Stabilization control for self-excited oscillation of cantilevered fluid-conveying pipe

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Summary. Fluid-conveying pipe has been studied widely for several decades. The energy transfer caused by flow is the main reason for the self-excited oscillation. In the paper, the variation of the dimensionless complex frequency of the two lowest modes of the cantilevered fluid-conveying pipe is theoretically derived with respect to the dimensionless flow velocity. Furthermore, some stabilization methods are proposed and the validity is experimentally examined.

Introduction

Flow-induced vibrations have been with us since time immemorial, in nature, but also in man-made facilities. An example of latter is versatile orchestral instruments and it seems that these vibrations are not always nuisance. However, in most instances, they are annoying or damaging to equipments and people. Among the flow-induced vibration problems, the fluid-conveying pipe is one of the most typical models.

Up till now, the vibration phenomena of fluid-conveying pipes have been studied for decades of years and the substantial theoretical approaches have been built. However, there are few stabilization methods that consider the nonorthogonality of the eigen modes which is the mathematical reason for the self-excited oscillation. In this presentation, an analytical model and the dimensionless equations of motion are introduced at first. Then the variation of dimensionless complex frequency with respect to the dimensionless fluid velocity is shown and the mathematical reason which causes the self-excited vibration is going to be discussed. In the end, some methods using feedback control are proposed.

Theoretical Analysis

Analytical Model and Dimensionless Equation of Motion

In this research, a cantilevered and uniform mass fluid-conveying pipe is taken into consideration. The fluid flowing through the pipe is incompressible and steady. As shown in Fig. 1, $v(s,t)$ represents the displacement of the flexible fluid-conveying pipe in y direction. The length, mass per unit length and bending stiffness of the pipe are l, m and EI, respectively. The mass per unit length of flow and fluid velocity are M and U.

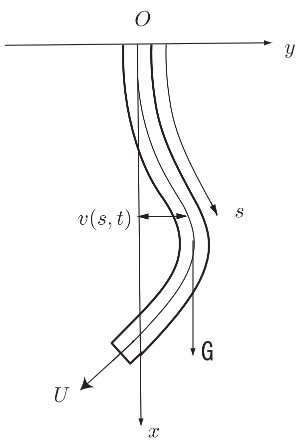

Figure 1: Analytical model of fluid-conveying pipe

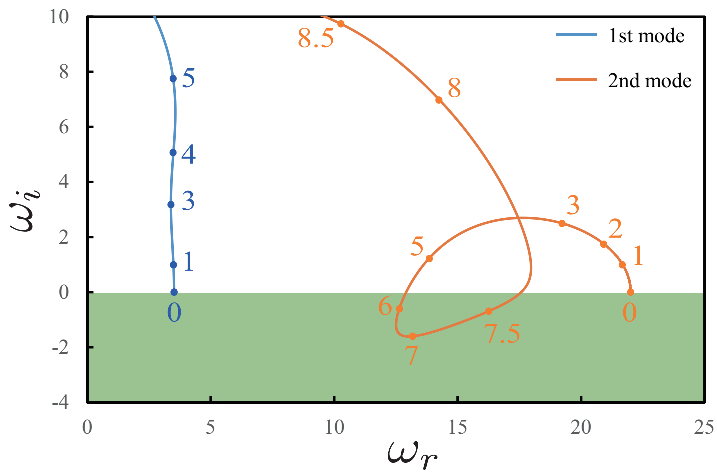

Figure 2: The complex frequency of the two lowest modes of the cantilevered pipe as a function of the dimensionless flow velocity, U ($\beta = 0.232, \gamma = 0$)

The dimensionless equation of motion can be obtained by the force balance for a tiny element of fluid and duct.

$$v'''' + U^2 v'' - \gamma[(1-s)v'' - v'] + 2\sqrt{\beta}U\dot{v}' + \ddot{v} - n(v^3) = 0,$$

where the dot and prime denote the derivative with respect to the dimensionless time and coordinate, respectively. v'''' is the shear force, $\gamma(1-s)v''$ represents the centrifugal force. The effect of gravity and Coriolis force are denoted by $\gamma[(1-s)v'' - v']$ and $2\sqrt{\beta}U\dot{v}'$, respectively. The dimensionless parameters are expressed using dimensional parameters as follows:

$$\beta = \frac{M}{m+M}\ ,\ \gamma = \frac{(m+M)gl^3}{EI}\ ,U^* = \sqrt{\frac{Ml^2}{EI}}U.$$

Also, the nonlinear term $n(v^3)$ is expressed as follows:

$$n(v^3) = v' \frac{\partial^2}{\partial t^2} \int_0^s \left(-\frac{1}{2}v'^2\right) ds - U\sqrt{\beta} v'^2 \dot{v}' - \frac{1}{2}U^2 v'^2 v'' + \frac{1}{2}v'^2 \ddot{v} - \left(\frac{3}{2}v''^3 + 3v'v''v''' + \frac{1}{2}v'^2 v''''\right)$$
$$- v'' \int_s^1 \left(\frac{\partial^2}{\partial t^2} \int_0^s \left(-\frac{1}{2}v'^2\right) ds + v'\ddot{v}\right) ds - \frac{1}{2}\gamma v'' \int_s^1 v'^2 ds + \frac{1}{2}v'^2 v'' \gamma(1-s)$$
$$+ \frac{1}{2}v''^2\Big|_{s=1} v''. \tag{1}$$

The Dimensionless Complex Frequency of The Two Lowest Modes

Expressing the mode shapes by using power series, the root locus of complex frequency of the two lowest modes as a function of the dimensionless flow velocity can be drawn out in Fig. 2[6]. It is clearly to see that ω_r and ω_i which denote the natural frequency and damping coefficient vary with the increase of dimensionless velocity U. In the second mode, when $\omega_i < 0$, in another word, the damping coefficient of fluid-conveying pipe is negative, the pipe is unstable and the self-excited oscillation occurs.

Stabilization Method

The experimental apparatus and signal flow is shown in Figs. 3 and 4. A piezoelectric actuator is attached to the upper end of the pipe and applies a bending moment proportional to the velocity of the pipe at the down end. The velocity is detected by the displacement sensor and is input into the DSP, in which the actuation signal is calculated according to the proposed feedback control. Then the output signal from DSP is amplified thorough a piezoelectric driver and applied to the piezoelectric actuator. In order to stabilize the self-excited oscillation based on the nonorthogonality, three different kinds of control methods, i.e., linear feedback control, nonlinear control, and linear plus nonlinear feedback control, are proposed to change the boundary condition. Finally, it has been verified that linear feedback control method can increase the critical fluid velocity and nonlinear feedback control method is able to decrease the flutter amplitude.

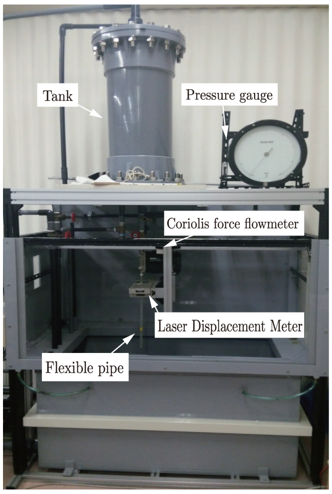

Figure 3: Experiment Apparatus

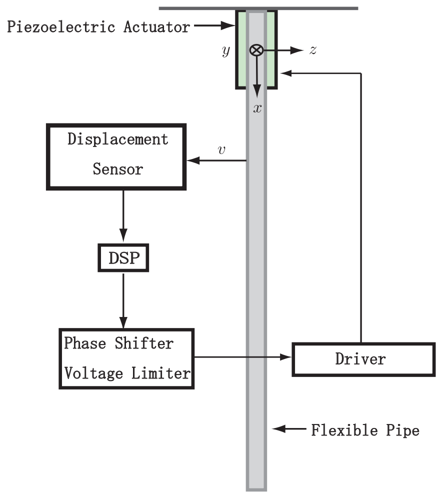

Figure 4: Feedback System

Conclusions

It is theoretically clarified that the self-excited oscillation is induced by the nonorthogonality of the eigen modes which means non-conservative system. To control the self-excited oscillation in a fluid-conveying, we propose some control methods and experimentally examine their validity

References

[1] Païdoussis, M. P., 1998, *Fluid-structure Interactions Slender Structures and Axial Flow*, Academic Press, Vol.1, pp. 531–537.

[2] Nayfeh, A. H., 1981, *Introduction to Perturbation Techniques*, Wiley-Interscience, pp. 388–412.

[3] Benjamin, T. B., 1961. “Dynamics of a System of Articulated Pipes Conveying Fluid. I. Theory,” Proceedings of the Royal Society(London), Vol.261, No.1307, pp. 457–486.

[4] Chen, S. S., 1972, “Vibration and Stability of a Curved Tube Coveying Fluid,” Journal of Acoustical Society of America, Vol.51, No.1, pp. 223–232.

[5] Yau, C. H., Bajaj, A. K., and Nwokah, O. D. I., 1995, “Active Control of Chaotic Vibration in a Flexible Pipe Conveying Fluid,” Journal of Fluids and Structures., Vol.9, pp. 99–122.

[6] Yamashita, K., Furuya, H., Yabuno, H., and Yoshizawa, M., August 2014, “Nonplanar vibration of a Vertical Fluid-Conveying Pipe,” Journal of Vibration and Acoustics, Vol. 136.