Application of Holo-Hilbert Spectral Analysis on Human Breathing Movement with Isovolume Maneuver

Jia-Hua Lee
Institute of Biomedical Engineering
National Chiao Tung University
Hsinchu, Taiwan R.O.C.
e-mail: jessie1992a@gmail.com

Ya-Chen Chen
Institute of Computer Science and Engineering
National Chiao Tung University
Hsinchu, Taiwan R.O.C.
e-mail: milktea0623@gmail.com

Tzu-Chien Hsiao*
Department of Computer Science, Institute of Biomedical Engineering, Biomedical Electronics Translational Research Center
National Chiao Tung University
Hsinchu, Taiwan R.O.C.
e-mail: labview@cs.nctu.edu.tw

***Abstract*—Breathing is one of essential processes for human to inhale and exhale air for gas translation. People modulate respiratory frequency (fast or slow) and depth (deep or shallow) consciously or unconsciously. Different breathing patterns perform distinct breathing movement and physiological mechanism. Breathing movement could be described by observing thoracoabdominal movement which is a combination of cooperated muscle contraction from rib cage and abdomen. Isovolume maneuver (IVM) is a typical respiratory pattern with different respiratory frequency and depth. To investigate the effect of respiratory pattern, it is important to observe the transition state between different respiratory modulations. In 2016, Huang proposed Holo-Hilbert spectral analysis (HHSA) for identifying the joint frequency and amplitude modulation. To obtain the transition period, HHSA is adopted to investigate time-frequency modulation (Time-FM) and time-amplitude modulation (Time-AM) during IVM. Simulation and experiment results indicate that time-AM spectrum and FM-AM spectrum can identify the time-variate transition period between spontaneous breathing (0.3 Hz) and paced breathing (0.1 Hz). This achievement could be helpful for detecting transition state of respiration, especially during exercises or suffering cardiopulmonary disease for long-term care.**

Keywords-Holo-Hilbert spectral analysis (HHSA); Empirical mode decomposition (EMD); Isovolume manuver (IVM)

I. INTRODUCTION

Breathing is an essential and important process for gas exchange. The mechanism of human breathing is the pressure gradient of airflow to induce inhaling or exhaling with a series of cooperation between ribs and muscles [1][2]. People can modulate instantaneous respiratory frequency (fast or slow) and depth (deep or shallow) consciously or unconsciously. There are two common breathing types, thoracic breathing (TB) and abdominal breathing (AB). TB is implemented by the contraction of intracostal muscles to raise rib cage and to increase lateral and anteroposterior dimension of thoracic cavity. Most of gas exchange happens in upper lungs. AB is commonly used during sleep and mainly implemented by the contraction of abdominal muscles. It would drive the deeper descending of the diaphragm and inhale air into the entire lungs. The lung volume during AB is usually larger than TB and performs slowly rate and more effective on gas exchange. In addition, different breathing types, especially AB, could stimulate parasympathetic nervous system and lead human to feel relaxed [3][4].

In physiological study, the dynamic function of breathing can be described by observing thoracoabdominal movement (TAM) consisting of related muscular contractions and relaxations between rib cage (RC) and abdomen (ABD) [5]. One of non-invasive methods to measure breathing pattern is respiratory inductive plethysmograph (RIP). In general, RIP belts are placed on the RC and ABD to measure the TAM and quantify the breathing features including respiratory rate, tilde volume, energy of breathing, and phase shift of TAM [6]. Literature has reported that patterns of RC and ABD movements can be used to identify breathing types (TB and AB) [7][8]. However, breathing pattern is dynamical changes, it is important to observe the transition state between different respiratory modulations.

In signal processing, noise reduction with band-pass filter has time delay problem. Empirical mode decomposition (EMD) [9] is used to decompose biosignals into oscillatory modes with different frequencies without introducing any phase delay [10]. Each component decomposed by EMD is regarded as a meaningful mode called intrinsic mode function (IMF). The instantaneous frequency responses of the IMFs derived through direct quadrature and showed in Hilbert spectrum [11]. In EMD process, mode mixing has seemed to be a problem, which is defined as a pattern of signals whose activities reside within the same frequency of different IMFs. In a new method, named Holo-Hilbert

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spectral analysis (HHSA) and proposed by Huang *et. al.* in 2016, there exists a physical phenomenon in the mode mixing [12]. It extends EMD method and uses nested EMD with Hilbert-Huang Transform (HHT) to identify the modulations in nonlinear systems [12]. In addition to frequency variation, data containing amplitude variation would influence EMD process. HHSA brings out a high-dimensional spectrum called Holo-Hilbert spectrum to see the variation in frequency and amplitude.

The iso-volume maneuver (IVM), which is widely used for calibrating respiratory sensors and thoracoabdominal movement evaluation [13][14], is a typical respiratory pattern with spontaneous breathing and paced breathing. To investigate the effect of respiratory pattern, it is important to observe the transition state between different respiratory modulations. HHSA has been proposed recently to identify the frequency and amplitude modulations in nonlinear systems. This study used HHSA to investigate time-frequency modulation (Time-FM) and time-amplitude modulation (Time-AM) during IVM.

II. METHOD AND METERIAL

A. Holo-Hilbert spectral analysis method

HHSA extends current spectral analysis such as Fourier analysis and Hilbert spectral analysis, which are based on additive expansion to show the variation on frequency. It gets the lower frequency envelop as amplitude fluctuation from the higher carrier frequency oscillations and expands original time-frequency spectrum into a higher-dimensional representation of the FM-AM spectrum, with the FM representing the fast-changing carrier intra-mode frequency variations and the AM representing the slow-changing envelope inter-mode frequency variations [12]. A best way to present the advantage in HHSA as shown in (1). A multiplicative data would be regarded as the addition from two terms by using an additively based method. On the other hand, it could be considered as a cosB term with the amplitude modulation by cosA term. Therefore, we could obtain the amplitude variation through HHSA if it exists amplitude modulation.

$$x(t) = \cos A \cdot \cos B = (1/2)\,[\cos(A+B)+\cos(A-B)] \qquad (1)$$

Before introducing HHSA method, realized the EMD algorithm ahead. The steps of EMD are shown in Fig. 1(a). First, we can find the local maximum and local minimum to produce upper envelope and lower envelope by a cubic spline and calculate the mean of these two envelopes. Then, subtract the mean envelope from the oringinal data. The above detrending operation is called sifting process, which is based on energy-associated extraction in each timescale [9]. After sifting process, we need to determine whether the result is an intrinsic mode function (IMF). An IMF would satisfy the following two requirements: (1) the number of local extrema must be equal or differ at most by one to the number of zero-crossing; (2) at any point, the value of the mean envelope must approximately equal to zero. If the

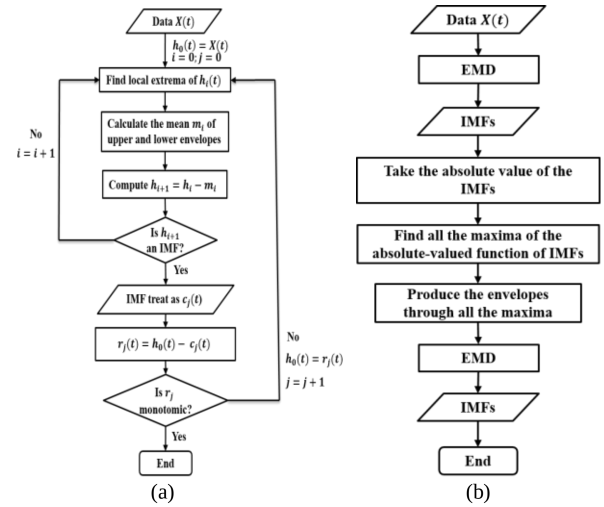

Figure 1. Illustration to the procedure of (a) EMD algorithm and (b) HHSA.

result is an IMF, output the IMF and deduct it from the original data to get the residue. If not, replace the original data by the result and perform sifting process again. Last, determine whether the residue is monotonic. If it is not a monotonic function, use the residue as original data and execute above steps. Else, EMD procedure is finished and gets lots of IMFs decomposed by EMD method.

The steps of HHSA method are shown in Fig. 1(b). Data would be decomposed by EMD method more than one time. First, original data execute EMD method and obtain many IMFs, treating as IMF_i that means i-th IMF. We take the absolute value on each IMF_i and identify all the maxima on it to produce envelope by a natural spline which be viewed as the time fluctuation of the amplitude function. Then, perform EMD method on these envelopes and produce another lots of IMFs, treating as IMF_{ij} that means j-th IMF in the envelop of IMF_i. The step, decomposing envelopes by EMD method, would constantly execute to delineate the amplitude function. With each additional layer of decomposition on the envelopes, need additional dimensions to accommodate the amplitude variations. This study presents two layers EMD method in HHSA and gets Holo-Hilbert spectrum with four –dimensional data including time, FM frequency, AM frequency, and energy density. Besides the FM-AM spectrum, defined in [12], we show the Time-FM spectrum and Time-AM spectrum to investigate FM frequency variation and AM frequency variation on breathing pattern in timescale.

B. Simulation and IVM data collection

This study simulated breathing pattern by using pure sinusolid wave and showed two different breathing types alternating appeared as Fig. 2. One breathing rate is 20 times per minute (0.3 Hz). The other one is 6 times per minute (0.1 Hz) and has larger amplitude than the amplitude of 0.3 Hz breathing rate. The breathing pattern executes five times in simulation.

Procedure of IVM includes alternate spontaneous breathing (near 0.3 Hz) and paced breathing (0.1 Hz) in

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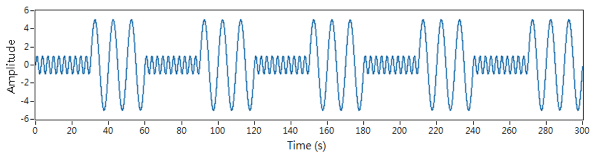
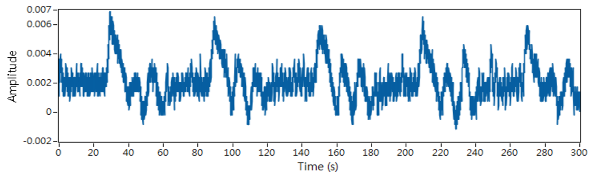
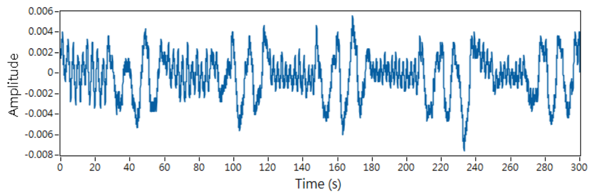


Figure 2. Simulation of spontaneous breathing (0.3 Hz) and paced breathing (0.1 Hz) with sinusoidal pattern.



(a)



(b)

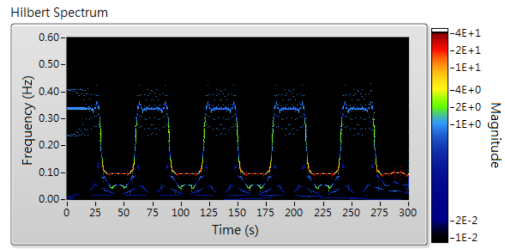
Figure 3. RIP signals from (a) RC movement and (b) ABD movement during IVM. The dense part is for spontaneous breathing and the loosely part is for paced breathing.

iso-volume status. Subject (female, 24 years old, 165 cm, 50kg) was instructed to perform IVM as following four steps for five times. (1) The subject breathed freely for 24 seconds and prepared to start the IVM. (2) The subject was asked to inhale deeply and slowly to hold the breath for 6 seconds. The lung volume kept equivalent during the IVM. (3) The subject was instructed to move abdominal wall inward for 5 seconds and moved outward for 5 seconds. The abdominal wall moved inward and outward for three times. (4) The subject was asked to exhale and take a break for 24 seconds. During IVM, shift air between RC and ABD as much as possible with the holding breath.

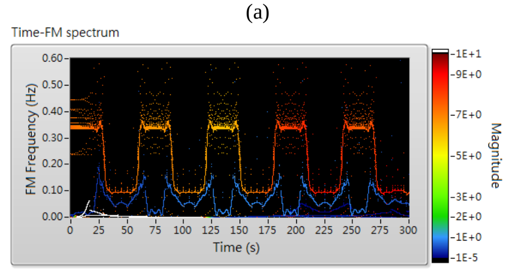
Fig. 3 illustrates the data, which were be acquired by two RIP sensors (RIPmate Adult Thorax Alice 5 Inductance Kit, Ambu Inc., Denmark) during IVM procedure. The RIP sensor was worn below the axilla to record RC movement as shown in Fig. 3(a), and the other RIP sensor was placed on the navel to record ABD movement as shown in Fig. 3(b). Both RIP signals were acquired by a data acquisition hub (NI SCB-68, National Instruments, USA) and a data acquisition card (NI USB 6255, National Instruments, USA) at a sampling rate of 50 Hz and were subsequently transferred to a computer (Acer Veriton M2610). The program controlling the instructions and data acquisition was developed using LabVIEW platform (LabVIEW 2012, National Instruments, USA).

III. RESULTS

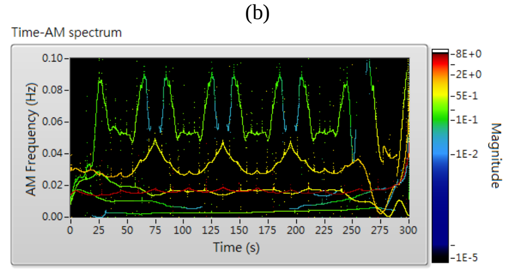
Fig. 4(a) illustrates Hilbert spectrum with EMD method and instantaneous frequency in simulation data. Fig. 4(b), 4(c), and 4(d) illustrate HHSA method including FM-AM



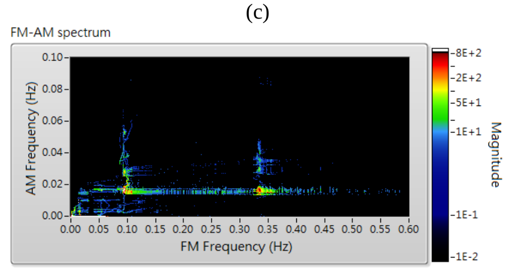
(a)



(b)



(c)



(d)

Figure 4. The spectra for the simulating data consist of (a) Hilbert spectrum, (b) Time-FM spectrum, (c) Time-AM spectrum, and (d) FM-AM spectrum.

spectrum, Time-FM spectrum, and Time-AM spectrum respectively. In Hilbert spectrum, we observe the alternate frequency, 0.33Hz and 0.1 Hz, in timescale which is consistent with the condition we gave. Because the magnitude is calculated by energy density, larger amplitude indicates as high magnitude and red color in this case. In FM-AM spectrum, it presents high energy (high magnitude) when FM frequency is equal to 0.1Hz and 0.33 Hz and obtain high energy when AM frequency is within the range of 0.015 to 0.02 Hz. In Time-FM spectrum, the distribution of frequency is similar to Hilbert spectrum but different in color. In Time-AM spectrum, we find the high energy at about 0.015 Hz in AM frequency and appear high frequency (0.09 Hz) near transition timing.

Fig. 5 and Fig. 6 indicate the results of RIP signals from RC and ABD movement. We see RC movement first. In Hilbert spectrum, it appears the floating frequency with time. The frequency in spontaneous breathing is about 0.2 to 0.4

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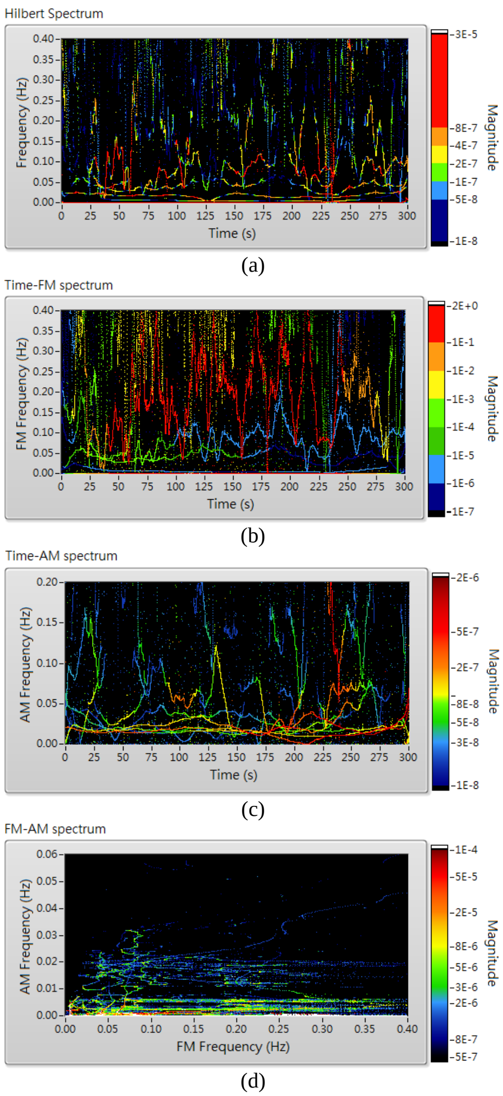

Figure 5. The spectra for the RIP signal with RC movement consist of (a) Hilbert spectrum, (b) Time-FM spectrum, (c) Time-AM spectrum, and (d) FM-AM spectrum.

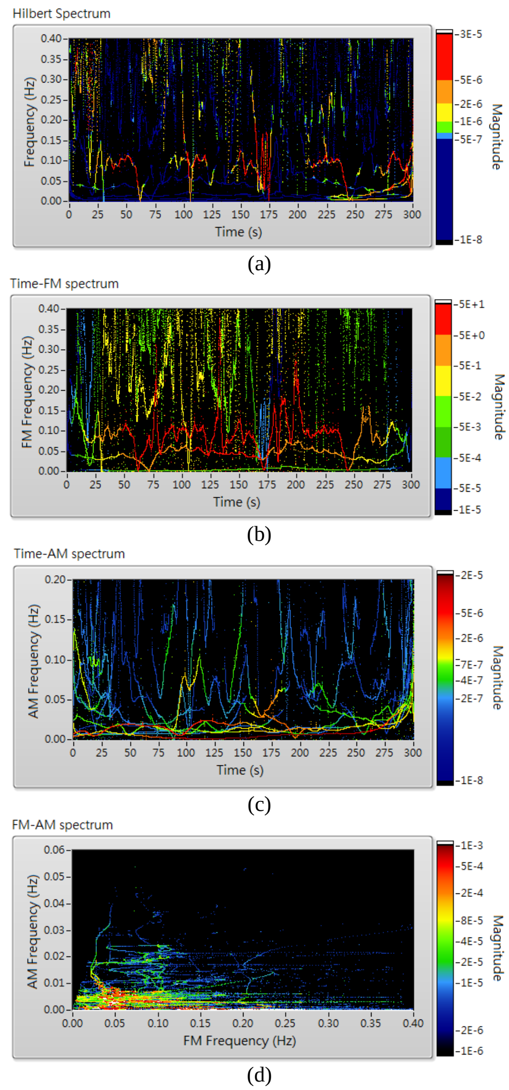

Figure 6. The spectra for the RIP signal with ABD movement consist of (a) Hilbert spectrum, (b) Time-FM spectrum, (c) Time-AM spectrum, and (d) FM-AM spectrum.

Hz with yellow and green color and the frequency in paced breathing range from 0.05 to 0.15 Hz with red color (higher energy). In FM-AM spectrum, there are two faint parts in FM frequency at 0.05 to 0.1 Hz and 0.15 to 0.4Hz respectively and appears higher energy near 0.02 Hz in AM frequency. In Time-FM spectrum, more complex than simulating data, we could recognize three distinct ranges. One of them is in the range of 0.05 to 0.1 Hz with green and blue color that is viewed as the frequency of paced breathing. Another is ranging from 0.2 to 0.4 Hz with yellow and green colors that refers to the frequency of spontaneous breathing. The other one is most obvious that joined both of above and crossed the range from 0.05 to 0.4 Hz. In Time-AM spectrum, there is a clear orange line in 0.02Hz but others information is irregular.

The spectra in ABD data compare to RC data, there are some difference in FM-AM spectrum and Time-FM spectrum. In FM-AM spectrum, the energy in lower frequency is larger and more centralized than RC in FM frequency. In Time-FM spectrum, the red region shows lower frequency than RC.

IV. DISCUSSION

We performed the simulated breathing data on four-type spectra and found that the similar distribution of frequency in Hilbert spectrum and Time-FM spectrum expect of 0.1 Hz and 0.3 Hz components allocated different colors, implying different energy densities. Compared to Hilbert spectrum, the pure frequency variation is clearly displayed in Time-FM spectrum. This performance could be the effect of 2nd EMD process, displaying it in another Time-AM spectrum. In addition, we find two bright points near 0.02Hz in AM frequency in FM-AM spectrum. AM is the slow changing envelope frequency variation that presents cyclic characteristics in the envelopes. In simulation, breathing pattern executed five times could be regarded as transition period with five periods in the envelopes and its frequency is 0.016 Hz. It is close to the higher energy in AM frequency indicated in FM-AM spectrum and Time-AM spectrum.

Comparing real breathing pattern with simulating breathing pattern and RC movement with ABD movement, we find some results. (1) There are two cases under the highly varied frequency of spontaneous breathing. In simulating case, we could clearly see the frequency in Hilbert spectrum and Time-FM spectrum. But in real case, the energy would spread to adjacent frequency, so the frequency is ambiguous. (2) In Time-AM spectrum, we find the higher frequency timing close to the transition timing in simulating case, but could not find in real case fellow the same rule. It may owing to the energy of higher frequency pretty lower than main energy that is difficult to indicate clearly in dynamical respiration. (3) The main distribution of frequency on ABD movement is lower than RC movement in Time-FM spectrum that present higher energy on paced breathing than spontaneous breathing. It may cause by performing TB during spontaneous breathing but we need to more experiment data to prove. (4) There are some unreasonable distribution of energy in Time-FM spectrum. As the Fig. 5(b) shows that the main distribution of energy range from 0.05 to 0.4 Hz, it is composed by two kind of frequency of breathing pattern. After being decomposed by EMD method, it should be divided into two different frequencies.

The IMFs decomposed by EMD on RC data shown as Fig. 7(a). We find the mode mixing problem in IMF_6. We repeat the same process after removing IMF_6 from RC data. In Time-FM spectrum shown as Fig. 7(c), we can find 0.1 Hz frequency of paced breathing obviously and 0.2 to 0.4 Hz in spontaneous breathing. Followed by above steps on ABD data, we can obtain clear frequency in spontaneous breathing and paced breathing.

V. CONCLUSION

In this study, we have used HHSA method on simulation of breathing pattern and respiratory movement data with IVM procedure. The frequency of amplitude fluctuation can be found in both Time-AM spectrum and FM-AM spectrum. Therefore, the transition period between spontaneous breathing (0.3 Hz) and paced breathing (0.1 Hz) can be found in Holo-Hilbert spectrum. Based on the HHSA method, we got the FM frequency and AM frequency in timescale to investigate the transition from spontaneous breathing to paced breathing. Related results are helpful for exploring the transition state on human breathing and dynamical respiratory pattern especially when people doing exercises or suffering cardiopulmonary disease for long-term care.

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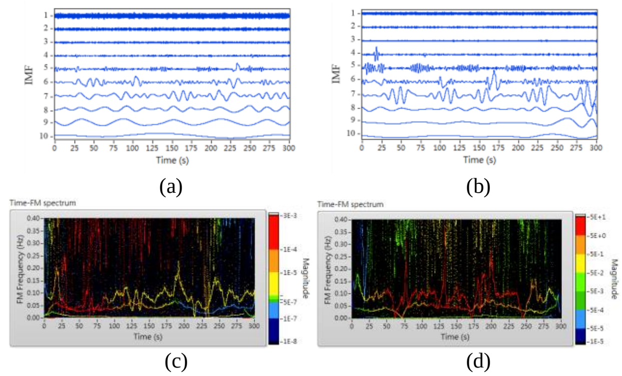

Figure 7. (a) The IMFs for the real data on RC. (b) The IMFs for the real data on ABD. (c) Time-FM spectrum of RC data removing IMF_6. (d) Time-FM spectrum of ABD data removing IMF_6.

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