THE MACROSCOPIC MODEL OF A SCANNING FORCE MICROSCOPE

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ABSTRACT

The paper presents a macroscopic model of atomic force microscope. The tool is designed for advanced physics experiment to be carried out in Physics Laboratory II at the Institute of Experimental Physics, Wroclaw University. The authors presents settings of the experiment. The image of model surface topography realized with the apparatus is also presented.

1. INTRODUCTION

The Atomic Force Microscope (AFM) is a type of Scanning Probe Microscope (SPM) allowing one to obtain a picture of a surface under study with single atom resolution. For the first time this kind of microscope was constructed in 1986 by G. Binning, C. F. Quate and Ch. Geber [1]. A lot of changes and modifications of the first AFM were made before a common, well known tool for investigation of solid state was created [2].

The authors have adopted the idea of Fredy R. Zypman and Claudio Guerra-Vela [3] and constructed a cheap, macroscopic model of AFM (MAFM). It brings to light physical bases of the tool and gives a chance to get information about a way a real AFM works in. We have also used the model to set up students' experiment to be carried out at Institute of Experimental Physics of Wroclaw University.

The paper describes the constructed model and presents its use for creating students activity at advanced level. The authors believe that the setup, together with proposed experimental procedure will help to enrich students' knowledge and skills in experimental physics significantly.

2. EXPERIMENT'S IDEA

Microscopic cantilever's vibrations show no difference from the vibrations of a macroscopic rod [4]. Theoretical calculations of cylindrical rod's frequency f_k can be done when its shape, cross-section area S, length l, density ρ and Young's modulus E of the material it is made of, are known:

$$f_k = \frac{\varepsilon}{2\pi}\left(\frac{\mu_k}{l}\right)^2 \sqrt{\frac{E}{\rho}}, \tag{1}$$

where: k is a natural number indicating a mode of vibration and μ_k are wave numbers (1,87; 4,69; 7,85; 10,99; 14,13 etc. [5]). For the circular cross-section of a rod with radius r, for which radius of inertia $\varepsilon=r/2$ and $n_k = \frac{\mu_k^2}{\mu_1^2}$:

$$f_k = n_k \frac{1}{4\pi}\frac{r}{l^2}\sqrt{\frac{E}{\rho}}\mu_1^2. \tag{2}$$

It is easily seen that the frequencies of natural vibrations of the rod mounted on its one end do not stand in natural numbers ratio – the composite vibration is not a periodic one.

The aim of the proposed experiment is to study characteristics of a macroscopic model of an atomic force microscope (MAFM) that are analogous with those of real AFM working in tapping mode. AFM works on the base of a well known physical phenomenon – changes of the amplitude and frequency of a vibrating cantilever due to forces acting on its free end. The value of the force depends on a distance between a surface and the tip, so the information about cantilever's behavior may be used to image topography of the investigated surface. In our MAFM the model of surface (MoS) consists of a metal platform, free to move, on which small iron based rare earth magnets ($Nd_2Fe_{14}B$) are located. The cantilever's role is played by a vibrating rod with small magnet mounted on its free end. The motion of the surface's model is controlled through interface with the use of a computer, in which the experimental data are stored.

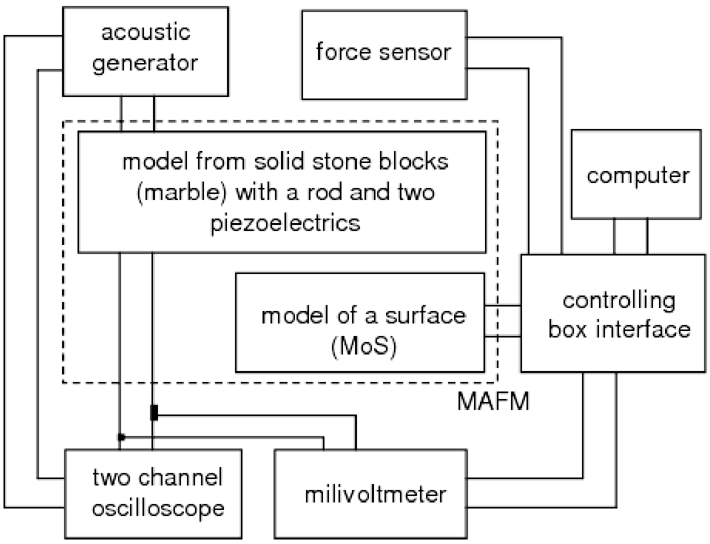

Fig. 1. The block scheme of the experimental setup.

3. EXPERIMENTAL SET-UP

The MAFM is built from two marble blocks: the smaller, of thickness of 55 mm and the bigger one, of thickness of 70 mm. The smaller block is put perpendicularly to the bigger one, on the left side of it. The experimental setup is shown in figure 1 while figure 2 shows real photo of it. The base stone stands on four rubber legs to dump external vibrations. The main part of the model with vibrating rod is put on the metallic holder attached to the building's wall, when model of a surface (MoS) stands on the table beneath the MAFM.

The model's cantilever is made of a steal rod stranded with aluminum plate screwed to the smaller marble block. Two small piezoelectric ceramics are attached to the rod – one close to the rod's end joined to the marble and the other one near to the free end of the rod. The piezoelectric element close to the stone is connected to an acoustic generator and channel x of the oscilloscope and works as a source of rod's vibrations that are received and registered by the second piezoelectric element, connected to milivoltmeter and to channel y of the oscilloscope. The frequency of vibration of second piezoelectric (free end of cantilever) can be measured when it is in resonance with the first one. Under free end of the cantilever a model of surface (MoS) is placed. The MoS consists of a square metallic plate on which magnets are located. Two step motors allow the surface to move in x and y directions. Step motors are connected to an interface box, controlled by a computer, on which an educational program COACH 5 runs.

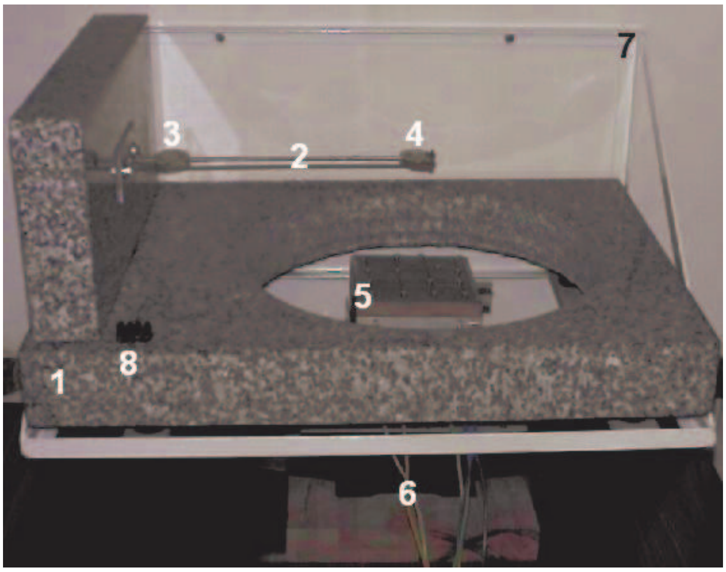

Fig 2 View of the macroscopic model of an atomic force microscope (MAFM), where: 1 – marble base, 2 – aluminum rod, 3-4 – piezoelectrics, 5 – model of a surface (MoS), 6 – elements allowing controlled motion of a model, 7 – metallic holder, 8 – electrical connectors.

The setup described above allows measurements of characteristics analogical with those of real AFM. The MAFM allows also imaging of the topography of the surface model.

4. RESULTS OF THE MEASUREMENTS

Table 1 presents values of frequency f_k calculated for our experimental set up on the base of equation (2). Two last columns show frequencies f_m being results of measurements together with their uncertainties $u(f_m)$ [6]. Linear dependence between f_m and n_k, expected from dispersion relation (1), is satisfied. Experimentally obtained frequencies are in agreement with the values coming from the results of calculations – the discrepancies are less than 20% (except for the first mode).

Tab. 1. Results of calculations f_k and measurements f_m where: k – index number; $u(f_m)$ – frequency uncertainty.

k	n_k	f_k	f_m	$u(f_m)$
1	1,00	82	51	1
2	6,27	513	365	5
3	17,50	1433	1171	10
4	34,37	2815	2681	20
5	56,84	4655	3717	25
6	85,5	7002	6892	30
7	119	9745	8396	50

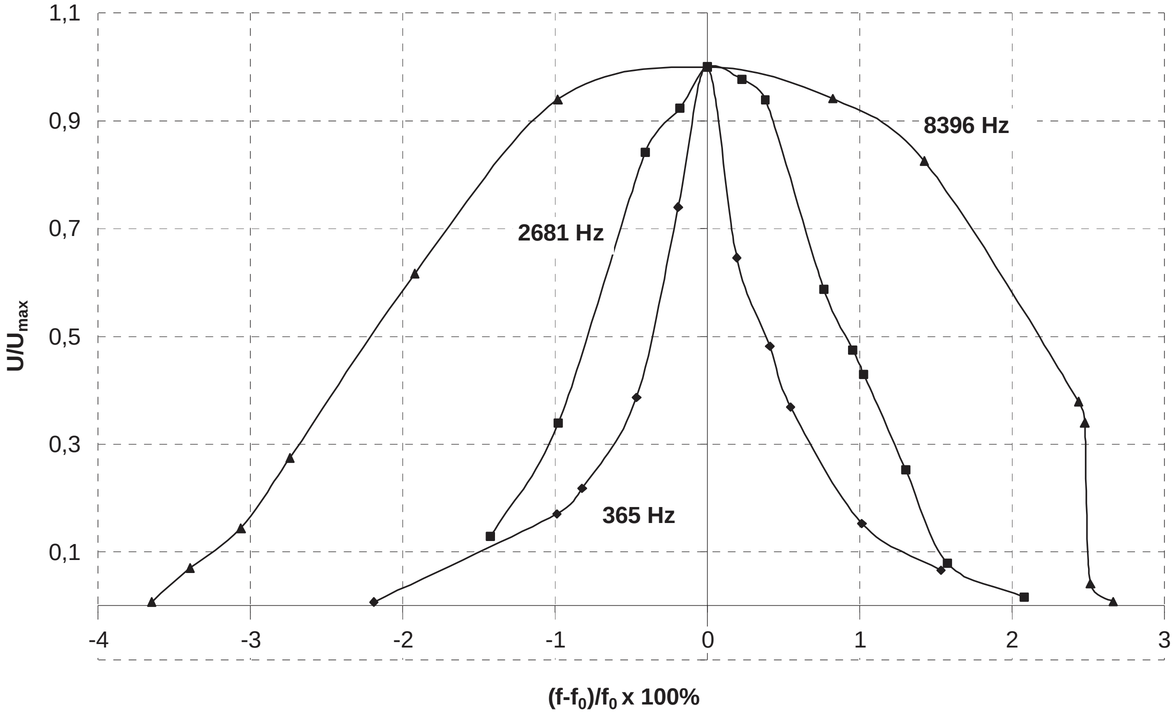

Fig. 3. Resonance characteristics of model's rod for k = 2 (rhombs), 4 (squares) and 7 (triangles).

Resonance characteristics obtained for the model's rod when k = 2, 4 and 7 are shown in figure 3. It is clearly visible that their FWHM increase with k. As the most suitable, from technical point of view – the signal level and acoustic generator features – frequency f = 371 Hz – near to the second resonance frequency f_m = 365 Hz has been chosen for our MAFM to simulate tapping mode of AFM work.

We have found shifts of the free rod's vibration frequency due to the force acting on the magnet on the free end of the rod. The shifts are in figure 4, when the distances between the magnets are d_1 = 8 mm and d_2 = 5 mm, respectively. Significant changes in resonance frequency are visible.

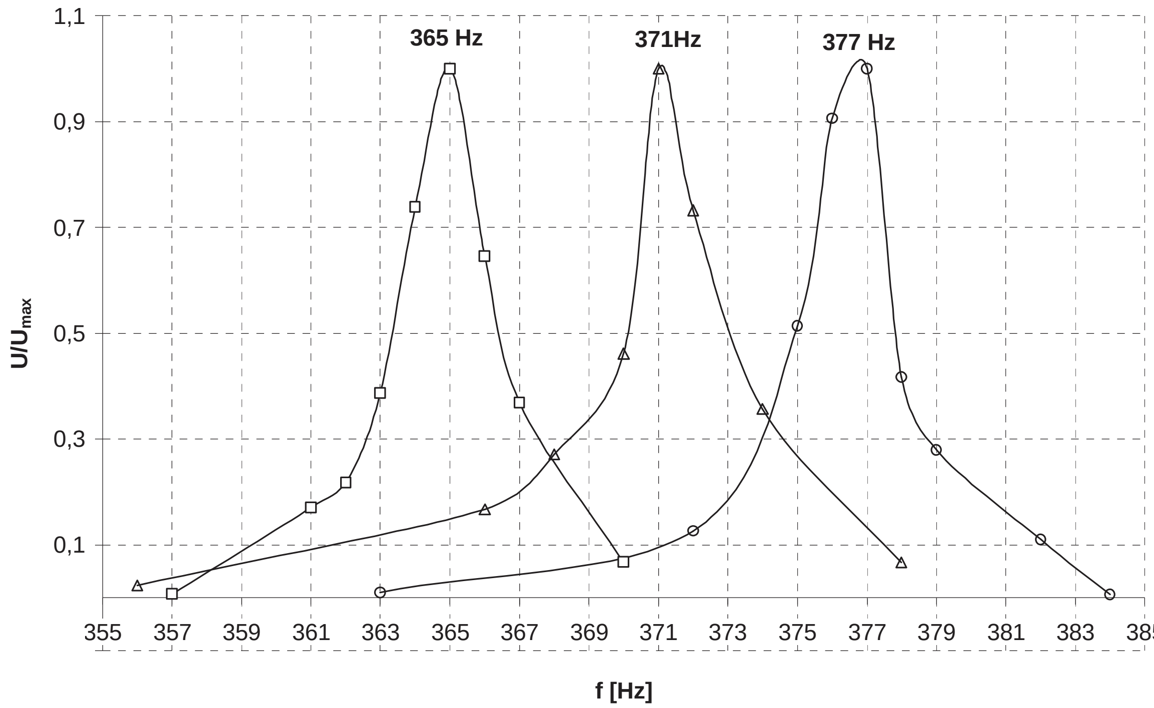

Fig. 4. Shifts of the rod's vibration frequency f_m = 365 Hz due to force (F_{d1} = 0,14 N; F_{d2} = 0,38 N) acting on its free end.

The visualization of the MoS topography at the distance between the magnets d = 4 mm is presented in figure 5a. The projection is impressively accurate. The real photo of the modeled surface is in figure 5b.

Our results illustrate, with success, the behaviour of MAFM – the tool that can be used to teach about a real AFM.

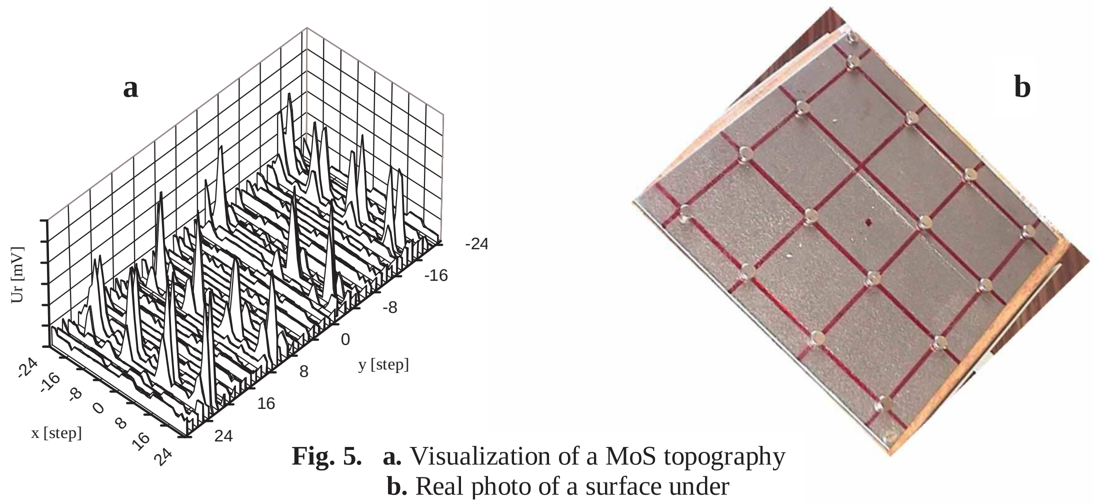

Fig. 5. a. Visualization of a MoS topography
b. Real photo of a surface under

3. CONCLUSIONS

The model and the experimental procedure presented in the paper, allow measurements of MAFM characteristics – resonance frequencies, frequency shifts – that are analogous with characteristics of a real AFM working in tapping mode.

Experimental resonance frequencies are in agreement with the theoretical dispersion relation (2). The differences between theoretical and experimental values are of the same magnitude as reported in [3].

The use of commercial controlling box interface allows simultaneous programmed controlling of MAFM and storing of experimental data. The image of a modeled surface is very spectacular.

The authors believe that the model is a valuable tool at advanced physics laboratory.

4. LITERATURE

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