Journal of Sound and Vibration 354 (2015) 13–33

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Active vibration isolation of macro–micro motion stage disturbances using a floating stator platform

Lufan Zhang [a], Zhili Long [b,*], Jiandong Cai [c], Yang Liu [c], Jiwen Fang [a], Michael Yu Wang [d]

[a] State Key Lab for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an, China
[b] Harbin Institute of Technology Shenzhen Graduate School, Shenzhen, China
[c] Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, NT, Hong Kong, China
[d] Department of Mechanical Engineering, National University of Singapore, Singapore 117575, Singapore

ARTICLE INFO

Article history:
Received 28 September 2014
Received in revised form
6 June 2015
Accepted 11 June 2015
Handling Editor: W. Lacarbonara
Available online 30 June 2015

Keywords:
Active vibration isolation
Macro–micro motion stage
Floating stator platform
Fixed stator platform

ABSTRACT

Macro–micro motion stage is mainly applied in microelectronics manufacturing to realize a high-acceleration, high-speed and nano-positioning motion. The high acceleration and nano-positioning accuracy would be influenced by the vibration of the motion stage. In the paper, a concept of floating stage is introduced in the macro–micro motion for isolating vibration disturbances. The design model of the floating stage is established and its theoretical analyses including natural frequency, transient and frequency response analyses are investigated, in order to demonstrate the feasibility of the floating stator platform as a vibration isolator for the macro–micro motion stage. Moreover, an optimal design of the floating stator is conducted and then verified by experiments. In order to characterize and quantify the performance of isolation obtained from the traditional fixed stator and the floating stator, the acceleration responses at different accelerations, speeds and displacements are measured in x, y and z directions. The theoretical and experimental analyses in time and frequency domains indicate that the floating stator platform is effective to actively isolate the vibration in the macro–micro motion stage.

1. Introduction

Macro–micro stage actuation concept has been realized by linear motor and piezoelectric ceramic transducer (PZT) to obtain a high-acceleration, high-speed and nano-scale positioning [1,2]. The platform could be applied to microelectronic manufacturing, nano-scale science and technology and optical and photon engineering, etc. [2–6].

A high-acceleration macro–micro motion stage could improve the production efficiency and reduce cost. However, vibration induced from the high-acceleration motion would have obvious influence on the positioning. In the macro–micro motion stage, the high-acceleration motion is obtained by voice coil motor (VCM) with a large driving force. Under actual working conditions, the platform is transiently driven and moves at reciprocating high accelerations. [7,8] This motion mode will result in excess impact force or unpredictable vibration which cannot be absorbed effectively by the rigid connection between VCM and base. The vibration will lead to large positioning errors of the macro–micro motion stage. To realize

---

* Corresponding author. Tel.: +86 13510281931.
E-mail address: longworking@163.com (Z. Long).

http://dx.doi.org/10.1016/j.jsv.2015.06.024
0022-460X/© 2015 Elsevier Ltd. All rights reserved.

Nomenclature

Variables

α	ratio of circular frequency ω_1 and ω_2
a	state variable matrix
a_1, a_2, a_3, a_4	state components
$\boldsymbol{A}$	system matrix
A_1, A_2	amplitude of x_1 and x_2
$\boldsymbol{B}$	input matrix
$\boldsymbol{C}'$	damping matrix
$\boldsymbol{C}''$	output matrix
c_0, c_1, c_2	damping coefficients of guide rail and slide block, damper, equivalent damper between base and ground
$\boldsymbol{F}$	force matrix
F_t	transferred force
F_0	reactive force
f_1, f_2	frequency of stator, base
$F(t)$	impulse function
$\boldsymbol{K}'$	stiffness matrix
k_1, k_2	stiffness coefficients of spring, equivalent stiffness between base and ground
m_1, m_2	equivalent mass of stator, base
$\boldsymbol{M}'$	mass matrix
P	amplitude of reactive force
t	time
Δt	pulse length
u	signal input
μ	ratio of mass m_2 and m_1
ω	circular frequency
ω_1,ω_2	circular frequency of stator, base
$\boldsymbol{X}$	matrix of displacement
x_1, x_2	displacement of stator, base
$Z(\omega)$	frequency function
ζ_1, ζ_2	damping factor of stator, base
ξ	damping factor
λ_1	ratio of circular frequency ω and ω_1

vibration isolation, many scholars have conducted much research on this problem. Liu et al. [9,10] described an active vibration isolation method using a voice coil actuator with absolute velocity feedback control. The absolute vibration velocity signal was acquired from an accelerator, processed through an integrator, and then input to a controller as a feedback signal. The controller output signal then drove the voice coil actuator to produce a sky-hook damper force. The analysis of the active vibration isolation system and the comparison between predictions and experimental results showed that the proposed method significantly reduced vibration transmissibility at resonance. Zhang et al. [11] used magnetostrictive actuators and air springs arranged in parallel as a vibration isolator and applied a three-layer neural network to realize active control. The simulation results indicated that the active vibration isolation system had good isolation performance against floor disturbance and direct disturbance acting on the micro-manufacturing platform in all frequency range. Yan et al. [12] proposed an active vibration isolation system that utilized feedback control of absolute vibration velocity to reduce the transmission of base excitations to a precision instrument. Experimental results indicated that even the instability due to the isolator resonances could be prevented. Tsai [13] developed a vibration isolation platform consisting of an active layer and a passive layer to attenuate high frequency vibration. The robust controller was adopted to design the controller considering payload uncertainties. Experimental results showed that the control could reduce vibrations by an average of 10 dB within a frequency range of 15–40 Hz. Lee et al. [14] suggested that six single axis isolators could be combined to form a Stewart platform in cubic configuration to provide multi-axis vibration isolation. The isolation performance of the developed multi-axis isolator was evaluated using a simple prototype reaction wheel model where wheel imbalance was the major source of vibration. The transmitted force without vibration isolator was measured and compared with the transmitted force with vibration isolator. More than 20 dB reduction of the x- and y-direction disturbances were observed for rotating wheel speed and higher. Wang [15,16] proposed a floating stator which could be embedded into linear motor to achieve vibration elimination from vibration source. Experimental results verified the effectiveness of the floating stator in base vibration suppression. Previous investigations mainly focused on creating vibration isolator and using feedback control to achieve vibration isolation.

In this paper, a floating stator platform was built as a vibration isolator and applied in a macro–micro motion stage. The active vibration isolation of the macro–micro motion stage disturbances using a floating stator platform was investigated. The paper is organized as follows: At first, the structure of the floating stator platform is described. And then, its dynamic analysis including natural frequency, transient and frequency response analysis is studied. Additionally, the design of floating stator platform is optimized and the experimental setup is built to verify the performance of the floating stator platform. At last, conclusions are summarized.

2. Description of floating stator platform

In this macro–micro motion stage, a high-acceleration motion is provided by VCM and the vibration is excited. Therefore, The VCM is a source producing a negative influence on the performance of the stage. Generally, VCM is fixed on the base, which means that the base is the receiver absorbing or transferring the vibration. However, the vibration cannot completely disappear and the base vibration is inevitable. In the paper, a floating stator platform as the isolation system is developed to reduce or isolate vibration between VCM and base. The floating stator platform consisting of damper, stopper, floating lock, spring, limiter and sub-base, etc. is shown in Fig. 1. Unlike the traditional stator of VCM fixed on the base, the floating stator moves on the linear guide under vibration force or driving force. The springs are used to buffer shock at both ends of the