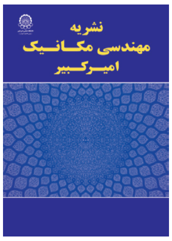

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Dynamic Behavior of a Micro-Beam Subjected to Voltage and Fluid Flow as a Micro Vortex Generator

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ABSTRACT: The present work investigated the nonlinear vibration of a cantilever cylindrical micro-beam subjected to voltage and fluid flow as a micro vortex generator. As the microbeam is subjected to the fluid with a given velocity, in addition to the load due to fluid added mass, the lift and drag forces as the two basic flow-induced factors affecting the dynamics of the micro-beam were modeled using Van der pol equation. The Euler-Bernoulli beam theory was used to model the cross fluid motion of beam under nonlinear electrostatic force as a result of the applied voltage. The Galerkin method was used to convert the partial differential equation to regular differential equations as well as to solve the coupled nonlinear equations governing the micro-beam motion and the wake oscillation to evaluate the response of the coupled structure to a combined applied voltage and fluid flow. The effect of fluid flow on the Reynolds number and fluid vortex frequency as two main parameters in the creation of the Lock-in phenomenon was studied. In addition to the effect of different fluid velocities, the response of the micro-beam to different input voltages in the presence of fluid flow was investigated and it was shown that for a given flowing fluid, the applied voltage can be used to control the lock-in regime.

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1- Introduction

Today the electrostatic force is highly used as an actuating force in different micro electromechanical systems due to its simple mechanism, high efficiency, reliability and less energy consumption [1].

Most researches dealing with fluid-structure interaction in micro-scale have studied the vibration of micro-structures immersed in the stationary fluid. Golzar et al. [2] studied dynamical behavior and instability of electrostatically actuated micro-beam in the incompressible viscous fluid cavity. Up to now, only a few studies investigated the effect of fluid flow on micro-structures, considering the physical characteristics of the vortex phenomenon. The only research regarding fluid flow effect on vibrational behavior of micro-structure is conducted by Rezaee and Sharafkhani [3] in which the dynamic behavior of cylindrical micro-beams as micro-energy-harvester under the simultaneous influence of the voltage and fluid flow is investigated.

In this paper, the dynamic behavior and vibrational characteristics of a micro-vortex generator are studied, and governing equations are solved using numerical methods helping MATLAB software.

2- Methodology

As illustrated in Fig. 1, when a cylindrical micro-beam with density of ρ and a diameter of D immersed in fluid with given constant velocity of U and kinetic viscosity of υ, vortex phenomenon could be happened under certain conditions influenced by the Reynolds number, $Re = UD/\upsilon$.

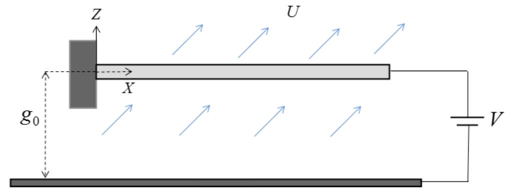

Fig. 1. A side view of a micro vortex generator subjected to fluid flow and voltage

Accordingly, in addition to the inertia force caused by still fluid, lift force [4] with frequency same as the frequency of vortex, $\omega_{vor} = 2\pi U_{rel} St/D$ [4, 5], and drag force with frequency twice of the vortex frequency will be created. The equation of motion for the lateral oscillations, w, of the cantilever Euler-Bernoulli cylindrical micro-beam with a cross-section area of A, subjected to the electrostatic force, f_e and fluid with a density of ρ_f is:

$$(EI)w_{xxxx} + \rho A\left(1+\frac{\rho_f}{\rho}\right)w_{tt} + \left[\frac{1}{2}\rho_f C_D D U_{rel}\right]w_t = f_e + \left(\frac{1}{4}\rho_f C_{l_0} D U_{rel} U\right)Q \quad (1)$$

Where C_{l_0} and C_D are lift and drag force constants respectively, and Q will be obtained from the Van der Pol equation:

$$\frac{\partial^2 Q}{\partial t^2} + \eta\omega_{vor}\left(Q^2 - 1\right)\frac{\partial Q}{\partial t} + \omega_{vor}^2 Q = \frac{P}{D}\frac{\partial^2 w}{\partial t^2}, \quad (2)$$

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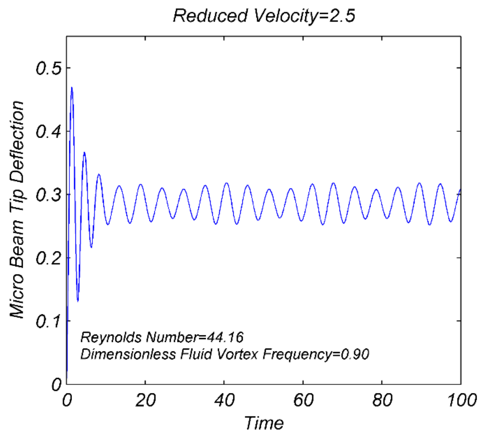
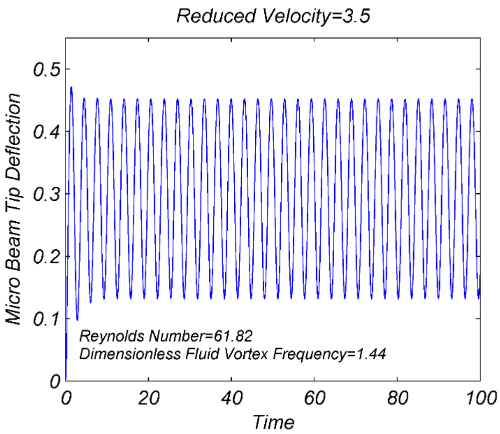
P and η are vortex phenomenon constants [4].
To convert the partial differential equation to a regular differential equation, the Galerkin's weighted residual method is used.

3- Results and Discussion

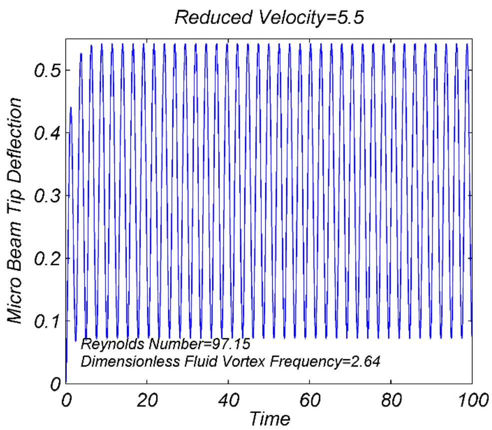
When fluid with Reynolds numbers between 40 and 300 encounters the micro-structure, with regards to high resulted pressure at the edge, fluid particles are led to the sides and there appears a phenomenon which is known as vortex channel.
Fig. 2 depicts the micro-beam vibration response under the given voltage, $\hat{V} = 3.8$, and fluid flow with four different velocities.



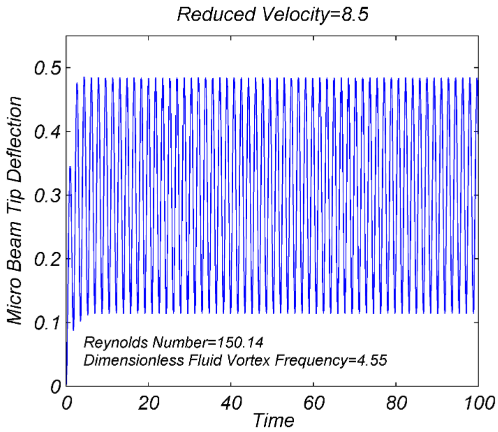
(a)



(b)



(c)



(d)

Fig. 2. Comparison of micro-beam vibration response under given voltage, $\hat{V} = 3.8$, and fluid with different velocities: (a) $\hat{U} = 2.5$ (b) $\hat{U} = 3.5$ (c) $\hat{U} = 5.5$ (d) $\hat{U} = 8.5$

As the applied voltage is constant, the structure fundamental frequency does not change, yet with increasing the fluid velocity, the fluid vortex frequency and the Reynolds number increase. As shown in Fig. 2, by increasing the fluid flow velocity from $\hat{U} = 2.5$ to $\hat{U} = 5.5$, the micro-beam vibration amplitude increases gradually and then decreases for $\hat{U} = 8.5$.
Fig. 3 illustrates diagrams of dimensionless micro-beam dynamic amplitude, $(\hat{W}_{max} - \hat{W}_{min})/2$, against the fluid velocity. As it is shown, by increasing the fluid reduced velocity up to that corresponding to the peak point, the dynamic amplitude will increase constantly. In other words, the lock-in phenomenon occurs when the structure vibration and the wake oscillation are in-phase and could reinforce each other in terms of amplitude. Differences in peak points are caused by the fact that as the voltage increases the fundamental frequency of the structure decreases, and as a result, the lock-in phenomenon occurs at lower velocities.

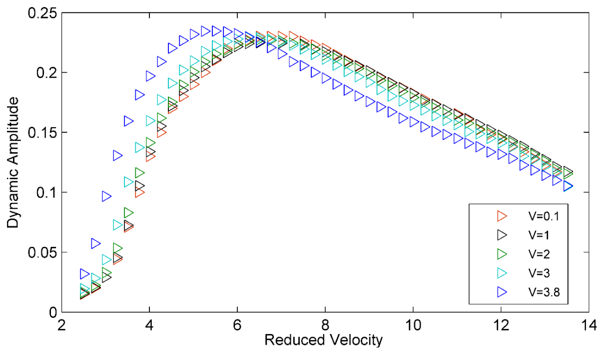


Fig. 3. Effect of the fluid reduced velocity on the dynamic amplitude of the micro-beam subjected to dc voltage

Beyond the peak point, by increasing the fluid reduced velocity, due to the receding of the structure frequency and the frequency of the fluid vortex from each other and thus, receding from the lock-in zone, the amplitude starts decreasing. The mentioned behavior is completely like the experimental results obtained in the references [4, 6].

4- Conclusions

In this study, for the first time, the governing equations of the micro-beam motion as a micro vortex generator under voltage considering fluid flow effect including drag and lift forces were derived using Van der Pol equation, Hamilton's principle, and Euler-Bernoulli beam theory. The coupled equations were solved helping numerical methods and the following results were obtained:

Under specific conditions related to fluid and structure characteristics, fluid flow can affect the micro-beam vibration. If the structure fundamental frequency is higher than the fluid vortex frequency, by increasing the fluid flow velocity which increases the vortex frequency and the Reynolds number, the micro-beam vibration amplitude will increase gradually and then decrease after reaching the peak point. The variable peak point and the proportional velocity is a function of fluid and structure characteristics.

The indicated increase of the amplitude and the followed reduction is due to the lock-in phenomenon which is the result of approaching or receding the fluid vortex frequency and the structure fundamental frequency. In other words, the lock-in phenomenon occurs when the structure vibration and the wake oscillation could reinforce each other.

By fixing the fluid flow, applying voltage may result in amplitude variation. The applied voltage, in addition to its main role as an applied external force, by changing the electrical stiffness, changes the fundamental frequency of the structure. Therefore, voltage as a regulating parameter can be used for occurring or receding from the lock-in phenomenon. Determination of the fluid characteristics in micro electro-mechanical systems is important as with fixing them, the accuracy of the applied voltage effect can be tuned by choosing the suitable structure geometrical features as well as proportional vibrational frequency.

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