ELECTRONIC DEVICE FOR SEISMOCARDIOGRAPHY

Noninvasive Examination and Signal Evaluation

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Abstract: The Quantitative seismocardiography (Q-SCG) opens a new field of cardiovascular dynamics examination. Using this absolutely non-invasive method, a new field of monitoring heart rate variability was opened up. Systolic forces as well as heart rate variability in relation to changes in external stimuli are registered. Q-SCG probably offers a more complex view of both isotropic and chronotropic heart functions. It will be suitable for: examining operators exposed to stress; for assessing the effect of work, fatigue and mental stress; for monitoring persons as part of disease prevention; for determining a person's ability to carry out their duties both on the ground and in the air. An electronic system for acquisition of data for noninvasive Q-SCG and signal processing is also presented. The measuring system is based on analog filter, analog/digital converter, microcontroller and personal computer. A special digital smoothing polynomial filter is used for signal processing. The example of real measured and evaluated signal is also shown.

1 INTRODUCTION

1.1 Balistocardiography

In balistocardiography (BCG), the body vibrations caused by the heart activity are registered. Balistocardiography is a non-invasive method enabling the examination of the cardiovascular dynamics. This field has a longer history than is commonly known. William Harvey (1578-1657) who discovered blood circulation called his work, published in 1628, „Exercitatio anatomica de motu cordis et sanguinis in animalibus." As the title suggests, this work covers two main topics:

a) Movement of the heart
b) Movement of the blood

Harvey also states that movement is one of the basic functions that sustain circulation. This process requires impulse and force (impetus et violentia), which are produced by the heart (impulsor). The heart itself may produce force and impulse, while blood is propelled and forced to leave its source and home, towards the peripheral parts of the body.
In 1936, Starr took part in a conference held by the American Society of Physiology which dealt with methods of determining cardiac output. For this purpose, he used a bed with tight springs, whereby by the movement against these springs increased the instrument's natural frequency to values higher than the heart rate. Thus began the era of high-frequency balistocardiography, which lasted approximately 15 years. Other types of instruments were developed later on which measured the displacement, velocity or acceleration of a body lying on a bed. Later studies showed that there are difficulties when comparing records registered on different apparatuses. This is mainly caused by two factors:

a) The instrument's natural frequency
b) The instrument's damping

The instrument's natural frequency lies within the range of the frequencies caused by the cardiac activity that we wish to observe. This leads to interference and the subsequent recording is a summation of the oscillations of the instrument and those of the heart. The other factor that significantly affects the shape of the registered curve is the damping installed in these instruments (which are basically oscillatory systems) in order to prevent the periodic oscillations of the instruments themselves. Records of heart activity are therefore deformed.

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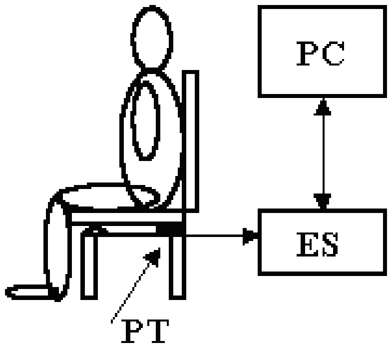

Figure 1: Principle of the noninvasive quantitative seismocardiography measuring: PT - piezoelectric transducer, ES - electronic system, PC - personal computer.

1.2 Quantitative Balistocardiography

Following the critical evaluation of all these facts, in 1952 it was begun with our own experiments related to the construction of an apparatus which would lack the aforementioned shortcomings. Thus, over the years, an apparatus was constructed whose advantages lie not only in the simplicity of its design, but also in its important functional qualities. The properties of the pick-up device and bearing structure, the subject's sitting position in close contact with the seat and an amplifier with a sufficiently long time constant reduce the possibility of shape, phase and time deformation of the records. All this enabled to conduct a physical and mathematical analysis of the balistocardiographic system and to calibrate our instrument. Based on these processes, the apparatus was designated a quantitative balistocardiograph. This was chiefly to distinguish it from previous instruments that registered displacement, velocity and acceleration and were designed to determine cardiac output on one hand, and also because our instrument was calibrated so that force expressed in Newton's registers an amplitude measurable in mm, whereby the relationship between the size of the active force and the registered amplitude is linear, on the other hand. The quantitative balistocardiographic method enabled to introduce two characteristic quantities: systolic force (F) and minute cardiac force (MF), thus using quantitative balistocardiography in an exact manner when studying cardiovascular dynamics at rest and during stress. Current applications of quantitative balistocardiography (Q-BCG) in papers published to date the fact that the relationship between the force acting on the pick-up device and the amplitude of the balistocardiographic curve is linear was proved. This enabled to study the evolution of systolic force in relation to age and ageing, the influence of hypoxia and hyperoxia. It was also possible to follow the changes in Q-BCG indices at rest and under workload in various groups of volunteers, and to determine the linear relationship between the skeletal muscle force and systolic force, and determine changes in Q-BCG indices in various pathological states. Our parameters, determined by Q-BCG, with parameters determined using other non-invasive methods were compared. (Trefny at all, 1996).

1.3 Quantitative Seismocardiography

During a visit to the Flight Psychophysiology Laboratory at Wright-Patterson Airforce Base, a new application field for Q-BCG emerged. This made use of the fact that our method enables the recording of force applied without phase or time deformation. Thus, heart rate may be monitored and analyzed using the method of heart rate variability. The method of Q-BCG was designated by the laboratory employees as absolutely non-invasive, as the persons examined did not have any electrodes attached to the body surface and was not connected by cables to the registering instrument. This new field of monitoring heart activity, whereby we determine both amplitude-force and time-frequency relationships, is termed Quantitative Seismocardiography (Q-SCG). (Trefny at all, 1998). Thus, one may determine the force-response of the cardiovascular system to changes in external stimuli, as well as the autonomous nervous system regulation of the circulation and the activity of the sympathetic and parasympathetic systems. The basic part of the Q-SCG is a rigid piezoelectric force transducer resting on steel chair. The examined person sits on the seat placed on the transducer and force caused by the cardiovascular activity is a measured (Figure 1). The natural frequency of the chair is higher then 1 kHz so that there is no interference with the vibrations caused by the heart activity. Neither damping nor isolation from building vibrations are necessary. These properties enabled to calibrate seismocardiographic system and determine the absolute value of force acting upon the pick-up-device. (Trefny at all, 1999).

The system described in the present study enable better signal evaluation based on high resolution analog/digital converter (ADC), digital filtration and digital correction of nonlinearities and noise suppression by means of personal computer (PC). The heart rate (HR), systolic force (F), minute cardiac force (MF) and breathing frequency (BF) is non-invasively measured.

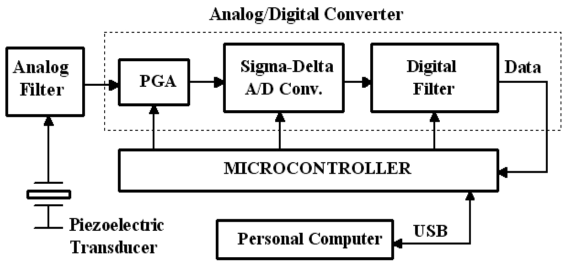

Figure 2: The simplified block diagram of the electronic system for Q-SCG measuring. The main parts of the system are: Piezoelectric force transducer, Analog Filter, PGA - programmable gain amplifier, Sigma-Delta A/D converter, Digital Filter, microcontroller and Personal Computer connected to system by means of USB (Universal serial bus).

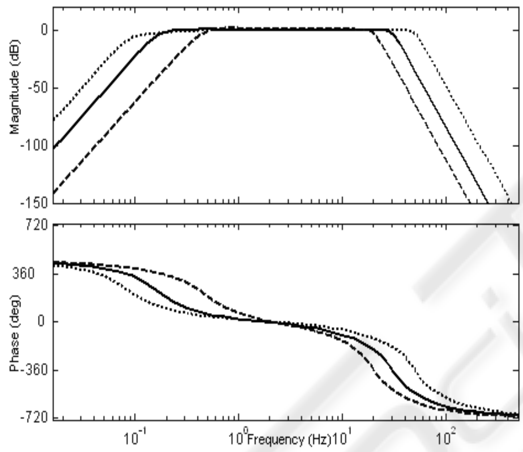

Figure 3: The frequency and phase responses of analog, electronically controlled filter.

2 MATERIALS AND METHODS

The electronic system used for data acquisition consists of a piezoelectric force transducer (PT), analog front end for low frequency measurement applications (containing ADC), microcontroller and PC. The block diagram of the whole system is shown in Figure 2. It is important to note, that amplitude of measured signal from PT is sometimes under 1 mV (depend on subject heart activity) and desired frequency spectrum is lower then 30 Hz.

The measured signal is corrupted by strong noise, baseline wander, etc. therefore the analog and digital signal processing (DSP) are used for signal denoising. The frequency and phase responses of electronically controlled analog bandpass filter are shown in Figure 3. The analog front end of A/D converter can accept either 2 low level input signals (± 10 mV to ±1.225 V, depends on PGA setting) and produce serial digital output. (AD7707, 2000). It employs a sigma-delta conversion technique to realize up to 16 bits of no missing codes performance.

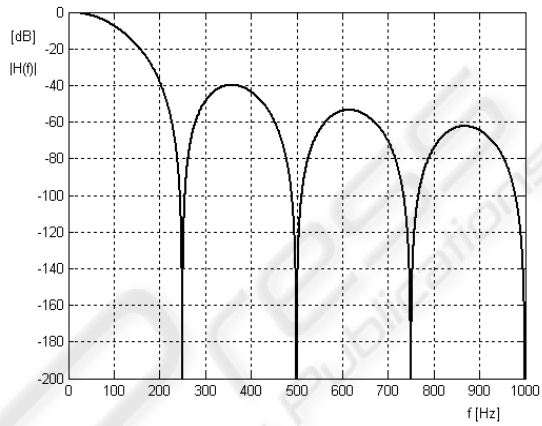

Figure 4: The frequency response of on-chip digital filter in A/D converter.

The sigma-delta modulator output is processed by an on-chip digital filter. The first notch of this digital filter can be programmed via an on-chip control register allowing adjustment of the filter cutoff (1.06 Hz to 131 Hz) and output update rate (4.054 Hz to 500 Hz). The -3 dB frequency f-3dB is determined by the programmed first notch frequency according to the relationship (1):

$$f_{-3dB} = 0.262\ f_{FN} = 0.262\ f_s \qquad [\mathrm{Hz}] \qquad (1)$$

where f_{FN} is filter first notch frequency and f_s is output update rate (sampling rate). The AD7707's digital filter is a low-pass filter with a *(sinx/x)*^{3} response (also called *sinc*^{3}). The transfer function for this filter is described in z-domain by:
and in the frequency domain by:

$$H(z) = \left| \frac{1}{N} . \frac{1 - z^{-N}}{1 - z^{-1}} \right|^3 \qquad (2)$$

and in the frequency domain by:

$$H(f) = \left| \frac{1}{N} . \frac{\sin(\pi N f / f_s)}{\sin(\pi f / f_s)} \right|^3 \qquad [\mathrm{Hz}] \qquad (3)$$

where N is the ratio of the modulator rate to the output rate (modulator rate is 19.2 kHz for Xtal=2.4576 MHz).

The frequency responses of the digital filter are shown in Fig. 3 and Fig. 4. Phase response is given by (4):

$$Phase(f) = -3\,\pi\,(N-2)\,f/f_s \qquad \text{[Rad]} \qquad (4)$$

The data from A/D converter are next filtered also by Savitzky-Golay Smoothing filter (SG).

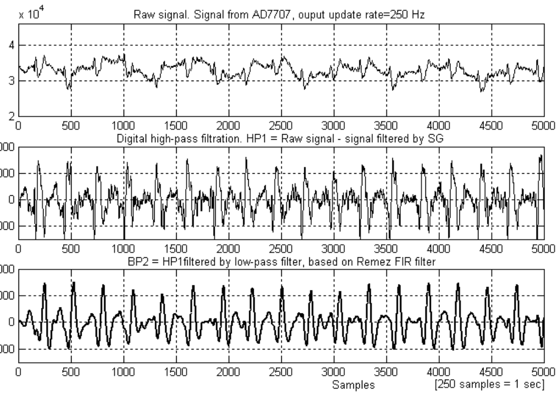

Figure. 5: Record of the Q-SCG in normal man, age 45 years, 78 kg, after lowpass and highpass filtration. Raw signal is filtered by SG filter and Remez, finite impulse response (FIR) filter; 250 samples = 1 sec.

Savitzki and Golay defined a family of filters which are suitable for smoothing and/or differentiating sampled data (commonly called Savitzki-Golay, DISPO - Digital Smoothing Polynomial, or least-square smoothing). (Savitzki and Golay, 1994). The data are assumed to be taken at equal intervals. The smoothing strategy is derived from the least squares fitting of a lower order polynomial to a number of consecutive points. (Madden, 1998). For example, a cubic curve which is fit to 5 or more points in a least squares sense can be viewed as a smoothing function. (Bromba, Ziegler, 1998), (King at all, 1999).

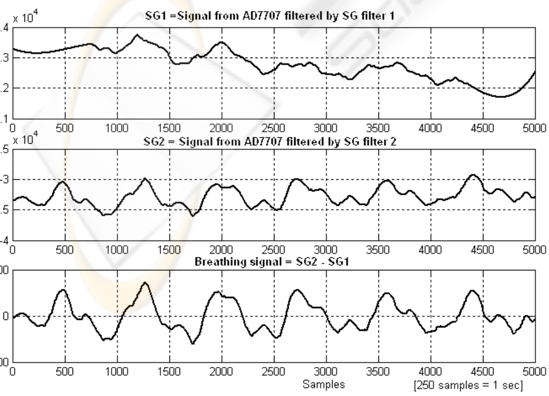

Figure 6: Breathing frequency derived from raw signal by means of two SG filters.

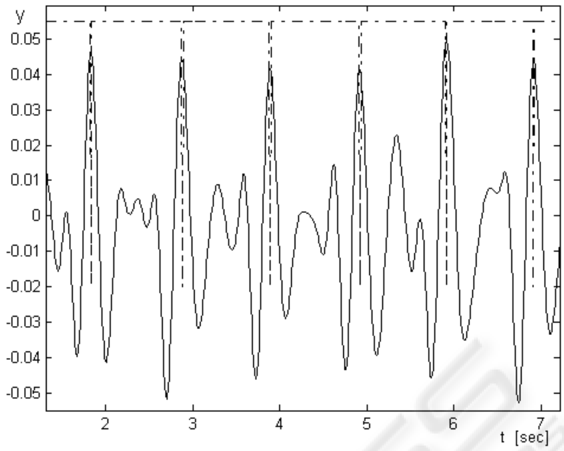

Figure 7: The heart rate variability can be also detected from Q-SCG signal.

An example of Q-SCG measurement is illustrated in Figure 5. The output update rate was 250 Hz, f_{-3dB} was 62.5 Hz. The tree SG filters with different window length were used for Q-SCG and breathing signal processing. Data on Y axis are decimal values of A/D converter. The breathing signal detection is shown in Figure 6.

The heart rate variability (HRV) can be also evaluated from Q-SCG signal. The signal processing example for beat to beat detection is shown in short time slice of signal in Figure 7. After calibration (Y axis in Newton), the systolic force *F* and minute cardiac force *MF* can be computed according (5) and (6):

$$F = (F_{HI} + F_{IJ} + F_{JK})/3 \qquad \text{[N]} \qquad (5)$$

$$MF = F * HR \qquad \text{[N. beats/min]} \qquad (6)$$

where *HR* is heart rate and F_{HI} , F_{IJ} , F_{JK} can be find according Figure. 8. The systolic force represent the force response caused by the heart activity and is expressed in units of force [Newton]. For the total intensity of the heart activity is introduced the minute cardiac force which equals the systolic force multiplied by the *HR*.

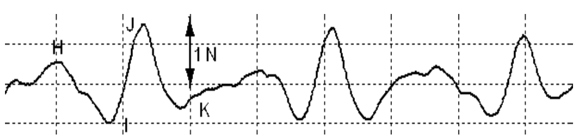

Figure 8: The systolic force (F) determination from Q-SCG measured signal from points: H, I, J K.

3 DISCUSSION

The anatomy and function of single organs of human organism are in correlation. This is true for muscle mass, the body weight and the muscle force too. The reason of this fact is that higher body weight needs for the defined movement greater force, which cannot be realised but by the development of the skeletal musculature. Consequently greater musculature needs more energy which is transported and distributed by the cardiovascular system. In addition, the increased performance of the cardiovascular must be adjusted by the heart muscle. From these relationship it can be concluded that there must be not only the correlation between the skeletal muscle force and the heart mass but also between the skeletal muscle force and the systolic cardiac force as it was observed in the present study. According to our opinion these results may be extrapolated generally for healthy men without pathological changes in cardiovascular system.

4 CONCLUSIONS

The principles of Q-SCG, measuring system for noninvasive measuring of heart activity, breathing and heart rate variability was presented. Also signal processing for Q-SCG evaluation was described.

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