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Investigation on fluid induced vibration of the flexible robot arm

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Abstract. In this paper the vibration of robot arm induced by fluid flow is investigated. Considering the flexibility of robot arm and the force of around fluid, the equation of motion is obtained using the Euler-Bernoulli beam theory. The force on the arm by the fluid is applied by coupled-motion model. After extracting the differential equations, the effect of system parameters such as geometrical and mechanical characteristic of arm, the effect of fluid velocity on the dynamic response of the arm are investigated. Results show that by increasing the velocity of the fluid, the inertial forces of fluid increase and thus are not negligible. This case leads to suddenly increase in the vibration and results in weak performance of the system in the case of high velocity and in locked-in zone. Therefore, by identifying the locked-in zone, the parameters of system should be chosen in a way that the arm not to be in the locked-in zone.

Key words. Robot arm, Fluid induced vibration, locked-in phenomenon.

1. Introduction

The fluid around any structure can be very effective in dynamic characteristics and vibration condition of the structure. The drag and lift forces of the fluid flow stimulates the body and leads to its obligatory vibration that have considerable effect on its performance.

Investigations on the vibrations caused by fluid vortices dates back to ancient time. In this field, the review studies have been done by some researchers like [1] Bearman, [2] Horowitz and Williamson, and [3] Williamson et al. that useful information can be obtained from them. Mittal and Prasanth [4] by applying the finite element method simulated the vibration caused by fluid flow on cylinder. The vibration caused by vortex can be the main resource of structures fatigue and damage in many of engineering structures especially in marine risers [5], heaters heat exchange tubes [6–8], robot arm, and etc. Pontes et al. [9] studied the vibration caused by fluid flow over a cylinder and with different mass relations. In [10] investigated the

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FIV for structures of different geometry and categorized this phenomenon through their vibration patterns.

2. Extracting the equation of motion

The geometry of robot arm affected by transverse load is illustrated in Fig. 1. The force element diagram of robot arm with the length of dx is presented in Fig. 1 in which $M(x,t)$ isthe bending moment, $V(x,t)$ is the shear force, and $f(x,t)$ is the external force applied on length unit of robot arm.

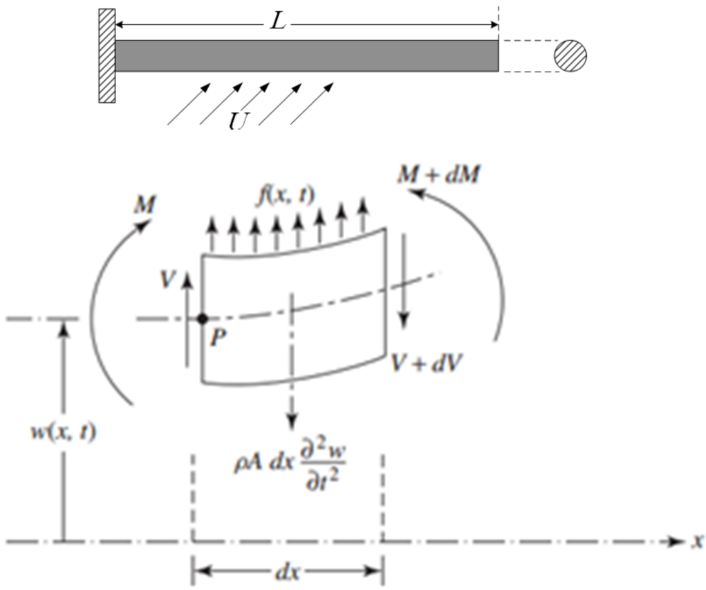

Fig. 1. The robot arm with circular cross-section affected by external fluid

Applying the Newton's second rule of mechanics and using the free body diagram of Fig. 1, the motion equation of robot arm caused by external forces reads:

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + \rho A\frac{\partial^2 w(x,t)}{\partial t^2} = f(x,t)\,, \tag{1}$$

where ρA is the mass per length unit and EI is the flexural rigidity of the robot arm.

2.1. Modeling of fluid flow effects

In the present work the model developed by Facchinetti et al. [11] is used for mutual effect of fluid flow force on the structure under study. In this model, the nonlinear Van der Pol equation is used for simulating the fluidic oscillator as follows:

$$\frac{\partial^2 \bar{q}(x,t)}{\partial t^2} + \delta\omega_{\mathrm{s}}\left[\bar{q}(x,t)^2 - 1\right]\frac{\partial \bar{q}(x,t)}{\partial t} + \omega_{\mathrm{s}}^2\bar{q}(x,t) = F_d\,, \tag{2}$$

where F_d is the fluid flow force on the structure and δ is a constant with value of 0.3 [11].Symbol ω_{s} is the vortex shedding frequency that depends on the fluid velocity and Strouhal number S_{t}.

$$\omega_{\mathrm{s}} = 2\pi S_{\mathrm{t}}\frac{U_{\mathrm{e}}}{D}\,. \tag{3}$$

Considering the theory of Facchinetti et al. [11], the best equation which defines these forces and has acceptable compatibility with experimental results is

$$F_d = \frac{P}{D}\frac{\partial^2 w(x,t)}{\partial t^2}\,. \tag{4}$$

By fitting the experimental and numerical data, $p = 12$ is obtained.

In equation (1), $f(x,t)$ is the resultant external forces acting on the robot arm which generally can be divided to lift force $f_{\mathrm{L}}(x,t)$ and the camping force of the vortex $f_{\mathrm{D}}(x,t)$. Considering the studies of Facchinetti at al. [11], these forces are as follows:

$$f(x,t) = f_{\mathrm{L}}(x,t) + f_{\mathrm{D}}(x,t) = \frac{1}{4}C_{\mathrm{L}}\rho_f DU_{\mathrm{e}}^2\bar{q}(x,t) - \frac{1}{2}C_{\mathrm{D}}\rho_{\mathrm{f}}DU_{\mathrm{e}}\frac{\partial w(x,t)}{\partial t}\,, \tag{5}$$

where C_{D} is the damping coefficient and the ρ_{f} is the specific mass of fluid.

2.2. The equation of motion of robot arm effected by fluid force

Considering eqs. (1), (2), (4) and (5), the equation of motion of flexible robot arm caused by fluid force reads

$$EI\frac{\partial^4 w(x,t)}{\partial t^4} + \rho A\frac{\partial^2 w(x,t)}{\partial t^2} = f(x,t) = \frac{1}{4}C_{\mathrm{L}}\rho_{\mathrm{f}} DU_{\mathrm{e}}^2\bar{q}(x,t) - \frac{1}{2}C_{\mathrm{D}}\rho_{\mathrm{f}}DU_{\mathrm{e}}\frac{\partial w(x,t)}{\partial t}\,, \tag{6}$$

$$\frac{\partial^2 \bar{q}(x,t)}{\partial t^2} + \delta\omega_{\mathrm{s}}\left[\bar{q}(x,t)^2 - 1\right]\frac{\partial \bar{q}(x,t)}{\partial t} + \omega_{\mathrm{s}}^2\bar{q}(x,t) = \frac{P}{D}\frac{\partial^2 w(x,t)}{\partial t^2}. \tag{7}$$

The dimensionless forms of eqs. (6) and (7) based on the variables read

$$\frac{\partial^4 \bar{\eta}}{\partial \xi^4} + \frac{\partial^2 \bar{\eta}}{\partial \tau^2} = \alpha_0 u^2 q - c_0 u\frac{\partial \bar{\eta}}{\partial \tau}\,, \tag{8}$$

$$\frac{\partial^2 \bar{q}}{\partial \tau^2} + \lambda\Omega_{0\mathrm{s}}u(\bar{q}^2 - 1)\frac{\partial \bar{q}}{\partial \tau} + \Omega_{0\mathrm{s}}^2 u^2\bar{q} = P\frac{\partial^2 \bar{\eta}}{\partial \tau^2}\,. \tag{9}$$

For solving nonlinear equations (8) and (9), the Galerkin method is used. Based on this method, the answer of nonlinear differential equations is considered as follows:

$$\bar{\eta}(\xi,\tau) = \sum_{i=1}^{N} \eta_i(\xi) p_i(\tau)\,, \tag{10}$$

$$\bar{q}(\xi,\tau) = \sum_{i=1}^{N} \eta_i(\xi) q_i(\tau)\,, \tag{11}$$

in which $\eta_i(\xi)$ are functions of vibration moods of robot arm with one end clamped—one end free backrest. The time part functions $p_i(\tau)$ and $q_i(\tau)$ are passive time functions that must be determined. In present research the functions of vibration mode are considered as follows:

$$\eta_i(\xi) = \cosh(\beta_i\xi) - \cos(\beta_i\xi) - \alpha_i\left[\sinh(\beta_i\xi) - \sin(\beta_i\xi)\right], \quad i = 1, 2, ..., N\,, \tag{12}$$

$$\alpha_i = \frac{\cosh(\beta_i) + \cos(\beta_i)}{\sinh(\beta_i\xi) + \sin(\beta_i)}\,, \tag{13}$$

in which β_i is the natural frequency of robot arm which can be obtained from equation

$$\cos\beta + \cosh\beta = 1\,. \tag{14}$$

By substituting eqs. (10) and (11) in Eqs. (8) and (9) and crossing each side in $\eta_i(\xi)$ term, then integrating from 0 to 1, the differential equations with normal derivatives will be obtained based on time related to variables $p_i(\tau)$ and $q_i(\tau)$.

3. Effect of fluid velocity

In this section the effect of velocity of fluid on amplitude of vibration of end point of robot arm will be investigated. In Figs. 2 and 3, the time response of end point and phase curves (the velocity based on amplitude of vibration of end point of robot arm) of robot arm are indicated for different values of dimensionless velocity of fluid. By attention to Fig. 2 it can be seen that in absence of external fluid flow the response of system in vibration form with dimensionless fixed amplitude is 1.2×10^{-3}.

As is illustrated in Fig. 2b, at low velocities of fluid the flow around the arm leads to decrease in the amplitude of vibration with time and in velocity $u = 0.01$ the dimensionless amplitude of vibration is converged with amount of 0.2×10^{-3}. By increasing the velocity of flow and, consequently, Reynolds number, the vortex zone behind the robot is developed. In this case, the drag force has dominant effect on total resistance force and arm vibrations. Therefore, in the zones with low velocities, this force causes to the amplitude of vibration be damped. By more increase of the velocity of the fluid, the inertia force increases and is not negligible any more. This causes to a sharp increase in the amplitude of vibration and then a steady vibration for high velocities. As it can be seen, the dimensionless amplitude of steady vibration is 210×10^{-3} that is more than the case of free vibration. As it can be seen from the results, the vibration amplitude of steady state for locked-in zone is more than

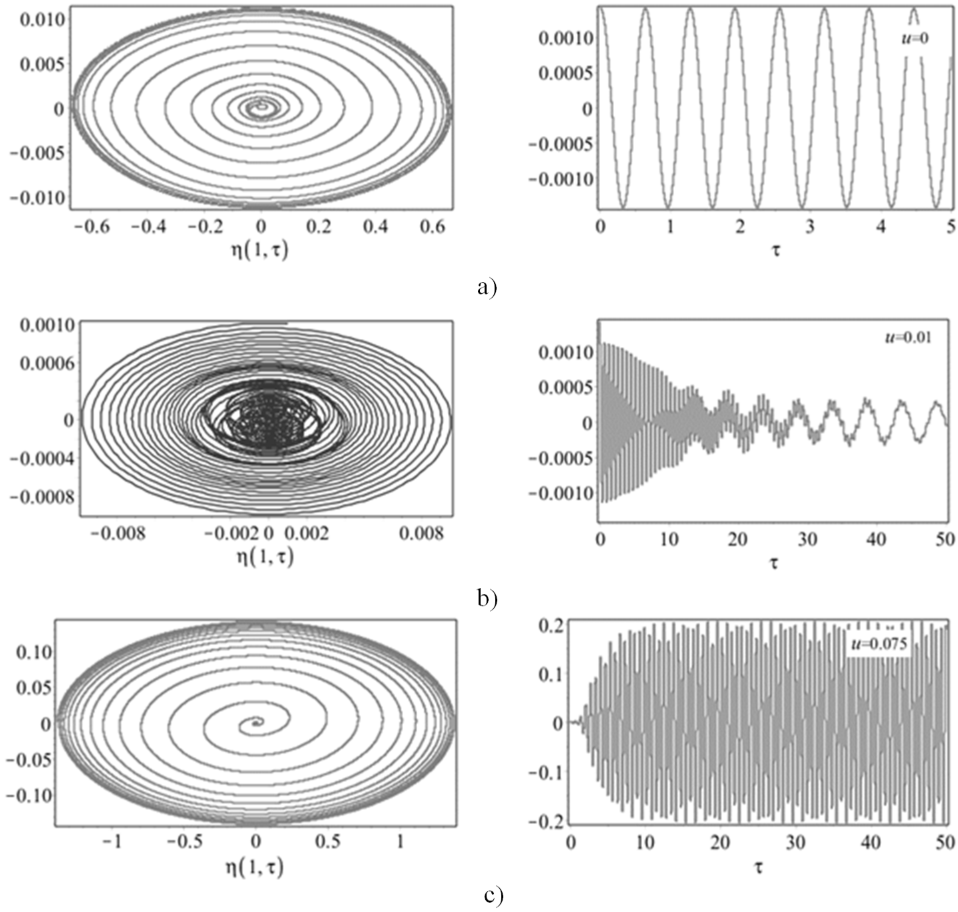

Fig. 2. The effect of velocity of fluid on motion of end point and phase curve of robot arm for a)–$u = 0$, b)–$u = 0.01$, and c)–$u = 0.075$

other two zones.

By more increase of the fluid velocity the amplitude of vibration of robot arm decreases. For sufficiently highly velocities, the flow of fluid acts as a damping factor and thus the amplitude of vibrations tends to zero (see Fig. 3b for velocity $u = 0.25$). This behavior of the system can be seen by attention to Fig. 2 in which the maximum amplitude of vibrations of end point of robot arm is shown based on the flow velocity of external fluid.

In Fig. 4 the effect of λ on the maximum amplitude of vibration is shown based on the velocity of fluid. The results pertain to three different amount of $\lambda = 0.1$, $\lambda = 0.3$ and $\lambda = 0.5$. As can be seen, the vibration amplitude decreases with increasing of λ, but it is often insensible to the velocity of fluid. The maximum amplitude of vibration of robot arm occurs around the dimensionless velocity of $u = 0.099$ and its amounts for $\lambda = 0.1$, $\lambda = 0.3$ and $\lambda = 0.5$ are 0.35, 0.25, and 0.22, respectively.

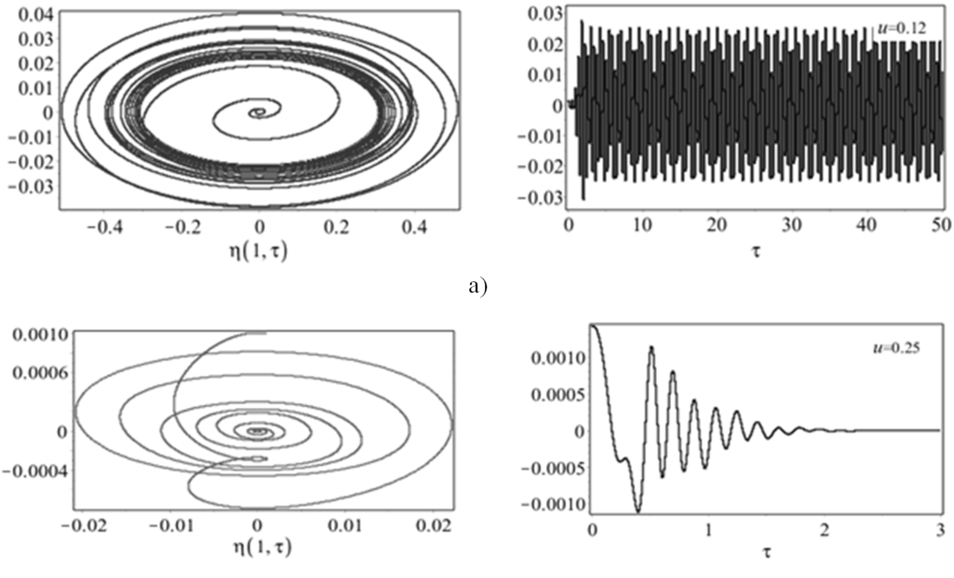

Fig. 3. The effect of velocity of fluid on motion of end point and phase curve of robot arm for a)–$u = 0.12$, b)–$u = 0.25$

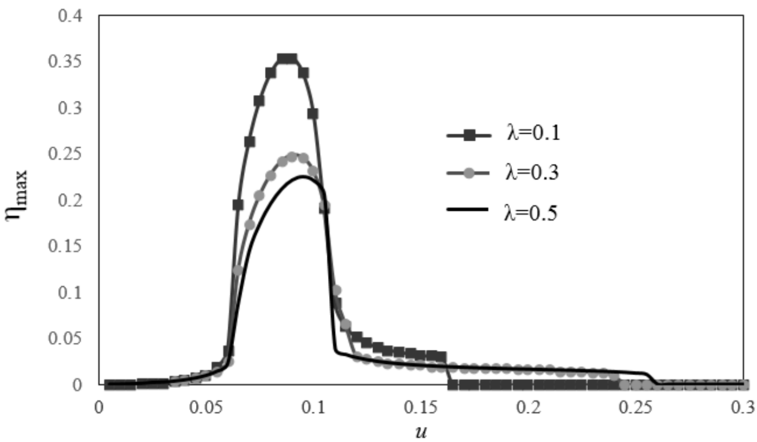

Fig. 4. The effect of λ on maximum amplitude

4. Conclusion

In this paper considering the flexibility of a robot arm, the fluid induced vibration of robot arm is investigated. Considering all the external fluid flow forces, the vibration equation of robot arm was extracted based on the Euler–Bernoulli theory. Then, the resulting differential equations were solved by Galerkin method. Some results of the present research can be listed as below:

- In the absence of external fluid flow the system oscillates with constant dimensionless amplitude of 1.2×10^{-3}. In this condition the effects of inertia are small and negligible and only the added mass caused by the surrounding stagnant fluid affects the system which leads to decrease in its natural frequency.

- By increasing λ, the amplitude of vibration of robot arm decreases but no sensible change is seen in fluid velocity corresponding to the maximum amplitude. The maximum amplitude of vibration of robot arm occurs around the dimensionless velocity $u = 0.09$ and its value for $\lambda = 0.1$, 0.3 and 0.5 are respectively 0.35, 0.25 and 0.22.

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