Sensors and Actuators A 233 (2015) 319–323

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Voltage proportional control reduces inertial force from an unbalanced weight in a dual-mounted actuator structure used for high performance scanning probe microscopes

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ARTICLE INFO

Article history:
Received 11 November 2014
Received in revised form 15 June 2015
Accepted 23 July 2015
Available online 28 July 2015

Keywords:
Inertial force
Unbalanced weight
Dual-mounted actuator
Base vibration
Scanning probe microscopy

ABSTRACT

A dual-mounted actuator structure is widely used to reduce the inertial force from high-speed actuators and to alleviate the vibration of the base in a scanning probe microscope. However, the inertial force resulting from an unbalanced weight should be considered and is conventionally performed by adding a dummy mass to balance the weight. In this paper, the inertial force resulting from an unbalanced weight is balanced by adjusting the amplitude ratio of the voltages applied to two actuators in a dual-mounted actuator structure. The experimental results show that the base vibration is well suppressed even if an unbalanced weight exists. The vibration suppression effect of the proposed approach is comparable to the effect generated when using the traditional method.

1. Introduction

Scanning probe microscopes (SPMs) are important scientific instruments because of their unique imaging capabilities [1–6]. A sample image is obtained by scanning the sample with a sharp tip according to the SPM working principle. The imaging speed is limited by the scanner's bandwidth, which is sometimes determined by the base supporting the actuator particularly in the Z direction, because the inertial force from the actuator causes a large vibration of the supporting base when the actuator works at the resonance frequency of the supporting base [3,7–13].

The base should be hard and heavy to reduce vibrations. However, such a supporting base is difficult to design for the Z scanner because the supporting base is usually the scanner's X–Y stage [9,10,12–16]. The X–Y stage should not be very heavy to achieve high-speed scanning in the X–Y plane. Another way to reduce the base vibration is to reduce the inertial force from the actuator on the supporting base [8–19]. The conventional method to achieve this vibration reduction involves the use of a symmetrical actuator structure to counterbalance the inertial force by supporting a single piezostack on all four sides within a hole [14], by fixing a single piezostack between two flexures, or mounting two actuators in an opposite manner (dual-mounted actuator structure) [3,9–13,15–18]. An asymmetric actuating structure using the voltage-adjusting method has also been recently proposed [8]. Among the aforementioned methods, the dual-mounted actuator structure is the most popular structure in high-speed SPM.

The main drawback of the dual-mounted actuator structure is that extra inertial force is generated by the unbalanced weight, which primarily comes from the sample or from the asymmetric distribution of the mass [9]. Conventionally, a dummy mass was added [9,11,17] to balance the weight of the sample. However, different samples have different weights; thus, the dummy mass must be replaced and carefully chosen for each test, which is time-consuming and inconvenient. The voltage-adjusting method [8] is new and possesses outstanding merits but requires modifications to use with a ready-made instrument.

In this study, the inertial force resulting from an unbalanced weight was balanced by applying voltages with proper amplitude proportion to two actuators. The experimental results show that when an unbalanced weight exists, the inertial force from the unbalanced weight can be balanced well without a dummy mass. The method proposed in this paper can be used in a widely used structure without any modification of the structure.

2. Theoretical analysis

The proposed method is shown in Fig. 1. P_1 and P_2 are two symmetrically mounted piezostacks sharing the same mass m, and m_u is the unbalanced mass. m_u comes from the sample or other

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http://dx.doi.org/10.1016/j.sna.2015.07.028

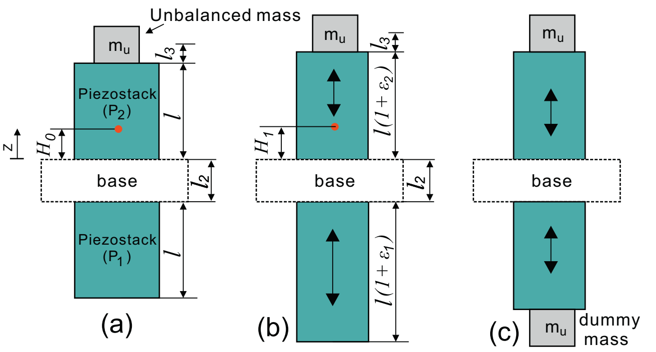

Fig. 1. (a) Simplified theoretical model of dual-mounted actuator structure with an unbalanced mass (b) The voltages on P1 and P2 are controlled to balance the inertial force (c) The traditional method is to add a dummy mass to balance the weight.

unbalanced mass within the structure. P_1 is used to compensate the inertia force from P_2 and m_u. Centre-of-mass theory is used to determine the driving strategy of P_1. The centre-of-mass of a system does not move in the absence of an external force and vice versa. Therefore, P_1 should be controlled to ensure that the centre-of-mass of the system, which contains P_1, P_2, and m_u, is stable. If this is achieved, there will be no inertial force transferred to the base that is supporting the actuators.

According to the centre-of-mass equation, when P_1 and P_2 are all powered with zero voltage at the beginning, the position of the centre-of-mass of the system that contains P_1, P_2, and m_u can be determined by the following:

$$H_0 = \frac{m_u(l+l_3)+m\frac{l}{2}-m(\frac{l}{2}+l_2)}{m_u+m+m} \tag{1}$$

when voltages change and bring strains to P_1 and P_2, the position of the centre-of-mass changes to

$$H_1 = \frac{m_u[l(1+\epsilon_2)+l_3]+m\frac{l(1+\epsilon_2)}{2}-m[\frac{l(1+\epsilon_1)}{2}+l_2]}{m_u+m+m} \tag{2}$$

where l is the length of the piezostack; l_2 is the thickness of the base; l_3 is the distance between the centre-of-mass of m_u and the top of P_2; ε_1 is the strain of P_1; ε_2 is the strain of P_2; m is the mass of a single piezostack (P_1 or P_2). H_1 should be equal to H_0 at any time to obtain a steady centre-of-mass. Therefore, $\varepsilon_1 = (1+2m_u/m)\varepsilon_2$. The proportion of V_{P1} to V_{P2} is the same as ε_1 / ε_2 because the strain of a piezostack is approximately proportional to the voltage applied to the stack. Here, V_{P1} and V_{P2} are amplitudes of the voltage applied to P_1 and P_2, respectively. Therefore, no inertial force will be transferred to the base if the proportion of V_{P1} to V_{P2} is controlled in this way.

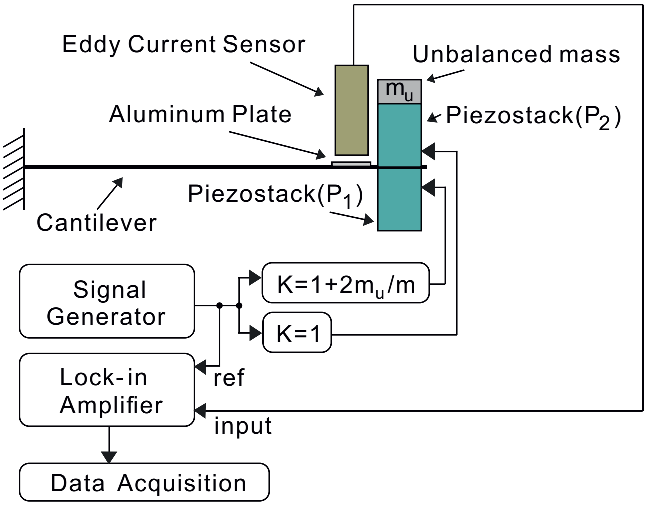

Fig. 2. Schematic diagram of the experimental setup.

Influences coming from the shearing force in the transition regions between the bottom of each piezoelectric actuator and the surface of the base was neglected to simplify the analysis, which is reasonable when the region is small. It was also assumed that the actuators were working far below their resonance frequencies; thus, their density and strain are approximately uniform. The centre-of-mass of each actuator is the same as its geometric centre.

3. Experiments and discussions

The experimental setup is shown in Fig. 2. A cantilever (50 mm × 5.84 mm × 0.35 mm, made of cold-rolled carbon structural steel) with a high quality factor (370) was selected to ensure that vibration due to the inertial force could be clearly observed. Two piezostacks (XP 1.2 × 1.2/1.7, Core Tomorrow Science & Technology Co., Ltd., China, 1.22 mm × 1.30 mm × 1.70 mm, 22 mg, 45 nF, 390 kHz resonance frequency with one end fixed) were symmetrically fixed to the free end of the cantilever. The vibration of the cantilever was detected by using an eddy current sensor (SMT9700-15N, KAMAN, USA, frequency range <10 kHz). The sensor has a negligible influence on the cantilever. A lock-in amplifier (Model 7265, AMETEK Co., USA) was used to obtain a high signal-to-noise ratio. The original lead wires of the piezostacks

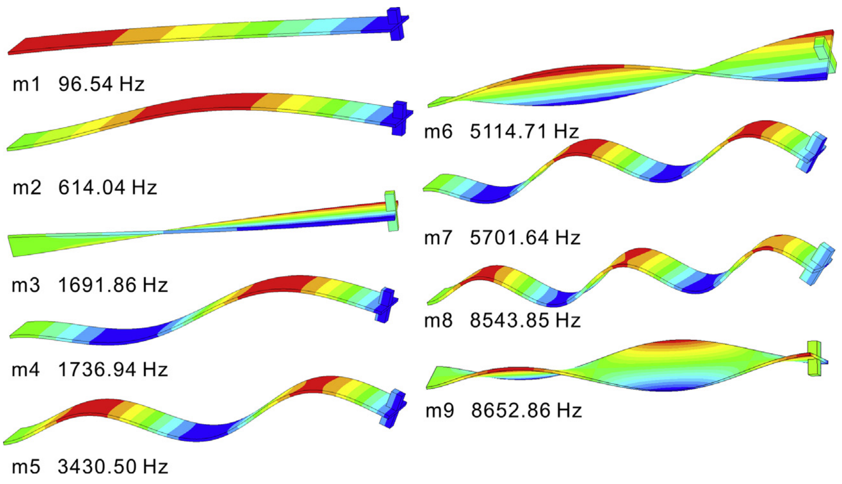

Fig. 3. Vibration modes of the cantilever.