G Model
PRE-5944; No. of Pages 11

ARTICLE IN PRESS

Precision Engineering xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Precision Engineering

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

Effects of the molecular forces on the free vibration of electromechanical integrated electrostatic harmonic actuator

Lizhong Xu*, Dan Zhao

Mechanical Engineering Institute, Yanshan University, Qinhuangdao 066004, China

ARTICLE INFO

Article history:
Received 23 February 2011
Received in revised form 13 July 2012
Accepted 21 September 2012
Available online xxx

Keywords:
Electromechanical integrated
Actuator
Molecular force
Free vibration
Natural frequency

ABSTRACT

The electromechanical integrated electrostatic harmonic actuator is favorable for miniaturization of the electromechanical devices. As the dimensions of the actuator decreases, the effects of the Casimir or van der Waals forces should be considered. Here, effects of the molecular forces on the free vibration of the actuator are investigated. The dynamic equations of the flexible ring for the actuator for three different situations are deduced. The three situations are: (i) only considering electrostatic force; (ii) considering electrostatic force and van der Waals force simultaneously; (iii) considering electrostatic force and the Casimir force simultaneously. Using these equations, the effects of the van der Waals force or the Casimir force on the natural frequencies and the vibrating modes of the flexible ring for the actuator are investigated. Results show: for high order modes, the effects of the van der Waals force and the Casimir force on the actuator are relatively large for mode one. The effects are more obvious and should be considered for small clearance, and large operating voltage. For clearance = 0.2 μm, the relative errors between natural frequencies with and without van der Waals force gets to 9.9%, and the relative errors with and without the Casimir force is 13.1%. Besides it, the vibrating amplitudes of the flexible ring become larger when the molecular forces are considered. The results are useful in theory and technique studies on further miniaturization of the actuator.

1. Introduction

The MEMS devices require high integration of the mechanical, electric and control techniques. So-called MEMS (microelectromechanical systems) are now the subject of a vast amount of scientific and technological works [1–3].

The authors proposed an electromechanical integrated electrostatic harmonic actuator [4]. The electromechanical integrated electrostatic harmonic actuator mainly consists of flexible ring and outer ring stator as shown in Fig. 1. The outer ring stator consists of several segments electrodes fixed. As soon as these segments electrodes are applied to voltage sequentially, a rotational electric field will be produced between flexible ring and stator. Under periodic electrostatic forces, periodic elastic deformation of the flexible ring occurs. The periodic deformation causes periodic capacity changes between flexible ring and stator. It produces tangential electrostatic forces to drive the flexible ring to rotate. The typical frequency of the rotating electrostatic field of the actuator is 50–2000 Hz, the typical speed of the rotor is 2–1000 rpm, its output torque is about 5–30 μN m.

Compared with piezoelectric and electromagnetic actuation principles [5,6], the electrostatic harmonic actuator needs neither additional elements like coils or cores, nor special materials like piezoelectric ceramics. It is favorable for miniaturization of the electromechanical devices. Compared with other electrostatic actuation principles [7–9], the actuator does not need fabrication of the teeth on microelements and its output axis does not wobble. So, it is easier to be fabricated and used.

In the actuator, the electrostatic force plays the main role in controlling its operating behavior. However, as the dimensions of the actuator decreases further, the effects of the Casimir and van der Waals forces should be considered [10,11]. The van der Waals force is related to the electrostatic interaction among dipoles at the atomic scale [12]. The Casimir force is the attractive force between two flat parallel plates of solids that arises from quantum fluctuation in the ground state of the electromagnetic field [13].

The van der Waals force and Casimir force can both be connected with the existence of zero-point vacuum oscillations of the electromagnetic field [14]. The microscopic approach to the modeling of both van der Waals and Casimir forces can be formulated in a unified way

* Corresponding author.
E-mail address: Xlz@ysu.edu.cn (L. Xu).

0141-6359/$ – see front matter
http://dx.doi.org/10.1016/j.precisioneng.2012.09.006

Please cite this article in press as: Xu L, Zhao D. Effects of the molecular forces on the free vibration of electromechanical integrated electrostatic harmonic actuator. Precis Eng (2012), http://dx.doi.org/10.1016/j.precisioneng.2012.09.006

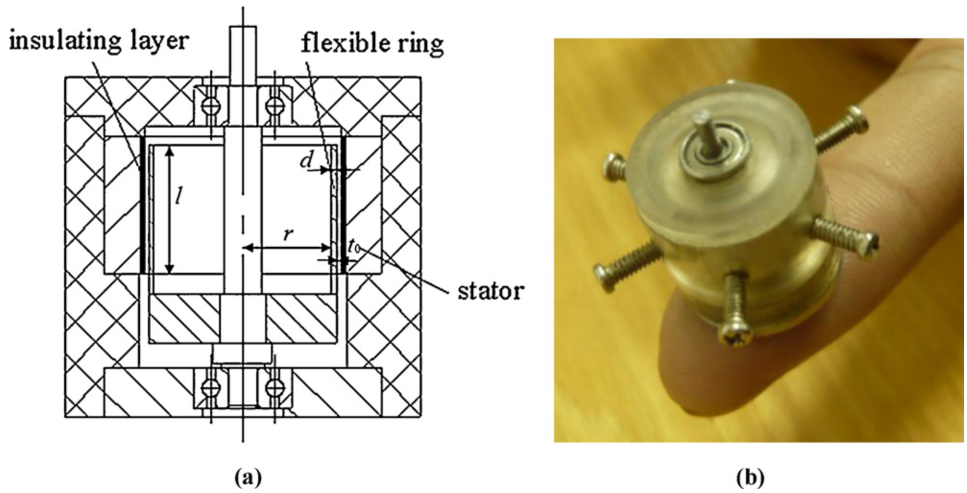

Fig. 1. An active electromechanical integrated harmonic actuator. (a) Structural diagram and (b) model machine.

using Quantum Field Theory [15]. The Casimir force between semi-infinite parallel plates is inversely proportional to the fourth power of the gap, van der Waals force is inversely proportional to the third power of the gap. Comparing with the van der Waals force, the Casimir force is effective at longer distance for perfect conductors. The van der Waals force is more effective at longer distance than the Casimir force for dielectric bodies [10]. Hence, the Casimir and van der Waals forces should not be considered simultaneously.

In this paper, the equations of the radial displacements of the flexible ring for the actuator are presented. Based on it, the dynamic equations of the flexible ring for the actuator for three different situations are deduced. The three situations are: (i) only considering electrostatic force; (ii) considering electrostatic force and van der Waals force simultaneously; (iii) considering electrostatic force and the Casimir force simultaneously. Using these equations, effects of the van der Waals force or the Casimir force on the natural frequencies and the vibrating modes of the flexible ring for the actuator are investigated. When the van der Waals force or the Casimir force are considered, changes of the natural frequencies and the vibrating modes along with the system parameters are analyzed. Results show: the van der Waals force or the Casimir force has obvious effects on the natural frequencies and the vibrating modes for the actuator when its dimension is small. The results are useful in theory and technique studies on further miniaturization of the actuator.

2. Electrostatic forces and molecular forces

A conducting flexible ring subject to electrostatic and molecular forces is shown in Fig. 2. The ring is inside an outer stator which consists of a number of conductive segments with an insulating layer. The central angle of each segment is 2β. When a voltage is applied between a segment of the stator and the flexible ring, a distributed electrostatic force is subjected to the flexible ring in angle 2β (see Fig. 2(b), here q_{re} is electrostatic force per unit length). Meanwhile, a distributed van der Waals force or the Casimir force is applied to the flexible ring in angle 2π (see Fig. 2(c), here q_{rn} is molecular force per unit length, the index n is 3 for the van der Waals force and 4 for the Casimir force).

As the clearance between the stator and flexible ring is quite small, the capacity between them can be calculated by equation of flat capacitor, $C=((\varepsilon_0 \cdot 2\beta rl)/(t_0-u_0+d_c/\varepsilon_r))$, here, t_0 is the design clearance between the stator and flexible ring, l is the effective length of the flexible ring, r is the average radius of the ring, d_c is thickness of the insulating layer, u_0 is the average transverse displacement of the flexible ring in $[-\beta, \beta]$, ε_0 is permittivity constant of free space, ε_r is relative dielectric constant of the insulating layer; ε is dielectric constant of the insulating layer.

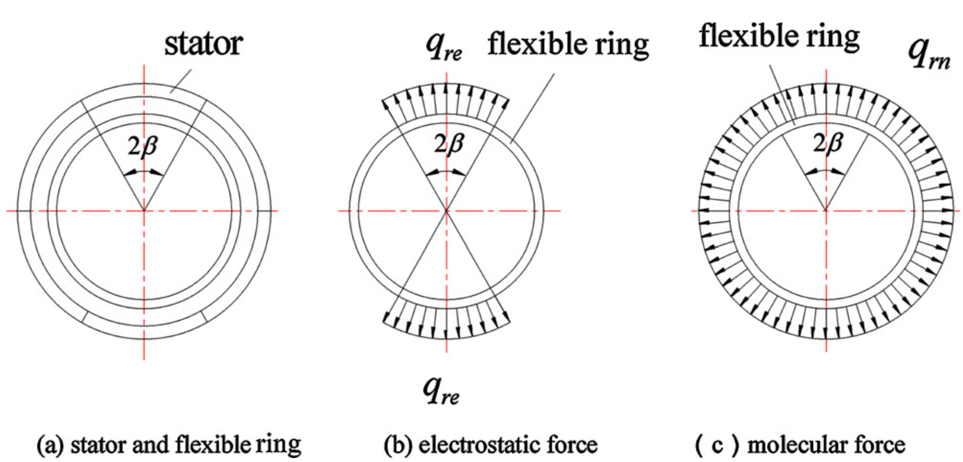

Fig. 2. Electrostatic and molecular forces on the flexible ring.