Hands-on steps of practical course: Vibrating wire monitors and beam profile measurements

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Contents

The scope of the work:

Practical course setup presents the main units of beam profile station based on Vibrating Wire Monitor (VWM). The steps of measuring the primary frequency data of a vibrating wire monitor and the mathematical processing of the data to reconstruct the beam profile are presented. Beam is modelled by laser.

1. Test-bench of the VWM station

Vibrating wire monitors were originally designed for accelerator beam profiling. Our test-bench uses a laser instead of an accelerator beam, which allows us to perform experiments to investigate the process of beam profiling (Fig. 1).

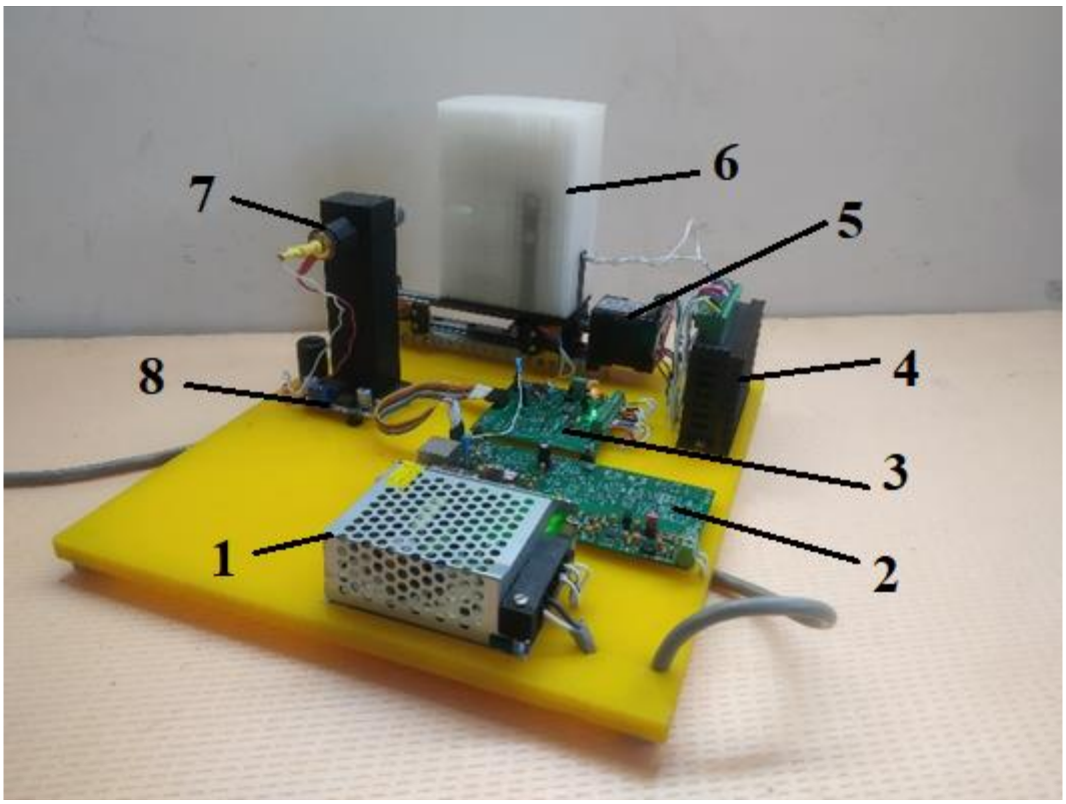

Figure 1. 1 - Power supply, 2 - wire autogeneration board, 3 - step motor control board, 4 - step motor driver, 5 - linear actuator, 6 - VWM covered by anticonvection box, 7 - laser, 8 - tunable DC converter for laser supply.

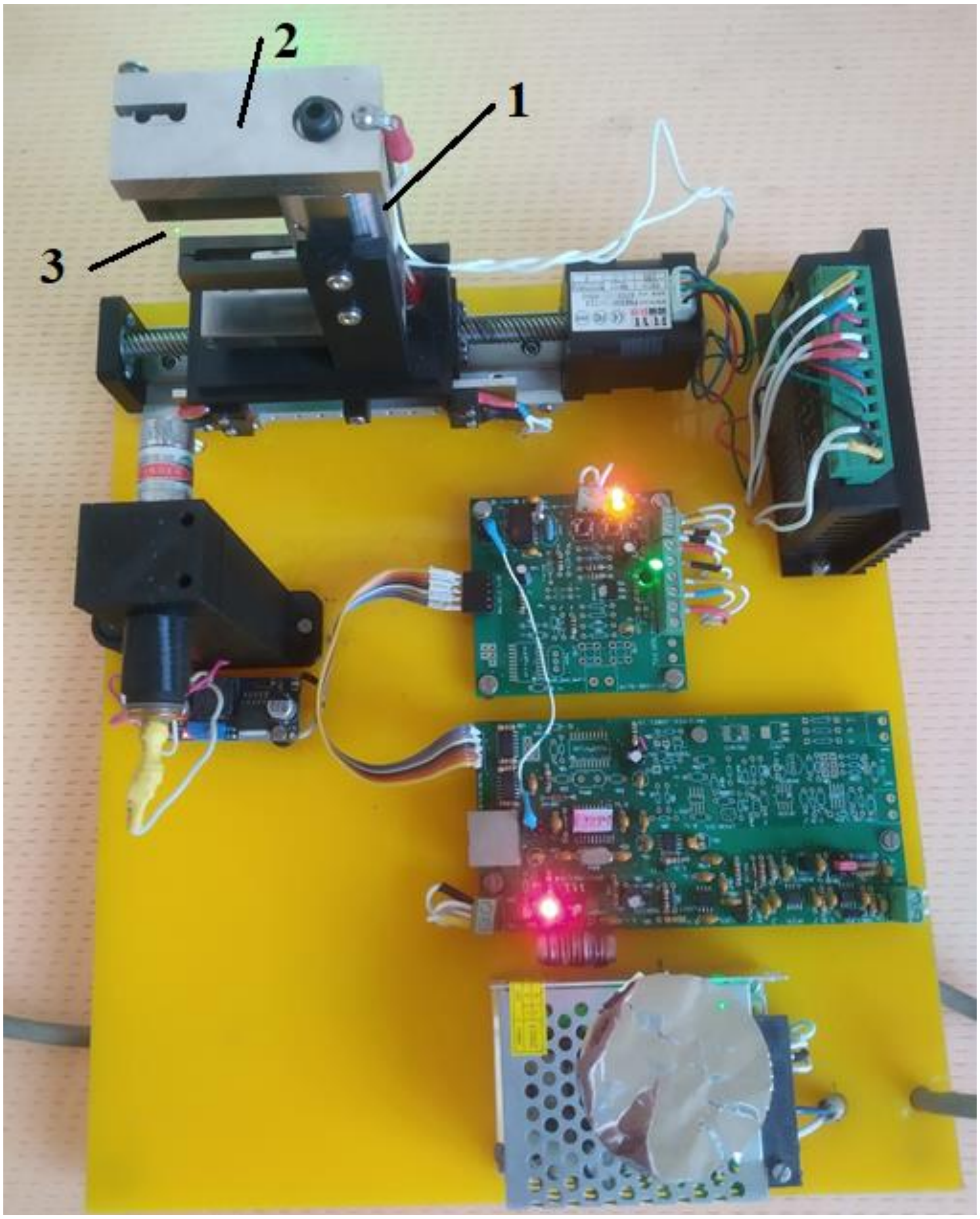

Figure 2. Main view with open anticonvection box. 1 - VWM, 2 - VWM upper clips, 3 - laser spot on the vibrating wire.

The power supply converts the 50 Hz and 220 V to a DC 12 V, which is used for the boards (2-4). The laser has a power of <100 mW and radiates light with a wavelength of 532 nm (±10 nm). Laser brightness is varied by DC voltage. The CTRL-2XTB board is designed to operate the step motor. VW-MIX_U board provides the wire frequency autogeneration and the recording of the wires oscillation frequency.

The VWM is housed in a anticonvection box to eliminate airflow noise.

TB6600 Step Motor Driver is an easy-to-use professional stepr motor driver, which could control a two-phase stepping motor.

The VWM is moved perpendicular to the laser beam by a step motor. When wires cross the beam, its frequencies decrease due to the loosening of the wires tension.

The schematic diagram of the test bench is showed in Fig. 2

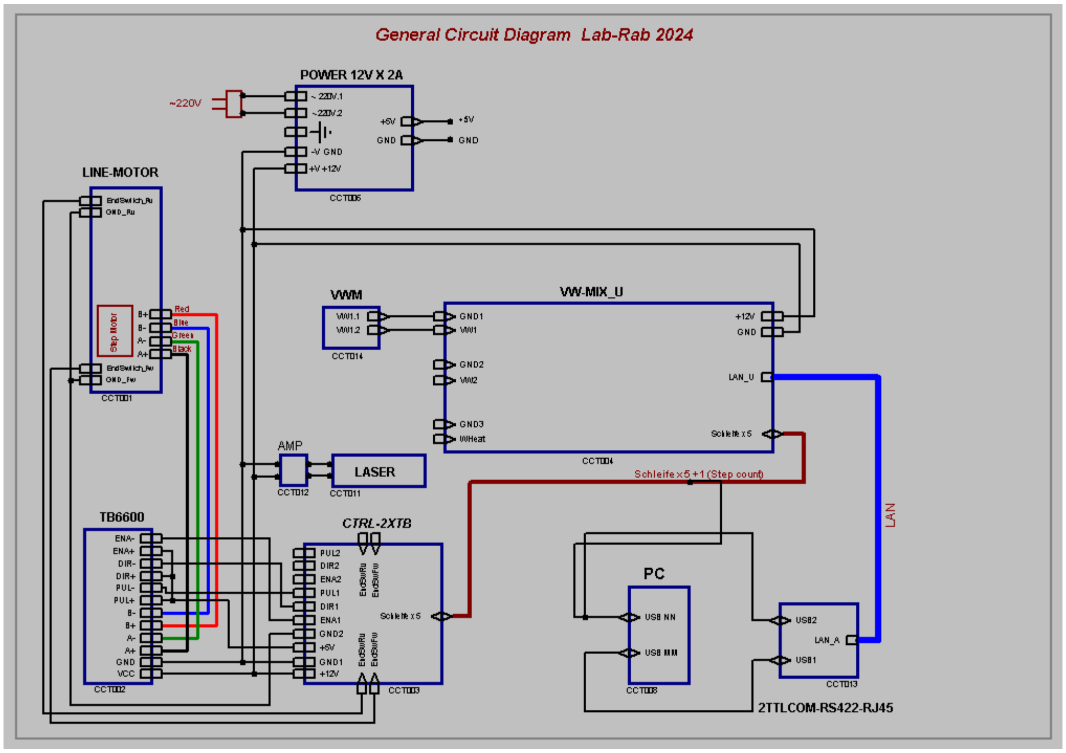

Figure 3. Schematic diagram of the test bench.

2. Vibrating wire monitor

Main view of vibrating wire monitor used in test-bench is presented on Fig. 4.

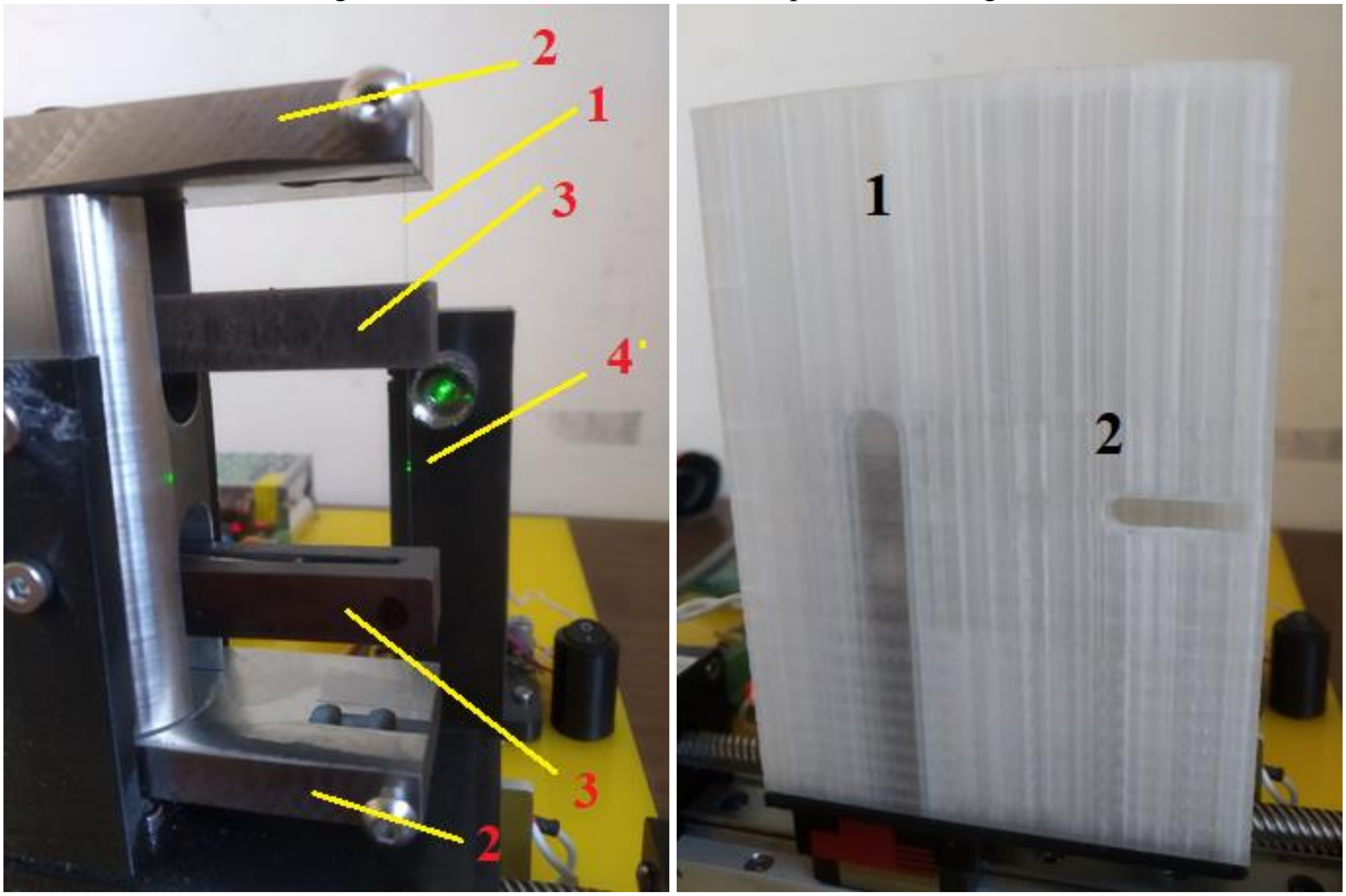

Figure 4. Main view of one wire VWM. (a) 1 - vibrating wire, 2 - clips, .3 - magnetic poles, 4 - spot of laser beam on the wire. (b) VWM covered by plastic box to avoid convections impact on wire oscillations, 1 - anticonvection box, 2 - feedthrough slot for laser beam passage.

2.1. VWM parameters

Number of wires	1
Wire material;	Stainless steel, A316
Wire length;	72 mm
Wire diameter;	100 µm
Base material;	Stainless steel
Aperture;	28 mm

2.2. Other parameters (see VWM_choice_Rev4.doc and Note to VWM_Choice_Rev3 VWM_Choice_Rev4.doc):

Wire frequency dependence on T, Hz/K;	1.5
Wire T dependence on deposited power, K/W;	3000
Response time (in air), s;	3
Wire T shifts limits, K;	min 0.0007 / max 120
Wire deposited power limits, W;	min 3E-06 / max 1E-02

Generation of wire oscillations is created on the second harmonics.

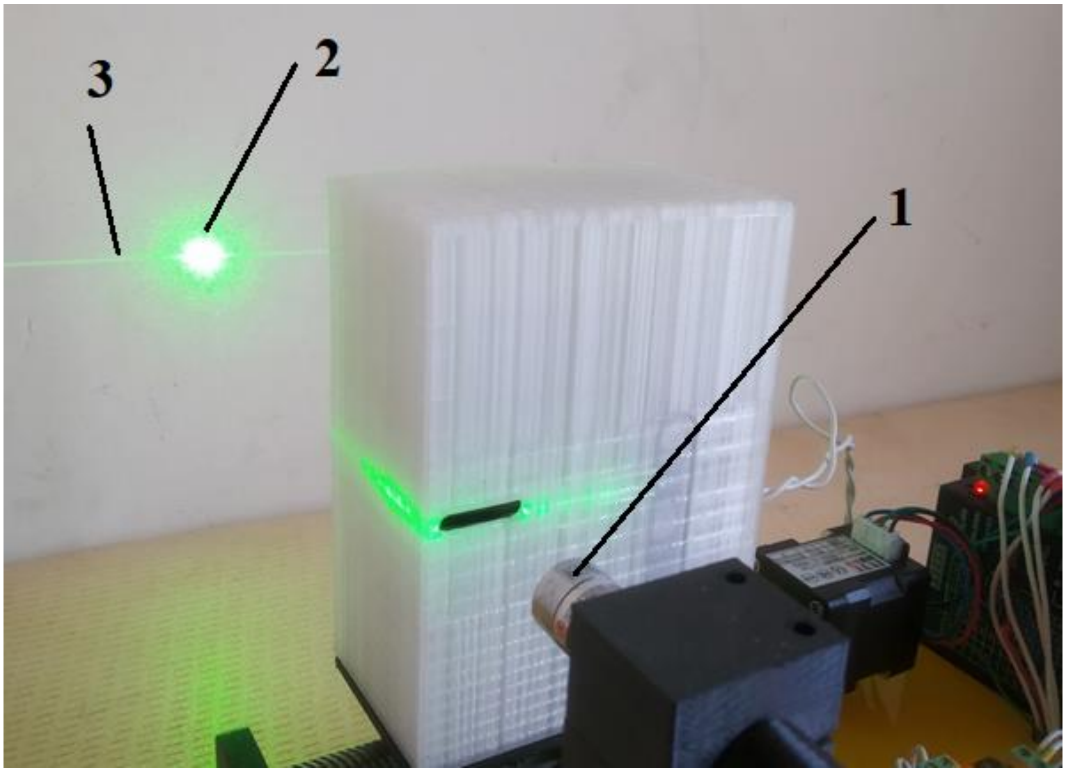

Figure 5. At the laser beam falling on the wire of VWM the characteristic beam reflection pattern arises. 1 - laser, 2 - spot of the laser on the wall, 3 - characteristic plane of reflected photons from the cylindrical surface.

Figure 5 shows a vibrating wire monitor on which the laser beam falls. Wire heats up by absorbing light photons leads to decrease of the wire oscillation frequency.

We have the ability to see the data from the wire with an oscilloscope connected to the autogeneration board (Fig. 6).

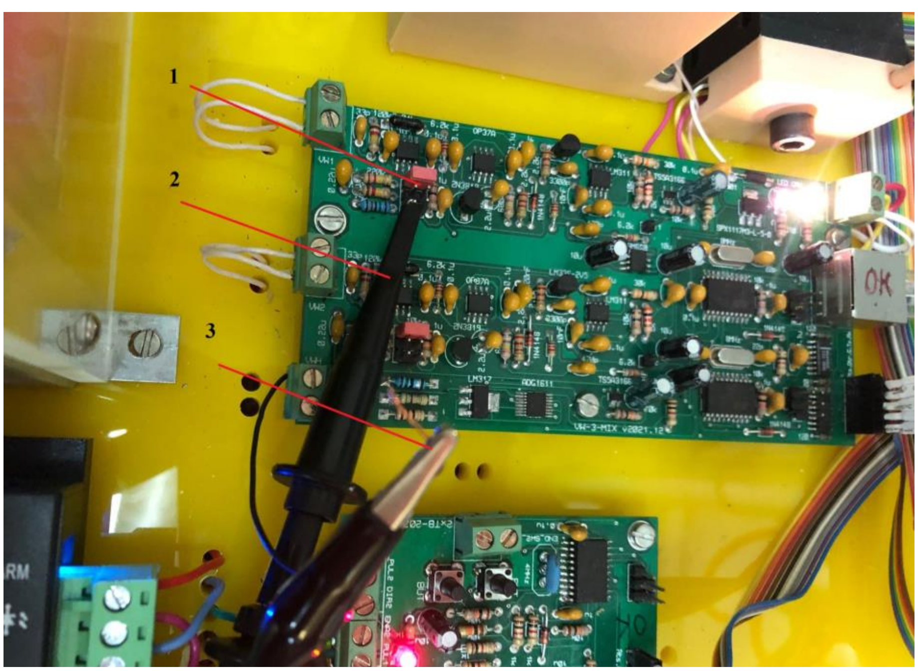

Figure 6. Wiring of oscilloscope on autogeneration board. 1 - first channel jumpers set for adjusting of feedback, 2 - probe of oscilloscope for first channel, 3 – ground.

The linear actuator is used for ensure the movement of the VWM:

Range, mm	100
Accuracy, mm	0.05
Material	Aluminum

3. Setup objectives

- Familiarization with the principle of operation of vibrating wire sensors/monitors and characteristic parameters (length between VWM clamps, wire diameter and material, permanent magnets polarization in magnet poles, aperture).
- Familiarization with R&S®RTB2004 Digital Oscilloscope and its adaptation to experimental stand and check proper generation of wire oscillation.
- Usage of the application program LabRab for wire frequency measurement and data acquisition.
- Carrying out the experiment of scan the Laser beam by means of VWM.
- Process the experimental data and recover beam profile.

4. Equipment and software

- Assembled vibrating wire monitor.
- Vibrating wire boards
- 12 V power supply.
- Linear actuator with step motor
- Semiconductor laser (green, 532 nm)
- R&S®RTB2004 Digital Oscilloscope.
- Software - VB_LabRab_VM (data acquisition)
- Software - Master_Form_LabRab_processing (data processing)

5. Description and procedures

- Prepare test-bench wiring
- Wire the oscilloscope as presented in Fig. 6.
- Check the wire oscillation generation quality and investigate of generation process, take corresponding graphs of oscilloscope.
- Switch on laser
- Use steps described in Section 6. Software.

6. Software LabRab

6.1. Data acquisition

Used Software:
Candle\2024\LabRab\Lab_Rab_V2\Soft\VB_LabRab_VM_v2_sg\VB_LabRab_VM\bin\Debug\VB_LabRab_VM.exe

The interface of the LabRab bench is realized by means of COM ports. Two ports are used, one for communication with the autogeneration and frequency measurement board VM-3-MIX-v2021, the other for communication of the step motor board 2xTB-2021-v2. COM ports are created by means of the 2USB-RS422-RJ45 board developed and manufactured by us (see Fig. 7).

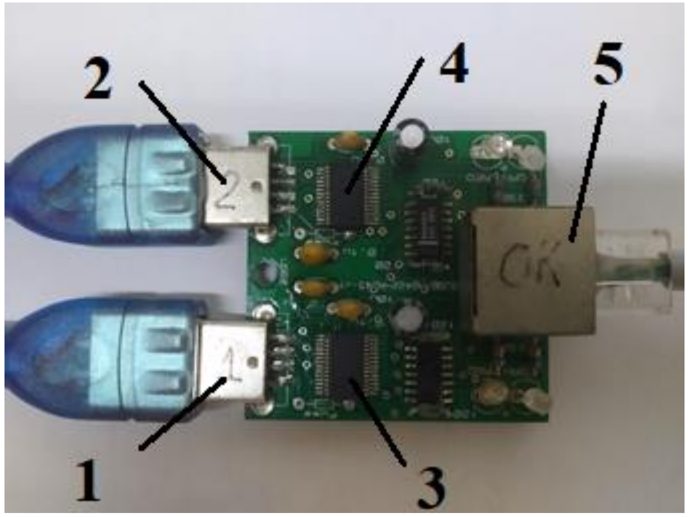

Figure 7. Two channel USB-COM interface with output to LAN cable. 1 - to USB port of PC (first channel for frequency), 2 - to USB port of PC (second channel for step motor), 3 - FT232RL chip of first channel, 4 - FT232RL chip of first channel, 5 - LAN cable to the VWM station.

Two FT232RL chips are used on the board (Single chip USB to asynchronous serial data transfer interface, entire USB protocol handled on the chip. no USB specific firmware programming required, data transfer rates from 300 baud to 3 Mbaud). The board is connected to the stand (board //MIX) with a lan cable and to the computer with USB cables. Output No. 1 (lower in Fig.) is used for communication with the frequency board, output No. 2 (upper in Fig.) for communication with the step motor board. Information with port assignment is stored in the file:
Candle\2024\LabRab\Lab_Rab_V2\Soft\VB_LabRab_VM_v2_sg\VB_LabRab_VM\bin\Debug\
Settings.txt. Structure of file is presented in Fig. 8:

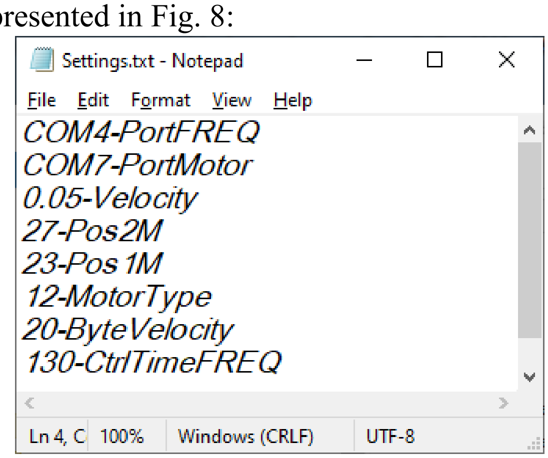

Figure 8. VB_LabRab_VM_v2_sg, Stettings.txt file.

The file saves important parameters that can be changed by the user either during a session or by editing the text file. The first two lines are communication parameters.
When the FT232RL chip is connected to the USB port of the computer, the computer operating system emulates a virtual com port with a specific number, independent of the user. Information about the port number can be found with the help of DeviceManager Windows program:

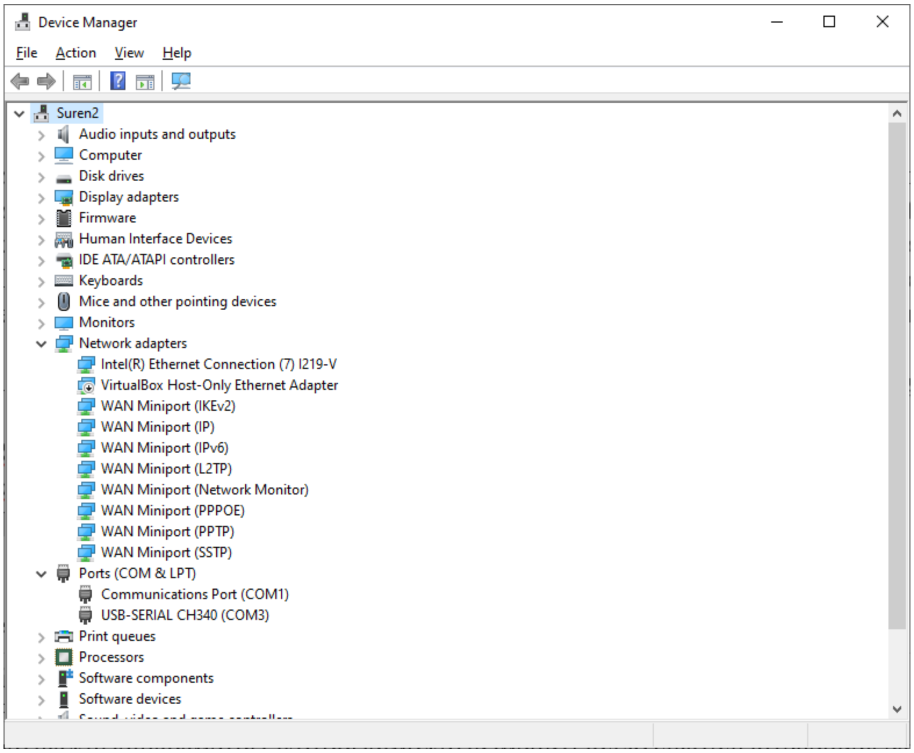

Figure 9. Device manager, initial view. Both cables are disconnected from the board, the existing ports (COM1 and COM3 are not connected to our program).

Connect output #1, com port number 4 appears, which should be identified as a frequency port (first line Stettings.txt file).

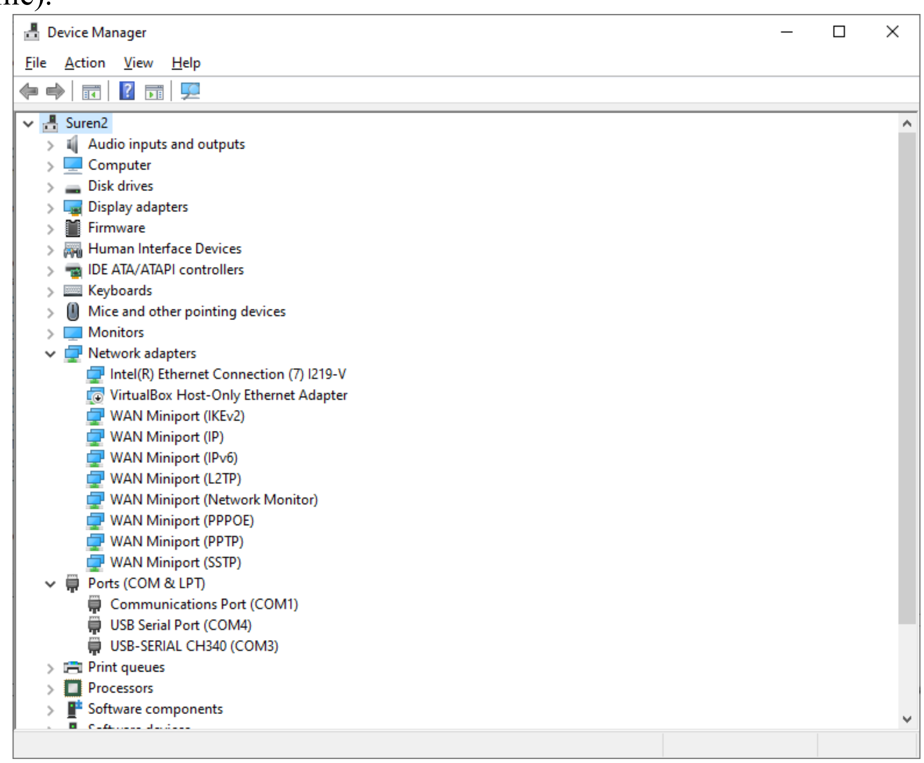

Figure 10. Device manager, COM4 is emulated.

Connection of the output #2 emulates the COM port number 7.

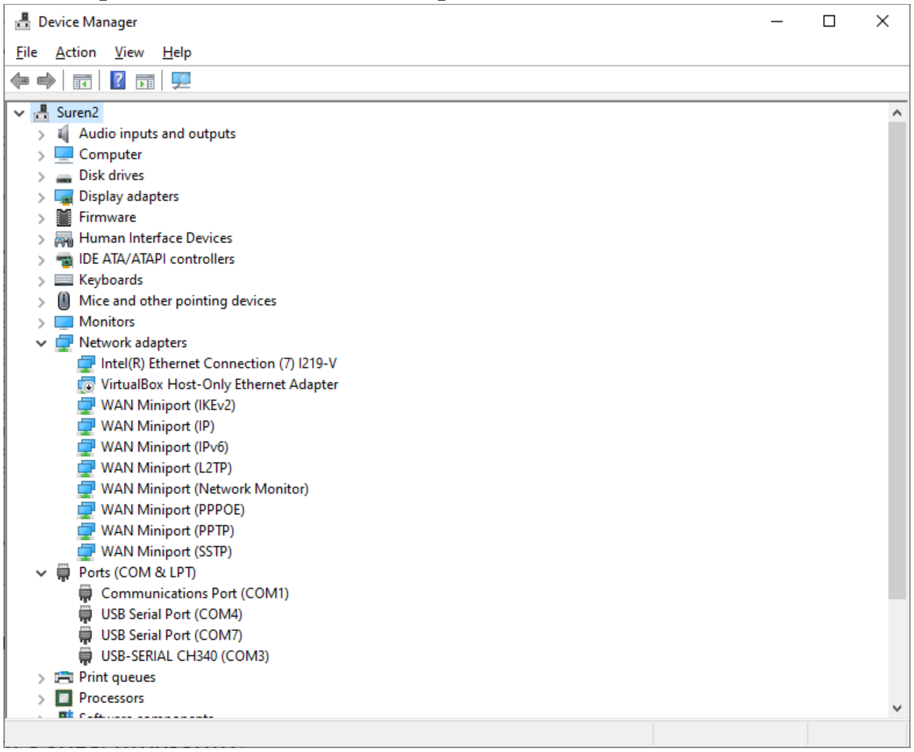

Figure 11. Device manager, COM7 is emulated (used for step motor).

The corresponding information is written in the second line of the Settings.txt file.

The program operation starts with placing the sensor on the ruler in the park position. In case of correct numbering the COM port of channels receives a message that the sensor is placed in the park position and is ready for operation:1

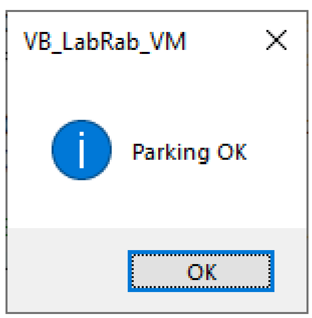

Figure 12. VWM is in park position message.

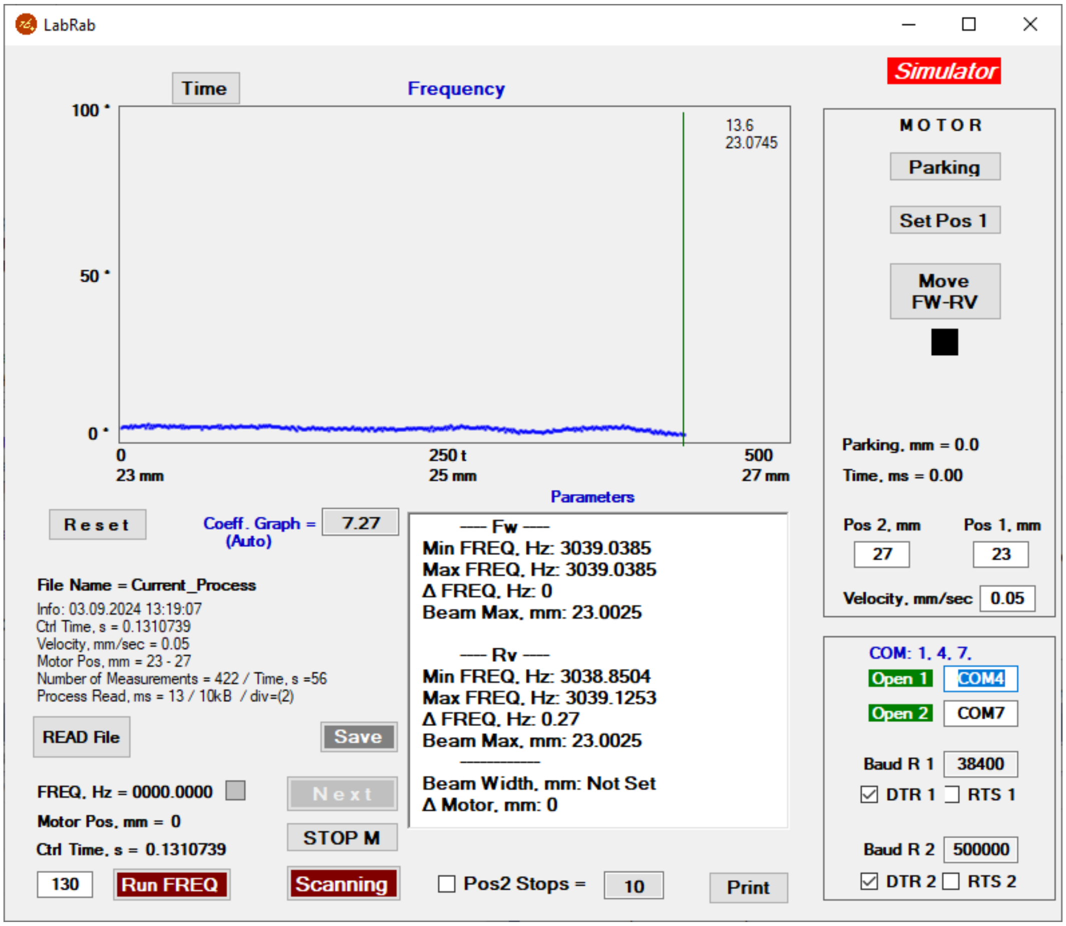

Figure 13. VB_LabRab_VM_v2_sg program main view.

Main program regimes decribed below.

6.1.1. Measurement and frequency reading in fixed position of the sensor on the linear actuator

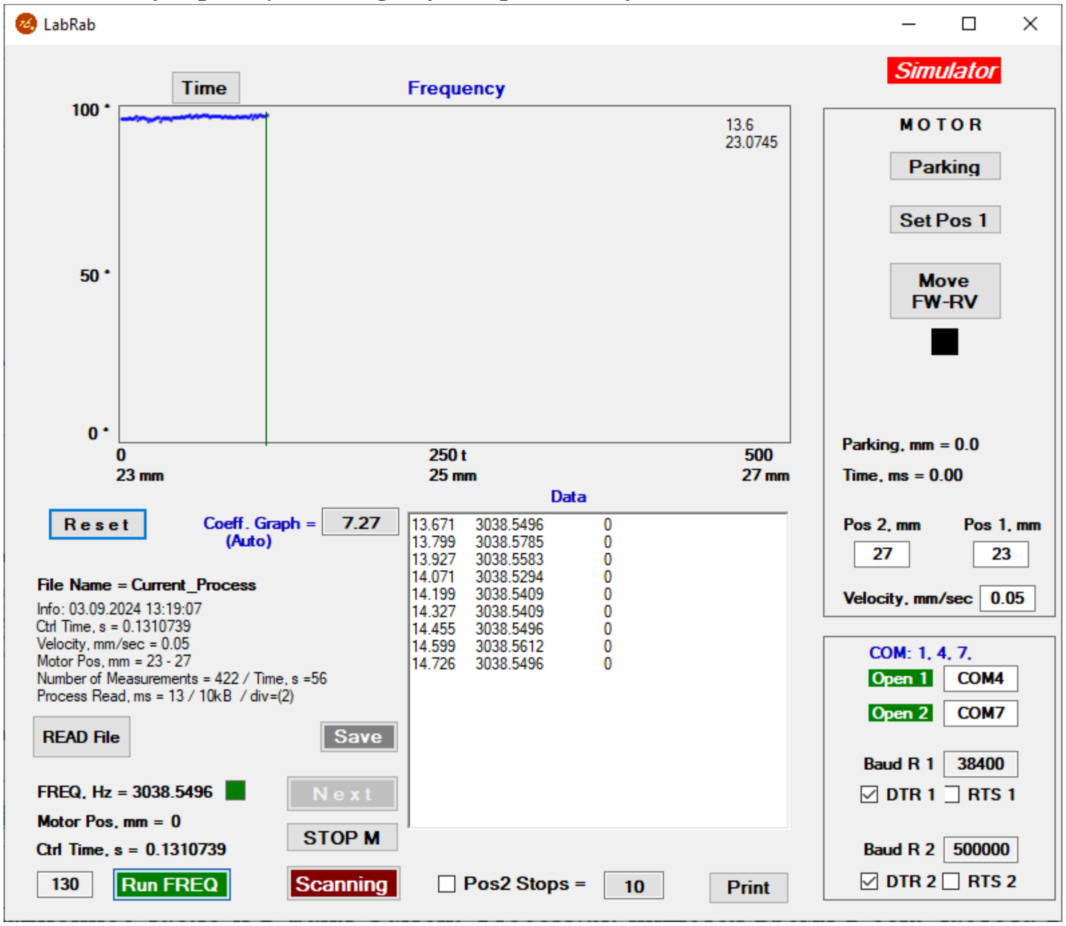

Figure 14. Frequency measurement.

The process of frequency reading is started by button Run Freq (after click become green).

The process of frequency reading is stopped by repeated pressing the Run Freq button (the button is colored brown). The Current_Process.txt file registers the current process and at restart all previous information in it is erased. In file Current_Process.txt time in s, frequency in Hz and sensor position are written.

By button Save the information from the file Current_Process.txt is saved in the ...\Data\FileName.txt file. The name of the file is formed by current date and time of file creation.

The sensor can be moved (after stopping the frequency process) to the Pos1 position specified in the window Pos 1, mm using the Set Pos 1 button. The transition to the new position is done by moving to the parking position and zeroing the coordinate:

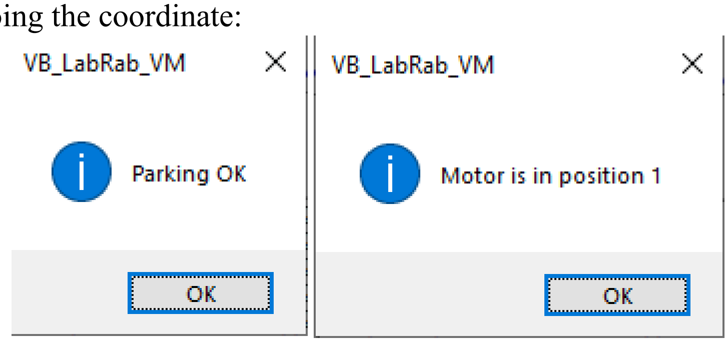

Figure 15. Move VWM to Pos1 position by of Set Pos1 button.

The further of the frequency process collection can be continued (the Current_Process.txt file is written again and when saving it, a file with a new name is created).

An important parameter of the program is the time of one frequency measurement, which is set in the lower left window in ms and written in the line Ctrl Time = ... in seconds.

6.1.2 Scanning

The scanning process is started by the Scanning button, initially colored brown.

The scanning procedure consists in fast movement of the sensor from park position to Pos1 position, and then at Velocity, mm/sec to Pos2 position (forward scanning). At selected position of the Pos2 Stops button the sensor stops in this position for several steps (indicated in the corresponding window) and with the same absolute speed returns to the position Pos1 (backward or reverse scanning). After that sensor returns to the park position.

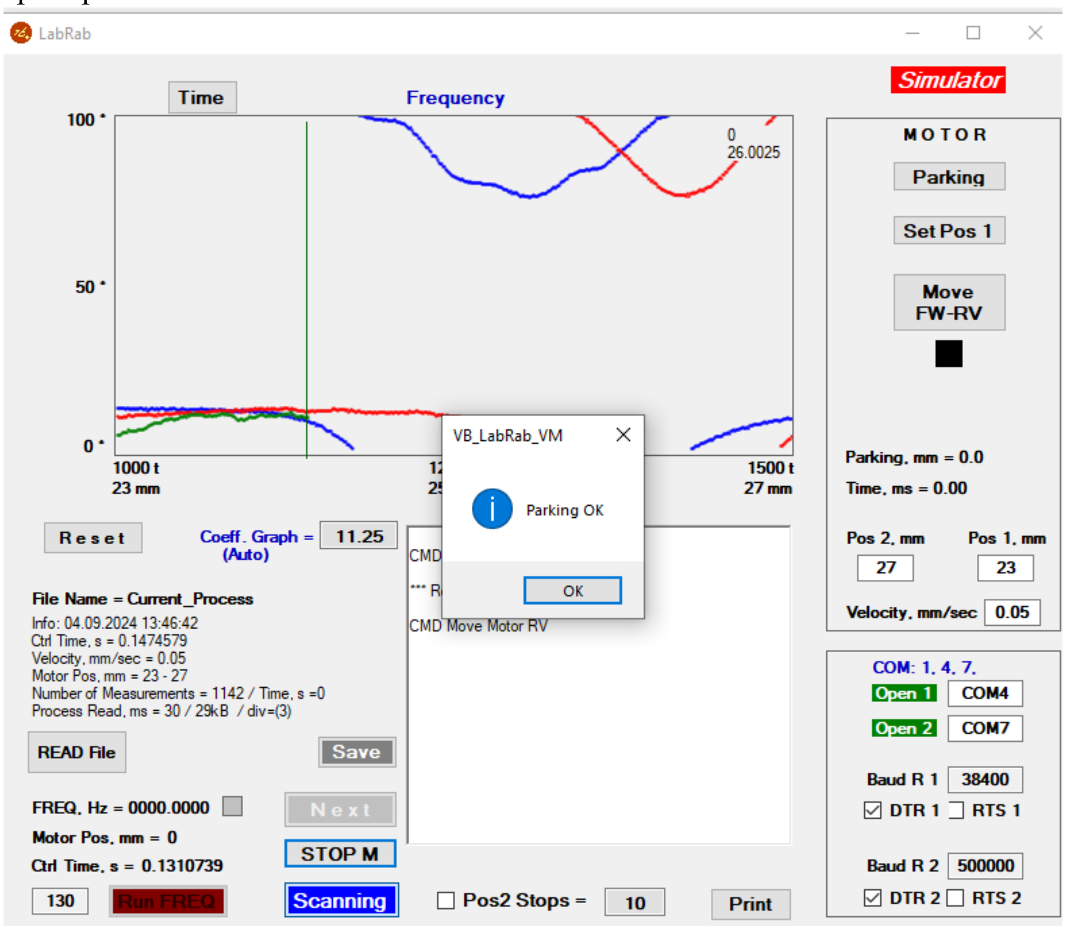

Figure 16. Scanning is initiated.

Figure 17. VWM is at Pos1 message.

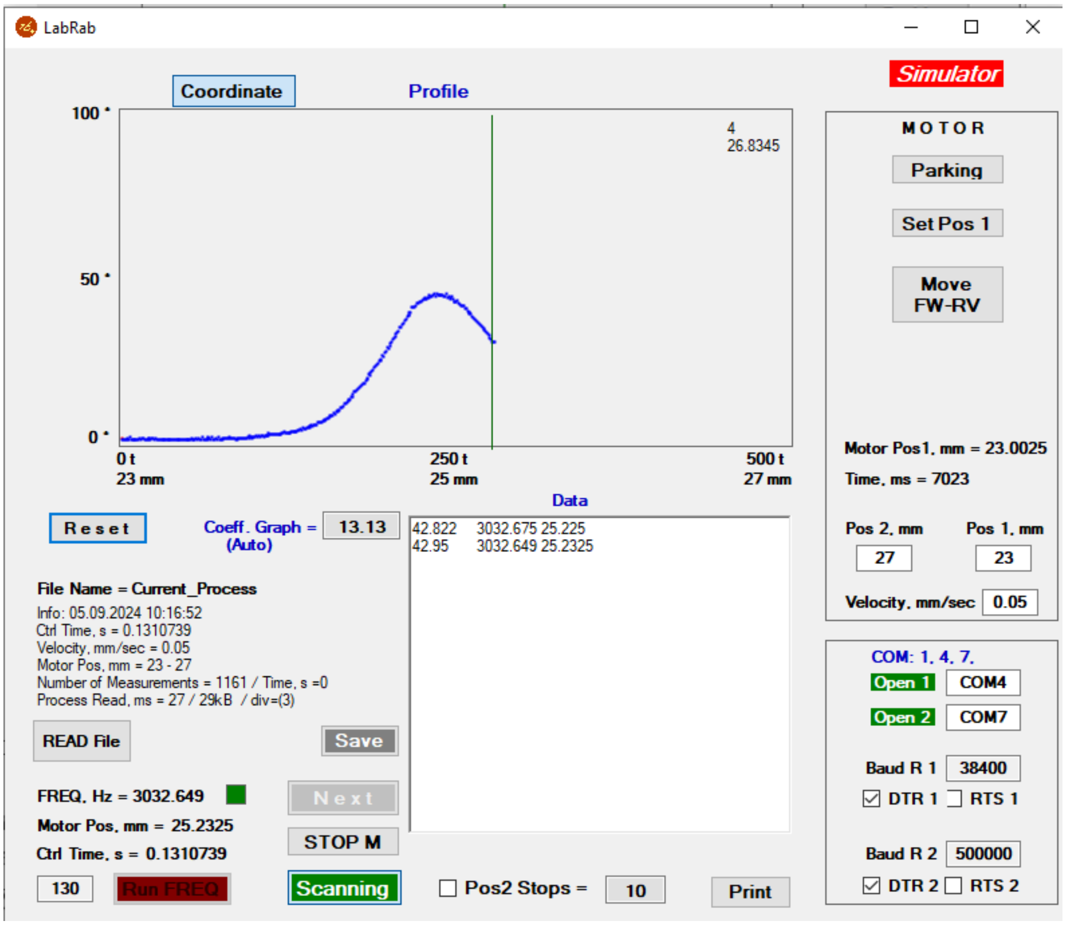

Figure 18. Scanning process.

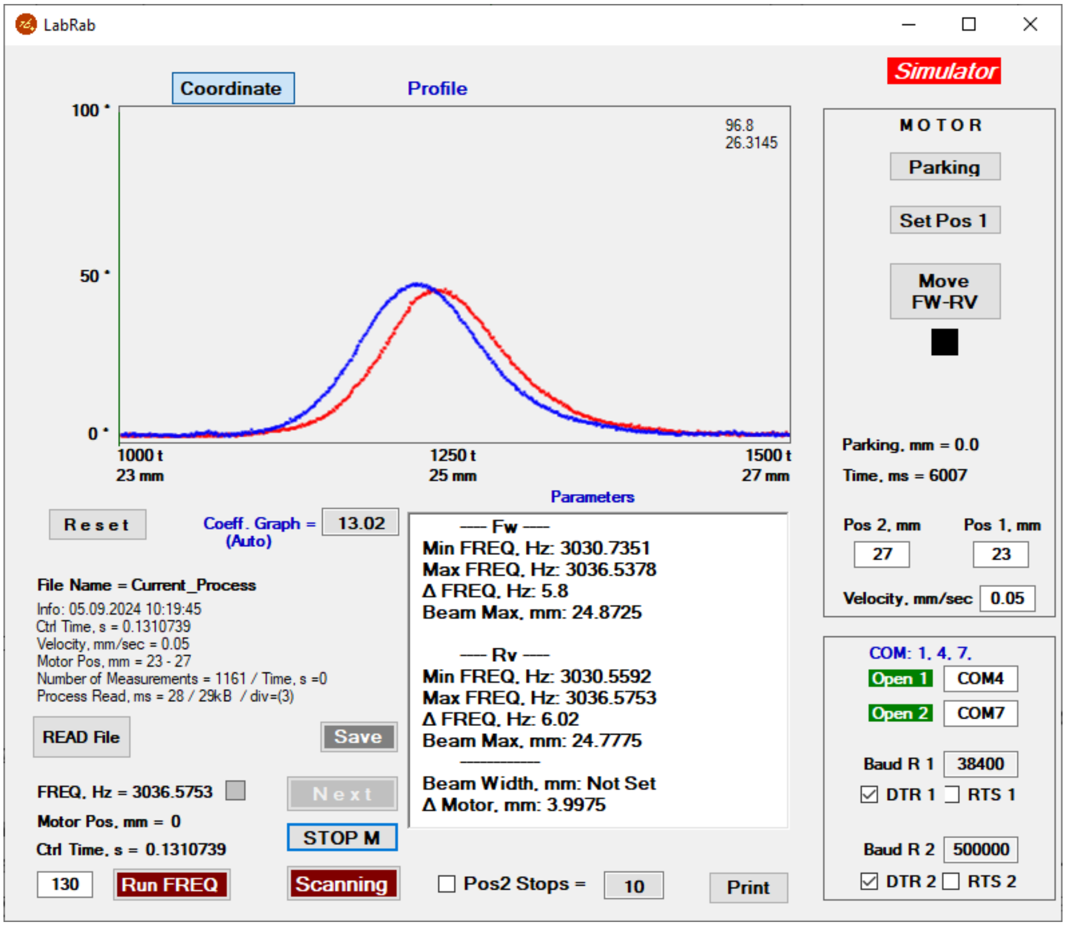

Figure 19. Scanning is finished.

After the scanning is completed, the program panel visualizes the scanning data (Fig. 19 shows the plots of the signal in arbitrary units from the coordinate). In red is marked the forward scanning and in blue the backward scanning. Information on min-max values of frequency and position of profile peaks for forward and backward scanning is also presented on the panel.

Zoom is possible by clicking on Coeff. Graph (defult is Auto state).

During scanning it is allowed to stop the movement with the STOP M button. Herewith the data of the experiment time, frequency and sensor position continue to be written to the file. Continuation of scanning is done with the button Next. The procedure is very useful for understanding the effects of thermal inertia associated with the delay of the real temperature of the wire from the momentary flux of the beam particles at a given position of the wire (see Fig. 20).

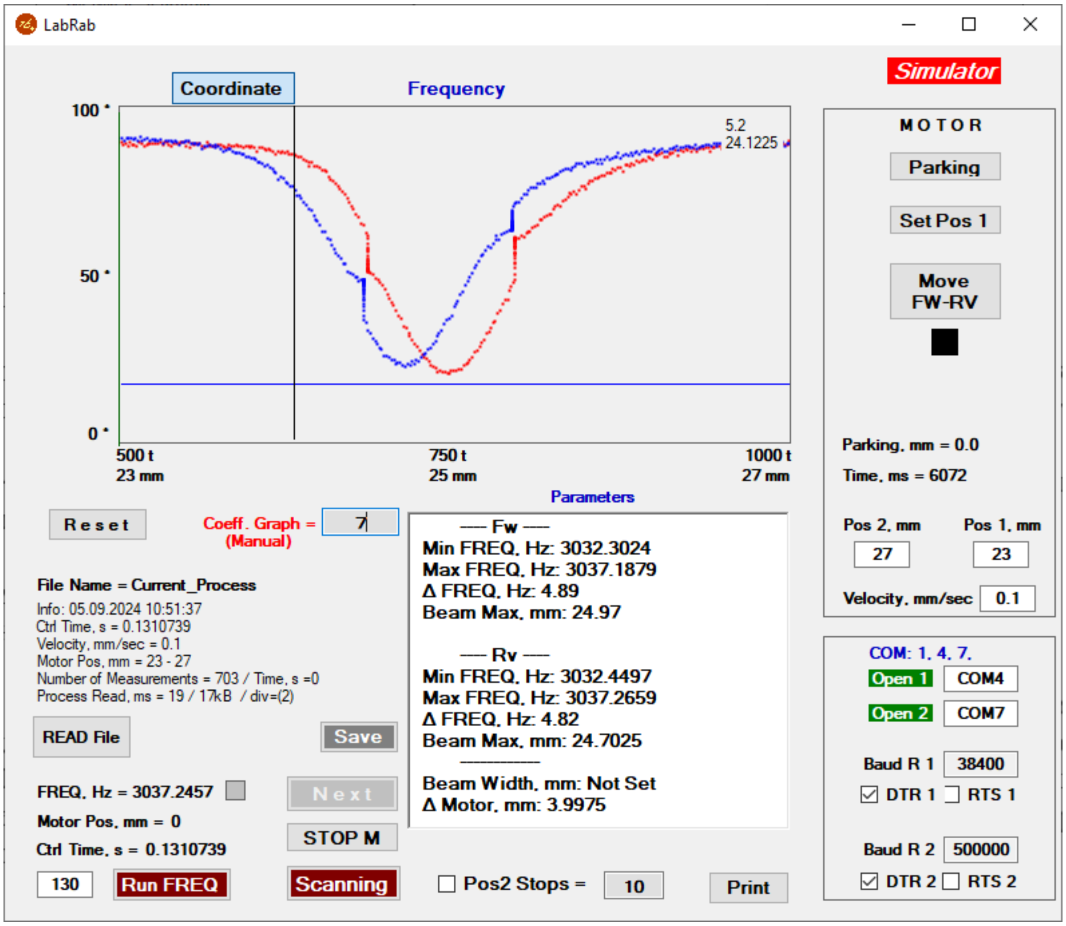

Figure 20. Scanning with Stop-Run events. Issues of thermal inertia impact are shown.

6.2. Data processing

The developed method of beam profiling is based on the dependence of the wire frequency on its temperature (an increase in the wire temperature due to the exposure section of the wire to the beam leads to a decrease in its tension, which is reflected in the frequency of its natural vibrations). However, there are several factors to consider here. Frequency measurement is based on filling a certain number of periods of wire vibrations with a high-frequency signal from a quartz generator and counting their number. The measurement accuracy becomes higher the larger the measuring range. However, the sensor position coordinate is referenced to the measurement time endpoint, which gives coordinate hysteresis during forward and backward scanning. A similar hysteresis is associated with mechanical backlash of the thread feed of the step motor based linear actuator. An important process leading to profile distortion, including hysteresis, is the thermal inertia of the wire. This is described in detail in [2022-4].

The process described above leads to the fact that the beam profiles in the forward and backward scans do not coincide. Nevertheless, by applying certain mathematical procedures to these two profiles, it is possible to reconstruct the real beam profile. Candle\2024\LabRab\Lab_Rab_V2\Soft\Master_Form_LabRab_processing program was developed for such mathematical processing.

Program Interface is presented in Fig. 21.

Figure 21. Master_processing program main view.

Data loading is performed by the Load Data button. It is assumed that the data file is created by the scanning program and has the following structure:
Information lines in the header
Label line “FW”
Forward scan data (time from scan start, frequency, sensor position)
Label line “RV”
Forward scan data (time from scan start, frequency, sensor position)
Line label “Stop”

After loading with the Plot_FW, RV button, the left panel visualizes the frequency plots with the presentation of the minimum and maximum values of the scan coordinate (counted from the park-position) and the minimum and maximum values of the frequency.

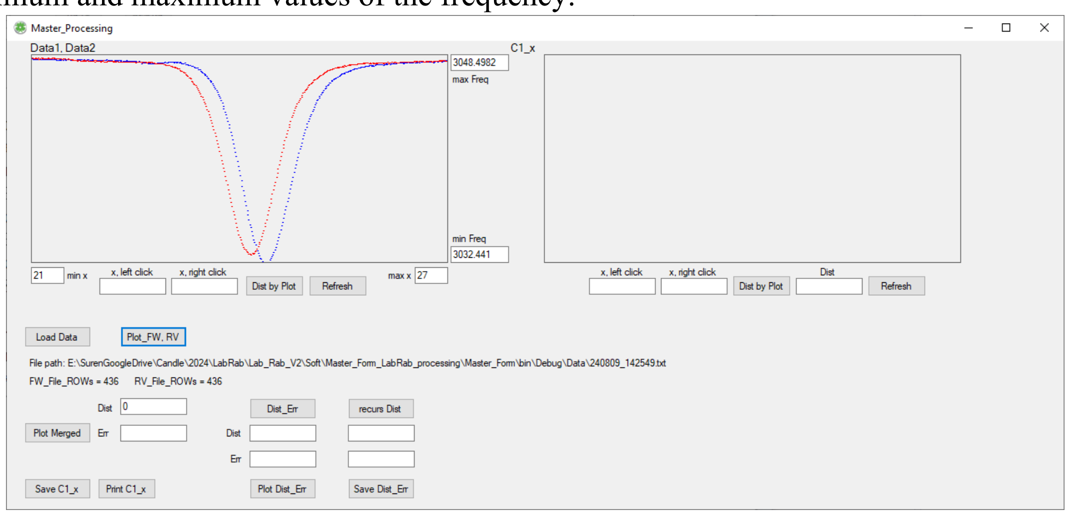

Figure 22. Load and plot of experimental data (frequency series). Blue indicates forward scan data, red indicates backward scan data.

Differences in frequency drop depths and shift of peak positions can be seen. Using the Plot Merged button, each set of experimental values is normalized by one using the following procedure

```
For i = 0 To _Rows_1 - 1
```

```
    F_C1_Array(i) = 1 - (F_Freq_Array(i) - F_minFreq) / (F_maxFreq - F_minFreq)
Next

For i = 0 To _Rows_2 - 1
    S_C1_Array(i) = 1 - (S_Freq_Array(i) - S_minFreq) / (S_maxFreq - S_minFreq)
Next
```

where label F denotes forward scanning and label S denotes backward scanning.

In addition, arrays `F_Freq_Array(i)` and `S_Freq_Array(i)`, as well as arrays of coordinate values `F_x_Array(i)` and `S_x_Array(i)` are combined into single arrays `merged_x_Array(i)` and `merged_C1_Array(i)` by the formulas

```
For i = 0 To _Rows_1 - 1
    merged_x_Array(i) = F_x_Array(i) - Dist / 2
    merged_C1_Array(i) = F_C1_Array(i)
Next

For i = 0 To _Rows_2 - 1
    merged_x_Array(i + _Rows_1) = S_x_Array(i) + Dist / 2
    merged_C1_Array(i + _Rows_1) = S_C1_Array(i)
Next
```

As can be seen, the coordinate data of the backward scan is shifted by Dist/2 and is shown in the right panel

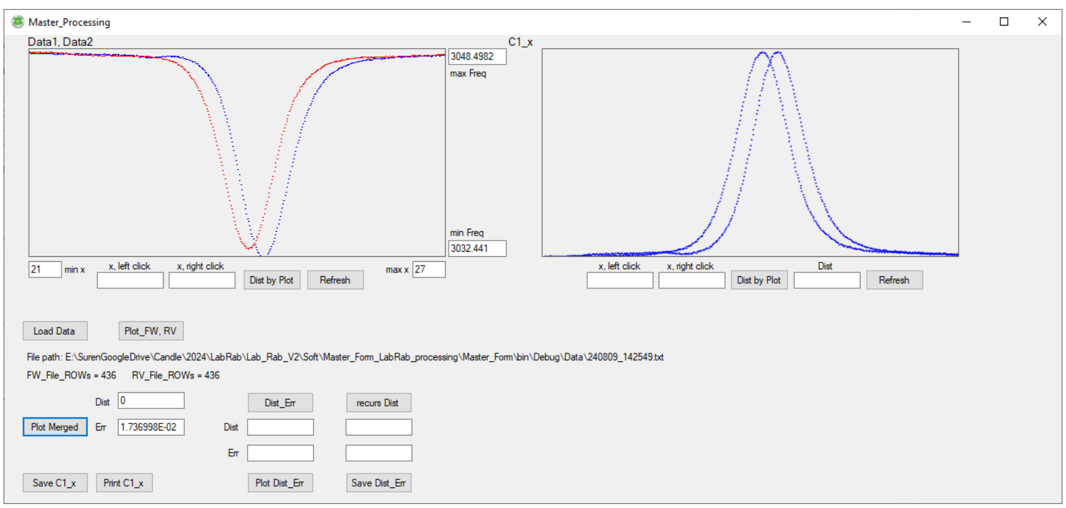

Figure 23. Normalized and merged profiles are shown (right panel). Scale the right panel on the vertical axis is 1.

One can search for a suitable Dist value manually by changing the values of the parameter in the corresponding window and applying the Plot Merged procedure, while evaluating the overlap of forward and backward scanning profiles “by eye”.

The program proposes a mathematical criterion for the concept of “good” overlapping of profiles at variation of the Dist parameter. The algorithm is based on unification arrays of forward and backward scanning data. Such an array contains data on measurement time, frequencies and coordinates. The initial data are structured by measurement time and do not provide information about the proximity of points (position, frequency) during forward and backward scanning.

Here we used a powerful feature of Visual Basic, namely the function of conjugate sorting of two one dimensional associated arrays (array of positions `merged_x_Array(i)` and array of normalized by frequency signals `merged_C1_Array(i)`). In other words, each key in the keys `merged_x_Array(i)` has a corresponding item in the items. When a key is repositioned during the sorting, the corresponding item in the items `merged_C1_Array(i)` is similarly repositioned. Therefore, the items `merged_C1_Array(i)` is sorted according to the arrangement of the corresponding keys in the keys `merged_x_Array(i)`. This is Array.Sort (Array, Array) command [6] (keys, in our case `merged_x_Array(i)`, is placed in the first Array). The Array.Sort procedure uses an effective method frequently called "divide and conquer" (see [https://visualstudiomagazine.com/articles/2004/11/01/sort-in-net.aspx ; https://en.wikipedia.org/wiki/Divide-and-conquer_algorithm]).

This procedure allows us to introduce the concept of error Err by comparing the signals of two consecutive points of the merged and resorted array $\tilde{C}_1(i)$:

$$Err = \frac{1}{N}\sum_{0}^{N-1}(\tilde{C}_1(i+1) - \tilde{C}_1(i))^2 ,$$

where N is the number of unified array rows.

The introduction of such a function allows us to apply standard methods of fitting, e.g., recursion on the Dist parameter by the method of division by halves (see, e.g., [https://habr.com/ru/articles/92591/]). The initial setting of the Dist parameter is required to start the recursion process. This parameter can be defined manually in the left panel by comparing the peaks of the forward and backward scans (Dist by Plot button). Another possibility is to define the minimum of the plot (Dist, Err). This is done by the button Dist_Err and consists in varying the parameter Dist with the definition of the error Err (see Fig. 24).

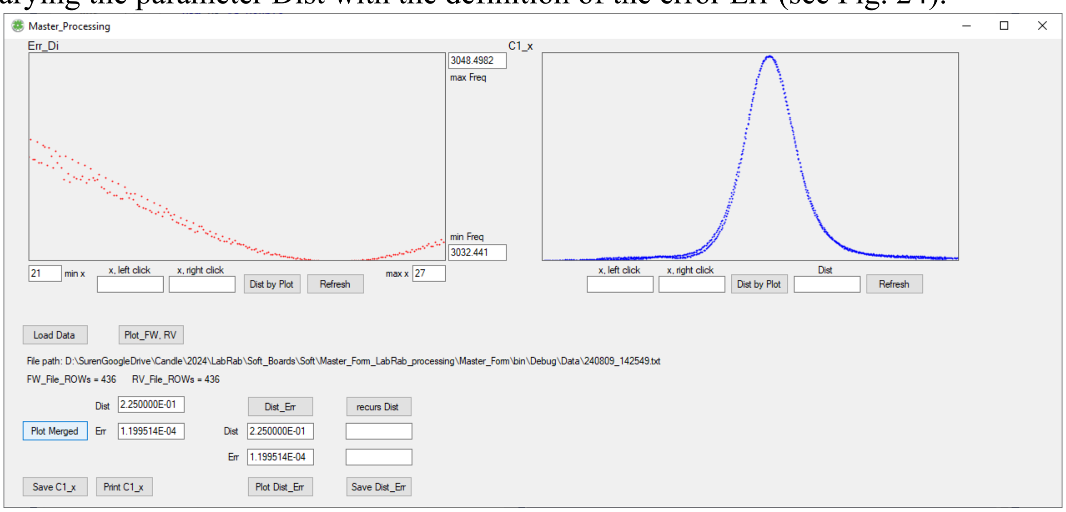

Figure 24. The Dist_Err procedure varies the Dist parameter with the error graph on the left panel.

As can be seen in Fig. 24, the parameter Dist = 0.225 found by this procedure reduces the error from the value of 1.74E-2 in Fig. 23 to a quite acceptable value and error of 1.2E-4 and the corresponding visual result. Applying further recursion for this experiment practically does not change the error result (see Fig. 25).

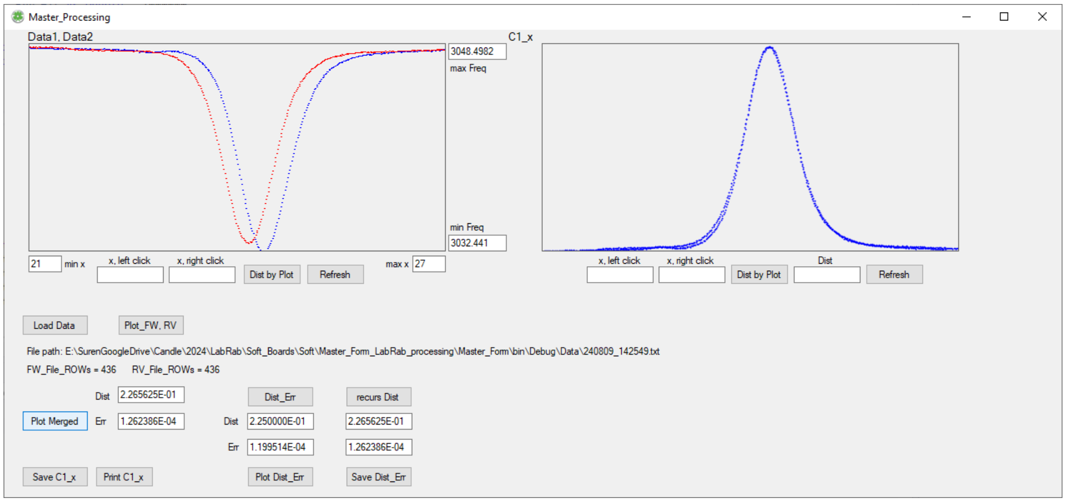

Figure 25. The recurs Dist procedure searches for the minimum error value of overlapped profiles using the recursive method of halving.

<u>Be careful during the experiment</u>

<u>ATTENTION!!!</u>

1. **<u>Make sure that you have completed laser safety training before working with laser.</u>**
2. **<u>Never intentionally look directly into the beam of a laser. Do not stare at the light from any laser. Allow yourself to blink if the light is too bright.</u>**
3. **<u>Do not view a laser with optical instrumentation.</u>**
4. **<u>Never direct the beam toward other people.</u>**
5. **<u>Operate lasers only in the area designed for their use and make sure that the beam is terminated at the end of its use path. Never allow a laser beam to escape its designated area of use.</u>**
6. **<u>Remove all unnecessary reflective objects from the area near the beam's path.</u>**
7. **<u>When working with lasers never wear jewelry or other items which may cause stray reflections.</u>**

Questions

1. Estimate temperature dependence of the frequency of the vibrating wire (Eq. (7) of Practical course: Vibrating wire monitors and beam profile measurements [2022-4].
2. Plot the frequency of vibrating wire and sensitivity of monitor to overheating of wire as functions of temperature of assembly with wires formed of tungsten, beryllium bronze (Beryllium Bronze - Cu97.5/Be2/Co-Ni0.5, UNS C17200), and stainless steel (AISI 316) (Fig. 20 of [2022-4])
3. Estimate the temperature shift caused by exposure of the wire be heating power (taking into account thermal transfer through the wire, thermal radiation and convection mechanisms (Eq. (7) of [2022-4])
4. Estimate the thermal inertia of the wire (response time). Taking into account thermal transfer through the wire (thermoconductivity), thermal radiation and convection mechanisms (Eq. (22) of [2022-4]).

[2022-4]= VWM_Practical course 2022_4 .pdf