The Impact of the Acute Hypoxia to Speech Inharmonicity

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***Abstract*—When people that live at the small altitude (up to 400 m above the sea level) climb on the mountain, they are exposed to the effects of an acute hypoxia. As a result, their oxygen concentration decreases in the tissue. This paper presents the analysis of the acute hypoxia effects to the speech signal at the altitude up to 2600 m above the sea level. For the experiment, the articulation of vowels (A, E, I, O, U) from the test group of persons was recorded at different altitude, which creates the speech signal database. This paper presents an algorithm, which is suitable for the evaluation of the acute hypoxia degree by analysing the inharmonicity degree of the speech. The algorithm is based on the estimation of fundamental frequency and the irregular fluctuations of its harmonic components. These irregular fluctuations are defined as inharmonicity. The inharmonicity is quantitatively gauged by the inharmonicity coefficient β. The analogy between the vibrating strings in musical instruments and vibration of the vocal cords in humans was established. Furthermore, the acute hypoxia effect to the inharmonicity coefficient of the speech signal is analysed. At the end, the comparative analysis of the acute hypoxia effects shows that the level of the hypoxia can be determined by the change of the fundamental frequency and the inharmonicity coefficient of speech signal. Hence, it is possible to bring conclusions about the degree of hypoxia, which in many situations can be of importance for avoiding catastrophic consequences.**

***Index Terms*—Acute hypoxia, inharmonicity coefficient, fundamental frequency, speech analysis, speech processing.**

I. INTRODUCTION

Hypoxia is a condition of insufficient concentration of oxygen in blood, cells and tissues. It causes functional disorder of organs, the nervous system and cells. Due to insufficient concentration of oxygen cells die off, tissues decay or the function of many organs is disturbed: brain, lungs, heart, blood vessels, liver, and kidneys [1]. Consequently, hypoxia can affect some organs, as well as the whole organism. The brain is the most sensitive to lowering and insufficiency of oxygen. Hence, studying of this condition is in the focus. The causes of hypoxia can be multiplied: (i) deficiency of oxygen in the atmosphere (staying on high mountains, during incidents in the mines in underground pits, in aviation, cosmic flights, underwater activities, etc.), (ii) lung diseases, (iii) disorders of the breathing centre, (iv) diseases of the blood vessels, (v) increased need of tissues for oxygen during extreme work of muscles, which usually happen to sportsmen and physical workers.

Characteristics of the effect of hypoxia on the organism are: a) lowering of mental activities (indicated through short memory, forgetfulness, slow thinking, sleepiness, euphoria, headache, nausea, sight and speech disturbances and finally jerks, convulsions and coma), b) lowering of the working capability of muscles (manifested in slow walk, feeling of powerlessness, weak and slow reflexes, bad coordination of motor movements, bad accommodation of eyes), and c) depression of the respiratory centre (losing consciousness, coma and death) [2]. Hypoxia affects the changing of total functional state of an organism as well as the human speech apparatus itself. Some investigations have been carried out concerning the effect of hypoxia on the speech as a result of changing the altitude [3], [4]. The concentration of oxygen in the atmosphere air is approximately 21 % when the pressure is 1 bar at the altitude. With higher altitude the air density decreases and by that the quantity of oxygen. With higher altitude one gets less oxygen, i.e. hypoxia intensifies. Investigations have shown that at 1600 m altitude a considerable effect of hypoxia appears. For that reason these altitudes are called the reaction threshold. The highest altitude where human settlements were formed and survived is 5500 m altitude [5]. This height is considered to be the outmost limit of human adaptability power. A healthy man, who is not accustomed to this height, can preserve his full working ability and state of full consciousness for approximately 30 minutes. However, a man can adapt to this height and to stay there for a long time. On the other hand, examinations have shown that at the height of 6700 m it is not possible to survive for a long time. Without any adequate protective devices a man can survive for at most 10 minutes.

There exist: a) acute, and b) chronic hypoxia conditions. Acute hypoxia represents the case when someone whose natural environment is at low altitude, has been exposed the stay on high mountains. In the period of adaptation we talk

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about the acute hypoxia. The chronic hypoxia represents the condition of the lowered amount of oxygen in people whose natural environment is on high mountains. References [3], [5] show that the fundamental frequency of the speech signal changes under the effect of hypoxia. According to [4], the processing of the fundamental frequency as well as its relation to the other frequencies in the spectrum can designate the emotional state of the speaker (happiness, sadness, anger, anxiety, boredom, disgust, and neutral) and the stress [6]–[9]. Reference [10] shows the results of digital signal processing made by filtering of dissonant spectral ranges. This approach is incorporated in order to improve quality of real speech in different ambient noise. The procedure included the fundamental frequency estimation, which was the basis for determination of dissonant interval limit. According to that, the spectral components from defined intervals have been wiped out by filtering. The dissonant ranges known as Devils intervals are defined by the theory of music [11]. Reference [12] shows that along with the fundamental frequency change, hypoxia has repercussions on the amplitude speech characteristic. This way, it changes the energy of the spectral components that belongs to the dissonant intervals.

The authors asked themselves the following questions: a) Is it possible to make a correspondence between wiring inharmonicity in musical instruments and the voice as an effect of the vocal tract activities? and b) How the acute hypoxia affects inharmonicity of the vocal tract? For the purpose of answering the question the authors have conducted a number of experiments.

In this paper, the tenderness of the acute hypoxia on the real speech inharmonicity is described. However, this problem hasn't been fully analysed. The basic idea is connected to the research of the inharmonicity in the stringed musical instruments [13]. Although, the inharmonicity linked with the oscillations of stretched strings was well known, the effects of the musical instruments inharmonicity weren't investigated. First important results that analysed the piano strings inharmonicity were published in [14]–[16]. Recently, the inharmonicity of different musical instruments like piano and guitar has been made [17]–[23]. These works show that due to the finite elasticity of the string the higher harmonics deviate from the position given by the integer multiple of the fundamental frequency. This deviation is modelled by the coefficient . Hence, the higher value of initiates the higher level of instruments inharmonicity.

Hypoxia has repercussions on the modification of the fundamental frequency and the energy of the spectral components [12]. Furthermore, it changes the frequency of the partials which leads to the inharmonicity. In order to determine the degree of the inharmonicity, the inharmonicity coefficient has been calculated for the persons under the effect of hypoxia. This is made by the proposed algorithm. After that, the algorithm is applied to the real speech database. The speech database is formed from the voices of the speakers, which live at the small altitude (up to 400 m above the sea level). These speakers pronounce the vowels (in Serbian): A, E, I, O, and U at the different altitude (up to 2600 m above the sea level). Speech is recorded on a PC. It is archived in the WAV format files on hard disk. From the obtained results the relation between the degree of hypoxia and inharmonicity coefficients is set.

The organization of this paper is as follows. In Section II the inharmonicity on wired musical instruments and voice signals is defined. In Section III an algorithm for estimating the inharmonicity coefficient of the speech signal is described. In Section IV testing results and comparative analysis are presented. In Section V conclusions are reached.

II. Inharmonicity of the Partials

Musical instruments generate acoustic waves by vibrating strings. Vibrating wire is a complex process which leads to the generation of sound with complex spectral content. In addition to the fundamental frequency of oscillation (fundamental frequency), there is a range of spectral components (aliquots). Each tone is characterized by amplitude, frequency and phase of each aliquot. This defines the unique colour tone for each type of instrument [11]. The aliquoties are called partials. With the respect to the fundamental frequency, the partials can be with frequencies that correspond to: a) f_0 integer multiples (harmonics) and b) fractional multiples of f_0 (inharmonic) [22].

A. Inharmonicity of the Oscillating Wire

Music theory defines harmonicity as the ratio between partial in the way that the frequency of partials represents the integer multiples of the fundamental frequency. It is given as

$$f_{ph} = p \cdot f_0, \tag{1}$$

where $p = 1,2,\ldots$, f_0 is the fundamental frequency, p is the ordinal of the partials, and f_{ph} is the frequency of the harmonic partial. Frequency displacement of the partials from the harmonic position represents inharmonicity of the tone. It is defined through inharmonicity coefficient . The frequencies of the harmonic and inharmonic partials are

$$f_p = p \cdot f_0 \sqrt{1 + \quad \cdot p^2} = f_{ph} \sqrt{1 + \quad \cdot p^2}, \tag{2}$$

where $p = 1,2,\ldots$. Inharmonicity coefficient depends on the type of string material that produces a tone. It is given as

$$= \frac{\text{®}^3 \cdot Q \cdot d^4}{64 \cdot l^2 \cdot F}, \tag{3}$$

where Q is the Young's coefficient of the material elasticity that the string is made of, d is the radius of the string, l is the length of the string, and F is the straining force.

B. Inharmonicity of the Musical Instruments

The inharmonicity of the wire that oscillates is manifested in the inharmonicity of string based musical instruments. The consequence of the inharmonicity on the reproduced sound is shown in Fig. 1. As an example, the tone A3 (fundamental frequency F_0 = 220 Hz) on August Forster piano is analysed. Figure 1(a) shows the temporal shape of the signal. For the purpose of further signal processing, the signal is divided into frames with the length of 32 ms (Fig. 1(b)). Spectral amplitude characteristics are shown in Fig. 1(c). Vertical dashed lines and sign 'o' represent the positions of expected frequency of partial (harmonics), while sign '□' represents the real position of the partial (inharmonic). It can be noticed that the frequencies of partials are displaced with respect to the frequencies of harmonics. The difference between the frequencies of the harmonic components and partials represent error $e(k) = f_{ph} - pf_0$ as a result of inharmonicity (Fig. 1(d)).

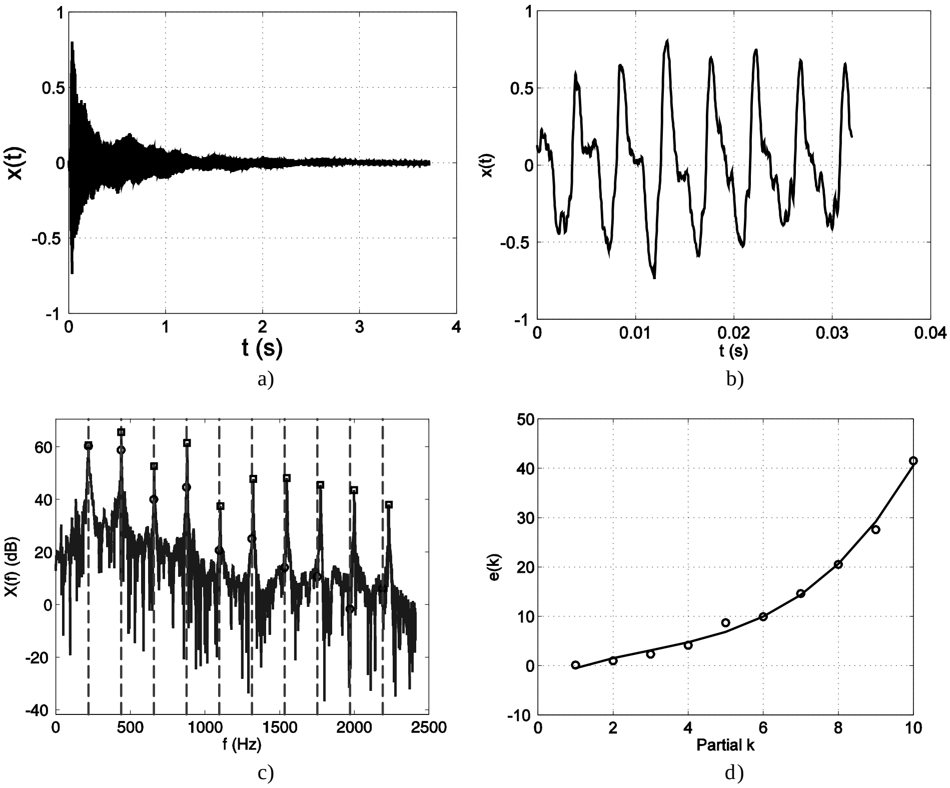


Fig. 1. Diagrams of the tone A3 (August Forster piano brands from 1972.) a) time waveform, b) time waveform for the frame of 32 ms, c) amplitude characteristics which indicate a harmonic and inharmonic and d) difference between harmonic and inharmonic components

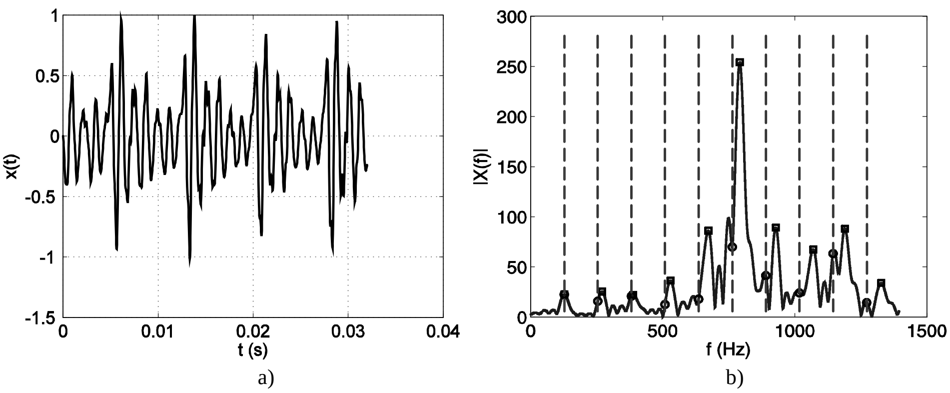
C. Inharmonicity of the Speech Signal

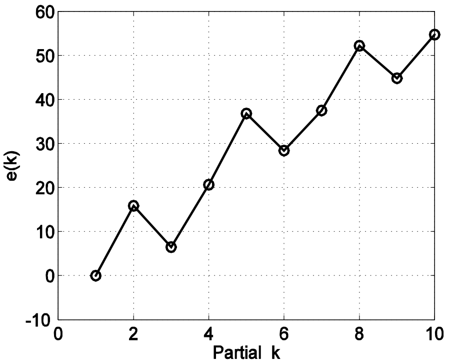
The speech signal originates by the loud wire vibration with the interaction of the whole vocal tract [23]. The pronouncement of the vowels (in contrast to the consonant) generates the acoustic signal which contains fundamental frequency and the high number of partials. Hence, the analysis of the amplitude characteristic of the speech signal can elaborate the effects of harmonicity or inharmonicity.

As an example, the effects of the partial frequency displacement due to inharmonicity for the vowel A (Serbian) is shown in Fig 2.

Figure 2(a) shows the temporal shape of the speech signal for 32 ms frame length. The instantaneous fundamental frequency is f_0 = 133.84 Hz (T_0 = 7.47 ms). Figure 2(b) shows the amplitude characteristic of the speech signal. Vertical dashed lines and sign 'o' represent the positions of expected frequency of partial (harmonics), while sign '□' represents the real position of the partial (inharmonic). It can be noticed that the frequencies of partials are displaced with respect to the frequencies of harmonics. This phenomenon was noted in the amplitude of piano tones (Fig. 1(c)). The difference between the frequencies of the harmonic components and partials which represent the error as a result of speech inharmonicity is shown in Fig. 2(c).

Furthermore, the difference is even more displaced for the highest order of partials. As a consequence, the speech signal is inharmonicity. The degree of inharmonicity can be determined by the estimation of inharmonicity coefficient.





c)

Fig. 2. Diagrams of the speech for vowel A: a) a frame length of 32 ms, the current fundamental frequency F_0 = 133.84 Hz, b) amplitude characteristics of the indicated harmonic and inharmonic and c) the difference between harmonic and inharmonic components.

III. Proposed Algorithm

Many algorithms have been proposed for the determination of the inharmonicity coefficient . Reference [23] describes the iterative algorithm in which the estimation accuracy is increased by analysing more partials as well as by positioning window according to the previously calculated values. Furthermore, the coefficient determination is based on the third degree polynomial, which approximates the error value. According to the polynomial coefficient, the inharmonicity coefficient is calculated. However, this algorithm is complex and computer time intensive. Due to the use of the high number of partials (up to 50), its application has been limited to the real speech signal processing. Reference [18] described the algorithm for the determination of the inharmonicity coefficient based on the interpolation function. Reference [21] proposed the algorithm for the calculation of the inharmonicity coefficient according to the frequency of two partials and without the use of the fundamental frequency. Nonetheless, the proposed algorithm showed inconsistent results under test. It means that the smallest change in the estimation of the partial frequency will lead to the considerable change of the inharmonicity coefficient .

Furthermore, the proposed algorithm which estimates the inharmonicity coefficient is described. It consists of three parts: a) estimation of the fundamental frequency, b) estimation of partials, and c) estimatition of the inharmonicity coefficient.

A. The Algorithm for Fundamental Frequency Estimation

Determination of the harmonic components of speech signal requires high accuracy during the estimation of the fundamental frequency. The fundamental frequency was calculated by the proposed algorithm. It works in the frequency domain using the PCC convolution along with the Keys convolution kernel. This algorithm achieves a high accuracy in the assessment and implementation of small FFT length. Firstly, the algorithm is proposed in [24]. It consists of the following steps:

Input: speech signal **x**

Output: trajectory of the fundamental frequency $\boldsymbol{F_0}$

Step 1: Speech signal $x(n)$ (Fig. 4(a)), n = 1, ..., L is divided into frames $\mathbf{x}_b$, b = 1, ..., B (Fig. 4(b)), where is the total number of frames

$$B = \left\lceil (L - N_F)/(N_F - N_O) + 1 \right\rceil, \tag{4}$$

where N_F is length of frame and N_O is overlapping.

FOR *b* = 1:*B*

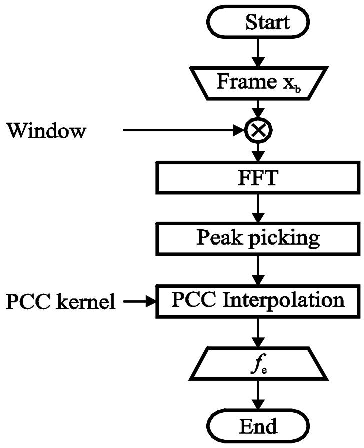


Fig. 3. Algorithm for fundamental frequency estimation.

Step 2: Window $w(n)$, length N_F is applied to modification frame

$$\mathbf{x}_b = \mathrm{w} \cdot \mathbf{x}_b. \tag{5}$$

Step 3: Spectrum is calculated by using DFT (Fig. 4(c))

$$\mathbf{X}_b = abs\left(DFT\left(\mathbf{x}_b, NDFT\right)\right). \tag{6}$$

Step 4: Maximum of the spectrum is determined by using the Picking-Peak algorithm $X_{b\_\max} \Rightarrow k_b^0$.

Step 5: The new frame length 2K+1, with central component k_b^0 is created

$$X_b^0 = \left\{ x_b\left(k_b^0 - K\right), \ldots, x_b\left(k_b^0\right), \ldots, x_b\left(k_b^0 + K\right) \right\}.$$

Step 6: The fundamental frequency f_0 estimated by Parametric Cubic Convolution kernel (PCC_kernel) length 2K + 1

$$f_0^b = PCC\left(X_b^0, \mathrm{PCC\_kernel}\right). \tag{7}$$

Step 7: The sequence of the trajectory of fundamental frequency is created (Fig. 4(c)) $F_0\left(b\right) = f_0^b$.

END FOR *b*

B. *Algorithm for the Estimation of Partials*

The algorithm for the estimation of partials is shown in Fig. 5. It consists of the following steps:

Input: speech signal **x**, trajectory of the fundamental frequency ***F*₀**, number of frames *B*, number of partials N_P.

Output: partials f_P

FOR *b*=1:*B*

FOR *p* = 1:N_P

Step 1: The new frame length 2*L* + 1, with central component $k_b^p = p \cdot k_b^0$, who is correspondence with fundamental frequency $f_0^b = F_0\left(b\right)$ is created $X_b^p = \left\{x_b\left(k_b^p - L\right),\ldots,x_b\left(k_b^p\right),\ldots,x_b\left(k_b^p + L\right)\right\}$.

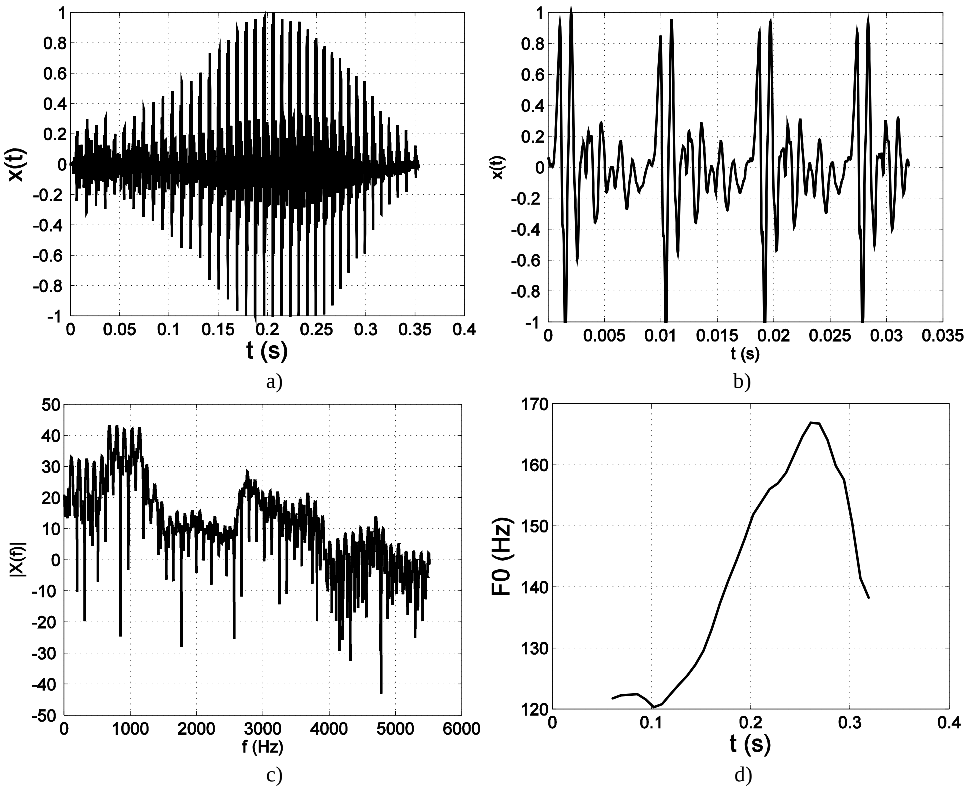


Fig. 4. The vowels A of the Speech signal: a) time waveform, b) time waveform for the frame of 32 ms c) amplitude characteristics and d) trajectory of the fundamental frequency.

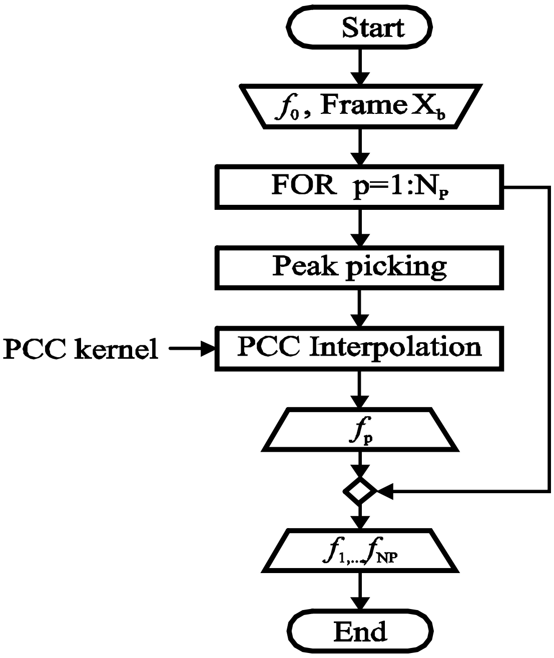


Fig. 5. The algorithm for the estimation of partials.

*Step 2***:** Maximum of the spectrum $X_{b\_\max}^p$ is determined by using the Picking-Peak algorithm. After that the new frame length 2K + 1 with central component $X_{b\_\max}^p \Rightarrow k_{b\_\max}^p$ is determined $X_{b\_PCC}^p = \left\{x_b\left(k_{b\_\max}^p - K\right),\ldots,x_b\left(k_{b\_\max}^p\right),\ldots,x_b\left(k_{b\_\max}^p + K\right)\right\}$.

Step 3: Estimation partials by using Parametric Cubic Convolution (Fig. 6(a))

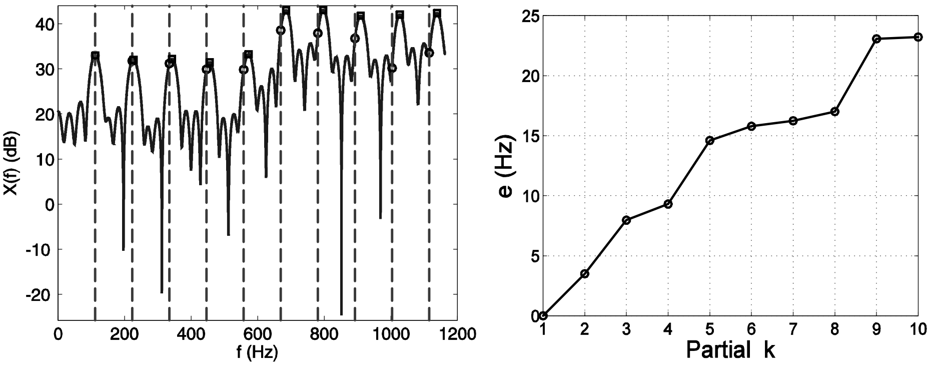
$$f_p^b\left(p\right) = PCC\left(X_{b\_PCC}^p, \text{PCC\_kernel}\right). \tag{8}$$

Step 4: Determination of the frequency partial displacement (Fig. 6(b))

$$e_b\left(p\right) = f_p^b - p \cdot f_0^b. \tag{9}$$

END FOR *p*

END FOR b



a) b)

Fig. 6. Amplitude characteristics: a) harmonic and inharmonic components, b) frequency deviation of partials.

C. The Algorithm for the Inharmonicity Coefficient Estimation

The algorithm for the inharmonicity coefficient estimation consists of the following steps:

Input: Numbers of the frame *B*, trajectory of the fundamental frequency ***F*₀**, Partials $e_b, \mathrm{b} = 1,...,\mathrm{B}$, step of iteration $\Delta\ _b$, estimation error *ε*.

Output: Mean value of the fundamental frequency $\overline{F}_0$, Mean value of the coefficient inharmonicity $\overline{\ }$.

FOR *b*=1:*B*

Step 1: initial conditions: $_\mathrm{b} = 0$, $\Delta\ _b = 1\cdot 10^{-6}$

$$MSE = \frac{1}{N_P}\sum_{p=1}^{N_P}\left(f_p^b - p\cdot f_0^b\right)^2. \quad (10)$$

WHILE $MSE \geq £$

Step 2: coefficient inharmonicity estimation:

$$_b = \ _b + \Delta\ _b, \quad (11)$$

$$f_p^b = p\cdot f_0^b\sqrt{1+\ _b p^2}, \quad (12)$$

where $p = 1,..., N_P$.

$$MSE = \frac{1}{N_P}\sum_{p=1}^{N_P}\left(f_p^b - p\cdot f_0^b\right)^2. \quad (13)$$

END WHILE $(b) = \ _b$

END FOR b

Step 3: Mean values of the fundamental frequency and mean value of the coefficient inharmonicity estimation:

$$\overline{F}_0 = \frac{1}{B}\sum_{b=1}^{B} f_0^b, \quad (14)$$

$$\overline{\ } = \frac{1}{B}\sum_{b=1}^{B}\ _b. \quad (15)$$

IV. RESULTS AND DISCUSSION

A. The Speech Database

For testing the efficiency of the proposed algorithm for estimation of inharmonicity coefficients, a test group was formed composed of persons whose natural environment was at 200 m altitude (Nis, Serbia). That test group was made of 5 persons (male from 18 to 50 years old). Further, the measurements were performed at 200 m, 800 m, 1400 m, 1800 m, 2200 m, and 2600 m altitude (mountain Pelister, Macedonia). Every tested person articulated the vowels A, E, I, O and U three times on each height with a pause of 5 minutes between the utterances. The speech signal was stored on the hard disc in the form of wav files and thus the speech signal database (f_S = 16 kHz) was formed.

B. The Parameters of the Algorithm

The algorithm was applied to the speech signal database with the following parameters: N_F = 512, $N_O = N_F/4$, *NDFT* = 2048, PCC_kernel: Keys length $2K + 1 = 3$, α = -1.03.

C. Results

Table I shows the fundamental frequencies for all vowels obtained at different altitudes.

TABLE I. THE FUNDAMENTAL FREQUENCIES FOR ALL VOWELS AS A FUNCTION OF ALTITUDE.

Vowel	F_0 [Hz]					
	200	800	1400	1800	2200	2600
A	114.14	117.14	126.55	132.44	136.67	139.95
E	114.48	119.57	126.89	134.62	138.58	143.33
I	117.94	120.47	129.82	140.38	147.21	150.07
O	110.80	112.98	125.19	137.93	140.07	144.27
U	112.05	113.96	117.66	121.43	128.87	135.58
$\overline{F}_0$	113.88	116.82	125.22	133.36	138.28	142.64

Figure 7 shows the values of the inharmonicity coefficients for the vowels A (Fig. 7(a)), E (Fig. 7(b)), I (Fig. 7(c)), O (Fig. 7(d)) and U (Fig. 7(e)). Figure 8(a) shows the mean values of the fundamental frequency as a function of altitude. The values of the Inharmonicity coefficient are shown in Table II. The mean value of the inharmonicity coefficient as a function of altitude is shown in Fig. 8(b).

TABLE II. INHARMONICITY COEFFICIENT.

Vowel	β (x10^{-4})					
	200	800	1400	1800	2200	2600
A	6.02	5.10	5.40	4.46	1.06	0.46
E	7.03	5.34	4.88	4.27	4.37	3.97
I	7.76	6.48	6.06	5.92	5.32	5.30
O	4.83	3.96	2.09	2.03	1.03	1.03
U	7.48	6.37	5.86	2.65	0.65	0.32
$\overline{\ }$	6.63	5.45	4.86	3.87	2.49	2.22

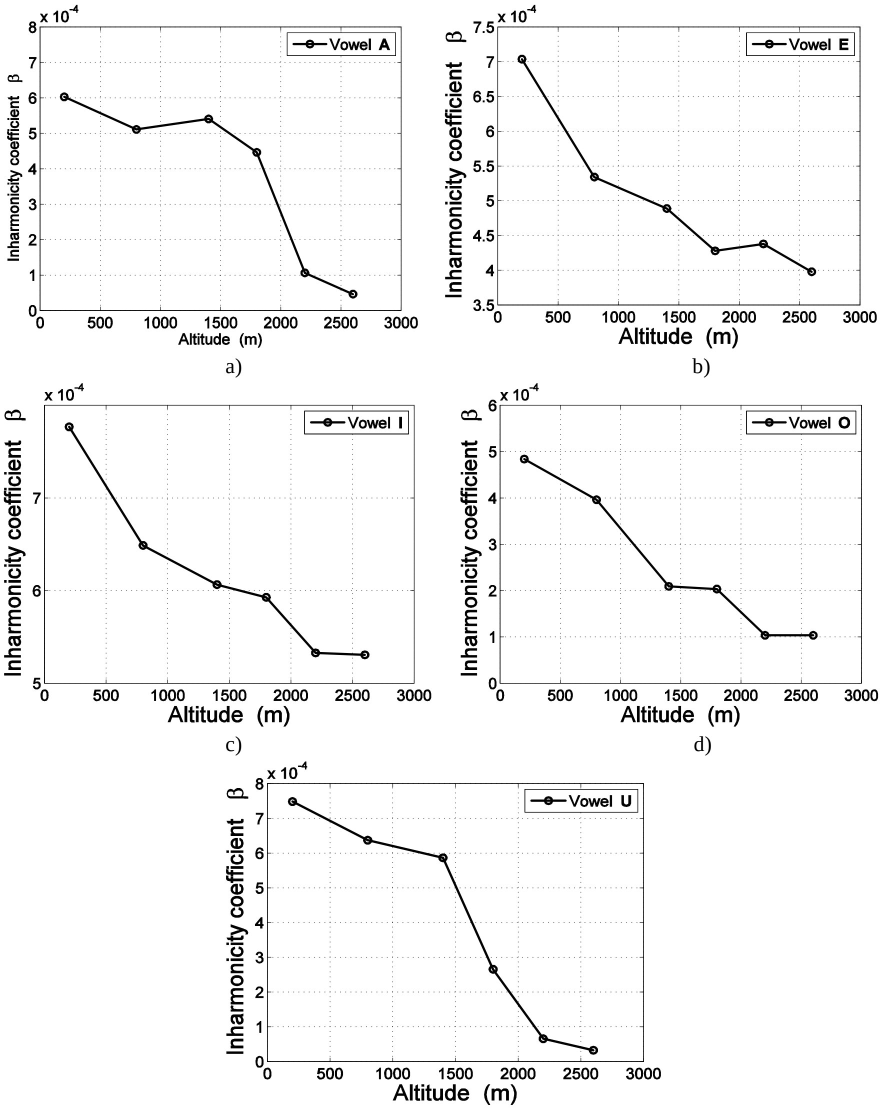


Fig. 7. The inharmonicity coefficient for the vowels A (a), E (b), I (c) O (d) and U (e) as a function of altitude.

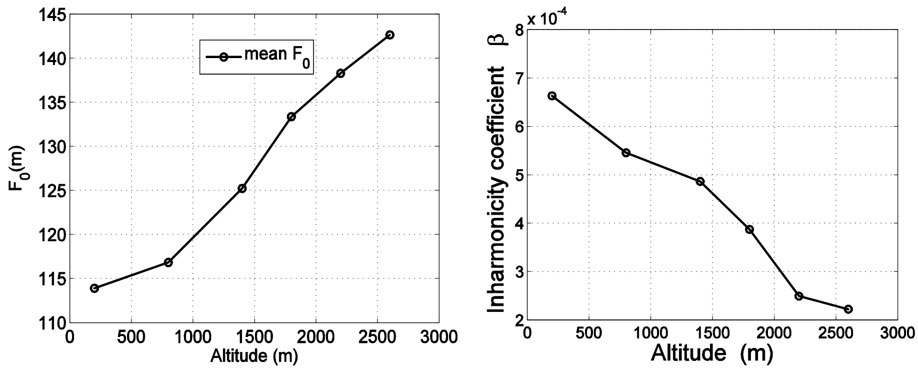


Fig. 8. Mean value of the a) fundamental frequency and b) inharmonicity coefficient as a function of altitude.

D. Analysis of the Results

According to the analysis of the results presented in Fig. 4–Fig. 8 and the results from [3] and [12] the following conclusion can be derived:

1. With the increase of the altitude, the fundamental frequency increases. In relation to 200 m altitude, it increases to 2.58 % at 800 m altitude, 9.95 % at 1400 m altitude, 17.1 % at 1800 m altitude, 21.42 % at 2200 m altitude and 25.25 % at 2600 m altitude. These values agreed with the results given in [3].

2. With the increase of the altitude the value of the inharmonicity coefficient decreases. In relation to 200 m altitude, reduces to 17.74 % at 800 m altitude, 26.67 % at 1400 m altitude, 41.61 % at 1800 m altitude 62.42 % at 2200 m altitude and 66.49 % at 2600 m altitude.

According to the analysis of inharmonicity coefficient , it is possible to recapitulate about the degree of hypoxia. Such data can be applied in many situations. For example, during the flight on great heights the pilot's mask can fail or it can come to the decompression of the plane. In such cases it is possible, on the base of processing of the pilot's conversation with the flight control, to discover signs of hypoxia in its initial stage and take adequate measures in order to prevent catastrophic consequences [3], [5].

V. Conclusions

In order to determine the degree of hypoxia the speech signal has been analysed. In the paper, a new method which is based on the analysis of inharmonicity coefficient is proposed. The coefficients were calculated for vowels A, E, I, O and U, articulated by the group of testing persons at different altitude (200, 800, 1400, 1800, 2200 and 2600 m). On the base of the analysis of inharmonicity coefficient , it is possible to use them as indicators of hypoxia, and even for determination of the degree of hypoxia.

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