Journal of Sound and Vibration 333 (2014) 3702–3708

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Dynamic response of sensor diaphragm with residual stress in contact with liquids

Huayong Wu [a,b], Shenjie Zhou [a,*]

[a] School of Mechanical Engineering, Shandong University, Jinan, Shandong 250061, China
[b] School of Mechanical Engineering, Shandong University of Technology, Zibo, Shandong 255049, China

ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form
16 March 2014
Accepted 5 April 2014
Handling Editor: L.G. Tham
Available online 28 April 2014

ABSTRACT

The dynamic response of a sensor diaphragm with residual stress in contact with a liquid is theoretically investigated in this paper. The liquid is assumed to be incompressible and inviscid. The acoustic radiation as the main source of energy dissipation in a medium virtually added the mass of the diaphragm and decreased the quality factor of the diaphragm. The effects of the residual stress on the added virtual mass and the quality factor of the diaphragm are presented. Finally, forced oscillations of the sensor diaphragm with residual stress in contact with a liquid are investigated. It is found that the requirements of high sensitivity and large vibration displacement are contradictory. The analysis and results are valuable for conducting the design of circular sensor diaphragms for biological applications.

1. Introduction

High-performance micro-biochemical sensors are urgently needed for detecting a targeted substance [1,2]. The system can be operated in a static or in a dynamic mode [2]. In the static mode, the deflection of sensors due to surface stress caused by mass loading is measured as the output signal. In the dynamic mode, the mass microbalancing technique is used to measure the change in resonant frequency, which reflects the change in mass loading. The sensor can be designed with large natural frequencies because it is extremely small. This ensures the dynamic mode has more higher sensitivity than the static mode.

The biomechanical transducers of the system usually take the form of cantilevers, bridges and diaphragms [3–5]. The use of micro-cantilevers as transducers in biochemical sensing systems has increased in recent years. However, since the biochemical sensors operate in the liquid medium, the quality factor (Q) value of the coated-resonant microcantilever is smaller than that of classical MEMS operating in vacuum [6]. Moreover, an extra passivation layer on the cantilever is required to electrically insulate the electrodes and the piezoelectric layer during the operation in a liquid media, which often degrades the performance of the sensors [7]. The diaphragm structures are advantageous compared to the cantilevers for three reasons. First, the influence of liquid media on the Q value of the diaphragm is much smaller than that of the cantilever [8,9]. Second, the diaphragm structures are more rigid than cantilevers, thus minimizing the structural fragility problem. Third, the diaphragm structures can be easily adapted to be used in liquid solutions without requiring an additional passivation layer because the top surface of diaphragms is physically isolated from the bottom surface [7,10]. Therefore, the

* Corresponding author. Tel.: +86 531 88396708; fax: +86 531 88392700.
E-mail address: zhousj@sdu.edu.cn (S. Zhou).

http://dx.doi.org/10.1016/j.jsv.2014.04.014
0022-460X/

diaphragm structure tends to be a promising candidate for the bio-chemical sensing applications. The bio-chemical sensor based on microdiaphragm consist of an analysis chamber, where the microdiaphragm is located; a micropumping device; a reservoir; and a microfluidic connection system conveying the sample fluid with the biomarkers from the pumping device to the reservoir through the analysis chamber [2]. The diaphragm surface is coated by molecules with the ability to recognize specific biomarkers dispersed in the fluid sample and make them adhere over the diaphragm. For a diaphragm vibrating in a fluidic chamber, the surrounding fluid degrades the quality factor and the vibration displacement of the sensor.

Vibrations of circular plates coupled to liquids have received much attention due to their importance. Amabili and Kwak [11] analyzed the natural frequencies of circular plates in contact with a liquid. Amabili and Kwak [12] studied the effect of free-surface waves on free vibrations of circular plates resting on a free fluid surface. Renard et al. [13] investigated the response of an infinite free plate–liquid system to a moving load. Jeong et al. [14] presented the free vibration of a circular plate partially in contact with a liquid. However, the residual stress was neglected in these studies. When the diaphragm is fabricated via sol–gel processed, the residual stress is inevitable generated [15–18]. Yu and other researchers studied the influences of residual stress on the dynamic behaviors of a sensor diaphragm and valuable results in this field were provided [19,20]. However, the liquid medium was not considered in the previous literature.

Therefore, the purpose of this article is to study the coupling effect of residual stress and liquid medium on the quality factor and the Vibration response of sensor diaphragm in contact with a liquid. The paper is organized into six sections. In Section 1, a brief introduction is provided. Section 2 presents the mechanics model based on a plate with residual stress. In Section 3, medium influences on the added virtual mass and quality factor of circular diaphragm are investigated theoretically. In Section 4, forced oscillations are considered. In Section 5, the effects of the residual stress on the added virtual mass, the quality factor, the mass sensitivity and the vibration displacement of the circular diaphragm are investigated when the diaphragm vibrates in contact with a liquid. Finally, concluding remarks are provided in Section 6.

2. Model and governing equations

Consider a thin circular plate with residual stress, as shown in Fig. 1, having thickness h and the mass density ρ_P vibrating in liquid. A circular plate is in contact with an incompressible and inviscid liquid on one side. The dynamic response of the diaphragm is governed by the equation

$$D\nabla^4 w - \sigma h \nabla^2 w + \rho_P h \frac{\partial^2 w}{\partial t^2} = f(r,\theta,t) + f_L \tag{1}$$

where the flexural rigidity $D=(Eh^3)/12(1-\nu^2)$; E and ν are Young's modulus of elasticity and Poisson's ratio of the diaphragm material, respectively. σ is the residual stress; w is the transverse displacement; $f(r,\theta,t)$ and f_L are the actuation loading and the liquid dynamic loading per unit area, respectively.

The boundary conditions along the clamped edge at $r=a$ and the requirement that the displacement be finite at the plate center are given by

$$w(r,\theta,t)|_{r=a}=0,\ \frac{\partial w(r,\theta,t)}{\partial r}\bigg|_{r=a}=0,\ |w(r,\theta,t)|_{r=0}|<\infty \tag{2}$$

In the absence of the actuation loading and the liquid dynamic loading, using separation of variables, the natural frequencies are written as [19]

$$\omega_{mn}^2 = \frac{D}{\rho_P h a^4}(\alpha a)^2\left[(\alpha a)^2 + k^2\right] \tag{3}$$

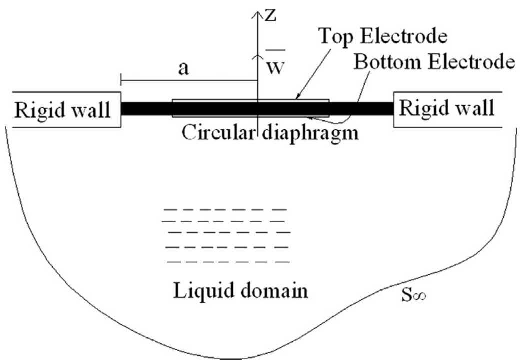

Fig. 1. The schematic of micro-diaphragm with residual stress in contact with liquids.