Carl von Ossietzky University Oldenburg – Faculty V - Institute of Physics
Module Introductory Laboratory Course Physics – Part I

Data Acquisition and Processing with the PC

Keywords:
Continuous and discrete signals, sampling, sampling rate, sampling frequency,resolution, analog/digital conversion, weighing method, multiplexing, dual numbers, bit, digit.

Measuring program:
Use of a MATLAB-script for data acquisition with an A/D board, determination of the resolution of an A/D board, measurement of alternating voltages, calibration of a pressure sensor, measurement of temporal pressure changes.

References:

/1/ Kose, V. [Hrsg.]; Wagner, S. [Hrsg.]: „Kohlrausch - Praktische Physik Bd. 3“, Teubner, Stuttgart, 1996

1 Introduction

In many physical experiments, the change of a value of a physical quantity G is to be acquired as a function of time t. Such quantities may be e.g.: Pressure p, temperature T, intensity of radiation I, force F, acceleration a, among others. For recording $G(t)$, sensors are used which convert the value of $G(t)$ e.g. into a voltage signal $U(t)$ (compare experiment "*Sensors...*").

Previously, so-called XT recorders were used to record the temporal course of $U(t)$ on paper. Nowadays, PCs are used instead in combination with data acquisition devices (DAQ devices), with which the course of voltage signals as a function of time $U(t)$ is recorded digitally.

In this experiment, the most important properties of such a data acquisition system and a software required for their control (exemplarily `MATLAB` with the `Data Acquisition Toolbox`) are illustrated.

2 Basics of Data Acquisition

2.1 Continuous and Discrete Signals

With a data acquisition system an analog voltage signal $U(t)$ is transformed into a time series of numerical values $N(i)$, $i \in \mathbb{N}$, that can be further processed with the PC. In general, the signal $U(t)$ is neither restricted to certain voltage values nor to certain time values according to Fig. 1 (top). Therefore, it is called a *time- and value-continuous* signal.

Even with very fast (and hence expensive) electronic components of a DAQ device, voltage values $U(t)$ can be recorded (*sampled*) only at discrete points in time t_i at the interval

$$(1) \qquad \Delta t = t_i - t_{i-1} \qquad\qquad i \in \mathbb{N} \setminus \{0\}$$

The quantity Δt is called *sampling interval*, the reciprocal value of this quantity,

$$(2) \qquad R = \frac{1}{\Delta t} \qquad\qquad [R] = \mathrm{s}^{-1}$$

is called *sampling rate* or *sampling frequency* and is given in *samples/*s or only in 1/s. The greater R, the better is the *temporal resolution* of the signal recording.
In practice, a restricted sampling rate is often used in order to reduce the amount of data to be stored. The question of how large R has to be chosen to enable the signal course to be recorded correctly will be investigated in detail later on in the experiment "*Fourier analysis*".

Due to R being restricted to $\Delta t > 0$, and hence $R < \infty$, a *time-discrete* signal $U(t_i)$ is generated by sampling $U(t)$ as shown in Fig. 1 (middle). For better visibility, vertical lines are drawn in the diagram instead of data points whose lengths correspond to the individual voltages $U(t_i)$.

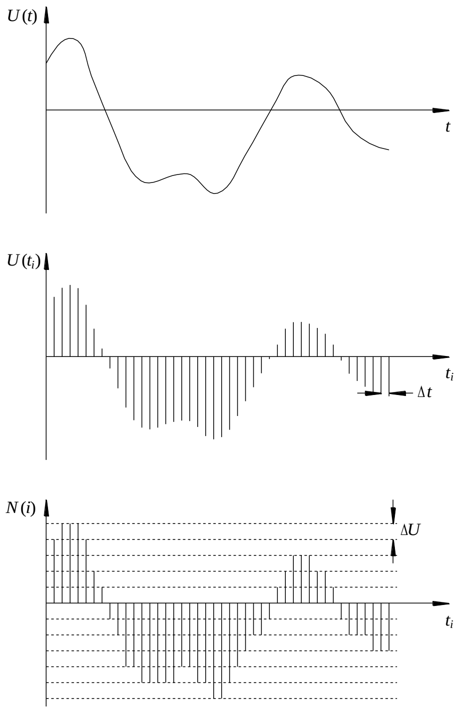


Fig. 1: Conversion of a value- and time-continuous voltage signal $U(t)$ (top) into a time-discrete signal $U(t_i)$ (middle) and a value- and time-discrete numerical sequence $N(i)$ (bottom).

The conversion of an analog voltage value $U(t_i)$ into a numerical value $N(i)$ by means of an *analog to digital converter* (A/D converter, cf. Chap. 2.2) of a DAQ device is not feasible at an arbitrary precision, but is restricted by the *resolution* A of the A/D converter. A is given in bit:

$$A = m\ \text{Bit}, \qquad m \in \mathbb{N} \tag{3}$$

For every DAQ device, the measurable input voltage is restricted to an interval of the width

$$U_e = U_{\max} - U_{\min} \tag{4}$$

For A/D conversion, m bit and thus 2^m numerical values in the range between $N = 0$ and $N = 2^m - 1$ are available for this voltage interval. Hence, the difference between two voltage values, the assigned numerical values of which differ by just 1 (1 *digit*), is

$$\Delta U = \frac{U_e}{2^m - 1} \tag{5}$$

This quantity is also called the *resolution* of the A/D conversion. With $\Delta U > 0$, the time-discrete signal in Fig. 1 (middle) becomes a time- and value-discrete signal by A/D conversion as shown in Fig. 1 (bottom). Within a maximum voltage range (e.g. ± 10 V), U_e may often be restricted to a smaller interval by software (cf. Table 1). This can be used to increase the resolution of the A/D conversion, if the input signal is known lie within this interval.

An example for this: If the voltage interval is set to ± 10 V, then $U_e = 20$ V and, according to Eq. (5) (rounded to 4 significant digits): $\Delta U = 0.07813$ V for $m = 8$ and $\Delta U = 0.0003052$ V for $m = 16$. If the voltage interval is constrained to ± 0.5 V, then $U_e = 1$ V and higher resolution is achieved for an equal number of bits: $\Delta U = 0.003906$ V for $m = 8$ and $\Delta U = 0.00001526$ V for $m = 16$.

2.2 Principle of A/D Conversion

Analog to digital converters (ADC) work on different principles. A conversion method frequently applied in data acquisition is the so-called *weighing method* working on the principle of *successive approximation*. This method is schematically represented in Fig. 2.
First, all m bits of the converter are set to 0. After that, the most significant bit (MSB) with the „number“ m and the significance 2^{m-1} is set to 1 on a trial basis. A voltage source contained in the A/D converter subsequently generates a voltage U_D with the value

$$(6) \qquad U_D = k\,2^{m-1} \qquad\qquad [k] = V$$

k being a proportional factor dependent on U_e. A *comparator* is used thereafter to verify

$$(7) \qquad U(t_i) \geq U_D \text{ ?}$$

If so:

- bit no. m continues to be set to 1,
- bit no. m-1 is set to 1, too,
- the internal voltage source generates a new voltage U_D with the value

$$(8) \qquad U_D = k\left(2^{m-1} + 2^{m-2}\right)$$

If not:

- bit no. m is set back to 0,
- bit no. m-1 is set to 1,
- the internal voltage source generates a new voltage U_D with the value

$$(9) \qquad U_D = k\,2^{m-2}$$

Thereafter, the validity of Eq. (7) is verified anew with the voltage U_D from Eqs. (8) and (9), respectively, and depending on the result, bit no. m-1 is treated like bit no. m was treated before.

Analogous steps are performed until the least significant bit (LSB) with the number 1 and the significance 2^0 has been obtained. In this way, the values 0 or 1 of the individual bits can be determined by means of successive approximation between $U(t_i)$ and U_D.

In the example from Fig. 2, the voltage level $U(t_i)$ (blue) is associated with the binary number 011 100 11, which is $N = 115$ in decimal representation. If we assume that $U_e = 10$ V, the binary number 111 111 11 (corresponding to $N = 255$) must be associated with the voltage level 10 V. This means, that for this value of U_e , we must have:

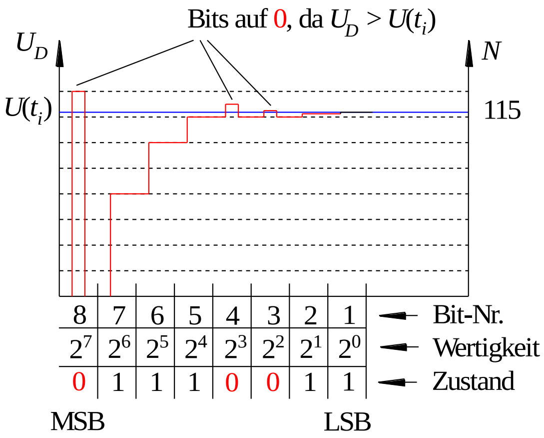
$$k = \frac{10}{255}\,\text{V}$$

Hence, under this prerequisite the binary number 011 100 11 from Fig. 2 corresponds to a voltage value $U = k\,N = k \times 115 \approx 4{,}51$ V.

Each conversion process takes a certain time period t_w, which increases linearly with the number m of bits. Therefore, $\Delta t \geq t_w$ must hold for the sampling interval Δt from Eq. (1). Thus t_w determines the minimal temporal distance between two successive samplings and hence the maximum sampling rate R_{max}:

$$(10) \qquad R_{\max} = \frac{1}{t_w}$$

The described weighting process only works, if $U(t_i)$ does not change appreciably over the time t_w. Hence, it is necessary to guarantee that $U(t)$ remains nearly constant over temporal intervals of width of t_w before a signal $U(t)$ is recorded by a DAQ device.



Bit-Nr.	8	7	6	5	4	3	2	1
Wertigkeit	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Zustand	0	1	1	1	0	0	1	1

Fig. 2: Principle of A/D conversion according to the weighing method for an A/D converter with $m = 8$ bits. For the voltages U_D generated by the A/D converter (red) that exceed the input voltage $U(t_i)$ (blue), the corresponding bits are set to 0. In the example, these are the bits having values 2^7, 2^3 and 2^2. The other bits are set to 1, since $U_D < U(t_i)$ is fulfilled for the voltages U_D.

2.3 Multiplexing

Normally, DAQ devices have *several signal inputs* (*channels*) of which M are used depending on the application. In most cases, however, only *one A/D converter* is available on the boards. Sampling of the M input signals must then be done in the so-called *multiplexing* mode. At first, the signal at channel 1 is sampled, then with a temporal delay of t_w each the signal at channel 2, the signal at channel 3 and so on, until channel M has been reached. After the time Δt has passed, the process starts anew with the signal at channel 1. This has the consequence that the maximum sampling rate R_{max} is reduced to R_{max}/M per channel in that case.

t_w being the minimal time difference between two samples, an actually simultaneous sampling of two or more signals is not feasible in the multiplexing mode. In practice, however, the time difference t_w is often small compared to the time in which the input signals vary appreciably, so that it can be neglected.

An example will illustrate this fact (Fig. 3). Two signals $U_1(t)$ and $U_2(t)$ are to be recorded simultaneously at a sampling rate of $R = 1$ kHz. The temporal distance between successive sample values of U_1 and U_2 shall thus be $\Delta t = 1$ ms. The A/D converter of the DAQ device is assumed to allow a maximum sampling rate of $R_{\text{max}} = 250.000\ \text{s}^{-1}$, the minimal temporal distance between two samplings thus being $t_w = 4\ \mu\text{s}$. The first value of the signal $U_1(t)$ is assumed to be recorded at time $t = 0$, the first value of signal $U_2(t)$ is then recorded at time $t = t_w$. Sampling of the second value of $U_1(t)$ is done at time $t = \Delta t$, the second value of $U_2(t)$ at time $t = \Delta t + t_w$ and so on. As $t_w << \Delta t$, it is a good approximation in this example to speak of ”simultaneous“ sampling.

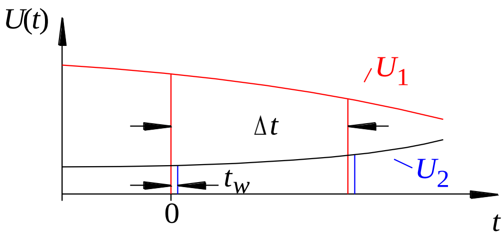


Fig. 3: “Simultaneous” acquisition of two voltage signals $U_1(t)$ and $U_2(t)$ using a DAQ device operated in multiplex mode. Refer to the text for details.

2.4 Connection Types for Voltage Signals

The channels of a data acquisition board can usually be connected differently. In the simplest operation mode, the *single-ended mode* (SE mode, or *grounded-source* mode: GS), all M input voltages $U_j(t)$ ($j = 1,\ldots,M$) are referred to the *case ground potential* of the DAB, cf. Fig. 4, left[1]. This mode involves two disadvantages:

1. Fluctuations in the case ground potential affect the measured potential difference between the connector j and the case ground.
2. All input voltages U_j must have a common reference potential, as in Fig. 5 (left) the voltages U_1 and U_2 with the case ground as reference potential.

If the input voltages U_j do not have a common reference potential[2], as e.g. the partial voltages U_j on the resistances of a voltage divider according to Fig. 5 (right), the *differential* operation mode (DI mode, or *floating-source* mode: FS) has to be used (Fig. 4 right). In this mode, the potential *differences* between two separate supply contacts each are recorded for each channel. The advantages of this mode are:

1. Identical potential fluctuations at both supply terminals of a channel[3] do not affect the measured signal, because only the potential difference U between the supply terminals is measured.
2. The input voltages U_j can have different reference potentials; there is no common reference potential.

However, the DI mode also produces one disadvantage. Since each DI input requires *two* separate contacts on the data acquisition board, the number of DI inputs is only half the number of SE inputs.

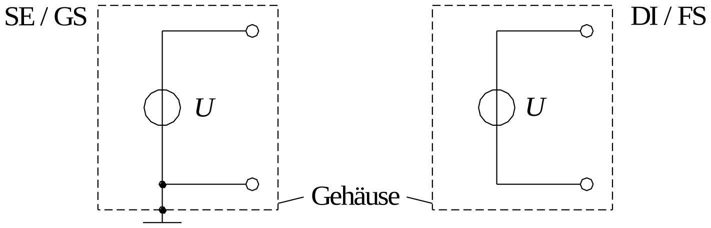


Fig. 4: *Left*: SE signal connection with the case ground (⊥) of the DAQ device as reference potential (*grounded source*, GS). *Right*: DI signal connection without reference to a potential of the DAQ device (*floating source*, FS).

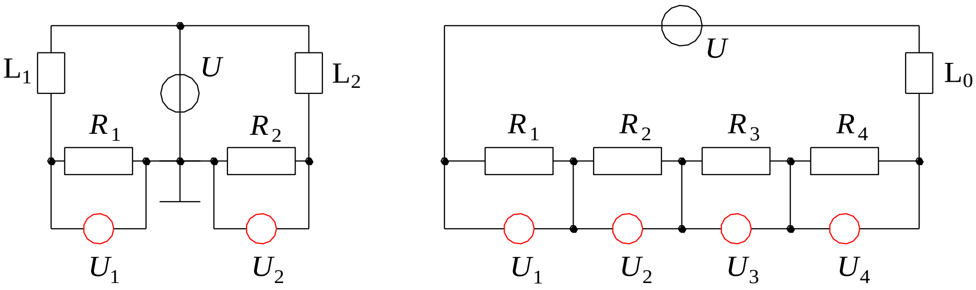


Fig. 5: Voltage source U with connected resistances R_j and loads L_j. *Left*: Partial voltages U_j with common reference potential (ground). *Right*: Partial voltages without common reference potential. Voltmeters for measuring the partial voltages are shown in red.

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[1] This is equivalent to the measurement of two voltages with a two-channel oscilloscope, for which the outer contacts of the BNC-socket connectors lie on the same potential.

[2] Such signals are also called *floating source* (FS) signals. The name comes from the fact that there is no common fixed reference potential. On the contrary, the potentials of both contacts can float at constant potential difference (voltage). Example: A potential difference of (5 V - 0 V) = 5 V yields the same measurement result as the difference (100 V – 95 V) or (1.000 V – 995 V).

[3] Potential fluctuations can e.g. be caused by feed throughs into the connecting cables which connect a sensor to the DAQ device.

3 Characteristics of the Data Acquisition Device

In the introductory laboratory a DAQ device supplied by NATIONAL INSTRUMENTS (NI) are used in the introductory laboratory course. The most important characteristics of this device are listed in Table 1.

Table 1: Characteristics of the NI myDAQ device used in the introductory laboratory course.

Parameter	**NI myDAQ**
A/D converter type	successive approximation
Number of inputs	2 DI / 1 stereo input
Maximum sampling rate R_{max} / s^{-1}	200.000
Resolution A / Bit	16
Range of input voltage / V (adjustable by software)	± 2 , ± 10

The data acquisition device, as shown in Fig. 6, offers the possibility to connect different signals. Thus the NI myDAQ device can be used with appropriate software as a multimeter utilizing the inputs for banana plugs, on the bottom of the device (Fig. 6 below). In addition there is an AUDIO IN input and AUDIO OUT output on the lower right side.

With the help of screw terminal connections on the right side of the device digital and analog signals can be connected, whereby in the basic laboratory we only will detect and convert analog voltage signals. A small box with BNC sockets is electrically connected to the two analog inputs AI 0 and AI 1 of the NI myDAQ device (Fig. 6 above). In addition to ON/OFF switches of the box, here are additional switches AGND 0 und AGND 1 for the analog ground. Furthermore, located at the bottom of the small box, there exist an additional AI 0 entrance for banana plugs.

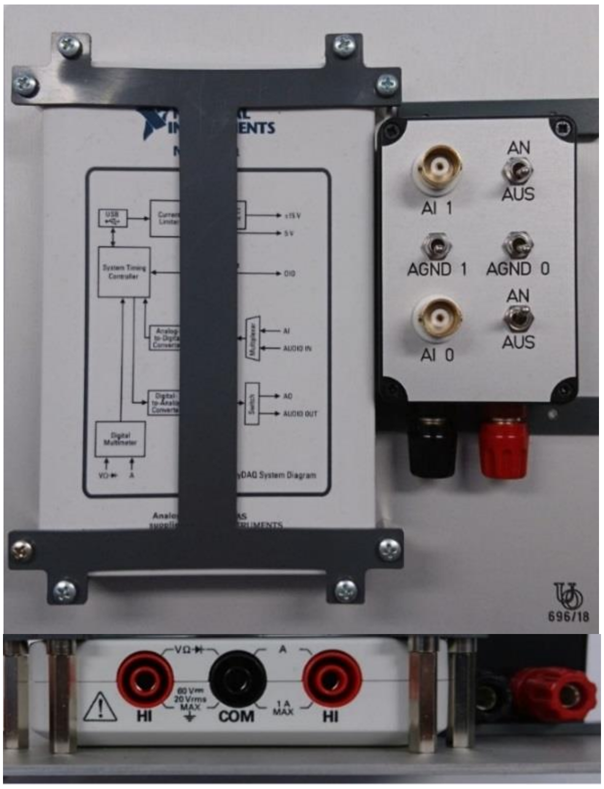


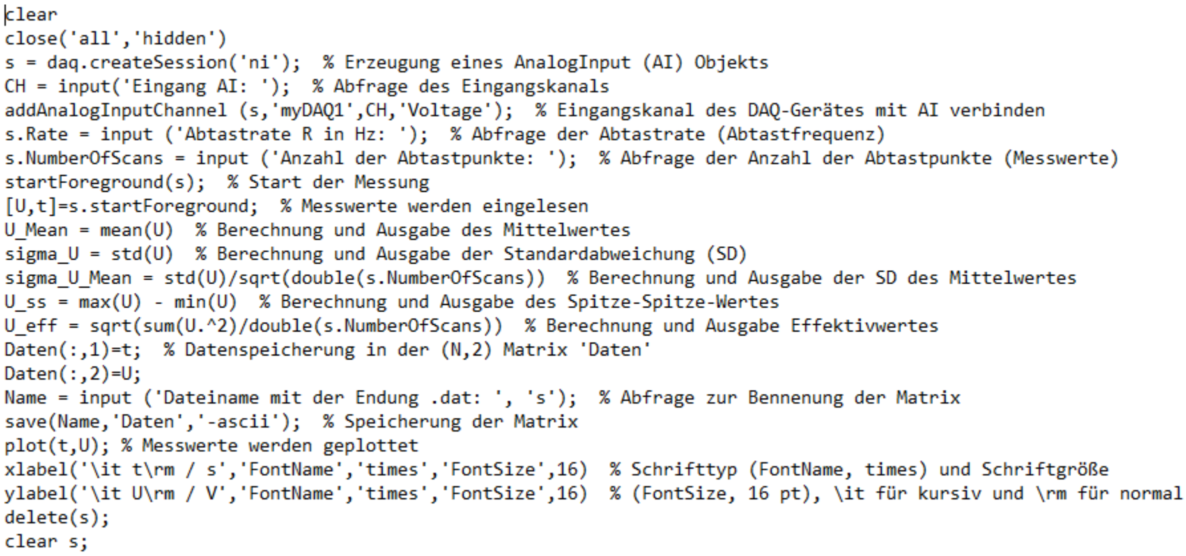
Fig. 1: A photo of the top view (top) and a photo of the bottom edge (bottom) of the NI myDAQ device.

The NI myDAQ device with the attached small box is treated as a “black box” because in the basic laboratory we are only dealing with the detection of a maximum of 2 different voltage signals.

4 MATLAB-Software for Controlling a Data Acquisition Device

In the Introductory laboratory course, the software `MATLAB` version 2017b with the `Data Acquisition Toolbox` is used to control the NI myDAQ device specified in Chapter 3. The interface between the operation system of the PC (`Windows 10`) and the `MATLAB` software is the driver `NI-ELVISmx`.

Fig. 7 shows a `MATLAB` script file (m-file) that can be used to read, process and store a voltage signal to the PC via the data acquisition device.
The `MATLAB` script file „Datenerfassung_PC_2019_Matlab2017b.m" is provided on the desktop of the lab PC and under StudIP for use.



```
clear
close('all','hidden')
s = daq.createSession('ni');  % Erzeugung eines AnalogInput (AI) Objekts
CH = input('Eingang AI: ');  % Abfrage des Eingangskanals
addAnalogInputChannel (s,'myDAQ1',CH,'Voltage');  % Eingangskanal des DAQ-Gerätes mit AI verbinden
s.Rate = input ('Abtastrate R in Hz: ');  % Abfrage der Abtastrate (Abtastfrequenz)
s.NumberOfScans = input ('Anzahl der Abtastpunkte: ');  % Abfrage der Anzahl der Abtastpunkte (Messwerte)
startForeground(s);  % Start der Messung
[U,t]=s.startForeground;  % Messwerte werden eingelesen
U_Mean = mean(U)  % Berechnung und Ausgabe des Mittelwertes
sigma_U = std(U)  % Berechnung und Ausgabe der Standardabweichung (SD)
sigma_U_Mean = std(U)/sqrt(double(s.NumberOfScans))  % Berechnung und Ausgabe der SD des Mittelwertes
U_ss = max(U) - min(U)  % Berechnung und Ausgabe des Spitze-Spitze-Wertes
U_eff = sqrt(sum(U.^2)/double(s.NumberOfScans))  % Berechnung und Ausgabe Effektivwertes
Daten(:,1)=t;  % Datenspeicherung in der (N,2) Matrix 'Daten'
Daten(:,2)=U;
Name = input ('Dateiname mit der Endung .dat: ', 's');  % Abfrage zur Bennenung der Matrix
save(Name,'Daten','-ascii');  % Speicherung der Matrix
plot(t,U); % Messwerte werden geplottet
xlabel('\it t\rm / s','FontName','times','FontSize',16)  % Schrifttyp (FontName, times) und Schriftgröße
ylabel('\it U\rm / V','FontName','times','FontSize',16)  % (FontSize, 16 pt), \it für kursiv und \rm für normal
delete(s);
clear s;
```

Abb. 2: `MATLAB` script for data acquisition with the PC.

5 Experimental Procedure

Equipment:

Digital oscilloscope TEKTRONIX TDS 1012 / 1012B / 2012C / TBS 1102B - EDU, digital multimeter (AGILENT U1251B / U1272A), function generator (AGILENT 33120A / 33220A), PC with data acquisition device (NATIONAL INSTRUMENTS myDAQ), 9 V battery with connector, power supply (PHYWE 0 - 15 / 0 - 30) V, pressure sensor (SENSORTECHNICS HCLA12X5DB) on base plate with valves on mount, ERLENMEYER flask with smoothed plug on table, U-tube manometer with holder and reading scale (filled with water), beaker glass on support jack, flexible tubes and couplings, air balloon, kitchen paper roll.

5.1 Operating the PC and the Data Acquisition Board

Before turning on the PC make sure that the DAQ device is connected with the PC (when the PC is running, this connecting cable must not be plugged in nor unplugged!). After turning on the PC, log in to with the known *username* and *password*.

The BNC adapters makes it easy to connect the signals to be measured to the DAQ by using coaxial cables. The connection of the signal sources (battery, power supply, pressure sensor) takes place in this experiment via one of the BNC inputs AI 0 or AI 1. The switch of the respective BNC socket AGND is switched off for this experiment and thus the DAQ device is in FS mode (see chapter 2.4)

The maximum input voltage range that the data acquisition board can withstand is ± 10 V; this range should not be exceeded. As a control, all of the input signals of the data acquisition board are therefore simultaneously displayed on the oscilloscope.

5.2 Starting MATLAB

`MATLAB` version 2017b is started by double click on the respective icon. Then the *m*-file *"Datenerfassung_PC_2017b.m"* is selected via the tab >OPEN<.

5.3 Measurement of a DC Voltage and Determination of the Resolution

A 9 V battery is connected to the input channel of the DAQ device and in parallel with a multimeter. The voltage is read into the PC ($R = 100\ \mathrm{s}^{-1}$ and $N = 100$ are good orientation values) and the mean and the standard deviation of the single measurement are determined from the N measured values U_i. The determined values are compared to the value measured with the multimeter and its maximum error.

The U_i are plotted over i using `Origin`. It can be seen from the plot, that the U_i differ only by integer multiples of a voltage value ΔU. ΔU is determined and compared to the expected resolution of the DAB according to Eq. (5). Here sufficiently number of digits must be specified.

5.4 Measurement of AC Voltages

A sinusoidal alternating voltage without direct current offset (frequency 50 Hz, amplitude 2 V) is generated using a function generator (FG). The output of the FG is connected to the input channel of the DAB and in parallel with the digital oscilloscope and the multimeter. The voltage is read into the PC ($R = 1{,}000\ \mathrm{s}^{-1}$ and $N = 1{,}000$ are good orientation values) and its peak-peak value U_{ss} as well as its effective value U_{eff} are determined. Error information should be taken into account for the respective quantities.

U_{ss} is, in good approximation, determined by the difference between the maximum and the minimum of the acquired N voltage values U_i. The corresponding formula in `MATLAB`-notation reads:

```
U_ss = max(U) - min(U)
```

U_{eff} is given by:

$$(11) \qquad U_{\mathrm{eff}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} U_i^2}$$

(cf. Chapter „*About the set-up of electric circuits..*" of this script). This value is called the *rms*-value *(root-mean-square* value).

The value of U_{ss} recorded by the DAQ device is compared to the value measured with the oscilloscope and the effective value U_{eff} recorded by the DAB is compared to the value indicated by the multimeter and to the theoretical expectation. Both devices must be configured so (V/DIV on the oscilloscope, measuring range on the multimeter) that U_{ss} ,and respectively U_{eff} can be measured with the highest possible resolution.

The measurements described above are repeated with a square-voltage signal of the same frequency and amplitude. Please plot the corresponding voltage curves as a function of time.

5.5 Measurement of Pressure Differences

A pressure sensor of the type HCLA12X5DB, which has already been used in the experiment "*Sensors...*", is available for measuring pressure changes in gasses. Details about its operational principle and its usage are to be taken from the accompanying script.

5.5.1 Calibrating the Pressure Sensor

The pressure sensor is calibrated by adjusting defined pressure differences Δp between the two connecting sleeves and by measuring the respective output voltage U for each value of Δp. Defined pressure differences can be adjusted using a set-up according to Fig. 6, which was already described in the script for the experiment "*Sensors...*" (valve H_1 open, valve H_2 closed).

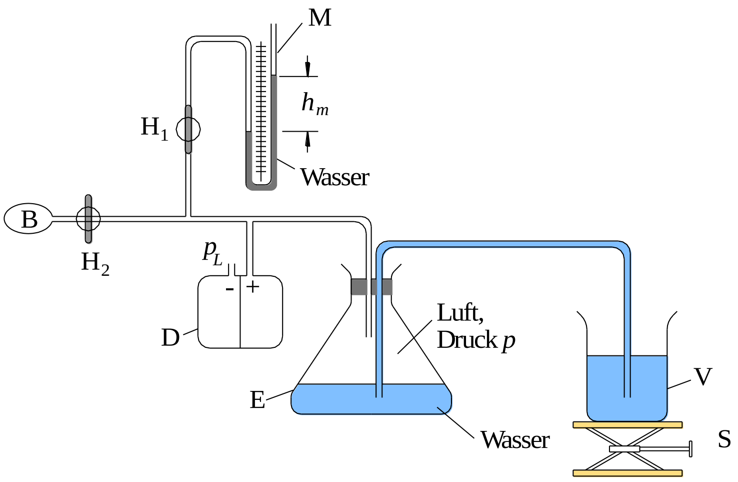


Fig. 6: Setup for adjusting pressure differences $\Delta p > 0$ as compared to the ambient air pressure p_L. Refer to the text and the script for the experiment "*Sensors…*" for details.

The pressure difference

$$\Delta p = p - p_L \tag{12}$$

at a level difference h_m in the manometer is given by:

$$\Delta p = \rho_m \, h_m \, g \tag{13}$$

ρ_m being the density of the fluid in the manometer (here water) and g being the acceleration of gravity. For g, the value for Oldenburg is used: $g = 9.8133\ \mathrm{m/s^2}$, which is assumed to be exact (error free)[4]. For the density ρ_m of water within the temperature range of (20 ± 2) °C a value of 998 $\mathrm{kg/m^3}$ can be used that is also assumed to be accurate.

The output voltage of the pressure sensor D is measured with the PC for at least ten different levels h_m (to be measured) ($R = 100\ \mathrm{s^{-1}}$ and $N = 100$ are good orientation values). The mean and standard deviation of the mean are calculated from the data measured for each individual height. It is most expedient to directly put these data into an `Origin` worksheet.

Finally, Δp is plotted over U and the parameters of the regression line are determined. With the aid of the parameters of this calibration curve, the output voltages of the pressure sensor can subsequently be converted into pressure differences.

5.5.2 Measurement of Temporal Pressure Changes

For measuring temporal pressure changes with a set-up according to Fig. 6, the valve H_2 is opened in addition to valve H_1 to establish a connection between the balloon B and the air volume in E. An overpressure in B is produced by raising the beaker glass V. Subsequently, the balloon is speedily squeezed together once and then released. While squeezing the balloon care must be taken that the maximum pressure difference of the sensor ($\Delta p = +1.25 \times 10^3$ Pa) is not exceeded and that the pressure at the „+"-connection of the pressure sensor remains always above the pressure of the ambient air. The latter condition is ensured as long as the water level in the right leg of the U-tube shown in Fig. 6 is higher than the water level in the left leg.

The temporal course of the pressure difference while and after squeezing the balloon is to be recorded until the water level in the manometer is again stable at its initial level. This measurement is carried out twice.

The recorded values of the output voltage of the pressure sensor are converted to pressure differences using the calibration data from Chap. 0. The results are plotted in diagrams $\Delta p(t)$ (including appropriate measurement uncertainties $\Delta\Delta p(t)$) and analysed.

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[4] Value taken from http://www.ptb.de/cartoweb3/SISproject.php (14.10.2018); the error of $2\times10^{-5}\ \mathrm{m/s^2}$ is neglected.