Dynamic Simulations of a Novel RF MEMS Switch

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ABSTRACT

We present a dynamic analysis of a novel RF MEMS switch utilizing the dynamic pull-in phenomenon. We study this phenomenon and present guidelines about its mechanism. We propose to utilize this phenomenon to design a novel RF MEMS switch, which can be actuated by a voltage load as low as 40% of the traditionally used static pull-in voltage. The switch is actuated using a combined DC and AC loading. The AC loading can be tuned by altering its amplitude and/or frequency to reach the pull-in instability with the lowest driving voltage and fastest response speed. The new actuation method can solve a major problem in the design of RF MEMS switches, which is the high deriving voltage requirement.

Keywords: Dynamic pull-in, RF switches, microbeams, electric actuation.

1 INTRODUCTION

The emerging technology of microelectromechanical systems (MEMS) has enabled the design and fabrication of an important class of devices, RF MEMS switches, which promises breakthrough advances in telecomunications and radar systems. RF MEMS switches overcome the limitations of existing conventional switches and present many attractive features, such as low-power consumption and high isolation. However, a major drawback of these devices is the requirement of high driving voltages [1]. It is highly desirable to bring the actuation voltage to a level compatible or close to that of the device circuits. Unfortunately, the state of the art of RF MEMS switches has not achieved this requirement, which forms a barrier toward the development of this technology.

In this work, we propose a novel RF MEMS switch that can be actuated by a voltage load as low as 40% of the static pull-in voltage. The new actuation method is based on the dynamic pull-in phenomenon, in which the switch is brought to pull-in by a voltage lower than the static pull-in voltage. The dynamic pull-in phenomenon has been previously reported and analyzed for switches actuated by a step voltage [2,3] and various ramping rates [2]. Both studies [2,3] indicate that the dynamic pull-in voltage can be as low as 91% of the static pull-in voltage. In the presence of squeeze-film damping, the dynamic pull-in voltage is shown to approach the static pull-in voltage [3]. Here, we propose to actuate the switch using a combined DC and AC loading. The AC loading can be tuned by altering its magnitude or frequency to reach the pull-in instability with the lowest driving voltage and fastest response speed.

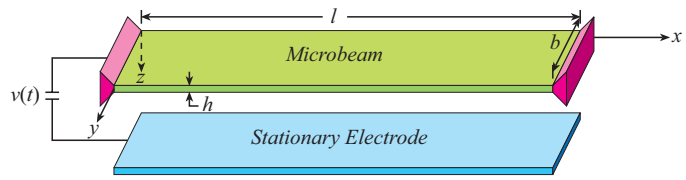


Figure 1: A schematic of an electrically actuated microbeam.

In [4-7], we presented a model, which predicts the static pull-in phenomenon. In [8], we utilized perturbation methods to predict the dynamic behavior of resonators undergoing small motions near the equilibria. In [6,7], we developed a reduced-order model to simulate the static and dynamic behaviors of resonators and switches undergoing small or large motions. In this paper, we use the reduced-order model in [6,7] to simulate the dynamic behavior of the proposed RF MEMS switch. We utilize a shooting technique [9] and long-time integrations of the equations of motion to predict periodic motions. This approach can be applied to a wide range of loadings and initial conditions, and hence it can be used to study the 'global' dynamics of switches (unlike the model presented in [8], which is based on perturbation methods and applicable for small motions near the equilibria). We use the global approach to demonstrate the new actuation method.

2 RESULTS

We consider a clamped-clamped microbeam, Figure 1, actuated by an electric load $v(t) = V_{DC} + V_{AC}\cos(\Omega t)$, where V_{DC} is the DC polarization voltage, V_{AC} is the amplitude of the applied AC voltage, and Ω is the excitation frequency. We utilize the reduced-order model in [6,7] to calculate the equilibria of the microbeam

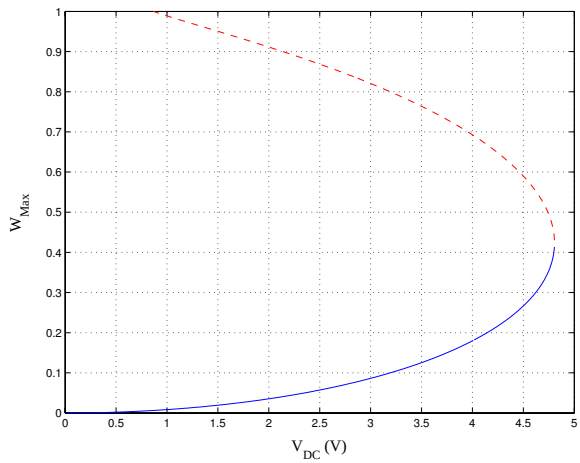


Figure 2: Equilibria of an electrostatically actuated microbeam.

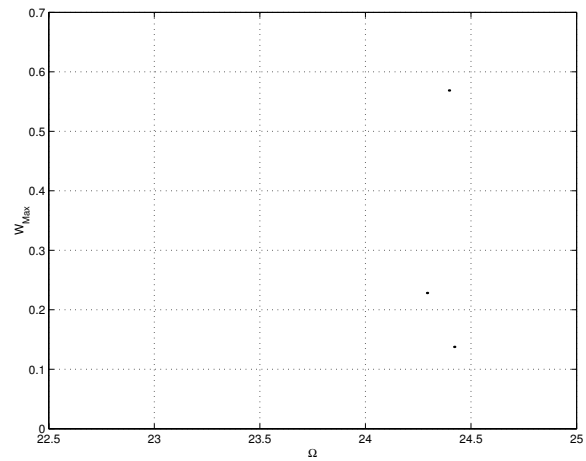


Figure 3: Frequency-response curves showing the onset of the dynamic pull-in.

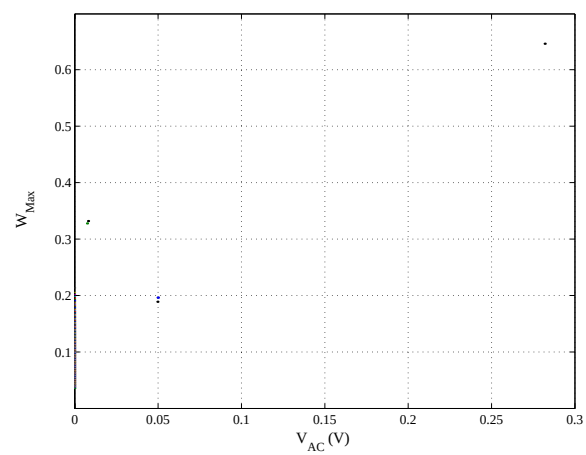


Figure 4: Force-response curves showing the onset of the dynamic pull-in.

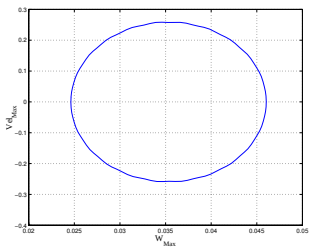
under a constant DC loading. Details of the calculations are presented in [6,7]. We study a microbeam of $\ell = 510\mu m$, $h = 1.5\mu m$, $b = 100\mu m$, a capacitor gap width $d = 1.18\mu m$, and subject to a nondimensional axial load of $N = 8.7$. The parameter N relates to the dimensional axial force $\hat{N}$ by $N = \frac{\hat{N}\ell^2}{EI}$, where I is the moment of inertia of the cross section and E is Young's modulus. Figure 2 shows a lower stable branch (solid line) and an upper unstable branch (dashed line), both collide in a saddle-node bifurcation at the static pull-in voltage, which is $V_{DC} \approx 4.8V$. Hence, the static analysis shows that MEMS devices should be designed to operate below this value to ensure stability.

For all the following results, we assume the microbeam to be actuated by a DC loading $V_{DC} = 2V$ and subject to a viscous damping with a quality factor $Q = 1000$. Figures 3 and 4 show variation of the mid-point deflection W_{Max} of the microbeam with Ω (Figure 3) and V_{AC} (Figure 4): $V_{AC} = 0.1V$ in Figure 3 and $\Omega = 24.15$ in Figure 4. The dynamic pull-in instability observed in both figures is characterized by a slope approaching infinity. In both cases, a Floquet multiplier approaches unity near pull-in. However, the magnitude of the Floquet multiplier can be used as a pull-in criterion for force sweep cases, like that in Figure 4, only because Floquet multiplier always approaches unity around the maximum point on the curve of a frequency sweep regardless of whether the point corresponds to pull-in or a cyclic-fold bifurcation [8].

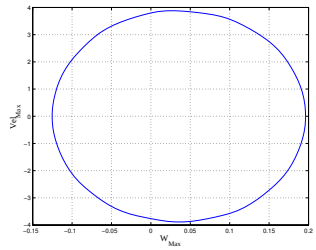
Figures 3 and 4 show that the dynamic pull-in instability occurs much earlier than the static pull-in limit. For this case, the static pull-in limit is at $V_{DC} \approx 4.8V$ while the total voltage loads where the dynamic pull-in occurs are less than $2.25V$ in both cases. This significant results suggest a novel actuation method, in which a switch is brought to pull-in at a voltage level as low as 40% of the static pull-in voltage. This is a very promising result in the search to reduce the actuation level of RF MEMS switches. The result also illustrates the importance of designing RF MEMS filters and resonant sensors based on a dynamic analysis to avoid possible failure of these devices.

Figure 5 shows phase portraits (plots of velocity versus displacement) for selected points in Figure 4. The solid lines correspond to stable periodic orbits and the dashed lines correspond to unstable periodic orbits. As V_{AC} increases, the size of the orbit increases until $V_{AC} = 0.2891V$ where it becomes large enough to trigger pull-in.

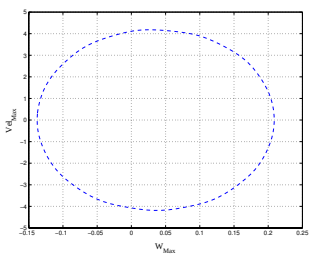
Figures 6 and 7 show a time history evolution and a phase portrait demonstrating the onset of the dynamic pull-in for the microbeam at $V_{AC} = 0.08V$ and $\Omega = 24.4$. The time is nondimensionalized with respect to $T =$



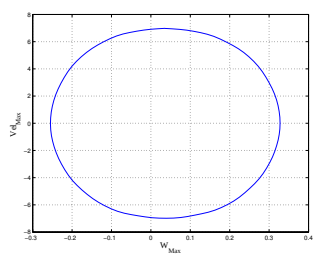
(a) $V_{AC} = 0.005V$.



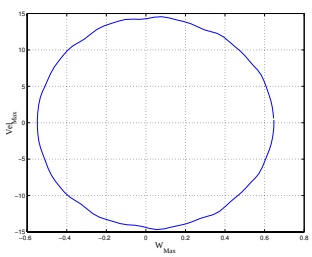
(b) $V_{AC} = 0.049807V$.



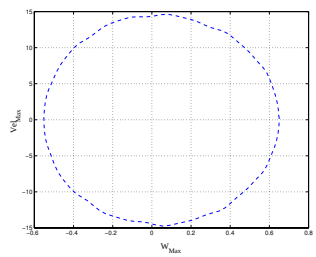
(c) $V_{AC} = 0.050007V$.



(d) $V_{AC} = 0.00738V$.



(e) $V_{AC} = 0.281910V$.



(f) $V_{AC} = 0.281950V$.

Figure 5: Phase portraits for some points on Figure 4. The dashed lines are unstable periodic orbits.

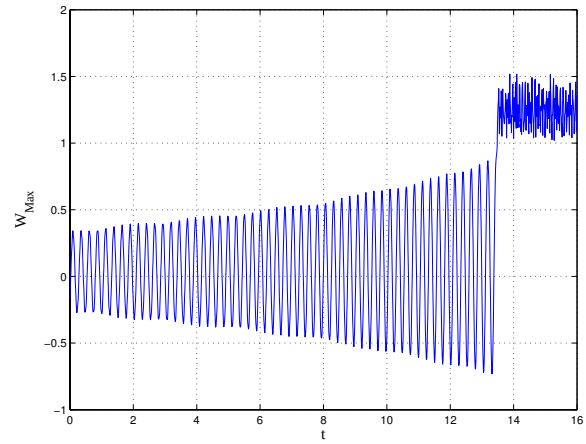


Figure 6: Time history showing the onset of dynamic pull-in.

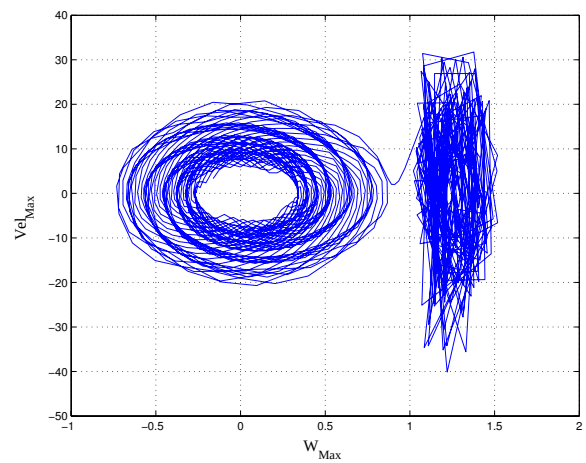


Figure 7: Phase portrait showing the onset of dynamic pull-in.

$\sqrt{\frac{\rho b h \ell^4}{EI}}$, where ρ is the material density. The figures are generated from a long-time integration of the reduced-order model equations in [6,7]. We note that, for this case, the dynamic pull-in occurs when the orbit collides with the saddle (the unstable equilibrium solution) and its stable manifold, which is at $W_{Max} \approx 0.91$ (compare the location of the saddle in Figures 2, 6, and 7). Figures 8 and 9 are generated from the same data of Figures 6 and 7 except that the sign of one initial condition is changed from positive to negative. We note that the motion is stable, which indicates a fractal dynamical behavior that is sensitive to initial conditions [9].

In light of the above results, we make the following remarks about the dynamic pull-in phenomenon. In the absence of the AC forcing and damping, a homoclinic orbit [9], which starts and ends at the saddle, encircles the stable fixed point (center). This orbit is composed of a stable manifold and an unstable manifold that intersect transversely at the saddle. Any initial conditions inside the closed orbit result in a stable oscillatory motion and any initial conditions outside it result in an unstable motion. In the presence of damping, the center becomes a stable focus, the saddle remains a saddle, and the homoclinic orbit is destroyed. Here, the stable and unstable manifolds do not intersect. If the system is excited by an AC force with initial conditions near the stable focus, the motion will be a stable periodic motion. As the amplitude of excitation increases, the response amplitude increases and the stable manifold approaches the unstable manifold. Eventually, both manifolds intersect each other transversally infinitely many times, resulting in a complex dynamic behavior called homoclinic tangles [9]. One implication of this complex behavior is the sensitivity to initial conditions or the unpredictability

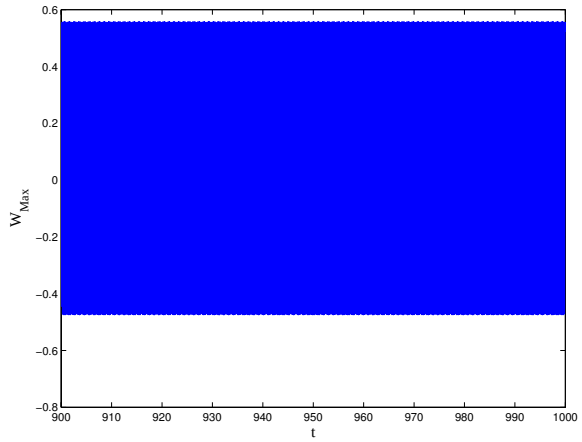


Figure 8: Time history for the same parameters of Figures 6 and 7 and different initial conditions.

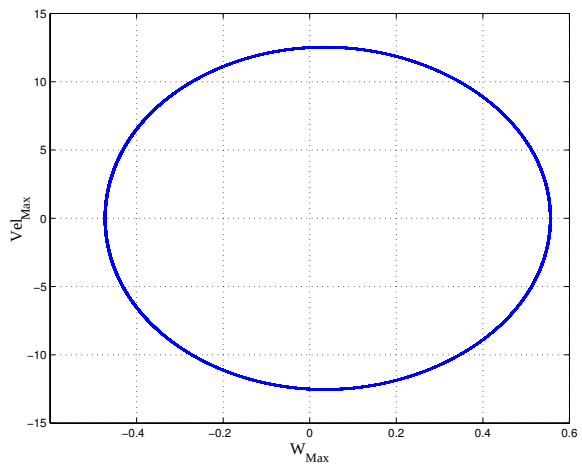


Figure 9: Phase portrait for the same parameters of Figures 6 and 7 and different initial conditions.

of motion. Increasing the amplitude of excitation further results in an erosion of the basin of attraction of bounded motions; and the possibility of finding a set of initial conditions that leads to a stable motion decreases. It is worth noting that the dynamic pull-in instability in this case is to a great extent similar to the phenomenon of capsizing of ships [9,10].

3 SUMMARY AND CONCLUSIONS

We proposed a novel actuation method for RF MEMS switches and presented a dynamic analysis of this method. We studied the dynamic pull-in instability and showed the danger inherent in device designs based on static analysis only. On the other hand, we showed that this phenomenon can be used to advantage to solve a challenging dilemma in the design of RF MEMS switches, namely the high deriving voltage requirement. Furthermore, it holds the promise of realizing switches of faster response by tuning the AC excitation amplitude to higher magnitudes than the pull-in limit and the frequency of excitation to be as close as possible to the resonance frequency. Experimental work is planned to investigate the feasibility of the new actuation method.

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