Pressure-Dependent Dissipation Effect at Multiple Cantilever Resonant Modes

Eun Joong Lee¹, Chul Sung Kim¹, Yun Daniel Park², and Taejoon Kouh¹,∗

¹Department of Physics, Kookmin University, Seoul 136-702, Korea
²Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea

Based on the optical deflection method, the resonant characteristics of a microcantilever under various pressure have been observed at room temperature to understand the pressure-dependent dissipation effect. Especially, the quality factor of the cantilever has been measured for up to fourth harmonic mode of cantilever resonance as a function of pressure between 0.1 and 1000 Torr. By considering the intrinsic dissipation present in the system at 0.1 Torr, the pressure-dependent fluidic quality factors were determined for the multiple cantilever resonant modes. The inverse of the fluidic quality factor appears to follow two different asymptotic behaviors at high and low pressure limits, which indicates that the dynamics of the fluid, due to the oscillating cantilever, changes from Newtonian to non-Newtonian with decreasing pressure. The experimentally observed transition of the fluidic dissipation effect agrees well with the recently proposed rapidly oscillating flow model based on the Boltzmann equation, regardless of the different mode shapes.

Keywords: Dissipation, Fluidic Quality Factor, Weissenberg Number, Microcantilever.

1. INTRODUCTION

Recently, miniaturized mechanical systems such as nanoelectromechanical systems (NEMS) and microcantilevers have regained much attention along with the advances in fabrication techniques.¹⁻³ They posses much improved mechanical properties, such as high resonance frequencies and quality factors in their resonant modes, compared to previously-studied bulk mechanical systems. Based on these superior mechanical characteristics, these miniaturized systems have been proven to be promising in many of technological applications. For example, the micro-fabricated AFM cantilever has been most commonly used for the precise determination of various surfaces.⁴ Also, the microcantilevers and NEMS devices have been explored as sensing elements in sensor applications.⁵⁻⁶

The energy dissipation effects are always present in these mechanical systems and there have been theoretical and experimental attempts to address this issue originating from various mechanisms.⁷⁻¹⁰ Typically, when one uses the mechanical sensing element, the detection sensitivity is closely related to the quality factor of the mechanical system.¹¹ Therefore it is imperative to understand the dissipation effect in these miniaturized mechanical systems operating under various gas or liquid flow to achieve the optimized detection sensitivity under various conditions. Under moderate vacuum, the damping of these mechanical systems will be dominated by the intrinsic dissipation effect. However, with increase in flow, one has to assess the additional fluidic dissipation factor affecting the motion of the mechanical system.

The fluid dynamics coupled with an oscillating mechanical element can be characterized with the oscillation frequency (ω) of the mechanical element and the relaxation time (τ) of the fluid. For ω < 1/τ, the flow due to the motion of the mechanical element follows the Newtonian approximation, but for ω > 1/τ, this approach is no longer valid. The expected break-down of the Newtonian approximation has been considered with a model of an rapidly oscillating plate based on the Boltzmann equation, where the fluidic dissipation factor has been given as a universal function of the Weissenberg number ωτ.¹² Following this theoretical description, the pressure-dependent dissipation effect in a wide range of ωτ has been investigated experimentally using doubly-clamped beams and cantilevers, mostly in their fundamental resonance modes.¹³