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Combined frequency and time domain sleep feature calculation

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Abstract— **In automated sleep analysis usually both frequency and time domain features are calculated from measured physiological (EEG, EOG, EMG) signals. Usually Discrete Fourier Transform (DFT) is used for different frequency domain measures and Digital Filtering (FIR or IIR) for time domain measurement. Here we demonstrate potential usefulness of using modified inverse DFT as a step for time domain feature calculation. Analytical formulas are shown for calculating interpolation, velocity and acceleration of filtered signals. Preliminary examples of electro-oculography (EOG) signal analysis during sleep are presented. Although same results could be obtained with conventional filtering followed by numerical differentiation the presented could be useful in some cases.**

I. Introduction

AUTOMATED sleep analysis provides objective, quantitative information about sleep [1]. Usually either sleep stages (e.g. discrete 30 s epochs) [2] or sleep related processes (e.g. Slow Wave Activity) are estimated [3,4]. In both estimations sleep related features are calculated after some artifact rejection [5] followed by sleep stage classification [6] or other estimation [3,4].

Early sleep EEG analysis focused on time domain measures. In Period Amplitude (PA) analysis zero crossings and amplitudes of individual waves were calculated [7]. Exact duration between two zero crossings is determined by linear interpolation [8, 9]. Later DFT based methods become more popular [10]. Recently time domain measures have resurfaced for calculating slope (velocity) parameters of slow waves during slow wave sleep [11, 12]. Other need for velocity (and acceleration) signal in sleep analysis is e.g. the detection of blinks [13], slow eye movements [14] and fast eye movements [15, 16, 17].

In this work frequency and time domain feature calculations are combined into same framework using DFT and IDFT. DFT is used to calculate power in selected frequency bands and then modified IDFT with interpolation is used for velocity and acceleration calculation of filtered signals. Analysis is then applied to simulated and real electro-oculography (EOG) signals during sleep.

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II. Methods

A. Discrete Fourier Transform

Discrete Fourier Transform (DFT) is defined [18] as following

$$X(k) \equiv DFT_k(x) \equiv \sum_{n=0}^{N-1} x(n) e^{-j2\pi nk/N} \quad (1)$$

Inverse Discrete Fourier Transform (IDFT) can be derived [18] as

$$x(n) = IDFT_n(X) = \tfrac{1}{N} \sum_{k=0}^{N-1} X(k) e^{j2\pi nk/N} \quad (2)$$

Transform can be thought as decomposition of signals into discrete frequencies of sinusoids. Magnitude *M(k)* and phase *P(k)* characterize these sinusoids

$$M(k) = \left| DFT_k(x) \right| \quad (3)$$

$$P(k) = \operatorname{atan2}(\operatorname{Im} DFT_k(x), \operatorname{Re} DFT_k(x)) \quad (4)$$

B. Modified Inverse Discrete Fourier Transform

With real signals *x(n)* inverse transform (2) can be expressed as a sum of cosines

$$x(n) = \tfrac{2}{N} \sum_{k=0}^{N/2} M(k) \left[\cos(2\pi nk/N + P(k)) \right] \quad (5)$$

If *N is* even then *M(N/2)* must divided by two for correct scaling. If *N* is odd the sum (5) is up to *(N-1)/2*. Filtered (band limited) signal can be obtained by zeroing *M(k)* of unwanted frequencies in (5).

With e.g. 200 Hz sampling rate and 2 s DFT using 0.5-6 Hz bandwidth calculation of sum in (5) is reduced from *N=201* to *N=12*. Also with 0.5-6 Hz bandwidth it is possible to evaluate *x(n)* e.g. at 24 Hz (4*sampling rate) instead of 200 Hz resulting in further reduction of calculation.

C. Interpolation

Using (5) it is easy to evaluate filtered signal at any given time point $0 \le t \le N$

$$x(t) = \tfrac{2}{N} \sum_{k=0}^{N/2} M(k) \left[\cos(2\pi tk/N + P(k)) \right] \quad (6)$$

Formula (6) can be used to obtain e.g. signal zero crossing in arbitrary resolution by iteratively evaluating *x(t)* around zero

crossings.

D. First and second derivate

First (velocity) and second (acceleration) derivates of signal can be obtained analytically from (6)

$$x'(t) = {}^{-4\pi}\!/_{N^2} \sum_{k=0}^{N/2} M(k)k\left[\sin(2\pi tk/N + P(k))\right] \quad (7)$$

$$x''(t) = \frac{-8\pi^2}{N^3} \sum_{k=0}^{N/2} M(k)k^2\left[\cos(2\pi tk/N + P(k))\right] \quad (8)$$

By having t non integer and zeroing (or shaping) $M(k)$ velocity and acceleration of filtered signal can be obtained in arbitrary time point. Used filtering could be different for amplitude, velocity and acceleration. Usually also windowing $w(n)$ function is used in calculating *DFT*.

$$X(k) \equiv DFT_k(x) \equiv \sum_{n=0}^{N-1} w(n)x(n)e^{-j2\pi nk/N} \quad (9)$$

With windowing normalization of IDFT is needed to obtain correct amplitudes.

E. Feature extraction

For sleep analysis we used previously studied approach [19, 20]. Shortly 2 s segments were analyzed with 0.5 s steps. Calculated DFT is used to obtain magnitudes and phases of different frequencies. Time domain calculation are done using 0.5-6 Hz bandwidth. Samples were reconstructed with 1000 Hz using formulas (6, 7, 8).

III. Simulation

Hann windowed 1 Hz sinusoid with Gaussian noise is simulated with 1000 Hz sampling rate, Fig. 1. Data is down sampled to 200 Hz and is reconstructed in 0.5-6 Hz bandwidth (6) using 1000 Hz, Fig. 2. Velocity and acceleration signals are shown in Fig. 3. and Fig. 4.

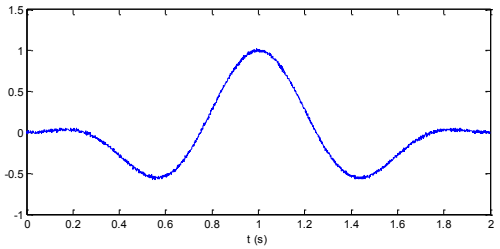

Fig. 1. Simulated signal.

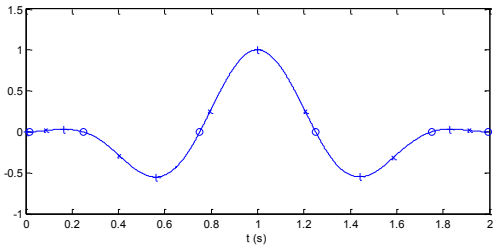

Fig. 2. Reconstructed signal with 0.5-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

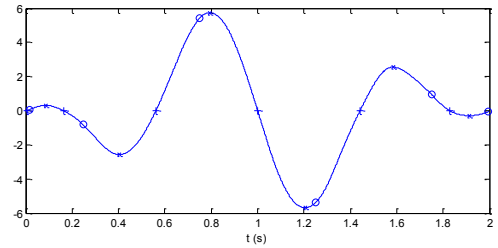

Fig. 3. Reconstructed velocity with 0.5-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

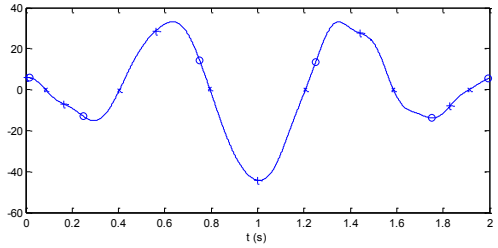

Fig. 4. Reconstructed acceleration with 0.5-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

IV. Electro-oculography data

Example data from previous studies [19, 20] is used. As an illustrations of calculations only EOG signals are presented. In Fig. 5-8 two saccades from REM sleep are analyzed.

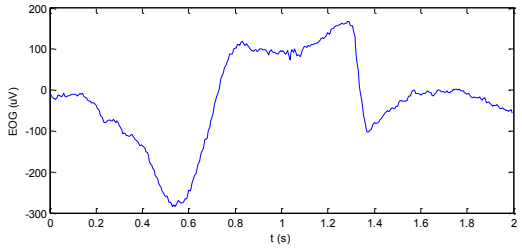

Fig. 5. Two saccades during REM sleep.

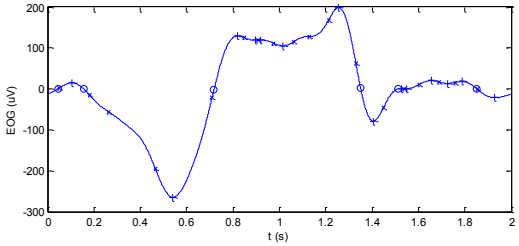

Fig. 6. Reconstructed saccades with 0.5-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

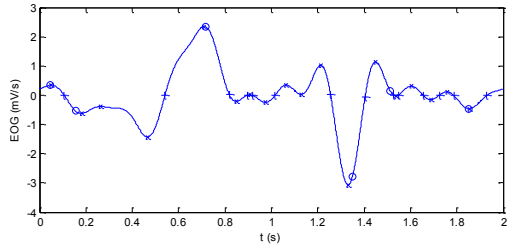

Fig. 7. Reconstructed saccades velocity with 0.5-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

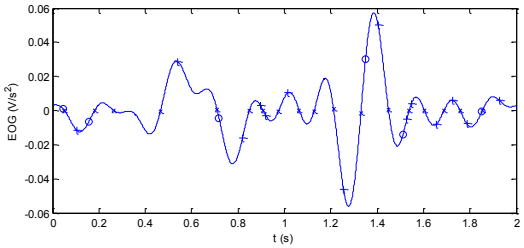

Fig. 8. Reconstructed saccade acceleration with 0.5-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

As expected by definition and noted also in simulations Fig. 2-4 zero crossing of velocity (+) indicates either local minimum or maximum of signal, Fig. 6. Similarly zero crossing of acceleration (x) indicates either local minimum or maximum of velocity, Fig. 7. Used velocity profiles could be used for saccade detection [15, 16, 17]. Another example is slow waves during slow wave sleep (SWS), Fig. 9-12.

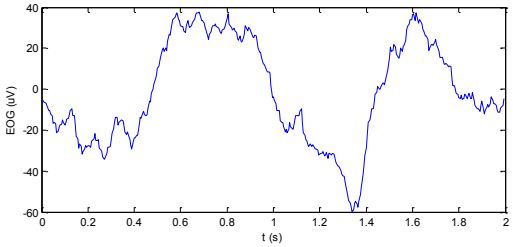

Fig. 9. Slow wave during SWS sleep.

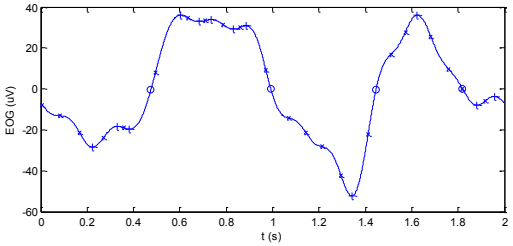

Fig. 10. Reconstructed slow wave with 0.5-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

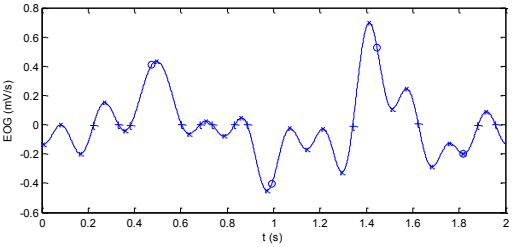

Fig. 11. Reconstructed slow wave velocity with 0-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

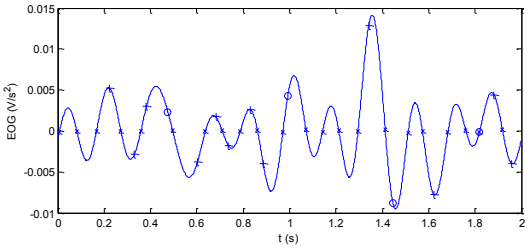

Fig. 12. Reconstructed slow wave acceleration with 0-6 Hz bandwidth. o indicates zero crossing, + indicates zero crossing of velocity and x indicates zero crossing of acceleration.

In Fig. 10 time differences between two zero crossings are 517 ms, 454 ms, and 373 ms. These correspond to 1.9 Hz, 2.2 Hz and 2.7 Hz. Velocities are in range of previous studies [12].

V. Conclusion

In this study we introduced combined frequency and time domain calculations of sleep features. Approach is based on calculating DFT of segment for frequency domain measures and band limited IDFT (as a sum of cosines) for time domain features. Formulas for time domain interpolation, first and second order derivates were also presented. Similar results could be obtained using filtering and numerical differentiation [11, 12] but presented approach could be useful in some cases.

With digital filtering also special attention has to be paid to different sampling rates of different studies which is not the case with the approach presented here. The needed DFT is readily available in multiple software packages and band limited IDFT is easily calculated as sum of cosines. In presented examples time domain reconstruction was done with fixed 1000 Hz rate. To reduce calculation velocity or

acceleration could be calculated at reduced rate and in case of desired duration between two zero crossings the interval could be evaluated at higher rate. In this study used bandwidth 0.5-6 Hz is likely not optimal either for REM detection or SWS detection. For REM detection higher e.g. 0-25 Hz [17] and for SWS detection lower e.g 0.5-2 Hz [12] could be better. Here single DFT values were used for time domain reconstruction but for longer signals closest DFT segments should be selected for reconstruction. In future work approach should be verified with e.g. detection of slow eye movements [14], saccades [15, 16, 17] or slow waves [11, 12].

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