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DYNAMIC PULL-IN INSTABILITY OF DOUBLE-SIDED ACTUATED NANO-TORSIONAL SWITCHES**

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ABSTRACT A nonlinear frequency-amplitude relation is developed to investigate the vibrational amplitude effect on the dynamic pull-in instability of double-sided-actuated nano-torsional switches. The governing equation of a nano-electro-mechanical system pre-deformed by an electric field contains the quintic nonlinear term. The influences of basic parameters on the pull-in instability and natural frequency are investigated using a powerful analytical approach called the homotopy perturbation method. It is demonstrated that two terms in series expansion are sufficient to produce an acceptable solution. The numerical results obtained have verified the soundness of the asymptotic procedure. The phase portraits of the double-sided nano-torsional-actuator exhibit periodic, homoclinic and heteroclinic orbits.

KEY WORDS homotopy perturbation method, frequency-amplitude relationship, double-sided actuated nano-switch, dynamic pull-in instability, homoclinic orbit, heteroclinic orbit

I. INTRODUCTION

Electrostatic torsional actuators are widely used in nano-electro-mechanical system (NEMS) devices such as torsional mirrors, tunable torsional capacitors and torsional radio frequency (RF) switches. As these nano-scale devices are highly sensitive to several system parameters, it is necessary to know how they affect the physical and mechanical properties of the system, e.g. its pull-in instability or its fundamental natural frequency. Recently several numerical and experimental studies have been conducted on the pull-in instability and dynamic behavior of NEMS devices[1–15]. However, to the authors' best knowledge, the amplitude dependence of nonlinear frequency and pull-in instability has not yet been studied. In the dynamic analysis of nano-systems, electrostatic and intermolecular forces have been found to make the relationship between input excitation and output response nonlinear. In the case of the torsional actuator, as the actuation voltage and/or initial tilt angle is increased, the electrostatic torque increases until it exceeds the restoring torque that results in the pull-in phenomenon.

Degani and Nemirovsky[1] proposed a pull-in polynomial algebraic equation for the pull-in angle and the voltage of electrostatic actuators. The influence of the van der Waals (vdW) force on the stability of the electrostatic torsional NEMS actuators was analyzed by Guo and Zhao[2]. They studied the pull-in phenomenon without electrostatic torque and derived a critical pull-in gap by considering the vdW effects. Plötz et al.[3] studied an electrostatic torsional RF switch with low actuation voltage

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theoretically, numerically and experimentally. The influence of damping on the dynamic behavior of the electrostatic parallel-plate and torsional actuators with the vdW or the Casimir force (torque) has been presented by Lin and Zhao[4]. They demonstrated that the values of the pull-in parameters and the number of the equilibrium points do not change no matter whether there is damping or not. Guo et al.[5] investigated the static and dynamic instability of a torsional MEMS/NEMS actuator caused by capillary effects.

A novel electrostatically driven torsional actuator was proposed by Hsieh and Fang[6]. The advantage of the proposed design was an increase in both the traveling distance of the actuator and the area of the moving plate. Senga et al.[7] used TEM observation and molecular dynamic simulation to examine the transitional behavior of carbon nanotube torsional actuator and to investigate how the torsional angle is determined.

The influences of the van der Waals and the Casimir forces on the stability of the electrostatic torsional NEMS actuators have been investigated by Guo and Zhao[8], who also derived the critical gap under the action of the vdW and the Casimir torque when there is no electrostatic torque. Casimir effects on the critical pull-in gap and pull-in voltage of nano-electromechanical switches have been studied by Lin and Zhao[9], who presented an approximate analytical expression of the critical pull-in gap with the Casimir force using the perturbation theory. Lin and Zhao[10–12] studied the bifurcation properties of the nano-scale electrostatic actuators including dispersion attraction. Furthermore, they obtained the phase portraits of the system, in which the periodic orbits exist around the Hopf point, while a homoclinic orbit passes through the unstable saddle point. Wang et al.[13] studied the pull-in instability of nano-scale tweezers under the influence of the van der Waals forces. Shabani et al.[14] investigated the super harmonics and chaotic responses in electrostatic torsional micro-mirrors near the pull-in condition. Moeenfard et al.[15] studied a coupled two degrees of freedom model considering both the bending and torsion of the supporting torsional beams for electrostatically actuated torsional nano/micro-actuators under the effect of the van der Waals force.

In the last two decades, substantial progress has been made in analytical solutions for nonlinear equations without small parameters[16–18]. A variety of asymptotic approximate approaches e.g. the energy balance method[19], the variational iteration and the energy balance method[20], the Lindstedt-Poincaré method[21], the Laplace transform method[22], the max-min method[23], the homotopy analysis[24], the parameter expansion method[25–27], the homotopy perturbation method (HPM)[28] and the Hamiltonian method[29,30] have been employed to solve the governing nonlinear differential equations. It is well known that while the perturbation methods provide the most versatile tools for the nonlinear analysis of engineering problems, they have also some limitations. In order to overcome these drawbacks, combining the standard homotopy and the perturbation method, known as the HPM, improves the drawbacks of both approaches, improves the homotopy method. He[28] developed the homotopy perturbation method for solving a variety of problems including the linear and the nonlinear as well as the initial and the boundary value problems by merging two aforementioned techniques. Thanks to its easily computable components and rapid convergence, it has been applied to an extensive class of functional equations.

In this paper the nonlinear behavior of double-sided-actuated nano-torsional switches with different actuation voltages is investigated. The acceptable ability of the HPM to predict the analytical response as well as the pull-in instability of double-sided-actuated nano-switches with odd and even nonlinearities including the quintic nonlinear term is exhibited. The effect of the vibrational amplitude on the pull-in instability and the fundamental natural frequency is investigated. To this end, analytical expressions for vibrational response of the nano-actuated switch are presented. The results are proof that the analytical method presented is very effective even in the case of highly nonlinear vibrations. Besides, it is demonstrated that two terms in the series expansions are sufficient to obtain a highly accurate solution for the nano-actuator vibration. Finally, the influences of the amplitude and several parameters on the pull-in instability behavior and the natural frequency are studied.

II. EQUATION OF MOTION

A nano torsional switch under double-sided electrostatically actuated voltages is considered as shown in Fig.1. The nano-torsional system has a rotational inertia J and a spring torque coefficient k_Θ. The air initial gap is g and the attractive electrostatic torques originating from voltages V_1 and V_2 from the lower and upper plates cause the nano-actuator to tilt.