Study on Resonance Frequency Detection System of Piezoelectric Micro-Cantilever

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Abstract. A kind of resonance frequency detection of piezoelectric micro-cantilever is presented, where there is piezoelectric film deposited. The alternating current is put on the film to make it vibrate, and when resonance frequency happens, the amplitude of piezoelectric micro-cantilever reaches the maximal. A series of experiments have been done by the driving power and detecting power designed by ourselves. The experiments show that resonance frequency can be detected by the amplifier, and the amplitude of the resonance frequency is obviously bigger than the amplitude of the other frequency. The maximal amplitude is about 600nm.

Introduction

With the invention of atomic force microscopy, a new kind of highly sensitive sensor, micro-cantilever, is presented, with which the AFM has atomic resolution and could detect the atomic force between probe and sample. The methods used to detect micro-cantilever is called beam bending technique. Laser beam irradiation in the micro-cantilever tip, the reflection light beam launched into position sensitive detector (PSD), the detection of reflected beam can detect the displacement of micro-arm beam changes. Though with high sensitivity, for a relatively complex of optical system[1], it is restrained for wide application in the field of biological detection. A kind of resonance frequency detection of piezoelectric micro-cantilever is presented, the vibration of the cantilever beam could be detected by detecting the currents generated by the vibration of micro-cantilever when the cantilever beam vibrating. Furthermore, as the micro-cantilever resonance frequency is inversely proportional to 1/2 power of the effective mass, then the micro-cantilever resonance frequency decreases when measured substance adsorbed on the micro-cantilever. Then the measured substance could be quantitatively analyzed[2] by detecting changes of micro-cantilever resonance frequency, and this principle can be applied to biological, biomedical, environmental, aerospace and other fields[3,4].

Theory Analysis of Micro-Cantilever Resonance Frequency

Micro-cantilever resonance frequency is related to its material properties, size, and the environment. And currently there are mainly two methods for calculation: spring-mass system and Rayleigh law. While only the spring - mass system is discussed here.

As shown in Figure 1, the reversion force of the "spring-mass" system is expressed as $F = -Kx$, and vibration equation is expressed as $Mx'' = Kx$, and the resonance frequency is expressed as...
following (1).

$$\omega_0 = \sqrt{\frac{K}{M}} \quad \text{(1)}$$

Without considering the bending of the micro-cantilever caused by its gravity, a micro-cantilever, the top displacement of the micro-cantilever with a mass $M$ at the end.

$$\omega_{\text{max}} = \frac{MgL^3}{4Ybh^3} \quad \text{(2)}$$

$$F = -Mg = -\frac{Ybh^3}{4L^3} \omega_{\text{max}} \quad \text{(3)}$$

When the quality of mass $M$ is much larger than micro-cantilever, the ideal micro-cantilever can be considered as a "spring - mass" system composed with spring vibrator and $M$. Then $\frac{Ybh^3}{4L^3}$ is equal to elastic coefficient $K$, and a micro-cantilever resonance frequency could be expressed as following (4).

$$\omega_0 = \sqrt{\frac{K}{M}} = \sqrt{\frac{Ybh^3}{4L'M}} \quad \text{(4)}$$

The resonance frequency of this kind micro-cantilever with the large mass at the end could be obtained with this "spring-mass" system, but this method is not applicable to micro-cantilever of even distributed mass. For the micro-cantilever of even distributed mass, the correction method is to add quality factor $n$ to the micro-cantilever as shown in formula (5), in which $m^{*}$ is the effective mass of the micro-cantilever, and $n = 0.24^{[5]}$ for a rectangular micro-cantilever.

$$\omega_0 = \sqrt{\frac{K}{M}} = \sqrt{\frac{Ybh^3}{4nL'M}} = \sqrt{\frac{Ybh^3}{4m^{*}L}} \quad \text{(5)}$$

In formula (5), $Y$, $b$, $h$, $L$ are the material properties and geometry size of micro-cantilever. It is a fixed value of a micro-cantilever fixed, so the micro-cantilever resonance frequency is inversely proportional to $1/2$ power of the effective mass. Therefore once the micro-cantilever surface absorbing the molecules to be tested, the micro-cantilever quality increasing, this causes a reduction in the frequency response. Then the measured substance could be quantitatively analyzed by detecting changes of micro-cantilever resonance frequency.

**The Excitation and Detection of the Resonance Frequency of the Micro-Cantilever**

The excitation and detection of the micro-cantilever is by piezoelectric method. There are many advantages of piezoelectric method. Firstly, when there is adhesion molecules in the micro-cantilever surface, the surface stress of micro-cantilever can be directly measured, of which no complex optical system and alignment is needed, with precision and high sensitivity measurement result. Secondly, this method can also be used for liquid and gas, the surface temperature compensation control can be done by the circuit.

When alternating voltage is applied to the up-down electrode of the piezoelectric layer, because of the converse piezoelectric effect, the deformation caused by piezoelectric layer would make the micro-cantilever vibrate. Meanwhile, the piezoelectric film has a bending deformation caused by the micro-cantilever vibration$^{[7]}$. For piezoelectric effect, the piezoelectric current is generated as the piezoelectric layer charge accumulation caused by micro-vibration. The current is proportional to the amplitude of micro-vibration. When the vibration frequency of the micro-cantilever is the same as its natural frequency, the vibration amplitude reaches its maximum, resulting in a maximum value of piezoelectric currents$^{[8]}$. So the vibration amplitude can be got as long as this current is measured, then the resonance frequency of the micro-cantilever could be obtained.
Design of the System

The piezoelectric micro-cantilever system structure is as shown in Figure 2 with the above analysis and design principle.

![Figure 2](image.png)

Figure 2. The block diagram of piezoelectric micro-cantilever system.

As Figure 2 shows, the system working process is described as follows: with the piezoelectric micro-cantilever fixed on the stent, sine voltage excitation signal is applied to piezoelectric film of the micro-cantilever through the analog output ports of a data acquisition card. To keeps invariant for the amplitude of the excitation signal, then do a frequency scan\(^7\) for the data acquisition card output signals controlled by computer, at a given frequency range by a small enough frequency interval, for a certain time at each frequency. The micro-cantilever is activated to vibrate by the sine deformation of its piezoelectric film. Consequently, the surface stress of piezoelectric film is changed by the vibration of the micro-cantilever and generated weak piezoelectric current. Then the current is transmitted to the preamplifier and is changed into voltage signal\(^9\). After second staged amplified, the output voltage signal indicated the amplitude of the micro-cantilever at this frequency. Finally, the voltage signal is recorded in computer through data acquisition card.

Design of the Excitation Circuit

As the current signal generated by piezoelectric micro-cantilever is very weak, it’s difficult to detect. Firstly the current signal is transferred into voltage signal. Then through the preamplifier, second staged amplifier\(^{10}\), the voltage signal is obtained. Circuit diagram is shown in Figure 3.

![Figure 3](image.png)

Figure 3. Circuit block diagram.

Test and Analysis

Leakage Resistance and Equivalent Capacitance Test of Piezoelectric Film

In the experiment, the relation curves of output signal and the frequency of the micro-cantilever is got by the amplified circuit as Figure 4 shown. In the experiment, when the excitation voltage \(u_i\) is 2.5V, the test results is shown in Table 1.

<table>
<thead>
<tr>
<th>frequency/KHz</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u_o/V)</td>
<td>0.14</td>
<td>0.28</td>
<td>0.55</td>
<td>0.95</td>
<td>1.40</td>
<td>1.85</td>
<td>2.30</td>
<td>2.65</td>
<td>3.00</td>
<td>3.35</td>
</tr>
</tbody>
</table>

Table 1. Test results of the output signal with different frequency.
According to Figure 5, the output voltage value and the theoretical amplification of amplifier, the equivalent impedance of piezoelectric micro-cantilever is got as shown in Figure 6. From the output voltage waveform and the results, the output signal is in phase with the input signal in low frequency (1KHz), and the output voltage amplitude increases as the input signal frequency increasing, with phase gradually changing. It shows that leakage resistance and equivalent capacitance test of piezoelectric film play a role.

Figure 4. Detection circuit of leakage resistance and equivalent capacitance test.

Figure 5. Output voltage-frequency diagram of piezoelectric film circuit.
Experiment of Sine Excitation Circuit

For the self-design sine excitation circuit, in order to achieve circuit sweep frequency function, the R values are obtained with different frequency output signal according to the relationship between the vibration frequency and the R value. The sine wave amplitude and frequency changes were recorded when resistance value changing. The oscillation frequency and output of sine RC oscillation circuit with different R values is as shown in Table 2. Experiments show that the output wave of this RC oscillation is stable with little change in amplitude when frequency changing.

And the amplitude of the piezoelectric micro-cantilever is collected by Doppler interference vibration measurement system. The amplitude-frequency curve of excitation signal amplitude of Doppler system is as show in Figure 7. It shows that with excitation circuit, the piezoelectric micro-cantilever vibrates when the R values changed. Then when the piezoelectric micro-cantilever achieves resonance, the amplitude near the resonance frequency is much larger than the amplitude of other frequencies, of which the amplitude maximum is close to 600nm.

Table 2. Oscillation frequency and output of sine RC oscillation circuit with different R values.

<table>
<thead>
<tr>
<th>frequency/KHz</th>
<th>1</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>R /kΩ</td>
<td>580.1</td>
<td>64.12</td>
<td>30.02</td>
<td>18.96</td>
<td>16.13</td>
<td>12.08</td>
<td>10.58</td>
<td>8.52</td>
<td>7.12</td>
</tr>
<tr>
<td>Output voltage/V</td>
<td>4.9</td>
<td>4.9</td>
<td>5.0</td>
<td>5.1</td>
<td>5.0</td>
<td>4.9</td>
<td>5.0</td>
<td>5.1</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Figure 6. Impedance of piezoelectric micro-cantilever.

Figure 7. Amplitude-frequency curve of excitation signal amplitude of Doppler system.
Conclusion

A kind of resonance frequency detection of piezoelectric micro-cantilever is presented, where there is piezoelectric film deposited. When the piezoelectric micro-cantilever achieves resonance, the amplitude near the resonance frequency is much larger than the amplitude of other frequencies. A series of experiments have been done by the driving power and detecting power designed by ourselves. The experiments show that resonance frequency can be detected by the amplifier, and the amplitude of the resonance frequency is obviously bigger than the amplitude of the other frequency. The maximal amplitude is about 600nm. Furthermore, as the micro-cantilever resonance frequency is inversely proportional to 1/2 power of the effective mass, then the micro-cantilever resonance frequency decreases when measured substance adsorbed on the micro-cantilever. Then the measured substance could be quantitatively analyzed by detecting changes of micro-cantilever resonance frequency, and this principle can be applied to biological, biomedical, environmental, aerospace and other fields.

References