DYNAMICAL STUDY OF A PIECEWISE-SMOOTH MODEL IN TAPPING MODE ATOMIC FORCE MICROSCOPE

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Abstract: This paper deals with the dynamics of a piecewise-smooth model used to represents the Tapping Mode Atomic Force Microscope behavior. Created by Binning et al (1986), Atomic Force Microscopy became a powerful tool in scanning probe process. A micro-cantilever vibrates, excited by a piezo electric transducer and its vibration is detected by a photo detector. Working close from its resonance, the micro-cantilever has a nonlinear behavior, due to this, chaotic behavior may occur. Represented by a piecewise SDOF system, the dynamics of the model are investigate via numerical simulations and the study of figures like, phase portrait, FFT, time history and Lyapunov exponent show evidences of chaotic oscillations of micro-cantilever tips in dynamic atomic force microscopy (AFM). This irregular behavior appears in a defined interval of time.

Palavras-Chave: Atomic force microscopy, chaos.

1. INTRODUCTION

In last decades, the Atomic Force Microscope (AFM) became a powerful tool in scanning probe microscopy (SPM). Atomic Force Microscope (AFM) is a powerful tool, its application includes manipulation of carbon nanotubes, DNA, imaging and actuation in nano-electronics, etc. (Rützel et al., 2003). In AFM, a micro-cantilever with a tip at its free end vibrates and sends a signal to a photo detector, the acquired images come from this movement and the scanning process starts.

Invented by Binning et al (1986) [3] the AFM has three modes of operation, non contact, tapping mode and intermittent mode. the non contact mode is characterized by the presence of the attractive forces, tapping mode and intermittent mode are characterized by the presence of attractive and repulsive forces. The most used operation mode is the tapping mode and in this case, strong nonlinearities may occurs [1].

Deterministic chaos underpins the dynamics of many nonlinear systems that display a very high degree of sensitivity to initial conditions, in AFM, chaotic behavior is very common and when this type of behavior occurs, the images are affected, what is not a desirable outcome.

Mathematical models are commonly used to understand the behavior of an AFM micro-cantilever. Numerical simulation and analysis of the obtained images are essential to understand the behavior of the system and to determine if there is or not chaos in the system. In other works, like [7], [6], [10], and [11], the study of the system was essential to find chaotic behavior and to project control methods to stabilize the system.

In AFM, chaos is characterized by an undesirable motion of the micro cantilever that vibrates close from its resonance. By [5], the presence of chaos can lead to errors, while the imaging of samples are obtained, thereby introducing an element of deterministic uncertainty in nanometrology.

In this paper, a model proposed by [2] that uses a one-degree-of-freedom model with linear coefficients to describe attractive and repulsive forces is used. Numerical simulations using software Matlab® obtained phase portraits, time history and Lyapunov exponents.

2. MATHEMATICAL MODEL

The tip-sample interaction is characterized by a short-range of the repulsive forces and by a long-range of the attractive forces.

In a piecewise-smooth model of an AFM micro-cantilever studied by Sebastian et al., the attractive forces are represented by a linear spring with negative stiffness, the repulsive forces are represented by a linear spring with positive stiffness, and linear dampers are introduced to
account for the energy dissipation during the tip-sample interaction.

The dynamics of the micro-cantilever are represented by a piecewise-smooth dynamical system.

\[
H(u, \dot{u}) = \begin{cases} 
0 & u + s > d \\
-A(u + s - d) + B_j \dot{u} & 0 \leq u + s \leq d \\
A_0(u + s) + B_j \dot{u} - A(u + s - d) + B_j \dot{u} & u + s < 0
\end{cases}
\]

With \((x, t) \rightarrow (u, t^*)\)

\[
t^* = \omega_0 t, \quad u = \frac{x}{u_0}, \quad \omega_0^2 = \frac{k}{m}, \quad \omega_s^2 = \frac{k_b}{m}, \quad \omega_d^2 = \frac{k_d}{m},
\]

\[
\alpha = \frac{\gamma}{\omega_0}, \quad B = \frac{c}{m \omega_0}, \quad B_s = \frac{c_s}{m \omega_0}, \quad B_d = \frac{c_d}{m \omega_0}, \quad A = \frac{\omega_s^2}{\omega_0^2},
\]

\[
A_0 = \frac{\omega_d^2}{\omega_0^2}, \quad s^* = \frac{s}{u_0}, \quad d^* = \frac{d}{u_0}
\]

3. NUMERICAL SIMULATIONS

By using software Matlab®, ode 45, step length \(10^{-3}\), and parameters, \(A_0 = 1; \ B_j = 0; \ B_b = 0.0000001; \ s^* = 0.01; \ d^* = 0.01; \ A = 0.000001; \ \alpha = 0.01\), the following figures are obtained:

Figure 3 – Phase portrait with nonlinear behavior.
In figure 6a and 6b, with $t = 10^4$, Lyapunov exponents obtained the follow results:

\[ \lambda_1 = 0.0099, \quad \lambda_2 = -0.0099, \quad \lambda_3 = 0. \]
4. CONCLUSIONS AND DISCUSSIONS

In atomic force microscopy, the micro cantilever chaotic behavior can result in an unsatisfactory obtaining of images. In the model presented in this paper, chaotic behavior is obtained after a study of the motion of the system via numerical simulations.

In figure 3, is possible to observe the presence of strange attractors, in figures 4a and 4b there is no presence of an only period. In figure 5, the Poincare map shows a stochastic motion [12], that commonly appears in undamped or lightly damped systems. The FFT shows picks of resonance and irregular spectrum, and finally, in figures 7a and 7b, the presence of a positive Lyapunov exponent imply in a chaotic behavior [12]. By this fact, is safe to affirm that chaotic motion is detected in the system. The chaotic motion occurs in a system without nonlinear term, by this, the system can be characterized as a strong nonlinear system [13].

In future work, the objective is to study the bifurcation map and basins of attraction to better understand the system, and to find a periodic orbit to develop a control system to stabilize it.

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6. REFERENCES


