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Hydroelastic Response of a Circular Tube in Eccentric Annular Flows

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Abstract

This paper presents the experimental study of the hydroelastic response of a tube located concentrically and eccentrically in a circular water-flow channel. Acceleration components in two orthogonal directions are measured at the midpoint of the test element using a pair of accelerometers. The investigation includes determination of natural frequencies, damping factors, rms displacements, and the variations of the above dynamic quantities with eccentricity and mean axial flow velocity.

The experimental data is processed into statistical forms, including power spectral density function and root-mean-square values. The results show that the natural frequency of the tube shifts as the eccentricity or flow velocity increases, that the damping in flowing water is greater than that in stationary water and increases with increasing flow velocity and eccentricity, and that the rms displacement increases as the eccentricity and/or flow velocity increases.

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1. Introduction

Many vital components, such as fuel rods and heat-exchanger tubes, of a nuclear-power plant are relatively closely packed and are subjected to nominally axial coolant flow. These components are normally long, slender, and beam-like members with low inherent damping. The flowing coolant exerts hyrdynamic forces on these components and causes them to vibrate. The motion of these structural components again alters the coolant flow field and the hydrodynamic force on the structures. The interaction of the coolant motion and the structure motion repeats again and again and becomes coupled.

The hydroelastic (or fluidelastic) interaction and the coupled response are enhanced by the close spacing between similar components and their locations in the flow channel.

This paper presents an experimental study of the hydroelastic response of an elastic tube in parallel flow. The objectives of this study are to evaluate experimentally the hydroelastic interactions resulting from the proximity of the test element to a rigid boundary, and to provide experimental data for developing mathematical models to predict fluidelastic responses and hydroelastic instabilities (i.e., critical flow speeds) in axial flows.

Experimental measurements were made of the dynamic response of the tube located concentrically and eccentrically in the water-flow channel. The experimental results include natural frequencies, damping factors, and rms displacements and are used to evaluate the effects of eccentricity and flow velocity on tube response.

2. Experiment

2.1 Flow Loop and Test Element

The flow loop and test section used in this experimental study are the same as those used in the study of wall-pressure fluctuations in annular flow [1,2]; the smallest annulus, with the inside diameter of the flow channel equal to 2.54 cm (1 in.), is used. However, in contrast to the test section used for the fluctuating wall-pressure study, the present test section has an upstream extension to eliminate the discontinuity that would otherwise occur at the inlet as a result of the change in cross section area of the flow channel.

The test element is a tube 1.27 cm (0.5 in.) in diameter and 122.0 cm (48 in.) long. The end conditions approximate a fixed support at the downstream end and a simple support at the upstream end. The test assembly and tube support are shown in Fig. 1. Figure 2 shows the tube positions inside the flow channel, and the values of the eccentricities (e) together with the ratios of eccentricity to hydraulic diameter (d_h).

2.2 Instrumentation, Measurement Method, and Data Acquisition

Tube motion in orthogonal directions, x and y, as defined in Fig. 2, is measured by two Endevco 22 Picomin piezoelectric accelerometers mounted on a pellet which is inserted into the tube and fixed at the midspan. The accelerometer leads are passed out from the downstream end of the tube, and the accelerometer signals are amplified using Endevco 2735 charge amplifiers with low-pass filters of 250 Hz.

As part of the data reduction, the recorded acceleration signals are converted to displacement using either a real-time double integrator or a digital conversion technique. Using the digital conversion technique, the displacement power spectral density (PSD) is obtained from that of the acceleration by applying the relationship

$$\phi_x(f) = \frac{\phi_a(f)}{(2\pi f)^4}, \tag{1}$$

where f is the linear frequency in Hz, and ϕ_x and ϕ_a are, respectively, PSDs of displacement and acceleration. Tests showed both the integration scheme and digital conversion technique to give the same results. For convenience, the digital conversion technique was used for all data reductions requiring displacements with the exception of the real time spatial plots.

Impact excitation is used to determine natural frequencies and damping values of the tube in air and in stationary water; the logarithmic-decrement method is used to estimate damping. In flowing water, the natural frequencies are determined from the center frequencies of response peaks shown in the PSD curves. Damping factors are also estimated from the PSD curves by use of the bandwidth method. The use of the bandwidth method to estimate the damping in flowing water is based on the assumption that the turbulent-boundary-layer pressure fluctuation is a random white-noise excitation so that the measured PSD for the tube response is proportional to the transfer function for the tube. Measurements have shown this assumption to be reasonable.

In order to determine the effects of eccentricity and mean axial-flow velocity on dynamic response of the tube, the tube is located at four different positions inside the flow channel, as shown in Fig. 2, and the mean axial-flow velocity is incrementally increased. All test data is recorded on magnetic tape and processed with the aid of a Hewlett Packard Fast Fourier Transform Analyzer (HP 5451C). The data processing includes computations of power spectra and mean-square values of displacement and acceleration, and spatial response. The analysis bandwidth is 0.0977 Hz, with a record length of 10.24 sec, a maximum frequency of 100 Hz and ten averages.

3. Test Results and Discussions

3.1 Frequencies and Damping Factors

The fundamental frequency of the tube in air is approximately 35.3 Hz, and the corresponding frequency in stationary water is about 31.2 Hz. The average damping factor, as a percentage of critical damping, is 2.9% in air, and 3.5% in stationary water. The above numerical values are averages from many tests. In some tests a beating phenomenon occurred making determination of natural frequencies and damping factors.

The coupled natural frequencies and damping facors for the tube in flowing water, as shown in Figs. 3-4, are weakly decreasing and weakly increasing, respectively, with mean axial-flow velocity when the tube is concentrically located in the circular flow channel. When the tube occupies one of its off-center positions, the coupled natural frequencies and damping factor both increase with increasing mean axial-flow velocity and with increasing eccentricity. That is, the values of the coupled natural frequencies and damping factors at a fixed value of mean axial flow velocity increase with an increase of eccentricity.

3.2 Power Spectral Density (PSD) of Acceleration

PSDs of tube acceleration are shown in Fig. 5 for all four cases of eccentricity, viz., for cases with eccentricities of 0, 0.32, 0.48, and 0.56 cm (0, 1/8, 3/16, and 7/32 in.). This figure is only intended to display the frequency content of the response; therefore, the vertical scale of the figure is arbitrary.

From Fig. 5, one can readily observe the behavior of the natural frequency and damping factor as presented in Figs. 3-4. For example, with the tube located eccentrically, the fundamental frequencies at low flow velocities (i.e., $U \leqslant 8$ m/s) shift to values lower than the corresponding ones observed in the concentric case, and those at high flow velocities ($U \geqslant 8$ m/s) shift to values higher than those observed in the concentric case. The magnitude of the frequency shift increases with respect to an increase of eccentricity for all ranges of mean flow velocities. For mean flow velocity above 8 m/s, the magnitude of the shift increases with increasing mean flow velocity. On the other hand, the magnitude of the shift decreases with an increase of mean flow velocity when the mean flow velocity is below 8 m/s. These effects increase with increasing eccentricity or proximity to the wall. In general, the smaller the gap between the tube and the channel wall, the more pronounced is the hydroelastic interaction.

3.3 Root-Mean-Square Displacement

Root-mean-square values of the tube displacements in the x and y directions are obtained by integrating the PSDs of displacements over the frequency domain. Due to contamination of the acceleration signals by high levels of flow noise, particularly at the higher flow rates, the raw data was bandpass-filtered to eliminate contributions at frequencies below 15 Hz and above 45 Hz, thereby retaining only the response centered about the fundamental frequency of the tube.

Results of rms displacements are plotted versus mean flow velocity in Fig. 6. As seen from the figures, the rms displacement increases with increasing eccentricity and with increasing flow speed with one exception, rms displacements associated with the case of an eccentricity of 0.56 cm (7/32 in.) are slightly less than those with an eccentricity of 0.48 cm (3/16 in.) when the flow velocity is above 15 m/s. This can be attributed to the larger increase of damping for the 0.56 cm (7/32 in.) case at the higher flow velocities. Also, if a power function relationship is assumed to represent the dependence of vibration response on mean flow speed it can be noted from Fig. 6 that the variation in the exponent is greater than 2 for the eccentric cases and is less than 2 for the concentric case.

Typical spatial patterns of tube response are plotted in Fig. 7. Each figure is for a different value of eccentricity; however, the flow speed is the same at a value of 6 m/s. Eight consecutive time instants are plotted for each case, with the interval between two neighboring plots being 12 seconds. The plots present the instananeous position of the center of the tube and are plotted to the same scale on all four figures. As seen from the plots, the response is random and, for a fixed flow speed, increases as the eccentricity (proximity to the wall) increases.

4. Concluding Remarks

This paper presents the results of an experimental study of the hydroelastic response of a cylindrical tube in eccentric annular water flows. A purpose of the study is to determine, through a series of systematic measurements of the tube response in eccentric annular flows, whether or not the hydroelastic interaction is sufficiently strong to cause large-amplitude motion or instability when the gap between the tube and flow channel is small.

The study also provides experimental data that may be useful in developing and validating response prediction methods.

The experimental measurements lead to the determination of natural frequencies and damping of the tube in air and in stationary water, and of coupled natural frequencies, damping factors, and buffeting response in eccentric annular water flow. With the tube concentrically located in the flow channel, the coupled natural frequencies decrease slightly and the damping increases slightly as the mean flow velocity increases. When the tube is eccentrically located in the channel, the coupled natural frequencies and the damping both increase with increasing eccentricity or mean flow velocity. The coupled natural frequencies are smaller than the natural frequencies of the tube in air because of added-mass effect caused by water. Also, the damping factors in water are greater than those in air because of the viscosity effect. In general, coupled natural frequencies in eccentric annuli with flowing water are greater than the corresponding ones in concentric annuli, because of hydroelastic interaction effects as the gap between the tube and the flow channel becomes small. RMS values of tube displacement also increase when the eccentricity or mean flow velocity is increased.

From the test results, it can be concluded that hydroelastic interaction effects are measurable in parallel flow when the gap between the test element and the flow channel wall becomes smaller. The particular test element used in the experiment has a relatively large in-air damping value (~ 3%) and structural-to-fluid mass ratio. For this test element, hydroelastic interaction is not sufficiently strong to cause large amplitude motion that could result in impacting with the bounding surface and have the potential for rapid component failure.

References

[1] MULCAHY, T. M., WAMBSGANSS, M. W., LIN, W. H., YEH, T. T., and LAWRENCE, W. P., "Measurements of Wall Pressure Fluctuations on a Cylinder in Annular Water Flow with Upstream Disturbances, Part I: No Flow Spoilers," GEAP-24310, DOE/N/4175-15, ANL-CT-81-11 (January 1981).

[2] LIN, W. H., MULCAHY, T. M., WAMBSGANSS, M. W., YEH, T. T., and LAWRENCE, W. P., "Measurements of Wall Pressure Fluctuations on a Cylinder in Annular Water Flow with Upstream Disturbances, Part II: Flow Spoilers," GEAP-24340, DOE/ET/34209-17 (January 1981).

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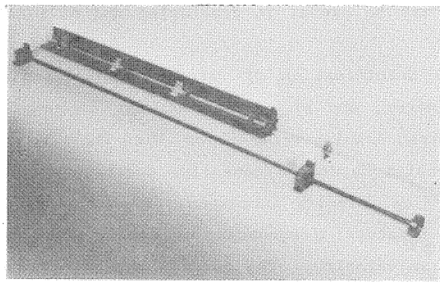

Fig. 1 Test Channel and Assembly of the Rod with End Supports

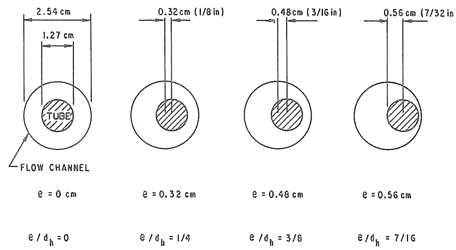

Fig. 2 Positions of the Tube in the Flow Channel

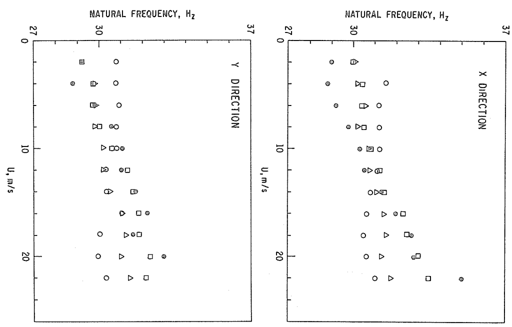

Fig. 3 Fundamental Frequencies of the Tube; e = 0 (◎), 0.32 cm (Δ), 0.48 cm (□), 0.56 cm (●)

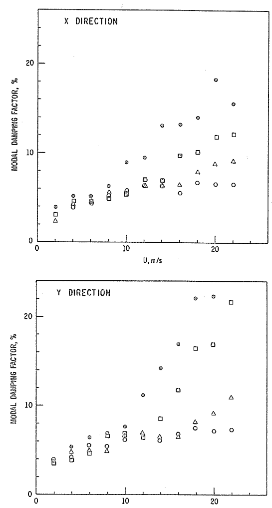

Fig. 4 Modal Damping Factors of the Tube; e = 0 (○), 0.32 cm (Δ), 0.48 cm (□), 0.56 cm (●)

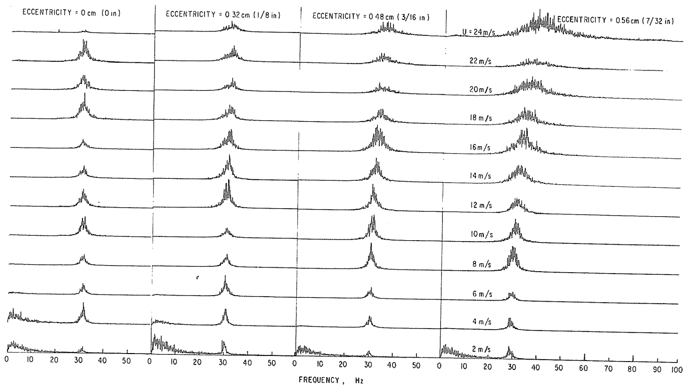

Fig. 5 Acceleration PSDs as a Function of Eccentricity and Flow Speed (Note: Intensities are not to scale)

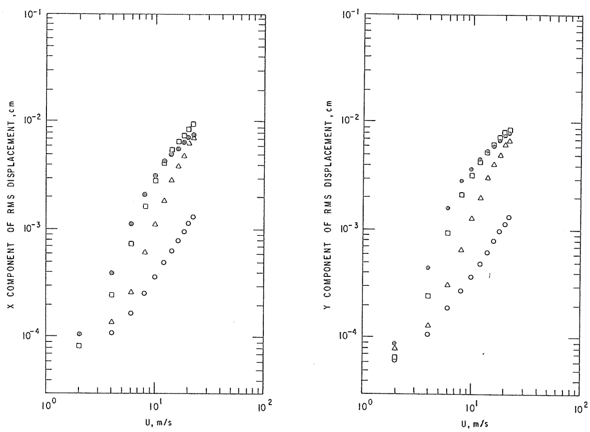

Fig. 6 RMS Values of Tube Displacement; e = 0 (○), 0.32 cm (Δ), 0.48 cm (□), 0.56 cm (●)

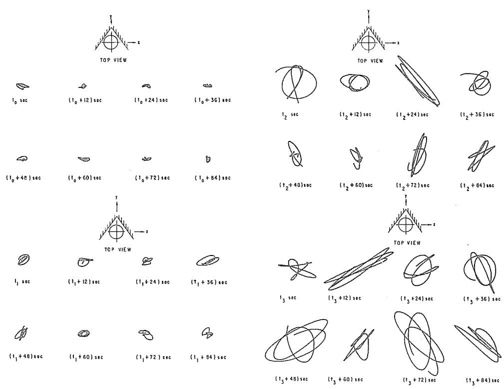

Fig. 7 Spatial Configurations of Tube Displacement at U = 6 m/s