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Amplitude Demodulation of Entrained Sway to Analyze Human Postural Control

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Abstract

This paper presents an innovative technique to study postural control. Our translating platform, the Sliding Linear Investigative Platform For Analyzing Lower Limb Stability and Simultaneous Tracking, EMG and Pressure mapping (SLIP-FALLS-STEPm), makes precise, vibration movements under controlled conditions. We look at the psychophysical thresholds to the perception of a sinusoidally induced sway. In the Sine Lock experiments described, an induced sinusoidal perturbation locks the subject's natural sway pattern at the frequency of the perturbation. The input / output system is treated as an Amplitude Shift Key (ASK) modulated signal modulating a carrier frequency (at or about a subject's natural sway frequency). The Position signal (input) and the Anterior-Posterior Center of Pressure (APCOP) signal (output) or the ankle angle are demodulated by mixing them with the pure sine wave carrier at the frequency of underlying oscillation and then low-pass filtering it to detect the amplitude envelope. These detected envelopes elucidate that the square pulse increase in the position sine wave amplitude yields a triangular increase in APCOP demodulated signal.

I. Introduction

THE aim of this human postural control study is to determine psychophysical thresholds to sinusoidal entrainment and to linear moves made during various phases of a sinusoidal entrainment cycle. During the postural control experimentation in our SLIP-FALLS-STEPm lab, a stimulus or none is presented in each trial and the subject is asked to decide whether a stimulus was indeed presented. The amplitude of the stimulus is iterated in sequential trials towards the threshold. Entrainment will lock-in sway before and after the move, but a transient and deterministic stage will be seen in the trials correctly detected. For the Sine Lock procedure, we have known a carrier (i.e. the test frequency) that is amplitude modulated to produce a perturbation signal. The variables that we measure (i.e., Position, APCOP, etc.) can show some degree of modulation by this perturbation. We can thus treat the resultant signal as if they were produced by an Amplitude Shift Keying (ASK) procedure.

ASK is the modulation process that represents digital data as discrete variations in the amplitude of a carrier wave (a sine wave). In ASK modulation, the amplitude of a modulation wave varies with the modulating signal, while the frequency and the phase of a modulation

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wave remain constant. Thus an ASK modulated waveform consists of burst(s) of sinusoid. The carrier signal is a single frequency signal.

Amplitude demodulation is the reverse process of modulation. Demodulation or enveloping is used to recover the signal or to detect the message coded on the carrier signal. It filters out the carrier to determine the original signal amplitude. We apply this envelope detection algorithm to our measured variables (Position, APCOP, Ankle Angle, etc.) to find the effect of the modulated perturbations on them.

II. Methods

A. Experimental Procedures

Our Sliding Linear Investigative Platform For Analyzing Lower Limb Stability with Synced Tracking, EMG and Pressure mapping (SLIP-FALLS-STEPm) is a novel device and data collection system designed to study human postural control mechanisms [2]. We employed a modified Single-Interval-Adjustment-Matrix (mSIAM) iterative procedure. Based on the mSIAM, our new protocol requires a subject to detect the stimulus present in just one interval. Every trial contains either randomly presented stimulus or a null stimulus, and the answer is either “present” or “not present.” The outcomes Hit, Miss, False Alarm, and True Rejection, with the category Guess if available, are determined by adjusting the signal level in a staircase manner until threshold is reached. mSIAM decides the next test step amplitude. The procedure mSIAM is described elsewhere [4].

For these tests, a subject is blindfolded and headphones are placed over the ears to provide a constant “masking white noise” and two commands, “Ready”, and “Decide”. After the word “Decide”, the subject presses a doorbell button only if (s)he felt that the stimulus occurred. All data is recorded at a sampling rate of 1000 Hz.

B. Amplitude Demodulation of Entrained Signal

Figs. 1 and 2 illustrate how ASK modulates the signal. We use a null, sub-threshold baseline perturbation that may or may not be followed by a test perturbation.

The platform perturbation is generated using the carrier wave at four different frequencies, giving four sets of 30 trials. Out of four frequencies, two frequencies are always 0.5 Hz and 0.75 Hz, which are assumed to be close to the normal human sway frequency. The others used are the frequencies of sway calculated based on an analysis of the subject's quiet standing APCOP. Here we analyze the 0.75 Hz trials. There is a small sub-threshold baseline perturbation of 0.25mm amplitude at the frequency under the test. The ASK modulation (or none of a null trial in mSIAM) occurs between 5 to 14 sec into the trial.

A modulating signal for a stimulus trial is generated as a single pulse as shown in Fig. 1C above and in Equation 1 listed below. At the start of the trial, the carrier is modulated by sub-threshold amplitude. Between 5 and 14 sec, the mSIAM test amplitude is applied following another 6 sec of baseline. Similarly, Equation 2 and Fig. 1A generate the carrier at required frequency ‘f’. The modulated Position signal is a waveform with an initial baseline sinusoid, and a full amplitude sinusoidal perturbation generated using the ASK modulation as shown in Fig. 1E and Equation 3. For a non-stimulus trial, the modulating signal contains only the sub-threshold baseline sinusoid as shown in Figs. 1B, 1D, and 1F. The modulated position signal for a non-stimulus trial has the waveform with only baseline sinusoid.

$$x(t) = 0.25 [u(t) - u(t - t_0)] + 3.75 \left[u(t - t_0) - u(t - t_0 - \Delta_p) \right] \quad (1)$$

$$f_c(t) = \sin(2\pi f_0 t) \quad (2)$$

$$\begin{aligned} f_p(t) &= x(t)f_c(t) \\ &= (0.2[u(t) - u(t-t_0)] + 3.7[u(t-t_0) - u(t-t_0-\Delta_p)]) \sin(2\pi f_0 t) \\ &= (0.2[u(t) - u(t-t_0)]) \sin(2\pi f_0 t) + (3.7[u(t-t_0) - u(t-t_0-\Delta_p)]) \sin(2\pi f_0 t) \quad (3) \end{aligned}$$

**Sub-threshold
Baseline**

**SIAM test
Amplitude**

Synchronous Demodulation—Figure 2 shows the standard signal processing for ASK demodulation. The response signal or the signal to be demodulated for envelope detection is mixed with a carrier (i.e. multiplied by it) and then rectified and low pass filtered to find the envelope.

However, phase information is lost with this general demodulation technique. Therefore, we use a variant of this method and look for “synchronous” demodulation, so as to maximize the energy in the demodulated envelope. The critical point here is to know the phase shift between the driven signal and the measured one.

This now involves two signals,

$$f_c(t) = \sin(2\pi f_0 t + \varphi_c) \quad (4)$$

$$f_R(t) = y(t) \sin(2\pi f_0 t + \varphi_m) \quad (5)$$

where $f_c(t)$ is the carrier, $f_R(t)$ is the response, and $y(t)$ is the modulation envelope that must be recovered

As the phase shift is invariant between the signals, we can rewrite Eqs. 4 and 5 in terms of the difference ($\Delta\phi$) between the phases of two signals, $\Delta\phi = \phi_c - \phi_m$.

$$f_c(t) = \sin(2\pi f_0 t) \quad (6)$$

$$f_R(t) = y(t) \sin(2\pi f_0 t + \Delta\phi) \quad (7)$$

To estimate the value of $\Delta\phi$, the above two signals shown in Equation 6 and Equation 7 are cross-correlated to get,

$$R_{f_R f_c} = \int y(\tau) \sin(2\pi f_0 \tau + \Delta\phi) \sin(2\pi f_0 (t + \tau)) d\tau \quad (8)$$

$$= \int y(\tau) \sin(2\pi f_0 \tau + \Delta\phi) \sin(2\pi f_0 \tau + 2\pi f_0 t) d\tau \quad (9)$$

For $R_{f_R f_c}$ to be maximum, $\Delta\phi$ must to $2\pi f_0 t$, so,

$$\Delta\phi = \frac{2\pi t_c}{t_p} \quad (10)$$

where, t_c is the time shift to maximize the cross-correlation and t_p is the period of one cycle respectively.

The product, $f_C(t)f_R(t)$ is maximized when $\phi_c=\phi_m$, i.e., $\Delta\phi=0$. This phase value can be automatically determined by adjusting the value of $\Delta\phi$ between -180° to $+180^\circ$ until the cross-correlation of $f_C(t)$ and $f_R(t)$ is maximum at the midpoint of the data (i.e., at the point where the maximum synchrony occurs). Once we know $\Delta\phi$, the phase shift can be added to the demodulation carrier such that new calculated $\Delta\phi$ becomes zero, i.e. there is no phase shift present between the driven signal and the measured one. This is the essence of synchronous demodulation.

Once maximized the value of the cross-correlation using the appropriate phase shift $\Delta\phi$, and then using the carrier demodulation technique yields:

$$\begin{aligned}
 f_{R-M}(t) &= f_R(t) f_C(t) \\
 &= y(t) \sin(2\pi f_0 t) \sin(2\pi f_0 t) \\
 &= y(t) \sin^2(2\pi f_0 t) \\
 &= y(t) \frac{(1 - \cos 4\pi f_0 t)}{2} \\
 &= \frac{y(t)}{2} (1 - \cos 4\pi f_0 t)
 \end{aligned} \tag{11}$$

From Equation 11 it is seen that the amplitude of the recovered signal $f_{R-M}(t)$ is reduced to half of the original amplitude of the response signal. $f_{R-M}(t)$ is then filtered at $f_f = f_0/4$ to remove the $\cos 4\pi f_0 t$ term to get the detected envelope, $\hat{y}(t)$, such that $\hat{y}(t) = 2f(t)$.

III. Results

Subjects

Various groups of subjects underwent testing on SLIP-FALLS-STEPm. We consider the test trials of Healthy Young Adults (HYA), over 18 yrs old, without diabetes.

As described above, we treat the input/output system as an ASK modulated signal. This ASK modulated position signal is demodulated by mixing the signal with a pure sine wave carrier at the frequency of the underlying oscillation, and then low pass filtering it to obtain position envelope.

Fig. 5A shows the ASK modulated position signal that undergoes demodulation with the carrier wave and outputs the demodulated position signal (Fig. 5B). Fig. 5C illustrates the detected amplitude envelope with the carrier at 0° phase when the demodulated position signal is low-pass- filtered.

Similarly, we expect some deterministic envelope from the output signal (i.e., APCOP) for stimulus-detected trials. For the same trial of position signal shown in above figures, APCOP demodulation and filtering is performed in the same way which is illustrated in Figs. 6B and 6C respectively. Note that in Fig. 6B, the APCOP has some bipolar excursions (i.e., not all positive or negative) in the demodulated signal.

If in the cross-correlation between APCOP and the carrier signal, the midpoint is not maximum, then the carrier phase is adjusted to maximize the value of cross-correlation at the midpoint. This adjustment allows us to consider synchronous detection. The phase angle needed for the adjustment can range from -180° to $+180^\circ$.

The effect of this phase shift can be seen on the demodulated APCOP signal, where all the values are now positive during the increased perturbation amplitude. Fig. 7 yields the filtered APCOP envelope as an effect of platform movement on APCOP response.

The same technique can be applied to find the effect of perturbations on ankle angle changes. Fig. 8 shows the detected envelope when the carrier is at 68° phase. The response seen in ankle angle takes almost same shape as the rectangular perturbation of the position signal.

Fig. 9 shows the comparison between the signals arising from correct HITS, false MISSES, and TRUE REJECTIONS to see if there are correlates between these psychophysical responses and some physiological measures that we captured.

Note the differences in APCOP and ANKLE ANGLE recovered waveforms between HITS and MISSES. Also, note that a square pulse increase in Position sine wave amplitude yields a triangular increase in the APCOP demodulated signal.

IV. Discussion

Treating the input/ output system as an ASK modulated signal is of great benefit. When the position signal is demodulated by mixing it with carrier at the frequency of underlying oscillation and then low-pass-filtered, we can detect the amplitude envelope. We were expecting a similar deterministic envelope in the APCOP response. A pulse increase in the demodulated Position signal yielded a triangular increase in the demodulated APCOP signal. These shapes of the waveforms may be telling us something about the underlying system (i.e., APCOP as differential, and Ankle Angle as linear). This thus is a powerful method to separate differences in postural control that develop with age and/or presence of diabetes.

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Figure 1. ASK Modulation of Position signal for stimulus trial (A, C, E), and non-stimulus trial (B, D, F)

Figure 2.
Demodulation of ASK modulated signal

Figure 3.

Carrier Phase calculation, where $f_{R-M}(t)$ is a resultant multiplied signal

Figure 4.

Demodulation at the calculated phase, $\Delta\pi = \pi_{\max}$, where $\hat{y}(t)$ is an estimate of $f(t)$

Figure 5. (A) ASK modulated Position signal, (B) Demodulated Position signal when $\emptyset=0^\circ$, (C) Recovered Position signal envelope.

Figure 6.

(A) APCOP signal, (B) Demodulated APCOP signal with a carrier signal at $\phi=0^\circ$. Note the portions of the demodulated signal go negative, (C) Recovered APCOP envelope.

Figure 7. APCOP, demodulated APCOP and recovered APCOP when carrier phase is -142° (Compare with Figure 6).

Figure 8.
Demodulated Ankle Angle and recovered Ankle Angle when carrier phase is 68°

Figure 9.
Comparison between the signals of HIT, MISS, and TRUE REJECTION trials