i=q,q+D,q+2D,\ldots;\ n=1,2,3,\ldots), \tag{15}$$

where q denotes the q-th characteristic value extracted in every period of $f_D(t)$. D denotes the periodic number of $f_D(t)$. n denotes the n-th period T of $f_D(t)$. When $D=1$, $f_{xy}(t)$ is a period 1 signal, $q=1$; when $D=2$, $f_{xy}(t)$ is a period 2 signal, $q=1,2$ respectively, and there are two characteristic values V_1, V_2 in every period of $f_{xy}(t)$; when $D=k$, $f_{xy}(t)$ is a period

k signal, $q = 1,2,3,\ldots,k$, respectively, and there are k characteristic values V_1, V_2, V_3, ..., and V_k in every period of $f_{xy}(t)$.

For non-periodic signals, the general formula of the characteristic signal is

$$f_{xy}(t) = f_N(t_i + \Delta t) = V_i,$$
$$(t_i + \Delta t \le t < t_{i+1} + \Delta t,\ i = 1,2,3,\ldots,j,\ j \to \infty). \quad (16)$$

It can be seen from the definition of ASM (Eqs. (15) and (16)) that the characteristic signal can be automatically extracted from a continuous signal $f(t)$ by ASM without any additional control signal, and can retain the characteristic information of $f(t)$.

3. The principle of choosing t_i

As can be seen from the above analysis and proof of ASM, the choice of marking time points t_i $(i = 1,2,3,\ldots)$ is related to the loss of extracted characteristic information. Therefore, it is necessary to study t_i. The principle of choosing t_i is explained below, combining with Fig. 2.

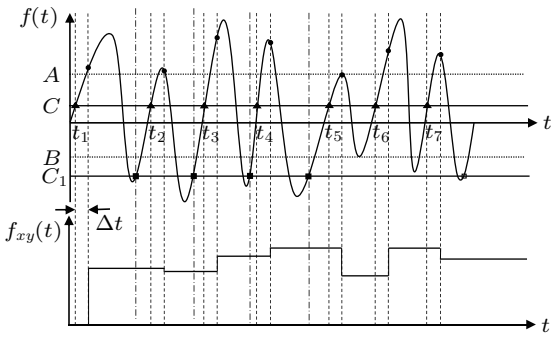


Fig. 2. The principle of choosing t_i.

The $f(t)$ in Fig. 2 is a tested continuous signal. According to the analysis in Section 2, marking time points t_i $(i = 1,2,3,\ldots)$ (as the abscissa of triangle shown in Fig. 2) are obtained by using a constant C to intersect with $f(t)$. It should be noticed that the choice of C directly determines each t_i. It will be best if C intersects $f(t)$ at every segment for $\mathrm{d}f(t)/\mathrm{d}t > 0$ (or $\mathrm{d}f(t)/\mathrm{d}t < 0$). Actually, for an extremely complex signal, it is difficult to select a suitable C by observing the tested signal, and the extracted characteristic signal may loss the state information of the tested signal. To obtain t_i $(i = 1,2,3,\ldots)$ as many as possible, C should be selected in the area where the degree of oscillation of the signal is smallest (as $[A,B]$ shown in Fig. 2). As shown in Fig. 2, C is selected between $[A,B]$ and the abscissa of the intersection points are taken as t_i $(i = 1,2,3,\ldots,7)$, there are 7 marking time points and 7 characteristic values. If C_1 intersects $f(t)$ (as shown in Fig. 2, C_1 out of $[A,B]$), only 5 marking time points and 5 characteristic values can be obtained.

4. Design and experiment of extracting characteristic signal system

4.1. Design of extracting characteristic signal system

According to ASM and the principle of choosing t_i, the circuit system for extracting characteristic signal has been designed in this paper. Its block diagram is shown in Fig. 3. This system is composed of 4 parts: time marker module, Δt module, control module, and extraction module.

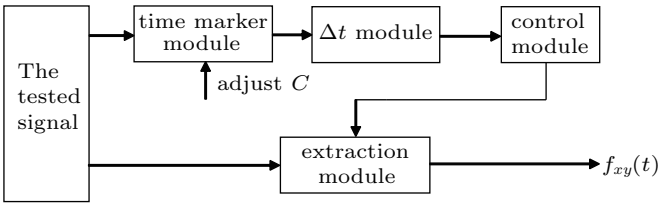


Fig. 3. The block diagram of the circuit system for extracting characteristic signal.

Time marker module is designed to determine the marking time points t_i $(i = 1,2,3,\ldots)$ based on the principle of choosing t_i. To avoid losing the characteristic values of the tested signal, the adjust C in this module can be used to adjust C for getting a suitable t_i $(i = 1,2,3,\ldots)$ as actual needs. Then according to Eq. (3), Δt module has been designed to make a delay time Δt. Control module generates a narrow pulse signal $f_{\mathrm{con}}(t)$ at $t_i + \Delta t$ for controlling extraction module to extract characteristic signal from tested signal $f(t)$. When control module gives a high level signal, extraction module starts to extract the characteristic value from $f(t)$ and keeps it until next high level. In conclusion, once the suitable C and Δt are determined, the control module can automatically generate $f_{\mathrm{con}}(t)$ at $t_i + \Delta t$. Namely, the characteristic signal $f_{xy}(t)$ can automatically generate with the change of the tested signal by the control of $f_{\mathrm{con}}(t)$.

4.2. Experiment

The typical Chua's system in Ref. [15] can generate a variety of periodic states and chaotic states by adjusting its internal parameters, such as period 1, period 2, period 3, period 4, ..., single scroll chaos, double scroll chaos, and so on. Therefore, the output y of Chua's system is chosen as the tested signal. The states of Chua's system can be changed by adjusting its internal linear resistance. The digital oscilloscope is used to do the following experiments.

When Chua's system turns into the state of period 1 by adjusting the resistance, the timing diagram of the tested signal is shown in Fig. 4(a) and its frequency spectrum diagram is shown in Fig. 4(b), where 2.90 kHz is the dominant frequency of the tested signal. According to formula (15), $q = 1$, $D = 1$,

$n = 1, 2, 3, \ldots$; the characteristic signal extracted from a period 1 signal contains one characteristic value V_1. As can be seen from Fig. 4(c) that the extracted characteristic signal has only one characteristic value. Figure 4(d) is the frequency spectrum diagram of the characteristic signal, which shows that the characteristic signal retains the dominant frequency of the tested signal.

Adjusting R to make Chua's system in the state of period 2, the timing diagram and frequency spectrum diagram of the tested signal are shown in Figs. 5(a) and 5(b), respectively. Figure 5(b) shows that the two-divided-frequency appears on the left side of the dominant frequency, which indicates that the system is in the state of period 2. According to formula (15), $q = 1, 2$; $D = 2$, $n = 1, 2, 3, \ldots$; the characteristic signal extracted from a period 2 signal contains two characteristic values V_1 and V_2. As shown in Fig. 5(c), there are two characteristic values in the extracted characteristic signal. Figure 5(d) is the frequency spectrum diagram of the characteristic signal, where the two-divided-frequency also appears on the left side of the dominant frequency. Therefore, it is still possible to clearly identify that the system is in the period 2 state from the frequency spectrum diagrams (see Figs. 5(b) and 5(d)).

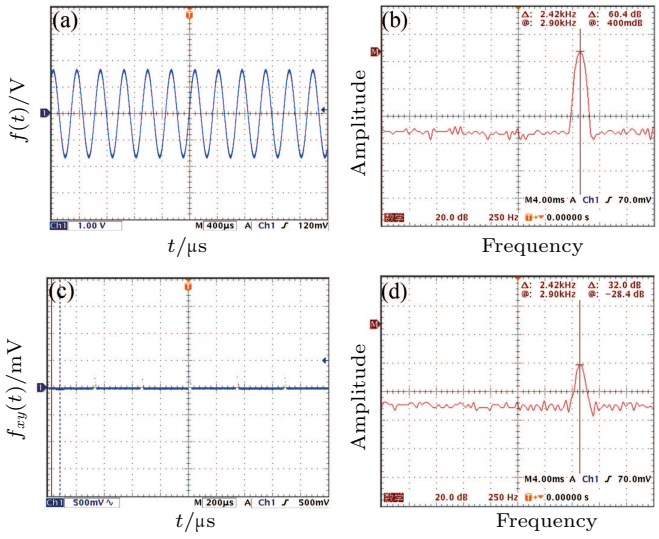


Fig. 4. Period 1 signal. (a) The timing diagram of tested signal; (b) the frequency spectrum diagram of tested signal; (c) the timing diagram of characteristic signal; (d) the frequency spectrum diagram of characteristic signal.

When Chua's system is in the state of period 3, the timing diagram and frequency spectrum diagram of the tested signal are shown in Fig. 6(a) and Fig. 6(b), respectively. As can be seen from Fig. 6(b) that the three-divided-frequency appears clearly, showing the system is in the state of period 3. According to formula (15), the characteristic signal extracted from a period 3 signal contains three characteristic values V_1, V_2, and V_3. As shown in Fig. 6(c), there are three characteristic values in the extracted characteristic signal. Figure 6(d) is the frequency spectrum diagram of the characteristic signal. It can be seen from Figs. 6(b) and 6(d) that the three-divided-frequency both appear on the left side of the dominant frequency, and the harmonic components of characteristic signal are more clear than the tested signal.

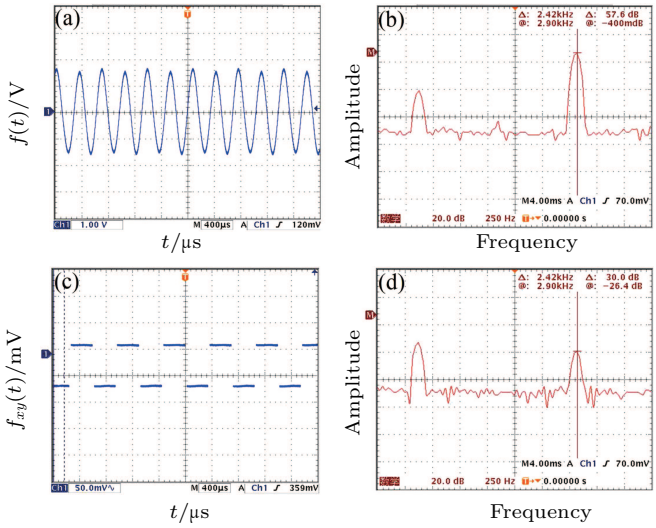


Fig. 5. Period 2 signal. (a) The timing diagram of tested signal; (b) the frequency spectrum diagram of tested signal; (c) the timing diagram of characteristic signal; (d) the frequency spectrum diagram of characteristic signal.

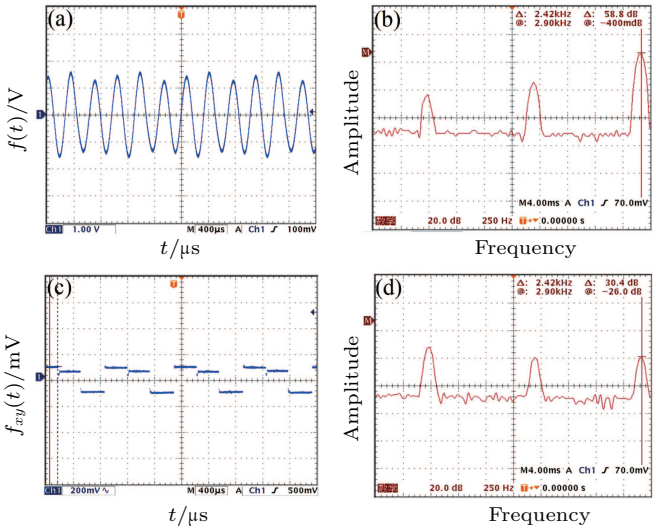


Fig. 6. Period 3 signal. (a) The timing diagram of tested signal; (b) the frequency spectrum diagram of tested signal; (c) the timing diagram of characteristic signal; (d) the frequency spectrum diagram of characteristic signal.

Keep on adjusting R, when Chua's system turns into the state of period 4, it is difficult to identify the periodic state of the system by the timing diagram shown in Fig. 7(a). However, from the frequency spectrum diagram of the tested signal shown in Fig. 7(b), the four-divided-frequency showing the system is in the state of period 4. According to formula (15),

the characteristic signal extracted from a period 4 signal contains characteristic values V_1, V_2, V_3, and V_4. Similarly, as shown in Fig. 7(c), there are four characteristic values in the extracted characteristic signal. Figure 7(d) is the frequency spectrum diagram of the characteristic signal. All of these figures confirm that the characteristic signal and the tested signal contain the same frequency components.

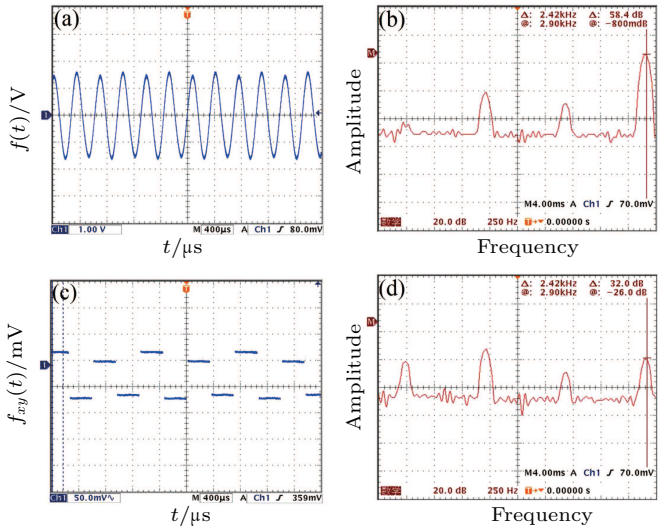


Fig. 7. Period 4 signal. (a) The timing diagram of tested signal; (b) the frequency spectrum diagram of tested signal; (c) the timing diagram of characteristic signal; (d) the frequency spectrum diagram of characteristic signal.

When Chua's system is in single scroll chaos state, it is hard to identify the running state of the system by the timing diagram shown in Fig. 8(a). Figure 8(b) is its frequency spectrum diagram, the continuous spectral shows that the system is in the non-periodic state. According to formula (16), the characteristic signal extracted from a non-period signal contains countless characteristic values V_1, V_2, V_3, ... As shown in Fig. 8(c), the extracted characteristic signal has many characteristic values. Although these characteristic values look like countable, their number will continually increase with time. Figure 8(d) is the frequency spectrum diagram of the characteristic signal. It is evident from Figs. 8(b) and 8(d) that the extracted characteristic signal will undoubtedly lose some information. However, ASM is a method for extracting a characteristic signal which can reflect the state information of the tested signal, the continuous spectra in Fig. 8(d) confirm that the characteristic signal still retains the characteristics of aperiodicity.

Adjust R to make Chua's system turn into the double scroll chaos state. The running state of the system cannot be identified by the timing diagram shown in Fig. 9(a) either. Figure 9(b) is the frequency spectrum diagram of the tested signal, with the continuous spectra showing that the system is in the non-periodic state. Similarly, there are countless characteristic values in the characteristic signal which are extracted from a non-period signal, as shown in Fig. 9(c), the same as formula (16). Figure 9(d) is the frequency spectrum diagram of the characteristic signal. As shown in Figs. 9(b) and 9(d), both the frequency spectra of the characteristic signal and the tested signal are continuous. It illustrates that the characteristic signal extracted from a non-periodic signal by using this method can also retain characteristics of tested signal.

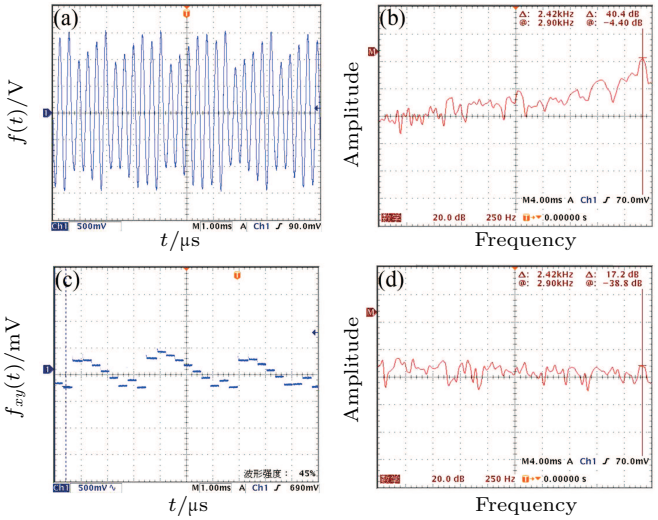


Fig. 8. Single scroll chaos. (a) The timing diagram of tested signal; (b) the frequency spectrum diagram of tested signal; (c) the timing diagram of characteristic signal; (d) the frequency spectrum diagram of characteristic signal.

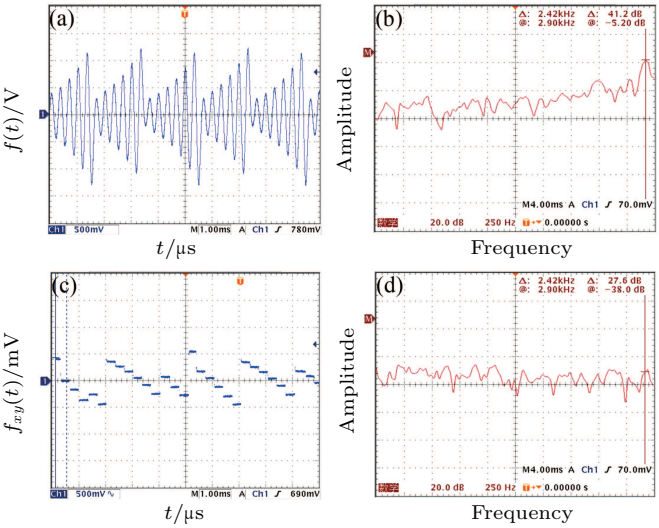


Fig. 9. Double scroll chaos. (a) The timing diagram of tested signal; (b) the frequency spectrum diagram of tested signal; (c) the timing diagram of characteristic signal; (d) the frequency spectrum diagram of characteristic signal.

As shown in Figs. 4–9, the extracted characteristic signal changes with the tested signal. The more complex the tested signal is, the more characteristic values will be extracted in each period. If the tested signal is a complex non-periodic

signal, an infinite number of characteristic values can be extracted. It can be seen from the timing diagrams that the characteristic signal only retains some voltage values and periodicity information of the tested signal. However, as shown in the frequency spectrum diagrams, the characteristic signals of periodic signals retain the main frequency information of the tested signal (as shown in Fig. 4(d), Fig. 5(d), Fig. 6(d), and Fig. 7(d)). Although the frequency information of the characteristic signal and tested signal are quite different, the non-periodic states can also be clearly identified, such as Figs. 8(d) and 9(d).

Now, the characteristic signals extracted by the designed system are applied to 45-degree line in Ref. [11] and SP in Ref. [12], then get Figs. 10(a)–10(f). Figure 10(a) is the phase diagram displayed by the output signals x and y of Chua's system, which shows the system is in the state of period 4. Figure 10(b) is the characteristic signal extracted from output signal y. Figures 10(c) and 10(d) are the frequency spectrum diagrams of signal y and the characteristic signal extracted from y, respectively. Figure 10(e) is a 45-degree line diagram, and figure 10(f) is an SP graph. It is clarified by Fig. 10 that the characteristic signal extracted by ASM not only can retain the frequency information of the tested signal, but also can quickly identify the running state of the tested system when applied.

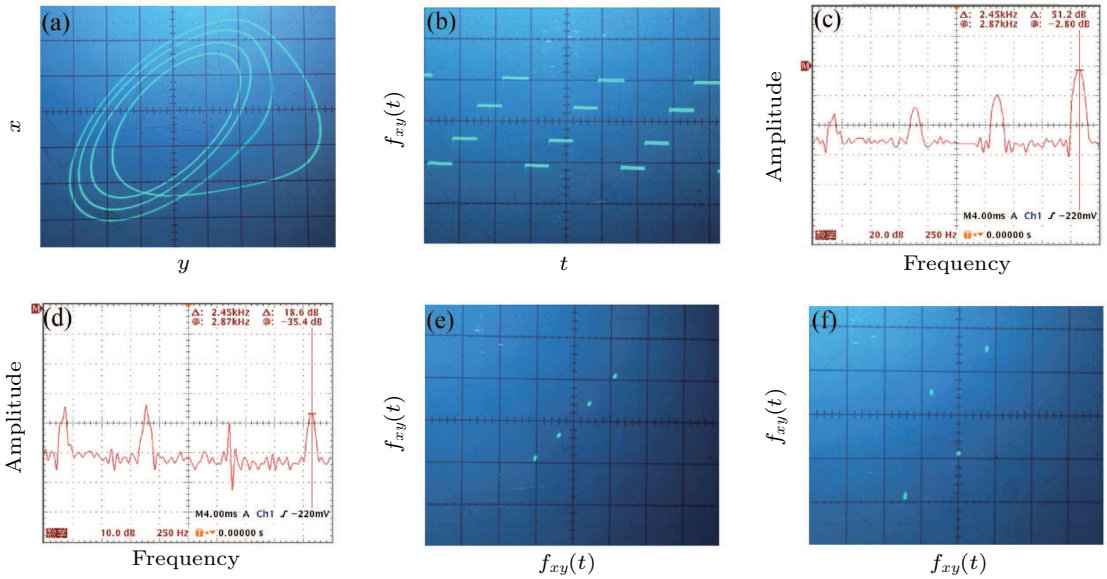


Fig. 10. Application of the characteristic signals extracted from period 4 signal (a kind of periodic window in chaotic area). (a) Phase diagram; (b) the timing diagram of characteristic signal; (c) the frequency spectrum diagram of tested signal; (d) the frequency spectrum diagram of characteristic signal; (e) 45-degree line diagram; (f) SP graph.

5. Conclusion

ASM is studied from theory and experiment, and it is confirmed that the characteristic signal extracted by this method can retain the frequency information of the tested signal. In order to clarify ASM, the general formulas of characteristic signals extracted by ASM are theoretically derived for the first time. In addition, ASM has the following features:

(i) ASM can automatically extract characteristic signal without an additional control signal.

(ii) It can be seen from Eqs. (15) and (16) that when q characteristic values are in each period of characteristic signal, the system is in the state of period q; otherwise, the system is in the non-period state. Therefore, ASM can analyze the stability of a nonlinear system.

(iii) ASM not only can be applied for analyzing the single-variable nonlinear systems, but also can be applied to analyze the multivariable-nonlinear systems.

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