Registration and processing of experimental data in research of martensitic transformations in TiNi alloys by acoustic emission method

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Abstract. The characteristics of the software and hardware system for recording acoustic emission in a wide frequency range are given. This system is used in studies of structural and phase transformations of metals and alloys under complex thermo-mechanical loading. The software and hardware system is the author's development of the team and provides an affordable solution for recording and processing data in real time, which is a determining factor in the choice of technology for the study of structural-phase transformations of metals and alloys by method of acoustic emission. The requirements for acoustic emission technique differ slightly from the approaches common in the field of non-destructive testing. The hardware complex consists of a standard ADC with a sampling rate of at least 10 MHz, which provides spectrum registration in the range up to 1 MHz. The cascade of amplifiers are provides requirements for study by method of acoustic emission. The set includes a low-noise heater, an Arduino-based recording unit for related experimental parameters (temperature, mechanical stress, strain), and a personal computer. The software part of the system is a light scientific open source shell for conducting a physical experiment - the "dotScope", developed by the author's team. The program includes an extensible plugins system for working with various ADCs, plugins for real-time data processing, and plugins for post-processing.

1. Introduction
Acoustic emission is a phenomenon that accompanies many different physical processes: structural and phase transformations of matter. Studying the nature of acoustic emission is a fundamental physics problem. Acoustic emission is not an independent phenomenon and always accompanies the processes occurring in a substance. Therefore, acoustic emission acts as an independent research method, allowing analysis of the processes and phenomena occurring in a condensed medium. A fundamental feature of the acoustic emission method is the ability to study the kinetics of the process in real time, which relates it to the in situ method. By analyzing the acoustic emission information channel, we can control the macroparameters of the system: temperature, pressure, electric, magnetic or acoustic fields formed in crystalline or amorphous media. Thus, we are able to control processes in real time, for example, to obtain materials with predetermined properties [1].

Traditionally, the acoustic emission method is used for non-destructive testing of materials. With the fundamental approach, it is necessary to obtain information about events that precede or accompany the phenomenon of acoustic emission. These approaches differ somewhat in terms of organizing the technique of recording and processing data. With non-destructive testing, we have high-energy emissions of acoustic emission energy with significant values of the dislocation rearrangement of materials, leading to the formation and development of cracks and subsequent
macroscopic destruction of the material. The shock waves of acoustic emission during cracking, in fact, are white noise with high energy. Therefore, the requirements for the equipment for recording these phenomena are not critical with respect to the distribution of spectral density and strip or selective sensors and amplifiers with a low quality factor can be successfully used.

A more critical requirement for acoustic emission recording equipment is the use of the acoustic emission method for basic research. Based on our experience and a number of recommendations known from the literature [2, 3, 4, 5, 6], it is possible to formulate, if not universal, then very general provisions regarding the characteristics and parameters of acoustic emission equipment. However, we emphasize that the specific requirements for the equipment for recording AE signals are entirely determined by the objectives of the study and any recommendations on this subject should be considered from the point of view of their adequacy to the tasks set.

The effective value of the intrinsic noise voltage of the amplifier path reduced to the input (in the input short circuit mode) should not exceed $5 \times 10^{-6} \mu V$. The dynamic range for measuring the amplitude of AE signals should be at least 60 dB. In this case, the total path gain should be at the level of $10^5 - 10^6$.

The operating frequency range of the equipment should be in the range of 10.0 kHz ÷ 1.0 MHz. The unevenness of the amplitude-frequency characteristic in the passband should not exceed ± 3 dB. The maximum deviations of the cutoff frequencies should not exceed 10% of their nominal values. As a rule, the attenuation outside the operating range when detuning relative to the cutoff frequencies per octave (2 times) should be at least 30 dB.

Regarding the structure of acoustic emission monitoring systems, we can agree with the authors of [7], who note that at present almost all AE detection paths are constructed according to the classical scheme, which necessarily includes an AE signal sensor, a preliminary amplifier, a filter unit, and a scaling amplifier. Thus, the structural diagram of the modern AE detection system as a whole (possibly with slight variations) corresponds to the following figure 1.

![Figure 1](image-url)

**Figure 1.** The structural diagram of the AE registration system: 1 - AE sensor; 2 - pre-amplifier; 3 - band-pass filter; 4 - scaling amplifier; 5 - analog-to-digital converter.

The technique of recording acoustic emission of non-destructive testing is quite common, however, in most cases it cannot be used for basic research, therefore there is a need for the own development of an inexpensive system for recording acoustic emission for a fundamental experiment.

At present, as a rule, piezoelectric sensors are used to record AE signals, the principle of which is based on the use of a direct piezoelectric effect. Sensor 1 is used to convert the energy of elastic waves generated by AE sources into an electrical signal.

Extensive information on various sensors (not only piezoelectric) and on the method of their application is available in the literature [8, 9, 10, 11, 12]. Depending on the research task, broadband, narrowband or resonant sensors can be used. It should be borne in mind that the sensitivity of the sensors (ceteris paribus) the higher, the narrower their bandwidth.

The choice of sensor for recording acoustic emission is determined by experimental tasks. Thus, if we know the geometry of the main elements of the setup and the sample, it is not difficult to calculate the frequencies of the emitting resonators.

2. **Software and hardware system for recording and processing data in real time based on acoustic emission method**

In our installation, for recording acoustic emission signals, a steel rod with a diameter of 4 mm and a length of 400 mm is used as a waveguide. The sample is a nickel-titanium beam (alloy TN-1B) with a section of 3x3 mm and a length of 30 mm. The wavelength can be determined by the frequency
(period) of the corresponding resonator and the speed of sound propagation in titanium nickelide for the sample and slalom for the waveguide. Thus, the longitudinal and transverse speeds of sound in titanium nickelide at a density of 6.44 ± 0.1 g/cm³ and at a temperature of 20 °C are 4660 m/s and 1940 m/s, respectively. Based on the ratio:

\[ L = k \left( \lambda / 2 \right) \]

It is easy to calculate the frequencies of the corresponding sample geometry.

Table 1. Titanium Nickelide Resonator Frequencies (\(k = 1\)).

| Frequency signal, kHz | Sound speed | Frequency signal, kHz | Sound speed |
|-----------------------|-------------|-----------------------|-------------|
|                       | 4660 m/s | 1940 m/s | 4660 m/s | 1940 m/s |
| L_{lon}, mm | L_{tr}, mm | L_{lon}, mm | L_{tr}, mm |
| 2330 | 1 | 0.42 | 90 | 26 | 10.8 |
| 970 | 2.4 | 1 | 86 | 27 | 11.3 |
| 777 | 3 | 1.25 | 67 | 35 | 14 |
| 466 | 5 | 2 | 44 | 53 | 22 |
| 323 | 7.2 | 3 | 41 | 57 | 24 |
| 233 | 10 | 4 | 33 | 71 | 29 |
| 194 | 12 | 5 | 19 | 123 | 51 |

Based on the data in table 1, we can conclude that, in order to identify events (frequencies) associated with geometry smaller than the geometrical dimensions of the sample, frequencies above 320 kHz (\(L < 3 \text{ mm}\)) are required. The characteristics of the piezoelectric transducers available for sale are shown in table 2. Accordingly, the high-frequency broadband sensor GT300 with a passband from 100 to 800 kHz was initially selected as a sensor for studying acoustic emission [13].

Later it turned out that when using the standard pre-amplifier supplied with this sensor, the GT200A is not enough to provide a condition for a minimum discrimination of the level signal over noise of about 5 - 10 µV. In addition, preliminary studies have shown that the maximum spectral density of acoustic emission is in the region up to 100 kHz. Therefore, in order to ensure acceptable conditions for recording acoustic emission during phase transformations in titanium nickelide alloys, it was decided to develop their own amplifier path by dividing the broadband interval. It was also decided to use a low-frequency narrow-band sensor GT205 with a passband from 40 to 100 kHz [14], capable of providing the highest electro-acoustic conversion coefficient - 70 dB (see table 2).

Table 2. Characteristics of piezoelectric transducers [13, 14].

|                        | GT 205 | GT301 | GT 300 | BC 601  |
|------------------------|--------|-------|--------|--------|
| Electro-acoustic conversion coefficient, dB rel. 1V/m/s | >70 | >55 | >50 | >45 |
| Working frequency, kHz | 50 | 220 | 280 | 300 |
| Bandwidth, kHz         | 40...100 | 50...500 | 100...800 | 100...800 |

The main difficulty that arises when processing a piezoelectric sensor signal is associated with a high value of its impedance. There are two main schemes for connecting the PP to the recording equipment: a voltage amplifier circuit and a charge amplifier circuit based on a current integrator [12, 15]. The circuit on the current integrator attracts with high linearity and small influence on the operation of the signal cable amplifier. However, under these conditions, the low input impedance of the integrator, which greatly affects the mechanical properties of the sensor and, ultimately, the spectrum of the analyzed signal, shunts the PP. A voltage amplifier with a high input resistance is practically devoid of this drawback, however, its output signal is highly dependent [12] on the
parameters of the connecting line (primarily its capacitance). Therefore, the circuit of a voltage amplifier can be recommended if it is located in the immediate vicinity of the sensor, or is connected to it by a short cable, the position of which is firmly fixed. The main purpose of the pre-amplifier 2 is to match the output impedance of the sensor with the input of the main amplifier.

Based on the above considerations, as well as our own experience in the technical implementation of the first stage of the pre-amplifier, it was decided to dwell on the circuit of a voltage amplifier on field-effect transistors with a control p n junction. The use of insulated effect transistors of gate field in the first stage with higher input impedance is not practical in this case, since they have an increased noise level in the frequency range of interest to us [16]. In addition, in order to reduce the noise level in the input stage, we used the parallel connection of four 2SK170 transistors, connected according to a common source circuit. According to [16], this allows halving the intrinsic noise of the amplifier. Previously, the cascade operation was investigated using the Multisim 11.0 circuit simulation system [17, 18]. The first stage schematic diagram of the pre-amplifier is shown in figure 2.

![Figure 2. Schematic diagram of the remote stage pre-amplifier, implemented in the environment of Multisim 11.0.](image)

The capacitors C4 and C5 indicated on the diagram simulate stray capacitances of the cables (output and input, respectively), with the help of which the remote stage of the preliminary amplifier is connected to the registration system. Structurally, it is located in the immediate vicinity of the sensor (with the exception of parts R1 and C3) and receives power via a signal coaxial cable from an autonomous direct current source V1. Its noise level (with a shorted input) is 1 μV, the passband is from 1 kHz to 1 MHz. The frequency response of the cascade obtained during simulation in the Multisim medium is shown in figure 3, which shows that the gain in the passband from 1 kHz to 1 MHz is approximately 32 dB.

![Figure 3. Frequency response of the remote stage of the pre-amplifier obtained by modeling in the environment of Multisim 11.0.](image)
The actual frequency response of the remote stage does not qualitatively differ from that obtained as a result of modeling (except for the gain value, which in the passband is 28 dB).

Further amplification in the pre-amplifier is carried out using the main stage (figure 4), implemented on the AD8066 chip. Chip AD8066 is a [19] high-speed dual operational amplifier (op-amp) with a low (7 nV/√Hz) level of intrinsic noise. The first op-amp is switched on according to the standard scheme of a non-inverting amplifier and therefore has sufficiently high input impedance, which practically does not have a shunt effect on the amplification of the remote stage.

The second op-amp is turned on according to the repeater circuit and serves to coordinate with the filter unit. The stage gain is 32 dB in the frequency band up to 1 MHz. Thus, the total preamplifier gain is 60 dB.

![Figure 4](image)

**Figure 4.** Schematic diagram of the main stage of the pre-amplifier, implemented in the environment of Multisim 11.0.

After preliminary amplification, a band-pass filter additionally filters the AE sensor signals 3 (figure 1). The need for this operation is due to a number of reasons, discussed below.

The voltage supplied to the input of the amplifier is a “mixture” of the useful signal and interference. In the case when their spectra do not overlap, the simplest way to get rid of interference is frequency filtering.

Since acoustic emission [3, 6] refers to the process of generation of mechanical waves by a material associated with a local restructuring of its internal structure, the spectral density of its sources will determine the spectrum of AE signals. Naturally, the bandwidth of the recording equipment should correspond (and ideally coincide) with the spectrum width of the AE signals. Moreover, AE sources (cracking, phase transitions, dislocation motion, etc.) can have different physical nature and generate signals in different frequency ranges. If these ranges are a priori unknown, then the bandwidth of the AE equipment should be wide enough.

However, the expansion of the bandwidth leads to an increase in the noise level, which negatively affects the overall sensitivity of the registration system. The latter circumstance directly affects the amount of data obtained from the experiment and sharply reduces the value of acoustic emission control as a method of scientific research. In this regard, the frequency range of the recording equipment has to be limited by choosing the parts of the spectrum for which observation is most informative.

The bandwidth of the equipment for recording acoustic emission is limited "automatically", since it is largely determined by the parameters of the sensor. However, the steepness of the decrease in the frequency response of the sensor outside its bandwidth in the light of the previously discussed requirements [2, 4] is insufficient, which forces the use of additional filtering of AE signals in the amplifier.
In order to conduct a physical experiment, as a rule, in addition to the channel for collecting and processing acoustic emission data, additional information channels are required to record the macroscopic physical parameters of the experiment: temperature, mechanical stress, strain, etc. Information from all data channels, in modern conditions, should be converted into a digital code by means of analog-to-digital converters and transmitted to a computer for the convenience of storage, processing and presentation of data.

Processing and presentation of data in the computer structure should be carried out by specialized software, the functionality of which, based on our needs, has the following requirements:
1. data collection from the ADC of various devices that vary in speed;
2. real-time data processing (scaling, conversion to spectrum);
3. ease of storage and processing of data obtained during the implementation of the method of cycles;
4. editing of final data in order to improve and for further post-processing (removal of outliers by smoothing or replacing by lines);
5. the availability of convenient functionality for post-processing data taking into account the tasks of the final experiment, for example: automatic allocation of data processing intervals, calculation of acoustic emission parameters;
6. the ability to automate the experiment;
7. the implementation of maximum performance and the lack of redundancy of the interface.

Based on the software requirements set, universal software was developed in the laboratory of the Physics of Metals and Alloys Laboratory of Altai State University - “ADC Data Logger” (dotScope) [20], due to the absence of such systems in principle. LabView may be considered alternative software, however, it was decided to abandon this product immediately, due to its excessive versatility, high demands on computer resources and the need to purchase a license.

The general view of the program dotScope version 2 is shown in figure 5.

**Figure 5.** Interface of the program “ADC data logger”: 1 - the main menu of the program, 2 - toolbar, 3 - desktop switching, 4 - left channel tabs, 5 - right channel tabs, 6 - displayed graphs of selected tabs, 7 - switching panel visualizers, 8 - progress panel, 9 - total experiment time, 10 - time output field between registrations, 11 - file of the current project.
This program allows creating an arbitrary number of data collection channels. At the same time, on the selected desktop (figure 5 - 3), the experimental data is displayed in one of the visualizers (figure 5 - 7: the graph or the oscilloscope displays two channels, the dial displays the current data of all channels), selected on the left (figure 5 - 4: the rms voltage of the acoustic emission) and the right (figure 5 – 5: temperature) tabs. Channel data on the graph is built depending on the survey number. Time is a separate data channel. The data of each channel in recording mode is saved in a separate file. Channel settings, calibration data and experimental log data are saved in a project file (windows format) with the ch extension.

The dotScope version 2 program is designed for a wide audience and a variety of tasks, Arduino compatible technology. The program is developed in a high-level language C ++ using the Qt5 framework. This software is cross-platform. The project website (http://dotscope.sf.net) lists the assemblies for Windows and Linux 32 and 64 bit architectures. For Linux, a version using the Qt4 framework for use on older systems is also supported.

The “ADC data logger” is an expandable system using a system of plug-ins (modules). The program uses four types of modules:

1. modules of devices of analog-to-digital converters;
2. processing modules given in real time (accounting for calibration information, rationing of scales, Fourier analysis);
3. data post-processing modules (data correction: linearization, smoothing; processing of experimental results: calculation of the average value and standard deviation, calculation of acoustic emission energy, activation energy, and other physical parameters),
4. experiment automation modules (turning on / off external devices).

Figure 5 shows the data obtained as a result of recording acoustic emission in broadband mode. The graph shows the rms voltage of the acoustic emission. In the post-processing process, we can consider each registration buffer by moving the progress bar pointer to the desired position. So, in the experimental data viewing mode, a part of the oscillogram is shown (figure 6-b) at the maximum intensity of acoustic radiation (figure 6-a).

![Graph and oscilloscope displays](image)

**Figure 6.** Data display in the acoustic emission dotScope program during a phase transformation B2 → B19 ′ of titanium nickelide during post-processing: a) is the rms value of acoustic emission in the graph mode (“Scope”); b) is the acoustic emission event in a wide spectrum of signal recording in oscilloscope mode (“Oscilloscope”).

In the process of post-processing in the program dotScope, we can get the averaged integrated spectra of the selected time sections. Figure 7 presents such data for two different temperature ranges for comparing the spectra at the beginning and at the end of the transformation B2 → B19 ′.
Comparison of the spectral composition of acoustic emission for different temperature ranges is very difficult. Thus, figure 7-b shows the spectrum in the 120-140 kHz region, near temperatures 140 (I) and 60 °C (II). From the figure above, it is not at all obvious the dynamics of the spectral lines 1, 2, 3, 4 in graphs I and II. Therefore, a visual study of the dynamics of the spectrum from the direct Fourier transform is a rather time-consuming and difficult process.

Figure 7. Acoustic emission spectrum during thermoelastic martensitic transformation in titanium nickelide: a) interval 0-200 kHz; b) interval 120-140 kHz: I - at a temperature of about 140 °C (beginning of direct martensitic transformation), II - at a temperature of about 60 °C (end of direct martensitic transformation).

In connection with the foregoing, the ADC data logger program included the subprogram “Spectrum Dynamics Visualizer” [21], which allows constructing a gradient picture illustrating the dynamics of the spectrum with time or temperature. The results of such processing for some frequency intervals are presented in figure 8.

Each vertical line of figure 8 represents a spectrum obtained as a result of a fast Fourier transform and averaged over small time intervals.

Figure 8. Dynamics of the spectrum of acoustic emission signals during thermoelastic martensitic transformation in titanium nickelide versus time in the frequency spectrum intervals: a) 60-80 kHz; b) 120-140 kHz.
The visualization of the spectrum dynamics (figure 8) clearly demonstrates the effect of a huge number of resonators in the sensor-waveguide-sample system. We also observe a significant decrease in the frequencies of most spectral lines in the range of martensitic transformations. Therefore, these spectral lines can be unambiguously attributed to the resonators belonging directly to the sample.

From the point of view of organizing an acoustic emission registration system, there is a need for recording ADC data with different sampling rates. For an acoustic emission channel in a wide spectral range up to 1 MHz, an ADC with a sampling frequency of at least 10 MHz is required, and a dozen hertz is sufficient to record the accompanying measurements (temperature, mechanical stress, strain). As a result, the developed electronic unit based on Arduino became the most convenient for recording signals slowly varying in time (figure 9-a). The block includes the HX711 strain amplifier, an amplifier for a thermocouple based on MAX6675. As a deformation sensor, we use the honeywell HOA-911-12 optical sensor for an encoder that connects to the processing ports via an external Arduino interrupt. In addition, for general purposes, connectors A1 and A2 from the Arduino internal ADC are displayed on the block body.

![Figure 9. Electronic units: a) low-frequency parameters collection unit; b) power control unit of the heating installation.](image)

The registration of acoustic emission signals requires minimizing electromagnetic noise, therefore, to control the power on the heating elements of the unit, an electronic power isolation unit was developed (figure 9-b) [22] based on the AVR microcontroller. Thinning of half-periods of alternating voltage (from 20 to 220 V) is carried out by the Bresenham method, which allows, even when using voltage sources - 220 V, to connect low-resistance heating elements. It should be noted that in this case a powerful magnetic field is formed that requires compensation, which is realized by bifilar winding of heaters.

### 3. Conclusion

Thus, the developed software and hardware system for recording and processing data allows conducting a physical experiment with registration of acoustic emission in a wide frequency range. In real time, various experimental parameters are recorded and processed. Processing the resulting spectra in the form of gradient patterns allows obtaining rich experimental material for subsequent processing of the dynamic characteristics of the spectral lines associated with a change in modules, which allows drawing conclusions in the field of fundamental research of matter.

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