Respiration Signal Extraction From Heart Rate

Dr. James Whitney
Assistant Professor
Department of Electrical and Computer Engineering
Morgan State University
whitney@eng.morgan.edu

Latasha Solomon
Department of Electrical and Computer Engineering
Morgan State University
lsnvg@eng.morgan.edu

INTRODUCTION

There is an ongoing need for more sensitive sensors and instrumentation to monitor parameters of human physiological functions. Often it is desired that this measurement process be as non-intrusive as possible, thereby requiring lightweight, high performance sensors and data acquisition systems. In the current application it is desired to measure and extract as much information from a single non-intrusive sensor as possible to avoid encumbering mission personnel with motion-inhibiting harnesses. One particular signal processing task of interest is extraction of respiration information by analysis of the heart rate (HR). Thus, signal-processing algorithms are described which perform this task using communication, non-uniform sampling, and spectrum analysis techniques.

MEASUREMENT OF HEART RATE

Results of previous research [1,2] indicate that the range of normal respiration extends from approximately 9 breaths/minute to 25 breaths/minute for a normal healthy subject. However, depending on individual physiology respiration rates from approximately 4 breaths/minute at rest to 40 breaths/minute during intense exercise are also acceptable. Therefore, in normal operating conditions respiration rates less than 3 breaths/minute and greater than 40 breaths/minute are disregarded when locating the maximum peak in the processed respiratory rate spectrum.

Normally, strain-gauge type halters are used to measure respiration directly. These devices tend to be uncomfortable and irritating to the skin. Pulse oximeters, which provide non-invasive measurements of HR and blood oxygenation, can provide an alternative to halter-based measurement systems. Pulse oximeters, in general, use two radiation sources, one in the visible region and one in the infrared. The two wavelengths are chosen based upon the optical properties of blood. For the oximeter used in this study, the two wavelengths are 660 nm and 910 nm respectively. Oxygenated blood, referred to as oxy-hemoglobin (HbO_2) is red and absorbs primarily at 910 nm. Deoxygenated blood, or, deoxy-hemoglobin (Hb), is blue and has its highest absorption, or extinction coefficient, at 660 nm. Using the Beer-Lambert law, these differences in absorption at the two different wavelengths are processed to provide hemoglobin oxygen saturation. The periodic change in blood density in the finger vascular bed during heart contraction and expansion provide the mechanism to also simultaneously obtain HR.

SIGNAL PROCESSING

Modulating Signal

In this work, respiration rate is not measured directly. Signal processing algorithms were derived to extract the respiratory modulating signal from the HR signal. The algorithm functions by finding all the positive peaks in a window length of data. Both the peak values and their locations are then stored in an array. Next, the average of the time difference between consecutive peak values, $\overline{T}$, is calculated. The inverse of this quantity is the carrier frequency, f_c. This mean value is then subtracted from each time difference, forming the modulating signal, ω_m.

Synthetic Heart Rate Signal

A synthetic heart rate signal was derived to model the effects of respiration on heart rate. The following equation was used to produce this synthetic heart rate signal:

$$x[n] = A\cos\left\{\left(\frac{\omega_c}{F_s}\right)n + \left(\frac{1}{\omega_m}\right)\sin\left[\left(\frac{\omega_m}{F_s}\right)n\right]\right\}$$

where,

A - Signal amplitude
Fs - Sampling frequency of heart rate data
ω_c - Carrier frequency
ω_m – Modulation frequency

For the synthetic data, the signal amplitude was arbitrarily set to '1'. The sampling rate, Fs, was set equal to that of the experimental data, 75 samples/second. The frequency of the carrier signal, f_c, was 1.25 Hz. Three different modulating frequencies, f_m, were used; .1, .2, and .4 Hz, corresponding to respiration rates of 6, 12,and 24 breaths/minute.

RESULTS

Various spectral analysis techniques were used to process the resulting modulation signal for both the experimental and synthetic data. These methods included the fast Fourier transform (FFT), power spectral density in the form of the Welch periodogram, and the Lomb-Scargle normalized periodogram. The FFT was tried initially to evaluate the efficacy of the algorithms. It did indeed provide encouraging results. As the subjects breathing rate increased, the location of the respiratory spectral peak obtained from the demodulated HR signal increased proportionately. Because processing of the original HR data results in a non-uniformly sampled modulation signal, the FFT, which is based on uniformly sampled data, is not technically appropriate. The Welsh periodogram and the Lomb-Scargle periodogram, which are both applicable for use on non-uniformly sampled data, were used instead. With the current data sets, the resulting modulating signals had data lengths which varied from approximately 32-38 samples. For the Welsh periodogram, the resulting data lengths were zero-padded to a length of 64 samples. When using the Lomb-Scargle algorithm the data length was left un-altered.

Three sets of experimental data were obtained from NASA. The experimental data had rates of 6, 12, and 24 breaths/minute. Fig. 1 illustrates a portion of the unprocessed 12 breaths/minute data. Fig. 2 illustrates the corresponding respiration signal extracted from the unprocessed data using the derived signal processing algorithms.

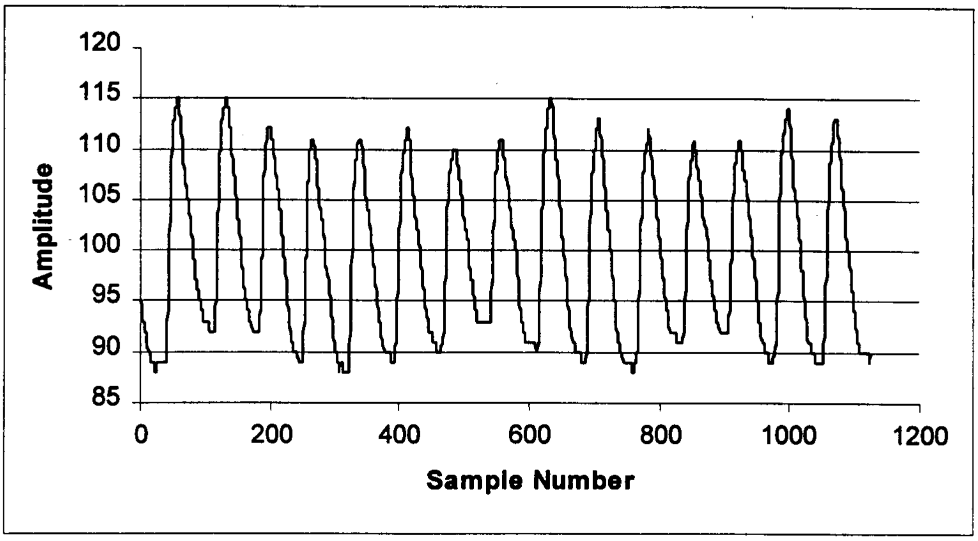

Figure 1 Unprocessed data, 12 breaths/minute.

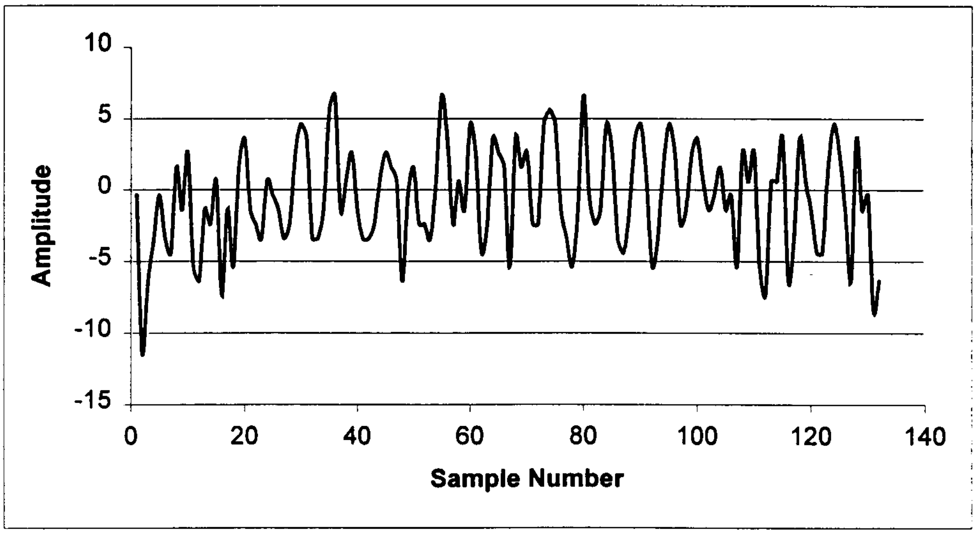

Figure 2 Extracted modulating signal, 12 breaths/minute data.

Figures 3-5 illustrate the HR spectrum of the unprocessed experimental 6, 12, and 24 breaths/minute data respectively. These spectra were obtained utilizing the FFT and a Hamming window. The data length was 4096 samples. In all three cases it is impossible to ascertain the frequency of respiration. Note that the unprocessed data is uniformly sampled, thus, use of the FFT is appropriate.

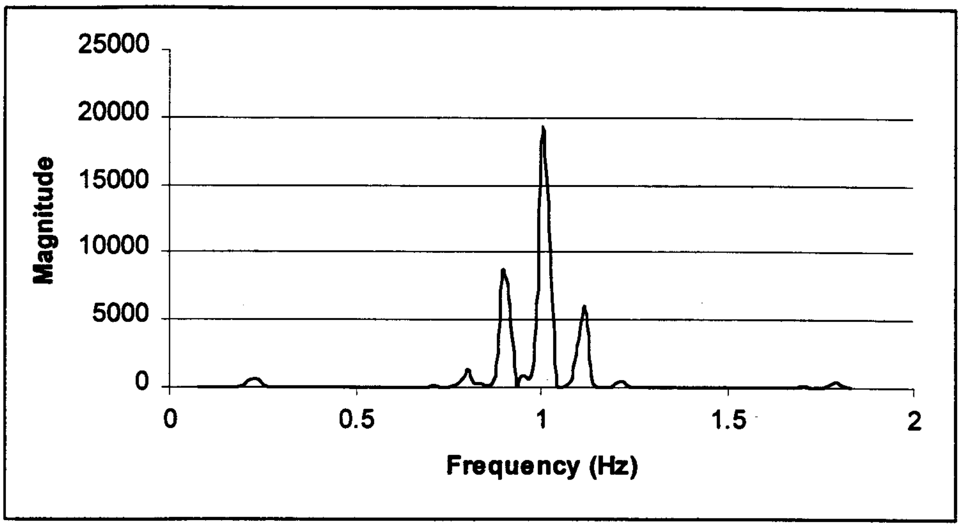

Figure 3 Spectrum of the unprocessed, nominal 6 BPM, experimental HR data.

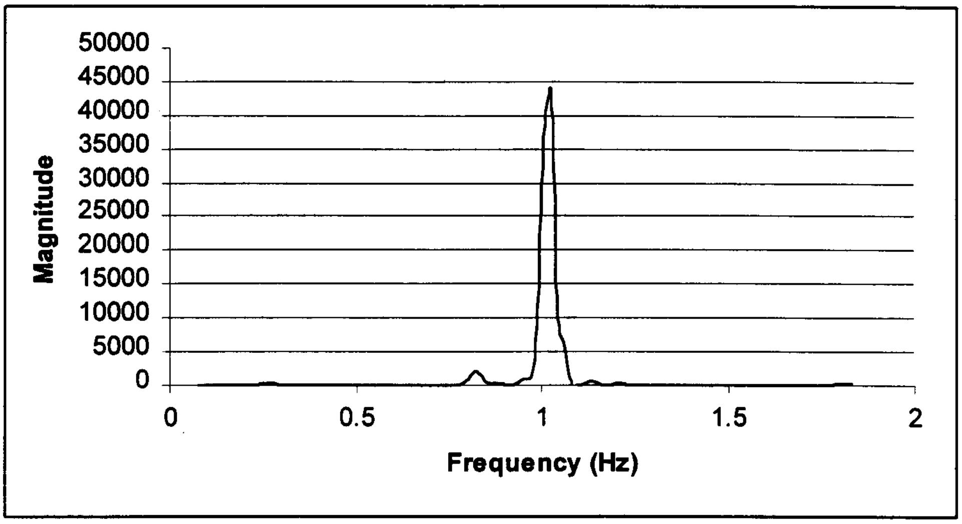

Figure 4 Spectrum of the unprocessed, nominal 12 BPM, experimental HR data.

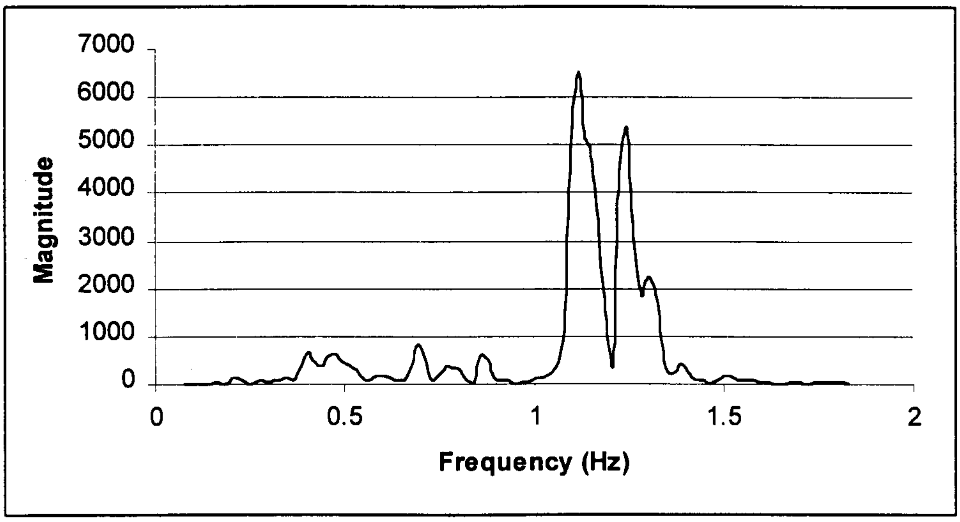

Figure 5 Spectrum of the unprocessed, nominal 24 BPM, experimental HR data.

Figures 6-8 illustrate the power spectrum of the modulating signals produced when the experimental 6, 12 and 24 breaths/min data was processed by the respiratory rate algorithm.

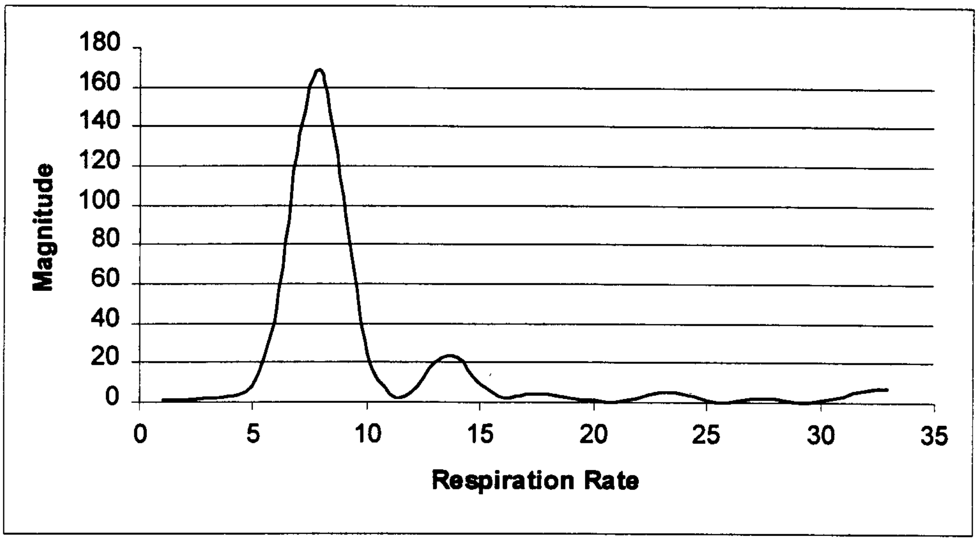

Figure 6 Respiration rate, nominal 6 BPM experimental data, standard periodogram.

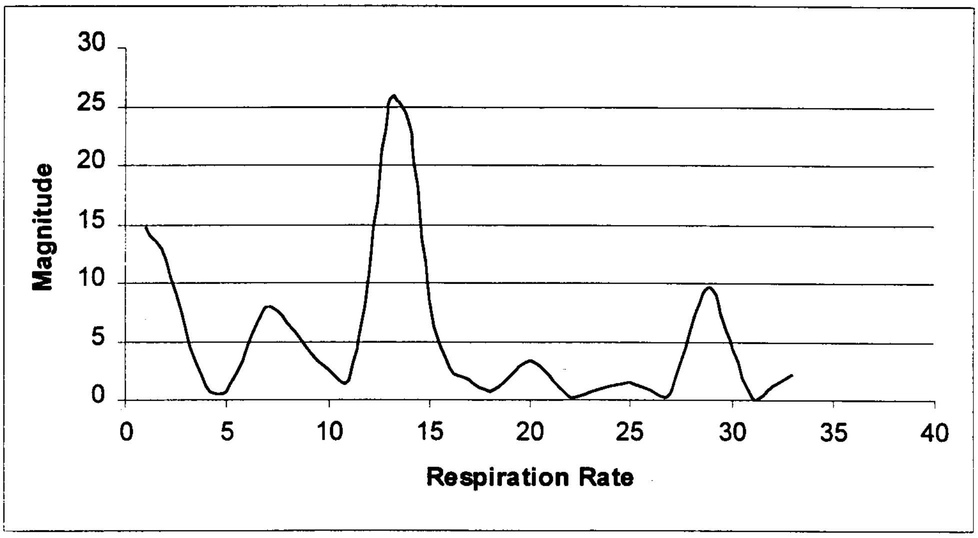

Figure 7 Respiration rate, nominal 12 BPM experimental data, standard periodogram

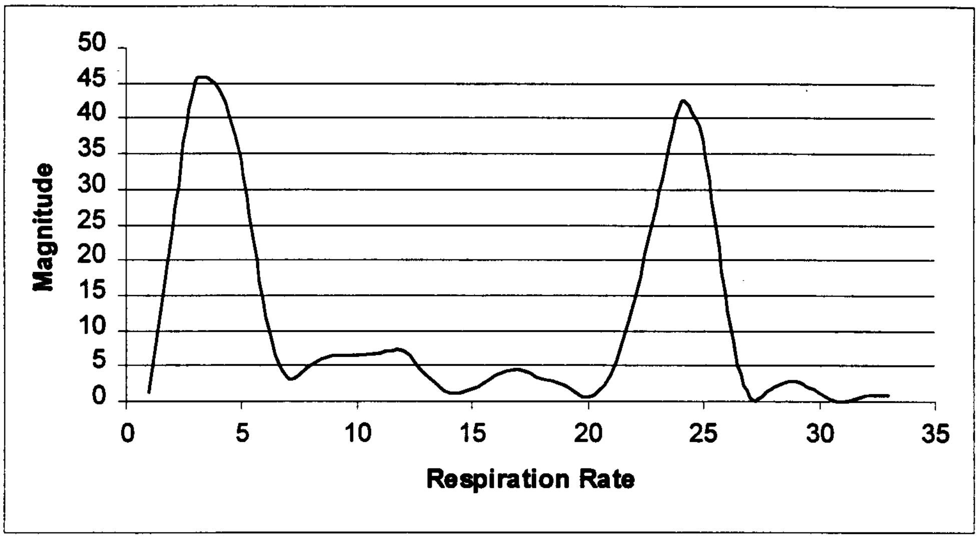

Figure 8 Respiration rate, nominal 24 BPM experimental data, standard periodogram.

Fig. 9 illustrates a segment of the synthetic signal for a respiration rate of 12 breaths/min generated by the HR model.

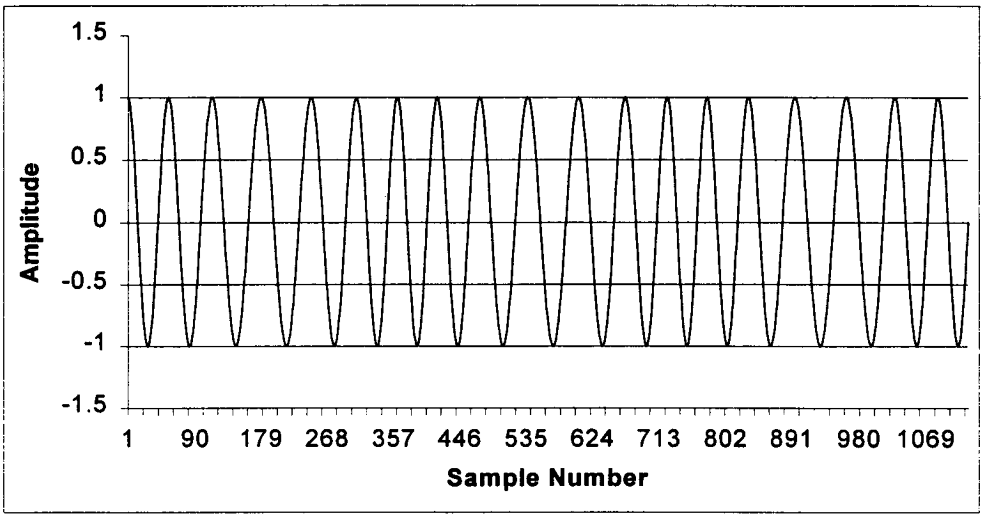

Figure 9 Waveform of synthetic HR signal.

Figures 10-12 illustrate the power spectral density obtained from the derived HR processing algorithm on the synthetic 6, 12, 24 BPM HR data respectively.

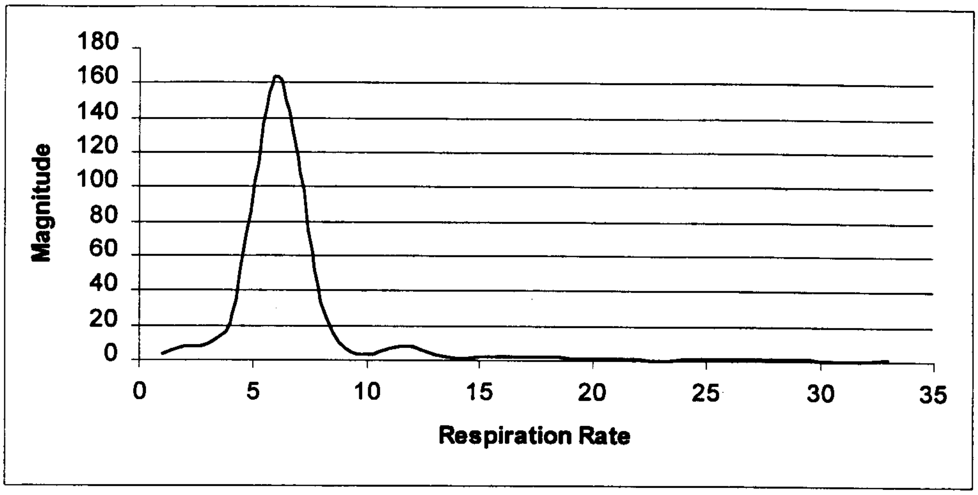

Figure 10 Respiration rate, nominal 6 BPM synthetic data, standard periodogram.

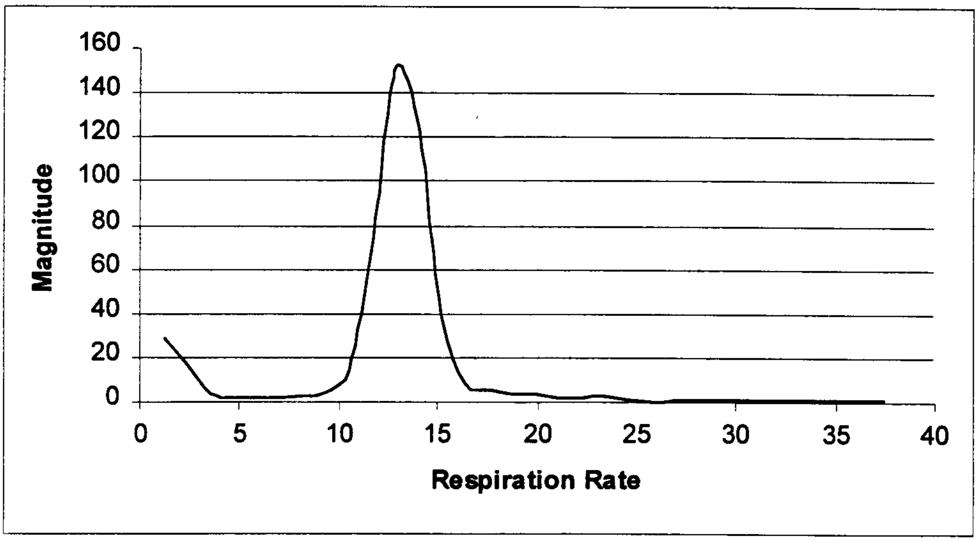

Figure 11 Respiration rate, nominal 12 BPM synthetic data, standard periodogram.

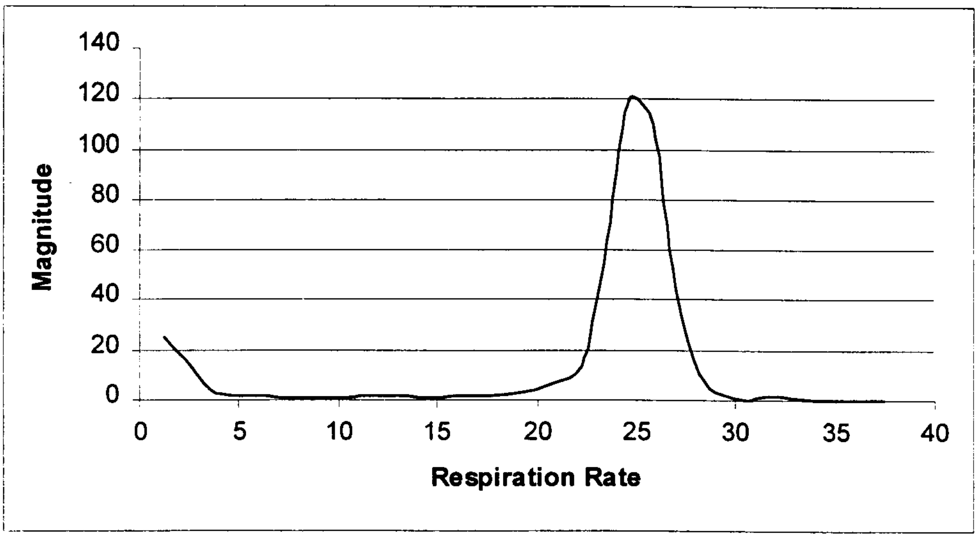

Figure 12 Respiration rate, nominal 24 BPM synthetic data, standard periodogram.

Figures 13-15 illustrate the results of Lomb-Scargle Normalized Periodogram on the respective modulating signals. Although several spurious peaks appear in Fig. 15, based upon the previously defined criteria their location eliminates them as possible candidates for estimated respiration rate.

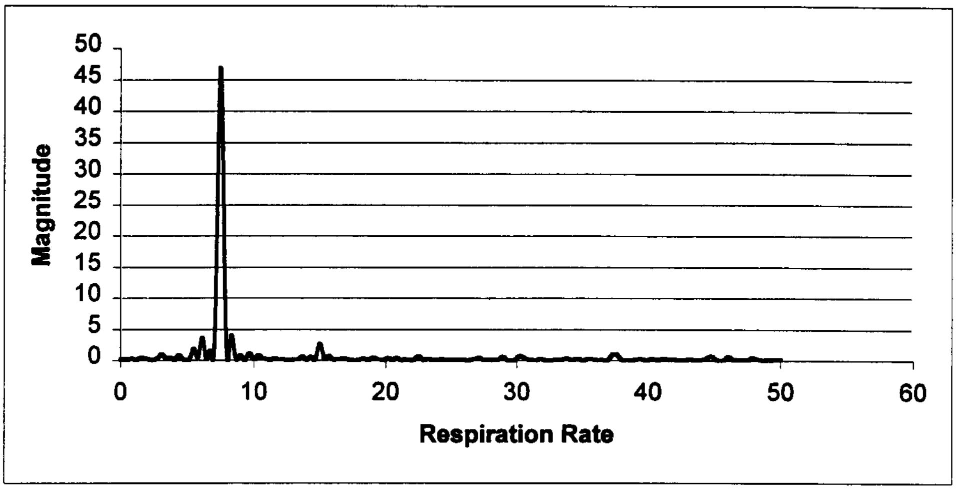

Figure 13 Respiration rate, nominal 6 BPM experimental data, L-S periodogram.

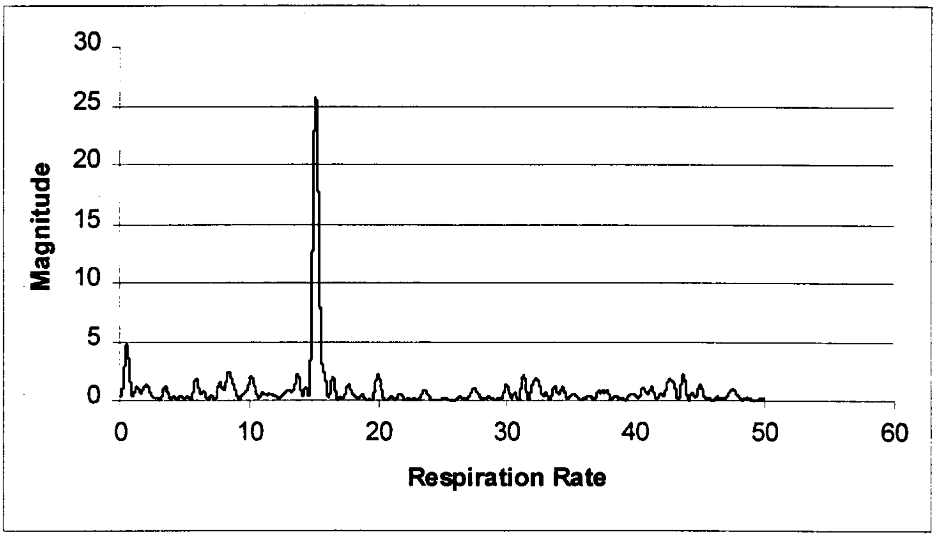

Figure 14 Respiration rate, nominal 12 BPM experimental data, L-S periodogram.

Figures 16-18 illustrate the results obtained when using the derived signal processing algorithms on the synthetic 6, 12, and 24 BPM heart rate data respectively.

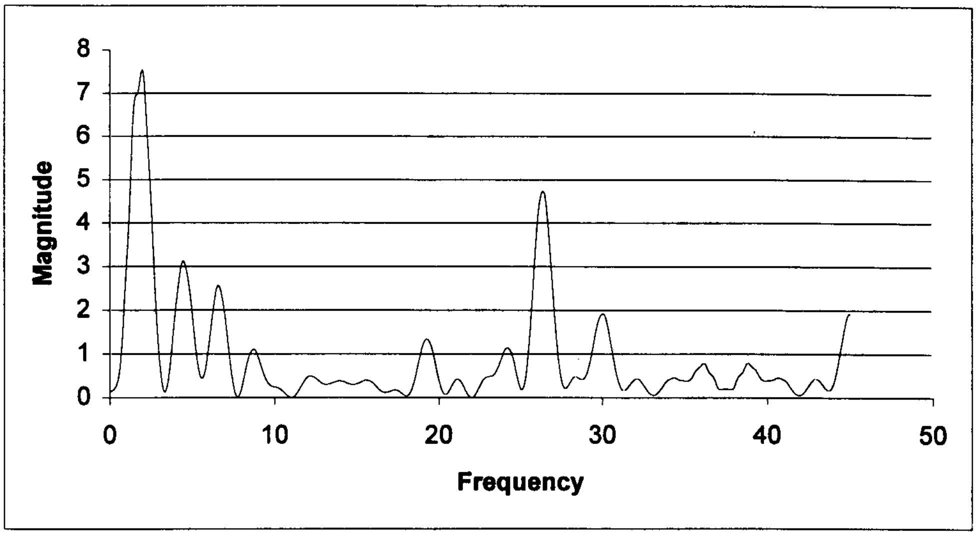

Figure 15 Respiration rate, nominal 24 BPM experimental data, L-S periodogram.

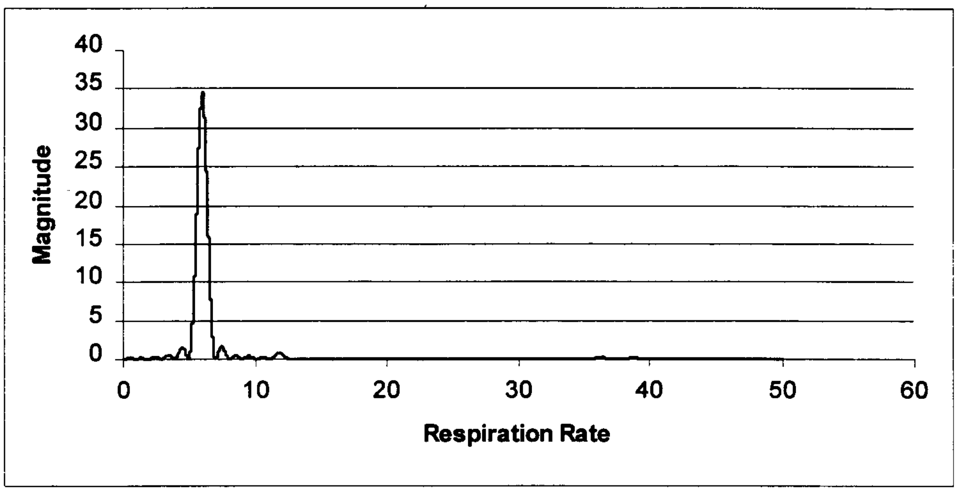

Figure 16 Respiration rate, nominal 6 BPM synthetic data, L-S periodogram.

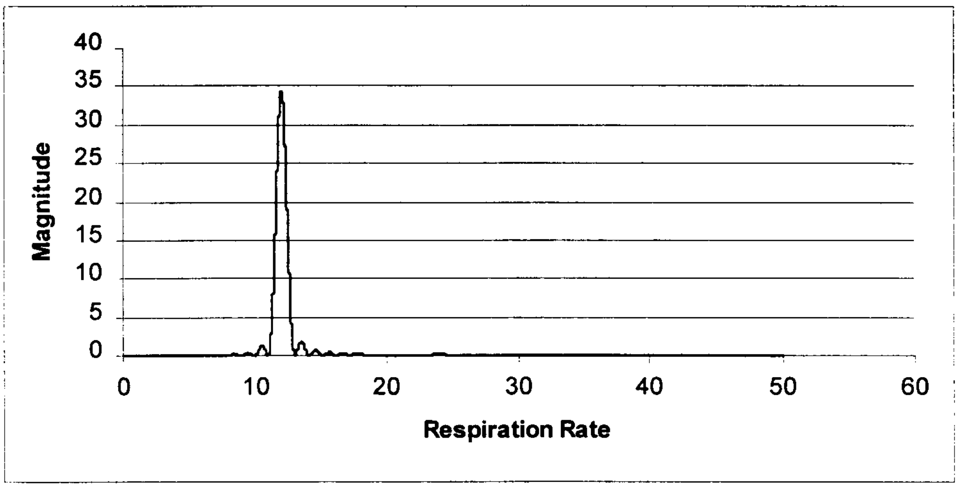

Figure 17 Respiration rate, nominal 12 BPM synthetic data, L-S periodogram.

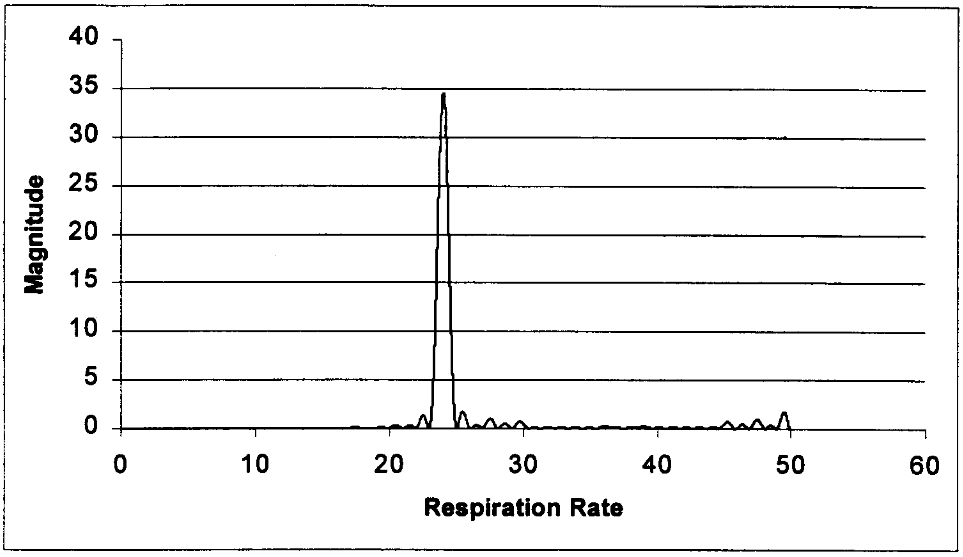

Figure 18 Respiration rate, nominal 24 BPM synthetic data, L-S periodogram.

SUMMARY

Our research has shown that the effects of respiration on heart rate can be successfully modeled as a frequency modulated (FM) process. By utilizing communication techniques, the modulating signal (respiration) can be demodulated from the carrier frequency (nominal heart rate). It was also shown that the Lomb-Scargle algorithm gave accurate spectral results on the resulting non-uniformly sampled modulation signal.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautical Space Administration (NASA), Johnson Space Center under the Faculty Awards for Research (FAR) program, grant number NAG-9-998.

REFERENCES

[1] Womack, B. F. "The Analysis of Respiratory Sinus Arrthymia Using Spectral Analysis and Digital Filtering," IEEE Transaction on Bio-Medical Engineering, Vol. BME-18, No. 6, pp. 399-409, November 1971.

[2] Zhao, L., S. Reisman, T. Findley, “Derivation of Respiration from Electrocardiogram During Heart Rate Variability Studies,” Computers in Cardiology, pp53-56, September 1994.