Semi-Analytical Study of Fluid-Induced Nonlinear Vibrations in Viscoelastic Beams with Standard Linear Solid Model Using Multiple Time Scales Method

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ABSTRACT

In this research, the behavior of nonlinear vibrations of the viscoelastic Euler-Bernoulli beam under the influence of external fluid flow has been studied. The governing equations of motion are obtained by assuming Von-Karman nonlinear strain-displacement relations and considering the interaction between structure and fluid. To consider more realistic hypotheses, contrary to previous researches, the effect of viscoelastic behavior has been evaluated using a more complete and practical model called the Standard linear solid model. After non-dimensionalizing the motion equations, the governing nonlinear differential equations are discretized using the Galerkin method. Then, the system's analytical response is acquired through the method of Multiple Time Scales. After verifying the results and confirming the semi-analytical method's accuracy with the numerical solution results, different parameters' effect on the system's dynamic behavior has been analyzed. The results indicate that the viscoelastic behavior and the nonlinear model significantly affect the lock-in area and the maximum amplitude of the viscoelastic beam vibrations. In most studies on viscoelastic beams' vibrations, the damping effect in nonlinear terms has been neglected. However, this study demonstrates that the effect of damping on terms related to the nonlinearity of strain fields is substantial.

KEYWORDS

Fluid-induced vibration, fluid flow, multiple time scales, standard linear solid, viscoelastic beam.

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Introduction

Flow-Induced vibration is a phenomenon that often occurs in tall and narrow structures that are exposed to transverse current. And it is one of the most substantial issues that can be seen in many industrial applications such as oil pipelines and risers, transmission lines, offshore platform bases, offshore turbine towers, etc. Therefore, it has been considered by many researchers. According to extensive scientific research in this field, these systems' vibrational and dynamic behavior has not yet been fully and ultimately revealed, and research in this field is still ongoing [1]. In recent years, the behavior of transverse vibrations of beams and their stability, from various aspects such as linear behavior [2], nonlinear [3], control [4], has been considered by many researchers. Using the Kelvin-Voigt model, Ghayesh et al. [5] investigated the dynamic nonlinear behavior of viscoelastic beams with simple supports at both ends. Their studies show that the system's dynamic response depends on parameters such as mass position, dimensionless mass ratio, and viscoelasticity parameters.

A review of previous studies demonstrates that so far, no study has been fully conducted on the behavior of fluid-induced vibrations in viscoelastic beams. In addition, most studies in this field have been confined to using numerical or elemental methods.

Methods

In the present study, utilizing the semi-analytical method and considering the nonlinear coupled model of structure-fluid interaction with Van der pol Nonlinear Differential Equation, the behavior of fluid-induced vibrations in viscoelastic beams with simple supports at both ends will be studied. In order to consider more realistic and practical conditions, the viscoelastic behavior of the materials is modeled employing a more accurate model (Standard linear solid model). By extracting the nonlinear equations governing such systems, the nonlinear behavior and the effects of the parameters affecting the vibrational characteristics of these systems will be studied. After discretizing the governing nonlinear differential equations using the Galerkin method, the equations are then solved using the multiple time scale method, and the results are extracted.

The Standard Linear Solid model is a three-parameter model (E_1, E_2, η) that predicts the behavior of many viscoelastic materials such as polymers and metals at high temperatures with great accuracy (Figure 1) [6]:

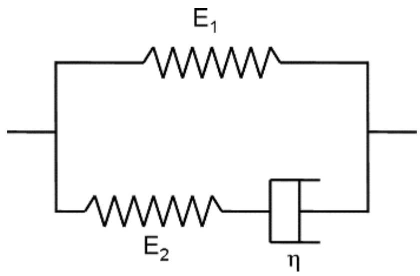

Figure 1. Standard Linear Solid model

In the present study, as shown in Figure 2, the Euler-Bernoulli beam with a circular cross-section with simple supports at both ends and under the influence of external fluid flow at a constant speed is investigated.

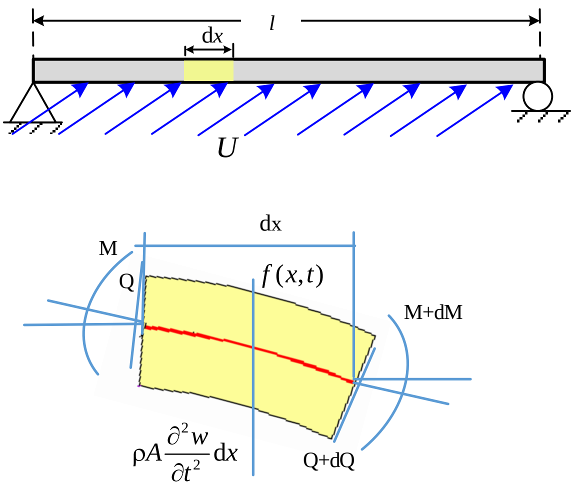

Figure 2. Simply supported viscoelastic beam under the influence of external fluid and a section of the beam

Concerning the transverse vibrations of the beam and the negation of the longitudinal and transverse motion of the beam, Von-Karman nonlinear strain-displacement relations are as follows:

$$\varepsilon_x = -z\frac{\partial^2 w}{\partial x^2} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 \quad (1)$$

where $w = w(x,t)$ is the deflection of any point on the beam and z is the distance from the neutral axis.

Results and discussion

In this section, the analytical solution results presented to study the behavior of nonlinear vibrations of viscoelastic beams under the flow of external fluid are presented. According to Figure 3, it can be seen that at low fluid velocities, the system response is vibrating with a constant amplitude. As the fluid velocity increases, the fluid flow around the beam is very slow or creepy. As the fluid around the beam flows, the Von-Karmen vortices are created symmetrically by negative pressure behind the beam, causing lift and drag forces on the beam, resulting in beam vibrations.

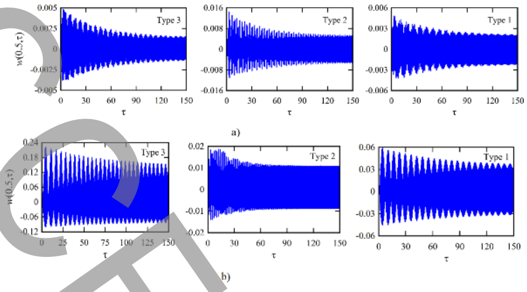

Figure 3. Time-response curves of viscoelastic beams for different fluid flow velocities a) $u = 0.5$ **b)** $u = 1$

Figure 4 illustrates the wavelet transform curves of the time responses shown in Figure 3. Another interesting result that can be seen is that fluid velocity also affects the frequency of system vibrations. Due to the effects of added mass due to the presence of external fluid flow, at low fluid velocities, the vibration frequencies of the system decrease, and then at higher velocities due to the formation of vortices, the vibration frequency increases.

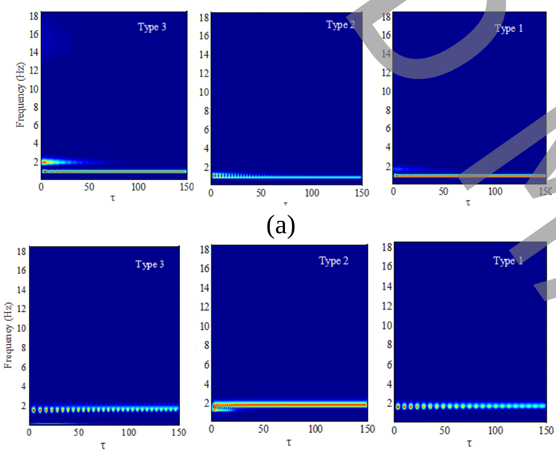

Figure 4. Wavelet transform of viscoelastic beam for different fluid flow velocity a) $u = 0.5$ **b)** $u = 1$

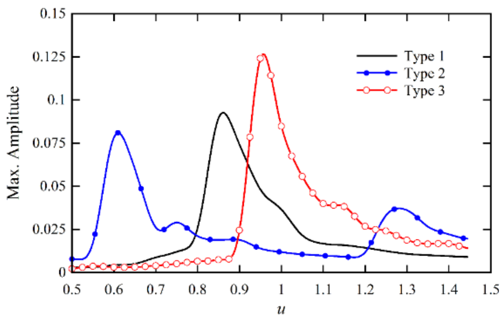

Figure 5. Maximum amplitude of vibration of a viscoelastic beam's midpoint in terms of external fluid flow velocity

As can be seen from the results shown in Figure 5, the amplitude of steady-state vibrations in the lock-in zone is greater than for the other two regions.

Conclusion

Based on the results of the present study, a summary of the important results can be expressed as follows:

At low fluid velocities, the only effect is the added mass due to the fluid, which reduces the beam's natural frequency.

- For low values of viscoelastic coefficients, the amplitude of vibrations increases with time first and then decreases and converges to a certain value, and the system response is vibrating, but the beam with high viscoelastic coefficients shows different behavior.

- The viscoelastic behavior and the nonlinear model have a significant effect on the lock-in area as well as the maximum amplitude of the viscoelastic beam vibrations.

The results of this study show that the effect of damping on terms stemmed from nonlinearity of strain fields is significant and these effects must be considered in deriving the equations of motion governing the vibrational behavior of viscoelastic structures.

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