Chapter 11
Clinical applications of Nyquist plot and time-frequency analysis of HSDP records of selected dysphonias

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Abstract

Here we provide examples of selected dysphonic cases to demonstrate the value of Nyquist plots and time-frequency method to analyze vocal pathologies.

Keywords: HSDP, Nyquist plots, ADDSD

Introduction

Efficacious treatment of dysphonia is rooted in correct and unequivocal diagnosis. We believe that application of Nyquist plots could be useful for quantitative analysis of HSDP. Consequently in this chapter we show examples of multiple dysphonias based on Nyquist plot analysis.

Spasmodic dysphonia of adductor type (ADDSD)

Spasmodic dysphonia of adductor type is a focal dystonia voice disorder [1] caused by involuntary contractions of intrinsic laryngeal musculature [2-4] and is characterized by a strained or strangled voice quality with 4-6 Hz semi-rhythmic interruptions that sound like a sudden voice break (vocal arrests) or wobbly tremor. All symptoms present typically within the first 1-2 octaves of the patient’s voice range. Symptoms also vary in severity, are phonotopically organized, and are task specific [5-6]. We used HSDP recordings of a patient with severe ADSD to analyze and characterize the vibratory behavior of the VF. The GAW extracted from the HSDP image sequences reveals the irregular nature of the VF vibration for this patient (Figure 1A). Two typical GAW patterns obtained from selected image sequences of the same recording. These GAW plots show the presence of modulation and decreased OQ value (~55%; Figure 1B) and the occurrence of sudden voice breakage (Figure 1C), which is consistent with the typical speech characteristics found for ADDSD.

VF vibrations in unilateral VF paralysis (UVFP)

UVFP can involve the left or the right VF. Typically causation is from a surgical or idiopathic injury to the innervation. If only the recurrent laryngeal nerve (RLN) is involved, the glottis can be approximated posteriorly. The glottis will not approximate if both the RLN and the ipsilateral superior laryngeal nerve (SLN) is injured. Voice quality is dependent on the extent of involvement and on the size of the glottic gap [7]. Recognizing the pathology is crucial for efficacious voice restoration [8].
Figure 1. A) GAW extracted from HSDP recording of a ADDSD patient showing intermittency in the glottal cycles. B-C) Distinctive GAW patterns selected from two segments of the same recording; sudden voice breakage occurs during phonation (C).

Figure 2 shows the results of an analysis of HSDP recordings from a patient diagnosed with UVFP. Paralysis was localized to the right VF. The results are summarized as follows:

1. Spatially-resolved time course of the VF motions or displacements on the left-right fold along the anterior-posterior portions (Figure 2 A-C)
2. GAW extracted from a sequence of 500 HSDP images, which represents a 250 ms record (Figure 2D)
3. Nyquist plot generated from the GAW (Figure 2E)
4. Nyquist plot generated from the displacement of the right VF around the medial location (Figure 2F)

Figure 2. VF displacements along the A-P portion (left-red, right-black) traced from HSDP images recorded from a patient with unilateral VF paralysis. A) anterior, B) medial, C) posterior, D) GAW extracted from the same recording, E) Nyquist plot obtained from GAW, and F) Nyquist plot obtained from displacement of the right fold (medial position).
These results demonstrate that UVFP results in an irregular vibration of the right VF (black trace) that is especially acute in the medial and posterior portion (Figure 2 B & C). This irregularity is revealed in the Nyquist plot as a spiral-scattered pattern (Figure 2F).

The left VF (red trace) undergoes a uniform and regular vibration that brings the two VF together in a synchronized manner. This latter property supports a conclusion derived from an analysis of the Nyquist plot obtained from the global GAW that VF function in this patient is not overly impaired (Figure 2E). Future studies using the HSDP and HSDP-acoustic analysis approaches will investigate how other types of localized paralysis (RLN, SLN, and combined), paresis, and isolated SLN injuries impact the spatio-temporal properties of VF vibrations and the GAW and how these findings correlate with the perceived voice qualities.

**Vocal tremor (VoT) using HSDP and acoustic recordings**

Analysis of VoT is a central subject to Chapter 29 in this publication. Because VoT can mimic other conditions, hence a different treatment plan must be used, it is crucial for the diagnostic clinician to differentiate between VoT and a tremor present in ADDSD and MTD. We really need objective evaluations and quantitative analyses that will generate unique signatures for each condition.

Hence, we present here evidence that HSDP analysis of VF kinematics generates distinct GAWs manifested by one or more properties of the VF vibration that can be used to identify and differentiate between ADDSD and VoT. Previous studies of ADDSD show that the ADDSD voice is characterized by intermittent vocal arrests (4-6 Hz), and exhibits over-pressured voice quality that can be quantified by a decrease in the OQ and different from normal or breathy voice LTAS slopes [9]. Overpressure and arrests are organized phonotopically within the first 1.5-2 octaves above the baseline F0 [6].

On the other hand, voice of a patient diagnosed with VoT shows quite different properties with oscillations at a similar rate of 4-6 Hz, but affects all vocal properties and is not task specific [10-11] as is demonstrated in Figure 3. In some cases VoT and ADDSD can be co-mixed, making separation of these two entities very difficult even in a chemical block condition [11]. For example, the GAW exhibits significant rhythmic variation in the amplitude (Figure 3A) that is even more obvious from the low-pass filtered envelope function shown in Figure 3B, which reflects the inter-cycle variations in the amplitude. The rhythmic variation occurs at approximately 4 Hz (Figure 3B), which is characteristic of and consistent with an independent clinical diagnosis of this patient having VoT. Frequency variation is unnoticeable from the spectrogram (Figure 4C).

![Figure 3. Results of analysis from HSDP recordings of VoT. A) Normalized GAW derived from the HSDP recording (1 second or 2000 image frames). B) Normalized envelope function obtained from the analytic signal of GAW (low pass filtered with a cut-off frequency of 50 Hz). C) Spectrogram of the GAW (window length: 256).](image-url)
Results of a comparative analysis of the VoT performed using HSDP and the simultaneously recorded acoustic data are shown in Figure 4. The rhythmic variation detailed above is noticeable from the acoustic analysis but a more dramatic variation is found in the HSDP-derived GAW and the envelope. The rhythmic variation in the F0 can also be seen in the spectrogram among the higher order harmonics and frequency components that reflect sound wave interactions and vocal tract dynamics. We suggest from this limited analysis that the HSDP-derived GAW provides a less complicated and more effective analysis of tremor. Further we argue that the HSDP-based analysis should be more reliable and sensitive for the detection of subtle rhythmic variations associated with tremor compared to the acoustic evaluation as the rhythmic variation may be further attenuated by other components related to the vocal tract interactions and the measurement noise.

VoT associated with Parkinson’s syndrome (PS)

VoT associated with Parkinson’s syndrome occurs within a typical frequency range of 4-7 Hz [10-11] and subtle tremor is usually poorly audible at an early stage of the disease. We hypothesize that a detailed time-frequency analysis of the HSDP-derived GAW that reveals local time-frequency contents of the VF vibration will be effective in detecting rhythmic variations associated with tremor and in differentiating between PS and the laryngeal form of essential tremor. HSDP data acquired from an idiopathic PS patient producing a sustained /i/ phonation at a normal pitch (F0: ~180 Hz) were analyzed using analytic signal method and spectrogram. The results of this analysis are summarized in Figure 5. The normalized GAW (Figure 5A) was derived from the HSDP recordings of the PS voice (0.5 second of recording or 1000 image frames) and the envelope (Figure 5B) was obtained from the analytic signal constructed from the Hilbert transform of the GAW after a low-pass filter (cut-off frequency of 50 Hz). This operation allows for the extraction of the envelope waveform, which reflects only the inter-cycle variations (i.e., after filtering out the F0 and high-order harmonics components that reflect intra-cycle variations caused by waveform harmonic distortion). The instantaneous phase (as a function of time) derived from the analytic signal and after a linear de-trend operation, is displayed in Figure 5C. Since the derivative of the phase defines an instantaneous frequency, the slope of the linear trend thus defines the F0 and the de-trended phase function defines
frequency variations around F0. The primary, slow-varying (low-frequency components) waveform revealed in the de-trended phase reflects an inter-cycle frequency variation while the high-frequency components simply reflect the intra-cycle harmonic distortion [12-13].

To summarize, these results show that a rhythmic variation in the amplitude is noticeable (Figure 5B) and determined to be around 8 Hz by FFT spectral analysis (not shown); and that a similar variation is shown in the de-trended phase function (Figure 5C), suggesting the presence of the same rhythmic variation in frequency. However, this frequency variation is unnoticeable from the spectrogram (Figure 5D). For comparison, the GAW/envelope obtained from HSDP recording of a normal voice is shown in Figure 5E.

These preliminary findings suggest that rhythmic variations in the PS voice can be revealed from an effective time-frequency analysis of the HSDP-derived glottal waveforms. Further analyses will help to explain the slight discrepancy in the range of frequency of the tremor in PS reported in the literature.

**Figure 5.** A) Normalized GAW. B) Envelope function (after low-pass filtering, normalized). C) Phase function (after de-trend operation). D) Spectrogram obtained from the GAW derived from HSDP recordings of PS voice (0.5 second of recording or 1000 image frames). E) GAW (black) and envelope (red) obtained from a normal voice.

**PS and ADDSD voices and other VoT voice types**

While VF vibrations for normal voicing exhibit distinct and consistent Nyquist patterns, those associated with neurological disorders such as PS, VoT, and ADDSD usually exhibit intermittency, which is recognizable in the Nyquist plots shown in Figure 6. We analyzed the behavior of the VF vibrations over three consecutive segments of the HSDP recording with each segment containing 300 image frames, or 150 ms of the recording period. The upper plots are from the PS patient, the organic VoT shown in the middle, and the bottom plots are from a patient with moderate ADDSD.
Figure 6. Nyquist patterns representing PS voice (upper); VoT voice (middle), and ADDSD voice (bottom).

In summary, our analyses show that VF vibrations in ADDSD are characterized by moderate perturbation and waveform distortion with a decreased OQ value. In contrast, significant irregularity and perturbations were present in VoT, including an irregular closure pattern and OQ and rhythmic variation (at ~4 Hz) in frequency and amplitude. Tremor was revealed from analysis of the PS voice and was especially evident in the rhythmic variation (at ~8 Hz) in amplitude. Results from these limited analyses suggest that HSDP-based analyses and evaluations of these disorders could lead to improvements in their identification and differentiation. A more precise study of the underlying cause of the vocal dysfunctions should provide a better understanding of these conditions and lead to more effective diagnosis and interventions.

References
