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Modeling and control of an atomic force microscope using a piezoelectric tuning fork for force sensing

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ABSTRACT

This paper investigates modeling and control issues associated with an atomic force microscope which uses a piezoelectric tuning fork for atomic force sensing. In the modeling part, the dynamics of piezoelectric tuning fork and its atomic interaction with the test sample via the scanning tip are physically characterized. The modeling results explain not only the atomic force sensing mechanism but also the important characteristics observed in experimental frequency responses. In the control part, an LTR controller is designed to maximize the controller bandwidth and yet maintain robustness against unmodeled dynamics and different operating conditions. Scanning results indicate that the LTR controller exhibits superior performance than a conventional PI controller.

1. Introduction

The atomic force microscope (AFM) was first introduced in 1986 to image the surface topology and examine material properties at scales ranging from micrometers to subnanometers. A typical configuration for the AFM is a probe which is formed by a tiny tip attached to a cantilever. As the tip is brought close enough to the sample surface, atomic force interaction is induced and causes the dynamics of the tiny tip, consequently the dynamics of the cantilever, to change. Such a dynamic change is measured by a sensor whose signal can be used to infer the ultrasmall atomic force.

Among the sensors for detecting the atomic force, the first AFM presented by Binnig et al. [1] employed the tunneling current to detect the deflection of the cantilever resulted from the atomic interaction. Since the tunneling-current method is only applicable to conductive samples, researchers have sought other means such as optical interferometry [2] and optical levers [3] to carry out atomic force sensing. The optical methods, although do not require samples to be conductive, demand accurate alignment of the optics. The alignment is probe-specific, and therefore is needed when one exchanges the probe. Moreover, the alignment also has to be repeated whenever the mechanical drift causes a shift in beam optics. To circumvent the problem, AFM probes with self-sensing capabilities have been proposed. For instance, in [4] a microfabricated cantilever with a piezoelectric thin film deposited on one side is built. The piezoelectric film therein acts as an atomic force sensor. Ref. [5] uses a similar design but instead a piezo-resistive film is doped. In [6–8], the authors employed quartz tuning forks which act as a combination of the cantilever and the self-sensing mechanism. The self-sensing in those cases are also

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piezoelectric-based in which the atomic force is monitored by either mechanically exciting the tuning fork and then measuring the voltage across the tuning fork electrodes, or electrically exciting the electrodes by a sinusoidal voltage and then measuring the current flown into the electrodes.

In the system under investigation, the piezoelectric tuning fork proposed in [9] as a self-sensing AFM probe is adopted. Different from the quartz tuning fork, which is an integrated body, the piezoelectric tuning fork is made of a non-conductive beam sandwiched by two piezo-bimorphs. When in operation, one bimorph is actuated by a voltage so as to drive the whole fork into resonance. The resonance maximizes the amplitude of the oscillating electric charges across the electrodes on the other bimorph. Such an amplitude signal is used for measuring the atomic force between the tip, which is made of diamond and mounted on the actuating bimorph, and the sample.

A picture of the piezoelectric tuning fork and the schematic diagram are shown in Fig. 1.

This paper addresses modeling and control issues associated with the piezoelectric tuning fork AFM. To begin with, the model of the piezoelectric tuning fork alone is physically characterized. Section 3 provides a model for explaining the atomic force sensing mechanism. In Section 4, frequency response tests are conducted to identify the AFM dynamics. The controller design and the associated experimental results are respectively given in Sections 5 and 6. Finally, conclusions are given in Section 7.

2. Modeling of piezoelectric bimorphs

In this section, we model the dynamics of the actuating and the sensing bimorphs respectively. The modeling results will be used later to construct the complete model of the tuning fork for atomic force sensing.

2.1. Modeling of the actuating bimorph

The bimorph is made of two identical piezoelectric elements with each of which has length L, width b, and thickness h. While the top of the upper element and the underside of the lower element are connected to one electrode, the common interfaces of the two elements are connected to the other electrode.

Because the piezo-elements are polarized in an opposite manner, the input voltage u across the electrodes causes one piezo-element to expand, the other to shrink, thus causing the whole bimorph to bend. Defining the length direction as the 1 axis, the width direction as the 2 axis, and the height direction as the 3 axis, the constitutive equation relating stress, strain and electric field in each piezo element is in the form of [10]

$$T_1 = c_{11}S_1 - e_{31}E_3 \tag{1}$$

where T_1 and S_1 are respectively the stress and strain in the 1-direction, E_3 is the electric field resulted from the input voltage, c_{11} is elastic stiffness constant, and e_{31} is piezoelectric stress/charge constant.

To reflect the fact that the electrodes are evenly distributed along the length of elements, we multiply to E_3 in (1) an effective function $F(x_1)$, where x_1 is the longitudinal coordinate and

$$F(x_1) = \begin{cases} 1 & \text{for } 0 \leqslant x_1 \leqslant L \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

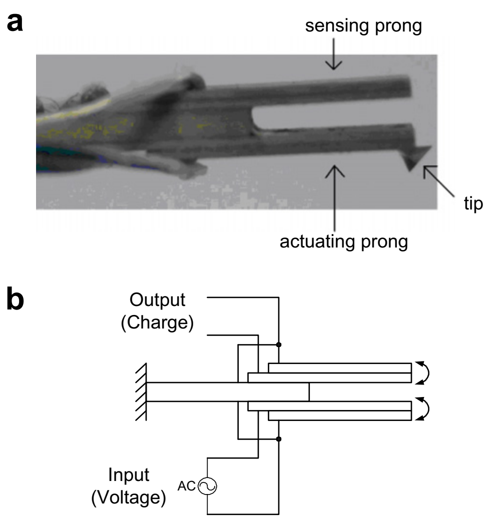

Fig. 1. The piezoelectric tuning fork: (a) a picture of the piezoelectric tuning fork and (b) the schematic diagram.