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Adaptive Frequency Evaluation Method

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Introduction

The main task of the periodical signal frequency evaluation problem is characteristic signal point detection. Nature of a signal often could be changed by some digital operators [1, 2]. Evaluation the length in time between two the same characteristic extremum points is frequent choice for frequency determination.

There are a lot of applications there the frequency evaluation task must be done in a portable monitoring units. The example is physiological parameters monitoring system. Respiratory rate or heart rate evaluation is one of the tasks in the system. Low power consumption is one of the main requirements for portable systems [3] or devices. Therefore low computational load of the method is big advantage for such applications. It is also desirable the method could be easily implemented in a processors operating in fixed point arithmetic.

There is presented a method which could be applied for frequency of the periodical signal evaluation based on relatively long adaptive difference window. The length of the window takes significant part of the signal period.

Steps of frequency evaluation

Application of the frequency evaluation method highly depends on nature of the signal and the noise. There is presented the main steps of the method application:

1) Adaptive signal processing;
2) Extremum detection. Further steps are taken if extremum is found. Else the procedure is started in step 1;
3) Signal amplitude evaluation at extremum point;
4) Determination is the current peak useful signal peak or by noise.peak. Further steps are taken if extremum is signal peak. Else the procedure is started in step 1;
5) Determination of the threshold amplitude;
6) Determination the length of the difference window;
7) Adjustment the operators of adaptive processing.

Some steps could be skipped depending on signal nature.

Maximum or minimum detection

While extremum of the known function lies where its derivative is equal to zero

$$f'(x_0) = 0\,, \tag{1}$$

extremum of the sampled signal could be found

$$y(n-1) - y(n-2) \geq 0\,\hat{}\,y(n) - y(n-1) \geq 0 = true; \tag{2}$$

where y(n) – n^{th} sample of a signal; ˆ – logical operator of the exclusive disjunction.

Second derivative test could be applied for determination whether of a known function extremum point x_0 is local maximum: $f''(x_0) < 0$ or local minimum: $f''(x_0) > 0$. Maximum of the sampled signal could be found

$$y(n-1) - y(n-2) \geq 0 \,\&\, y(n) - y(n-1) < 0 = true \tag{3}$$

and minimum

$$y(n-1) - y(n-2) \leq 0 \,\&\, y(n) - y(n-1) > 0 = true\,, \tag{4}$$

where & – operator of the logical conjunction (when difference window length is one sample period).

Detection of the useful signal extrema becomes more reliable when relatively wide difference window is applied

$$y(n-1) - y(n-\Delta n-1) \geq 0\,\hat{}\,y(n) - y(n-\Delta n) \geq 0 = true\,, \tag{5}$$

where Δn is the length of the difference window expressed by a number of a sample periods. The length of the difference window must be chosen according to a length of the useful signal wave. It has to take a significant part of it.

Respiratory signal obtained by inductance plethysmography sensors [4] during motion is presented in Fig. 1 and Fig. 2.

Peaks induced by noise are detected with a short difference window (Fig. 1). When a difference window is relatively long (Fig. 2) and takes a significant part of the period, noise peaks are missed while peaks of the useful signal are detected.

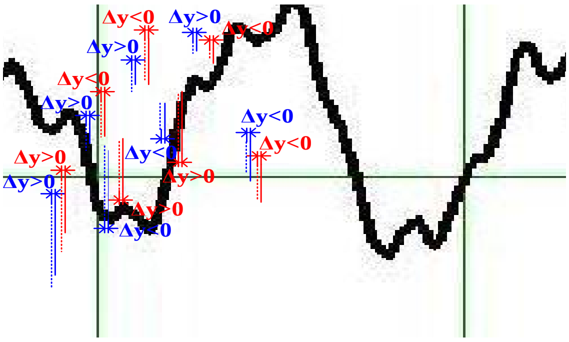

Fig. 1. Extremum detection by applying a narrow difference window

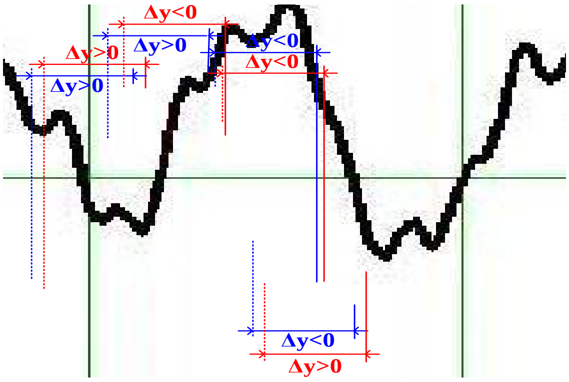

Fig. 2. Extrema detection by applying a wide difference window

The criteria of the difference window length determination could be the minimal time error of detection of the period where extremum lays. Let's assume the useful signal could be approximated by a sine wave. This approximation is close to reality for a respiratory signal gathered by inductance plethysmography sensor (Fig. 3).

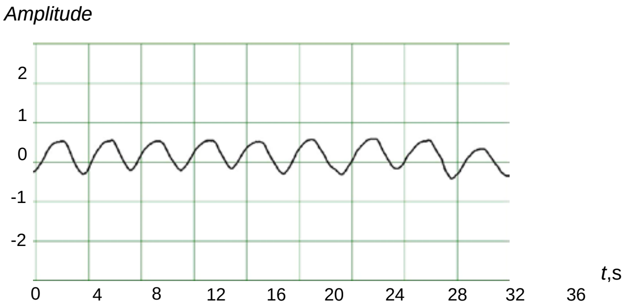

Fig. 3. Respiratory signal obtained by inductance plethysmography sensor during rest

Value of the difference window side values difference Δ could be expressed in a case a signal is approximated by a sine wave

$$\Delta = \sin(\omega t + \frac{\varphi}{2}) - \sin(\omega t - \frac{\varphi}{2}) , \qquad (6)$$

where φ is the length of the difference window.

The point where difference of side values of the difference window changes its sign from positive to negative could be expressed by difference

$$\Delta\Big|_{\omega t=\frac{\pi}{2}} = \sin(\omega t + \frac{\varphi}{2} + 2\pi n) - \sin(\omega t - \frac{\varphi}{2} + 2\pi n) , \qquad (7)$$

where n is integer value: n=0,1,2,3…

The fastest change of the difference window value is for the window length φ for which modulus of the derivative according to phase ωt of the expression 6 is equal to maximum

$$\left|\Delta'\Big|_{\omega t=\frac{\pi}{2}}\right| = \left|\cos(\omega t + \frac{\varphi}{2} + 2\pi n) - \cos(\omega t - \frac{\varphi}{2} + 2\pi n)\right| = \max. \qquad (8)$$

Maximal speed of difference Δ modulus change near maximum detection point is

$$\left|\Delta'\Big|_{\omega t=\frac{\pi}{2}}\right| = \max = 2 \qquad (9)$$

for a difference window length $\varphi = \pi$.

The optimal window length could be expressed by a number of sample periods

$$n_{\Delta} = \frac{T}{2T_s} = \frac{f_s}{2f} , \qquad (10)$$

where n_{Δ} – optimal signal length expressed by a number of sample periods; f – frequency of the signal (average); f_s – sample frequency, T – period of the signal (average) T_s – sample period.

Application of the difference window the length of which is half of the signal period could be restricted by a possible signal period change. Adaptive window could be used. Length of the window could be recalculated after detection of each characteristic point. Therefore the length of the difference window is restricted just by a possible maximum signal change during a period in this case.

Adaptive signal processing

The main task of the signal processing is noise suppression in many applications. The other application of the signal processing could be a change of a signal shape. In a case a signal characteristic point (extremum) lies on the wide signal wave noise suppression is the task. There is presented (Fig.4 and Fig. 5) noise of the respiratory signal obtained by inductance plethysmography sensor smoothing by a moving average filter.

In a case the characteristic signal point (extremum) lays on a sharp signal wave long difference window is not applicable. Therefore, signal processing could be used not just for noise suppression but for a change of the signal form also.

There is presented original ECG signal (Fig. 6) and processed ECG signal (Fig. 7) by applying band pass filter, derivative, squaring and moving window integration [5].

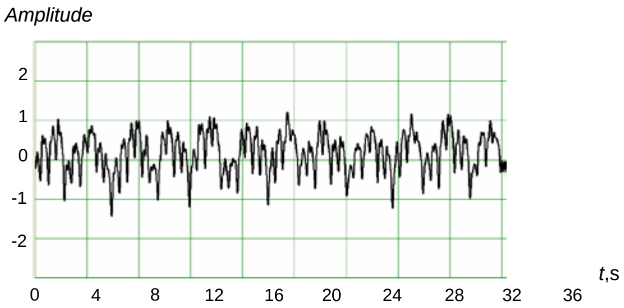

Fig. 4. Original respiratory signal obtained by inductance plethysmography sensor during motion

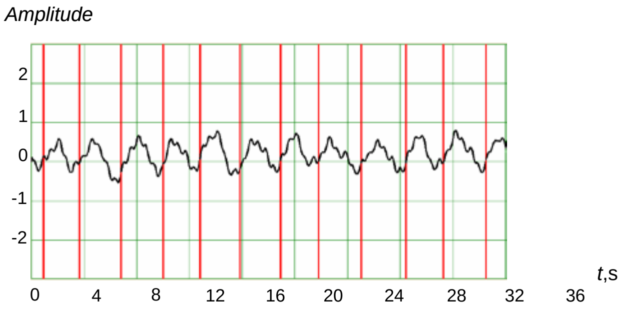

Fig. 5. Respiratory signal obtained by inductance plethysmography sensor (presented in Fig. 4) processed by moving average filter

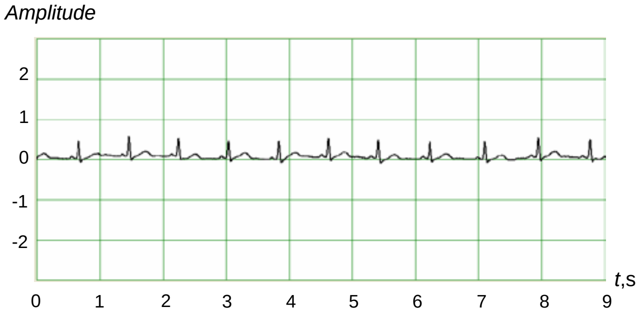

Fig. 6. ECG signal during rest

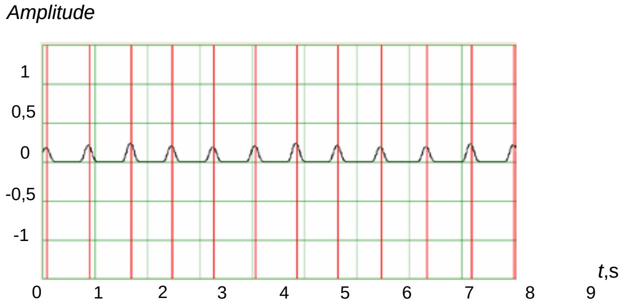

Fig. 7. Processed ECG (presented in Fig. 6) signal during rest

The processing is used for a noise filtering and for a change of the characteristic wave (QRS complex) shape (Fig. 8 and Fig. 9). QRS complex takes a significant part of the period (Fig. 7 and Fig. 9) in a processed signal therefore relatively wide difference window could be applied for a maximum detection. There are some peaks in a processed signal which are induced by a noise in both cases (Fig. 5 and Fig. 9), therefore some additional conditions could be evaluated for increasing a reliability of the method.

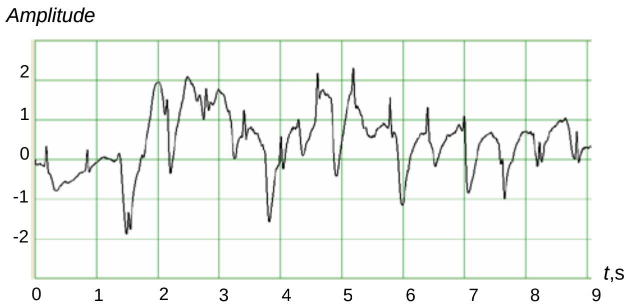

Fig. 8. ECG signal during motion

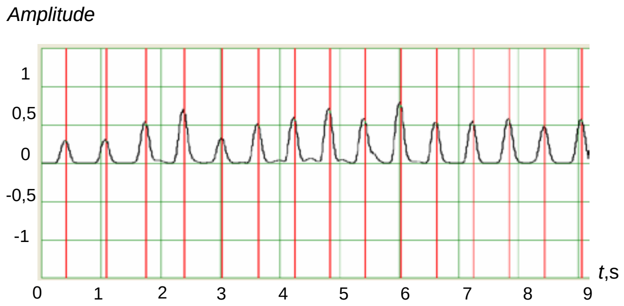

Fig. 9. Processed ECG (presented in Fig. 8) signal during motion

Evaluation of additional conditions

Some peaks caused by noise are present in a processed signal despite noise suppression. Amplitudes of the peaks are smaller in comparison to amplitudes of the peaks caused by useful signal after processing in many cases. Therefore amplitude evaluation could be made for improving reliability of the method.

Maximum and minimum detection for amplitude evaluation is essential for a signal where low frequency noise is present after signal processing. The example of the signal is respiratory signal obtained by inductance plethysmography sensor and processed by moving average filter. Amplitude of the peak signal could be found approximately

$$A = y\left(n_{\max} - \mathrm{round}\left(\frac{n_{\Delta\max}}{2}\right)\right) - \\ -y\left(n_{\min} - \mathrm{round}\left(\frac{n_{\Delta\min}}{2}\right)\right), \tag{11}$$

where $y(n)$ – the n$^{\text{th}}$ value of the signal; $n_{\max}$ – number of sample on which maximum detection condition is met; $n_{\min}$ – number of sample on which minimum detection condition is met; $n_{\Delta\max}$ – the length of the maximum detection difference window; $n_{\Delta\min}$ – the length of the minimum detection difference window; round – rounding to integer value function.

The amplitude could be evaluated by searching minimum and maximum values in respectively maximum detection and minimum detection windows

$$A = \max\ [y(n_{\max}), y(n_{\max}-1),\ldots,\ y(n_{\max}-n_{\Delta\max})] - \\ \min\ [y(n_{\min}), y(n_{\min}-1),\ldots,\ y(n_{\min}-n_{\Delta\min})], \tag{12}$$

where max – maximum value detection function; min – minimum value detection function.

Just amplitudes of the maximum values could be evaluated in a case a processed signal has no significant low frequency noise and peaks are positive sign (Fig. 9). To define is a peak caused by noise or is a peak caused by useful signal the peak is compared to a threshold value. Threshold must be adaptive in many cases of applications and could be formed from a number of previously detected peaks which are considered as useful signal peaks

$$A_{th}(k+1) = c_{th} \cdot \mathrm{TF}(A(k), A(k-1), ..., A(k-l)), \quad (13)$$

where $A_{th}(k+1)$ - threshold value will be used for next peak amplitude evaluation; c_{th} - threshold coefficient, depends on possible amplitude variation and noise level; TF – threshold formation function (median, average, combined median-average or other); $A(k)$ - amplitude of the k^{th} useful signal peak; l – length of an array applied for threshold formation.

The other mean to improve reliability of the method is application of blanking time after detection of each peak. Detection of the same type peak is forbidden immediately after peak detection for a time close to a minimal possible period. The minimal period is determined by maximal possible frequency of the measured process as for example maximal heart rate determined by refractory period or maximal possible respiratory rate.

Conclusions

Frequency evaluation of a periodical signal is common task in a variety kind of systems. Characteristic signal wave point detection also as Fourier transform is commonly used for frequency evaluation. Extremum of the specific signal wave of the original or processed signal is commonly a good choice of a characteristic signal point in many cases. Application of a relatively wide difference window for extremum detection is preferable, because it provides better robustness to higher frequency noise. Optimal width of the difference window could be chosen considering to maximal speed change of difference of the window side values. Application of the adaptive difference window, length of which depends on signal frequency is preferable. Preprocessing must be made to suppress noise or to change a shape of the characteristic signal wave form in some cases. Application of relatively wide difference window and other criterions as amplitude evaluation, blanking improves reliability.

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Frequency evaluation of the periodical signal which is affected by noise is common problem in a variety of the systems. Low frequency noise often could be very big in comparison to useful signal. Application of the infinity impulse response filters could be unacceptable in some cases because of the filters induced ripples. High order finite impulse filters are needed for sufficient suppression. Furthermore power consumption is important factor for portable battery powered devices. There is presented frequency evaluation method based on adaptive relatively wide difference window application for peaks detection and on amplitude evaluation. The method could be easy implemented in fixed point arithmetic. Ill. 9, bibl. 5 (in English; abstracts in English and Lithuanian).

R. Lukočius, J. A. Virbalis. Adaptyvus dažnio nustatymo metodas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 1(107). – P. 3–6.

Periodinio, triukšmų paveikto signalo dažnio nustatymo uždavinys yra aktualus daugeliui įvairių sistemų. Žemojo dažnio triukšmai neretai gali būti labai dideli, palyginti su naudingo signalo amplitude. Begalinės impulsinės reakcijos filtrai šiems triukšmams filtruoti tam tikrais atvejais negali būti naudojami dėl jų sukeliamų svyravimų. Pakankamam slopinimui pasiekti reikia aukštos eilės baigtinės impulsinės reakcijos filtrų. Mobiliems elementais ar baterijomis maitinamiems įtaisams svarbi metodo greitaveika. Straipsnyje pristatomas siūlomas periodinio signalo dažnio nustatymo metodas, pagrįstas adaptyviu santykinai plačiu skirtumų lango panaudojimu pikams aptikti ir amplitudės įvertinimu, kuris lengvai gali būti įgyvendintas fiksuoto kablelio forma veikiančiuose mikroprocesoriuose. Il. 9, bibl. 5 (anglų kalba; santraukos anglų ir lietuvių k.).