

## **SPECTRAL ENVELOPE ANALYSIS OF SNORING SIGNALS**

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### **ABSTRACT**

In recent years, several studies have shown the relationship between snoring and obstructive sleep apnea syndrome (OSAS). Besides time domain analysis of snoring signal, the spectral features and shapes of snores can be used to discriminate simple snorers and OSAS patients. In this study, we propose a method to classify simple snorers and OSAS patients based on spectral envelope estimation of snoring signals. The formant frequencies and corresponding bandwidths are computed for both group, and the variation and consistency of the formant distributions are computed. A total of 1400 snoring episodes from 7 simple snorer and 7 OSAS patients were analyzed. Significant differences are found in the formant frequencies of both groups. The results are discussed from the view point of patho-physiological aspect.

### **KEY WORDS**

Spectral analysis, formant frequency, OSAS, snore

### **1. Introduction**

Snores are breathing sounds produced during the sleep. Breathing triggers mechanical oscillations of the tissues such as soft palate or tongue around the constriction due to the relaxation of the tissues in the upper airway. The American Sleep Disorders Association (ASDA) defined snoring as “Loud upper airways breathing, without apnea or hypoventilation, caused by vibrations of the pharyngeal tissues” [1]. In the last 15 years, snoring problem has entered the realm of clinical medicine. It is a prevalent symptom, and about 50% of the adult population snores frequently [2, 3]. It has been reported as a risk factor for the development of diseases such as ischemic brain infraction, systemic arterial hypertension, and coronary artery disease and sleep disturbance [4]. Sleep apnea is the cessation of airflow to the lungs during sleep for 10 sec. or more [5, 6]. It may result from either upper airway collapse (obstructive sleep apnea) or lack of neural input from the central nervous system to the diaphragm (central sleep apnea) [6]. OSA is the more common form of sleep apnea. Common symptoms of OSA are fatigue, daytime sleepiness, coroner problems, and systemic hypertension [5, 6]. It is usually associated with loud, heavy snoring

[6]. In recent years, several studies have shown the relationship between snoring and obstructive sleep apnea syndrome (OSAS). These studies have shown that the frequency domain analyses of snores can be used to discriminate simple snorers and OSAS patients [7].

Analyzing snoring sounds is very useful and promising tool in sleep related breathing disorders. Time domain parameters of snoring sounds such as the snore rate (number of snoring episodes per hour), intensity of the snoring and the regularity of the snoring episodes showed that simple snorers and OSAS patients can be classified by using snoring sound analysis instead of polysomnographic studies which requires spending the whole night in the hospital.

Hill et. al. [8] proposed the use of acoustic crest factor of snoring episodes (the ratio of peak amplitude to root mean square value) to distinguish palatal from nonpalatal snore. Abeyratne et. al. [9] proposed the measure “intra-snore-pitch-jump” to diagnose OSAS. Sola-Soler et. al. [10] studied the differences in spectral envelopes of simple and OSAS snores and suggested the standard deviation of formant frequencies as a criterion for distinction among simple snores and OSAS snores. Miyazaki et. al. [11] found significant differences in fundamental frequency depending on the snore production site. Spence et. al. found a significant correlation between median frequency of snore and apnea/hypopnea index (AHI). Cavusoglu et. al. [12] developed an interface system based on time domain characteristics to differentiate the simple snorers and OSAS patients as well as to determine the efficiency of applied snoring treatment objectively.

Most of the studies are focused on the fundamental frequency of the snores but spectral envelope estimation of the snoring signals also contains information about the pressure pulses and anatomical filtering involved in snore production [10]. Thus, the spectral analysis values, the “formant type” structure and the shape of the spectrum help to distinguish simple snorers and OSAS patients [13]. Polysomnography (PSG), performed over a full night sleep, is presently the gold standard for diagnosis of sleep apnea [14, 15]. Since PSG analysis requires spending the night at a hospital with many measurement electrodes connected to the body, it is time consuming

and uncomfortable for the patient. The motivation of this study was to use spectral envelope analysis of snoring signals to differentiate the simple snorers and OSAS patients as an alternative to polysomnography. This analysis may also provide information in localization of the snoring site such as palate or tongue.

Our approach in modeling snoring sounds is motivated by the well-known source-filter modeling framework of speech sounds. According to the source filter-model, speech is produced by the excitation of the vocal tract (the acoustic filter) by an acoustic pressure wave due to the motion of vocal folds or due to a constriction created by the speech articulators. The resulting excitation signal has a mixed periodic and noise content in varying proportions for different phonemes. Source-filter model is also very suitable for modeling snoring sounds. The mechanism of snoring is similar to that of voiced speech. The main difference arises at the source part. The vibration of vocal folds is replaced by the vibration of relaxed pharyngeal tissues and tongue. Snorer's relaxed tissues tend to come into contact when there is no airflow for example, around the intake-outlet turnover instants of breathing. Following the start of an intake or outlet, the pressure difference across the contact causes the separation of contacting tissues. Once the tissues are separated, the pressure difference drops and the tissues come into contact again and the cycle continues in this manner. The location of the contact in the pharynx, the type of contacting tissues, the physical properties of the tissues depending on age and/or fat content affects the dynamics of this vibration. The excitation of the vocal and nasal tracts as a consequence of this vibration yields the lip and nose radiation of the snoring sound.

The formant frequencies are the resonant frequencies of the vocal tract filter its range depends on the shape of the resonant cavities. Since the source of the snoring sound differs in simple snorers and OSAS patients, it motivates to the investigation of how the formant frequencies and their bandwidths changes in simple snorers and OSAS patients.

## 2. Materials and Methods

### 2.1 Recording Set up and Database

A Sennhiser ME 64 condenser microphone with a 40–20000 Hz  $\pm$  2.5 dB frequency response was used for recording sounds. This microphone has a cardioid pattern which helps to suppress some of the echoes from the environment. It was placed 15 cm over the patient's head during sleep. The signal was fed via a BNC cable to the Edirol UA-1000 model multi-channel data acquisition system connected to a personal computer via universal serial bus. The computer was placed outside the sleeping room not to disturb the sleeping patients. The acquired signal was digitized at a sampling frequency of 16 KHz with 16 bit resolution.

A total of 1400 snoring episodes were analyzed obtained from 7 simple snorers and 7 OSAS patients equally. Snoring episodes were selected by an automatic detector [15] and validated by a medical doctor. Apnea/Hyponea Index (AHI) of simple snorers and OSAS patients are 4.29 and 39.21 respectively.

### 2.2 The Formant Type Spectrum Structure of Snoring Sounds

Unlike the highly non-stationary character of speech because of the continuous motion of the articulators (jaw, lips, tongue, and velum) along the vocal tract, snoring signal bears non-stationarity at a much lower level. Articulators keep their positions unchanged most of the time during snoring. Spectral envelope estimations of snoring signals are shown in Figure 1. The spurious peaks with very low amplitude are rejected by 3dB threshold. Inspecting the snoring intervals clearly indicates the highly stationary behavior of the signal. This is much like the production of sustained vowels.

Figure 1 shows that the greater part of the energy content is below 2500 Hz and the main components lie in the low frequency range, at about 150 Hz. The envelope peaks also at the frequencies about 500, 1800 Hz, and 2200 Hz. The spectrum shows a fundamental frequency and a "formants type" structure.

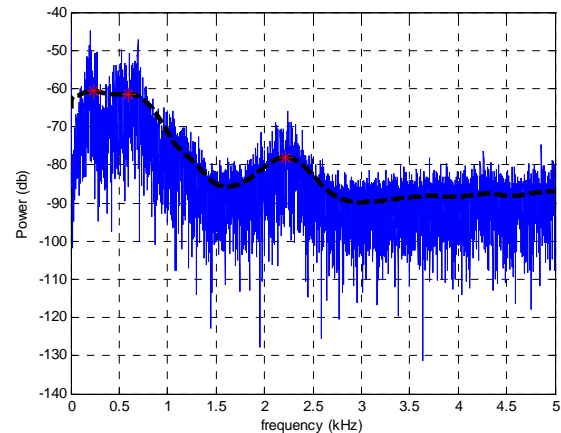


Figure 1. Spectral envelope estimations of snoring signals

In the context of speech processing, formants are the frequencies around which the peaks of the spectral envelope are observed. They are the resonant frequencies of the vocal tract filter. Each formant is characterized by frequency, bandwidth and amplitude level, and its range depends on the shape of the resonant cavities. The different conditions in which the subjects and the patients who snore can affect the formants range in the frequency spectrum. The formants of a snoring signal including 5 snoring episodes is shown in Figure 2.

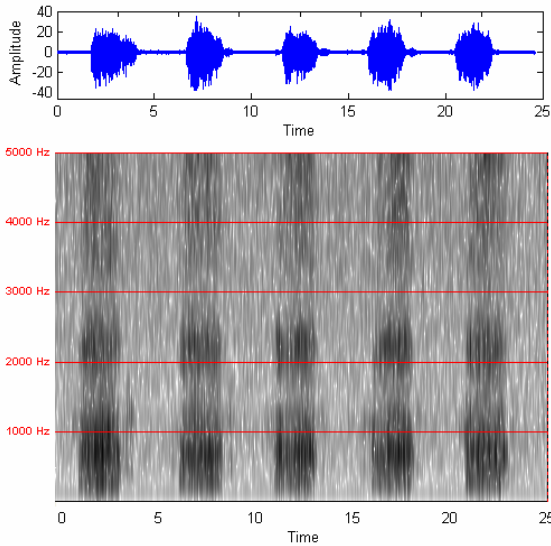


Figure 2. The formants of a snoring signal including 5 snoring episodes

Automatic spectral envelope estimation of the snores in the database shows that formants stay almost unchanged within and across the snoring intervals and the formant frequencies of snoring episodes have almost common formants in some frequency range.

### 2.3 Formant Frequency Analysis

We compute the formant frequencies based on linear prediction coefficients (LPC) of the snoring episodes. These coefficients are computed using auto-correlation method with Levinson-Durbin recursions.

$$x(n) = e(n) + \sum_{i=1}^p a_i x(n-i) \quad (1)$$

In equation (1),  $x(n)$  represents the snoring signal and  $p$  is the degree of linear prediction. In addition,  $a_i$  and  $e(n)$  corresponds to the linear prediction coefficients and prediction error respectively. We can express the signal in frequency domain as follows:

$$X(z) = E(z) + \sum_{i=1}^p a_i z^{-i} X(z) \quad (2)$$

we can modify (2) in order to obtain the transfer function that is expressed by (3).

$$H(z) = \frac{X(z)}{E(z)} = \frac{1}{1 - \sum_{i=1}^p a_i z^{-i}} = \frac{1}{A(z)} \quad (3)$$

The sound signal  $X(z)$  is generated by stimulating the  $H(z)$ , location of the production (uvula, soft palate, etc), with  $E(z)$ . The transfer function,  $H(z)$  is

determined by minimizing the linear prediction coefficients.

The formant frequencies are computed by finding the roots of the linear prediction polynomial obtained from LPC analysis. The prediction polynomial can be expressed as follows:

$$A(z) = 1 - \sum_{k=1}^p a_k z^{-k} = \sum_{k=1}^{p/2} (1 - c_k z^{-1})(1 - c_k^* z^{-1}) \quad (4)$$

where  $p$  is the order of the LPC filter. Resonance frequencies are found using only the complex roots of prediction polynomial. The  $k^{\text{th}}$  complex root of the  $A(z)$  is expressed in equation (5).

$$c_k = |c_k| e^{jw_k} \quad (5)$$

The  $k^{\text{th}}$  formant frequency and the corresponding bandwidth can be written as:

$$f_k = \frac{w_k}{2\pi T_s} \quad (6)$$

$$b_k = -\frac{\ln|c_k|}{\pi T_s} \quad (7)$$

where  $T_s$  is the sampling period. In this study, the order of the linear prediction filter is selected as 10.

## 3. Results

We investigate the inter- and intra-patient variation of formant frequencies and their bandwidths for simple snorers and OSAS patients. To visualize these variations, we have randomly selected 10 snoring episodes from each of the 7 simple snorers and 7 OSAS patients and compute the formant frequencies. Figure 3 and Figure 4 shows the inter- and intra- patient variation of formant frequencies in simple snorers and OSAS patients respectively.

Average formant frequencies and corresponding bandwidths are calculated for the snoring episodes in the database. Table 1 and Table 2 show the average values of formant frequencies and corresponding bandwidths respectively for simple snorers and for OSAS patients.

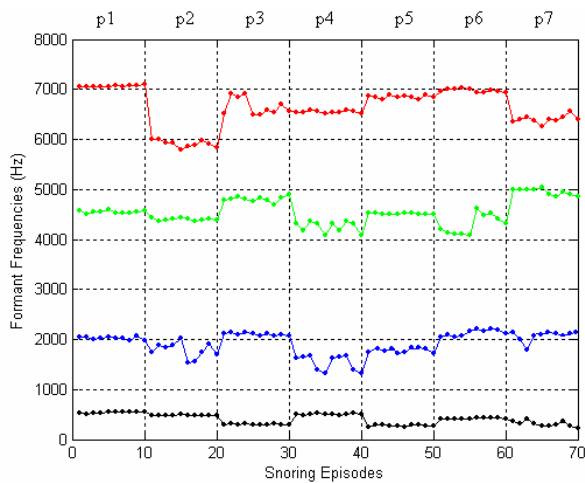


Figure 3. Inter- and intra- patient variation of formant frequencies in simple snorers

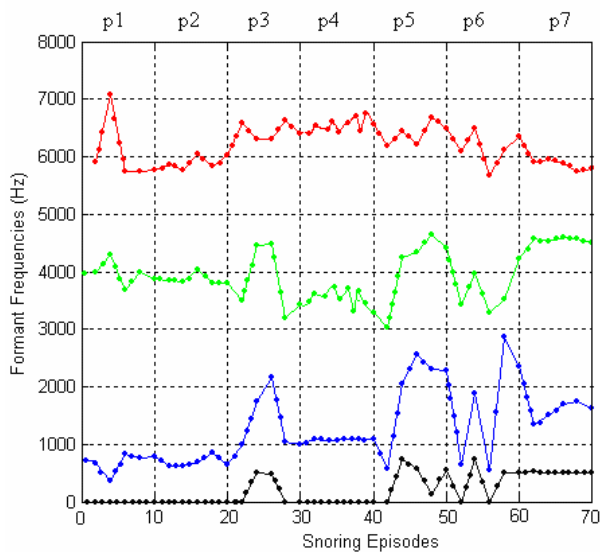


Figure 4. Inter- and intra- patient variation of formant frequencies in OSAS patients

Table 1  
Average values of formant frequencies for Simple snorers and OSAS patients

Subject	F1	F2	F3	F4
Simple snorer	512.8	1678.2	4326.5	6728.9
OSAS patient	112.4	1386.6	4203.8	6404.2

Table 2  
Average values of formant bandwidths for Simple snorers and OSAS patients

Subject	BW1	BW2	BW3	BW4
Simple snorer	9.4	18.6	19.8	28.6
OSAS patient	27.5	64.3	44.6	31.9

#### 4. Discussion and Conclusion

The production mechanism of snoring sound is similar to that of voiced speech; hence we can apply the well-known source-filter model to analyze the snoring sounds.

Spectral envelope analysis of snoring signals provides an efficient way in simple snorer/OSAS classification which is very important both in the diagnostic and treatment or uvulo-palatopharyngoplasty (UPPP) type surgery process of patients. Filtering characteristics of upper airway and the location of pressure production are strongly related to the spectral envelope. For example, the shape of resonant cavities in the upper airway changes the range and value of formant frequencies [10].

In simple snorers (Figure 3), while the formant frequencies are consistent in different snoring episodes of same individual, there may be some shifting in different patients. The magnitude of these shifting is less in the first formant frequency than those of other three formant frequencies. The intra-patient consistency of formant frequencies is highest in the first formant and lowest in the second formant. For each patient, the formant frequencies may vary. However, from figure 2, it can be seen that the formant variations are correlated among the patients.

In OSAS patients (Figure 4), there is no considerable coincidence in formant frequency locations both inter- and intra patient snoring episodes. The significantly lower variability of formant distributions in simple snorers than in OSAS patients can be explained as follows:

- i) The source of the snoring sound (vibrating tissue in the upper airway) is in a multi-segmental structure in OSAS patients.
- ii) In OSAS patients, upper airway resistance is relatively lower compared to simple snorers. The reduction in the upper airway resistance is related to the site of snoring.

In this study, we propose a method to discriminate the simple snorers and OSAS patients based on spectral envelope estimation of snoring signals. The experimental results are promising and show that the approach given here can be used not only for source localization of

snoring but also for detection of the obstructive sleep apnea.

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