Experimental Research of Improved Sensor of Atomic Force Microscope

Vytautas Bučinskas[✉], Andrius Dzedzickis, Ernestas Šutinys,
Nikolaj Šešok, and Igor Iljin

Vilnius Gediminas Technical University, Vilnius, Lithuania
{vytautas.bucinskas,andrius.dzedzickis,
ernestas.sutinys,nikolaj.sesok,igor.iljin}@vgtu.lt

Abstract. Atomic force microscope (AFM) – is device widely used in many scientific fields for nano-scale surface scanning. AFM also can be used to probe mechanical stiffness, electrical conductance, resistivity, magnetism and other properties. The main limitation of AFM implementation is relatively low scanning speed. This speed depends from dynamical characteristics of AFM sensor and from surface roughness of scanned sample. Our research is focused on increasing scanning speed of AFM microscope assuming AFM mechanical sensor as sensitive dynamic system. Our proposed method enables increase of scanning speed by modifying some features of mechanical sensor by adding non-linear force to the surface of cantilever of AFM sensor. Proposed method is modelled theoretically using Simulink features. This paper presents research of mechanical sensor of AFM. After performed research, obtained results are presented on graphical form. At the end of paper discussion presented and conclusions are drawn.

Keywords: Atomic force microscope · Cantilever · Modelling · Nonlinear stiffness

1 Introduction

Atomic force microscopy (AFM) invented by Binning et al. in 1986 as a type of scanning probe microscopy. Since that time, AFM used in various research disciplines as versatile imaging technique for visualizing sample surfaces at very high resolution. Ability of atomic force microscope to measure force in nanometric scale range has made this microscope attractive tool suitable for measurement of various properties like friction, adhesion, density, viscoelasticity and even intermolecular forces [1, 2].

AFM working principle based on measurement of interaction forces between scanning probe tip and sample surface. Mechanical part of AFM sensor consist of two main elements – probe and micro cantilever. Sensor probe is attached to the free end of micro cantilever; other end of cantilever is attached to the AFM base. During scanning process probe interacts with imperfections of sample surface and creates deflections of cantilever. The surface properties obtained by observing the cantilever deflections.

Initially, AFM designed to operate in contact mode. Contact mode is scanning mode, in which the probe's tip scans the sample surface by contacting it. From

deflection of the micro cantilever due to the interaction force between probe's tip and sample's surface, topography of the sample being obtained [3]. Applications of this scanning method limited by hardness of sample surface. In order to avoid this limitation and increase application possibilities in 1987 was developed non-contact mode AFM. Non-contact AFM scanning mode is suitable to obtain image from the soft biological tissues where the contact mode may not be applicable due to the damage to the surface. Nonetheless, in non-contact AFM mode, the probe needs to be excited at near its resonant frequency while the distance between the tip and sample's surface must be kept constant [4]. In this mode, the surface properties are revealed by observing dynamic changes of the vibration parameters (amplitude, resonance frequency and phase angle) due to tip–sample interaction [3].

Tapping mode is another AFM mode, which has characteristics typical to contact, and non-contact modes. Tapping mode was developed in 1993 [5]. In this technique, the probe's tip can hover over the sample's surface while the micro cantilever is oscillating at amplitudes mainly higher than the amplitudes in the non-contact mode. However, the nanoscale interaction forces may cause the amplitude of the oscillation decreases when the probe's tip approaches the surface [3, 4, 6].

In addition to conventional AFM techniques, which are capable of achieving images of the sample's surface, most recent innovations have been carried out in revealing the structure formation under the surface [3].

Despite all improvements and numerous studies carried out after the AFM invention exists many challenges related with such AFM characteristics like resolution or scanning speed. Usually when AFM works in contact mode, its resolution is limited by finite size of probe tip, scanning speed is limited by dynamic characteristics of cantilever [7–9]. Oscillation frequency of mechanical sensor cantilever during scanning process depends from scanning speed and from roughness of sample surface. If cantilever oscillation frequency becomes too high and goes close to the resonant one, contact between probe and sample surface became unstable and scanning results are distorted. Resonant frequency of cantilever of the mechanical sensor is determined by its material properties and geometric parameters [10]. Despite numerous work done on analyzing relationships between geometry, stiffness and resonant frequencies of cantilever versatile solution of increasing atomic force microscope scanning speed is still requested.

In this paper will be presented important intermediate results of research aimed to deliver solution of increase AFM scanning speed in contact mode.

2   Object of Research

From engineering point of view, atomic force microscope is typical mechatronic system with feedback loop. During scanning process probe with initial force is pressed to the sample surface. Then piezoelectric actuators of the AFM platform are activated and scanning starts; deflection of cantilever follows topography of sample surface [9], thus allowing to record surface parameters. Deflection of cantilever is measured using non-contact optical interferometry method [1–3] or using piezo resistive or piezo-electric sensors installed on cantilever surface [6, 11–14]. Moreover, from cantilever

deflection normal interaction force between probe and sample is determined. This force is kept in specified range using actuator, operating in the direction normal to surface of sample. This AFM platform actuator is controlled by feedback loop [15].

For easier control of complex AFM structure, al AFM components are classified into functional electrical and mechanical systems such as scanned sample positioning system, mechanical sensor with scanning tip and cantilever displacement measurement system. All systems within AFM are interdependent on each other [7, 8].

Our research is focused on increasing of speed of sample scanning process by affecting to mechanical part of AFM sensor. Increase of scanning speed could be achieved by altering dynamic characteristics of AFM cantilever. Idea of improvement of AFM sensor lays in method of increase of resonance frequency of mechanical sensor cantilever. In this case, cantilever displacement response for cinematic excitation generated by roughness of sample surface will not create distortions, this will allow scan samples at higher speed not losing contact between probe and sample. Cantilever resonance frequency can be increased by changing geometric parameters of cantilever like described in [10, 16] but in this case cantilever stiffness is changed irreversibly. Cantilever spring constant is very important parameter if cantilever is to stiff probe will damage sample surface and scanning results will became inaccurate.

In this paper proposed method of increasing AFM scanning speed is based on idea to add to AFM sensor system additional controllable stiffness element [7–9]. Implementation of this element not require essential changes in AFM construction, moreover this method is suitable for use with different types of cantilevers. Additional stiffness to the cantilever added as external nonlinear force. This force created using stream of compressed air [7–9]. Directed stream of gases creates nonlinear aerodynamics force which depend from size of cantilever surface area, gases pressure, diameter of air duct, gap size between cantilever surface and air duct. Main advantage of aerodynamic force that it is distance dependent [7] and on cantilever surface acts as complex spring, which prevents probe bounce from sample surface in critical moments, but not pressing probe to much then contact between probe and sample surface is stable. Size of additional force is controlled by gas stream. Whereas size of additional stiffness depends on parameters related with probe, cantilever, sample surface and other properties, for each configuration individual gas pressure identified and set during the initial scanning.

For practical implementation of this idea, standard AFM construction requires design change. Only specialized cantilever holder with installed micro air duct should replace the standard holder. Function of gas pressure control then installed to the AFM control system, or pressure control performed by additional independent system. Schematic illustration of proposed AFM sensor improvement presented in Fig. 1.

In order to realize proposed improvement was carried out modelling of dynamic system of mechanical sensor. There were analysed most common AFM cantilever modelling methods [17]. There was build mathematical model of mechanical part of AFM sensor, which proves effect of aerodynamic force to cantilever frequency response [8]. Characteristics of aerodynamic force acting on cantilever surface were investigated [7]. In addition, initial experimental research, which showed that cantilever displacement could be controlled using aerodynamic force, was performed [9].

Purpose of our research presented in this paper is to modify initial mathematical model for better detection of probe and surface contact loss.
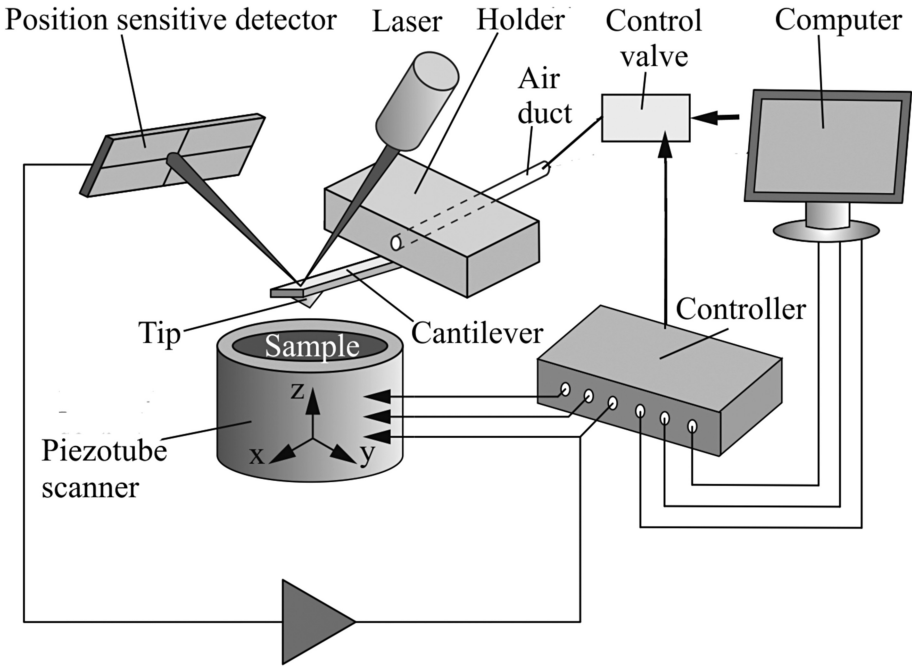
Fig. 1. Structural schematic of improved AFM sensor

3   Mathematical Modelling of Mechanical System of AFM Sensor

There are big variety of mathematical models of AFM cantilevers and probe – surface interactions, different methods of analysis are applied as presented in [17] also in [1–5, 10]. The focus in modelling of the AFM sensor – correct representation of probe – sample surface interaction. In the majority of papers, this interaction is approximated as one degree of freedom system with stiffness and damping elements of various linearity.
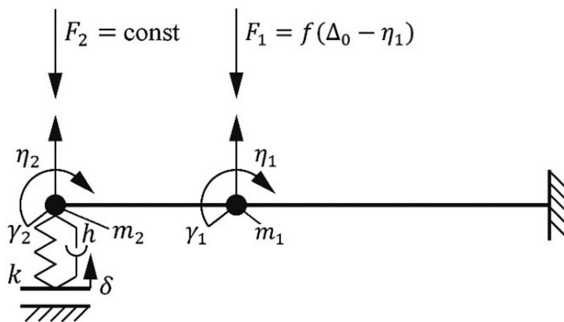

Fig. 2. Mathematical model of improved AFM sensor [7–9]

Proposed dynamic model of modified AFM sensor presented in Fig. 2. Mathematical model and corresponding equation are presented in details in [8, 9].

Analyzing results of model, presented in Fig. 2 we obtain that moment contact loss between probe and sample surface is not clearly detected. Problem is in approximation of probe – surface interaction forces. When these forces are modelled as spring in corresponding equations are created virtual relationship between probe and surface, or point on which cinematic excitation is applied. This relationship disturb simulation of moment then probe – surface contact is lost because probe and surface all the time are connected by spring. We improved our model by adding additional function for control stiffness k in moments then conditions of probe – sample contact loss met. Calculation scheme for determination probe – surface contact loss conditions presented in Fig. 3.
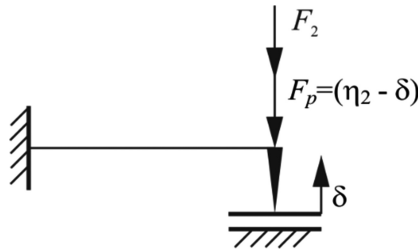
Fig. 3. Scheme for determination probe – surface contact loss conditions

In scheme, F_2 represents initial probe clamping force, F_p represents contact resistance force. Kinematic excitation, which simulates surface roughness represented by δ. From scheme presented in Fig. 2 we obtain main condition which corresponds to situation when probe detach sample surface:

$$m\ddot{\eta}_2 > F_2 + F_p + mg \tag{1}$$

First equation transformed to corresponding form.

$$\ddot{\eta}_2 > \frac{F_2}{m} + \frac{k(\eta_2 - \delta)}{m} + g \tag{2}$$

Second condition is determined from geometric properties it describes case then probe is in contact with surface.

$$\eta_2 > \delta \tag{3}$$

Second and third conditions transformed to corresponding Simulink diagram are added to stiffness control block. This block generate control signal, which allows to eliminate effect of contact stiffness k then cantilever moves up to peak of surface roughness. Then cantilever moves down our contact spring is pressed and have no effect to results. Improved mathematical model was tested using various excitation parameters.

4   Results of Research of AFM Sensor

Results of the Simulink model simulation with different excitation frequency were
obtained. Also we calculate cantilever response for stochastic excitation. Obtained
results presented in Figs. 4, 5 and 6 respectively.
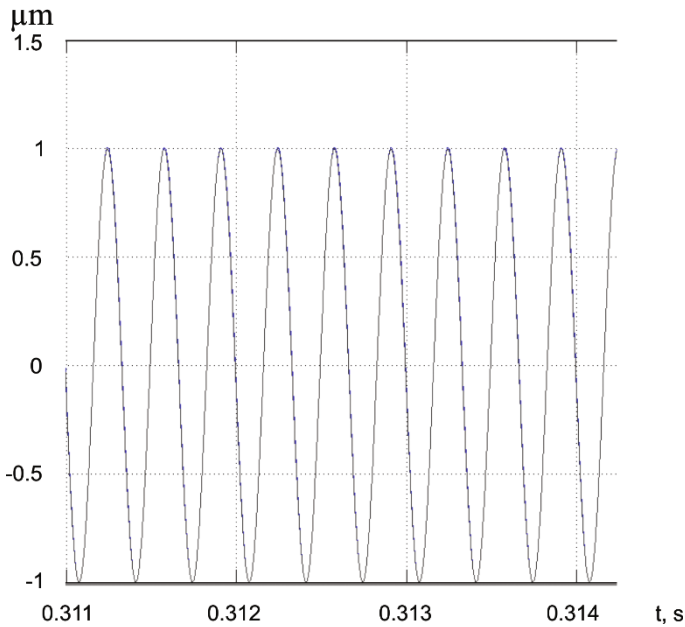
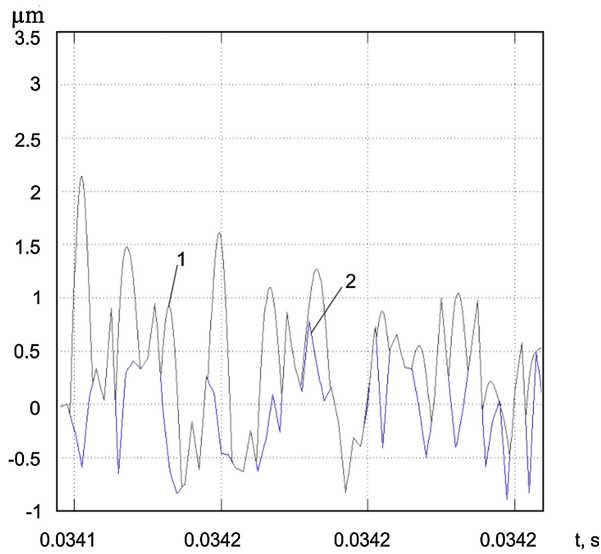**Fig. 4.** Cantilever response when excitation frequency is 3 kHz

From graph presented in Fig. 4 it is seen that AFM probe trajectory ideally cor-
responds to the excitation signal which frequency is 3 kHz. This case simulates situ-
ation then AFM sensor works in normal conditions and contact between probe and
sample surface is stable.

In case then excitation frequency is increased to 15 kHz probe starts bouncing and
shape of excitation signal is not repeated properly. This case corresponds to situation
then in real AFM scanning speed is increased and probe sample contact is interrupted.
This case presented in Fig. 5.

Graph presented in Fig. 6 shows cantilever response for stochastic signal. Line
represents 2 chaotic excitation signal, line 2 represents behavior of AFM probe.
Stochastic signal is more suitable for simulation of sample surface topography. From
graph it seen that situation is similar to presented in Fig. 5. In case then excitation
frequency becoming to higher probe stops repeating topography of sample surface.
Improved mathematical model is suitable to detect moment of tip – surface loss and this
is desired result of our research.
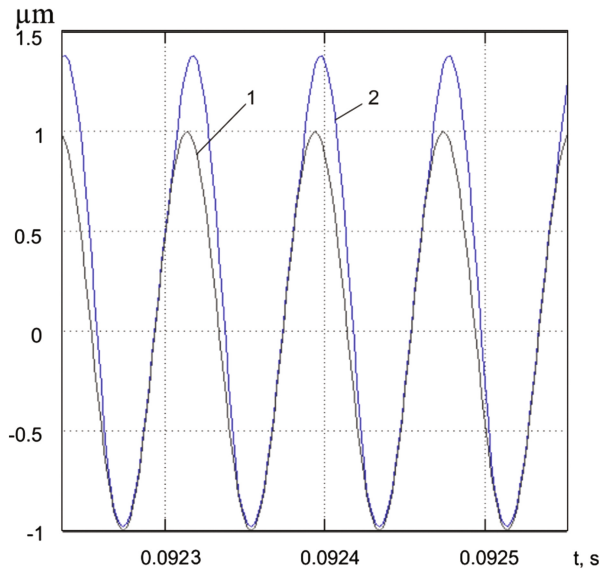
Fig. 5. Cantilever response when excitation frequency is 15 kHz: 1 – excitation signal; 2 – cantilever response

Fig. 6. Cantilever response for stochastic excitation frequency: 1 – cantilever response; 2 – excitation signal

5   Conclusions

After performing the theoretical research of the mechanical sensor of AFM, some useful and interesting results were found. Performed theoretical research gave us possibility improve mathematical model for more clear detection of contact loss between probe and surface. Improved model is suitable simulate AFM cantilever behavior at different excitation conditions. In future researches this model will be used for simulation of various AFM sensor characteristics.

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