Nonlinear Dynamical Detection of Normal Vowels Using PPS Algorithm and WDP of Neural Networks

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Abstract—Normal vowels are confirmed to have irregular property which is possibly due to chaos. In this paper, we employ two approaches to detect the existence of underlying dynamics in Chinese normal vowels recorded from both male and female adults. The PPS algorithm that can test pseudoperiodic time series against the hypothesis of periodic orbits with uncorrelated noise presents that these data sets follow chaos. Meanwhile, another novel technique, weight distribution projection (WDP) of neural networks, is proposed to identify dynamical property of these given time series. Intuitively, their WDP graphs exhibit the chaotic property. So both methods give the same conclusion that the measured Chinese vowels are consistent with chaos.

Keywords—normal vowels; surrogate algorithm; neural networks; weight distribution projection

I. INTRODUCTION

Linear dynamical systems analysis, such as the power spectrum analysis and the linear predictive coding model, has been widely applied to human speech analysis in the past decades [1-2]. Many studies suggest that speech may be a nonlinear process. Moreover some reliable experimental evidences show that human speech, strictly speaking, is a nonlinear dynamical phenomenon. That is, some important qualities of speech are inherently characterized by nonlinear dynamics. In fact, a number of studies have been conducted to seek of the possible underlying chaotic features in speech phonemes [3-6].

Recently, with the development of nonlinear prediction models for vowel synthesis, people begin to study the irregularity in vowels from the viewpoint of nonlinear systems, especially deterministic chaos. Several studies have reported that there exist chaotic dynamical properties in vowels. However it is still difficult to confirm. Because analysis of very long-term speech data may suffer from nonstationarity while for short-term speech data, reliable estimation of nonlinear dynamical quantities requires delicate numerical computation. In addition, we must be very careful in analyzing and discussing low-dimensional chaos in real-world systems, since noisy data can sometimes mimic chaotic behavior and the current technique for chaos detection are sensitive to the noise [7].

In this paper, we adopt PPS algorithm and WDP of neural networks to detect nonlinear dynamics in normal vowels, i.e. to confirm whether the normal vowels present chaotic dynamics. In the next section we describes details of vowel signals used in the paper and section 3 briefly reviews the two approaches, and demonstrate their abilities to distinguish chaotic orbits from periodic ones. In Section 4 we apply both methods to several typical male and female Chinese vowels and obtain the consistent results. Finally, we take the conclusion.

II. EXPERIMENTAL DATA

For general analysis, we consider speech signals of two Chinese vowels /a/ and /o/ recorded from male and female speaker respectively, which are digitized with a sampling rate of 44.1 kHz and 16-bit resolution. We choose a short segment of 20000 data (approximately 0.5 second). The speech signals of vowel /a/ are shown in Figure 1 and Figure 2.

Figure 1. (a) Speech signals of male vowel /a/. (b) A short section of /a/.

Figure 2. (a) Speech signals of female vowel /a/. (b) A short section of /a/.
III. METHODOLOGY

A. pps algorithm

The surrogate method has been successfully applied to detect nonlinear dynamical structure in time series data observed from an unknown dynamical system. The pseudoperiodic surrogates (PPS) algorithm as a form of surrogate hypotheses testing can test pseudoperiodic time series against the hypothesis of periodic orbits with uncorrelated noise [8]. The PPS surrogates are generated as follows. First, we randomly select an initial point in the phase space of the original data and then choose the neighbour of the current point in a certain radius as its successor. We repeat the above procedure to generate the PPS surrogate with the same length as the original one. So the key parameter of this surrogate generation algorithm is the radius, \( \rho \). The suitable selection of \( \rho \) determine the dynamics of generated surrogates. As the range of \( \rho \) is from zero to the infinite, we define an alternative parameter \( pro \), which is the probability that the next point of the surrogate is not the next point of the original data from the current point. With varying \( pro \) we can change the noise radius. We set eight different values of \( pro \), \( [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8] \), and get the corresponding different values of \( \rho \). For example, when \( pro \) is equal to 0.1 it means the selection radius is small. So the generated surrogate as well as its dynamics is very close to the original data. For each \( \rho \) we generate 100 PPS surrogates. We estimate statistical criterion, complexity for both original time series and PPS data.

Here we take an example of the Rössler system to explain how to distinguish chaotic time series from the pseduoperiodic counterparts. With different parameters the Rössler system exhibits period and chaotic behaviours. Figure 3 demonstrates the results of application of PPS to chaotic and a period time series. From panel (a) we can see that complexities of surrogates remain almost constant for increasing \( pro \) since periodicity is the sole dynamics in the given data while for the chaotic time series, due to its sensitivity to initial conditions, even a small noise can result in big variation of complexity, which can be observed in panel (b).

B. weight distribution projection (WDP)

Recently neural network has gotten a great attention as a way of capturing the dynamics of given time series [9]. The WDP method which reflects the internal structure of neural networks, can also exhibit periodic or irregular property, i.e. distinguish chaos from periodicity. The WDP figure of a well-trained neural network has close connection with the dynamical property of the input data fed to the neural network. That is, if the input data is purely periodic, the corresponding WDP presents cycle graph while for the chaotic input data the figure exhibits irregular [9-10]. In order to avoid overfitting of neural networks training, we use minimum description length criterion to select the optimal model [11].

Again we take the example of the classical Rössler system to demonstrate how the WDP method to identify dynamics. The Rössler system generates periodic data with the period of 4 and chaotic data respectively. We choose 2000 data from each dynamical system. Figure 4 illustrates the WDP of the periodic and chaotic time series, respectively. We can see that the WDP figure of the periodic data exhibit periodicity with the same period as the data but the WDP figure of chaos exhibits obviously irregular.

IV. DETECTION OF NONLINEAR DYNAMICS IN NORMAL VOWELS

In this section, we employ the PPS algorithm and the WDP of neural networks to investigate whether Chinese normal vowels have chaotic property or not. First we plot one generated PPS data for the female vowel /a/ shown in Figure 2 (b) when \( Pro \) is equal to 0.5. This PPS data is presented in Figure 5. Its waveform is similar to the original signal but the periodic dynamics of the original data has been destroyed during generation of this surrogate. Application of the PPS algorithm to both male and female vowel /a/ is shown in Figure 6. In comparison with the results of the Rössler system we find that both normal vowels /a/ are consistent with chaos.

![Figure 3. Complexity estimation for Rössler data and its PPS data sets with increasing value of pro. (a) Rössler periodic data (b) Rössler chaotic data](image)

![Figure 4. Weight distribution projection for the test Rössler data. (a) the Rössler periodic data (b) the Rössler chaotic data](image)
Figure 5. A short section of PPS data for the female vowel /a/ when pro is equal to 0.5

Figure 6. Complexity estimation for speech signal of vowel /a/.
(a) the male speaker (b) the female speaker

Then we apply the WDP method to such vowel data. The WDP figures are shown in Figure 7. We notice that both figures present irregular, which reveal that there are chaotic properties in these vowels /a/.

TABLE I and TABLE II shows the complexity estimation for the original speech signals of vowel /o/ and its surrogates recorded from male and female speakers, respectively. We calculate some statistics for the PPS data, including mean, standard deviation, minimum and maximum. We can find that the complexities of surrogates remain upward as the value of Pro increases. At the certain value of Pro (0.5), the complexity deviates greatly from the one of original data. It is suggested that Chinese normal vowel /o/ also has chaotic dynamics. Similarly we apply the WDP method to the vowel /o/ data and obtain the same results. Due to the space constraint we neglect those WDP figures.

<table>
<thead>
<tr>
<th>Pro</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
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<tr>
<td>Mean</td>
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<td>0.3343</td>
<td>0.3429</td>
<td>0.3574</td>
<td>0.3671</td>
<td>0.3832</td>
<td>0.3928</td>
<td>0.4115</td>
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<tr>
<td>Standard Deviation</td>
<td>0.0127</td>
<td>0.0153</td>
<td>0.0111</td>
<td>0.0118</td>
<td>0.0136</td>
<td>0.0121</td>
<td>0.0120</td>
<td>0.0127</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.3459</td>
<td>0.3805</td>
<td>0.3701</td>
<td>0.3944</td>
<td>0.3978</td>
<td>0.4117</td>
<td>0.422</td>
<td>0.4393</td>
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<tr>
<td>Minimum</td>
<td>0.2871</td>
<td>0.3044</td>
<td>0.3079</td>
<td>0.3286</td>
<td>0.339</td>
<td>0.3563</td>
<td>0.3632</td>
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<tr>
<td>Original Data</td>
<td>0.3286</td>
<td>0.3286</td>
<td>0.3286</td>
<td>0.3286</td>
<td>0.3286</td>
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<td>0.3286</td>
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TABLE II. COMPLEXITY ESTIMATION FOR THE FEMALE VOWEL /o/

<table>
<thead>
<tr>
<th>Pro</th>
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<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
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<td>0.2187</td>
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<td>0.2331</td>
<td>0.2399</td>
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<tr>
<td>Standard Deviation</td>
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<td>0.0119</td>
<td>0.0111</td>
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<td>0.0102</td>
<td>0.0114</td>
<td>0.0101</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.2318</td>
<td>0.2352</td>
<td>0.2422</td>
<td>0.2491</td>
<td>0.2594</td>
<td>0.2629</td>
<td>0.2698</td>
<td>0.2871</td>
</tr>
<tr>
<td>Minimum</td>
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<td>0.1833</td>
<td>0.1903</td>
<td>0.2041</td>
<td>0.2145</td>
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<td>0.2350</td>
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<tr>
<td>Original Data</td>
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<td>0.1833</td>
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V. CONCLUSION

This paper aims to detect nonlinear dynamics hidden in Chinese normal vowels. We choose two kinds of typical vowels /a/ and /o/ record from male and female adults for analysis.

We introduce the PPS algorithm and the WDP method for the identification of vowels dynamics. For the PPS algorithm, we generate surrogates data through different values of pro so as to avoid the influence of unsuitable selection of the parameter, while for the WDP of the selected neural network method we need to guarantee the adequate generalization of the neural network.

Applications of both methods to vowel signals obtain the consistent results. We find that there are chaotic dynamics in Chinese vowels. It is suggested that nonlinear speech analysis techniques are preferred for accurate simulate such behavior, or the short-time window is required to keep the approximate periodicity of data in the given window for linear analysis techniques.

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REFERENCES