Detecting synchronizations in an asymmetric vocal fold model from time series data

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Abstract

A novel modeling approach is presented for the reconstruction of synchronization structure in an asymmetric two-mass model from time series data. The asymmetric two-mass model describes a variety of normal and pathological human voices associated with synchronous and desynchronous oscillations of the two asymmetric vocal folds. Our technique recovers the synchronization diagram, which yields the regimes of synchronization as well as desynchronization, which are dependent upon the asymmetry parameter and the subglottal pressure. This allows the prediction of the regime of pathological phonation associated with desynchronization of the vocal folds in a parameter space from a few sets of recorded time series. We discuss the applicability of the present approach as a diagnostic tool for voice pathologies.

1. Introduction

It has been known that the concept of nonlinear dynamics is quite important and useful for speech analysis and synthesis. Four types of nonlinear dynamics, namely, (1) *limit cycle*, (2) *subharmonics*, (3) *biphonation*, and (4) *chaos*, have provided a well defined framework to characterize human voice signals. Transitions between different attractor types induced by a change in the vocal parameters have been well elucidated in terms of *bifurcations*. These ideas have been successfully applied to the studies of speech signal analysis [1], vocal fold modeling [2], voice pathology [3], and animal vocalization [4,5].

In the nonlinear study of voice pathology, a large imbalance of tension between the left and the right vocal folds is considered as one of the main causes for the desynchronization of the vocal folds [2]. Depending on the asymmetry parameter, normal 1:1 synchronization, abnormal synchronization with other than 1:1 ratios, and desynchronization are observed. It is therefore quite important to study the dependence of such synchronous states on the asymmetry parameter. From a recording experiment of a human patient, however, it is almost impossible to study such dependence, because the asymmetry parameter cannot be smoothly and continuously changed. What is desired here is the estimation of the synchronization structure of vocal folds from speech signals recorded with a fixed asymmetry parameter.

In our presentation, we introduce a novel method for reconstructing bifurcations as well as synchronization structures of asymmetric vocal folds from recorded data.

2. Asymmetric Vocal Fold Model

As an asymmetric vocal folds model, we use the Steinecke-Herzel model [2]:

$$\begin{aligned} &m_{i\alpha}\ddot{x}_{i\alpha} + r_{i\alpha}\dot{x}_{i\alpha} + k_{i\alpha}x_{i\alpha} + \theta(-a_i)c_{i\alpha}(a_i/2l) \\ &+ k_{c\alpha}(x_{i\alpha} - x_{j\alpha}) = F_i(x_{1l}, x_{1r}, x_{2l}, x_{2r}) \end{aligned} \quad (1)$$

The four variables $x_{i\alpha}$ represent the displacements of masses $m_{i\alpha}$ (i=1: lower; i=2: upper; α=l: left; α=l: right), the forces F_i describe the action of the pressure in the glottis, and $\theta(x) = \tanh(50x/x_0)$ $(x>0)$; 0 $(x<0)$. Due to the asymmetry parameter Q that describes asymmetry between the left and the right vocal folds,

$$\begin{aligned} k_{ir} &= Qk_{il} \\ c_{ir} &= Qc_{il} \\ m_{ir} &= Qm_{il} \end{aligned} \quad (2)$$

the model is able to reproduce a variety of voice pathologies with desynchronization behaviour. In our simulations, all parameter values of the vocal fold model are set as the same as the parameters of ref. [2], which are considered to be of physiological relevance.

As a recording condition, we assume that bivariate data $\{ x_{1l}(t), x_{1r}(t) \}$ are simultaneously measured from the right and the left vocal folds. With two different asymmetry parameter values, Q = 0.588 and Q = 0.598, the bivariate data are collected from the asymmetric two-mass model (1).

3. Method and Results

Our problem is to reconstruct synchronization structureof the original asymmetric two-mass model only from the two data sets $\{ x_{1l}(t), x_{1r}(t) \}$. Our method is based upon the nonlinear data modeling and the extraction of the model parameters that correspond to the original voice parameters [6]. The significance of our approach is that it requires no *a priori* knowledge of the original voice equations (1). An artificial neural network is fitted to the two data sets and then the fitted model is used to predict the bifurcation structure. The detailed modeling technique can be found in [6,7].

Figs. 1 and 2 show bifurcation diagrams and synchronization structures of the asymmetric two-mass model and its

reconstruction by our modeling technique. We see that essential features of the bifurcation diagram as well as the synchronization diagram of the original voice system are precisely reproduced. Our modeling technique is quite practical in the sense that it exploits only two sets of the bivariate data recorded with fixed asymmetry parameter.

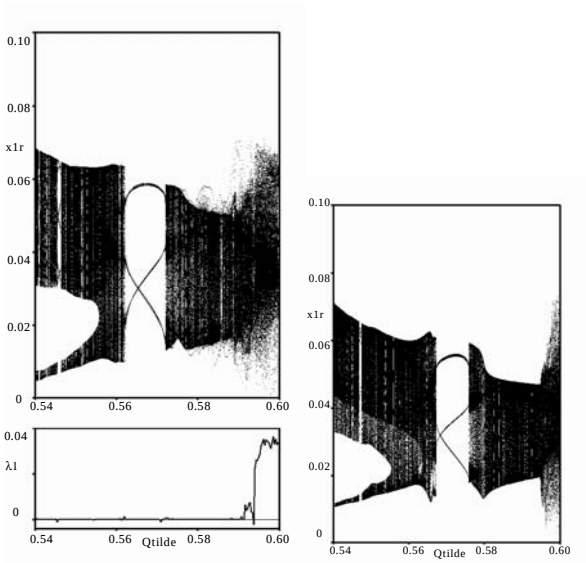

Figure 1: Bifurcation diagrams of the original (left) and its reconstruction (right). Horizontal axis corresponds to the asymmetry parameter 0.54<Q<0.6 and the vertical axis represents dynamical states of the right vocal fold x_{1r}. For the original voice system, the corresponding first Lyapunov exponent λ_1 is plotted (left, bottom).

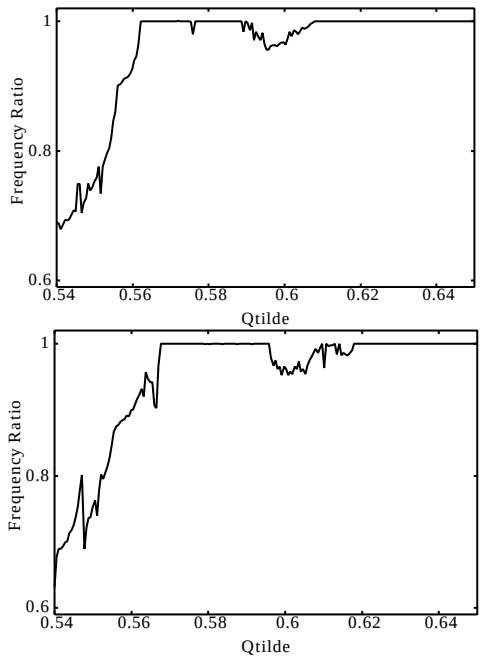

Figure 2: Synchronization diagram of the original (up) and its reconstruction (down). Horizontal line corresponds to the asymmetry parameter 0.54<Q<0.65 and the vertical line corresponds to the frequency ratio ω_r / ω_l between the right and the left vocal folds.

4. Conclusions

To conclude, the modeling approach presented here enables the reconstruction of the synchronization diagram as well as the bifurcation diagram of the vocal fold system from only a few measurements of bivariate time series. By using our technique, we can predict the regimes of abnormal desynchronization in the asymmetry parameter space without any knowledge of the equations modeling the voice. This approach should be of significant importance for the study of pathological human voices. It is planned in our future studies to apply our technique to glottographic data of human patients with vocal disorder.

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5. References

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