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Stabilization of Electrostatically Actuated Micro-pipe Conveying Fluid Using Parametric Excitation

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ABSTRACT

This paper investigates the parametric excitation of a micro-pipe conveying fluid suspended between two symmetric electrodes. Electrostatically actuated micro-pipes may become unstable when the exciting voltage is greater than the pull-in value. It is demonstrated that the parametric excitation of a micro-pipe by periodic (*ac*) voltages may have a stabilizing effect and permit an increase of the steady (*dc*) component of the actuation voltage beyond the pull-in value. Mathieu type equation of the system is obtained by applying Taylor series expansion and Galerkin method to the nonlinear partial differential equation of motion. Floquet theory is used to extract the transition curves and stability margins in physical parameters space (V_{dc}-V_{ac}). In addition, the stability margins are plotted in flow velocity and excitation amplitude space (u-V_{ac} space). The results depict that the micro-pipe remains stable even if the flow velocity is more than the critical value for a certain *dc* voltage. For instance, in absence of the (*ac*) component, it is shown that pull-in voltages associated to critical velocities 3 and 6 are 14.06 and 5.4 volt, respectively. However, transition curves show that superimposing an (ac) component with forcing frequency Ω=10 increases the pull-in voltage beyond these values. Furthermore, for the present pull-in voltages the critical velocities 3 and 6 could be increases with imposing some (ac) component. These results are discussed in detail in simulation results section where the transion curves are ploted quantitatively.

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NOMENCLATURE

		Greek Symbols	
C	Coriolis acceleration matrix		
E	Young's modulus of the micro-pipe material (GPa)	ρ	Density (kg/m^3)
g_0	Initial gap between electrodes and the micro-pipe (μm)	τ	Dimensionless time
I	Area moment of inertia of the beam (m^4)	α	Electrostatic force coefficient
K_e	Electrical matrix	β	Mass ratio
K_m	Stiffness matrix	ε_0	Permittivity of free space
K_u	Centrifugal force matrix	η	Dimensionless Deflection of the micro-pipe
K^*	Parametric electrical matrix	ξ	Dimensionless Axial coordinate varies 0-1
L	Length of the micro-pipe (μm)	ζ	Dimensionless Coriolis coefficient
M	Mass Matrix	Ω	Excitation frequency (hertz)
m	Mass of the empty micro-pipe per unit length (kg/m)	$,\delta\ \varsigma$	Constants of Mathieu equation
U	Steady flow velocity (m/s)	ω_n	Dimensionless natural frequency
u	Dimensionless fluid flow velocity	φ_n	The nth linear mode shape of the micro-pipe in the absence of fluid

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1. INTRODUCTION

There has been a considerable amount of interest in the use of micro-electro-mechanical systems "MEMS" over the last two decades. Electrostatically actuated micro-sensors and actuators are widely used in many applications such as aerospace, biomedicine, information technology and so forth. Recently, micro-structures coupled with fluid flow have been used widely in MEMS applications such as micro fluidic devices [1], micro scale ink printers [2] and micro-pumps [3]. Among these devices, micro-pipe conveying fluid is significantly important and its flow induced vibration and instability has been drawing huge attention. Dynamic analysis and stability of pipe conveying fluid in macro-scale have been extensively studied for many years [4-7]. It has been reported that increasing the flow velocity can lead to both static and dynamic instability in the form of divergence and flutter. Several studies of fluid solid interaction in nano-scale structures have been reported in connection with flow through carbon nanotubes [8-10]. Most recently, using MCST for modelling the rotating single-walled carbon nanotubes (SWCNTs), SafarPouri and Ghadiri investigated how rotational speed and velocity of viscous fluid flow affect SWCNTs stability and free vibration behavior [11]. Studies were continued and extended to analyze the instability of pipe conveying fluid in the intermediate micrometer range where remains mostly unexplored [12-15]. For example, Kural et al. showed that in order to stability analysis, the effects of shear stress on micro-beam conveying fluid made by some special materials shouldn't be neglected [13]. Abbasnejad et al. [14] studied the stability of a fluid-conveying micro-pipe axially loaded with a pair of piezoelectric layers located at its top and bottom surfaces. They investigated the effects of intermediate support on the stability margins.

Micro-pipe conveying fluid may also operate as a micro resonator for measuring the operating fluid properties. Measuring is achieved by detecting small changes in natural frequency. In this case, the micro-pipe should be excited harmonically. Excitation can be triggered by various mechanisms where the electrostatic actuation is preferred over other actuation methods because of its ease of use and compatibility with micro-fabrication process. In this regard, Enoksson et al. [16] presented a double loop micro-pipe resonator structure as a mass flow sensor. In the other work, they proposed four different double loop designs and investigated the effects of the loop shapes on the sensitivity of the sensor as a fluid density meter [17, 18]. Westberg et al. [19] proposed a CMOS-compatible rectangular resonating micro-tube for measuring the density of fluids. Later, Najmzadeh et al. [20] proposed a new and simple silicon straight micro-tube with a hexagonal cross section as a fluid density sensor. Taking into account electrostatically harmonic actuation, they addressed the Q-factor and the fluid density sensitivity for the first three vibration modes. The investigations were continued by spark et al. [21] who examined the use of electrostatically resonating cantilever micro-pipe to measure both the viscosity and density of fluid.

One of the main issues related to design a resonant micro-pipe is to adjust the electrical load away from the pull-in instability, a condition that causes failure in the system. Concerning this, Dai et al. [22] derived a theoretical model in order to predict pull-in instability of electrostatically actuated micro-pipes conveying fluid. They addressed the effects of fluid flow and electrostatic force on the buckling and pull-in instability. Later, Yan et al. comprehensively investigated the pull-in instability and dynamic characteristics of an electrostatically actuated micro-beam conveying fluid by considering the elastic structure and laminar flow. They studied the energy dissipation caused by the fluid viscosity and showed that the quality factor decreases by increasing the mode order as well as flow velocity [23]. In their another paper, Yan et al. studied comprehensively the dynamic behavior of an electrostatically actuated suspended microchannel resonator and showed that the steady flow could extend dynamic stable region of pull-in. They also demonstrated that applying dc voltage and steady flow could shift the resonant frequency [24].

Furthermore, Krylov et al. [25] proposed a symmetric actuation mechanism, which included a steady (dc) and time dependent (ac) component of the voltage to extend the stable margins of a micro-beam beyond the pull-in value. As well, Rhoads et al. [26] studied the same geometry that couples the inherent benefits of a resonator with purely parametric excitation. Moreover, Abbasnejad et al. [27] shows that the parametric excitation of a symmetrically actuated micro mirror superimposing the harmonic (ac) component could have a stabilizing effect and allow an increase of the steady (dc) component beyond the pull-in value.

It seems that, instead of single side electrode, a symmetrically double side actuation mechanism could be used in resonant micro-pipe conveying fluid to extend the thresholds of instability. In this paper, a double clamped resonant micro-pipe with rectangular cross section is actuated symmetrically with electrostatic electrodes. It is shown that the parametric excitation of the micro-pipe using harmonic (*ac*) voltage may have a stabilizing effect and permits an increase of the bias (dc) component of the actuation beyond the pull-in value. Employing Galerkin projection method a Mathieu type governing equation is derived. Floquet theory is used to extract the transition curves and stability margins in physical parameters space (V_{dc}-V_{ac}). In addition, the stability margins are plotted in flow velocity and excitation amplitude space (u-V_{ac} space). The results depict that the micro-pipe remains stable even the flow velocity is more than the critical value for a certain *dc* voltage.

2. MATHEMATICAL MODELING

Figure 1 shows a double clamped micro-pipe conveying fluid placed symmetrically between two electrodes. The micro-pipe is subjected to bias V_{dc} and superimposed harmonic V_{ac} voltage equally in both sides. Here b, h, L, and EI are the width, height, length and flexural rigidity of the micro-pipe, respectively. M and m are the mass per unit length of the Micro-pipe and flowing fluid with average velocity U. Lateral deflection is denoted as W and internal dimensions are specified in the cross section view.

The governing equation of the transverse motion of the micro-pipe subjected to symmetrically electrostatic loads is:

$$EI\frac{\partial^4 w}{\partial x^4}+mU^2\frac{\partial^2 w}{\partial x^2}+2mU\frac{\partial^2 w}{\partial x\partial t}+\left(m+\rho A\right)\frac{\partial^2 w}{\partial t^2}=\frac{\varepsilon_0 bV\left(t\right)^2}{2\left(g_0-w\right)^2}-\frac{\varepsilon_0 bV\left(t\right)^2}{2\left(g_0+w\right)^2} \tag{1}$$

where $V(t)$ is the actuation voltage, g_0 is the initial gap between the pipe and the electrodes and $\varepsilon_0=8.854\times10^{-12}$ Fm^{-1} is the permittivity of free space. The first term in the above equation stems from the elastic flexural restoring force and the second term corresponds to the centrifugal force of the fluid flowing with constant speed U. The third term is recognized as being associated with the Coriolis acceleration and the last term represents inertial effects of both pipe and fluid. To ease the calculations following dimensionless parameters are defined.

$$\eta=\frac{w}{g_0}\ ;\ \xi=\frac{x}{L}\ ;\ \tau=\left[\frac{EI}{\left(\rho A+m\right)}\right]^{\frac{1}{2}}\frac{t}{L^2}$$
$$\beta=\frac{m}{\left(\rho A+m\right)};u=\left[\frac{m}{EI}\right]^{\frac{1}{2}}UL\ ;\ \alpha=\frac{\varepsilon_0 L^4}{2EIg_0^3} \tag{2}$$

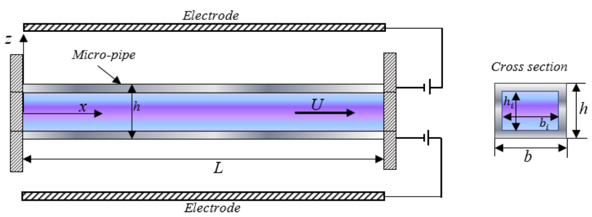


Figure 1. Schematic view of the micro-pipe conveying fluid with side electrodes

Substituting these parameters into Equation (1) results in the following dimensionless equation of motion:

$$\frac{\partial^4\eta}{\partial\xi^4}+u^2\frac{\partial^2\eta}{\partial\xi^2}+2\beta^{1/2}u\frac{\partial^2\eta}{\partial\xi\partial\tau}+\frac{\partial^2\eta}{\partial\tau^2}=\alpha\left(\frac{V\left(\tau\right)^2}{\left(1-\eta\right)^2}-\frac{V\left(\tau\right)^2}{\left(1+\eta\right)^2}\right) \tag{3}$$

where, in the double clamped case the following boundary conditions should be satisfied.

$$\eta\left(0,\tau\right)=\frac{\partial\eta(0,\tau)}{\partial\xi}=\eta\left(1,\tau\right)=\frac{\partial\eta(1,\tau)}{\partial\xi}=0 \tag{4}$$

Bearing in mind that finite vibrations of the micro-pipe around the equilibrium position $\eta=0$ will be studied, the nonlinear electrostatic terms appearing in the governing equation are expanded into a Taylor series up to the second order. Therefore, the resulting equation takes the following form:

$$\frac{\partial^4\eta}{\partial\xi^4}+u^2\frac{\partial^2\eta}{\partial\xi^2}+2\beta^{1/2}u\frac{\partial^2\eta}{\partial\xi\partial\tau}+\frac{\partial^2\eta}{\partial\tau^2}=4\alpha V_{dc}^2\eta+4\alpha V_{dc}\eta\delta V \tag{5}$$

where $\delta V=V_{ac}\cos(2\Omega\tau)$ is the harmonic component of the exciting voltage and V_{dc} is the bias or tuning voltage. Rearranging Equation (5) yields the following parametric equation.

$$\frac{\partial^4\eta}{\partial\xi^4}+u^2\frac{\partial^2\eta}{\partial\xi^2}+2\beta^{1/2}u\frac{\partial^2\eta}{\partial\xi\partial\tau}+\frac{\partial^2\eta}{\partial\tau^2}=4\alpha\,\eta\left(V_{dc}^2+V_{dc}V_{ac}\cos(2\Omega\tau)\right) \tag{6}$$

The lateral deflection of the micro-pipe η can be formulated as the summation of a finite number of suitable shape functions with time dependent coefficients as:

$$\eta\left(\xi,\tau\right)\cong\sum_{n=1}^{N}q_n(\tau)\varphi_n(\xi) \tag{7}$$

where $q_n(t)$ represents the nth generalized coordinate and $\varphi_n(\xi)$ denotes the n^{th} linear mode shape of the micro-pipe in the absence of fluid. The symmetric configuration of the proposed micro-pipe and the electrostatic loading mechanism reveals that the first mode could be the dominant mode of operation. Hence, by letting N=1 in Equation (7) and employing the orthogonality of the mode shapes, the single mode approximation yields the following equation:

$$M\ddot{q}\left(\tau\right)+C\dot{q}\left(\tau\right)+\left[K_m+K_u-K_e+K^*\cos\left(2\Omega\tau\right)\right]q\left(\tau\right)=0 \tag{8}$$

where:

$$M=\int_0^1 \varphi^2(\xi)d\xi;\ K_m=\int_0^1 \varphi^{IV}(\xi)\varphi(\xi)d\xi$$

$$K_e=4\alpha V_{dc}^2\int_0^1 \varphi^2(\xi)d\xi;\ C=2\beta^{1/2}u\int_0^1 \varphi'(\xi)\varphi(\xi)d\xi \tag{9}$$

$$K_u=u^2\int_0^1 \varphi(\xi)\varphi''(\xi)d\xi$$

$$K^*=-4\alpha V_{dc}V_{ac}\int_0^1 \varphi^2(\xi)d\xi$$

Applying the transformation $\tau^*=\Omega\tau$ Equation (8) will take the following Mathieu equation:

$$\frac{d^2q}{d\tau^{*2}}+2\zeta\omega_n\frac{dq}{d\tau^*}+\left[\delta+2\varepsilon\cos\left(2\tau^*\right)\right]q=0 \tag{10}$$

where:

$$\omega_n^2=M^{-1}\left(K_m+K_u-K_e\right);\ \ \tilde{C}=\frac{C}{\Omega};$$

$$M^{-1}\tilde{C}=2\zeta\omega_n;\ \ \delta=\left(\frac{\omega_n}{\Omega}\right)^2;\ \ \varepsilon=\frac{M^{-1}K^*}{2\Omega^2} \tag{11}$$

3. SIMULATION RESULTS

At first, with ignoring the fluid effects and applying bias dc voltage, the stability of micro-pipe in single side and symmetrically double side actuation cases are presented. Then, taking into account the fluid flow, the effect of the bias voltage on the critical fluid velocity u_{cr} is depicted. Finally, superimposing ac components to the bias voltages and utilizing Floquet theory, the possibility of parametric stabilization of the micro-pipe is reported. The fluid density used in the simulations is 1000 kg/m^3 and the geometrical and material properties of the micro-pipe are listed in Table 1.

TABLE 1. Geometrical and material properties of the micro-pipe and the fluid

Parameters	Value
Length, *L(μm)*	0.198
Width, *b(μm)*	
Height, *h(μm)*	
Inner width, b_i*(μm)*	
Inner height, h_i*(μm)*	
Young's modulus, *E(Gpa)*	
Poisson's ratio, *v*	
Mass density, *ρ(Kg/m^3)*	0.184

Figure 2 illustrates micro-pipe conveying fluid midpoint deflection versus applied voltage in the absence of fluid flow velocity for both single and double side actuation states. It is depicted that the static pull-in voltage for single and double side actuations are *12.8 volts* and *16 volts* respectively. Namely, in the case of symmetrically double side actuation state, with increasing the bias voltage the micro-pipe remains in the equilibrium position and the instability is taking placed suddenly. The figure shows that symmetric state is more stable.

It should be noted that the centrifugal fluid force acts as a compressive load and the side electrodes produce lateral forces on the micro-pipe. Therefore, beyond some values of the fluid velocity, critical velocity u_{cr}, the micro-pipe loses its stability by divergence '[14]'. Furthermore, as it can be seen from the Figure 2, the midpoint deflection of the micro-pipe with double side electrodes, is zero. In other words, there is no vertical deflection caused by implementing any voltage level. Hence, the effect of the large deflection in this study is not considered.

In order to examine the effects of taking into account the fluid flow velocity on the stability of the micro-pipe, variations of the critical fluid velocity versus the applied symmetric bias voltage are shown in Figure 3. It is observed that the critical fluid velocity decreases in the presence of the side electrodes. Specifically, decreasing the applied voltage will increase the critical fluid velocity.

As stated in the literature review, micro-pipes conveying fluid may operate as a micro resonator for measuring flowing fluid properties. Measuring is achieved by detecting small changes in its vibrational properties. In this case, the micro-pipe should be excited harmonically. Hence, a harmonic *ac* voltage is superimposed to the present bias *dc* component in the symmetrically actuated case. This will result a Mathieu type equation (Equation10) with classical parameters δ and ε.

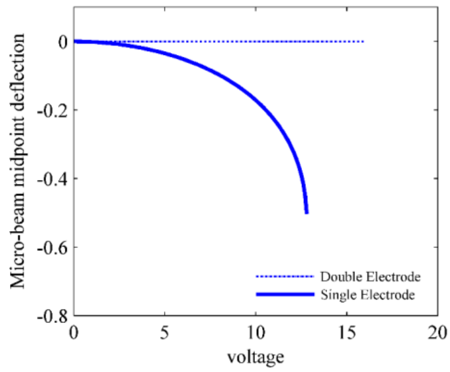


Figure 2. Micro-pipe midpoint deflection versus the applied voltage in absence of fluid flow for both single and double side actuation states

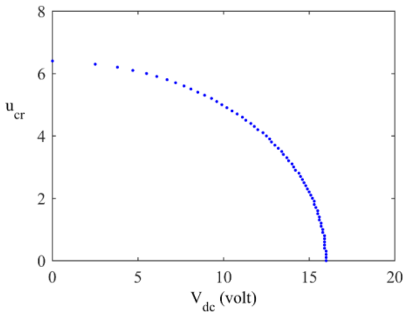


Figure 3. Non-dimensional critical fluid velocity u_{cr} versus V_{dc} for the double clamped micro-pipe conveying fluid.

It should be noted that the parameter δ (equivalent stiffness of the micro-pipe) is a function of the flexural rigidity, applied *dc* voltage, and fluid velocity while time varying the equivalent stiffness of the micro-pipe ε is a function of applied *dc* and *ac* voltages. There are a few well-known methods to solve Mathieu equation. Among them, the Floquet theory, perturbation method, and iteration techniques are the common methods. In this paper to obtain the stable margins of the micro-pipe, the Floquet theory [28] is employed. Figure 4 depicts the stable and unstable regions in the classical parameters plane (δ-ε). It was proved that along the boundaries (transition curves) there exists at least one normal solution, which is periodic with the period of either 2π or 4π depending on the case.

To provide transition curves in the plane of the physical parameters of the system a nonlinear mapping is carried out from (δ-ε) plane to the (V_{dc}-V_{ac}) plane for a given forcing frequency Ω and fluid velocity u. Taking into account the nondimensional forcing frequency as $\Omega=10$, the stability margins of the micro-pipe for different values of the fluid velocity are plotted in Figure 5. In the absence of the *ac* component (horizontal axis), the static pull-in voltages of the system are stated on the figures.

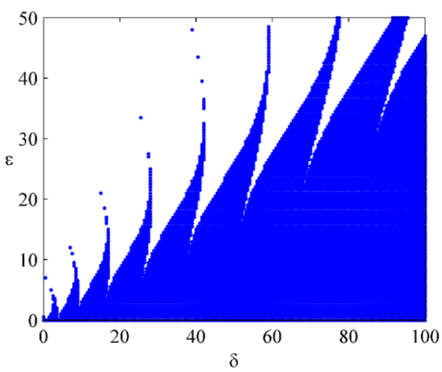


Figure 4. Stable (shaded) and unstable regions in the parametric plane (δ-ε).

It is found that the harmonic component (*ac* voltage) has a stabilizing effect and permits an increase of the bias (*dc*) component of the actuation voltage beyond the pull-in value. With due attention to the figure, one observes however that the stability can be attained only through the application of relatively high *ac* voltage comparable with *dc* component. In addition, it can be seen that the fluid velocity has a strong influence on the area of the stability regions (compare Figures 5a and 5b).

In order to study the influence of the forcing frequency on the stability margins of the micro-pipe, we increase the nondimensional forcing frequency to $\Omega=15$ and plotted the transition curves in (V_{dc}-V_{ac}) plane 'Figure 6'. Comparison of the shaded areas beyond the static pull-in value in Figures 5 and 6, one observes that this influence more pronounced and leads to the extension of the stability areas.

The region of stability of the micro-pipe in terms of the dimensional fluid velocity U and harmonic voltage V_{ac} is shown in Figure 7. Stability regions for dimensionless forcing frequency Ω=10 and different static pull-in voltages, namely $V_{dc}=14.06$ and *5.40 volt*, are depicted in Figures 7a and 7b, respectively. These pull-in voltages are related to fluid velocities 73.84*m/s* and 147.68*m/s* (dimensionless fluid velocities 3 and 6), respectively.

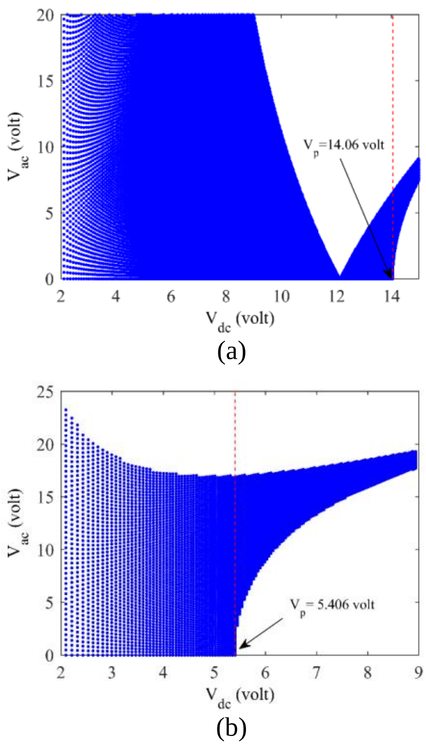


Figure 5. Stable (shaded) and unstable regions of the system in the plane of physical parameters (V_{dc}-V_{ac}) for excitation frequency Ω=10, (a) $u=3$, (b) $u=6$.

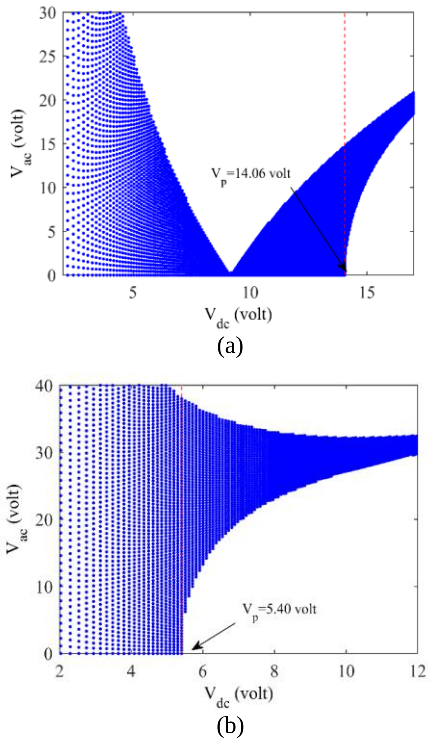


Figure 6. Stable (shaded) and unstable regions of the system in the plane of physical parameters (V_{dc}-V_{ac}) for excitation frequency Ω=15, (a) *u=3*, (b) *u=6*.

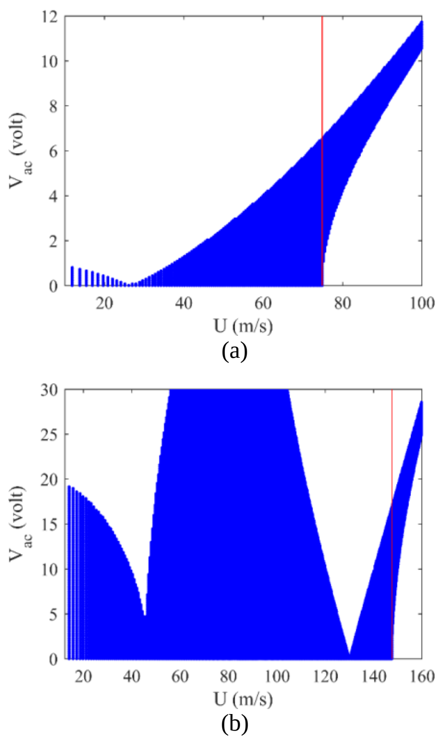
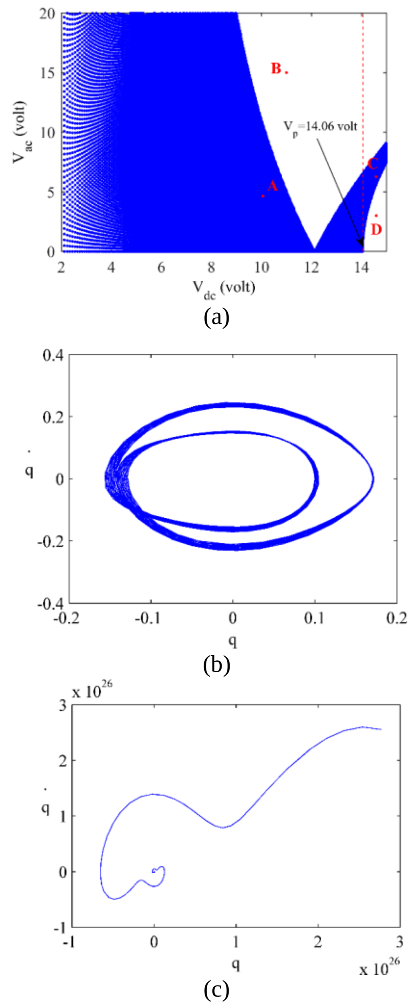


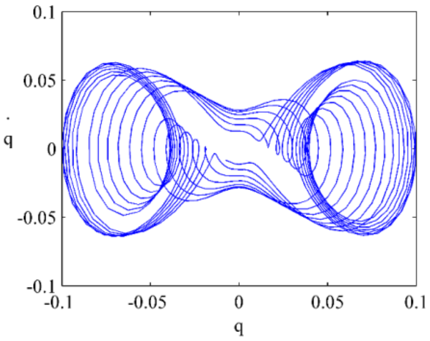
Figure 7. Stable (shaded) and unstable regions of the system in the plane of physical parameters (U-V_{ac}) for excitation frequency Ω=10, (a) V_{dc} *=14.06*, (b) V_{dc} *=5.40 volt*

Figure 7b shows that, due to increased forcing amplitude V_{ac} the stable fluid velocity increases and could be higher than the static critical fluid velocity (compare Figures 3 and 7b). In addition, it is revealed that the stable higher fluid velocity requires higher *ac* amplitude.

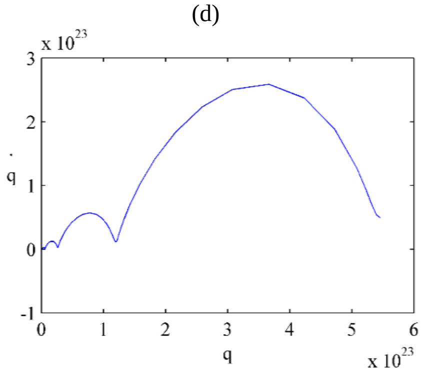
In order to check the correctness of the obtained stability margins, direct numerical integration method is employed to extract the phase portrait corresponding to specific points on the stable and unstable regions. Another goal of the numerical analysis is to check the effects of the higher modes, which was neglected in driving the Mathieu type Equation (10).

Figure 5a is repeated here where some points are specified on the stable and unstable regions 'Figure 8a'. Namely, points A and C are located in stable region and B and D are in the unstable region. Figure 8b shows a bounded phase portrait corresponding to point A located in the stable region. The phase plot related to unstable point B for V_{dc}=11 and V_{ac}= 15 is shown in Figure 8c. The numerical result associated with stable point C for V_{dc}=14.59 and V_{ac}= 6.25 is depicted in Figure 8d.





(d)



(e)

Figure 8. Stable (shaded) and unstable regions of the micro-pipe for Ω=10 , u=3 and phase portraits corresponding to different points, a) stable and unstable regions b) Phase plot of point A (Vdc=10.06, Vac=4.63), c) Phase plot of point B (Vdc=11, Vac=15), d) Phase plot of point C (Vdc=14.59, Vac=6.25), e) Phase plot of point D (Vdc=14.6, Vac=3).

It should be noted that with the increase of V_{dc} beyond the pull-in value ($V_{dc}>V_{\text{pull-in}}$ = 14.06) the values of the *ac* voltages V_{ac} required for the stabilization increase as well. For this reason, time history corresponding to point D with low *ac* amplitude is unbounded 'Figure 8e'.

4. CONCLUSION

In the present work, we demonstrated the possibility of stabilization of electrostatically actuated micro-pipe conveying fluid using parametric excitation. Expansion of the nonlinear electrostatic forces around the equilibrium position leads to a parametric Mathieu type equation. The stability regions of the system in the physical parameters plane (u-V_{ac}) and (V_{dc}-V_{ac}) for different forcing frequency were built employing Floquet theory. It was shown a micro-pipe conveying fluid, which is subjected to symmetric actuation by steady *dc* and harmonic *ac* voltages, might remain stable under application of the *dc* voltages beyond the pull-in value. In order to stabilize the micro-pipe at the voltages higher than the pull-in value, relatively high amplitudes of the harmonic voltages are needed. It was found that the *ac* voltages might increase the critical fluid velocity. It is shown that, the critical pull-in voltage for the micro-pipe under certain excitation frequency Ω=10 and dimensionless flow velocity u=6 is 5.40 volt in which micro-pipe will collapse. However, by superimposing periodic (ac) voltage the micro-pipe remains stable beyond pull-in voltage (5.40 volt). The results revealed that the *ac* voltages increase with an increase of the forcing frequency. The obtained results could be used in the design of micro-pipes for measuring the operating fluid properties. Moreover, the effect of geometrical parameters and the gap between micro-pipe and electrodes might change the results which will be considered in the future studies.

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Stabilization of Electrostatically Actuated Micro-pipe Conveying Fluid Using Parametric Excitation

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چکیده

در این مقاله، پایداری یک میکرولوله حامل سیال در شرایط تحریک پارامتریک مورد بررسی قرار گرفته است. که این میکرولوله حامل سیال به صورت متقارن در بین دو الکترود از نوع تحریک الکتروستاتیک قرار دارد. این میکرولوله که تحت تحریک الکتروستاتیک قرار دارد، در شرایطی که ولتاژ تحریک بزرگتر از ولتاژ ناپایداری استاتیکی باشد، ناپایدار میگردد. با اضافه کردن ولتاژ متناوب به ولتاژ ثابت و با به کاربردن سری تیلور و روش گلرکین، معادله حاکم بر سیستم که به فرم معادله ماتیو میباشد، استخراج شده است. با استفاده از تئوری فلوکه و با تغییر پارامترهای تحریک سیستم نظیر اندازه ولتاژ ثابت و دامنه ولتاژ تناوبی منحنی های گذر و نواحی پایدار میکرولوله مشخص شده اند. بعلاوه منحنی های گذر و نواحی پایدار با تغییر سرعت سیال و دامنه ولتاژ هارمونیک نیز به دست آمده اند. . نتا یج نشان میدهند که با افزودن یک مولفه هارمونیک میتوان ولتاژ ناپایداری سیستم را افزایش داده و به مقدار بالاتر از ناپایداری استاتیکی نیز رساند. نتایج به دست آمده برای نقاط خاص به صورت عددی نیز حل شده و پایداری سیستم به صورت موردی بررسی شده است. به عنوان مثال در غیاب ولتاژ هارمونیک، اندازه ولتاژ ناپایداری سیستم به ازای سرعت های بحرانی ۳و ۶ به ترتیب ۱۴/۰۶و ۵/۴ ولت می باشد. در صورتیکه منحنی های گذر نشان می دهند که با افزودن مولفه هارمونیک به ولتاژ اعمالی با فرکانس تحریک Ω=10، ولتاز ناپایداری را می توان به اندازه قابل توجهی افزایش داد. علاوه بر این، نتایج نشان می دهند که سرعتهای بحرانی ۳و۶ نیز به ازای ولتاژهای ناپایداری متناظر، با اعمال ولتاژ هارمونیک افزایش می یابند. تمامی این نتایج به تفصیل در متن مقاله در قسمت نتایج توضیح داده شده اند.

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