MODERN METHODS OF BIOSIGNAL DATA PROCESSING IN MATLAB ENVIROMENT

M. Penhaker

VSB - Technical University of Ostrava, FEI, K450

Abstract

The aim of this work, whose interim results were published in previous years, has been mastering mathematical wavelet transform and techniques of application software in MATLAB. Signal processing based on wavelet transformation, which transforms the signal in time domain signal at about half the number of values at the same time interval allows for a suitably chosen transformation based signal compression. The advantage of this method can be used for archiving and data transfer speed and the communication cost savings for expensive storage media, which. The advantage of this transformation is very little loss of information during compression and subsequent decompression, which can also be applied to multiple signals.

1 Discreet Wavelet Transform

Analogous as discreet Fourier transform the algorithm was created that solves wavelet transform of discreet signals and it is called discreet wavelet transform (DWT). The discreet wavelet transform could be created by multidesintegration.

We could see the DWT as a matrix formula in which the calculation is base on the multiplication of vectors of data matrix coefficients of wavelet base. If we use the method of the multidesintegration then we can divide the signal in two parts (wavelet coefficients) namely on the compressed signal and orthogonal complement.

DWT enables to divide the signal into two parts namely on the part with the low frequency - approximate s_1 and on the apart with the high frequency – detailed (complementary) d_1. The proceeding is possible to repeat in this way that we transform the approximate part and we obtain the parts of the second stage s_2 a d_2. When we repeat the proceeding we obtain then parts of another levels. The result is one approximate supporting signal and a lot of detail components. By the reverse proceeding we can make the synthesis of the original signal.

This transform enables during the reverse syntheses some of data omit. For example if the signal contains the noise of the high frequency it is possible to filter it off during the reverse synthesis .WT enables to find out this part in which we want the noise to filtr off and it is the difference from another methods for noise filtration. Then it is not need put the whole signal through filtration. It is very advantageous at these signals where noise is created only in the transient section.

For the selected area exists infinite many wavelet bases that must fulfilled of course some conditions to be possible to calculate the reverse transformation of the signal. Generally is possible to say that wavelet bases must fulfilled the condition of existence of inverse transformation with the possibility of reconstruction of the original signal.

The advantage is also this that we could use this transform to the compression of one-dimensional signals. During the reverse synthesis is possible complements to set to zero. The threshold of sensitivity is possible to set according the demanded level of resolution. The technology of signal compression with the help of DWT is used for saving space on computer discs and for the acceleration of transmission for Internet or local nets. For guarantee of reverse transform with the possibility of reconstruction of the original signal wavelet must fulfilled the condition of orthogonality and it is calculated from the dilatation formula $\phi(x)$.

$$\phi(x) = \sum_{k=0}^{M-1} c_k . \phi(2.x - k) \tag{1}$$

$$\psi(x)=\sum_{k=0}^{M-1}(-1)^k h_{1-k}\phi(2x-k) \qquad (2)$$

where :

$\phi(x)$	dilatation function
$\psi(x)$	transform function (basic – maternal wavelet)
k	wavelet order
c_k	scale coefficients of filtration which warrants the orthonormality
M	Number of nonzero coefficients of wavelet base

Among the well-known wavelet bases belong Rademacher, Haar, Walsh, Walsh modified and Daubechies. The example of dilatation formula for determination Daubechies base about four coefficients l_0, l_1, l_2, l_3 is following:

$$\phi(t)=l_0.\phi(2t)+l_1.\phi(2t-1)+l_2.\phi(2t-2)+l_3.\phi(2t-3) \qquad (3)$$

In the paper are described only the chosen bases which I work with and which I realize for further use on the computer in MATLAB environment.

1.1 Principle of Multi Dissociation

For the calculation of DWT some effective techniques were created and in practice is the most used the pyramidal algorithms of dissociation.This dissociation works with the final number of samples and their number is the exponent of 2 - $N=2^n$. The calculation of multi dissociation begins with transform matrix generation. It contains the coefficients of the base.

Transform base is at first applied on the original vector about the length N values. The result is a data vector with number N/2 values which contains low frequencies and vector, which contains high frequencies (supplement). In the next step is data vector with number N/2 values again dissociated on the new data vector with number N/4 values and the new vector supplement with number N/4 values.

For creation of wavelet transform is possible to use every one of mentioned bases. As example is shown Haar window (H) at the shifting from one level of Rademacher base (RB) to the another one. In theory it is speaking about Haar base, but in the reality we work with Haar window and Rademacher base. Important is that during the multi dissociation every frequency level is analysed RB. Process of transform (multi dissociation)of signal during the shifting from lower level to the higher one we can write by the following matrix register.

$$Y_{m+1}=\mathbf{P}_m Y_m+\mathbf{Q}_m Y_m \qquad (4)$$

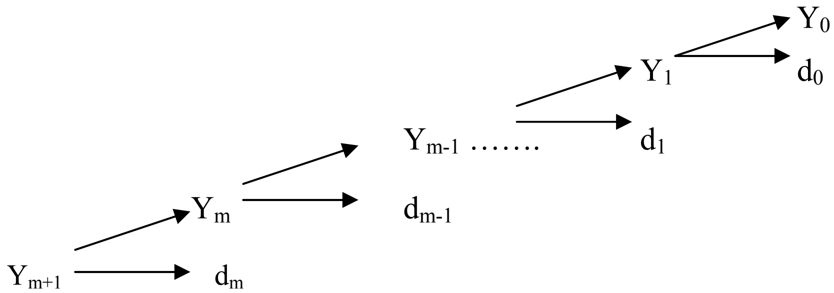
E.g. During the shifting from one level to the another:

$$Y_2=\mathbf{P}_1 Y+\mathbf{Q}_1 Y=(\mathbf{P}_1+\mathbf{Q}_1)Y \Rightarrow Y_1=(\mathbf{P}_1+\mathbf{Q}_1)^{-1}Y_2=\mathbf{M}^{-1}Y_2 \qquad (5)$$

where: Y_m transform signal on level m

$\mathbf{P}_m,\mathbf{Q}_m$ matrix forming transform base

Multi dissociation of signals is possible to demonstrate in this way :



Here: $Y_{m+1}=Y_m+d_m$, $m=n-1,..,1,0;$

where: m index of frequency (transform) level

Y_m compressed signal on the level m

d_m orthogonal supplement on the level m

$$Y_m = \mathbf{P}_m Y_{m+1} \quad , \quad d_m = \mathbf{Q}_m Y_{m+1}$$
$$\mathbf{Q}_m = \mathbf{P}_{m+1} - \mathbf{P}_m \tag{6}$$

At the calculation of wavelet transform (multi dissociation) input data vector is dissociated on the new data and supplement. We are therefore interested in projection coefficients **P** and **Q**.

In matrix way it is possible the process of compression to express:

$$\begin{bmatrix} y^1 \\ d^1 \end{bmatrix} = \begin{bmatrix} \mathbf{H} \\ \mathbf{Q} \end{bmatrix} \cdot y = \mathbf{M} \cdot y \tag{7}$$

For reconstruction (decompression) of original signal:

$$y = \mathbf{M}^T \cdot \begin{bmatrix} y^1 \\ d^1 \end{bmatrix} \tag{8}$$

Matrix M is created by the matrixes **P** and **Q**, coefficients of matrix **M** warrants orthonormality. For Haar base we mark matrix **P** → **H.** For Matrix $\mathbf{M} = \begin{pmatrix} \mathbf{H} \\ \mathbf{Q} \end{pmatrix}$ for Haar base n -th level has the form:

$$\mathbf{H} = \begin{bmatrix} h_0 & h_1 & h_2 & h_3 & \cdot & \cdot & h_n & 0 & 0 & 0 & 0 & \cdot & \cdot & 0 \\ 0 & 0 & h_0 & h_1 & h_2 & h_3 & \cdot & \cdot & h_n & 0 & 0 & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & \cdot & \cdot & 0 & h_0 & h_1 & h_2 & h_3 & \cdot & \cdot & h_n \\ h_{n-1} & h_n & 0 & 0 & \cdot & \cdot & 0 & 0 & 0 & h_0 & h_1 & \cdot & \cdot & h_{n-2} \end{bmatrix} \tag{9}$$

Matrix $\mathbf{P}_m$ is created directly by the coefficients of the transform Haar base h_n. Matrix $\mathbf{Q}_m$ is created by coefficient q_n, that we determine from the reason of orthogonality according the relation (21).

$$q_n = (-1)^n . h_{3-n} \tag{10}$$

Original data vector is gradually transformed into minimal number of points in the relation of window magnitude of maternal wavelet.

The calculation of the inverse DWT is analogical as at direct transform. To the transformed data vector we allocate vector of supplements and with this vector we multiply the inverse transform matrix. We shall get the decompressed data vector with twofold number of points ad to it we assign relevant complement. The process we repeat till we have the original data vector.

For the backward transform pays the similar matrix record:

$$Y_{m+1} = \mathbf{M}^T . Y_m \tag{11}$$

Schematic exhibit of the calculation of DWT we show in an example:

We think over the input data vector Y=(3, 1, 6, 2, 3, 7, 9, 5). We transform the vector with the help of Haar base with two coefficients.

At first we create matrix $\mathbf{M} = \begin{pmatrix} \mathbf{H} \\ \mathbf{Q} \end{pmatrix}$, that will be created by matrix **H** and Matrix **Q**.

The first four lines will contained vector (1 1) matrix **H** shifting themselves about the length of vector in matrix M and further for lines will be coefficients of the matrix **Q** determined from the relation (20). According the relation (14) we determine the compressed data vector Y_2.

$$Y_2 = \frac{1}{2}\begin{pmatrix} \mathbf{H}_2 \\ \mathbf{Q}_2 \end{pmatrix}.Y = \frac{1}{2}\begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{pmatrix}\begin{pmatrix} 3 \\ 1 \\ 6 \\ 2 \\ 3 \\ 7 \\ 9 \\ 5 \end{pmatrix} = \begin{pmatrix} 2 \\ 4 \\ 5 \\ 7 \\ 1 \\ 2 \\ -2 \\ 2 \end{pmatrix}$$

We obtained data vector Y_2 that contained compressed data vector (2,4,5,7) and

supplement (1,2,–2,2). In the next step of compression we can compressed data vector put through further transformation.

$$Y_1 = \frac{1}{2}\begin{pmatrix} \mathbf{H}_1 \\ \mathbf{Q}_1 \end{pmatrix}.Y_2 = \frac{1}{2}\begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \end{pmatrix}\begin{pmatrix} 2 \\ 4 \\ 5 \\ 7 \end{pmatrix} = \begin{pmatrix} 3 \\ 6 \\ -1 \\ -1 \end{pmatrix}$$

We obtained data vector Y_1 that contains compressed data vector (3,6) and supplement (-1,–1).

For reverse transformation holds : $Y_{m+1} = \mathbf{M}_m^T.Y_m$

$$Y_2 = \begin{pmatrix} \mathbf{H}_1 \\ \mathbf{Q}_1 \end{pmatrix}^T.Y_1 = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & -1 \end{pmatrix}\begin{pmatrix} 3 \\ 6 \\ -1 \\ -1 \end{pmatrix} = \begin{pmatrix} 2 \\ 4 \\ 5 \\ 7 \end{pmatrix}$$

$$Y_3 = Y = \begin{pmatrix} \mathbf{H}_2 \\ \mathbf{Q}_2 \end{pmatrix}^T.Y_2 = \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \end{pmatrix}\begin{pmatrix} 2 \\ 4 \\ 5 \\ 7 \\ 1 \\ 2 \\ -2 \\ 2 \end{pmatrix} = \begin{pmatrix} 3 \\ 1 \\ 6 \\ 2 \\ 3 \\ 7 \\ 9 \\ 5 \end{pmatrix}$$

By this calculation of the reverse DWT we obtained the original data vector Y.

2 Implementation Wavelet Transform

For verification of proceedings at application DWT the original library of some functions was suggested and realized in the program MATLAB that solves direct and reverse wavelet transform with the use of various maternal wavelet (bases). The part of this library is original graphical users program Bioeave for analysis and elaboration of the pulse wave that uses functions of this library and enables transformed signals of pulse wave to analyze by the classical mathematical and statistical methods.

Program Biowave enables :

- use of Daubechies, Haar, Walsch-Paley and Walsh-Paley modified base
- choice of various signals (noise, rectangle, EEG signal, self signal)
- choice of the length of the input signal 64 - 4096 values
- choice of the length of vector base: 1 ,2, 4, 8 values
- choice for option to elimination of periodicity (at Daubechies base) display FFT signals and wavelets
- choice of the option of type of wavelet filtration(hard, soft, kvantil, universal)
- display of polygons, scalograms AKF, PSD

2.1 Walsh-Paleyho Modificated Base

Another system, which is added to the toolbox, the original Walsh-Paleyho modified base This base takes advantage Rademacherovy and Walsh system is a system we call the modified Walsh system. While Walsh basis was published until the 20th years of this modified base is mentioned in connection with applications in communications technology since 1905. The advantage of this network is that it is based on an index plus a complete line matrix agrees with the number of zeros. This can be based on a recurrent basis Walsh of the formula:

$$W_n^* = W_{2j+p}(x) = W_j(2x) + (-1)^{j+p} . W_j^*(2x-1) \qquad (12)$$

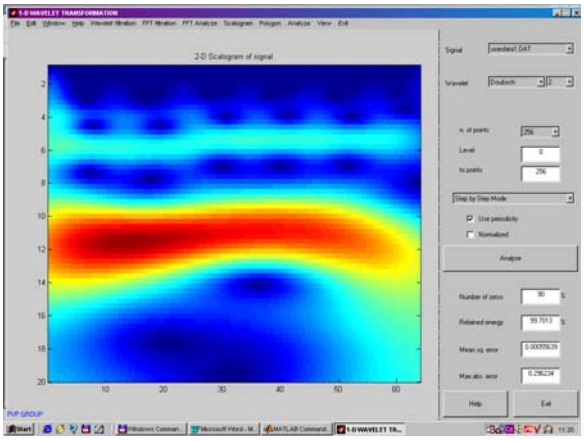


Figure 1: 2D Scalogram of pulse displacement curves record

3 Signal Processing in MATLAB

The Wavelet transform I have used in this study for the filtration of plethysmografycal record (PZ) to eliminate possible failures and inaccuracy during the scanning. The compress quality of wavelet transform I then utilised for the saving of archive space for data storage on recording mediums.

Therefore I must the acquired PZ to compress with various types of transform bases into various depth (compression to 1/2, 1/4, 1/8 a 1/16 of the original signal length), without use of filtration (zeroing). Then it was also need to determine the suitable zeroising in the relation on the type (hard, soft, kvantil, universal) and various sizes (60%, 80% a 100%).

I divided the task into three basic parts :

- Compression of the signal
- filtration of signal

- filtration and following compression of signal

It was a task to find out the best type of transform base for the compression of the signal, at the filtration the best type of zeroing (also the magnitude of zeroing) and in the end to integrate filtration and compression to save storage space on the disc. The graphical results of the transformation of the plethysmografycal record were consulted with physician. In Cupertino with the physician I had chosen as the maximum compression (at which is the signal for physician well readable – not distort) on 1/4 of its original length with the use of Daubechies base of the 2. Grade (D2). For filtration I had chosen the kvantil zeroing with the magnitude 90% - 100 % at base D8 namely at all compressions (1/2, 1/4, 1/8), from that the compression was set and the signal was decompressed. At 1/16 the distortion was manifested , and the physician could made the false diagnosis. It is why are rather better 1/2, 1/4 a 1/8.

If we want to conclude, the best from physician point of view is:

- compression D2 to 1/4
- kvantil zeroing with magnitude 90% - 100%at base D8

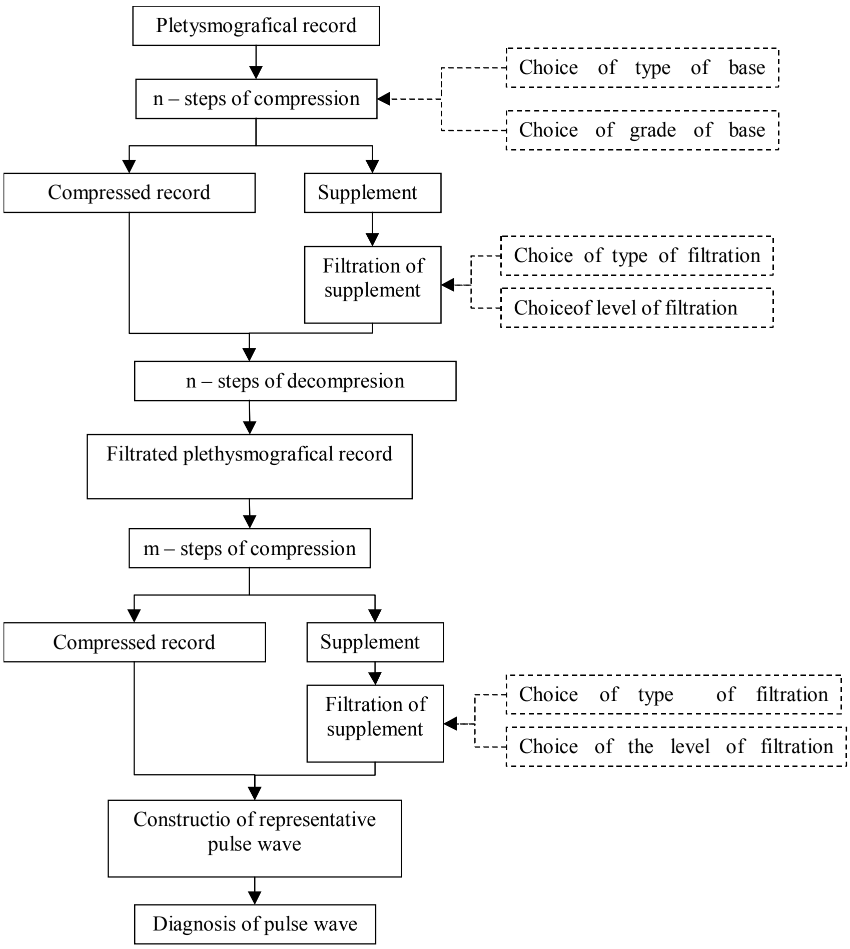


Figure 2: Diagram of evaluation of plethysmografycal record by wavelet transformation

Diagram of evaluation of plethysmografical by wavelet transform (fig. 4) contains the construction of representative pulse wave until the end because during the transformation rises distortion in some initial points of evaluated signal and it depends on the type of used base and it could affect the form of the resulting pulse wave. Therefore in contrast from the scheme of evaluation plethysmografycal record in time domain is better as a transformed signal to choose the whole plethysmografycal record and after the processing by wavelet transform then the representative course of pulse wave to create. The entire processing I did with plethymografycal record its length is given in the number of points and not in seconds what is in virtue of discretisation. For these purposes it is more advantageous. Finally I can the number of points transfer on a time scale in seconds with the help of sampling frequency that is 100 points.s^{-1}, e.g.512 points is 5,12 s.

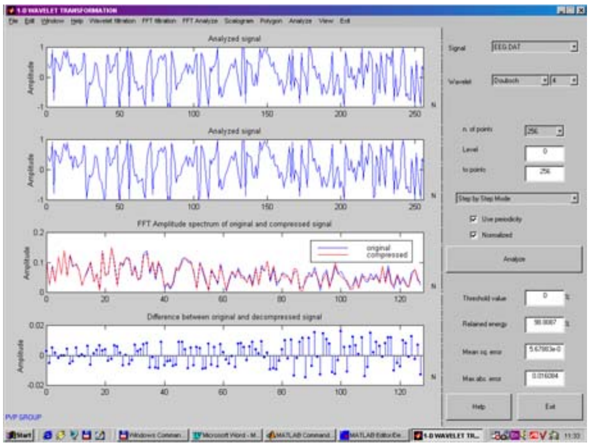


Figure 3: Front panel Biowave

3.1 The choice of the suitable base

The transformation was applied on a signal of pulse wave with the characteristic vector with the length 512 . Wavelet transform was applied on the signal with base:

- Daubechies
- Haar
- Walsh - Paleye

Results of compression and decompression of particular signals are shown in Diagram and the compression was done on the one quarter of original length.

During the evaluation of signal compression it is not possible to check the quality only according the numeric values of particular parameters but it is also very important to evaluate it by eye of an expert. Such evaluation is also very important at all medical records.

It is evident that results for Daubechies bases grade 4 give the best numeric results during the processing of the pulse wave. From it appears the applicability of its use for further processing. Even the expert verified this fact.

I applied those bases :

- Daubechies: D2, D4, D8
- Haar: H1, H2, H4
- Walsh-Paley: W-P2, W-P4, W-P8
- Walsh-Paley modified: W-Pm2, W-Pm4, W-Pm8

Number at base means the level of base (e.g.. D2 means that the base is 4 values). In diagrams is also visible suppression or the use of periodicity of signal in the next period. At bases Walsh-Paley and Walsh-Paley modified suppression of periodicity is not used thanks to the difference of matrix coefficients structure. For Daubechies base coefficients c_n of filtration are tabulated.

WT makes decomposition on signal components and the result of the transformation is the signal on length 1/2 of original signal it is 256 points PV and supplement on length 256 points as well. The results of compression and decompression of particular signals are shown in diagram 4 - 7, whereas the compression of the signal was done on the 1/4 of its original length it is on 128 points.The supplement in this case did not underwent any of filtration methods.

In the chart are these parameters: retained energy (E_r) (25), maximum error at comparing of original and decompressed signal (ε_{max}) (23), standard deviation σ (24).

$$\varepsilon_{max} = \max\left(|X|\right) \tag{13}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2} \tag{14}$$

$$E_r = \left(1 - \frac{\sum_{i=1}^{N}(X_i)^2}{\sum_{i=1}^{N}(Y_i)^2}\right).100\ [\%] \qquad (15)$$

where:

X_i	difference between original and decompressed signal
Y	original signal
N	number of values of PV record

Table 1: RESULTS OF COMPRESSION BY DAUBECHIES BASE

Base	*D 2*			*D 4*			*D 8*		
Pulse wave	*Er [%]*	*εmax [mV]*	*σ [mV]*	*Er [%]*	*εmax [mV]*	*σ [mV]*	*Er [%]*	*εmax [mV]*	*σ [mV]*
Original	*99,86*	*0,17*	*0,0*	*99,99*	*0,03*	*0*	*99,99*	*0,005*	*0*
Normed	*99,82*	*0,31*	*0,0*	*99,92*	*0,13*	*0*	*99,99*	*0,024*	*0*
Original with periodicity	*99,72*	*0,29*	*0,0*	*98,76*	*0,53*	*e-7*	*96,58*	*0,621*	*0,006*
Normed with periodicity	*98,77*	*0,86*	*0,0*	*95,09*	*1,06*	*e-06*	*90,51*	*1,004*	*0,015*

At Daubechies transform base is the original signal without use of periodicity after the reverse decompression very little distorted. It pays before all at Daubechies base of the 2nd level.

At compression and decompression the transform matrix W was arranged into form in which the base inhibits the periodicity of the signal. Numeric results are shown in the first two lines of the chart. In the third and fourth lines matrix W was arranged in this way not to suppress the periodicity of signal.

Results from decompression with the use of Haar, Walsch-Paley and Walsch-Paley modified base are the same as at base H1, then retained energy = 100%, maximum error and standard deviation is place value of about 10^{-6} [mV], this error is caused by rounding of numbers during the calculations done by computer. These bases are not suitable for processing of compressed signal of pulse wave because they exhibits big distortion of its course.

From the text is visible that the results for Daubechies base of the level 2 do not have otherwise the best number results during the processing of pulse wave but after the consultation with the physician it was chosen as suitable. From it results that is possible to use it for further processing.

Conclusion

The use of toolboxes and applications developed for the use and knowledge of the wavelet transformation in the teaching fields of biomedical engineering. Practical use is mainly in a new perspective on the analysis of bio-signals. New findings were used in establishing a program for automatic evaluation of pulse volume curve, electrocardiogram and electroencephalogram. The programming environment including toolbox functions are freely modifiable and also allow a suitable graphical user comfort

Acknowledgement

The work and the contribution were supported by the project: Ministry of Education of the Czech Republic under Project 1M0567 “Centre of Applied Cybernetics”, Student grant agency SV 4501141 “Biomedical engineering systems VII” and TACR TA01010632 “SCADA system for control and measurement of process in real time”. Also supported by project MSM6198910027 Consuming Computer Simulation and Optimization. This paper has been elaborated in the framework of the

IT4Innovations Centre of Excellence project, reg. no. CZ.1.05/1.1.00/02.0070 supported by Operational Programme 'Research and Development for Innovations' funded by Structural Funds of the European Union and state budget of the Czech Republic.

References

[1] O. Krejcar, *Problem Solving of Low Data Throughput on Mobile Devices by Artefacts Prebuffering*. EURASIP Journal on Wireless Communications and Networking, 2009, Article ID 802523, 8 pages. Hindawi publishing corp., New York, USA, DOI 10.1155/2009/802523

[2] Kasik, V., Stankus, M.: *Graphical development system design for creating the FPGA-based applications in biomedicine*. XII Mediterranean Conference on Medical and Biological Engineering and Computing 2010. IFMBE Proceedings, 2010, Volume 29, Part 5, pp. 879-882, DOI: 10.1007/978-3-642-13039-7_222.

[3] Stankus, M., Penhaker, M., Srovnal, V., Cerny, M., Kasik, V.: *Security and reliability of data transmissions in biotelemetric system.* XII Mediterranean Conference on Medical and Biological Engineering and Computing 2010. IFMBE Proceedings, 2010, Volume 29, Part 2, pp. 216-219, DOI: 10.1007/978-3-642-13039-7_54.

[4] O. Krejcar, D. Janckulik, L. Motalova, Complex Biomedical System with Biotelemetric Monitoring of Life Functions. In Proceedings of the IEEE Eurocon 2009, May 18-23, 2009, St. Petersburg, Russia. pp. 138-141. DOI 10.1109/EURCON.2009.5167618

[5] Machacek, Z, Hajovsky, R., Ozana, S., Krnavek, J., "Experiments of Thermal Fields of Sensors Supported by Digital Image Processing", In 2008 MEDITERRANEAN CONFERENCE ON CONTROL AUTOMATION, VOLS 1-4, June 25-27, pp. 960-965, Ajaccio, France (2008)

[6] Srovnal, V., Machacek, Z, Srovnal, V., "Wireless Communication for Mobile Robotics and Industrial Embedded Devices", In 2009 EIGHTH INTERNATIONAL CONFERENCE ON NETWORKS, Mar 01-06, pp. 253-258, Gosier, France (2009)

[7] Machacek, Z, Srovnal, V., "Automated system for data measuring and analyses from embedded systems", In 7th WSEAS International Conference on Automatic Control, Modeling and Simulation, Mar 13-15, pp. 43-48, Prague, Czech Republic (2005)

[8] Skapa, J., Siska, P., Vasinek, V., Vanda, J. Identification of external quantities using redistribution of optical power - art. no. 70031R In Book OPTICAL SENSORS 2008 Volume 7003, p. R31-R31, 2008,ISSN: 0277-786X , ISBN: 978-0-8194-7201-4

[9] Majernik,J., Molcan,M., Majernikova, Z.: Evaluation of posture stability in patients with vestibular diseases, SAMI 2010, 8th IEEE International Symposium on Applied Machine Intelligence and Informatics, Óbuda University, Budapest, Hungary, 2010, ISBN 978-1-4244-6423-4, pp. 271-274

[10] Kašík, V.: The Framework for Parallel Computing Systems Design. In conference proceedings PDS2004, Gliwice, Poland. IFAC WS 2004 0008 PL, 2004, p. 238-240, IFAC, ISBN 83-908409-8-7

Penhaker, M.
VSB-TUO, FEI, K450
17. listopadu 15
Ostrava –Poruba
70833
e-mail: marek.penhaker@vsb.cz
phone: +420 59732 3510