Low cost miniature data acquisition and control system for photoacoustic experiments

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ABSTRACT

The paper describes a truly miniature system for data acquisition and control, dedicated for photoacoustic measurements. Due to intensive use of electronics and digital signal processing most of expensive and / or inconvenient elements of photoacoustic setups, like mechanical chopper or lock-in amplifier, were eliminated. The advantages of the designed device are very low cost, small size, and high functional flexibility. Most of the measurement factors, e.g. analog path gain, light source modulation frequency, number of samples a period, etc. are programmable and can be changed at run-time. Implementation of real-time and stroboscope PAS signal sampling makes possible to acquire high resolution samples while preserving wide input bandwidth. Due to in-circuit programmable components, upgrades of the device are very easy. Small size and low power consumption make the device a very good choice for implementation of portable photoacoustic instruments.

Keywords: photoacoustics, data acquisition and control, virtual instruments, stroboscope sampling

1. INTRODUCTION

Virtually in any kind of research, it is usually required that multiple measurement conditions can be changed independently, so that it is possible to evaluate their influence on measurement results and to find optimal conditions for the measurements. It can be easily noticed from papers published in the field of photoacoustics, that such an approach usually results in huge, complex and very expensive photoacoustic systems,[1-3] despite from the fact that, due to constant and significant progress in technology, at least standard components of photoacoustic experimental setups should decrease in size and price. It should be emphasized that even improved designs of photoacoustic setups, that are based on microcontrollers and modern technology, do not make optimal use of electronics and digital signal processing techniques.[4-8] This paper presents a design of an inexpensive device, that has flexibility comparable to the mentioned sophisticated systems, while due to substantial reduction of size, weight and power consumption, has advantage of portability, which is quite important e.g. when the measurements are to be performed outdoors.

2. INITIAL CONSIDERATIONS

Technical characteristics assumed for the project is given in Table 1. In order to reduce size and cost of the device, the solution was based on the concept of virtual instruments, which means that as many mechanical and optical components of the equipment as possible had to be replaced by electronics. The electronic part of the system was strongly reduced by intensive implementation of digital signal processing techniques instead of traditional hardware solutions.[9, 10]

Taking into consideration common use of semiconductor lasers and LED diodes as light sources,[6-13] the output light source modulation signal was to be a square wave (TTL/CMOS compatible; 50% duty cycle) electric signal with the frequency adjustable in the range of 20 Hz - 20 kHz. As a result of such an approach, a small external driver circuit was required, but at the same time light modulation method wasn't restricted only to semiconductor laser or LED current modulation; acoustooptical or electrooptical modulators could have been used as well.

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General requirements:
low cost (< 100$)
small size and weight
low power consumption (< 5W)

PAS signal input:
amplitude 50 nV to 5.0 V
software-selectable gain of 1:10:100:1000 plus jumper-selectable gain of approx. 100
noise optimization of the analog input stage

Additional analog inputs:
input voltage range 0 to 5.0 V
ADC resolution 10-bits

LED / laser modulation signal output:
TTL/CMOS compatible, 50% duty cycle
frequency in the range of at least 20 Hz to 20 kHz (software-programmable)

PAS signal data acquisition features:
PAS signal ADC resolution - 12 bits (with possible easy upgrade to higher resolution ADCs)
whole signal shape recording (not just amplitude and / or phase)
real-time and stroboscope sampling of the PAS signal
number of samples a period software-programmable
digital signal averaging (software-programmable)
digital DC offset cancellation
further DSP processing implemented (optionally) in a master controller

Interfaces:
SPI (for implementation of additional hardware and microcontroller firmware upgrades)
RS232 (for communication with the master controller)

Table 1. Assumed specifications of the designed system

Another crucial assumption was that the device should be capable of recording the whole signal shape instead of its amplitude and / or phase only. Of course, in order to obtain reasonable quality of shape recording, horizontal resolution couldn't be smaller than at least a few tens of points per period.

The system was designed in such a way that additional functions, e.g. temperature measurements and control, can be easily implemented later on. The feature is very important when a photoacoustic cell with high Q-factor is used, because in such a case even small deviation from the resonance due to temperature change, may result in significant decrease of the photoacoustic signal amplitude.[14] If the photoacoustic experiments are to be performed in moderate range of temperatures (e.g. 10°C - 50°C), the temperature adjustment of the cell and / or laser diode can be relatively easily implemented by means of electronically controlled Peltier element. Temperature can be measured in a relatively wide range (from -55 to +125°C) with semiconductor sensors. Some of such sensors (e.g. DS 1624) have digital output, resolution of 0.03125 K, and maximum total error of 0.5 K, some of them have functionality of thermostat circuits so that only upper and lower temperature threshold values setting is required (e.g. DS 1721).[15] Additional dedicated analog inputs, can be used e.g. for light beam power measurements, and thus implementing autocalibration that might be used for reduction of photoacoustic measurement errors resulting from the light source aging effects or even temporary variations of the light power.

3. BLOCK DIAGRAM

A block diagram of the device is presented in Fig. 1. The analog part of the device consists of blocks in which the photoacoustic signal is amplified and converted to digital samples. As photoacoustic signals can be very weak and fast digital circuits produce significant level of noise, the digital part of the device was separated from the analog part with optocouplers. Similarly, the light source modulation circuit, in which strong current pulses (e.g. if a semiconductor laser is used as the light source) may produce high level of noise, was isolated from the other circuits by means of optocouplers. In order to minimize number of optocouplers, serial output A/D converter was used in the analog path. As photoacoustic signal level may change in the range of a few decades, the amplification of the photoacoustic signal path can be selected in a programmable gain amplifier A1 as 1:10:100:1000, while the other three decades of the input signal dynamic range are covered by the resolution of the A/D converter. For this reason a 12-bit A/D converter was chosen. Such a resolution of the converter results in the resolution of photoacoustic signal amplitude measurements better than 1% (despite from very rough amplifier gain switching). The only exception is low level signal measured at the most sensitive input range selected. However, in such a case the ground noise level is so high, that needs for amplitude measurements with the precision higher than 1% are questionable. Final matching of the photoacoustic signal level to the A/D converter input signals level was achieved by means of a fixed gain amplifier A2 (gain = 101). Taking into consideration, that fixed gain amplifiers have better noise figures than programmable gain amplifiers, the A2 amplifier was placed as the first one (in front of the A1 amplifier) in the photoacoustic signal path.

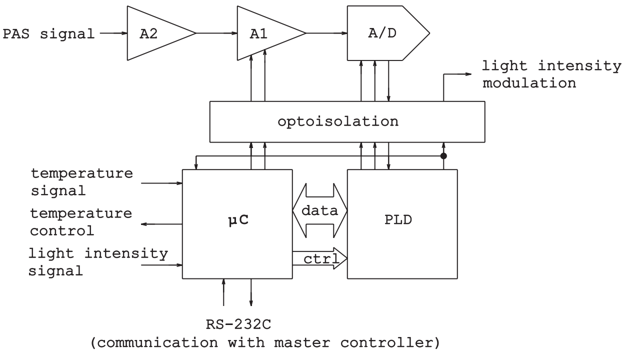


Fig. 1. Block diagram of the system.

As at the assumed horizontal resolution of photoacoustic signal sampling, the A/D converter control signals have to be quite fast and precisely positioned in time domain, some of logic was implemented inside a PLD circuit. In addition to control A/D converter signals, its role was to produce appropriately synchronized light beam modulation signal. Implementation of these functions based exclusively on a microcontroller is in fact possible. However, this would require at least 16-bit microcontroller with relatively fast internal counter/timer blocks with compare function, and fast synchronous serial communication port. Such a solution would be much more expensive and still wouldn't approach the speed of fast PLD circuits (e.g. clocked with the frequencies of 100 MHz and above).

The digital part works as a circuit that controls the analog part, but simultaneously it acts itself as a slave that must be controlled by an external master device. For the purpose of communication between the slave and master an RS-232 interface was chosen (as one of the most common and simplest standards). The solution in which the designed device is not self-contained one may seem not very reasonable at first glance, but its main advantage is increase of functional flexibility achieved at low costs. Because the device can be implemented on an inexpensive 8-bit microcontroller, that performs data acquisition and some basic digital signal processing (e.g. averaging) only. Such preliminary results are then transferred via RS-232 interface to the master controller for final processing. Form of the master controller depends on particular application e.g. it can be a laptop computer - if we are looking for a portable photoacoustic measurement system with the option of precise adjustment of multiple measurement conditions, intensive data processing and presentation - or a dedicated, simple and inexpensive controller equipped with an LCD alphanumerical display and a mini-keyboard that would transform our device in a miniature photoacoustic instrument designed for performing some particular measurement outdoors. It should be noticed, that in both cases the hardware and firmware of the main described device remains unchanged.

4. ANALOG BOARD

A detailed circuit diagram of the analog board is presented in Fig. 2. The input signal from the CON1 connector is fed through a high-pass filter (R1, C17) to a fixed gain (G = 101) low-pass amplifier based on a low-noise op-amp OP 27 (U1). The C6 capacitor sets the upper limit frequency of the amplifier, while C5 and R2 form another high-pass filter. The signal is then directed through the JP1 jumper to another amplification stage, implemented on a PGA 202 (Burr Brown) digitally programmable gain amplifier (G = 1:10:100:1000). If the amplitude of the signal received from the CON1 connector is too high (greater than 50 mV), the OP 27 amplification stage can be by-passed, by setting the JP1 jumper in the 1-2 position. The C1, C2 capacitors set the upper cut-off frequency of the amplifier to approximately 20 kHz, while C7, R20 and internal input impedance of the MAX 176 (U4) A/D converter form additional high-pass filter with the lower limit frequency of approximately 20 Hz. The R20 resistor together with the internal components of the converter sets the DC

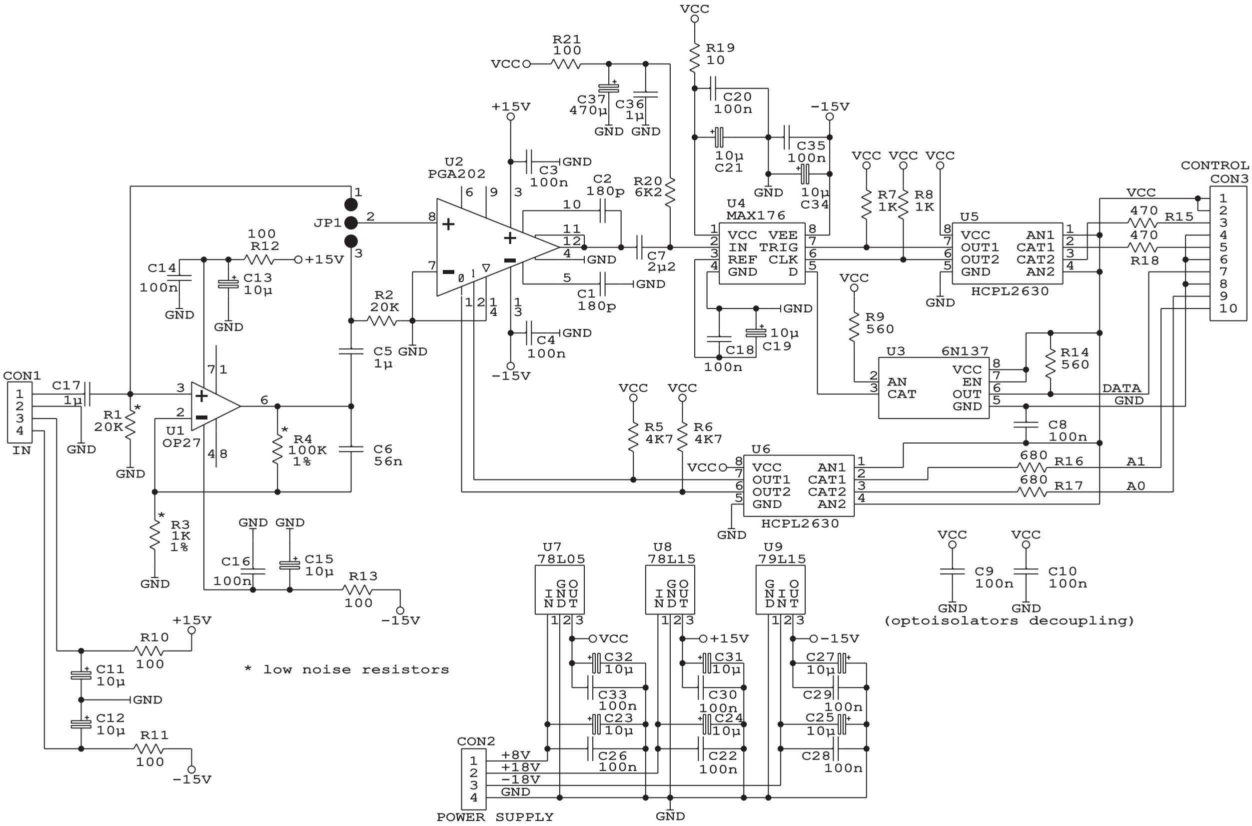


Fig. 2. Analog board circuit diagram.

offset of the signal at the converter input to approximately 0 V. A very precise adjustment of the offset is not necessary, as it can be easily performed later, by means of digital signal processing of the sampled signal. The U3, U5 and U6 optocouplers are used for the purpose of galvanic separation of the signals that control the U2 gain and the A/D converter from the digital part of the device.

The input impedance of the designed analog input stage of the device is approximately 20 kOhms. Hence, the device cannot be directly connected to a high-impedance detector like condenser microphone. In such situations additional (external) voltage follower / separator circuit must be used. The conventional design of such a voltage follower / separator circuit is relatively simple, but it requires high-impedance (e.g. 10^9 Ohms) resistors. Such resistors are a very strong noise source, hence designing the input stage of the device as general-purpose (meaning high-impedance input), would decrease the noise quality of the device if a low-impedance detector were used.

Due to very low input signal levels, quality of power supply voltages becomes a critical factor of the analog part design. It can be easily noticed that even in case of PSRR = 120 dB of the input amplifier U1, 50 mV of the power supply voltage change would produce similar results as 50 nV input signal. For this reason power supply pins of the U1, U4 and the voltage follower / separator circuit (powered through the CON1) are not connected to the U7, U8, and U9 voltage regulators directly, but through the smoothing filters (R12, C13, C14), (R13, C15, C16), (R19, C21, C20), (R10, C11), (R11, C12), (R21, C37, C36). For the same reasons, power supply voltages of the analog circuits are produced not in the external power supply, but in the local voltage regulators, placed directly on the device printed board. Ground and power supply paths routing is also critical.

The A/D converter used in the system was MAX 176, but there is number of faster and higher resolution A/D converters available on the market, which can be used instead. However it should be noticed, that there is no point in choosing much faster one. If we do so, e.g. because we wanted to obtain real-time sampling of a 20 kHz signal with the resolution of 100 samples a period, the converter should have had maximum sampling speed of at least 2 Msps (in comparison to max. 250 ksps of MAX 176). And due to the serial output of the converter, the mentioned 2 Msps would result in the serial data transfer speed of approximately 30 Mbauds, so that simple optocouplers may be not fast enough and galvanic separation would have to be implemented in a more sophisticated way (e.g. as magnetic coupling). Another thing is that real-time data acquisition with the speed of 2 Msps would require much faster microcontroller - probably at least a 16-bit microcontroller with the speed of over 10 MIPS or a DSP processor. Hence, use of a much faster (means also more expensive) A/D converter would result in a significant increase of the device costs and may require the system to be redesigned. At the same time it should be mentioned, that similar result (i.e. sampling of a 20 kHz signal with the resolution of 100 samples a period) can be obtained even in case of much slower converters, if a stroboscope sampling technique is applied. The main disadvantage of the stroboscope sampling is longer data acquisition of the input signal, but it should be noticed that the technique is used only at relatively high input signal frequencies, while as long as the speed of the converter is sufficient, real-time sampling is implemented. For MAX 176, assumed 100 samples a period and real-time sampling, the maximum input signal frequency is 2.5 kHz, which is still satisfactory for probably most of photoacoustic applications.

5. DIGITAL BOARD

A detailed circuit diagram of the digital board is presented in Fig. 3. The A/D converter control signals are produced in a programmable logic circuit U51 (ispLSI 1032, Lattice Semiconductor) and, together with the A1 stage gain selection signals, are routed to CON55 connector (which is connected by means of a flatcable with CON3 connector of the analog part). The U51 generates also a light source modulation signal, which is galvanically separated from the main (external)

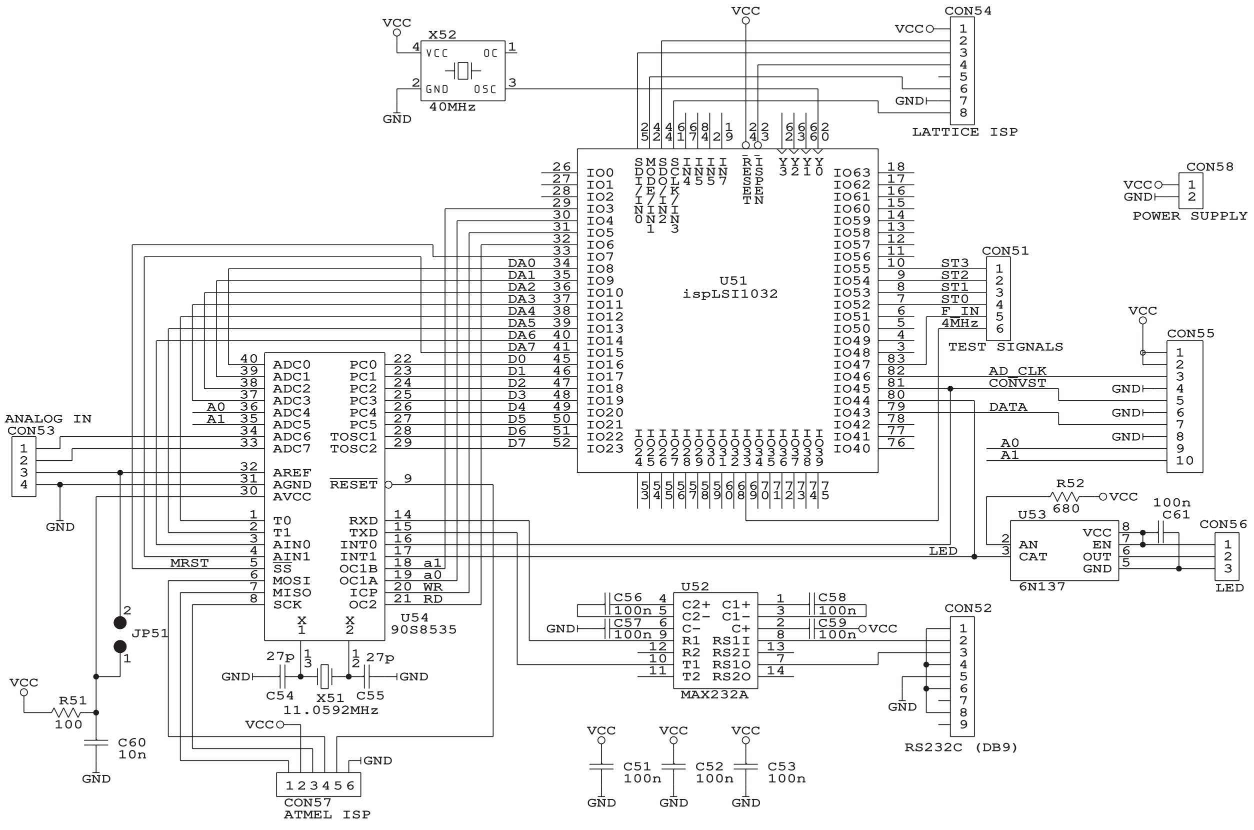


Fig. 3. Digital board circuit diagram.

light source modulation circuit by means of U53 optocoupler. The signal is also connected to an external interrupt input of U54 microcontroller, so that it can be used e.g. as a time position reference of the collected photoacoustic signal samples to the light modulation signal. Input voltage signals from the light beam power sensor and temperature sensor are taken from CON53 connector and fed directly to the internal A/D converter of the microcontroller. In case of SPI-based digital temperature sensor or thermostat circuit, the circuit can be controlled via CON57 connector, which is also used for in-system programming of the microcontroller (for this purpose the RESET signal of the microcontroller is also present at the connector).

Communication between the device and external master is based on RS-232 interface. MAX232A (U52), used as TTL/CMOS <-> RS-232 level converter, supports baudrates up to 120 kbps, so that a standard baudrate of 115.2 kbps can be used. Such a transfer speed is sufficient if taken into account that 12-bit sampling (at maximum MAX 176 conversion speed) with a resolution of 100 samples a period and averaging of 2500 periods will take approximately one second, while transferring the results of such a measurement (300 bytes) will last only 26 ms.

An AT90S8535 (Atmel) was chosen as the microcontroller (the choice was based mainly on performance and cost). It is an 8-bit RISC with computation power of a few MIPS (which is sufficient for 250 ksps data acquisition and real-time implementation of some basic operations, like averaging), Flash in-system programmable program memory (nice feature if firmware updates are planned), data EEPROM (in which calibration data can be stored) and internal 10-bit A/D converter (can be used for analog temperature, light beam power measurements, etc.). Internal data memory of the microcontroller has size of 512 bytes, which is enough to perform 12-bit data acquisition with the resolution of 150 samples a period and averaging of over 4000 periods. The clock speed was set to 11.0592 MHz which can be easily divided in order to obtain standard baudrates and is also sufficient for performing the data acquisition and basic digital signal processing operations. These operations consume most of the computation power of the microcontroller, and much lower clock frequency would result in incorrect performance of the device. The clock frequency exceeds the maximum clock speed defined in the manufacturer's data sheet of the microcontroller. However, it should be noted, that the data sheet contains e.g. I_{CC} vs. frequency and voltage characteristics, which show that microcontroller was tested with the speed of 11 MHz at supply voltage of only 2.7 V.[16] Besides the given min./max. values are guaranteed for the worst case of power supply voltages and temperatures. Extrapolation of the worst case (guaranteed value) of 8.0 MHz at 4.0 V of supply voltage gives the value of 11 MHz at power supply voltage of 5.0 V.

5. DATA ACQUISITION AND CONTROL

In photoacoustic instruments signal used for light source modulation is precisely correlated with the photoacoustic signal being recorded. This means that the light source modulation signal can be used as a trigger. Moreover, the device can be designed in such a way that the light source modulation signal as well as the A/D converter control signals, are generated as already properly correlated and that number of samples recording per period of the photoacoustic signal is an integer number, which can be a strong advantage in case of some digital signal processing operations (averaging, filtering, etc.).

Assuming that during a single period of the light source modulation signal (of frequency f_{mod}) N samples of the photoacoustic signal are taken, the sampling frequency f_s equals $f_{mod} * N$. Such f_s and f_{mod} signals can be produced in a simple circuit, in which the f_{osc} frequency from a crystal oscillator is digitally divided. In order to get quasi-continuous tuning, value of f_{osc} should be much higher than f_s. In the described device f_{osc} was set at 40 MHz, while the maximum sampling speed f_{s_max} of the A/D converter was 250 ksps.

With the increase of f_{mod} and / or N, the $f_{mod} * N$ product may become greater than the maximum sampling speed of the A/D converter (f_{s_max}), so that real-time

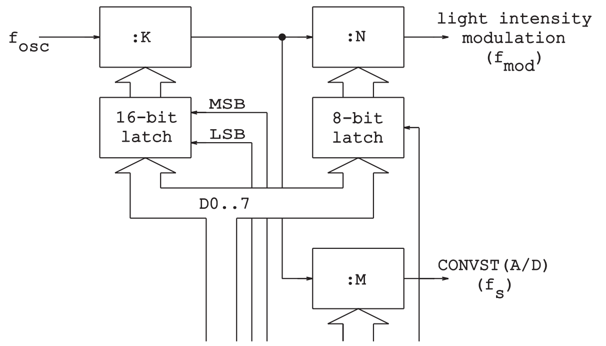
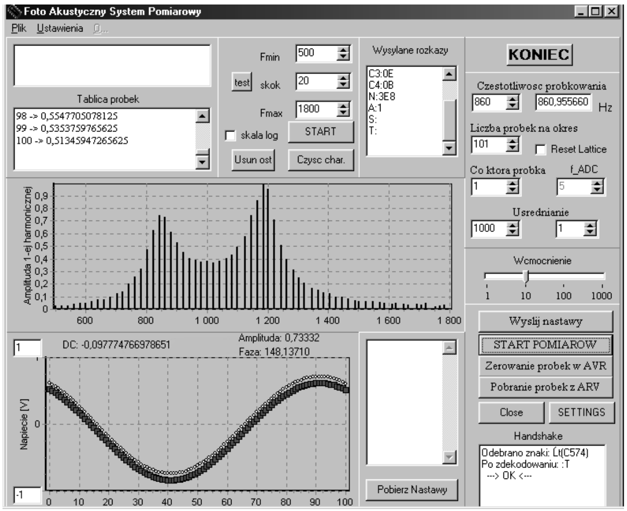


Fig. 4. A simple circuit supporting real-time and stroboscope sampling of photoacoustic signal.

sampling is impossible. To overcome this problem, stroboscope sampling technique can be used. A simple circuit supporting both real-time and stroboscope method of data acquisition is shown in Fig. 4. It should be mentioned, that for the correct operation of the circuit, M and N must be relatively prime numbers. Details of the functional structure implemented inside the PLD are described elsewhere.[17]

6. APPLICATION EXAMPLES

The designed device was tested in an experimental setup used for calibration of photoacoustic cells. The system was controlled by a simple application written in Borland Delphi (Fig. 5). The application lets user change the gain of the analog signal path, number of samples a period, number of periods to be averaged, fix modulation frequency at a selected value or define a frequency range and sweeping step, etc. Two graphic components present amplitude vs. frequency characteristics and shape of the signal being recorded. Some other information, e.g. DC offset, amplitude and phase values are given in a digital form. The measurement results can be saved in a file.



98 -> 0,5547705078125
99 -> 0,5353759765625
100 -> 0,51345947265625

Fmin 500
skok 20
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C3:0E
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Fig. 5. A screenshot of an application used for calibration of photoacoustic cells.

Sample result of the measurements of a photoacoustic cell frequency response is shown in Fig. 6. The setup was later easily reconfigured for some preliminary experiments with photoacoustic water vapour measurements (in which the device and the software remained unchanged).

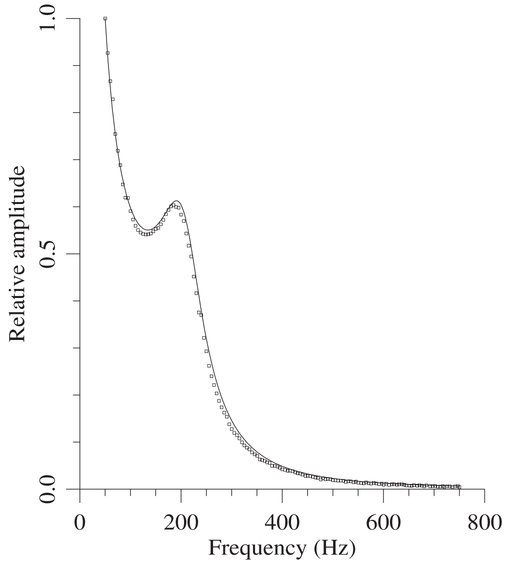

Fig. 6. Sample result of a photoacoustic cell resonance curve measurements (solid line - theory, sqares - experimental).

7. CONCLUSIONS

A result of the described work is a system for data acquisition and control, dedicated for photoacoustic measurements. Design of the system, based on the concept of virtual instruments, significantly reduced number of expensive and big components of photoacoustic setups, like mechanical chopper or lock-in amplifier, which finally resulted in substantial reduce of the device cost (below 100$), small size (Fig. 7), and very high functional flexibility. Taking into consideration, that most of the settings are software-programmable and can be changed at run-time, the system is a low-cost, powerful tool for research and development in the field of photoacoustics. Small size and low power consumption cause that the device can be used as well in portable photoacoustic applications. Implementation of stroboscope sampling feature makes possible to use slower, high-resolution A/D converters while preserving wide bandwidth of the input PAS signal. In-circuit programmable components make modifications of the device very easy.

Detailed information about the designed system, including microcontroller firmware and PLD configuration files, can be obtained directly from the authors.

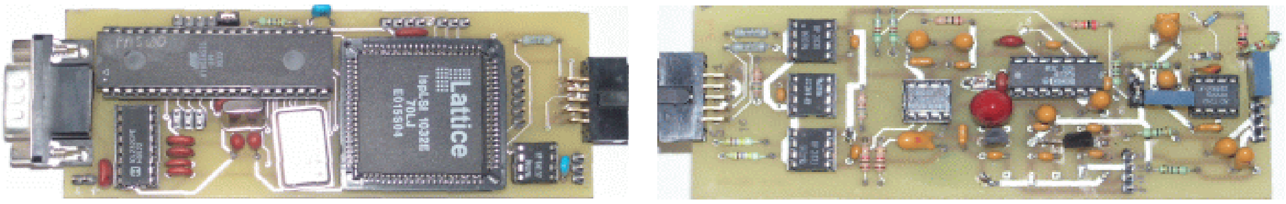

Fig. 7. Photograph of the system; size of the boards (12.0 x 4.5 cm) can be easily reduced by use of SMD components.

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