AN EXPERIMENTAL STUDY OF VIBRATION OF A CLUSTER OF FLEXIBLE HOLLOW CYLINDERS IN AXIAL AIR-WATER FLOW

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Abstract

Experiments have been carried out to measure the vibration response of a cluster of 7 air-filled, thin-walled tubes representing part of a nuclear fuel element structure. The vibration of the tubes was detected by a strain gauge device fitted inside each tube.

The fluid mass flux varied over the range 186 to 371 $kg.m.^{-2}s.^{-1}$ and the volumetric flow ratio (β) varied between 0.50 and 0.94. Vibration of the tubes reaches a maximum at a value of β which depends only slightly on the mass flux and, for the tests reported in this paper, these maxima occur for values of β between 0.86 (at 186 $kg.m.^{-2}s.^{-1}$) and 0.80 (at 371 $kg.m.^{-2}s.^{-1}$).

The results can be summarised by a simple empirical expression relating the value of the vibration level (S), relative to its maximum value at a specific mass flux, as a function of β; thus

$$S = K\beta^{n}(1-\beta).$$

Other published data, obtained in steam-water, air-water and nitrogen-water experiments, are consistent with the above expression. The formulae may be of use in estimating the change in vibration levels to be expected when the operating conditions of a nuclear reactor are altered.

1. Introduction

The mechanical vibration of cylindrical reactor fuel elements has received the attention of a number of workers over the last fifteen years. Most of the early workers, led by Burgreen, Byrnes and Benforado [1] concentrated on the vibration of rods induced by the flow of water in parallel flow.

In the flow of a liquid the pressure fluctuations, which are the driving forces, are considered to arise from general turbulence and the lateral movement of eddies. In the two phase case, the cause of the pressure fluctuations is much more complex and may be due to vapour bubble growth and collapse as well as the fluctuation in momentum caused by the very different densities of the liquid and the vapour phases.

A mixture of air and water is thought to be a suitable fluid to simulate the momentum fluctuation part of the driving forces and was first used by Gorman [2] to study the vibration of a single rod in parallel flow. Gorman also gives some data generated by Pettigrew, who measured the vibration of a boiling water reactor fuel element in SAWFT loop operating at 520°F. Cedolin [3] used a mixture of nitrogen and water in his simulated experiments and Harris and Holland [4] used an air-water mixture in an experimental study of the response of a cylindrical cantilever. Harris and Holland, although presenting results only up to a value of volumetric flow ratio β of 0.3, argued theoretically that, if the flow regime remains bubble-like over the whole range, then the vibration level would be proportional to $\beta(1-\beta)$, the form being independent of the particular geometry of the test assembly.

The work reported in this paper used empty (i.e. air-filled) tubes as representing part of a fuel element cluster. Although the natural frequency of vibration would be very different from that of a real fuel element, the damping, which is mainly dominated by the fluid, would be roughly similar to a reactor situation with vertical upward coolant flow. The necessary assumption is that the spectrum of the driving forces must encompass the dominant natural frequencies inherent in the mechanical assembly. This implies that, even if the frequency response of the assembly is changed, for example by loading with internal weights, the relative response would be invariant, even though the absolute vibration level might change.

From background experiments by the authors, it was found that, in the frequency domain, the driving forces over the experimental range of volumetric flow ratios and mass fluxes were in the form of band-limited white noise which occupied the frequency spectrum from about 1 to 20 Hz; so that a wide range of variation in the natural frequency response of the test assembly, in this frequency range, could still be expected to produce a similar, relative vibration response.

2. Experimental Apparatus and Procedure

A schematic diagram of the experimental apparatus is shown in Figure 1 which contains essential information relating to physical sizes and flow rates.

The vibration of each tube was detected by a strain gauge carrier inserted into the bore of each tube. Although this carrier stiffened the tube locally, and thus reduced the effect of the vibration, as the stiffened section was very short compared to the length of the tube and only relative results were sought, this effect was ignored.

The output from the strain gauge system was suitably amplified and the R.M.S. level of vibration determined by averaging with an RC circuit with a time constant of about 30 seconds. As the fundamental mode of vibration was around 2.5 Hz, this averaging time was taken to be sufficiently long.

The air and water were mixed together by injecting the air into the water via a cylindrical distributor with six radial holes. The mixing unit was seven diameters upstream of the start of the test assembly and this was judged to be a sufficient number of diameters by observing the resulting flow pattern visually. The volumetric flow ratio β of air to total flow was chosen at the start of each run and allowed a few minutes to settle before readings of the vibration were taken.

Each run was taken sequentially at constant water flow rate (and hence essentially constant mass flux) and varying air flow rate over the value of β from 0.50 to 0.94. This range of β was chosen to have a similar range to that encountered in nuclear reactors. Each run was repeated ten times and the results presented as an average value of these ten runs.

3. Experimental Results

In Table 1 below, the time-averaged output (S, arbitrary units) from a typical strain gauge unit as a function of mass flux and volumetric flow ratio β, is tabulated. Each set of data is normalised by assigning the value of 100 to the maximum response occurring when β is varied at constant mass flux. In this way, the effect of changing the mass flux is suppressed and the relative relationships made clearer.

For comparison purposes, the data of Pettigrew, Gorman and Cedolin are treated in the same way and included in the table. Relative vibration data, obtained from experiments by Harris and Holland 5 , are also included in Table 1. Some extrapolation was necessary to normalise the data, as these experimental results did not quite reach the probable maximum vibration zone ($0.80<\beta<0.88$), but it was thought useful to include this extra data to show the trend at low values of β.

4. Discussion of Results

Consideration of the model proposed by Harris and Holland, i.e. that the R.M.S. value of vibration S should be proportional to $\beta(1-\beta)$, led intuitively to the suggestion that a modified form might be more consistent with the experimental results. Several modifications were tried and, by a process of elimination, the simplest one that seemed to fit the data reasonably well was $S = K\beta^n(1-\beta)$.

Accordingly, a plot of log $S/(1-\beta)$ versus log β is given in Figure 2 which shows that grouping the data around three separate lines appears reasonable. The appropriate values of the factors K and n are:

$n = 5.2$, $K = 1470$, $0.70<\beta\leqslant0.94$
$n = 2.6$, $K = 580$, $0.30<\beta<0.70$
$n = 1.3$, $K = 114$, $0.16<\beta<0.30$

The data of Pettigrew, Gorman and Cedolin are also plotted in this same way and, in the range of β above 0.7, their data is consistent with that presented here. This could lend support to the suggestion that momentum fluctuations caused by moving mixtures of vapour (or gas voids) and liquid are the dominant driving force in two phase flow induced vibration. The relative data from Harris and Holland [5] are not inconsistent with the

Table 1

Summary of Available Experimental Results

Symbol used on Fig. 2		ɸ	∅	□	△	●	■	▼	+	⊕	⦶	⊖
Source		1	1	1	1	2	2	3	4	5	5	5
Mass Flux $kg.m.^{-2}s.^{-1}$		186	247	314	371	?	?	170	1100	750	1350	1950
Mass Flow $kg.h.^{-1}$		4100	5450	6920	8180	18800	40700	3100	?	1370	2460	3570
*Q	β	Relative Vibration Level S										
	0.16	-	-	-	-	-	-	-	-	-	-	10
	0.21	-	-	-	-	-	-	-	-	-	12	-
	0.25	-	-	-	-	-	-	-	-	-	-	16
	0.32	-	-	-	-	-	-	-	-	18	-	-
	0.33	-	-	-	-	-	-	-	-	-	25	-
	0.34	-	-	-	-	-	-	-	-	-	-	28
	0.42	-	-	-	-	-	-	-	-	-	34	-
	0.45	-	-	-	-	-	-	-	-	32	-	-
	0.47	-	-	-	-	-	-	-	-	-	-	48
0.02	0.50	45.5	58.0	49.2	58.8	-	-	-	-	-	-	-
	0.52	-	-	-	-	-	-	-	-	43	-	-
	0.56	-	-	-	-	-	-	-	-	51	67	52
0.03	0.60	60.9	76.2	67.8	81.0	-	-	-	37	-	-	-
	0.65	-	-	-	-	-	-	-	-	-	65	-
0.05	0.70	79.4	90.5	88.0	94.6	69	60	53	53	90	-	-
	0.78	-	-	-	-	-	-	-	-	84	-	-
0.10	0.80	94.5	99.2	99.4	100	94	91	85	83	-	-	-
0.11	0.82	96.8	99.6	100	98.9	-	-	-	-	-	-	-
0.12	0.83	-	-	-	-	100	100	98	-	-	-	-
0.13	0.84	98.9	100	98.6	96.6	-	-	-	-	-	-	-
0.15	0.86	100	98.6	95.6	93.1	99	98	100	97	-	-	-
0.20	0.88	-	-	-	-	83	82	87	100	-	-	-
0.24	0.90	95.4	91.0	85.0	81.6	-	-	-	95	-	-	-
0.25	0.91	-	-	-	-	58	-	68	-	-	-	-
0.40	0.94	85.5	76.6	67.6	62.2	-	-	-	-	-	-	-

Source: 1 Winsbury & Ledwidge
2 Pettigrew
3 Gorman
4 Cedolin
5 Harris & Holland

*Q = Approximate equivalent steam mass flow rate fraction (simulated quality) rest of the data in the range of β below 0.7.

It should be noted that, although the results have been presented with the volumetric flow ratio β as a parameter, a simple relationship between this value and the equivalent steam mass flow rate fraction (Q - simulated quality) exists [2] and indeed was used to convert the data of Pettigrew, Gorman and Cedolin into volumetric flow ratios so that they could be compared to the data presented in this paper.

The reason why transition regions occur is not clear, but may be related to changes in flow regime. Bennett [6], who investigated flow patterns produced by boiling in a 12.7 mm bore tube at 6.89 MPa, showed that the transition between bubbly and slug flow was almost independent of the mass flux and depended only on the thermodynamic quality. This fact may help to explain why data taken at very different mass fluxes with different test assemblies in different rigs are very similar in form.

5. Conclusions

1. The vibration amplitude of the arrangement of flexible tubes appears to reach a maximum level of vibration for a volumetric flow ratio in the range 0.80 to 0.88 (which in a typical reactor corresponds to a steam quality of about 0.1 to 0.2).
2. Previously published experimental work by others, using different test assembly geometries and different fluids, has very similar features to that reported here.
3. The empirical expression used in this work may be of use in estimating the change in vibrational level that may be brought about by a change in reactor operating conditions.

6. Acknowledgements

Mr. N. Reed collected and tabulated the data and played a large part in developing the strain gauge devices, Mr. G.W. Herfurth assisted with the electronic equipment and the A.A.E.C. Workshops constructed the mechanical equipment.

7. References

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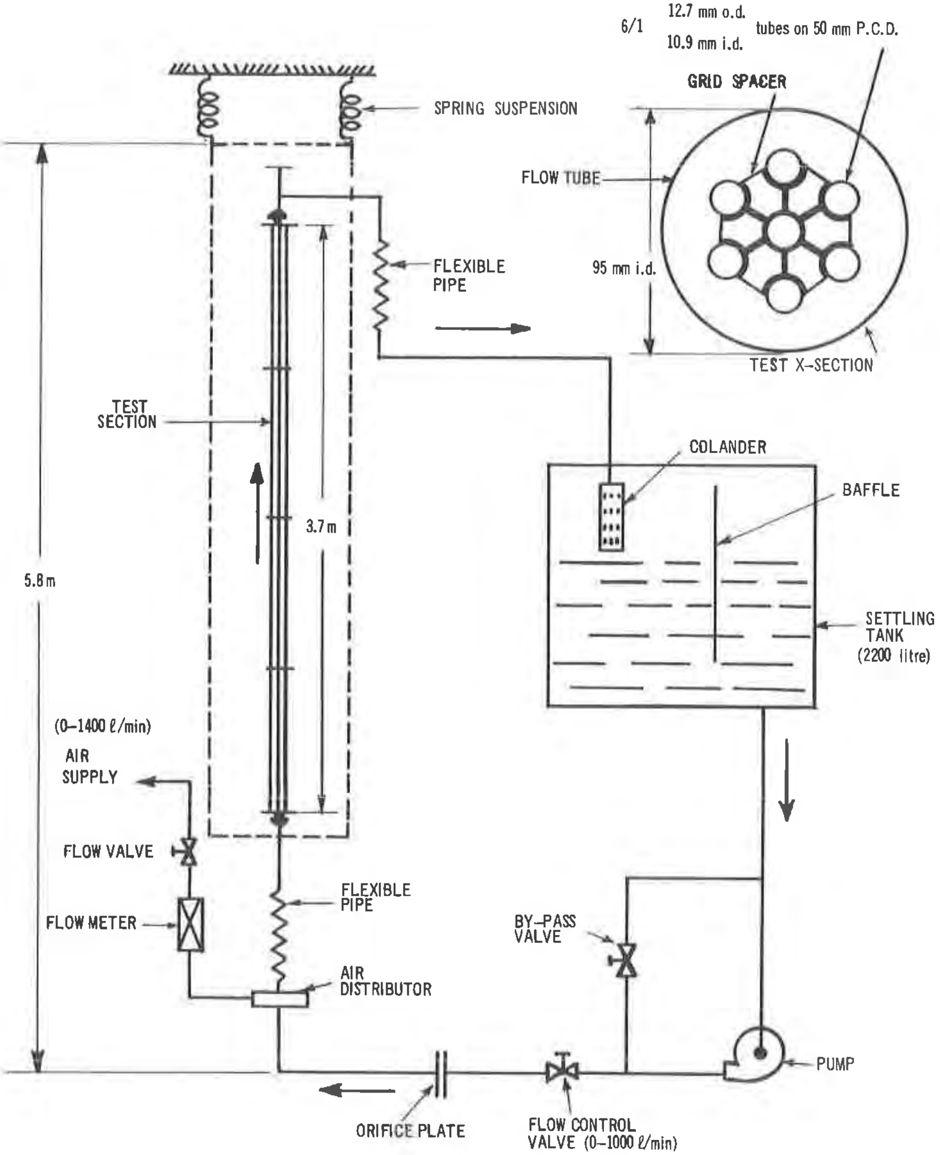

Figure 1

Schematic Diagram of Test Rig

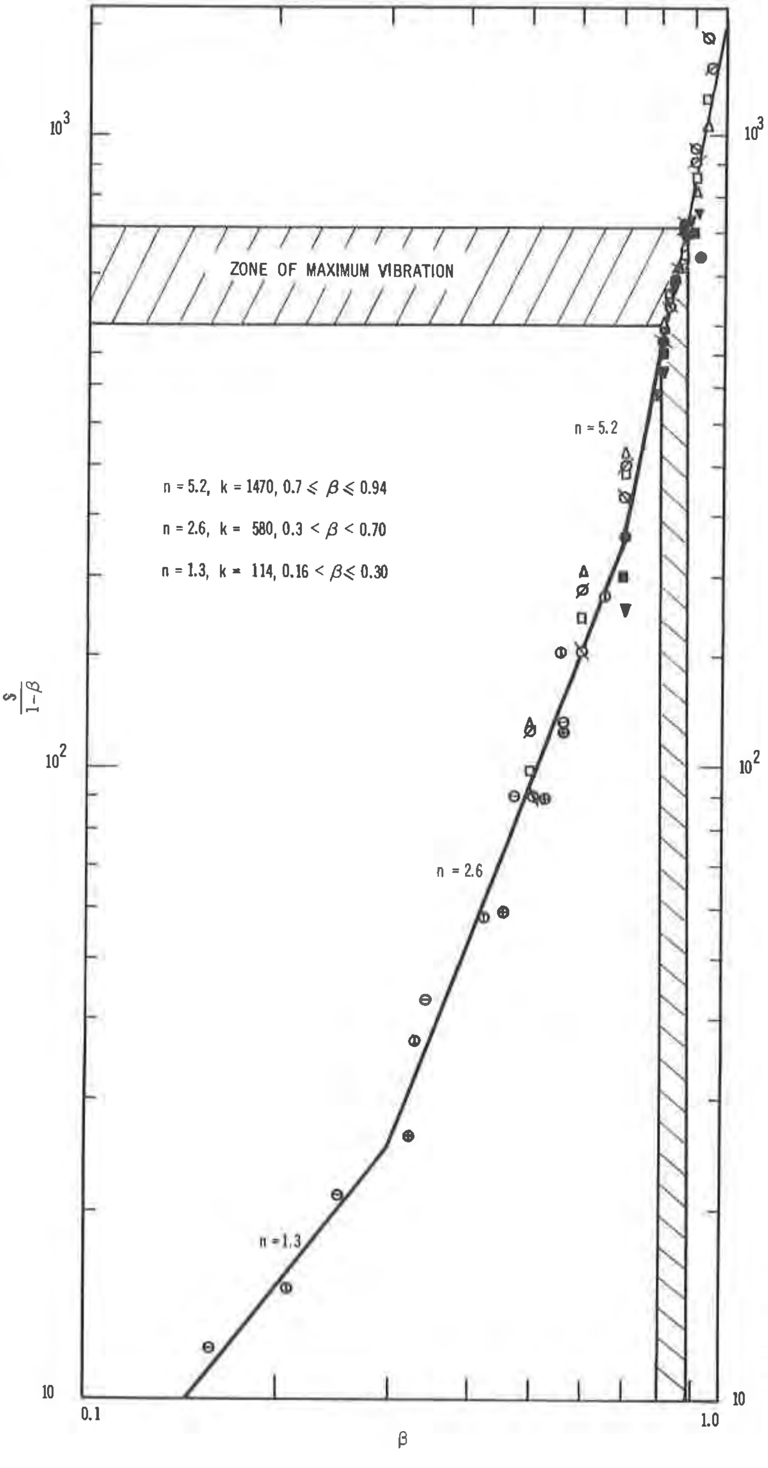

Figure 2

Correlation of Available Data