THE RESPONSE OF A REACTOR FUEL STRING TO FLOW AND STRUCTURALLY TRANSMITTED EXCITATION*

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SUMMARY

In a pressure tube reactor, relative motion between the fuel string and the flow tube may cause damage to individual bundles in the string and to the flow tube walls. Two possible sources of this motion are, (i) the inherent turbulence in the flow, and (ii) motion of the support structure caused by external sources and transmitted to the flow tube and the string via its piping connections and structural supports. This paper describes an experimental study of the latter.

The experimental apparatus consisted of a vertical flow tube containing a hanging string of six 0.5 m long UO_2 CANDU fuel bundles which were loaded end to end on a central support tube. The test section was isolated from external excitation sources by flexible connectors. Excitation was imposed by water upflow (average velocities $\leqslant 14$ m/sec) and band limited random vibrations (0 to 80 Hz, constant acceleration) introduced by an excitor attached to the lower end of the flow tube. Motion of the flow tube (x) and relative motion between the string and flow tube (y) were monitored with velocity transducers.

The vibration signals, x and y were processed digitally to determine the fuel string frequency response which was calculated as follows:

$$|H(f)| = \frac{G_{xy}(f)}{G_{xx}(f)} \quad \underline{/H(f)} = \underline{/G_{xy}(f)} \tag{1}$$

where $G_{xx}(f)$ is the flow tube (input) excitation spectral density function and $G_{xy}(f)$ is the cross-spectral density function of the flow tube-fuel string relative motion with respect to the input excitation. We note that $G_{xy}(f)$ also contains the effects of that portion of the inherent flow excitation which is correlated with the imposed structural excitation.

The string frequency response, $H(f)$, was found to be dominant at approximately 10 Hz which corresponds to the fourth bending mode of the string. The effect of the structural excitation on $H(f)$ decreased with increased flow velocity; i.e. there is an apparent coupling between the flow and structural excitations. Further, the relative motion due to the structural excitation became small at velocities above 9 m/sec.

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* Work performed under Atomic Energy of Canada Limited Contract WS11J94577 by Westinghouse Canada Limited.

1. INTRODUCTION

In a pressure tube reactor, relative motions between the fuel string and the pressure tube may cause damage to individual fuel bundles in the string and to the pressure tube. Two possible sources of this motion are: (i) flow borne disturbances and (ii) motion of the support structure caused by external sources which are transmitted to the pressure tube and fuel string via piping connections and structural supports. Flow borne disturbances are comprised of inherent turbulent pressure fluctuations which are supplemented by pressure fluctuations originating at pumps, valves and other flow disturbers. Appelt et al [1] and Kadlec and Ohmer [2] have shown that different test facilities having identical test assemblies and operating conditions may have significantly different vibratory behaviour. They conclude, based on static pressure measurements, that these differences are due to differences in flow borne excitation. No attempt, to the present authors' knowledge, has been made to determine the effect of structurally transmitted excitation.

This paper presents the results of an experimental investigation of the vibratory response of a vertically hanging string of six 0.5 m UO_2 CANDU fuel bundles to water upflow and band limited random vibrations (2 Hz to 30 Hz, constant velocity) introduced by an electrodynamic vibrator attached to the lower end of the flow tube. Motion of the flow tube and relative motion between the string and the flow tube are monitored employing variable reluctance velocity transducers. The signals so obtained are analyzed to obtain power spectral density functions and root-mean-square displacements. These results are employed to determine the fuel string response to the imposed mechanical excitation.

2. EXPERIMENTAL APPARATUS

The experimental program was conducted with the loop configuration shown in Figure 1. A maximum water flow of 35 kg/s (at 32°C) was supplied to the vertical test section, which is isolated by flexible connectors to minimize transmission of external excitation, by a centrifugal pump. Flow control was achieved by a globe valve located downstream of the pump.

The test section consisted of a 103.5 mm internal diameter stainless steel flow tube which contained a hanging string of six 0.5 m long, 18 element UO_2 CANDU fuel bundles (mass = 25 kg). The bundles were loaded end-to-end on a 13.6 mm central support tube and held in compression against a downstream stop by a spring force of 2600 N. Figure 2 shows a typical bundle with the spring tensioning device. The downstream end of the central support tube passed through a gland which approximated a fixed support. The diametral clearance between the bundle bearing pads and the flow tube was 1.7 mm.

Mechanical excitation was introduced to the lower end of the flow tube, which is hinged at the upper end, by an MB-C10 electrodynamic vibrator. The excitation in the present experiments was band limited random noise, from a Hewlett Packard 8057-A generator, which, with no load on the vibrator, would yield a constant velocity over the frequency range 2 Hz to 30 Hz. When fixed to the flow tube, this excitation yielded the frequency spectrum shown in Figure 3. The excitation level was adjusted to obtain a root-mean-square velocity of 500 mm/s.

The velocity of the flow tube lower end and mid-point, and the relative velocity between the fuel string and flow tube at six axial positions were monitored with variable reluctance transducers. In the latter case transducers were mounted on the flow tube opposite magnets inserted into fuel bundle elements; transducer positions are shown in Figure 1. Signals from the transducers were amplified and recorded on magnetic tape. Spectral density and cross-spectral density functions were subsequently obtained employing a Hewlett Packard 3721-A correlator [3] and 3720-A spectrum display [4].

3. ANALYSIS

As noted above, velocity signals obtained in the present experiments have been processed to obtain the conventional spectral density and cross-spectral density functions. It will be seen in the following section, that the velocity spectral density functions exhibit content within broad frequency bands. To facilitate the determination of displacements we have introduced the following mean velocity:

$$\bar{V} = \frac{1}{\bar{f}} \int_{f_\ell}^{f_u} G(f)\, df \qquad (1)$$

where $\bar{f} = \frac{1}{2}(f_\ell + f_u)$

f_ℓ, f_u = lower and upper frequency limits respectively

$G(f)$ = spectral density function

An estimate of the corresponding root-mean-square displacement, assuming sinusoidal motion at frequency $\bar{f}$, may be obtained from

$$\bar{X} = \frac{\bar{V}}{2\pi \bar{f}} \qquad (2)$$

The effect of flow tube motion (x) on the relative motion between the fuel string and the flow tube (y) may be specified by a frequency response function which is defined as follows [5]:

$$|H(f)|^2 \equiv \frac{G_{yy}(f)}{G_{xx}(f)} \qquad (3)$$

Where $G_{xx}(f)$ and $G_{yy}(f)$ are the spectral density functions of the flow tube motion and of the fuel string to flow tube relative motion respectively. In the present work, band limited random vibrations are imposed on the flow tube and the response, i e. x(t) and y(t), is monitored. Because other effects, e.g. flow borne excitations, contribute to $G_{yy}(f)$ as well as the imposed mechanical excitation, we wish to examine only that relative motion which is correlated with the flow tube motion. It is convenient, therefore, to introduce the following alternate definition for the frequency response function:

$$H(f) \equiv \frac{G_{xy}(f)}{G_{xx}(f)} \qquad (4)$$

where $G_{xy}(f)$ is the cross-spectral density function of x and y. H(f) is a complex function, as is $G_{xy}(f)$, and is defined in polar coordinates by its absolute magnitude H(f), and a phase angle $\angle H(f) = \angle G_{xy}(f)$. Employing H(f) we will determine the effect of the imposed flow tube excitation on the relative motion between the fuel string and the flow tube.

4. DISCUSSIONS OF RESULTS

4.1 Flow Tube Motion

Figures 3a and b show typical power spectral density functions for the flow tube velocity, both with and without the imposed mechanical excitation, at the lower end and mid-span positions respectively; the transducer positions are shown in Figure 1. The cross-spectral density function, modulus and phase angle, for these velocities is given in Figure 3c. The lower end and mid-span velocities are shown to be correlated at 7 Hz and 23 Hz with phase angles of 0 and 180 respectively. We conclude that the flow tube is vibrating in its first and second bending modes. This conclusion is further supported by the observation that the 23 Hz component is significantly reduced at mid-span. In addition we note that there is no significant flow tube motion due to flow excitation alone; root-mean-square (rms) displacements are presented in Section 4.3 below.

4.2 Fuel String Frequency Response

Figures 4a, b, c, and d show power spectral density functions for the relative velocity between the fuel string and flow tube for flow velocities of 0, 4.4, 9 and 13* m/s respectively. The numbers 1 through 6 refer to axial positions starting from the lower end of the string and proceeding downstream at 500 mm intervals as shown in Figure 1. In each of the figures the solid line represents the response due to flow plus mechanical

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* The corresponding Reynolds' numbers, based on the equivalent diameter, are 0, 40700, 83200 and 120000 respectively.

excitation and the dotted line represents the response due to flow excitation alone; the vertical scales are equivalent at each position but vary from position to position.

In the absence of mechanical excitation we see, from Figures 4a through d, that the relative motion between the fuel string and flow tube is insignificant for flow velocities less than 9 m/s. At flow velocities of 9 m/s and 13 m/s there is significant relative motion over the frequency range 2.5 Hz to 15 Hz which exhibits a peak in the region of 7 Hz to 10 Hz. As will be shown in Section 4.3, the rms displacement is a maximum at the fuel string free end (position 1) and decreases towards the fixed end.

With the introduction of mechanical excitation the relative motion between the string and flow tubes exhibits peaks in the spectral density functions at 7 Hz and 23 Hz; these frequencies, as noted earlier, are associated with the flow tube first and second bending modes. In general, the second mode motion is of secondary importance; particularly in terms of displacement. We note that the effect of the mechanical excitation, on the relative velocity between the fuel string and the flow tube, decreases as the flow velocity is increased until, at 13 m/s, it becomes almost negligible. This behaviour will be examined further in the sections that follow.

4.3 RMS Displacements

Root-mean-square displacements, calculated employing the spectral density functions of Figure 4 and equation (1) and (2) with $f_\ell = 5$ Hz and $f_u = 10$ Hz, are shown in Figure 5 for the flow tube and fuel string to flow tube relative motions.

As noted earlier, in the absence of mechanical excitation, flow tube displacements are negligible up to a flow velocity of 9 m/s. At a flow velocity of 13 m/s a maximum rms displacement of 10 m occurs at mid-span. Relative motion between the fuel string and flow tube increases with increasing flow velocity. Measurable displacements are present at flow velocities greater than 4.4 m/s; the displacement being greatest at the free end (position 1). Results obtained for flow velocities of 9 m/s and 13 m/s indicate that the free end displacement increases by slightly greater than the square of the flow velocity ratio.

The flow tube displacement increases significantly upon application of the mechanical excitation. As noted earlier the flow tube responds in its first bending mode and hence the greatest displacement occurs at mid-span. The energy input to the electrodynamic vibrator was maintained constant throughout the experiments and, with the exception 13 m/s flow condition, we note that the flow tube motion was reproducible. The reduction in flow tube motion at the 13 m/s flow condition is attributed to the influence of the increased string motion on the electrodynamic vibrator.

Under the no flow condition, we note from Figure 5, that the relative motion between the flow tube and fuel string closely resembles the flow tube motion. We conclude that the relative motion is principally due to the flow tube with negligible transfer of motion to the fuel string. At the other extreme, in this case at a flow velocity of 13 m/s, the relative motion between the fuel string and flow tube, with mechanical excitation, closely resembles that obtained without mechanical excitation. Thus we conclude that the motion here is determined by flow borne excitation and the effect of the mechanically imposed excitation is negligible. At the intermediate flow conditions there is an apparent reduction in the effect of the mechanical excitation with increasing flow rate.

4.4 Frequency Response Functions

Figures 6 a,b,c, and d give frequency response functions for the fuel string to flow tube relative motion at position 1, calculated employing equation (4) for each of the four flow rates. These figures show the magnitude (or gain) and phase angle of the relative motion resulting from the correlated flow tube motion. In general the functions are valid only in the range 2 Hz to 25 Hz. Outside this range the signals, due to filtering and transducer sensitivity, are of the order of the analyzer noise.

The following two general features of the gain variation with frequency are noted: (i) there is an apparent attenuation of the flow tube first bending mode at 7 Hz, and (ii) a distinct 10 Hz component has emerged. The 10 Hz component has been found [6], employing cross-correlation techniques, to be associated with the fourth bending mode of the fuel string. The apparent attenuation of the flow tube motion is attributed to intermittent contact between the fuel string and flow tube.

As noted earlier, under the no flow condition, an examination of rms deflections suggested that the relative motion between the fuel string and flow tube was due principally to the imposed flow tube motion. One would therefore expect, in the case of unrestrained motion, to obtain a near unity value of the gain at frequencies less than 10 Hz in Figure 6a. The resultant frequency response, however, suggests that not all of the imposed motion was realised due to intermittent contact. In turn, intermittent contact apparently results in fourth bending mode string motions, which, as expected are 180° out of phase.

At the intermediate flow velocities both the 7 Hz and 10 Hz components are attenuated. There is an apparent decrease in the attenuation of the 10 Hz string motion as flow is increased. In previous experiments [6], with flow borne excitation alone, we have observed that the first intermittent contact between the fuel string and flow tube at position 1 occurs at a flow velocity of 9 m/s. As noted in Section 4.3 above, the motion at the higher flow velocities is apparently dominated by flow borne disturbances. The results shown in Figures 6c and d are consistent with this viewpoint.

5. CONCLUSIONS

For the case of a vertical fuel assembly, consisting of a flow tube and a hanging fuel string, subjected to both flow borne excitation and mechanical excitation imposed on the flow tube we have found that:

(i) In the absence of flow the relative motion between the flow tube and fuel string is principally due to flow tube motion with only a relatively small transfer of motion to the fuel string. The resultant fuel string motion appears to be in the fourth bending mode (10 Hz).

(ii) As flow is increased there is an apparent reduction in the effect of the mechanical excitation. In the present experiments, at a flow velocity of 13 m/s, the relative motion between the flow tube and fuel string is determined by the flow borne excitation and the effect of the mechanically imposed excitation is negligible.

Although it appears from the above that the relative motion between the fuel string and flow tube is independent of structural excitation above a limiting velocity, there is no evidence to suggest that the mechanical interaction between these components will not be affected.

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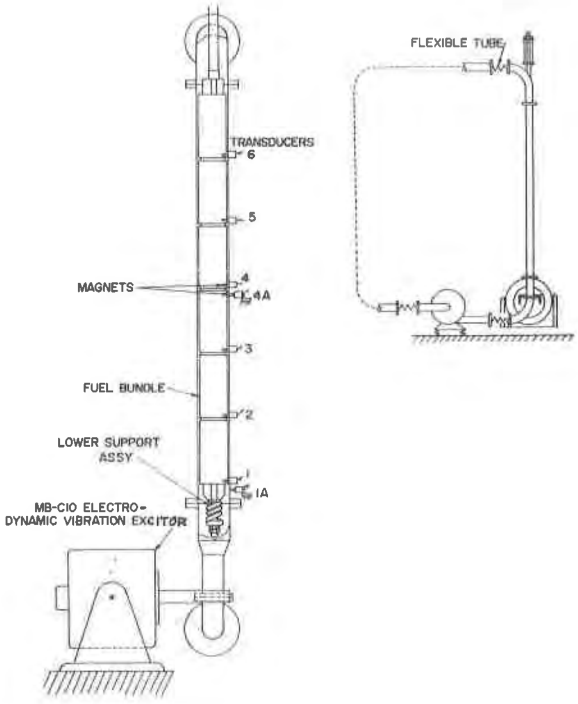

Figure 1 Schematic drawing of the experimental apparatus.

Figure 2 CANDU fuel bundle with lower spring support assembly.

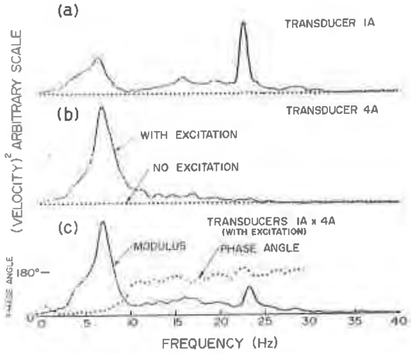

Figure 3 Velocity Spectral density functions for the flow tube motion.

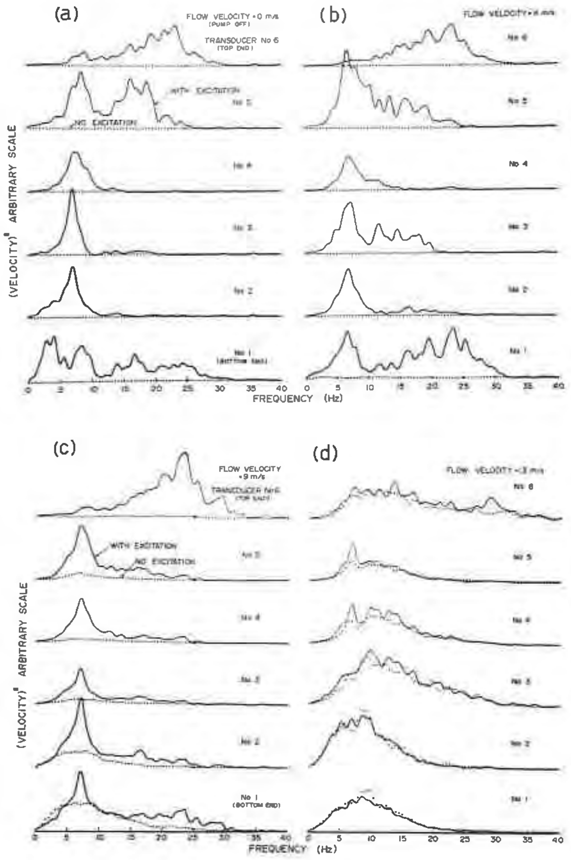

Figure 4 Velocity spectral density functions for the relative motion between the fuel string and flow tube.

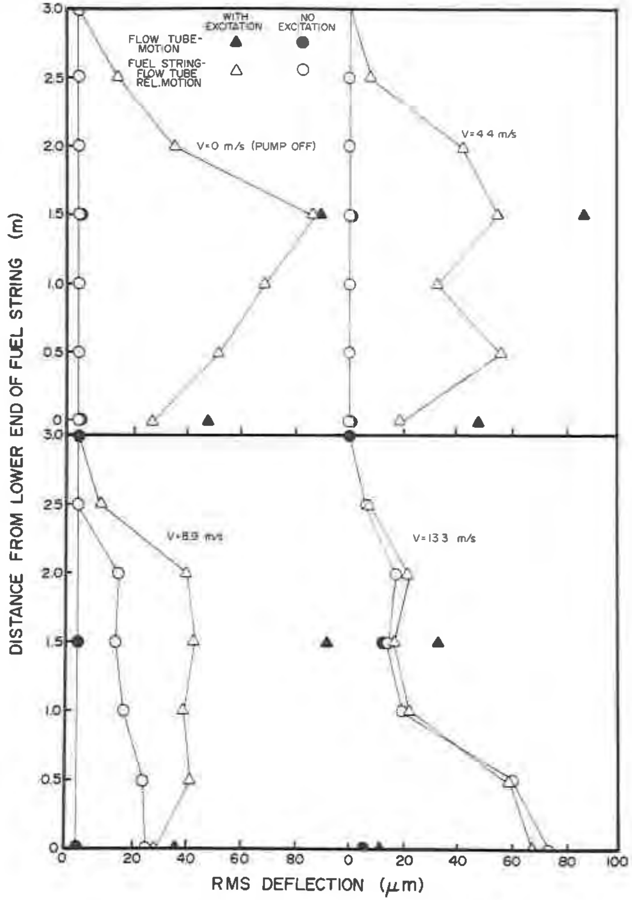

Figure 5 RMS displacements.

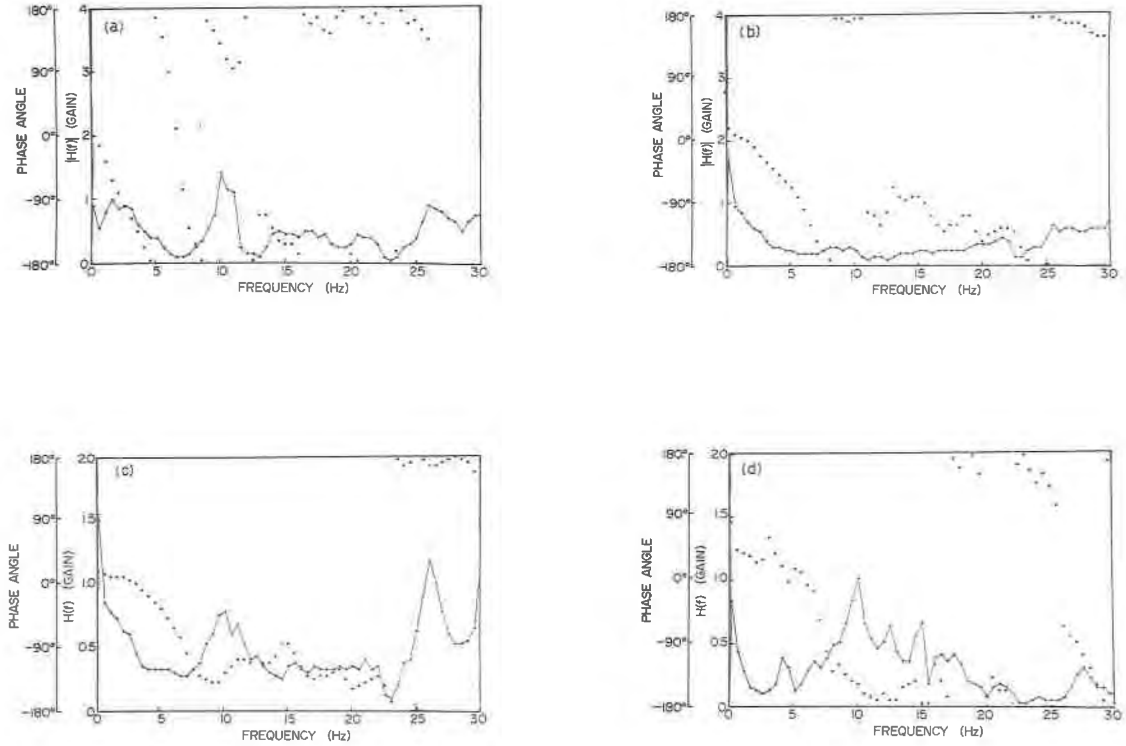

Figure 6 Fuel string to flow tube frequency response functions:
+ - + - gain, * * * phase angle.