Dynamic characteristic measurement for MEMS microstructures in environment beyond normal

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Abstract
Methods and techniques for measuring the dynamic characteristics of microstructures in environment under high acceleration, high or low temperature environment were studied, and testing instruments were developed. The high \( g \)-force acceleration environment is generated from the centrifugal acceleration and over 10,000 \( g \) acceleration has been obtained for testing of microstructures. The base excitation device with piezoelectric ceramic was used as the driving source. The optical testing method used in MEMS dynamic testing can not be applied in high \( g \)-force testing, so the microstructure with typical beam-proof mass structure which integrates the sensing element is designed and fabricated for dynamic testing under high \( g \)-force acceleration. Laser Doppler vibrometer was used for measurement under low or high temperature environment. The dynamic testing experiments for the microstructures with different sizes under different constant high \( g \)-force accelerations from 0 \( g \) to 10,000 \( g \) were carried out. The experiments results were analyzed and compared with finite element analysis. The dynamic testing experiments for the microstructures under high and low temperatures were also done with the developed instruments.

Keywords: MEMS microstructure, dynamic characteristics measurement, beyond normal environment, Base excitation methods

1. Introduction
The micromachined MEMS devices offer a lot of advantages such as small size, low power dissipation, high reliability and high shock resistance, and have great potential applications. MEMS devices used in harsh environments have become one focus of study. Because MEMS devices have movable structure, the dynamic characteristics is an important and determinant factor on the performance of the micro devices. The dynamic characteristics of MEMS microstructures is also an important aspect of MEMS research. Corresponding to the study of MEMS devices used in the harsh environments, its testing technology, especially dynamic testing technology falls behind relatively.

Generally speaking, the dynamic testing techniques for microstructures mainly include excitation methods and vibration measurement techniques [1].

As to excitation methods, there are three categories, i.e. base excitation, embedded element for excitation and outside field energy excitation. Vibration measurement techniques for microstructures can be divided into two types, i.e. non-contact optical methods and methods with embedded sensing element [2]. In recent years, many efforts have been paid on developing techniques for dynamic measurement of microstructures, especially the non-contact optical methods [3], e.g. Laser Doppler Vibrometry (LDV), Electronic Speckle Pattern Interferometry (ESPI), etc. The optical methods have several advantages over the methods with embedded sensing elements, for there are no added elements needed and thus no modification on the dynamic characteristics of the original microstructures. Methods with embedded sensing elements have the features of easy acquisition of excitation response signal.
The actual function of the microstructure and the embedded sensing function can be integrated together to form a compact micro system with self-checking capability. The sensing principle of the methods with embedded sensing elements includes: a) Piezoresistive detection; b) Piezoelectric effect; c) Capacitive detection.

As for the micro device which has the features of small size, light weight and high resonance frequency, to obtain its dynamic characteristics, conventional methods cannot be applied without modification.

Regarding the environment beyond normal, including high acceleration (or high g-force, where \( g \) is the unit of gravitational acceleration), high or low temperature, some research work were done on the testing instruments and measurement techniques for dynamic characteristic measurement of MEMS microstructures. Base excitation method and a combination of the above mentioned measurement techniques were utilized in the research presented in this paper.

2. Measurement under high-g acceleration environment

For testing of MEMS microstructures under high loads, a testing instrument for experiment was developed. The instrument has the following functions: a) providing a high g-force acceleration environment; b) exciting the microstructure with an impact force; c) measuring the input and associated response; d) transmitting the measured signal; e) acquiring and processing the signals [4].

The instrument involves an industrial computer, electric spindle unit, rotation plate unit, data acquisition unit, on-site dynamic balancing unit, and piezoelectric ceramics driver power unit. The high g-force acceleration environment is generated by the centrifugal acceleration of the centrifugal rotation plate (Fig. 1a). The centrifugal rotation plate is driven by the high-speed electric spindle, directly. The rotating rate is controlled by a frequency converter which communicates with the computer through a RS-485 serial bus and thus the computer can regulate the rotating rate. By changing the rotating speed of the rotation plate, the different high g-force acceleration can be obtained. The highest rotate speed for the spindle selected is 15,000 rpm, and the radius of turn for the tested microstructure is 0.2 m, therefore the peak centripetal acceleration can reach 50,000g.

While the microstructures have high natural frequencies, the excitation device should have the capability to excite the modes of interest in a specified frequency range, and this implies that the excitation frequency bandwidth of the device needs to be greater than the highest natural frequency of interest. Because of its wide bandwidth, piezoelectric ceramic is selected as micro-shaker which can then be used to excite microstructures based on the principle of base excitation, shown in Fig. (b)(c).
The optic testing method used in MEMS dynamic testing can not be applied in high g-force testing device, so the microstructure with typical beam and proof mass structure which integrates the testing element is designed and fabricated for dynamic testing under high g-force acceleration. By diffusing the piezoresistance in the micro-beam, the dynamic testing signal is acquired by the output change of the Wheatstone bridge formed by the piezoresistances. As a new fabrication procedure for the microstructure, the wet and dry combined bulk micromachining techniques are developed in order to eliminate the step of encapsulating the above electrode layers, and thus simplify the fabrication process. The fabrication process is designed and the microstructures are successfully fabricated using the microfabrication processes [5]. The photograph and sizes of the fabricated microstructures used in experiments are shown in Fig. 2 and Table 1.

![Fig. 2. Micromachined microstructure for testing.](image)

<table>
<thead>
<tr>
<th>Nr.</th>
<th>l (μm)</th>
<th>b (μm)</th>
<th>L (μm)</th>
<th>B (μm)</th>
<th>h (μm)</th>
<th>f_{FEA} (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>350</td>
<td>600</td>
<td>400</td>
<td>800</td>
<td>10</td>
<td>29.7</td>
</tr>
<tr>
<td>2#</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.3</td>
</tr>
<tr>
<td>3#</td>
<td>1500</td>
<td>600</td>
<td>1000</td>
<td>1500</td>
<td>10</td>
<td>1.60</td>
</tr>
<tr>
<td>4#</td>
<td>800</td>
<td>600</td>
<td>1000</td>
<td>1500</td>
<td>10</td>
<td>2.98</td>
</tr>
</tbody>
</table>

The dynamic testing experiments for the microstructures under different high g-force accelerations from 0g to 10,000g were carried out. Through the impulse excitation of the piezoelectric ceramic, the dynamic characteristics such as resonant frequencies and damping ratios are obtained by analyzing the impulse response signals. The experimental results indicate that when the deflection of the micro-beam in the microstructure is small and in linear state, the external transverse high g-force load has no evident effects on the dynamics of the microstructures (1# and 2#). While the micro-beam in the microstructure is in large deflection under external high g-force and performs the geometrically nonlinear state, the natural frequency of the microstructure gets higher while the external high g-force acceleration increases (3# and 4#), as shown in Fig. 3.

![Fig. 3. Resonant frequency change of microstructures 3# and 4# under different high g-force.](image)
The finite element analysis with stress stiffness modal was also done and the simulation results ($f_{FEA}$, shown in Table 1) are in good agreement with the experimental results. The damping ratios show almost no change during experiments.

3. Measurement in high or low temperature environment

The dynamic testing system developed for MEMS in the environment of low temperature (ranging from room temperature to -50°C) is shown in Fig. 4. A thermoelectric cooling refrigerator was utilized as the low temperature environment. To prevent frost influence the testing precision in low temperature environment, dynamic testing was carried out in the vacuum environment. Excitation device used in the low temperature environment is also based on the piezoelectric ceramic as the excitation driving source. Two schemes were designed to realize measuring and acquiring the oscillation signal of micro structure in low temperature, which one is adopt the Laser-Doppler Vibrometer to measure from outside of low temperature environment, another one adopts the BIST (Built-In Self-Test) method, the micro structure export signal by itself after exciting, the signal magnified by the amplification circuit and then sampled into the computer by high speed data acquisitions card.

(a)                                                   (b)                                                  (c)

Fig. 4. The dynamic testing system for MEMS microstructure at low temperature.
(a) thermoelectric cooling refrigerator; (b) vacuum chamber for testing; (c) the window of the chamber.

(a)                                                                           (b)

Fig. 5. Impulse response (a) and Frequency spectrum (b) of microstructure in the -50°C surroundings.

A testing instrument for dynamic characteristics measurement in high temperature was also developed, as shown in Fig. 6. Small alumina ceramics heater (MCH) is used for heating the microstructure to be tested, the temperature can reach to up to 300°C. Base excitation with PZT is also used. Because piezoelectric ceramic is not effective when the temperature is elevated approaching its curie point, a separable mechanism was designed for moving the PZT unit to contact the heating unit and moving away after excitation. PZT unit can be cooled with water or air flow, and heat isolation material is place between the PZT and the heating unit. Laser Doppler vibrometer (Polytec OFV534) coupled with an optical microscope was used to measure the response signals of microstructures.
The dynamic testing experiments for the microstructures under different temperatures were also carried out. The resonance frequency also shows slight variations with temperature changes.

![Fig. 6. The dynamic testing system for MEMS microstructure at high temperature.](image)

(a) laser Doppler vibrometer and testing instrument for high temperature; (b) heating and sensing elements inside the testing chamber; (c) structure of the PZT unit and the heating unit.

Testing instrument for higher temperature is under development. Electrostatic discharge impact will be utilized for excitation in high temperature environment. Some experiments were done and the feasibility was demonstrated.

![Fig. 7. Experiment of excitation with electrostatic discharge impact.](image)

(a) Experiment setup for excitation with electrostatic discharge impact; (b)(c) impulse response and frequency spectrum.

4. **Conclusion**

Dynamic testing equipments or instruments for MEMS microstructures under environment beyond normal including, high g-force and low-and high temperature, were developed. Some experiments were done to study the dynamic characteristics of microstructures under different environment. The following work being done was also briefly introduced.

5. **Acknowledgements**

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**References**