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Removing Power Line Noise From Recorded EMG

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***Abstract*—Three methods for offline removal of power line interference (hum) from electromyograms (EMGs) were compared using both simulated and recorded EMG signals. The first method was a simple recursive digital notch filter. In the second method (Regression-Subtraction), the amplitude and phase of the interference were estimated by regressing sine and cosine functions onto a 'quiet period' before the start of the muscular contraction. A sinusoid with this frequency, magnitude and phase was then subtracted from the entire length of the signal. In the third method (Spectrum Interpolation), it was assumed that the magnitude of the original component of the signal at the frequency of the interference can be approximated by interpolating between the adjacent frequency bins in the power spectrum. While Regression-Subtraction was found to give the highest SNR for the output signal under ideal conditions, Spectrum Interpolation was found to be comparable if the phase of the interference was not constant and superior if the interference contained strong harmonic components.**

***Keywords*—EMG, signal processing, digital filtering.**

I. Introduction

It is difficult to obtain high-quality electrical signals from biological sources because the signals typically have low amplitude (in the range of mV) and are easily corrupted by capacitively or inductively coupled electrical noise. The most important source of such noise is power line hum (50/60 Hz) and its harmonics.

The EMG (electromyogram, electrical activity of muscles) is becoming increasingly important in biomechanical or physical therapy applications, and is recorded either from 'surface' electrodes on the skin above the muscle of interest, or 'intramuscular' electrodes inserted into the muscle. Surface EMG can only be recorded only for larger superficial muscles but is more convenient than intramuscular EMG. However, it also suffers from greater interference. This can be reduced by careful skin preparation to ensure good electrical contact with the electrodes and differential amplification with common-mode rejection ratio > 100 dB [1], but the interference may still be present in the recorded signal. Removing hum from surface EMG is difficult because the signal lacks a distinctive waveform and its bandwidth includes components at power line frequencies.

II. Signal Processing

A. Notch Filter

The simplest method of removing narrow bandwidth interference from a recorded signal is to use a linear, recursive digital notch filter:

$$H(z)=\frac{1-2\cos(\omega_0)z^{-1}+z^{-2}}{1-2r\cos(\omega_0)z^{-1}+r^2z^{-2}} \tag{1}$$

where ω_0 is the angular frequency corresponding to the central frequency of the interference and the width of the notch at –3 dB is $2(1-r)$ radians, $r < 1$ for a stable filter. Hence the Q-factor of the filter is:

$$Q=\frac{\omega_0}{2(1-r)} \tag{2}$$

Obviously the filter cannot discriminate between hum and the component of the EMG signal at that frequency, so the filter distorts the signal.

B. Regression-Subtraction

The Regression-Subtraction method (time-correlated power line noise subtraction) [2] assumes that the power line interference is a superimposed sinusoid with constant amplitude and phase throughout the recording. This limits the method to experiments where there is no movement, otherwise the phase of the interference will vary as the electrodes move relative to the noise source. The amplitude and phase of the interference are estimated from a 'silent period' of little or no muscle activity, which may be at the beginning or end of the recording.

Unit amplitude, quadrature sinusoids are generated at the power line frequency ω_0:

$$X_1(n)=\sin(\omega_0 n),\ X_2(n)=\cos(\omega_0 n) \tag{3}$$

These are then regressed onto the 'silent period' $Y(n)$:

$$\begin{aligned}Y(n)&=a+bX_1(n)+e_1(n)\\ Y(n)&=c+dX_2(n)+e_2(n)\end{aligned} \tag{4}$$

where a, b, c and d are regression coefficients and e_1 and e_2 are error terms. The estimated power line interference is then subtracted from the entire record:

$$\mathrm{EMG}'(n)=\mathrm{EMG}(n)-b\sin(\omega_0 n)-d\cos(\omega_0 n) \tag{5}$$

Provided that the assumption about the interference is correct, this final step removes the hum without affecting the signal.

C. Spectrum Interpolation

Suppose that the 'true' power spectrum of the corrupted EMG signal is a continuous curve with a superimposed peak at the power line frequency ω_0. Then the magnitude of the 'true' frequency component of the EMG at ω_0 can be estimated by interpolating this curve. Based on this concept, we propose the following procedure for removing power line interference from EMG:

1. Using an m-point Hanning (or other) window and discrete Fourier transform, calculate the averaged m-point spectrum $S(\omega)$ of the EMG, $\omega \in (-\pi, \pi)$.
2. Estimate the corrected value $S'(\omega_0)$ by interpolating between $S(\omega_0 - d\omega)$ and $S(\omega_0 + d\omega)$ where $d\omega$ is frequency resolution.
3. In the Fourier transform of the entire EMG signal, replace the magnitude at $\pm\omega_0$ with $S'(\omega_0)$. The phase remains unchanged.
4. Finally, take the inverse Fourier transform of this 'corrected' spectrum to give the EMG signal with reduced interference.

III. EXPERIMENTAL METHODS

A. Simulated Data

Simulated EMG signals were used to allow a controlled signal-to-noise ratio (SNR). Each signal $x(n)$ consisted of two sections: a 'quiet' section representing no muscle activity, and an 'active' section representing muscle activity. The quiet section was a sequence of 1000 zeros and the active section was 4000 samples of EMG simulated assuming a sampling frequency of 1 kHz. A 5000-point Gaussian white noise sequence with variance of 5×10^{-3} was then added to each signal to represent thermal noise in amplifiers.

The model used was a modification of the autoregressive-moving average (ARMA) model used by Karlsson & Yu [3]. Zero-mean, unit-variance Gaussian white noise sequences were passed through a filter with the magnitude of its frequency response specified by:

$$|H(f)| = \frac{kf^2}{(f^2 + f_L^2)(f^2 + f_H^2)^2} \qquad (6)$$

where f_L and f_H are low and high frequencies (respectively) controlling the shape of the curve and k is chosen so that the maximum value of $|H(f)|$ is unity. A least-squares fitting algorithm [4] was used to generate ARMA(20,20) models from $|H(f)|$. Both stationary and non-stationary signals were generated as follows.

1) *Stationary EMG Signals:* The active sections of the signals were generated using 100 different models, obtained by changing the settings for f_L and f_H. For each model, f_L was between 15–30 Hz and f_H was between 120–160 Hz. Each model was driven by a different white noise sequence.

2) *Non-Stationary EMG Signals:* The active sections of the signals were generated using a single time-varying model, which was driven by 100 different white noise sequences. The model parameters (f_L, f_H) were decreased from (30, 160) Hz to (15, 120) Hz in 100 uniform steps.

3) *Power Line Interference:* The power line hum $p(n)$ was a simulated 50 Hz sinusoid with an initial phase of 45°. To simulate a phase shift due to movement, the phase of $p(n)$ was increased to 60°, 75° and 90° over 0.2 s (200 samples), starting at 2 s, 3 s and 4 s. Input signals $x(n) + A.p(n)$ were then generated at SNRs between 0 and 40 dB. The SNR of this input signal (SNR_{in}) was varied by changing the amplitude A of the interference while the amplitude of $x(n)$ remained constant:

$$A = \frac{\sqrt{2} \cdot \sigma_x}{10^{SNR_{in}/20}} \qquad (7)$$

where σ_x is the RMS amplitude of the 'active' part of $x(n)$.

These inputs were processed to give outputs $y(n)$ using $Q = 50$ and $Q = 25$ notch filters, the Regression-Subtraction method, and the Spectrum Interpolation method. For Spectrum Interpolation, the length of the Hanning window used was between 128 and 2048 points and the overlap between successive windows was varied between 0 and 50%.

To calculate the output SNR (SNR_{out}), only the 'active' part of the signal was used so that the startup transients of the notch filters would have no effect. SNR_{out} was calculated from the variances σ^2 of the noise-free input $x(n)$ and an error signal $e(n)$ (the difference between the output and x):

$$SNR_{out} = 10 \cdot \log_{10}\left(\frac{\sigma_x^2}{\sigma_e^2}\right) \qquad (8)$$

B. Real Data

The spectrum of a particularly noisy EMG signal is shown in Fig. 2. This signal was recorded from the right brachioradialis muscle using Noro-Trode™ adhesive dual Ag-AgCl surface electrodes (Myotronics-Noromed, Inc.) and custom-built 10–500 Hz EMG amplifiers. Skin preparation prior to attaching electrodes included wiping with an isopropyl alcohol swab to dissolve skin oils, shaving hair from the recording site and rubbing the skin 20 times with 800-grade silicon carbide paper to thin the keratin layer and thereby decrease the skin's resistance. Data was recorded digitally at 2000 samples / s using a 12-bit data acquisition card with input limits ± 5 V (National Instruments PC-LPM-16PnP). Despite this skin preparation, the electrical contact apparently was not good (inter-electrode resistance was 16 kΩ) and the signal contains not only 50 Hz hum but also odd harmonics (150 Hz, 250 Hz etc.). The Regression-Subtraction and Spectrum Interpolation methods were applied repeatedly, once for each power line harmonic frequency, and the $Q = 50$ notch filter was modified to give a comb filter with notches at these frequencies. The EMG signal was presumed stationary during the segment analysed here (1 s of data at constant force, 5 s into the recording), but the subject was asked to keep the muscle relaxed for the first 1 s of recording so that the Regression-Subtraction method could be applied.

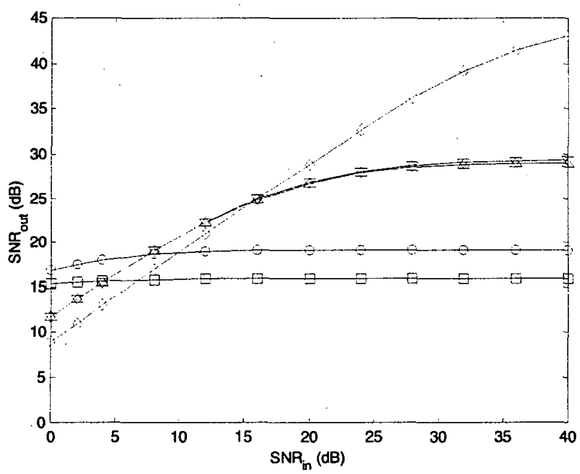

Fig. 1. Mean output SNR vs input SNR for the simulations where the 50 Hz interference contained a 30° phase change over 0.2 s, starting at $t = 3$ s. ○ $Q = 50$ notch filter, □ $Q = 25$ notch filter, ◊ Regression-Subtraction, ∇ Spectrum Interpolation with w = 128, Δ Spectrum Interpolation with w = 2048.

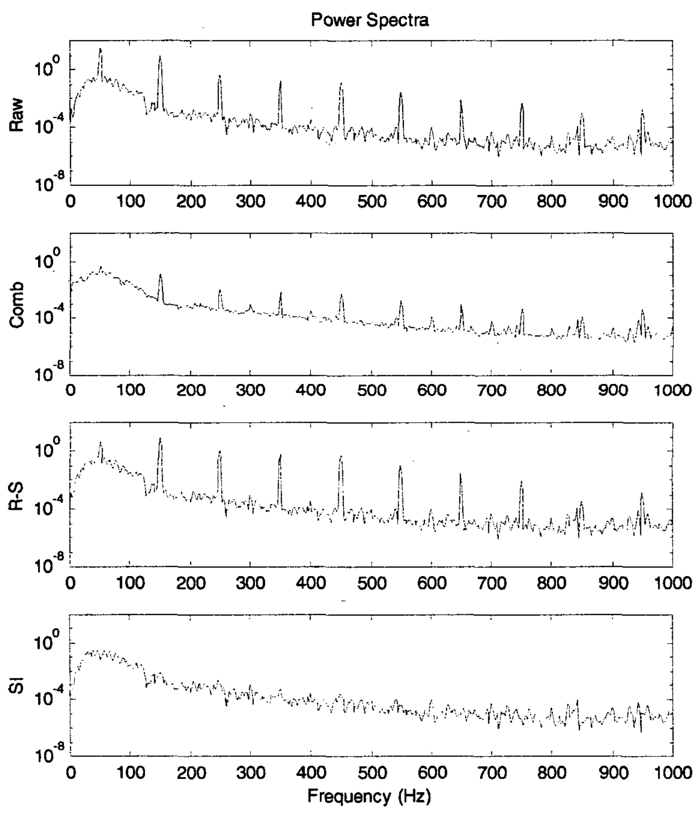

Fig. 2. *Raw*: Power spectrum of 1 s of a recorded EMG signal, showing high levels of power line interference. *Comb*: Spectrum after processing with a linear comb filter (1 Hz-wide notches). *R-S*: Spectrum after processing with Regression-Subtraction method. *SI*: Spectrum after processing with Spectrum Interpolation method, using a 1024-point Hanning window. All spectra calculated via Welch's averaged modified periodogram method using a 1000-point Hanning window with 50% overlap.

TABLE 1

SNR_{out} (dB) for stationary simulated EMG, no phase change in 50 Hz interference, mean and standard deviation (σ) calculated over 100 simulations. Spectrum Interpolation results varied slightly with SNR_{in} and window length ($\sigma \approx 0.5$ dB); values marked * are mean values of the means and standard deviations.

Method	SNR_{out}	
	Mean	σ
Notch filter (Q = 50)	19.2	1.9
Notch filter (Q = 25)	16.0	1.6
Regression-Subtraction	44.7	5.4
Spectrum Interpolation	29.3*	5.4*

IV. RESULTS

A. Simulated Data

If the interference had constant phase, SNR_{out} was independent of SNR_{in} as shown in table 1. The general characteristics of results for stationary EMG simulations when the phase of the interference changed are shown in Fig. 1. Other results not shown in this figure are as follows. Changing the size of the window used in Spectrum Interpolation made little difference to the results, and changing the overlap between windows made no difference. The time at which the phase change occurred had the greatest effect on the Regression-Subtraction results, with SNR_{out} being lower for earlier phase changes. But the magnitude of the phase change had a greater effect on all methods, with larger changes giving a lower SNR_{out}. For a constant-phase interference, the mean results of the non-stationary EMG signals were within 1 dB of the mean results of the stationary signals.

B. Real Data

Based on the results from the simulated data, it was expected that Regression-Subtraction would give the greatest improvement in the quality of the EMG signal. As shown in Fig. 2 however, Regression-Subtraction reduced the power in the power-line hum interference fundamental but not the harmonics. The comb filter further reduced the power in the fundamental as well as the harmonics, but altered the shape of the EMG spectrum. Spectrum Interpolation resulted in the most improved spectrum, with the peaks from the power line interference removed but no visible changes to the rest of the spectrum.

V. DISCUSSION AND CONCLUSION

Previously, we have presented comparisons between notch filters, Regression-Subtraction and Spectrum Interpolation using a less satisfactory model to simulate EMG signals [5]. The model presented here gives a spectral characteristic closer to those we have observed in practice. Based on simulated data only, it is still difficult to specify a single 'best' processing method for removing power line interference; Fig. 1 and table 1 indicate that different methods may be better under different conditions. Overall, Regression-Subtraction seemed the most promising but cannot be applied in all situations and didn't work very well with experimental data. The subject did not move during the recording of this signal, so the conditions for using Regression-Subtraction were seemingly satisfied. Errors could have been introduced if the power line hum was not exactly 50 Hz or if the sampling rate was not exactly 2000 Hz, but neither of these problems were indicated; a 13000-point DFT on the entire signal showed the peak interference to be at 50 Hz with little leakage into the adjoining frequency bins. A more likely cause is that compared to a pure sinusoid, Regression-Subtraction seems not to reduce the fundamental frequency as well if there are also harmonics.

For higher SNR_{in}, the SNR is degraded by notch filters (Fig. 1) because their nonlinear phase response and reduction of bona fide signal frequencies actually introduce distortion into the signal. This effect was also evident in the spectral alteration caused by the comb filter (Fig. 2).

Spectrum Interpolation is not an ideal method: it does not distinguish between periodic interference and the aperiodic signal of interest. It might be described as a nonlinear notch filter, where the interference is attenuated rather than removed as such. But because it is effectively zero-phase, there is not the phase distortion associated with linear recursive notch filters. Of course it should be possible to avoid having to use any DSP methods to reduce power line hum if the EMG amplifier and subject connections are good enough, but in the event that the recording is affected by this interference, Spectrum Interpolation is a promising method of suppressing it.

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