Measurements of Wall Pressure Fluctuations on a Cylinder in Annular Water Flow with Upstream Flow Disturbances

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Abstract

Data for surface pressures on a finite length rod in an annular region with upstream disturbances are presented and related to the existing data for well developed flow. Normalizations of the power spectral densities for different flow rates and three hydraulic diameters are presented, and the possible spurious effects on pressure measurements are discussed. Power spectral density levels are identified which predict the same order of magnitude response as measured in a vibration study, and a general approach for predicting rod response to axially nonhomogeneous pressure fields is outlined.

1. Introduction

A number of reactor components are beam-like members exposed to reactor coolant flows that are nominally parallel to their long axis. Many of these components, being long and slender, will have relatively low natural frequencies and, in some cases, low inherent damping. With exposure to highly turbulent flow fields, and flow velocities as high as 10 m/s, these components are prone to flow induced vibration. While the number of vibration-caused outages, or forced reductions in power, attributed to parallel flow-induced vibration have been minimal, there is the potential for failure from fretting/wear as reactors accumulate months and years of operation. This and the unknown effects from expected increases in coolant flow velocities in future reactors provide the motivation for studying parallel flow induced vibration.

Turbulent boundary layer wall pressure fluctuations are one major excitation source for the flow induced vibration of components subjected to nominally axial coolant flows, and various empirical and analytical models have been proposed to predict component response [1-10]. The empirical models [1-6] have generally been developed using dimensional analysis and test results. The analytical models [2,6,8-10] are based on random vibration theory in which a phenomenological model proposed by Corcos [11] is used to describe the random wall pressure field. The empirical models have the advantage of correlating actual response data, however they are only applicable for the components and system parameters included in the testing to develop the model. The analytical models, while theoretically applicable to a broad range of components and parameters, require experimental determination of the statistics of the wall pressure fluctuations for each flow condition. Further, response is easier to measure than wall pressures. For either model, response can only be predicted within an order of magnitude [12]. Evidently, a proper role for analytical models is to provide simplified means of obtaining response upper bounds where typical flow conditions prevail.

The theory of random vibrations of structures is much more developed than are characterizations of wall pressure forcing functions. The pressure field associated with fully developed flow in pipes [13] and in annular regions [14] is well understood compared to other geometries. However, progress has been made for tube bundles [6] and several piping transitions such as expansions, orifices, elbows [15]. Characterization of the pressure fields associated with discontinuities in the flow channel, in particular, is important, because of their relatively large strength in comparison to fully developed flows even though they occur at wide intervals along the component's axis. Because these flows are much more complex than fully developed flows, simplifications must be made in characterizations of their pressure fields, but this is not incompatible with the role of analytical models described above. After outlining the general analysis approach, pressure field characterizations of entrance effects in annular regions are presented.

2. A Cylinder in Fully Developed Flow

Assuming the wall pressure field statistics are ergodic and the equations of motion can be uncoupled to allow solution by modal analysis, then a general expression for the spatial power spectral density of the cylinder response is [16]

$$S_y(x_1,x_2;\omega) = S_{po}\ell^2 \sum_{j,k=1}^{\infty} \phi_j\phi_k J_{jk}^2 |H_j||H_k| \qquad (1)$$

where $\phi_j(x)$ is the j^{th} mode satisfying the orthogonality relation

$$\int_0^{\ell} m\phi_j\phi_k dx = \begin{cases} m_j & j = k \\ 0 & j \neq k \end{cases} \quad . \tag{2}$$

The m is the mass per unit length including any added mass effects, m_j the generalized mass in the j^{th} mode, and ℓ the rod length. The frequency response function is

$$H_j(\omega) = m_j^{-1}(\omega_j^2 - \omega^2 + 2i\zeta_j\omega\omega_j)^{-1} \tag{3}$$

where ω is the circular frequency, ω_j the j^{th} mode natural frequency, and ζ_j the ratio of damping to critical damping in the j^{th} mode. The joint acceptance is

$$J_{jk}^2(\omega) = [S_{po}\ell^2]^{-1} \int_0^{\ell}\int_0^{\ell} S_p\phi_j\phi_k \exp[-i(\theta_j - \theta_k)]dx_1dx_2 \tag{4}$$

where $S_p(x_1,x_2,\omega)$ is the cross spectral density of the pressure field forces per unit length at two different axial locations: $x = x_1$, $x = x_2$. $S_{po}(\omega)$ is the single point spectral density at a reference axial location: $x = x_o$. The modal phase angles are

$$\theta_j = \tan^{-1}\left[\frac{2\zeta_j\omega_j\omega}{\omega_j^2 - \omega^2}\right] \quad . \tag{5}$$

The $J_{jj}^2(\omega)$ gives the relative effectiveness of a random forcing function in exciting the j^{th} mode, while $J_{jk}^2(\omega)$, $j \neq k$, represents the contribution from the coupling effect between two modes. In general the responses in two different modes are dependent on each other.

A simplified characterization of the spatial spectral density of the wall pressure field which will bound response due purely to a turbulent boundary layer is

$$S_p(\bar{x},\omega) = d_e^2 S_{po} \exp(-\bar{x}/\ell_c)\cos\left(\frac{x\omega}{V_c}\right) \tag{6}$$

where

$\bar{x} = x_2 - x_1$, $x_2 > x_1$

d_e = 1.25 d is an effective pipe diameter bounding the circumferential correlation of the pressure field around the diameter d.

V_c = 0.8 V is an average convection velocity of turbulence eddies in flow with mean velocity V.

ℓ_c = one-half channel width is the distance over which pressures remain significantly correlated.

$S_{po}(\omega) = (q^2 d_h/V)S(\omega)$ is the single point ($x_1 = x_2$) surface pressure spectral density, where q is the dynamic pressure, and d_h is the hydraulic diameter. The recommended frequency distribution $S(\omega)$ is recoverable from Fig. 1, with K = 1; noting $\phi \approx 6 \times 10^{-6}$, $\Phi_{po} = 2\pi S_{po}$, and (0.01 K, Kϕ) and (4,ϕ) are coordinates on the approximation curve.

Application of eq. (6) is limited to the parameter range

$$0.63 < \frac{\omega d_h}{V} < 15.7 \quad ; \quad 0.03 < \frac{\omega d}{V} \quad ; \quad 7.0 < \frac{\omega\ell}{V} \quad . \tag{7}$$

Since damping ratios ζ_j increase with flow velocity, upper bounds on response can be obtained by using damping estimates for still fluids. For structures with widely separated natural frequencies, only the response in the lowest mode need be calculated, since it is dominant [9]. Otherwise the response in all modes must be calculated.

It is proposed that the response of a rod in an annular region with flow channel discontinuities (abrupt changes in cross section, etc.) be determined by piecewise application of (6) over axial segments, ℓ_s, with different K and ℓ_c. Each axial segment should be small enough to justify the use of averaged flow parameters, but it must be larger than ℓ_c (factor of 10) for piecewise application of eq. (6) to be valid. The correlation length ℓ_c is estimated as the channel width, based on measurements of this difficult parameter for somewhat similar geometries [15]. A discussion of the single point spectral density follows.

3. Experimental Results and Interpretation

The objectives of the experiments were to obtain turbulent boundary layer wall pressure data from the surface of a 1.37 cm diameter rod in annular water flow and to evaluate the effects of upstream flow disturbances and hydraulic diameter, d_h. While the primary interest is at low frequencies, where response predominates, the need to consider the entire range of frequency response will become apparent. The test element was an ℓ = 1.26 m long circular pipe concentrically positioned in a flow channel of circular cross-section. Liners with diameters of 3.81 and 2.54 cm were inserted into the test section to provide three different sized flow annuli; d_h = 1.17, 2.44, and 3.71 cm. Also, the liners created sharp changes (discontinuities) in channel area at the upstream end (x = 0) of the rod: solid blockages, referred to the upstream flow channel, were 51% and 82%. Additional upstream turbulence was generated by three different flow spoilers located immediately upstream of the entrance to the test section. To study the decay of contributions to the wall pressures from upstream disturbances, transducers were equally spaced at four locations along the length of the test element, beginning at x/ℓ = 0.125 [17]. A description of the flow facility is included in a report on the response of similar test elements [18].

When normalized, all the single point spectral densities, $\Phi_{po} = 2\pi S_{po}$, at x/ℓ = 0.625 fit into the data band shown in Fig. 1. The high frequency plateau at ordinate value 6×10^{-6} was determined [19] to be the spectrum level of fully developed flow. The higher plateau at lower frequencies is the remnants of upstream disturbances. Utilizing the curve shown in Fig. 1, K = 1 approximates fully developed flow while K = 5 approximates the data; corresponding pressure coefficients are C_p = 0.005 and 0.006, respectively. The transducers at x/ℓ = 0.875 failed, and disappearance of the high plateau could not be confirmed. All the data at x/ℓ = 0.375 fit in the band of Fig. 1, except for the largest hydraulic diameter with an upstream grid.

At x/ℓ = 0.125, the effects of upstream disturbances were significant. No high frequency plateau region existed, as shown in the data of Fig. 1; the shape of the spectra were closer to the approximate curve, with relatively more energy being concentrated at lower frequencies. Blockage effects, pipe-to-annulus or grids, created these relatively larger pressure fluctuation levels at x/ℓ = 0.125, but they were attenuated as they convected down the rod. Because larger attenuation occurs at higher frequencies, the smallest eddies are most immersed in the boundary layer, the plateau region associated with a fully developed boundary layer is revealed at x/ℓ = 0.375 and 0.675. As would be suspected, the attenuation rate depends on hydraulic diameter, which made the normalized data band at x/ℓ = 0.125 wider than for the other locations.

For the axial location closest to the entrance and grids, the effects of upstream disturbances were significant and depend upon the flow channel hydraulic diameter. This is

illustrated in Fig. 2 by the pressure coefficients' magnitudes. As another comparison, the curve of Fig. 1 was best fit to the spectral data with the result: for d_h = 3.71 cm with a grid spoiler, K = 250 and C_p = 0.0625, while without K = 10 and C_p = 0.0075; for d_h = 2.44 cm or 1.17 cm with or without a grid spoiler, K = 15 and C_p = 0.009 or K = 50 and C_p = 0.018, respectively. Essentially, the grids had no effect on the surface pressures, except in the largest hydraulic diameter channel: the sharp contraction in channel size at the upstream end of the rod dominated any grid effects. Even for the largest channel size only grids approaching solid blockages of 50% produced significantly different results. All these same qualitative dependencies on channel contractions and grids were observed in a companion study [18] of the rod response. Currently under study is the correlation of K and C_p with the solid blockages of the upstream disturbances.

4. Discussion of Results

The low frequency range (< 200 Hz) of the wall pressure field is of most interest as a source for the excitation of reactor plant component vibrations. While a significant number of investigations of turbulent boundary layer wall pressure fluctuations have been reported (see Willmarth [20] for a summary), there have been only a few that have emphasized measurements in the low frequency range [20,14]. There are a number of difficulties associated with the measurement of wall pressure fluctuations: (1) transducer size effects, (2) extraneous acoustic noise, particularly at low frequencies, (3) surface roughness and pressure transducer surface discontinuities, (4) pressure gradients, (5) misalignment of axis from parallel flow, (6) transducer sensitivity to vibration and rod strain, and (7) the small magnitudes of the pressures being measured. All these factors were considered in the data interpretation [19].

The most important consideration in obtaining or interpreting the data was elimination of the effects of acoustic noise. To circumvent the problem, a measurement method was employed utilizing, at each axial location, the difference signal from two diametrically opposed pressure transducers [14]. The method is based on the theoretical result that for pipe flow, in which the acoustic cutoff frequency is relatively high, only plane waves of long wavelength will propagate; higher order acoustic noise will exponentially decay with distances from the source. The acoustic cutoff frequencies and decay lengths were calculated [19] and found to be out of the parameter range of interest. Implied in the use of the pressure signal differencing technique is very accurate calibration and matching of the transducers [17], because the noise can be an order of magnitude larger than the turbulent boundary layer pressure signal.

The most meaningful verification of the interpretation given to the data is its usefulness in predicting response of components. Assuming the pressure field axially homogeneous and the same as at $x/\ell = 0.625$, the rod response measured in the companion study [18] was predictable within a factor of 2 except for the case of the smallest hydraulic diameter and the largest hydraulic diameter with a grid. In the exceptional cases, the nonhomogeneity of the pressure field had to be accounted for as discussed earlier. The companion study provided the information on structural response including damping as a function of flow rate, which was found to increase by a factor of 2.5 over the small still water damping values (ξ = 0.01). Thus, utilization of still water damping values would decrease the accuracy of the predictions by $\sim \sqrt{2.5}$.

5. Conclusions

The measurement of the wall pressure single point power spectral densities presented show that discontinuities in the flow channel can create flow disturbances which dominate the turbulent boundary layer as an excitation mechanism for rod response in parallel flow. However, the channel sizes must be large or the discontinuity very severe before prediction of response assuming an axial homogeneous pressure field due to fully turbulent flow becomes significantly inaccurate. The data presented and analysis method are expected to enable an order of magnitude estimate of the response of a rod subject to typical entrance conditions formed by fuel assembly grids.

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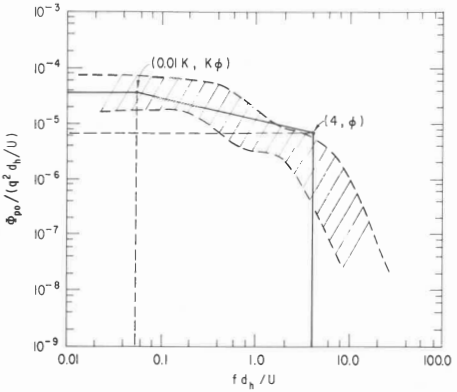

Fig. 1. Normalized spectra data band (////) for $x/\ell = 0.625$ and no upstream flow spoilers. The curve (——) is drawn for $K = 5$ and $\phi = 2\pi \times 10^{-6}$.

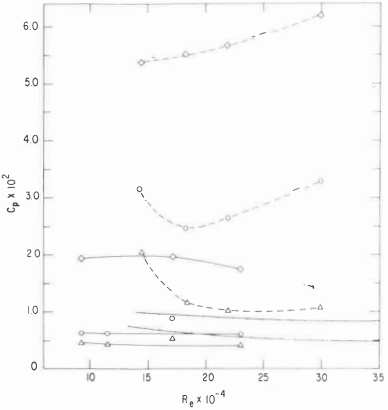

Fig. 2. Pressure coefficients for $d_h = 1.17$ cm, ——; and $d_h = 3.71$, - - -. Locations denoted by ◇, $x/\ell = 0.125$; ⊙, $x/\ell = 0.375$; Δ, $x/\ell = 0.625$.