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Analytical modeling of dynamic pull-in instability behavior of torsional nano/micromirrors under the effect of Casimir force

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ABSTRACT

In this study, the dynamic stability of torsional electrostatic micro/nano-electromechanical systems (MEMS/NEMS) using single degree of freedom model under Casimir force and size effect is investigated. First, the equation of motion of system is developed. Afterwards, dimensionless equation of motion by using normalized parameters is presented and by considering state space method, dynamic equations are solved and intended results are achieved. Afterwards, pull-in angle and pull-in voltage of system which include the parameters affecting its performance, are investigated and its dependence on Casimir force and size effect are shown. Results show that equilibrium points include center points, stable focus points and unstable saddle points. The phase portraits related to these points exhibit periodic orbits, heteroclinic orbits and homoclinic orbits which with regard to considered particular circumstances for system are illustrated. Furthermore, in present study by using modified couple stress model, the influence of size effect on amplitude and frequency of system is considered. Obtained results show that proposed model is in better agreement with experimental data and is able to shorten the distance between the classic theory and the experimental results.

1. Introduction

Human progress in modeling, design and fabrication of micro and nano systems causes MEMS/NEMS optical systems for specific purposes to be built in such a way that have high performance. So new generation of these systems named optical MEMS or optical micro electromechanical systems is created that include micro/nano mirrors and varactors. Optical MEMS/NEMS because of desired dynamic response and possibility of less instability are used in the field and various means widely. For example they are used in digital projection displays [1], spatial light modulators [2] and optical crossbar switches [3]. In general, torsional NEMS varactors are composed of two fixed and moving parts. The moving part comprises a main plate for reflecting light and two beams which are linked to the plate from one end. The fixed part is composed of two supporting bases to which the beams are linked from the other end and an electrode placed under the main plate. The mechanical retrieval force which is created by supporting bases linked to torsional beams, opposes to rotation of torsional varactor. Therefore, when a voltage is applied to the system, the moving part rotates and returns to initial state after eliminating the voltage. If the voltage exceeds the critical limit, the electrostatic force overcomes the mechanical retrieval force and the moving part suddenly sticks to the lower fixed part so that the system becomes instable. Therefore, in designing torsional NEMSs and torsional varactors, parameters of pull-in instability such as pull-in angle and pull-in voltage must be determined. As well as, for considering more accurate of MEMS/NEMS's behavior, in addition to excitation parameter and pull-in parameters, intermolecular forces such as Casimir force, van der Waals (vdW) force must be determined. In nature, these intermolecular forces have electromagnetic essences that create specials property in materials, such as surface effect and capillarity force.

Researchers have examined the static behavior of torsional electrostatic micro/nanomirrors by considering intermolecular forces such as Casimir force and van der Waals (vdW) force. Casimir attraction could highly affect in NEMS structures. In fact, this effect is an attraction force between two objects very close to each other that is created in macro scale. But Casimir effect between the objects which the distance

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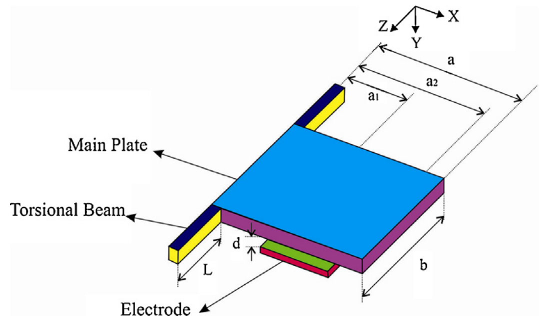

Fig. 1. Torsional electrostatic NEMS varactor.

changed from several nanometers to several micrometers is very important. Therefore MEMS is affected by Casimir force. The role of Casimir effect on operating parameters of MEMS/NEMS is investigated either theoretically or experimentally. Chan et al. [4] by using experiment showed that how Casimir force can be used for exciting MEMS instrument. Guo and Zhao [5] investigated the effect of van der Waals and Casimir forces on electrostatic micromirror and analyzed dependence of critical angle of micromirror and instability voltage on geometry of system. As well as the influence of van der Waals moment is compared with Casimir moment and modified coefficients of van der Waals and Casimir moment on pull-in voltage are calculated. When the distance between plate and electrode is small well enough, because of van der Waals and Casimir moment operation, without electrostatic moment pull-in instability can still occur with small angle perturbation. Beni et al. [6] examined the coupled torsion/bending pull-in instability of torsional electrostatic nano-mirrors by considering the molecular vdW force. Also, Beni et al. [7] investigated the effect of Casimir force on the coupled bending and torsion in the pull-in instability of an electrostatic nano-actuator. Gusso and Delben [8] developed equations to show the effect of Casimir force on the parameters of instability of NEMS torsional actuators made of silicon and investigate the influence of temperature and surface roughness on Casimir force. Moeenfard et al. [9] study the effect of Casimir force on the static behavior and the pull-in specifications of micro-mirrors under the capillary force. The obtained results show that Casimir effect can reduce limitation of pull-in instability of micro mirrors. Also angle of rotation under capillary force highly is dependent on Casimir force applied on mirror. In other study they [10] investigated the static behavior of nano/micromirrors under the Casimir force.

In general the behavior of micro electrostatic systems is considered statically and dynamically. For example Li et al. [11] investigated the torsional dynamic and static behavior of circular nano-objects such as nanorods, nanoshafts and nanotubes based on the nonlocal elastic theory. Static and dynamic behavior difference is the time parameter eliminates in the static mode and applying high order theory governing differential equations are solved accurately. For example Beni [12] used the continuous mechanical theory to examine the size-dependency of the pull-in instability of coupled nanoelectrostatic torsional actuators of torsion and bending. Tsiatas and Katsikadelis [13] developed a new model of the modified couple stress theory for the Saint-Venant torsion of microrods with arbitrary cross-sections. Beni and Abadyan [14] by using nonclassical strain gradient theory investigate size-dependency of the pull-in instability of nano mirrors and considering van der Waals effect and electrostatic force develop the equation governed mirror. Tong et al. [15] investigated size effects on the torsion of beams with different cross-sections. In other study [16] using static model, rotation of angle and vertical displacement of torsional micro mirrors is considered. Huang et al. [17] compared experimental data with theory model by applying the coupled bending and torsion effect and investigated static properties of torsional electrostatic micro mirrors especially pull-in effect.

However for considering dynamic behavior of optical MEMS/NEMS against static behavior, time parameter involved in problem and governing equation is the dimensionless equation of motion of system which in general solved by applying state space method. Many researchers are developed the dynamic behavior of these systems. Nemirovsky and Bochobza-Degani [18] developed a general model for the pull-in phenomenon in electrostatic actuators with one degree of freedom. Also they [19] studied the behavior of micromirrors using a two-degree-of-freedom coupled bending/torsion model. In other study [20], a theoretical model of the dynamic properties of nanomirrors is developed by considering their torsion and bending at the same time that in this study researcher analyzed the step response and stable harmonic response of nanomirrors through the Runge–Kutta method. Other researchers [21] investigated the effect of vdW force on static and dynamic stability of NEMS mirrors. They developed the motion dimensionless equation of micromirror and conducted a qualitative investigation of dynamic behavior. In other study [22], a NEMS varactor is proposed using torsional beams and is obtained analytical results for electrostatic moment. Afterwards, it is compared that system with the present systems for the dynamic range and actuation voltage. Also, a theoretical model for the dynamic properties of torsional micromirrors by considering the coupled bending and torsion effect is developed by Shabani et al. [23]. Using a two-degree-of-freedom model, Khatami and Rezazadeh [24] discussed the dynamic response of a micromirror to mechanical shock.

Considering the above discussion, in present study for more accurate considering of dynamic behavior size-dependent of torsional NEMS varactor, modified couple stress theory is applied and for involving intermolecular forces in nano scale, effect of Casimir force into modeling is considered. The equation of motion of system as dimensionless is developed and by using state space method is solved. Afterward pull-in parameters such as angle and voltage of system are discussed, equilibrium points are obtained and phase portraits for equilibrium points of system in both stable and unstable situation is drawn. Present model because of considering size effect and Casimir intermolecular force has high accuracy and is able to predict the empirical results with higher precision than the classical models.

2. Governing equations

Fig. 1 shows an electrostatic torsional NEMS varactor. NEMS varactor is made of a main plate and two torsional elastic beams mounted above a fixed electrode. The beams are clamped from both ends. According to Coulomb's law, to apply a voltage between the main plate and electrode creates attraction between them and causes the plate to turn toward the electrode. To develop the governing equations of the problem, vertical and axial displacements of the torsional nanobeam are assumed to be infinitesimal so that the pull-in instability