Experimental study on annular-flow-induced vibrations of a simply-supported tube in a finite-length loose gap support

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1. Introduction

Several methods to predict the dynamic behavior of a rod subjected to annular flow have been developed. These include the linearized potential flow theory based model by Mateescu, Paidoussis and Sim [1], and the pressure-loss model by Hobson [2] and Langthjem [3]. Recently, Kang, Mureithi and Pettigrew [4] proposed a theory based on the pressure-loss model with consideration of flow friction. They showed the critical flow velocity of a simply-supported cylinder could go down to a dimensionless velocity of 2.4. The basic dynamics due to annular flow are known by virtue of these models.

For heat exchanger tubes, the support causes highly confined annular flow with a divergent or convergent flow at the exit or the entrance of the support, which is due to chamfering of the support hole for manufacturing convenience.

Gorman, Goden, and Planchard [5] qualitatively reported that a finite-length diffuser caused a thimble tube in a pressurized water reactor to reach dynamic instability.

Yasuo and Paidoussis [6] tried to solve the flow-induced instability problem of heat exchanger tubes subjected to axial flow in a diffuser-shaped, loose intermediate support. They suggested critical flow velocity equations either for divergence or flutter. Application of this theory to practical problems is, however, limited because of the inaccurate prediction of the critical flow velocity for flutter.

The purpose of this study is to obtain experimentally the critical flow velocity of a cylinder subjected to annular flow in a finite-length narrow-gap support at the middle of the cylinder and to identify instability.

2. Experiment

2.1 Experimental setup

Experiments were conducted in a 2.5m long test section. A 2.2 m long and 15.9 mm diameter inner tube was used with a finite-length narrow-gap support having a length of 38.7 mm. The inner tube was supported by four pins at each end to simulate pinned-pinned boundary conditions. The gaps between the inner tube and supports were 0.29 mm, and the annular gap between the inner tube and outer plexiglass tube is 5.15 mm. A diffuser angle of 20° was provided at the downstream end of the support.

The test section with associated instrumentations is schematically shown in Fig. 1.

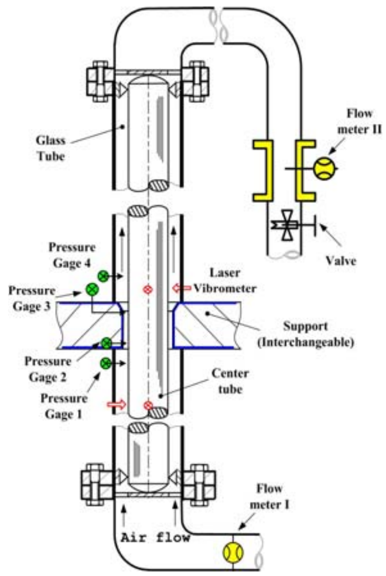


Figure 1 Schematic drawing of the test section and instruments

Fluid parameters and vibration characteristics of the inner cylinder are summarized in Table 1.

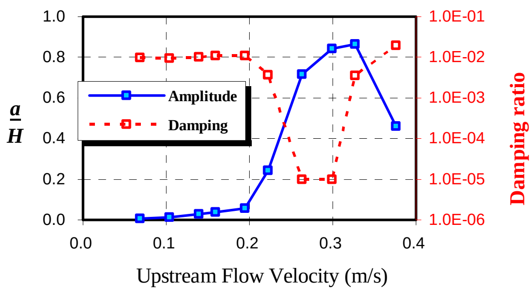
Table 1 Fluid parameter and vibration characteristic

Item	Dimension
Fluid	a. compressed air : 100 *psig* b. density: 8.5 kg/m^3
Hydraulic dia. (mm) at support (L/D_h)	16.51 support: 0.58 mm (50)
Hydraulic dia. (mm) at glass tube (L/D_h)	10.31 mm (203.6)
Natural frequency (Hz) without flow	1st natural frequency: 12.5 2nd natural frequency: 40.2

As seen in Fig. 1, vibration amplitudes are measured with four laser sensors in two directions near the support, at mid-span and at the one-fourth position along the test section. The measurement signals were acquired and analyzed using an Oros data acquisition system.

2.2 Experimental results and discussion

Fig. 2 shows the measured *rms* vibration amplitude and damping factor as a function of the upstream flow velocity. The vibration amplitude starts increasing rapidly from 0.2 m/s. At the same time, the damping ratio has decreased to nearly zero. Then, as the inner cylinder starts impacting the support, the amplitude decreases while the "effective" damping ratio increases.



Fi

gure 2 Vibration amplitude and damping ratio

Figure 3 shows X-Y plots of the cylinder motion at the support elevation. As the amplitude increases, whirling motions are clearly observed, which is believed to be a limit cycle. It is well known that a limit cycle is followed by flutter instability. Once impacting starts, the limit cycle disappears. When the cylinder contacts the support, the cylinder seems to vibrate in a one-dimensional motion. This is a very typical vibration behavior with increasing flow velocity.

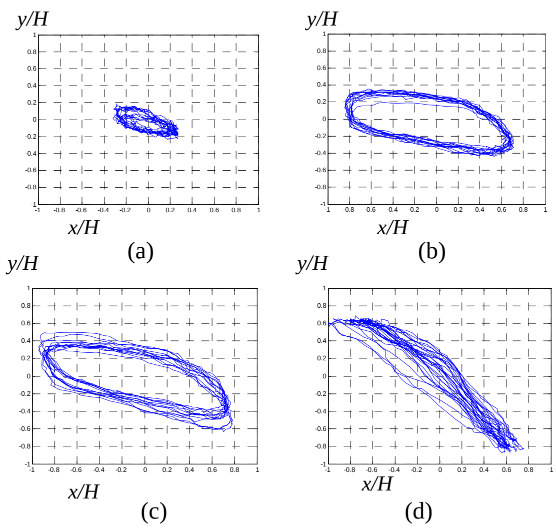


Figure 3 X-Y plots for the vibration of the inner cylinder. Velocity in m/s (Rey. No.): (a) 0.22 (1,682), (b) 0.26 (1,994), (c) 0.30 (2,262), (d) 0.38 (2,843)

The inner pinned-pinned cylinder loses its first mode stability at very low flow velocity. The instability is believed to be a dynamic instability. The reasons are:
(1) At a certain flow velocity where the vibration amplitude increases rapidly, the damping ratio starts decreasing drastically, which is shown in Figure 2.
(2) The critical flow velocity is too low to overwhelm the stiffness of the steel cylinder by negative fluid stiffness,
(3) Limit cycles are clearly observed above the critical flow velocity,

3. Conclusions

The stability behavior of a pinned-pinned flexible rod subjected to annular flow over a finite-length gap support has been experimentally studied. At significantly low air flow, flutter instability is observed. With annular flow, the simply supported cylinder is known to lose stability by divergence at very high flow velocity beyond practical engineering applications. Interestingly, a small support plays a significant role to change the dynamic behavior of the pinned-pinned rod, decreasing the critical flow velocities down to engineering flow velocities.

Further studies to unveil the basic mechanism behind the instability shown by this study are highly recommended for heat exchanger tubes with the tube support plates.

REFERENCES

[1] Mateescu, D., Paidoussis, M.P and Sim, W. G., 1988, Dynamics and Stability of a flexible cylinder in a narrow coaxial cylindrical duct, subjected to annular flow, *International Symposium on Flow-Induced Vibration and Noise*, ASME, Nov. 27-Dec. 2. 125-145 Chicago, Illinois.
[2] Hobson, D.E., 1982, Fluid-elastic instabilities caused by flow in an annulus, *Proceeding of BNES, 3rd international conference on vibration in nuclear plant*, 440-460. Keswick, U.K.
[3] Langthjem, M. A., Morita, H. Nakamura, T. and Nakano, M., 2006, A flexible rod in annular leakage flow: Influence of turbulence and equilibrium offset, and analysis of instability mechanism, *J. of Fluids and Structures*, **22** 617-645.
[4] Kang, H. S., Mureithi, W. N and Pettigrew, M. J., Analytical solution for a vibrating simply-supported cylinder subjected to 2-D concentric annular flow considering friction, *J. of Fluids and Structures (Accepted).*
[5] Gorman, D. J., Goden, J.L. and Planchard, J., 1987, Analytical and Experimental Study of the Vibratory Response of a Flexible Tube Subjected External Annular Flow, Part way along its Length, *Proceedings of International Conference on Flow-Induced Vibrations*, ed., R. King, Bowness-on-Windermere, U.K., 1987, pp. 339-347.
[6] Yasuo, A. and Paidoussis, M. P., 1989, Flow-Induced Instability of Heat-Exchanger Tubes due to Axial flow in a Diffuser-shaped, Loose Intermediate Support, J. of Pressure Vessel Technology, 111, pp.428-434.