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Design and Development of Advanced Lock-in Amplifier and its Application

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Abstract: Lock-in amplifiers are used to process the analog signals even in the presence of noise sources of greater amplitude. In the present study, an attempt is made to design a C8051F060 microcontroller based lock-in amplifier. The microcontroller contains all the on-chip features to design a single-chip lock-in amplifier. The reference signal for lock-in amplifier is generated by on-chip digital-to-analog converter (DAC) and timer. The signal whose amplitude is to be measured is acquired by on-chip ADC. The ADC values are directly stored on to XRAM through on-chip DMA controller. Later, these stored values are processed by using quadrature sampling method to get amplitude and phase of the 100 waves. The amplitude and phase values of 100 waves are averaged to eliminate the random noise of the signal and are displayed on the LCD module. The amplitude and phase are sent to the PC through on-chip serial port (UART) to store/plot the graph. The proposed lock-in amplifier is applied to study the phase transitions of sulfur sample by varying the temperature at slow rate (0.3 °C/min) using microcontroller based temperature control system. *Copyright © 2013 IFSA.*

Keywords: Lock-in amplifier, C8051F060 microcontroller, Phase, Amplitude, PAS.

1. Introduction

The precise and accurate measurement of physical, chemical, and biological parameters plays an important role in unraveling the mysteries of nature. Modern measuring instruments play an important role for studying the nature closely and clearly. New discoveries in science provided new instruments for the study of nature and these studies in turn give feedback to develop sophisticated instruments; Lock-in amplifier is one such instrument. In many scientific and industrial applications, a situation exists where one needs to measure amplitude of the signal which is much smaller than the noise component present in the environment. In such case, the lock-in amplifier is very essential. Lock-in amplifier uses phase sensitive detection to measure small signals buried in noise. The lock-in amplifier can be designed with conventional analog circuits or with digital systems. The analog lock-in amplifiers use complicated circuitry to perform phase sensitive detection and filtering. Also, the analog lock-in amplifiers are susceptible to the environmental changes and aging effects. These difficulties can be overcome by digital lock-in amplifiers. Lock-in amplifier can measure small ac signals of only few nano-volts even in the presence of noise sources of much greater amplitude. They do this by phase sensitive detection circuit that discriminates a single frequency of interest by comparing the phase and amplitude of incoming signal with a reference. Signals from interfering

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sources, which do not have the same frequency and phase relationship with the reference, are rejected by the phase sensitive detector (PSD). It is called an '*amplifier*' because the signal level at the output is usually greater than that of the input, and the term '*lock-in*' because it locks to, and measures the particular frequency of interest ignoring all other signals at the input. Lock-in amplifier is used to measure the amplitude of the signal and phase difference between reference and measuring signal. In most of the digital lock-in amplifiers analog interface (ADC-DAC) circuit and other external units are used [1-10]. Here, an attempt is made to design a digital lock-in amplifier using on-chip features of C8051F060 microcontroller with minimum external circuits.

2. Theory and Principle of Lock-in Amplifier

The block diagram shown in Fig. 1 explains the principle involved in lock-in amplifier. It uses a pre-amplifier, phase shifter, phase sensitive detector, and a low pass filter [2].

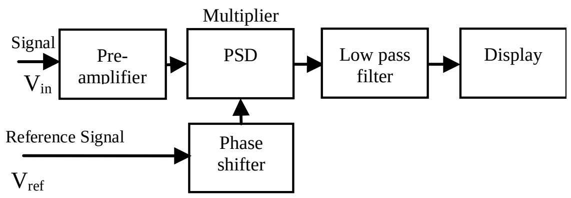

Fig. 1. Block diagram of lock-in amplifier.

The PSD is used to improve the signal-to-noise ratio in ac signal measurements. It is a common signal processing element which is often used to demodulate a signal frequency from its fixed frequency carrier. If two signals are multiplied, the result will be a signal consisting of the sum and difference of two signals as expressed in the following derivation.

$$x = V_{in}\ sin(\omega_1 t)$$
$$y = V_{ref}\ sin(\omega_2 t + \theta)$$

where x and y are the signal and reference respectively. V_{in}, V_{ref}, ω_1 and ω_2 are the amplitude and angular frequency of signal and reference respectively. 'θ' is the phase difference between the two signals.

$$V_0 = x * y. \quad (1)$$

$$V_0 = V_{in}\,sin(\omega_1 t) * V_{ref}\,sin(\omega_2 t + \theta)$$
$$V_0 = V_{in}V_{ref}\,[cos(\omega_1 t - (\omega_2 t + \theta)) - \\ - cos(\omega_1 t + (\omega_2 t + \theta))]$$

$$where, \omega_1 = 2\pi f_1 ; \omega_2 = 2\pi f_2$$
$$V_0 = \frac{V_{in}V_{ref}}{2}[cos(2\pi(f_1 - f_2)t - \theta) - \\ - cos(2\pi(f_1 + f_2)t + \theta)]$$

If the frequency of signal, and reference are equal, then $f_1 = f_2 = f$

$$V_0 = \frac{V_{in}V_{ref}}{2}[cos\,\theta - cos(2 * 2\pi f t + \theta)]$$
$$V_0 = \frac{V_{in}V_{ref}}{2}[cos\,\theta - cos(2\omega t + \theta)] \quad (2)$$

If the frequency of reference is equal to the frequency of interest, then the term $\cos(2\omega t + \theta)$ can be removed by passing the output signal through a low-pass filter leaving the final DC signal. This is proportional to the magnitude of the input signal and phase relationship between the input signal and reference [11, 12].

3. C8051F060 based Lock-in Amplifier

3.1. Hardware Details

The proposed lock-in amplifier is designed using C8051F060TB microcontroller board from Cygnal Integrated Products, Inc., Austin, USA. The on-chip peripherals of microcontroller will facilitate to design a single chip lock-in amplifier. Except PCA module, rests of the features of microcontroller have been used in the design of lock-in amplifier. The microcontroller has the following features [13].

- High-speed pipelined 8051-compatible CIP-51 microcontroller core (up to 25 MIPS).
- Two 16-bit, 1 MSPS ADCs (ADC0 & ADC1) with a direct memory access controller.
- Two 12-bit, DACs (DAC0 & DAC1) with programmable update scheduling.
- 64 KB of in-system programmable Flash Memory.
- 4352 (4096 + 256) bytes of on-chip RAM.
- External Data Memory Interface with 64KB direct address space.
- SPI, SM Bus/I^2C, and two UART serial interfaces implemented in hardware.
- Five general purpose 16-bit Timers.
- Programmable Counter/Timer Array (PCA) with six capture/compare modules.
- On-chip Watchdog Timer, VDD Monitor, and Temperature Sensor.

In most of the digital lock-in amplifiers, the processing is performed in the digital domain using software and dedicated digital signal processor (DSP). The system still features a pre-amplifier and anti-aliasing filter to remove any signal component higher than half of the sampling frequency of ADC.

The lock-in amplifier requires a reference signal to perform the phase sensitive detection. The reference signal is generated internally or derived from sampling an external signal. In case of internally generated signal, the individual sample points of the reference signal can be calculated to a high degree of accuracy, and therefore do not suffer from the typical errors found in analog lock-in amplifier. The reference signal is also phase-shifted by 90° by either look-up table or simple mathematical operations. Here the reference signal is derived internally by look-up table with 256 sine codes, Timer 3 module for scheduled update, and DAC0 module of the C8051F060. Since, it is essential for this routine never be interrupted or delayed; it is assigned a high priority level. A simple circular buffer counter moves through a table of values that are output to DAC0 module for every 10 µSec. This will produce a sine wave with maximum amplitude of 2.4 V.

The signal is acquired with on-chip ADC0 module with 16-bit resolution. The ADC0 can be initiated from various sources such as AD0BUSY bit, Timer 2 overflow, Timer 3 overflow, and external trigger. In the present design, it is important that all the clocks for sampling, and signal generation need to be synchronized because there is a possibility of change in phase relationship of the signal with the change in timings. For this reason, the ADC0 conversion is also derived from Timer 3 overflow and it is set to produce the start-of-conversion signal for every 10 µSec (at a sampling frequency of 100 kHz) so that the signal generation and acquisition will be done at the same time. Fig. 2 shows the block diagram of most of the commercial DSP based lock-in amplifiers [3]. Here, the reference and phase-shifted reference values are multiplied directly to generate the intermediate X´ and Y´ signals. Finally, these signals are passed through digital low-pass filter to generate the final output values X and Y. Fig. 3 shows digital lock-in amplifier implemented using C8051F060TB board. If the sampling is performed with 16-bit resolution at 100 kHz rate, then an anti-aliasing filter needs to be set at 50 kHz to attenuate any signals above 50 kHz. As the ADC0 conversion time is 1µSec, it can be extended up to 1 MHz. Since, on-chip ADC of microcontroller is unipolar, the microcontroller board is provided with a circuit to convert input bipolar wave to unipolar wave.

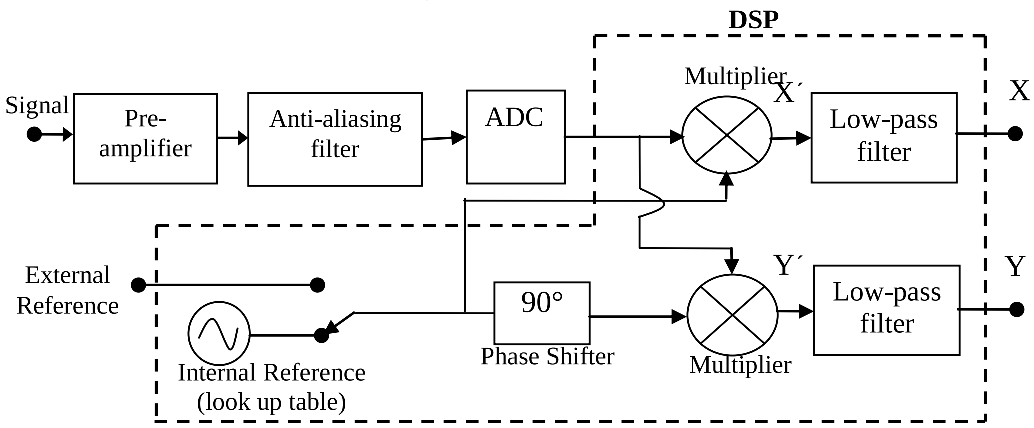

Fig. 2. DSP based lock-in amplifier.

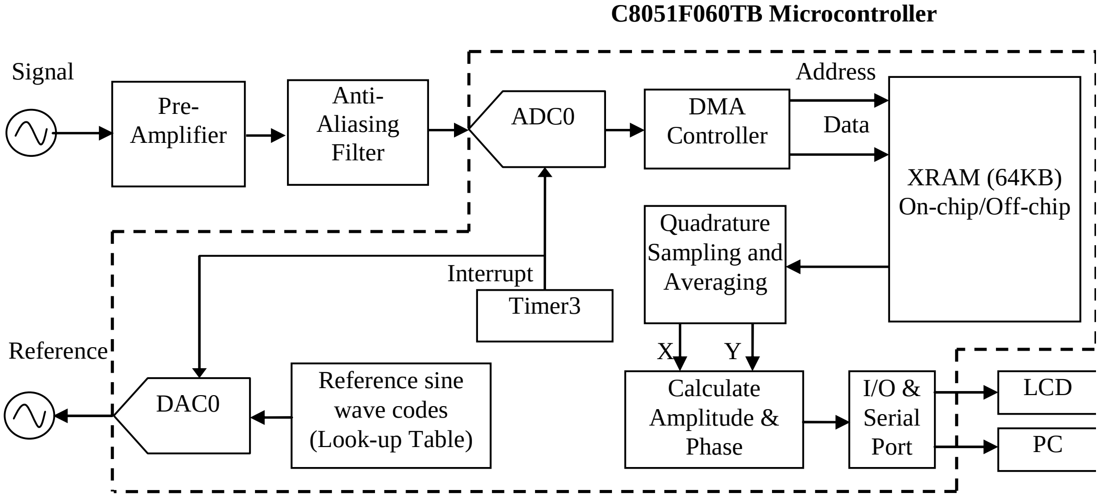

Fig. 3. Microcontroller based lock-in amplifier.

Since, the data will be arriving at such a high rate; it is not possible to complete the entire signal processing task between batches of the arriving samples. For this reason, the software stores 32768 sampled data directly onto the external data memory through on-chip DMA controller and only then performs multiplication and filtering operations. After collecting these many samples, the results of any subsequent data points are ignored until the current data have been processed. This introduces a problem if the restart of sampling occurs at different points in the waveform for next cycle which will introduce a phase change and error in the final output. To overcome this problem, the sampling is resynchronized to start of the output waveform for each batch. Since, the generation and acquisition is done at the same time with Timer 3 interrupt at every 10 µSec. After receiving data of 100 cycles, the in-phase and 90° phase shifted (quadrature) components are performed only at four points on each wave to get X´ and Y´ values as shown in Fig. 4.

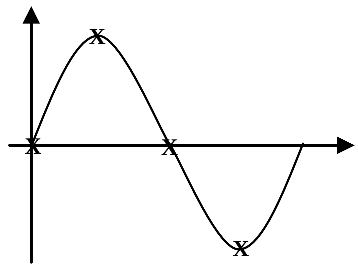

Fig. 4. Quadrature sampling.

Consequently, the operations performed by the PSD are reduced to a sequence of addition and negations without requiring any multiplications saving the entire processing time. These X´ and Y´ of 100 waves are averaged to eliminate random noise of the signal, and to get X and Y. These values are substituted in the equations (3) and (4) to find amplitude and phase of the signal [11, 14] and are display on LCD module.

$$Amplitude = \sqrt{X^2 + Y^2} \tag{3}$$

$$Phase = \tan^{-1}(Y/X) \tag{4}$$

3.1. Software Details

An embedded 'C' program has been developed for lock-in detection. The flowchart of the program is shown in Fig. 5. The Silicon Laboratories IDE and Keil full-version embedded 'C' cross compiler is used to develop the code. Program first initializes the on-chip peripherals such as, ADC0, DAC0, DMA, UART0, Oscillator, and LCD module. After initialization the program generates sine wave with help of on-chip DAC0 and Timer 3 modules. The sine codes are placed in the look-up table. These sine codes are scheduled updated to DAC0 using Timer 3. The Timer 3 is programmed to generate an interrupt every 10 µsec. When interrupt occurs, the program reads the sine code from table by calculating the step through phase accumulator algorithm and sends to DAC0 module. By varying the step size the frequency of sine wave, thus generated, can be varied. Next, the program reads signal through ADC0 module and calculates the amplitude of the signal by averaging 100 waves, to eliminate random noise, and displays on LCD module. Finally, it enters the serial communication subroutine to send the measured amplitude and phase to PC through UART0. The above procedure will be repeated continuously.

4. Application

The proposed digital lock-in amplifier based on C8051F060 microcontroller is applied to photoacoustic spectrometry to measure amplitude and phase of an acoustic signal. The Fig. 6 shows block diagram of photacoustic spectrometer (PAS). It consists of 10 mW IR laser (830 nm) source, photoacoustic (PA) cell, microphone, pre-amplifier, band-pass filter, and microcontroller (lock–in amplifier). In PAS, the sample is irradiated by modulated laser beam; as a result, the absorption of light energy by the sample generates excited internal energy levels. All or part of the absorbed light energy is then transferred into heat through non-radiative relaxation process in the sample. Since, radiation incident on the sample is intensity modulated, the internal heating of the sample is also modulated at the same frequency. The air at the sample surface undergoes compression and rarefactions by this internal heating of the sample, which in turn produces acoustic signal of same frequency as that of the modulating signal [15]. The acoustic signal generated from the PA cell is converted into electrical signal by a microphone. Since, the PA effect is based on the absorption of light energy by a sample resulting in the production of electric signal of a very low amplitude, it is amplified by a high input impedance, high gain, and low noise amplifier designed using LM308 operational amplifier. The signal to noise ratio is further improved by passing through a band-pass filter. The band-pass filter is designed using op-amps LM308 for Q=10, G=10, and f_c=350 Hz.

Finally, the filter output is given to on-chip ADC0 of C8051F060 microcontroller. The ADC0 acquires this signal every 10µsec. The sampled data will be stored directly on data RAM through DMA controller. 64KB of data-RAM is available on C8051F060 TB board. Hence, about 100 cycles (284 data samples for each cycle of 350 Hz signal) at the sampling rate of 100 kHz will be stored. After collecting these many samples, the results of any subsequent data points are ignored until the current data has been processed. The data collected will be processed to find amplitude and phase of the signal and are displayed on LCD module and later will be sent to the PC for storing and plotting.

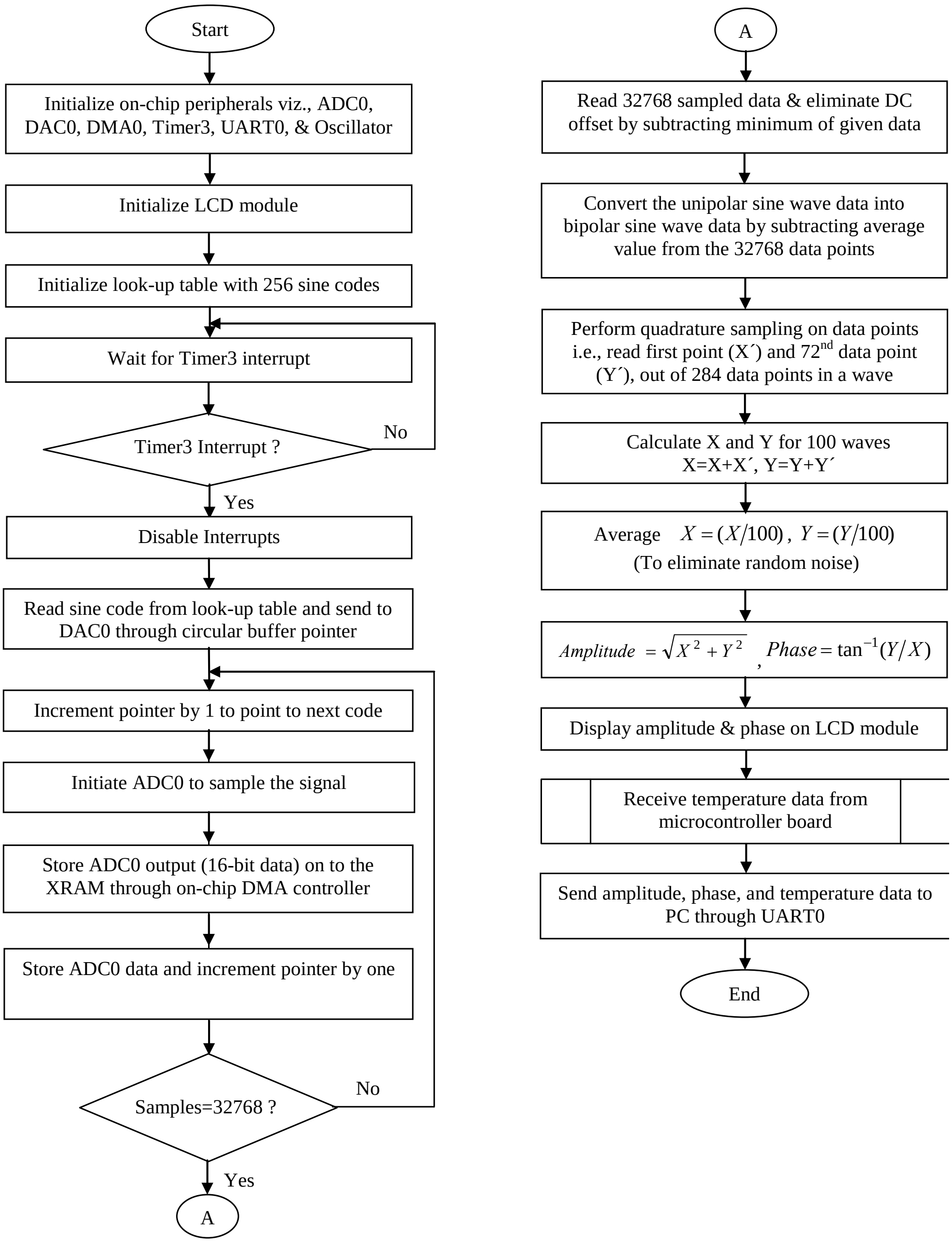

Fig. 5. Flowchart of the lock-in detection algorithm.

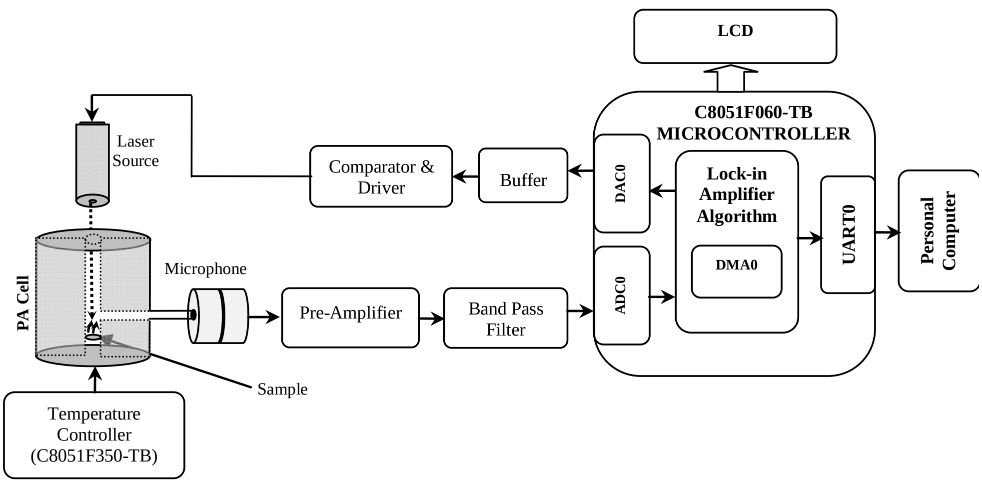

Fig. 6. Application of lock-in amplifier for photoacoustic spectrometer.

5. Results

The system is applied for studying phase transition of sulfur sample. The sample is irradiated with modulated laser beam and PA signal is detected using an electret microphone. The lock-in amplifier designed for the present study is employed to record the PA signal amplitude (in mV) variations as a function of temperature (in °C). A temperature controller is also designed using C8051F0350TB [16] microcontroller employed to vary the temperature of the PA cell at the rate of 0.3 °C/min, which is a standard rate for PA measurements. The experimental setup is initially standardized using carbon black as the sample [17].

The sulfur sample is a yellow powder and does not absorb optical radiation in the visible and IR region. Hence, in order to generate PA signal, the sample is mixed with small amount of carbon black, which has very good absorption in IR region. The sample is taken in a small volume and kept in PA cell. The PA signal amplitude is recorded during heating of the sample from room temperature (30 °C) to 110 °C. The graph, as shown in Fig. 7, is drawn between amplitude and temperature. From the graph, it is observed that there is a remarkable variation in PA signal amplitude and a phase transition occurs at 80 °C. The unique behavior of PA signal is obviously due to sudden changes in the thermal parameters, like heat capacity, thermal conductivity etc., of the sample under investigation. Such changes occur normally during the transition from one phase to another phase of the material.

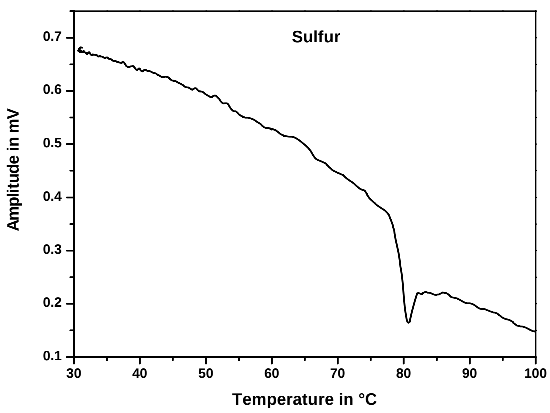

Fig. 7. Phase transition of sulfur obtained using PAS.

6. Conclusions

We have successfully designed and developed an advanced microcontroller based lock-in amplifier of high sensitivity, compact size, and low cost for the detection of low-level optical signals in PAS. The instrument is capable of recovering the low signals buried in large noise. The design contains novel solution to problems arising from the use of microcontroller as central processor. Programming flexibility, re-configurability, and low cost are the good reasons for using microcontroller, but the disadvantage is poor signal processing performance. The proposed design is a good example of single-chip instrument as it contains all the features needed to design standalone system. The application of proposed instrument for PA studies showed as good performance as any commercial instrument available in the market.

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