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The implementation and the performance analysis of the multi-channel software-based lock-in amplifier for the stiffness mapping with atomic force microscope (AFM)

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Abstract. In this paper the implementation of the surface stiffness mapping method with the dynamic measurement mode of atomic force microscopy (AFM) is presented. As the measurement of the higher harmonics of the cantilever's torsional bending signal is performed, we are able to visualize non-homogeneities of the surface stiffness. In order to provide signal processing with the desired sensitivity and selectivity, the lock-in amplifier-based solution is necessary. Due to the presence of several useful frequencies in the signal, the utilization of several simultaneously processing channels is required. Therefore the eight-channel software-based device was implemented. As the developed solution must be synchronized with the AFM controller during the scanning procedure, the real-time processing regime of the software is essential. We present the results of mapping the surface stiffness and the performance tests results for different working conditions of the developed setup.

Key words: atomic force microscopy, stiffness mapping, lock-in amplifier, software development, torsional oscilators.

1. Introduction

Current development of various disciplines in science and technology is related to progress in advanced diagnostic methods which allow us to observe and understand certain processes and phenomena. In particular, the nanotechnology science has provided significant knowledge and was the reason for the introduction of some new products into the market. In order to observe sophisticated processes with ultimate resolution, it is necessary to have access to suitable tools and measurement techniques.

Atomic force microscopy (AFM) is one of the surface topography imaging methods with submicron, and, in some cases, atomic resolution [1–3]. As the scanning cantilever is used as a tip-sample force-sensing device, it can be utilized for the measurement and mapping of the mechanical properties of the sample. Although there are some measurement techniques available on the market such as: Force Volume Microscopy [4], Force Modulation Microscopy [5] and HarmoniX [6, 7], they can be inaccessible for some AFM users due certain hardware or budget limitations. Therefore a relatively easy method of implementing the mechanical properties mapping in the existing AFM systems is desired.

As the tip-sample interaction changes periodically in the dynamic measurement technique (known also as the intermittent or tapping mode) [8–10], one can use this feature in order to extract necessary information about the forces acting on the cantilever. Eventually, one can obtain the data in order to create the map of local non-homogeneities of the stiffness. Such information can be used for estimating the size, shape and dispersion of the nanofillers in the bulk material, determining the shape and size of the crystallites in various chemical compounds and many others quantifications of the material properties.

2. Principles of the torsional bendigs of the cantilever

As in most cases the tip-sample interactions can be described with the DMT (Derjagin, Muller, Toropov) model [11, 12], it can be easily shown that the dynamics of the tapping of the tip against the surface is related to the stiffness of the sample (Fig. 1). One can note, that as the stiffness increases, the slope of the force curve becomes narrower. Therefore, the bandwidth of those signals changes, and one can distinguish the variation of the mechanical properties of the surface by observing the level of certain harmonics.

One of the major limitations in such a task is the mechanical response of the cantilever, when the flexural oscillations in typical AFM setup are observed (Fig. 2) [13]. The higher modes of the mechanical resonances can disturb significantly the wide bandwidth response, therefore another approach is necessary. By observing the cantilever's torsional oscillations, one can obtain undistorted signal up to the frequency approximately 20 times higher than the longitudinal base frequency [14] and this is how the analysis of higher harmonics is possible. It should be underlined, that such detection method in the case of typical AFM cantilevers is very complicated due to extremely low signal, as the torque is near to zero. In order to enhance the torsional oscillation bending, Sahin et al. [15, 16] developed special T-shaped cantilevers (Fig. 2). Although originally such cantilevers were used in much more complex

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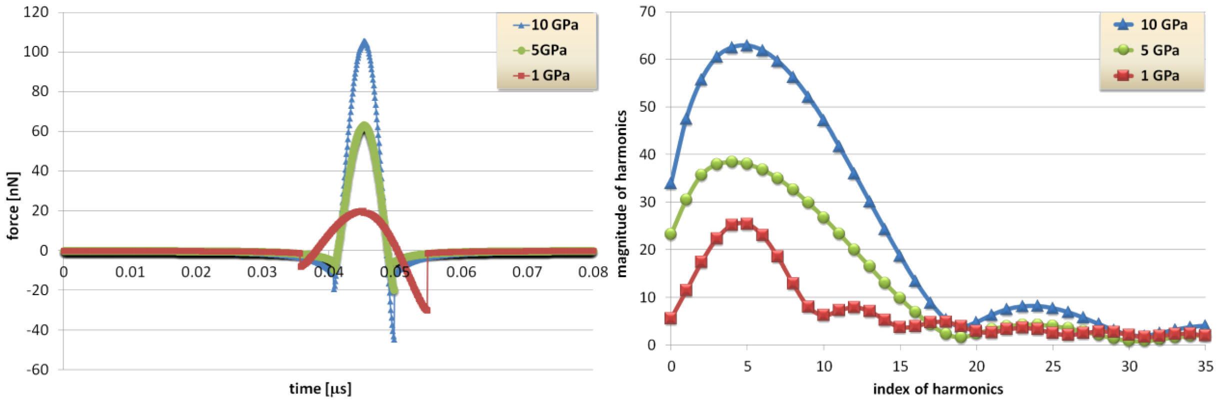

Fig. 1. DMT model based calculated force-time tip-sample interaction (left). Fast Fourier transformation (FFT) of those signals (right)

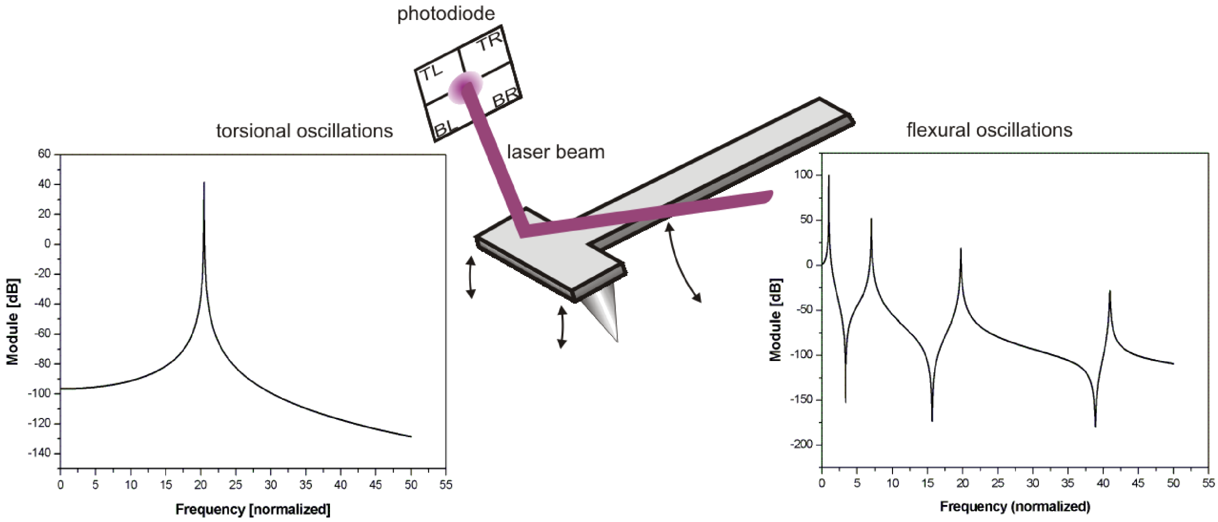

Fig. 2. The comparison of the mechanical responses of flexural and torsional oscillations of the cantilever

fashion [12–14], the mapping of surface's stiffness by utilizing the higher harmonic of the cantilever's torsional oscillation was successfully performed by Sahin [6]. It allowed observation of the changes of the PS and PMMA polymer film changes while the temperature increased. Also Sikora et al. developed advanced measurement mode for the mechanical properties mapping [17, 18]. This technique called *NanoSwing* was successfully applied in the diagnostics of various materials at the nanoscale [19, 20].

The measurement of certain frequency's amplitude in a complex signal requires a device which exhibits high detection selectivity. Typically the lock-in amplifier is a suitable tool for such a task. Therefore, in order to provide simultaneous acquisition of several harmonic levels of the torsional signal, the software-based solution was implemented.

3. Measurement setup

The typical setup used for the optical detection of the T-shape cantilever bending is presented in Fig. 3. The laser beam is reflected from the cantilever and points at the quadrant photodiode detector. As the sinusoidal excitation signal is applied to the piezoactuator and causes the cantilever bending, the laser beam lights different parts of the photodiode. Therefore the simple adding and subtracting of the signals from certain sections of the detector allows to determine the movement of the cantilever.

In order to provide the measurement of the torsional bending of the cantilever, the operations on the signals should be modified. Instead of vertical travel of the laser beam, the horizontal one is to be analyzed. The Innova AFM system from Bruker (former Veeco) was used to perform the experiment. The signal from the scanning head was processed by the PXI unit from National Instruments (Fig. 4) equipped with the 2.53 GHz dual-core processor, 60 MS/s, 12 bits ADC card and digital I/O interface. This module was able to work in the real-time mode as well as in the embedded system under Windows7 control.

In order to enable the mapping of certain harmonics, the pixel synchronization signal was used allowing the PXI unit to follow the scanning process controlled by the NanoDrive AFM controller. The software was developed in LabView 2010 graphic programming environment. The idea of this programming tool is shown in Fig. 5, which presents the screenshot of the development process of the application. The most important part of the structure can be seen as well as the inter-

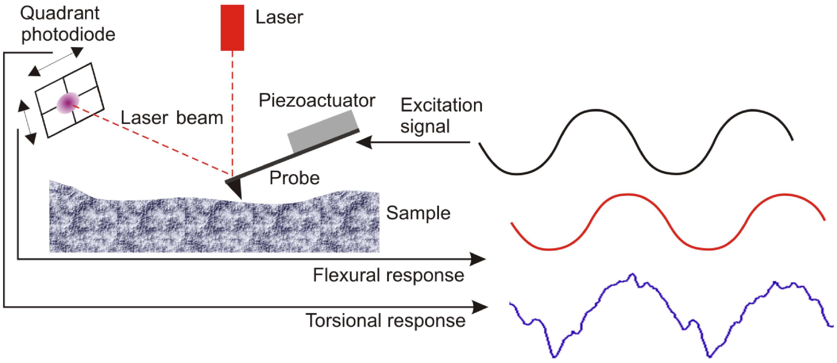

Fig. 3. The idea of optical detection of the bending of the cantilever in typical AFM setup. Additional processing of the signals from the quadruple photodiode allows to observe the torsional oscillations

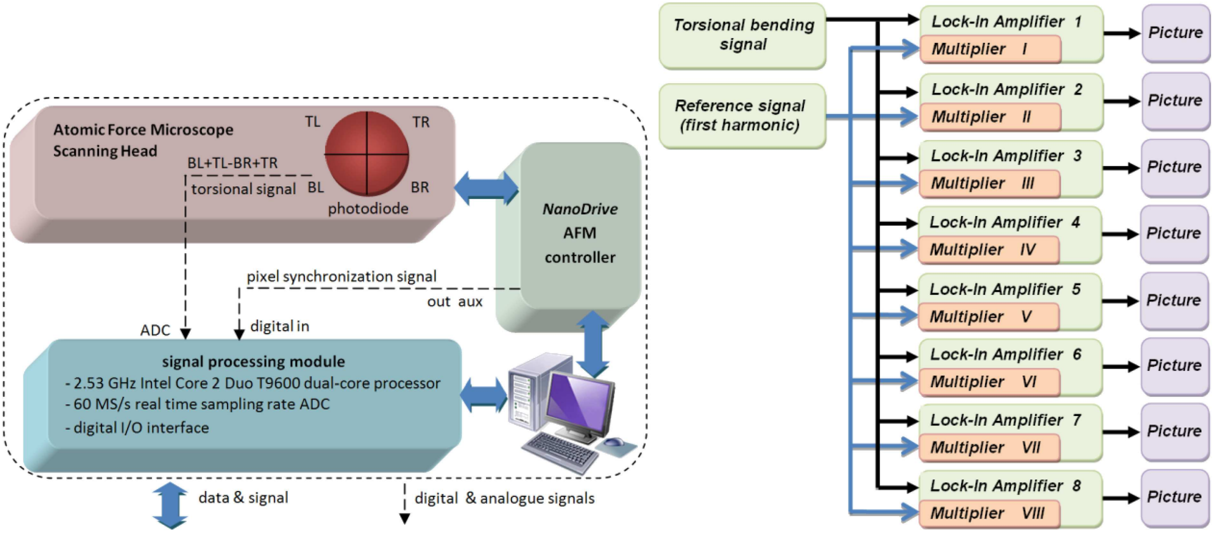

Fig. 4. The simplified diagram of developed test setup (left). The diagram showing simplified design of the algorithm of the eight-channel lock-in amplifier (right)

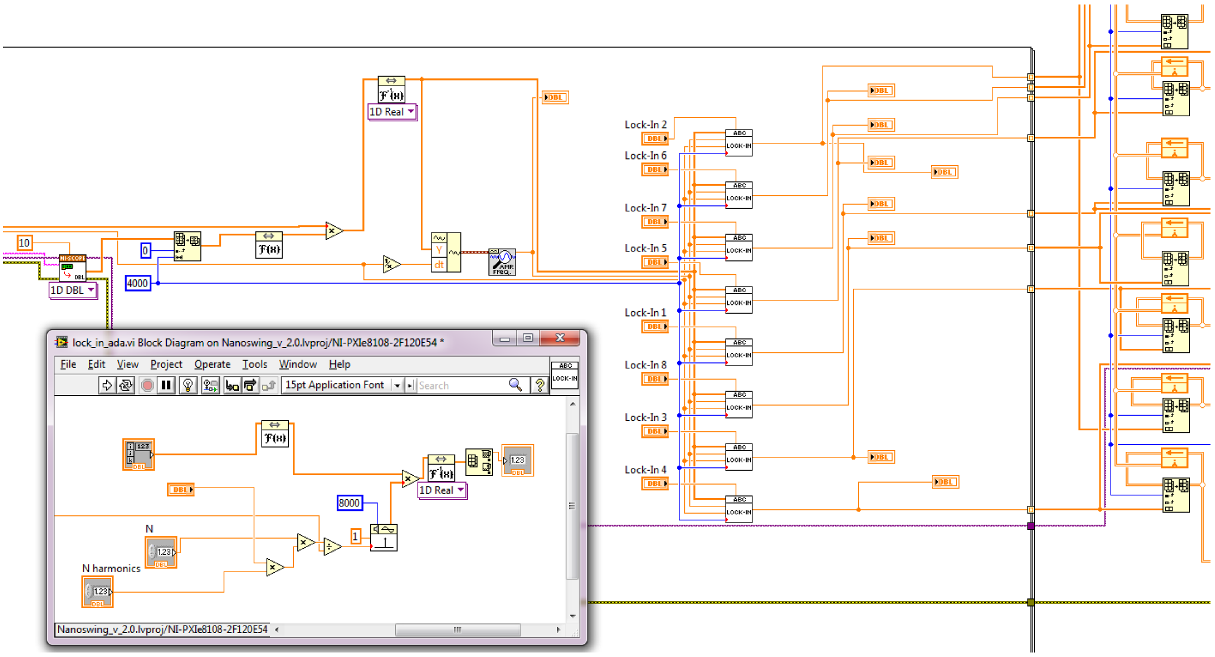

Fig. 5. The screenshot of the application during the development process in programming environment LabView 2010. The most important part of the structure can bee seen as well as the internal structure (sub-VI) of the lock-in amplifier (internal window)

Fig. 6. The view of the measurement system: 1 – scanning head, 2 – PXI unit, 3 – personal computer with AFM measurement software and LabView 2010 programing envirnoment, 4 – AFM controller, 5 – AFM measurement software, 6 – developed software working simultanously

nal structure (sub-VI) of the lock-in amplifier. The user's interface of the developed software allows to observe all acquired maps during the measurement, in order to verify if the scanning process is performed properly. It should be underlined, that the flexibility and the versatility of PXI/ LabView setup is essential, as it is utilized for various AFM experiments and measurement techniques. Additionally, the development and testing procedure can be performed very quickly.

Developed algorithm allows to run up to eight simultaneously operating lock-in amplifiers analyzing different high-order harmonics of acquired signal. The user can choose the reference frequency for every lock-in amplifier module, therefore the most important harmonics can be mapped. The photography of the measurement setup is shown in Fig. 6. The most important components are as follows: the scanning head, AFM controller, PXI unit, the personal computer with AFM scanning process control program.

It should be underlined, that the critical condition concerning the implementation of the software, was the data processing time. Its value and repeatability is essential, as the results of the calculations should be delivered within certain time frame in order to provide the data for the stiffness mapping as the scanning process is being performed. Therefore various operation modes of the device were verified.

It is worth of mentioning, that the optimal utilization of the computational power is an general issue in various scientific and industrial applications, therefore advanced tools and method are developed and utilized [21–23].

4. Measurement results

The tests of the performance of developed multichannel lock-in amplifier were performed for two operation modes of the PXI unit: real-time and Windows7 embedded. Additionally, the impact of the activity of other applications in the Windows system was verified. More than 65 000 repetitions of the data processing operation were performed for each operation mode. The execution time of every repetition was measured and stored. The histograms of the execution time measurements are shown in Fig. 7.

One can see a significant dispersion of the computation time in the case of the embedded system. This is due to additional processes launched by Windows7 during its work. Moreover, we could observe a significant increase of the loop execution time after launching a few additional applications. As one cannot fully disable various scanning, monitoring and upgrading processes controlled by the operational system, such situation can occur while the measurement is performed. As a consequence, data loss and corruption of the final result may take place. As there is no possibility to fully control Windows7 system, the real-time operation mode of the PXI unit is desired. In such a case, only one process is launched, therefore very narrow distribution of the processing time is provided. Such setup can be successfully applied also in other demanding applications. It should be underlined, that in presented solution, the maximum time among the whole group of the test repetitions at certain conditions is a real indicator of the performance, as no single timing violation is acceptable (Table 1). The issue of the real time data computing in advanced AFM signals processing was also described by Legleiter at al., as their system did not fulfill the real time criteria, causing the measurement data loss [24].

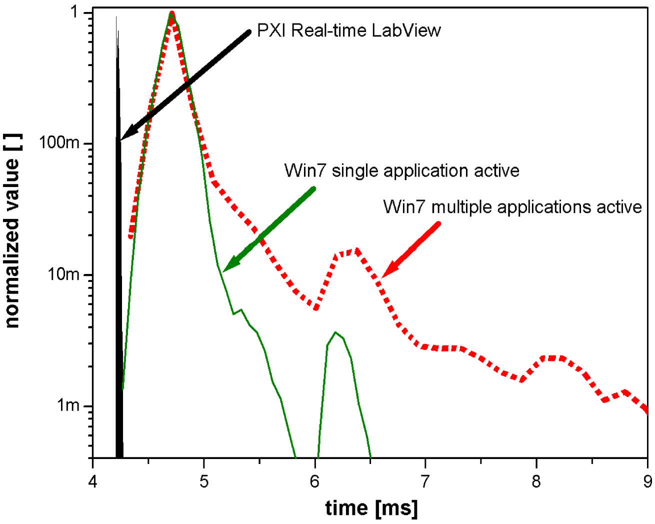

Fig. 7. The histogram showing execution time of the PXI unit for various work modes and code optimization levels: Real-Time, Win 7 with developed algorithm only (Win7 1 process online), as previous but with few more applications running in the background: internet browser, text editor, file browser (Win7 multi process online)

Table 1
Comparison of the statistics parameters of the data processing execution time

Parameter	Mode of operation and conditions		
	PXI Real-Time	Windows7 single process	Windows7 multiple processes
average – μ [ms]	4.23	4.73	4.92
standard deviation σ	10.95	225.37	1 209.20
variance σ^2	119.98	50 793.32	146 145.12
maximum time [ms]	4.28	32.13	77.29

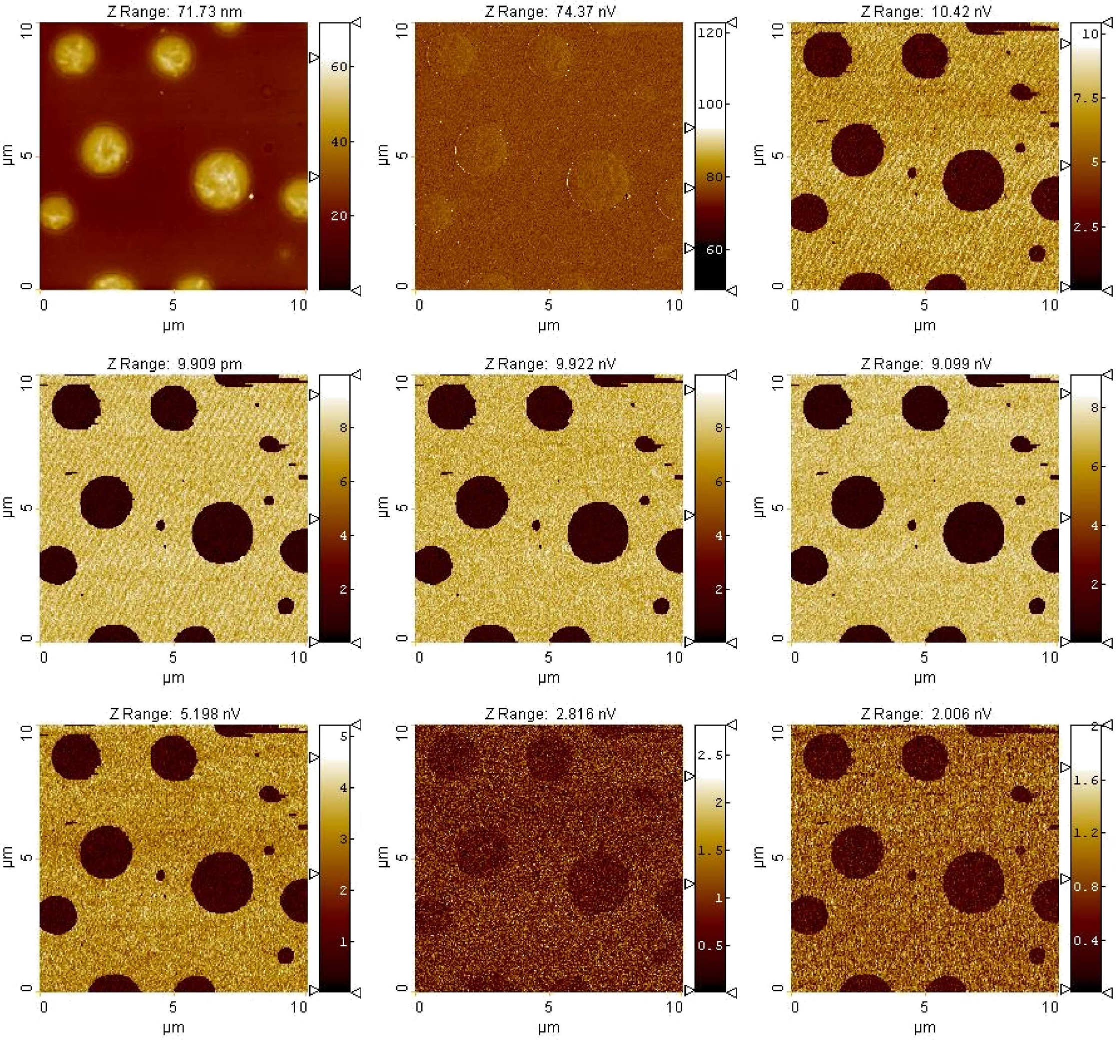

Fig. 8. The topography and related stiffness maps obtained on the test sample. Following harmonics were acquired: 1, 3, 5, 7, 9, 11, 13, 15

In order to verify the efficiency of the detection method, the test sample from Bruker was used: a blend of polystyrene and polyolefin elastomer (ethylene-octene copolymer) deposited on a silicon substrate with spin-cast method. The PS regions of the sample have elastic modulus value – approximately 2 GPa, while the copolymer regions have elastic modulus value – approximately 0.1 GPa. The topography map as well as the high harmonics (1, 3, 5, 7, 9, 11, 13, 15) maps are shown in Fig. 8.

One can see very clearly the areas of higher (bright) and lower (dark) stiffness. The distribution of measured values of acquired harmonics is shown in Fig. 9. In order to make the distributions comparison easier, the count and the voltage axis were normalized (fitted into that same range). The first harmonic does not give satisfying information, but situation improves in the case of 5th, 7th and 9th harmonics, where the distribution delivers legible separation of two groups of data representing high and low stiffness. For the 13th harmonic the separation becomes difficult to resolve and for the 15th harmonic the result improves again. Therefore it is essential, that in order to provide high quality data, one needs to perform the mapping of appropriate harmonics. The solution presented in this work allows to acquire sufficient amount of information during single scan process and to use the best dataset afterwards.

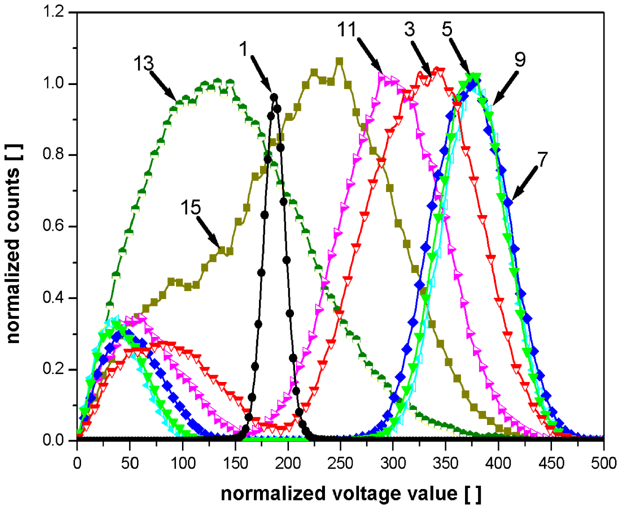

Fig. 9. The histogram showing the difference in detection dynamics of the stifness for various harmonics of the signal

It should be underlined, that the detection level of the signal is related to the resolution of the analogue-digital converter. Therefore the development of dedicated, high speed (10 MS/s) and high resolution (24 bits) converter has been recently launched in order to improve the performance of the presented system. It should, however, be taken into account, that higher amount of data will increase the load of the data bus as well as the need of the computational power.

5. Summary

In this paper we have presented the solution allowing to perform the mapping of the surface stiffness in the dynamic mode of atomic force microscopy. As the T-shaped cantilever was used as a sensor of the tip-sample interactions, it was possible to observe the high-order harmonics of the torsional oscillation signal. In order to measure and acquire simultaneously several harmonics, we have developed software-based eight-channel lock-in amplifier. We have also demonstrated that the computing units cooperating with an AFM should work in real-time regime as the calculating process lags can compromise the measurement.

It should be underlined, that the presented approach can be successfully utilized in other applications, where simultaneous analysis of multiple harmonics is necessary. The software-based approach is much cheaper and versatile than utilization of several lock-in amplifiers. As the commercial version of the presented solution is concerned, FPGA-based modules can be developed in order to provide required computational power and reasonable unit price.

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