ANALOG WAVELET TRANSFORM EMPLOYING DYNAMIC TRANSLINEAR CIRCUITS FOR CARDIAC SIGNAL CHARACTERIZATION

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ABSTRACT

An analog QRS complex detection circuit, for pacemaker applications, based on the Wavelet Transform (WT) is presented. The system detects the wavelet modulus maxima of the QRS complex. It consists of a wavelet transform filter, an absolute value circuit, a peak detector and a comparator. In order to achieve the low-power requirement in pacemakers, we propose a new method for implementing the WT in an analog way by means of the Dynamic Translinear (DTL) circuit technique. Simulations indicate a good performance of the Wavelet Transform and the QRS complex detection. The resulting circuit operates from a 2-V supply voltage, dissipates at most 55nW per scale and can be fully integrated.

Keywords – Wavelet transform, dynamic translinear circuits, ECG characterization, analog electronics

1. INTRODUCTION

In [1], we proposed a method for implementing the WT in an analog way. An analog Gabor transform filter was proposed, of which the impulse response is an approximated Gaussian window function. This analog Gabor Transform filter, subsequently, was implemented with Complex First Order Systems (CFOS).

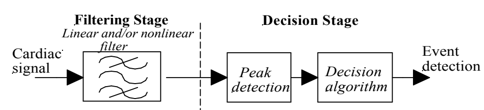
Since the Gaussian function is perfectly local in both time and frequency domains and is infinitely differentiable, a derivative of any order n of the Gaussian function may be a Wavelet Transform (WT). For cardiac signal characterization we are interested in the first derivative Gaussian wavelet function [2]. In this paper we propose a method for implementing the first derivative Gaussian Wavelet function by means of dynamic translinear circuits. Also we describe an algorithm an its circuit implementation based on local modulus maxima (i.e., both positive and negative peaks) point detection for ECG characterization.

Section 2 treats the characteristics of the QRS complex detection algorithm. Next, Section 3 describes the circuit design. Some results provided by simulations are shown in Section 4. Finally, Section 5 presents the conclusions.

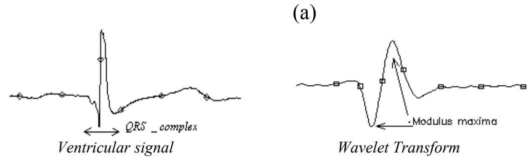
2. QRS DETECTION ALGORITHM

QRS complex detection is important for cardiac signal characterization [3]. Many systems have been designed in order to perform this task. In [4] it was shown that, in spite of the existence of different types, a basic structure is common for many algorithms. This common structure is given in Fig. 1a. It is divided into a filtering stage (comprising linear and/or nonlinear filtering) and a decision stage (comprising peak detection and decision logic).

The Wavelet has been shown to be a very efficient tool for local analysis of nonstationary and fast transient signals due to its good estimation of time and frequency localizations. This feature can be used to distinguish cardiac signal points from severe noise and interferences. Therefore, the algorithm detection of the QRS complex presented here is based on modulus maxima of the wavelet transform. The two maximas with opposite signs of the WT correspond to the complex QRS and are illustrated in Fig. 1b.



(a)



(b)

Fig. 1. (a)Block diagram of the basic structure of the QRS detectors [4]. (b) Cardiac signal and the modulus maxima of the WT

The main idea of the WT is to look at a signal at various windows and analyze it with various resolutions. It depends upon two parameters, being scale a and position τ. For smaller values of a, the wavelet is contracted in the time domain and gives information about the finer details of the signal. In the same way, a global view of the signal is obtained by larger values of this scale factor. Furthermore, in order to avoid redundancy, the scale

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parameter can be sampled along the dyadic sequence $(2^j)_{j\in Z}$, i.e., $a = 2^j$. The wavelet transform $C(t,a)$ of a function $x(t)$ is defined by the following equation

$$C(t,a) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t)\Psi^*\left(\frac{t-t}{a}\right)dt \quad (1)$$

The Wavelet analysis is performed by convoluting a signal, x(t), with a prototype function called mother wavelet, ψ(t). Gaussian functions are often used as mother wavelets since they provide the best resolution in time and in frequency (minimum time-frequency product, *DtDw*).

Often systems employing the WT are implemented using Digital Signal Processing (DSP). However, for pacemaker applications, it is not favourable to implement the WT by means of digital signal processing due to the high power consumption associated with the required A/D converter.

A promising technique for the design of ultra low power analog integrated circuits, that can be implemented without the need for resistors (these would become too large for on-chip integration) and presents a high functional density, is the one of Dynamic Translinear (DTL) circuits [5]. The DTL principle can be applied to the implementation of functions described by linear and nonlinear polynomial differential equations.

We thus propose a new method for implementing the WT in an analog way by means of dynamic translinear circuits.

3. CIRCUIT DESIGN

In this section we discuss the building block configuration of the basic setup depicted in Fig. 1. Its block diagram is given in Fig. 2 and contains the required circuits to design the system as outlined in Section 2.

At the input, a wavelet filter is situated which implements an approximation to the first derivative Gaussian WT. The complete filter comprises multiple scales in parallel in order to compute the WT in real time. From the characteristics of cardiac signals we have chosen to use the scales as defined in Table 2. Subsequently, the signal is fed through an absolute value circuit, followed by a peak detector, to generate an adjustable threshold level according to:

$$Thj = Abs - \frac{3}{4} Peak \quad (2)$$

with

$$\begin{cases} Peak = Abs & for \quad Abs \geq Peak \\ \dot{P}eak = -t . Peak & for \quad Abs < Peak \end{cases}$$

where *Thj* is the threshold value for scale a=2^j, *Abs* is the absolute value and *Peak* is the output value of the peak detector circuit. τ is the time constant of the peak detector and the dot represents differentiation with respect to time.

The final signal processing block is a comparator in order to detect the modulus maxima position of the QRS complex. The time localization of the modulus maxima and the classification of characteristic points of the cardiac signal is processed by the digital logic circuit, and will not be described here.

3.1 Filtering Stage

3.1.1 Wavelet Transform filter

We first propose an analog bandpass filter, of which the impulse response is an approximated first-derivative gaussian window function. In order to achieve this, we adapted the Wavelet Transform filter introduced in [1].

This filter has been implemented with a cascade of Complex First Order Systems (CFOS) [6]. The choice of the number of stages is based on Table 1, where *Dt* (time resolution), *Dw* (frequency resolution) and their product *DtDw* have been given for a cascade of *n* stages. An improvement in the approximation to a Gaussian function is obtained for an increase in the number of stages. However, this improvement will be at the expense of a larger noise contribution, or alternatively, a larger current consumption to overcome the effects of accumulation of noise.

n	Δt	Δω	ΔtΔω
1	0.7068	1.3732	0.9705
2	0.6124	1.1544	0.7069
3	0.5773	1.0954	0.6323
5	0.5477	1.0541	0.5773
11	0.5222	1.0235	0.5344
50	0.5050	1.005	0.5075
Gaussian	0.5	1	0.5

Tab. 1. Number of stages versus time-bandwidth product

We apply the DTL circuit technique to the design of the analog implementation of the WT. In Fig.3, the equivalent dynamic translinear circuit for realization of a CFOS is depicted. The related expressions are given by

$$\dot{I}_{x\_re} = \frac{I_o}{CU_T} I_{x\_re} - \frac{I_o}{CU_T} I_{x\_im} + \frac{I_o}{CU_T} I_{u\_re} \quad (3a)$$

$$\dot{I}_{x\_im} = \frac{I_o}{CU_T} I_{x\_im} + \frac{I_o}{CU_T} I_{x\_re} + \frac{I_o}{CU_T} I_{u\_im} \quad (3b)$$

where I_{u_re} is the real input signal, I_{u_im} is the imaginary input signal; I_{x_re} and I_{x_im} represent the real and imaginary part of the output signal, respectively. In order to implement a Wavelet Transform, we need to be able to scale and shift this Gaussian function in time. By changing the values of the capacitance *C* accordingly we implement short windows at high frequencies and long windows at low frequencies.

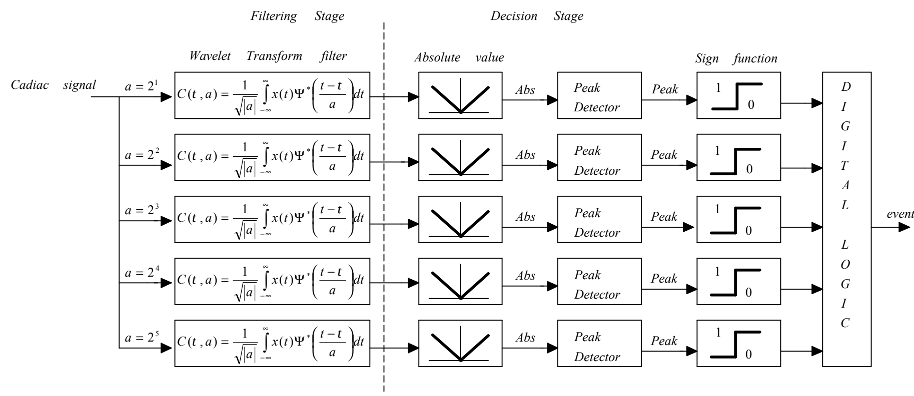

Fig. 2. Block diagram of the wavelet system

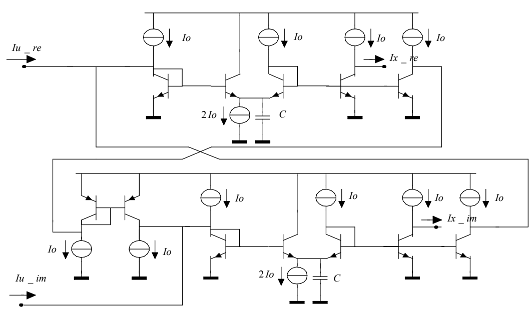

Fig. 3. Equivalent DTL circuit for complex input for the analog CFOS stages.

3.2 Decision Stage

3.2.1 Absolute value circuit

Fig. 4a. shows a simple circuit [7] to implement an absolute value function. Its operation is given as follows: when *Iin* is positive, it is handled by current-mirror Q1-Q2; when negative, it is conveyed to the summation node *S* by cascode transistor Q3. The bias voltage at the base of Q3 is obtained by the two diode-connected transistors Q4 and Q5.

3.2.2 Peak detector

The basic design of the employed peak detector is shown in Fig. 4b. Its operation is as follows: When $I_{in} > I_{c,Q1}$ (collector current of Q1), capacitor C is rapidly charged by Q4 until $I_{in} = I_{c,Q1}$. For $I_{in} < I_{c,Q1}$, C is discharged by the rather small base current of Q3.

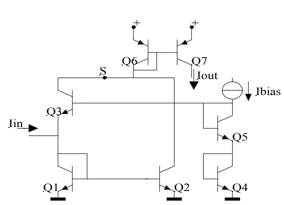

Fig. 4a. Absolute value circuit.

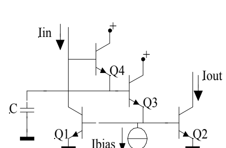

Fig. 4b. Peak detector circuit.

3.2.3 Comparator (Sign function) circuit

Since TL circuits can implement polynomial functions only, we first need to approximate the Sign function by a polynomial function. A static translinear loop equation to achieve a good approximation to the Sign function is described by [8]:

$$(I_o+I_{in})(I_o-I_{out})(I_o+I_{out})=(I_o-I_{in})(I_o-I_{out})(I_0+I_{out}) \quad (4)$$

yielding

$$\begin{cases} Iout = 0 & if \quad Iin < 0 \\ Iout = Io & if \quad Iin > 0 \end{cases}$$

Its corresponding TL circuit is given in Fig. 5.

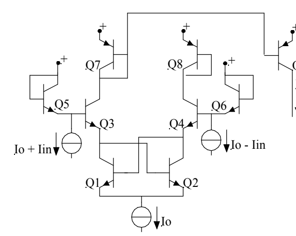

Fig. 5. Comparator circuit.

4. SIMULATION RESULTS

To validate the above QRS complex detector, the whole circuit has been simulated using models of our in-house bipolar semi-custom IC process SIC3A [9]. Typical transistor parameters are $f_{T,\text{npn,max}}$ = 15GHz and $\beta_{F,\text{npn}}$ = 150 (smallest emitter size). The circuit has been designed to operate from a 2-V supply voltage.

Fig 6. shows the impulse response of the wavelet filter with 3 CFOS stages. The number of stages has been chosen by trading time-frequency resolution (Table 1) for power consumption and noise contribution. For cardiac signal characterization, we are interested in the approximation to a first derivative Gaussian function, which is present in the imaginary output. As described above, the wavelet transform can be obtained by just scaling the impulse response of the filter in time. This is done by simply controlling the capacitance value C, or, alternatively, the control current *Io* in Fig. 3. The resulting capacitances range from 27.5pF to 440pF in a set of integral powers of 2 (dyadic scales). The value of current *Io* equals 0.5nA. The wavelet pass bands are shown in Table 2.

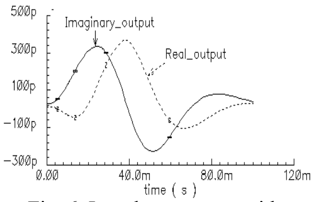

Fig. 6. Impulse response with 3 CFOS stages

Scale a	Capac. C (F)	Center Freq. (Hz)
2^1	27.5p	115,74
2^2	55p	57,86
2^3	110p	28,93
2^4	220p	14,46
2^5	440p	7,23

Tab. 2. Frequency response of the Wavelet at dyadic scale

The DC response of the absolute value circuit is given in Fig.7a. $|I_{in}|$ is also shown, for reference purposes. In Fig. 7b, the DC transfer of the comparator circuit, with *Io* equal to 0.5nA, is shown. The transient responses of the absolute value and the peak detector circuits are provided in Fig. 7c, respectively, for a ventricular signal at the absolute circuit input.

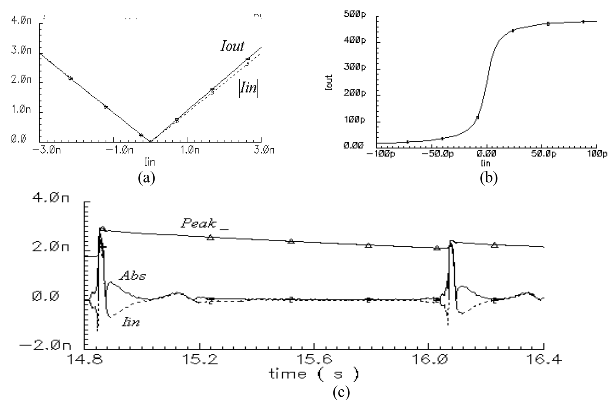

Fig. 7. (a) DC Response of the absolute value circuit (b) DC Response of the comparator (c) Transient response of the absolute value and peak detector circuits with a ventricular signal at the input.

Finally, in order to verify the performance and efficiency of the whole system, a set of cardiac signals was applied to the input of the system. Fig.8b shows a typical ventricular signal with 50Hz interference (input signal) and in Fig.8c gives the wavelet transform at various scales. We can see in Fig.8d that the modulus maxima of the QRS complex for a specific scale (a=2^4) of the WT indeed have been detected. The total power consumption is 55nW per scale.

5. CONCLUSIONS

A new QRS complex detection circuit for pacemaker applications has been proposed. The circuit is based on the Wavelet transform. WT provides multiscale information and thus is an efficient tool for local analysis of nonstationary signals, especially for processing biomedical signals. An analog circuit has been designed,

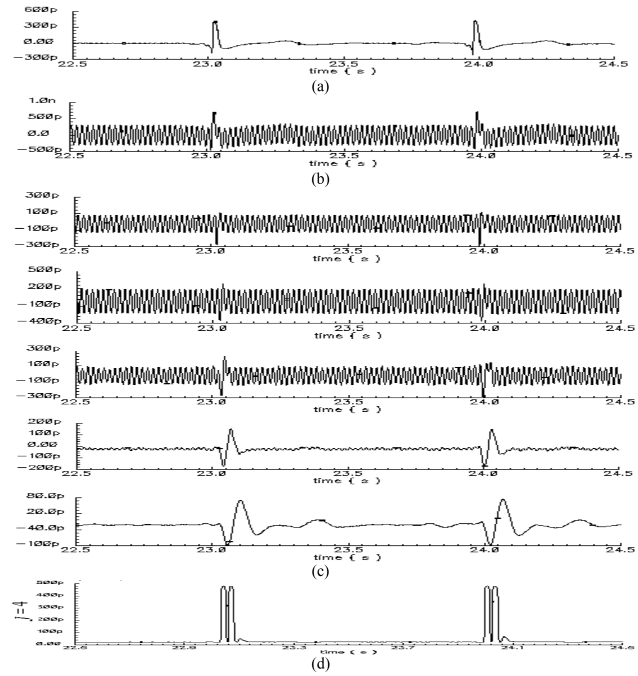

Fig. 8. (a)Ventricular signal (b)Ventricular signal with 50Hz interference (c) the wavelet transform at five subsequent scales (d) QRS complex modulus maxima detection for j=4.

applying the Dynamic Translinear principle, to match the need for an ultra low-power system. The whole system operates from a 2-V supply voltage and dissipates 55nW. The obtained results for a typical cardiac signal demonstrate a good performance in generating the desired Wavelet Transform and achieving correct QRS complex detection.

6. REFERENCES

[1] S. A. P. Haddad and W. A. Serdijn, "Mapping the Wavelet Transform onto silicon: the Dynamic Translinear approach," *Proceedings IEEE International Symposium Circuits & Systems*, vol. 5, pp. 621-624, May 2002.

[2] J.S. Sahambi, S.N. Tandon and R.K.P. Bhatt, "Using Wavelet Transform for ECG Characterization," *IEEE Eng. in Medicine and Biology*, pp. 77-83, Jan/Feb. 1997.

[3] Cuiwei Li, C. Zheng and C. Tai, "Detection of the ECG characteristics points using wavelet transform," *IEEE Trans. Biomed. Eng.*, vol. 42, no.1, pp. 21-28, Jan. 1995.

[4] B. Kohler, C. Hennig and R. Orglmeister, "The Principles of Software QRS Detection," *IEEE Eng. in Medicine and Biology*, pp. 42-57, Jan/Feb. 2002.

[5] J. Mulder, A. C. van der Woerd, W. A. Serdijn, and A. H. M. van Roermund, "Dynamic translinear circuits – An overview", in Proc. *ISIC*, Singapore, Sept. 10-12, 1997, pp.31-38.

[6] H. Kamada and N. Aoshima, "Analog Gabor Transform Filter with Complex First Order System," in Proc. *SICE*, 1997, pp.925-930.

[7] B. Gilbert, "Current-mode circuits from a translinear viewpoint: a tutorial," Chapter 2 in C. Toumazou, F. J. Lidgey and D. G. Haigh (editors), "Analogue IC design: the current-mode approach," *IEE circuits and systems series 2*, *Peter Peregrinus,* 1990.

[8] E. Seevinck, "Analysis and synthesis of translinear integrated circuits," *Elsevier*, Amsterdam, 1988.

[9] W. Straver, "Design Manual – SIC3A", Internal Report, Delft University of Technology, January 1999.