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A New Method of Observing The States of A Single Variable Nonlinear System in Three-Dimension Space in Real Time

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Abstract. *In order to observe the states of a single variable nonlinear system in real time more clearly, a qualitative three dimension scatter point method is proposed. The method can overcome the weakness of overlapping information in original SP. Its complete definition is given and proved, then its principle is explained with a set of diagrams in detail. According to the definition, a display system has been designed based on virtual technology, which can display the three dimension scatter points of a tested single variable nonlinear system in real time for observing the states of the system directly. In this paper, observation experiments for a typical Chua's circuit have been done by using this system. A large number of experimental results prove that the proposed method is feasible and practical.*
Keywords: SP, Single variable, System state, Three-dimension display

1. **Introduction.** Different non-linear systems produce different non-linear signals. These complex signals not only relate to the complexity and parameters of the tested systems but also reflect the running states of the systems in real time. The running state of a system can directly reflect whether the system is in normal working condition. It is not enough to observe these complex signals with conventional instruments and methods. In order to grasp the running states of the tested system and predict its fault in time, people have been working hard to study some new methods and apply their achievements to many fields. For instance, reference [1] analyzes the pressure fluctuation characteristics of hydro-turbine by comprehensively using a variety of methods of analyzing chaos phenomenon to achieve the operating monitoring and fault diagnosis of hydro-turbine; reference [2] studies and proposes a method of diagnosing mechanical fault of rolling bearings based on chaos theory; reference [3] proposes a hybrid fault diagnosis approach based on combining spectral kurtosis and non-local means weight envelop spectrum; reference [4] puts forward an intelligent method based on wavelet packet transform, which can effectively diagnose the faults of rotating machinery; reference [5] studies the chaotic characteristic of nonlinear metal rubber vibration isolation system by combining the Poincare section, frequency spectrogram and Lyapunov exponent for avoiding the harmful chaotic vibration; reference [6] proposes a chaotic analysis method based on adjacent data dependency. With this method, combining qualitative observation and quantitative analysis, the different states and the changes of rotor working condition can be done well. The above

achievements and applications have shown the importance of studying the methods of observing nonlinear systems. However, they are not versatile and are only suitable for some applications. And it may take quite some time and/or need complex process to get the correct analysis results. For these reasons, sometimes people need more general and direct methods to observe and analyze the tested system to quickly detect or predict problems in real time. Reference [7] proposes a 45-degree line method for observing the running states of a single variable nonlinear system on an oscilloscope, which can show whether the system is stable or unstable. But it is only suitable for the relatively simple nonlinear signals. Reference [8] proposes a SP method, which is a special method to observe the nonlinear signals generated by the single variable nonlinear system on the oscilloscope and quickly determine the states of the system. This method has more application value than the method in reference [7]. However, there are some limitations of SP method, the general oscilloscope can only display the state of the tested system in a two-dimensional plane. For example, if the tested system is more complex, the overlap of scatter points on the two-dimensional oscilloscope may cause unobservable information lost. In order to solve this problem, this paper proposes a Three-Dimension Scatter Point method (3D SP for short) based on SP [8]. It overcomes the problem that the scatter points may be superimposed, thus we can be easier to observe.

The second chapter in this paper gives the definition of 3D SP method based on original SP firstly, and then conducts a detailed explanation and proof from two aspects: stable and unstable states of the tested system. Finally, the inference is given. The third chapter discusses the principle of realizing 3D SP with combining diagrams in detail. In chapter four, in order to verify the validity and practicability of 3D SP, according to its definition, we design a 3D SP observation system by using virtual technology and experimentally observe the typical Chua's circuit [9] which can generate rich states. In the end, conclusions are given in chapter five.

2. **The definition of 3D SP.** 3D SP is that the characteristic values which obtained from a continuous signal by a special method are displayed in three-dimension space as scatter points. It's defined as follow:

Any signal $V(t)$ generated by a deterministic single variable nonlinear system is continuous on $[M_1, M_2]$, where $M_1, M_2 \in R$. There is $V(t_i) = C, (i = 1, 2, 3, ...)$ for $dV(t)/dt > 0$, C is a constant in $[V_{emin}, V_{emax}]$(V_{emin} is the minimum maxima of $V(t)$ and V_{emax} is the maximum minima of $V(t)$). If we choose Δt_1, Δt_2 and Δt_3 based on t_i one after the other, three sets of time points can be gotten: $t_i+\Delta t_1$, $t_i+\Delta t_1+\Delta t_2$ and $t_i+\Delta t_1+\Delta t_2+\Delta t_3$,$(i = 1, 2, 3, ...)$. Then there are three sets of corresponding values on these time points respectively: $V(t_i + \Delta t_1)$, $V(t_i + \Delta t_1 + \Delta t_2)$ and $V(t_i + \Delta t_1 + \Delta t_2 + \Delta t_3), (i = 1, 2, 3, ...)$. Now take them as the values of X, Y and Z coordinates in 3D coordinate system respectively. A series of scatter points can be formed in the 3D space in time order.

The following explanation and proof of 3D SP definition are from two aspects: stable and unstable states of the tested system.

1. Assuming that the system is in a stable state, it can produce a stable periodic signal.

(1) A continuous period 1 signal $V_1(t)$ with a period of T_1, which is

$$V_1(t) = V_1(t + nT_1), (n = 1, 2, 3, ...) \tag{1}$$

According to the definition, a C satisfies:

$$V_{emax} < C < V_{emin} \tag{2}$$

Then, we can obtain for $dV_1(t)/dt > 0$

$$V_1(t_i) = C, (i = 1, 2, 3, ...) \tag{3}$$

Then, we choose one increment Δt_1 to obtain

$$V_1(t_i+\Delta t_1)=V_1(t_i+\Delta t_1+nT_1),(i=1,2,3,...,n=1,2,3,...) \quad (4)$$

We choose another increment Δt_2 to obtain

$$V_1(t_i+\Delta t_1+\Delta t_2)=V_1(t_i+\Delta t_1+\Delta t_2+nT_1),(i=1,2,3,...,n=1,2,3,...) \quad (5)$$

We continue to choose the third increment Δt_3 to obtain

$$V_1(t_i+\Delta t_1+\Delta t_2+\Delta t_3)=V_1(t_i+\Delta t_1+\Delta t_2+\Delta t_3+nT_1),(i=1,2,3,...,n=1,2,3,...) \quad (6)$$

Let $V_1(t_i+\Delta t_1+nT_1)=N_{Xj}$, $(i=1,2,3,...,n=1,2,3,...,j=1,2,3,...)$, and the sequence N_{Xj}, $(j=1,2,3,...)$ is taken as the values of X coordinate.

Let $V_1(t_i+\Delta t_1+\Delta t_2+nT_1)=N_{Yj}$, $(i=1,2,3,...,n=1,2,3,...,j=1,2,3,...)$, and the sequence N_{Yj}, $(j=1,2,3,...)$ is taken as the values of Y coordinate.

Let $V_1(t_i+\Delta t_1+\Delta t_2+\Delta t_3+nT_1))=N_{Zj}$, $(i=1,2,3,...,n=1,2,3,...,j=1,2,3,...)$, and the sequence N_{Zj}, $(j=1,2,3,...)$ is taken as the values of Z coordinate. In the 3D coordinate system, the points (N_{Xj},N_{Yj},N_{Zj}), $(j=1,2,3,...)$ in each period T_1 will appear once at the same position. Then, we can get one stable point.

(2) A continuous period 2 signal $V_2(t)$ with a period of T_2 can be decomposed into two signals $g_1(t)$, $g_2(t)$, which is

$$V_2(t)=g_1(t)+g_2(t) \quad (7)$$

$$V_2(t)=V_2(t+nT_2)=g_1(t+nT_2^{'})+g_2(t+nT_2^{''}),(n=1,2,3,...) \quad (8)$$

Where $T_2^{'}$ is the period of $g_1(t)$, $T_2^{''}$ is the period of $g_2(t)$. There are two integers k_1 and k_2 to satisfy

$$T_2=k_1T_2^{'}=k_2T_2^{''} \quad (9)$$

Let f_2' and f_2'' denote the frequencies of $g_1(t)$ and $g_2(t)$ respectively. If f_2' is the fundamental frequency of f_2'', then $f_2''=2f_2'$.

From (9) we can get $k_1=2k_2$, and $T_2^{'}=2T_2^{''}$. In one period T_2, $V_2(t)$ in equation (7) will have two peaks.

When we choose a suitable constant C according to the definition, we can obtian

$$V_2(t_i)=g_1(t_i)+g_2(t_i)=C,(i=1,2,3,...) \quad (10)$$

So, in one period T_2, two values $V_2(t_1)$ and $V_2(t_2)$ can be obtained for $dV_2(t)/dt>0$.

We choose one increment Δt_1 to obtain two sequences in each period T_2:

$V_2(t_i+\Delta t_1)=V_2(t_i+\Delta t_1+nT_2)=g_1(t_i+\Delta t_1+nT_2^{'})+g_2(t_i+\Delta t_1+nT_2^{''}),(i=1,2,3...,n=1,2,3,...)$

$V_2(t_{i+1}+\Delta t_1)=V_2(t_{i+1}+\Delta t_1+nT_2)=g_1(t_{i+1}+\Delta t_1+nT_2^{'})+g_2(t_{i+1}+\Delta t_1+nT_2^{''}),(i=1,2,3,...,n=1,2,3,...)$

Let $V_2(t_i+\Delta t_1)=N_{X1j}$, $V_2(t_{i+1}+\Delta t_1)=N_{X2j}$, $(i=1,2,3,...,j=1,2,3,...)$.

Therefore there are two values N_{X1j}, N_{X2j}, $(j=1,2,3,...)$ in each period T_2. Then two unequal sequences N_{X1j}, N_{X2j}, $(j=1,2,3,...)$ are produced alternately.

Similarly, we continue to choose another increment Δt_2. There are two values N_{Y1j}, N_{Y2j}, $(j=1,2,3,...)$ in each period T_2. Then two unequal sequences N_{Y1j}, N_{Y2j}, $(j=1,2,3,...)$ are produced alternately.

We choose the third increment Δt_3 in the same way, there are two values N_{Z1j}, N_{Z2j}, $(j=1,2,3,...)$ in each period T_2. Then two unequal sequences N_{Z1j}, N_{Z2j}, $(j=1,2,3,...)$ are produced alternately.

In the 3D coordinate system, two points $(N_{X1j},N_{Y1j},N_{Z1j})$ and $(N_{X2j},N_{Y2j},N_{Z2j})$, $(j=1,2,3,...)$ in each period T_2 will appear once at two different positions. Then, we can get two stable points.

(3) In a similar way, for a continuous period m signal $V_m(t)$ with period T_m, which is

$$V_m(t) = V_m(t + nT_m), (n = 1, 2, 3, ...) \tag{11}$$

There will be m values $N_{X1j}, N_{X2j}, ..., N_{Xmj}$, $(j = 1, 2, 3, ...)$ in each period T_m. Then, m unequal sequences $N_{X1j}, N_{X2j}, ..., N_{Xmj}$, $(j = 1, 2, 3, ...)$ are produced alternately and taken as the values of X coordinate.

Similarly, there will be m values $N_{Y1j}, N_{Y2j}, ..., N_{Ymj}$, $(j = 1, 2, 3, ...)$ in each period T_m. Then, m unequal sequences $N_{Y1j}, N_{Y2j}, ..., N_{Ymj}$, $(j = 1, 2, 3, ...)$ are produced alternately and taken as the values of Y coordinate.

Similarly, there will be m values $N_{Z1j}, N_{Z2j}, ..., N_{Zmj}$, $(j = 1, 2, 3, ...)$ in each period T_m. These m unequal sequences $N_{Z1j}, N_{Z2j}, ..., N_{Zmj}$, $(j = 1, 2, 3, ...)$ are taken as the values of Z coordinate.

Therefore, in the 3D coordinate system, m points $(N_{X1j},N_{Y1j},N_{Z1j})$,$(N_{X2j},N_{Y2j},N_{Z2j})$,...,$(N_{Xmj},N_{Ymj},N_{Zmj})$, $(j = 1, 2, 3, ...)$ in each period T_m will appear once at m different positions. Then, we can get m stable points.

2. Assuming that a tested nonlinear system is in an unstable state, a signal $V(t)(M_1 \geq V(t) \geq M_2, M_1 \& M_2 \in R)$ generated by this system is a nonperiodic continuous signal. In order to lose information as little as possible, choosing a constant C according to (2) will intersect $V(t)$ for $dV(t)/dt > 0$ at $V(t_i) = C$, $(i = 1, 2, 3, ...)$. Based on the time $t_i, (i = 1, 2, 3, ...)$ of corresponding to each intersection point on the time axis, we choose three increments Δt_1, Δt_2 and Δt_3, similarly, let:

$V(t_i + \Delta t_1) = M_{Xi}, (i = 1, 2, 3, ...)$,

$V(t_i + \Delta t_1 + \Delta t_2) = M_{Yi}, (i = 1, 2, 3, ...)$,

$V(t_i + \Delta t_1 + \Delta t_2 + \Delta t_3) = M_{Zi}, (i = 1, 2, 3, ...)$.

Take M_{Xi}, M_{Yi} and M_{Zi}, $(i = 1, 2, 3, ...)$ as the values of the X, Y, Z in the 3D coordinate system respectively. Since $V(t)$ is a nonperiodic signal, the value of each point (M_{Xi},M_{Yi},M_{Zi}), $(i = 1, 2, 3, ...)$ will not be equal. Therefore, as time goes on, the number of points in a certain area increases constantly. When $t \to \infty$, there will be numerous scatter points in the 3D space.

According to the proof and analysis above, the 3D SP can extract the characteristic values from the single variable signal of the tested nonlinear system in this special way. Thus we can get the points in the 3D coordinate system.

Therefore, we can get a inference: In 3D space, if the scatter points by 3D SP are finite and stable, the system is in a stable state. Otherwise, the system is in an unstable state.

3. **The principle of 3D SP.** The principle of 3D SP is shown in Figure 1. Assuming that $V(t)$ is a continuous signal generated by a single variable nonlinear deterministic system, and its waveform is shown in Figure 1(a). According to the definition of the 3D SP and Figure 1(a), we know that if a constant C is chosen arbitrarily to satisfy equation (2), C certainly intersect $V(t)$ at $V(t_i) = C$, $(i = 1, 2, 3)$. Let C and $V(t)$ intersect for $dV(t)/dt > 0$, we can get $V(t_1) = V(t_2) = V(t_3) = C$ at $t_i, (i = 1, 2, 3)$, as shown in Figure 1(a).

In order to obtain the characteristic values of signal $V(t)$, we choose one increment Δt_1. $V(t_i + \Delta t_1)$, $(i = 1, 2, 3)$ can be obtained at corresponding $t_i + \Delta t_1$, as shown in the pentagrams of Figure 1(a). Obviously, the value of each $V(t_i + \Delta t_1)$, $(i = 1, 2, 3)$ will not be equal, but they satisfy: $M_1 \geq V(t_i + \Delta t_1) \geq M_2$, $(i = 1, 2, 3)$.

We choose second increment Δt_2, then we can get another set of signal $V(t_i+\Delta t_1+\Delta t_2)$, $(i = 1, 2, 3)$ corresponding to time $t_i + \Delta t_1 + \Delta t_2$, $(i = 1, 2, 3)$, as shown in the triangles of Figure 1(a). Obviously, $V(t_i+\Delta t_1+\Delta t_2)$, $(i = 1, 2, 3)$ satisfy $M_1 \geq V(t_i+\Delta t_1+\Delta t_2) \geq M_2$, $(i = 1, 2, 3)$.

Then we choose the third increment Δt_3, we can get the third set of signal $V(t_i+\Delta t_1+\Delta t_2+\Delta t_3)$, $(i=1,2,3)$ corresponding to $t_i+\Delta t_1+\Delta t_2+\Delta t_3$, $(i=1,2,3)$, as shown in the squares of Figure 1(a). Obviously, $V(t_i+\Delta t_1+\Delta t_2+\Delta t_3)$, $(i=1,2,3)$ satisfy $M_1 \geq V(t_i+\Delta t_1+\Delta t_2+\Delta t_3) \geq M_2$, $(i=1,2,3)$.

There are three sets of values numbered 1, 2 and 3 in Figure 1(a) and each of them has a pentagram signal $V(t_i+\Delta t_1)$, $(i=1,2,3)$, a triangle signal $V(t_i+\Delta t_1+\Delta t_2)$, $(i=1,2,3)$ and a square signal $V(t_i+\Delta t_1+\Delta t_2+\Delta t_3)$, $(i=1,2,3)$. We take them as the values of the X, Y and Z axes in 3D Cartesian coordinate system respectively. The values of each set in Figure 1(a) correspond to one point in Figure 1(b). It can be also seen from Figure 1(b) that the three scatter points correspond to the three sets of values in Figure 1(a) respectively, which are labeled the same number in Figure 1(a) and in Figure 1(b). The coordinates of these points in Figure 1(b) are:

Point 1: $(V(t_1+\Delta t_1), V(t_1+\Delta t_1+\Delta t_2), V(t_1+\Delta t_1+\Delta t_2+\Delta t_3))$

Point 2: $(V(t_2+\Delta t_1), V(t_2+\Delta t_1+\Delta t_2), V(t_2+\Delta t_1+\Delta t_2+\Delta t_3))$

Point 3: $(V(t_3+\Delta t_1), V(t_3+\Delta t_1+\Delta t_2), V(t_3+\Delta t_1+\Delta t_2+\Delta t_3))$

According to this method, as time goes on, we can observe the n-th point $(V(t_n+\Delta t_1), V(t_n+\Delta t_1+\Delta t_2), V(t_n+\Delta t_1+\Delta t_2+\Delta t_3))$ in the 3D coordinate system.

(a)

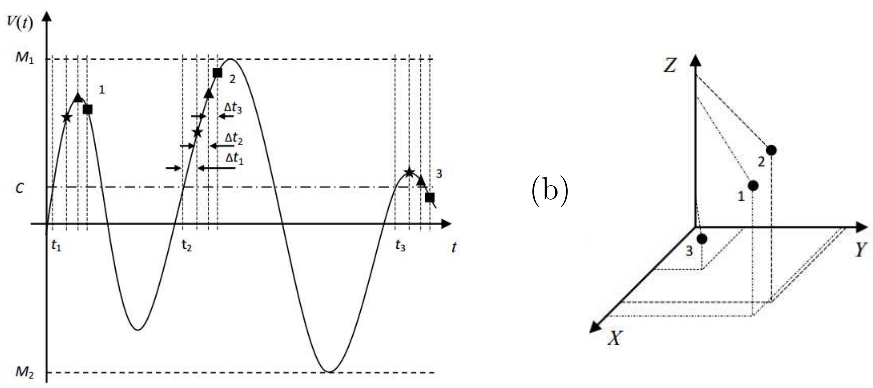

FIGURE 1. The principle of 3D SP: (a) Nonlinear continuous waveform, (b) Scatter point graph

t_i in the definition can be adjusted. When we choose a different t_i, we can get distribution of scatter points.

From Figure 1(a) and Figure 1(b), it can be seen that the more complex the signal is, the more scatter points are observed in Figure 1(b) and the more complex of its distribution is. Obviously, according to the definition of 3D SP, when the tested system generates a stable one-cycle signal, only one stable point can be obtained on the 3D coordinate system. When it is a stable two-cycle signal, two stable points can be obtained. When it is a stable n-cycle signal, n stable points can be obtained. When the tested system is in an unstable state, it will generate nonperiodic signals. At this time, we can get an infinite number of scatter points in the some area of the 3D coordinate system.

4. Design and experiment of 3D SP observation system.

4.1. Design of 3D SP observation system.

As shown in the right of Figure 2, the two modules surrounded by dashed lines are the two major parts of the 3D observation system. According to the definition of the 3D SP and the principle shown in Figure 1(a), the characteristic value module is realized by programming. This module can extract characteristic values from a signal $V(t)$. The different characteristic signals may be obtained by using t_i to adjust the basic values $V(t_i)$ of the signal. The virtual instrument module contains the display function of 3D SP diagram, phase diagram, waveform etc, and still the interface of the virtual oscilloscope, which are realized by Labview programming. The left part of Figure 2 is the adjustment and acquisition module for adjusting and collecting the tested signal. If the tested non-linear circuit system only has a single variable signal (one signal), this signal can be directly sent to the characteristic value module after adjustment and acquisition for displaying 3D SP diagram. If the tested system has multivariable signals, these signals can be directly sent to the virtual instrument for displaying other diagrams.

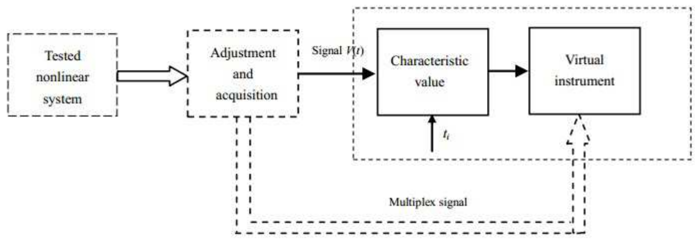

FIGURE 2. The main block diagram of 3D SP display system

Due to the fact that the system of Figure 2 is realized by software programming, it can be easy to add other functions. In this paper, the virtual instrument module designed by Labview on a general PC. It can display 3D scatter points and waveform of single variable signal in real-time. In order to facilitate observation, 3D SP diagrams can be magnified and rotated manually. If the tested system has multivariable signals, two-dimensional and 3D phase or other diagrams can be displayed.

4.2. **Observation experiment.** Since the typical Chua's circuit can generate various periodic and chaotic states (stable states and unstable states) with the change of its internal parameters, we choose it as the tested nonlinear system for experiment. Therefore, we may change the states of Chua's circuit by adjusting its linear resistor R. Since Chua's circuit have three variable output signals: x, y and z [9], these signals are collected to display the 3D phase diagrams for illustrating its running states, and signal z is chosen as its single variable output signal for testing 3D SP diagrams during the experiments in this paper. During the observation experiment, time t_i can be adjusted at any time according to actual need. The following is the 3D SP observation experiment.

First adjusting R of Chua's system to get its period one state, we can see a closed ring in Figure 3(a), which means that the tested system generated one cycle signal. Its 3D SP graph is one stable point, as shown in Figure 3(b). Both Figure 3(a) and Figure 3(b) show that the tested system is in a stable period one. Then adjusting the linear resistor of Chua's circuit again, there are two rings on the phase diagram, as shown in Figure 4(a). At the same time, two stable points are displayed on the 3D SP graph, as shown in Figure 4(b). These two graphs show that the tested system is in a stable period two. Going on adjusting R, there are four rings in Figure 5(a). At this time, four stable points are displayed in Figure 5(b), it shows that the tested system is in a stable period four. From the experiment above we come to a conclusion: the stable periodic state of the tested system can be determined by only observing the number of stable points on 3D coordinate system.

The single-scroll chaotic state diagram is shown in Figure 6(a) by going on adjusting R. Then, countless scatter points appear on 3D coordinate system, as shown in Figure

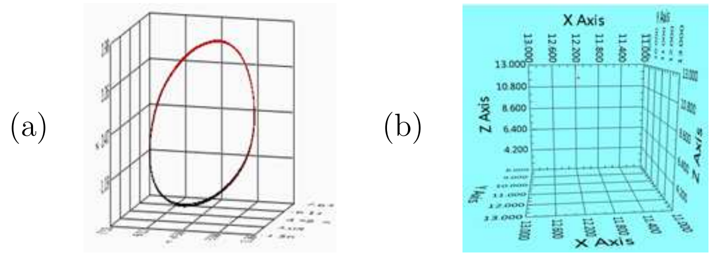

FIGURE 3. Period one: (a) Phase diagram, (b) 3D SP graph

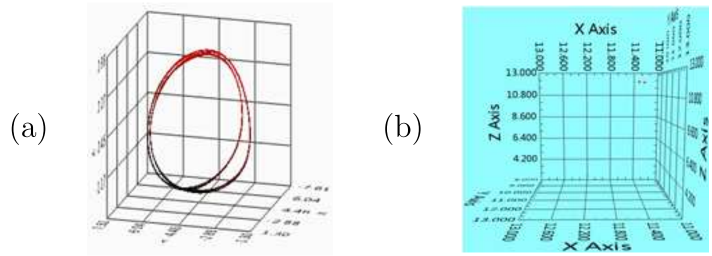

FIGURE 4. Period two: (a) Phase diagram, (b) 3D SP graph

6(b). These points have been constantly flashing, shaking, disappearing and appearing, which shows that the tested system is in an unstable state. Furthermore, the 3D SP graph in Figure 6(b) can be zoomed in and rotated for making them observed more clearly, as shown in Figure 6(c) and Figure 6(d). Going on adjusting R, the double-scroll chaotic state is shown in the Figure 7(a). At the same time, countless scatter points also appear on 3D coordinate system, as shown in Figure 7(b). These points are constantly flashing and shaking, which shows that the tested system is in an unstable state, as shown in Figure 7(b). Figure 7(c) is the magnified the 3D SP graph of Figure 7(b), and Figure 7(d) is the rotated 3D SP graph of Figure 7(c). Obviously, both of them are clearer than Figure 7(b).

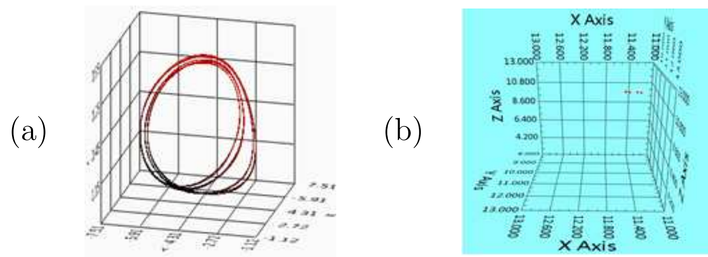

FIGURE 5. Period four: (a) Phase diagram, (b) 3D SP graph

Since the tested system is in a nonperiodic state, the tested scatter points in real time can not appear in the same place. These scatter points in the 3D space only stay for some time, and then they will disappear automatically. Then new points constantly appear in different places. These points scatter over a certain area, which shows that the system is deterministic and its signal is bounded. Since scatter points irregularly appear and disappear during the real-time observation period, these scatter points look like constantly flashing and shaking. These experiments show that the designed observation system can observe the unstable states of the tested system. In order to observe the best results, we can adjust the system at any time during the observation. This experiment also proves that the 3D SP is feasible and practical.

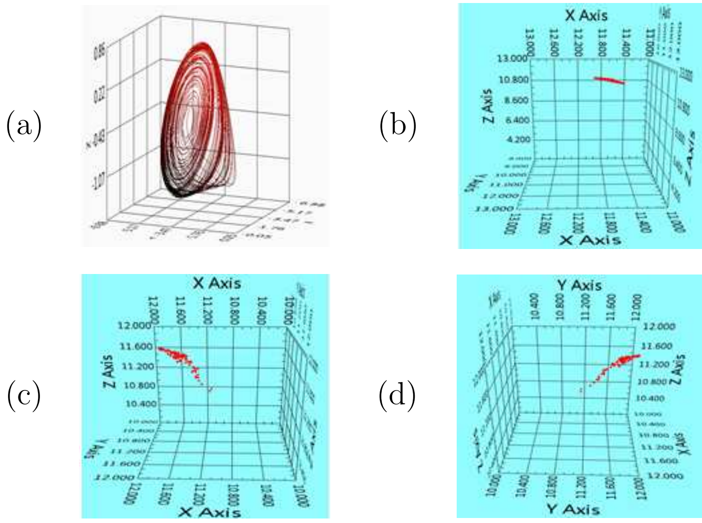

FIGURE 6. Single scroll chaos: (a) Phase diagram, (b) 3D SP graph, (c) The magnified 3D SP graph, (d) The rotated 3D SP graph

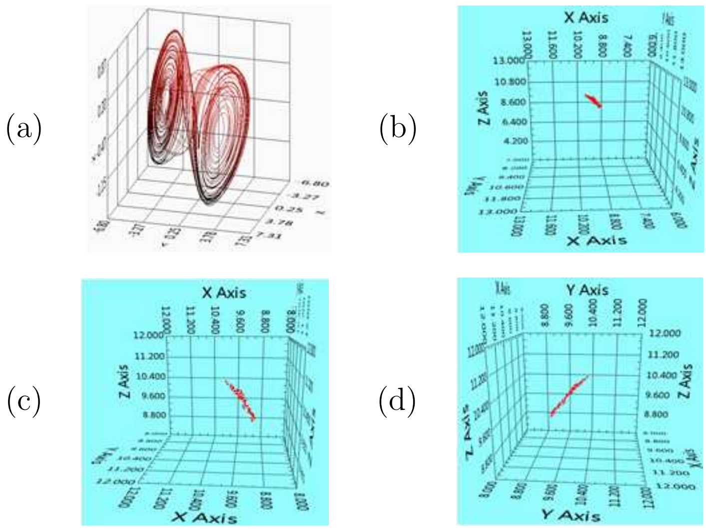

FIGURE 7. Double scroll chaos: (a) Phase diagram, (b) 3D SP graph, (c) The magnified 3D SP graph, (d) The rotated 3D SP graph

5. **Conclusion.** 3D SP is studied and proposed in this paper. This method in the form of real time scatter point can directly displays the running states of the tested single variable nonlinear system in 3D space. And it solves the problem that the scatter points displayed by the oscilloscope are easy to overlap. This paper has proved its feasibility from theory and observational experiments. All of these demonstrate that this method is practical, versatile and effective for quickly determining the stable state and unstable state of the single variable nonlinear systems. In addition, the 3D SP has the following characteristics:

1. When the scatter points are finite and stable, the system is in a stable state; when there are an infinite number of scatter points, the system is in an unstable state.
2. Although the definition of 3D SP is for the tested single variable system, it can be used to observe multivariable system when needed.

3. 3D SP not only can be realized by the observation system of virtual instruments in this paper, but also by other means to design a more convenient and flexible system for observing nonlinear single variable systems.

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