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# Multi-channel recorder for forces and accelerations

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**Abstract**

The operation of four – channel microprocessor controlled recorder to be used in combination with ENDEVCO piezoelectric force and acceleration sensors has been described in the present study. The purpose of the equipment is to record the data obtained in the course of bruise testing for fruit and vegetables with high water content. The data from four sensors are recorded with 12 bits resolution and maximum sampling frequency of 153 kHz.

## 1. Introduction

Every year significant part of fruit and vegetables is damaged in the course of harvesting, transportation and other processes. The damages encompass among others cuts, abrasions and bruising. Not long ago, the compression tests in quasistatic load conditions were the prevailing method of laboratory testing of mechanical properties for plant materials owing to the unavailability of sufficiently sensitive equipment required to record the processes lasting a few milliseconds. However in real conditions the plant materials are exposed to damages resulting from dynamic loads occurring with high relative velocities of the objects being tested. For instance, falling from the height of 5 cm, in the case of fruit and vegetables results in the impact with velocity of about 1 m/s and consequential displacing and damaging pressure wave [1-3]. The characteristics and the effects of dynamic load significantly differ from the characteristics and the effects of the load applied in quasistatic conditions. Therefore the determination of damage origination mechanism occurring in dynamic load conditions is an essential issue from the point of view of the producers, food processing sector and the designers of plant materials processing machines,

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because it may contribute to increased work effectiveness and reduced costs of manufacturing and storage.

At the moment, precise piezoelectric force and acceleration sensors are available in the market enabling the plant materials testing in dynamic load conditions by means of data acquisition systems with high sampling frequency.

## 2. ENDEVCO force and acceleration sensors

After the review of force and acceleration sensors being available on market, the products offered by ENDEVCO (USA) have been selected by the authors as the most interesting solution. Their high geometrical rigidity is an essential feature enabling accurate measurement of material reaction force at the impact. In the case of acceleration sensors, their minimized weight is the essential parameter enabling their installation directly on the object under testing. If the weight of the object being tested is much greater than the weight of the sensor, disturbance of natural vibration measurement for that object caused by the installed sensor is negliglby small.

The authors have assumed the execution of measurement of dynamic damages for fruit and vegetables in the initial phase on the basis of signals generated by two piezoelectric sensors:

– pressure force sensor, model 2311-10, with sensitivity of 2,27 mV/N and pressure dynamics range within ± 2200N [4],
– acceleration sensor, model 7259A-10, with sensitivity of 10 mV/g and acceleration dynamics range within ± 500g [5].

The functioning principle of a/m sensors consists in the measurement of electric charge generated by piezoelectric elements being subject to deformations caused by the loads. The sensors are characterized by monolithic design solution and incorporate the electronic circuits converting the electric charge generated by piezoelectric element into voltage signal. The sensors are characterized by flat attenuation and frequency response in the range between 10Hz and 20kHz for gain deviation of 1dB (2Hz up to 30kHz for gain deviation of 3dB).

Owing to design solution of the electronic circuit of the sensor, its power supply and connection to measurement circuit is possible by means of a single pair of cables. Refer to Figures 1b,c for the connection of the sensor to its measurement and power supply circuit. The sensor must be supplied by means of CS1 source with current efficiency of 2 up to 10mA. In respect of electric circuit properties, the sensor is represented by two low impedance voltage sources: DC voltage source $U_{E0}$ and AC voltage source $U_{ES}$ (Figure 1a). The value of $U_{E0}$ voltage is constant and included in the range between 8 and 12V as the individual feature of each sensor. Any changes of acceleration / pressure on the sensor are represented by AC voltage source $U_{ES}$ and are included within ±5V in the relation to $U_{E0}$.

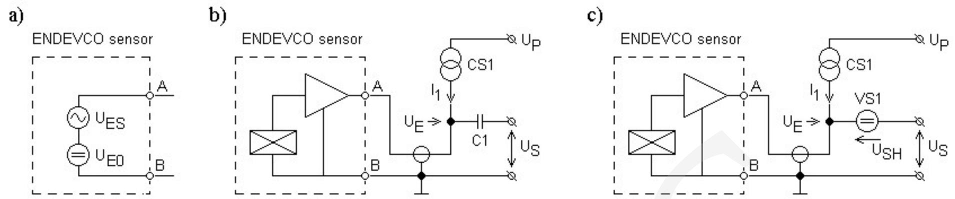



Fig. 1. ENDEVCO sensor in the measuring system: equivalent circuit diagram for the electric system of the sensor (a), measurement system proposed by the manufacturer (b), measurement system applied in the present study (c)

### 3. Design assumptions – selection of micro-controller system

According to assumptions in the initial phase of the designing, the instrument should be designed as an autonomous unit with independent power supply. The electronic system of the recorder should be designed in the manner enabling the measurement in accordance with the predetermined scheme. The results obtained from measurement should be saved in its internal RAM memory. The recorder operation should be monitored by IBM PC computer. The exchange of control data and transmission of measurement data accumulated by the recorder should be carried out by means of serial transmission link.

According to another assumption, the electronic system of measurement circuit will ensure complete integration with ENDEVCO force and acceleration sensors. Additional assumption is that the instrument should record the signals generated by the sensor supplied by any manufacturer and also the static signals e.g. constant pressure signals. It has been assumed that in the case of incompatibility between power supply/ signal interface associated with such a sensor and ENDEVCO paired interface, the sensor will be connected to the recorder by means of an additional electronic system in order to reduce the interface problem according to ENDEVCO standard. The assumptions associated with electrical/mechanical features of measurement circuit have been specified in the following paragraphs:

– the recorder should be provided with four independent measurement circuits with common electric bonding for all sensors (point ‘B’ in Figures 1a,b,c),
– each measurement circuit should be supplied by means of CS1 source with constant current efficiency $I_1$ = 4mA for voltages $U_E$ varying within the range of 0V up to +18V,
– each measurement circuit should be provided with possibility of DC voltage compensation for the sensor, $U_{E0}$, by means of the voltage $U_{SH}$, generated by “floating” voltage source VS1 (Figure 1c).

The assumption presented in the last paragraph above enables the extension of measurement capabilities of the recorder in form of measurement of static signals generated by constant pressure applied to the sensor.

As mentioned above, ENDEVCO piezoelectric sensors are designed for the dynamic measurements. The amplitude sampling for the signal generated by sensor should be carried out with at least 12 bit resolution owing to possible (and to certain extent unpredictable) wide range of signal amplitude variations. In order to detect the details of dynamic signal, the measurement should be performed as frequent as possible. In the case of the attempt to record the sensor signal with the frequency of 20 kHz from 4 sensors, the sampling with the frequency of at least 160 kHz is required. According to the assumption, it will be the highest frequency of signal sampling.

According to the assumption, the duration of signal measurement being performed with maximum sampling frequency, should be longer than 0.5 second. In the case of simple recording methods without compressing, the maximum recording time is proportional to RAM memory size of the recorder. Assuming that a single 12 bit measurement sample is saved in 2 bytes, RAM memory size of 256 kB enables continuous measurement during 0.8 second at sampling frequency of 160 kHz.

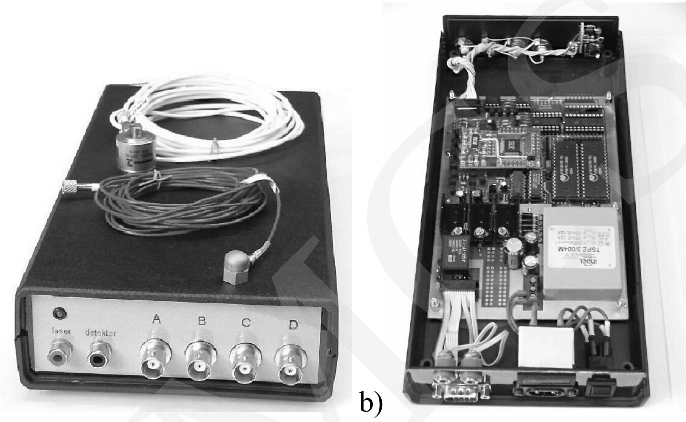
According to the assumptions, ADuC812 micro-controller supplied by Analog Devices [6] will be used for direct management of recorder operation. The micro-controller belongs to MCS51 [7] systems family. Except for standard features of MCS51 family, the ADuC812 system architecture has been supplemented with several auxiliary devices and associated services. The designed recorder described in the present paper will be directly integrated with a/m devices encompassing the following:

– two DAC 12 bit converters – ensuring voltage level regulation, $U_{SH}$, for "floating" voltage source VS1 (Figure 1c),
– high speed 8-channel ADC 12 bit converter – for complete measurement operation,
– stable source of reference voltage – for DAC and ADC operation,
– wide 24-bit address bus – for direct RAM memory addressing,
– DMA unit.

The service provided by DMA unit is extremely valuable and enables the printout of ADC conversion result directly to RAM memory and automatic starting of the next measurement. In the course of DMA unit operation, the execution of program saved in inner ROM memory by micro-controller core is possible in the manner completely independent of ADC converter operation. Therefore the measurements can be performed with very high speed (up to 200 kHz).

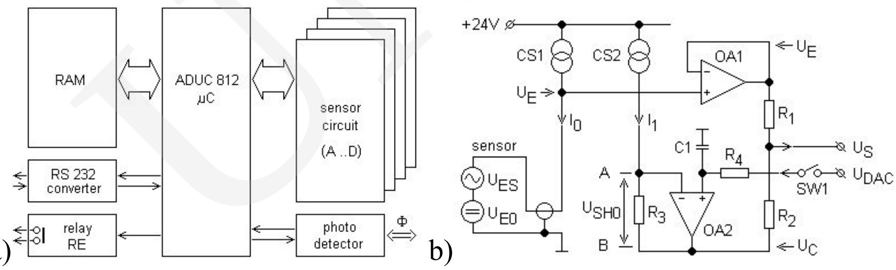
## 4. Microprocessor recorder system

The electronic section of the recorder has been designed as the typical structure for microprocessor systems, enabling data exchange with an external computer by means of RS232C interface. The appearance of the recorder has been illustrated in the photos 1a and 1b with ENDEVCO sensors (7259A-10 and 2311-10) visible on its cover (Photo 1a). Refer to Figure 2a for the block diagram of the recorder and to Figure 2b for the simplified diagram of single measurement circuit. The design solution of remaining channels is identical.




a) b)

Photo 1. The recorder for forces and accelerations: external view (a) and interior (b)




a) b)

Fig. 2. Block diagram for the recorder (a) and single measurement channel (b)

ENDEVCO sensor with paired interface is supplied by means of the power supply source built on the basis of integrated circuit LM344 [8]. The voltage $U_E$ ($U_E = U_{E0} + U_{ES}$), generated by the sensor is supplied to R1/R2 resistance divider via OA1 voltage follower. The voltage level of the signal generated by the sensor is reduced by means of the divider to the level acceptable to ADC converter of the micro-controller. The voltage level on another end of R1/R2 resistance divider is established by means of OA2 operational amplifier. The purpose of the system of OA2 operational amplifier is to perform the function of controlled generator of voltage shift VS1 (Figure 1c). The voltage shift $U_{SH}$, is obtained by adding the voltage $U_{DAC}$, generated by DAC converter of the micro - controller and constant voltage, $U_{SH0}$. The voltage $U_{SH0}$ is generated on R3 resistor as a result of current $I_2$ supplied to that resistor, generated by the current source CS2. The voltage $U_{DAC}$ is applied to non-converting OA2 operational amplifier by means of SW1 analogue key. Owing to the existing C1 capacitor, OA2 operational amplifier performs additional function in analogue memory system for the voltage $U_{DAC}$. It is necessary owing to four measurement channels of the recorder and only two DAC converters incorporated in the micro-controller. The voltage $U_{DAC}$ must be transmitted to measurement channels by means of multiplexing method.

The solution described above has been designed as a "static" solution fully equivalent to the system with "floating" source of reference voltage illustrated in Figure 1c.

In the course of measurements with high sampling frequency and limited RAM size, the time of measurement commencement becomes important. The double i.e. mechanical and electronic measurement release mechanism has been applied in the recorder described herein. The first measurement release stage has been designed in the form of electromagnetic relay, RE (Figure 2a) enabling the electrical releasing of the object under test from mechanical fixture on the gravity falling device. The second release stage consists of photoelectric system ensuring the determination of the time of measurement commencement in a precise manner. The detector system operating in standard transoptor configuration has been illustrated in Figure 3. The system consists of light beam generator and detector circuit. According to the assumption made in the designing phase, the role of the element breaking the light stream Φ, can be performed by CR cable supporting the object under test on the gravity falling device (Photo 2b). It has been also assumed that the linear velocity of CR cable in relation to the detector circuit will be not higher than 3 m/s corresponding to the free fall of the body from the height of about 0,5m. The assumed minimum diameter of cable amounts f = 1mm. For a/m parameters, the change of light stream intensity Φ with light stream diameter $\phi$ = 1mm, should occur within about 300μs. A standard semiconductor laser indicator ($\lambda$ = 660nm) has been used for light beam generation and T, SFH300-3 [9] phototransistor has been applied for light stream Φ detection. Owing to the use of laser transmitting high power radiation in slightly divergent light beam, the influence of external lighting on phototransistor working point could be neglected and the electronic circuits incorporated in the receiver have been reduced (Figure 3).

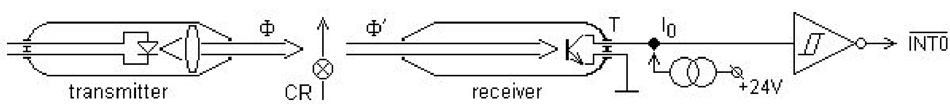



Fig. 3. Measurement start optical detector system

In order to improve the response time efficiency of the detector, T transistor of the photo-detector is provided with power supply from the current source with current $I_0$. The measurement start detection signal, after forming, is transmitted to the interrupt input INT0 of the micro-controller being responsible for direct measurement starting. By means of proposed system, it is practically possible to detect the events with duration time of 150 μs with resolution of 20 μs.

The recorder system has been prepared for operation with two static RAM memories with the total size of 256 kB or 1 MB. The selection of memory size is possible by means of single jumper defining the size of memory.

The serial transmission link has been selected for data exchange between the recorder and the control computer owing to UART port incorporated in ADuC812 micro-controller. The adaptation to electrical requirements of RS232C standard has been achieved by means of MAX232 [10] interface system ensuring correct transmission with 57600Baudrate.

## 5. Programs supervising recorder operation

The recorder system described in the present paper has been designed as a microprocessor based device. In order to enable its correct operation, the software set consisting of two elements has been prepared i.e. the internal program of ADuC812 micro-controller enabling the performance of the simplest controlling and checking functions in the recorder system and the exchange of information between the micro-controller and IBM PC computer supervising the operation of the recorder. The main purpose of the internal program is the execution of measurement in accordance with the settings provided by IBM PC computer. The program supervising the operation of the recorder to be installed in IBM PC computer is another element of a/m software set. The program is suitable for operation in WIN 95/98/XP environment. Its graphical interface has been illustrated in Figure 4.

The desk of recorder operation manager has been subdivided into several topic boxes. The boxes for sensors operation are situated in the LH side of the desk. The boxes enabling the measurement parameters definition are situated in the upper side of the desk. The functions associated with recorder testing and with measurement execution are also incorporated in the RH side of the desk. The graphic box enabling the presentation of single measurement result is situated in the central lower part of the desk.

The presence of the sensor is automatically detected by the program and indicated in the form of selective highlighting of background in the boxes for sensors operation. The user is informed on voltage condition, $U_{E0}$, on individual sensors and is able to define the level of compensating voltage, $U_{SH}$ manually.

Prior to commencement of the first measurement, the sensors to be used for the measurement should be indicated by the user. The user should also perform the settings associated with signal sampling process and the settings associated with the manner of measurement execution. All settings are saved in the program configuration file and are automatically restored after program restarting.

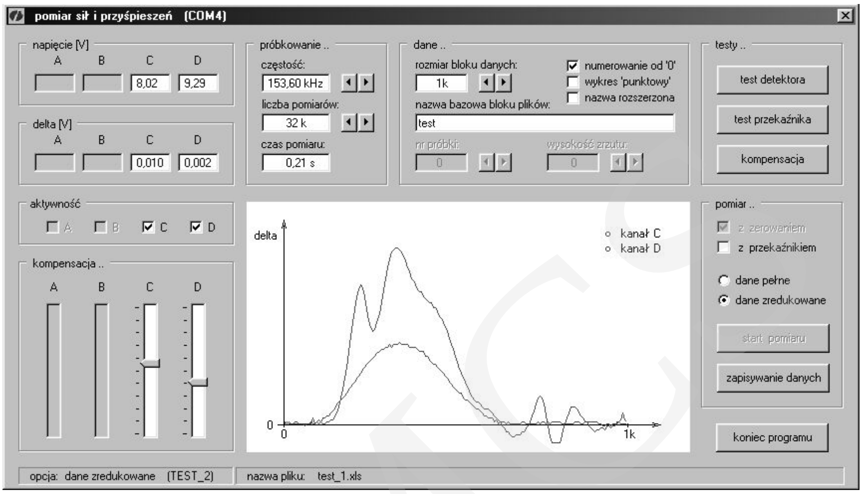


Fig. 4. Recorder operation manager – graphical interface

Owing to significant size of data block accumulated in RAM memory of the recorder in the course of single measurement, high operation rate of the recorder serial transmission channel has been assumed i.e. 57600 Baud. Assuming the transmission of individual bytes with single stop bit and with parity check disabled, the duration of data block with the size of 256 kB will be equal to 45 s approximately. However the occurrence of relatively many corruptions is possible, because the rate of 57600 Baud is one of the highest rates in the case of RS232 interface. To minimize the problem associated with the necessity to repeat the transfer of the whole data block in the case of transmission errors, the transmission of the data is carried out in the form of sub-blocks of 8 kB supplemented with the bytes of complete checksum. In the case of any transmission errors, the transmission of defective data sub-block is automatically restarted by the program. After occurring of three successive errors, data transfer is suspended, After measurement completion, the measurement data can be recorded in the result box. The data file program is recognized by standard spreadsheets.

As mentioned above, various measurement modes are possible by means of the program. In the case of basic measurement mode, RAM memory content indicated by the settings is transmitted to the main program. This measurement mode is difficult when the user has to check the measurement results on current basis and make the decision regarding the mode of measurement continuation. In order to avoid a/m problem, an additional “simplified” measurement mode has been introduced into the program. The program has been provided in preliminary measurement data analysis mechanism enabling automatic selection of interesting data range and their transfer from that area. After selection, the data are entered into the graphical box of the program in the graphical form.

Additionally the successive numbers are assigned to each new measurement in that mode. The assigned number is added to the basic name of data files. Therefore the user is released from the operation consisting in declaration of the data file name at its archiving.

The options associated with switching ON/ OFF test for optical detector and electromechanical relay are also available in the program. A/m options are useful as the help in the course of preparatory phase of recorder starting system. The laser is switched on and the system of photoelectric receiver is activated by means of detector test. The lighting of phototransistor is indicated by acoustic signal extremely facilitating the trimming of optical circuit of the recorder.

### 6. Measuring station for dynamic tests

Refer to Photos 1a,b for the layout of the measuring station designed for testing of fruit and vegetables sensitivity to bruise process [3]. The measuring position consists of the gravity falling device with scale (1), optical system of measurement commencement detector (2) and impact force sensor (3). The object under test, e.g. an apple, is attached to the gravity falling device by means of cables (4). The acceleration sensor to be installed directly on the object under test, is not visible in the photos.

a) b)

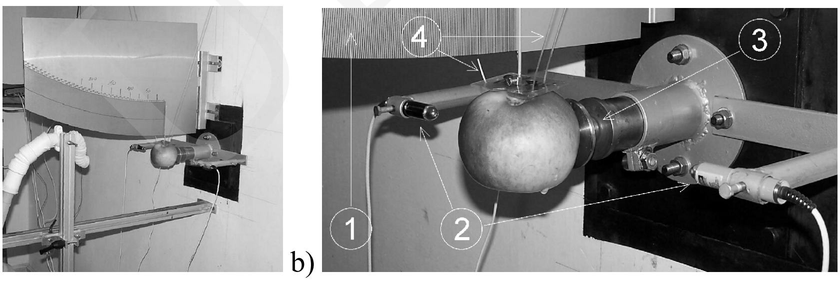



Photo 2. The measuring station designed for dynamic tests: external view (a) and measuring system elements (b) [3]

The measurement consists in the release of the object under test from its position on the gravity falling device and in recording the impact time by means of impact force sensor. The measurement is repeated many times until the inner structure of the sample is destroyed. The incorporation of the acceleration sensor on the object under test will enable the monitoring of stress wave propagation in that object in the manner synchronized with impact force measurement.

### 7. Problems associated with ADuC812

As mentioned above, ADuC812 micro-controller has been selected for direct monitoring of the recorder operation owing to the capacities of that system. The possibility to perform ADC measurement in the manner completely independent of micro-controller core was one of more important features of the system. Therefore DAC converters generating the compensation voltage for sensors in the multiplexed mode could be operated continuously. Furthermore, the direct and automatic operation of external RAM memory with 24 bit address box was also ensured by means of the controller in the course of measurement. A/m features were possible by means of DMA controller block enabled for the measurement time.

In the course of the programming of micro-controller it appeared that in the case of high signal sampling frequencies, the measurement could be possible only once. It was possible after RESET signal generated by means of computer for the micro-controller. Such a situation occurred when DMA channel released with T2 timer was used for measurement management. Every attempt of measurement after the first measurement was unsuccessful. After many tests it appeared that each attempt of DMA mode calling after the first measurement resulted in immediate generation of interruption ending DMA cycle. A/m fact has been not recorded in the official list of errors for the micro-controller ADuC812 [11]. The problem has been avoided by means of WatchDog system incorporated into the controller structure. After each execution of the measurement, RESET of the micro-controller was executed by WatchDog system without losing any data stored in the internal and external RAM memory of the micro-controller system.

## Conclusions

The recorder has been designed as a specialized device to be used for tests associated with the mechanisms of fruit and vegetables damaging in dynamic load conditions. The integration of the recorder with four sensors is possible. The inputs of the device have been adapted to direct operation of piezoelectric ENDEVCO sensors. The static signal measurement is possible by means of the set consisting of four floating, independent of each other, and regulated voltage sources. The application of ADuC812 micro-controller enables the signal recording with 12bit resolution and maximum sampling frequency of 153 kHz.

The recorder for forces and accelerations meets all assumptions established in the initial phase of the design. Its measuring capacity has not been lost as a result of the problems associated with DMA channel re-activation detected in the course of ADuC812 system programming.

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