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EXPERIMENTAL STUDIES ON FLOW INDUCED VIBRATION TO SUPPORT STEAM GENERATOR DESIGN

PART I: VIBRATION OF A HEATED CYLINDER IN TWO-PHASE AXIAL FLOW

by

M.J. PETTIGREW and D.J. GORMAN

Paper presented at
the International Symposium on Vibration Problems in Industry,
10-12 April 1973, Keswick, England.

Chalk River Nuclear Laboratories

Chalk River, Ontario

May 1973

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EXPERIMENTAL STUDIES ON FLOW INDUCED VIBRATION TO SUPPORT STEAM GENERATOR DESIGN*

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M.J. Pettigrew
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SUMMARY

An exploratory vibration experiment on a heated cylinder in axial flow was conducted in a steam/water test loop. Vibration measurements were taken under various flow conditions while steam was either added at the inlet of the test section or generated by the heated cylinder.

The contribution of subcooled and bulk nucleate boiling noise to vibration amplitude were investigated. The effects of other flow parameters such as pressure, mass flux and steam quality were also studied.

The results show that the vibration response appears highly dependent on flow regime. Nucleate boiling noise did not cause excessive vibrations in this experiment.

Chalk River Nuclear Laboratories
Chalk River, Ontario
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Etudes expérimentales sur la vibration engendrée par l'écoulement pour faciliter la conception des générateurs de vapeur*

Partie I: Vibration d'un cylindre chauffé dans un écoulement axial biphasé

par

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Résumé

Dans une boucle d'essai vapeur/eau, on a effectué une expérience de vibration explorative sur un cylindre chauffé avec écoulement axial. Des mesures de vibration ont été effectuées dans diverses conditions d'écoulement tandis que la vapeur était, soit ajoutée à l'entrée de la section d'essai, soit engendrée par le cylindre chauffé.

La contribution du bruit d'ébullition, en sous-refroidissement et en nucléation, à l'amplitude de la vibration a fait l'objet d'une enquête. Les effets d'autres paramètres d'écoulement, comme la pression, le flux de masse et la qualité de la vapeur, ont également été étudiés.

Les résultats montrent que la réponse à la vibration semble dépendre fortement du régime d'écoulement. Le bruit d'ébullition en nucléation n'a pas causé de vibrations excessives dans cette expérience.

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PART I: VIBRATION OF A HEATED CYLINDER IN TWO-PHASE AXIAL FLOW

1. INTRODUCTION

Recirculating type steam generators with "U" bend tubes are used in CANDU-PHW* reactors(1). Two-phase axial flow exists on the shell side of the steam generators. As intense heat is transferred, subcooled nucleate boiling and bulk nucleate boiling** occur somewhere along the outer surface of the tubes. To what extent nucleate boiling noise contributes to vibration excitation is not clearly understood.

So far two-phase flow induced cylinder vibration investigations have been conducted in adiabatic test facilities and primarily in simulated steam/water flow in gas/liquid test loops(2,3,4). An opportunity to conduct an exploratory experiment to study the effect of boiling noise arose following a two-phase flow experiment(5) in which a heated cylinder was used in a steam/water loop. Vibration measurements of the cylinder were taken under various flow conditions while steam was either added at the inlet of the test section or generated by the cylinder. The effects of nucleate boiling and flow parameters such as pressure, mass flux and steam quality on the vibration response of the cylinder were investigated. The experiment yielded valuable results although the test section was not ideally suited for vibration studies.

2. EXPERIMENTAL

2.1 Flow Conditions and Test Section

The flow conditions of interest are those of a typical steam generator. For example, in the axial flow region of a Bruce steam generator, the mass flux, the maximum heat flux, the maximum steam quality and the pressure are respectively 0.35×10^6 lb/h.ft^2, 82×10^3 BTU/h.ft^2, 20% and 620 psig.

The experiment was conducted in a steam/water loop called FLARE. As this loop is discussed in detail elsewhere(5), it is only briefly described here. The FLARE loop is a steam/water recirculating system consisting of a test section, pump, boilers, condenser, controls and data acquisition system. The loop can supply from 200 to 5000 lb/h of water. Steam which can be added at the test section inlet is generated by boilers at a power rate of up to 200 kW electrical. With the test section used in this experiment, the loop

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* CANDU-PHW: CANADA Deuterium Uranium - Pressurized Heavy Water.

** The term "bulk nucleate boiling" is used here to describe nucleate boiling occurring above saturation whereas "subcooled nucleate boiling" occurs below saturation.

was limited to 1.3 x 10^6 lb/h.ft^2 at 815 psia and at a steam quality of 15% (adiabatic).

The test section is sketched on Figure 1. It consists of an 0.77 in. OD heated cylinder installed in a 1.125 in. ID tube. This forms a concentric annulus into which subcooled water or steam and water enter radially at the bottom.

The test cylinder is in two portions. The upper portion is effectively a 2 ft long solid stainless steel cylinder (EI = 0.488 x 10^6 lb.in^2; W = 0.134 lb/in.) clamped at the top closure. The lower portion is a 10 ft long, 1/16 in. thick wall nickel cylinder (EI = 0.260 x 10^6 lb.in^2; W = 0.091 lb/in.) of which the upper four feet are heated with an inner electrical coil of more than 100 kW capacity. The lower six feet provide sufficient distance for proper flow development. It is held below the heated section by several three-pin type supports. The two portions are rigidly secured together.

2.2 Instrumentation

Two integral lead weldable strain gauges ("Microdot" Model No. SG-125) were installed on the test cylinder to measure the dynamic strains induced by transverse vibration. The strain gauges were connected to a carrier wave amplifier. The amplifier output was recorded on light sensitive paper and analysed with a constant percentage (6%) bandwidth spectrum analyser.

As the amplitude of the vibration signal was of a random nature, the mean square value was obtained by squaring and integrating the signal over a period of time T = 60s. The operation was done on-line with an analog computer. It was done several times to ensure the repeatability of the results. Before squaring, the signals were fed through a band-pass filter set at 5 Hz to 100 Hz to eliminate undesirable D-C shift due to thermal transients and high frequency extraneous noise.

3. RESULTS AND DISCUSSIONS

3.1 General

Approximately 180 tests were done at different flow conditions. The effect of the various flow parameters on the vibration response of the heated cylinder are presented below.

First, it is necessary to qualify the results. The test section was not designed for vibration studies. The boundary conditions were not well defined. It is possible that the relatively large (0.156 in. D) weldable strain gauge juctions acted like a simple support at the center of the heated portion of the cylinder. We could not dismiss that possibility from the accumulation of dimensional tolerances.

To analyse the results, we considered the test cylinder as a stationary linear system forced to vibrate by random pressure fluctuations due to the flow around it. We made sure that the system and its boundary conditions remained unchanged throughout the experiment. This was done by comparing the frequency spectra from test to test and by repeating some tests at different times throughout the experiment. Repeatability was better than ± 10% (standard deviation $\sigma = 5.5\%$). The above approach permitted us to compare the results at least relatively. The results are simply presented in terms of measured RMS dynamic strains. Because of the uncertainties in the boundary conditions, we did not attempt to deduce the vibration amplitudes from the dynamic strains*. Typical dynamic strain traces are presented in Figure 2.

3.2 Effect of Flow Parameters

In the two-phase flow tests and at 100% steam quality (single phase vapor), the dominant frequency was 48 Hz. This may be seen in the typical frequency spectrum shown in Figure 3. In liquid flow the dominant frequency was roughly 40 Hz. This frequency difference is well explained by the added mass in liquid flow. The frequency ratio, f_1/f_2, corresponds closely to the inverse of the square root of the mass ratio, $(W_2/W_1)^{\frac{1}{2}}$, assuming no added mass in two-phase flow and calculating the added mass in liquid flow following Stokes as reported by Fritz(6) for a cylinder in an annulus (i.e., $f_1/f_2 = 1.2$; $(W_2/W_1)^{\frac{1}{2}} = 1.21$).

We note from the frequency spectra that most of the vibration signal is at the fundamental natural frequency. This is expected, since flow induced random excitation energies are generally absorbed by lightly damped mechanical systems at their natural frequency.

The effect of mass flux on the amplitude of vibration may be seen on Figure 4 for a system pressure of 800 psig. The maximum vibration amplitudes taken from Figure 4 and from similar data for 600 psig are plotted on Figure 5. It shows that the maximum vibration amplitude is roughly proportional to the mass flux. Amplitude/mass flux relationships must be interpreted with care in two-phase flow because the amplitude is also largely dependent

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* To get a rough idea of the magnitude of vibration, consider a simply supported cylinder of the same frequency and of similar mechanical properties (i.e., $f = 48$ Hz, $EI = 0.374 \times 10^6$ lb.in^2, $W = 0.112$ lb/in., $L = 34.3$ in). In such a cylinder, a dynamic strain of 1 $\mu\varepsilon$ Root Mean Square would correspond to a midspan amplitude of 0.32×10^{-3} RMS.

on steam quality and flow regime as discussed below.

The effect of system pressure and steam quality on vibration amplitude at a mass flux of 0.35×10^6 lb/h.ft^2 is shown on Figure 6. Figure 4 shows the effect of quality and Figure 5 the effect of pressure at higher mass fluxes. The vibration amplitude generally decreases with increasing pressure in two-phase flow.

The amplitude of vibration is generally largest at qualities between 10 and 25%. This is in agreement with earlier results (2). The quality for maximum vibration amplitudes is lower at higher mass fluxes or at lower pressures. The quality dependent peaks in the curves (Figures 4 and 6) are also sharper at higher mass fluxes and lower pressures. At lower mass fluxes, it was operationally possible to attain high steam qualities. A second slightly smaller peak in vibration amplitude was observed between 40 and 50% steam quality.

3.3 Flow Regime Considerations

It has been mentioned before (2) that the vibration behaviour of components in two-phase flow is dependent on flow regime. This experiment provides further supporting evidence.

Flow regimes may be categorized for the purpose of this discussion as follows (7):

(1) Liquid Flow

(2) Bubbly/Slug Flow: in which the liquid phase is continuous and the vapor is distributed in the form of bubbles or slugs. This flow regime occurs at relatively low void fraction or low flow velocity.

(3) Annular Flow: in which the liquid phase is continuous in a layer along the walls while the vapour phase is continuous in between. This flow regime occurs at high void fraction and high flow velocity.

(4) Dispersed/Fog Flow: in which the vapour phase is continuous with dispersed liquid droplets.

We postulate that the first peaks in the vibration amplitude vs steam quality curves occur at the quality corresponding to the transition between bubbly flow and annular flow. Two-phase flow regime investigations show that the steam quality at which this transition occurs is lower for higher flow velocities or higher void fractions (7,8,9). Accordingly, Figures 4 and 6 show that at higher velocities the peaks occur at lower qualities. The effect of lowering the pressure, or effectively increasing the void fraction and flow velocity, is also to lower the quality at which the cylinder vibrates most. Hence, maximum vibration amplitudes evidently occur at a steam quality related to the transition between bubbly and annular flow.

References 8 and 9 generally indicate that the transition should occur at lower qualities than those found in this study. However, this may be attributed to a difference in geometry (annulus vs free channel).

The second peak in vibration amplitude observed at lower mass flux and at steam qualities between 40% and 50% is more difficult to explain. We postulate that this peak corresponds to the transition between annular and dispersed flow. Figure 3-3 of Reference 7 shows that this transition occurs at roughly the above flow conditions.

The results presented in Figure 6 are plotted against mean flow velocity in Figure 7. Under the conditions of these tests, mean flow velocity and void fraction are approximately related. Figure 7 shows that for each pressure the maximum and minimum vibration amplitudes occurred at roughly the same mean velocity. As flow regimes are strongly dependent on flow velocity, the above further emphasizes the flow regime relationship in two-phase flow induced vibration.

Vibration amplitudes also decrease with increasing pressure. This cannot be explained in terms of flow regime changes alone. It is probably related to changes in the fluid properties due to the difference in pressure and associated temperature.

Forrest and Sandig(10) have done similar vibration tests on a 68 Hz, 19.5 in., single element in adiabatic steam/water flow at higher mass fluxes. Their results shown on Figure 8 indicate similar pressure and steam quality effects.

In summary, the vibration response vs steam quality relationship of a cylinder in axial flow for a given mass flux appears as follows. At low steam quality, bubbly/slug flow regime exists and the vibration amplitude increases with increasing quality until it reaches a maximum. This is reasonable since higher vibration amplitudes are expected at the higher velocities related to higher steam qualities. The maximum amplitude corresponds to the start of the transition between bubbly/slug and annular flow regime. As the quality is increased, annular flow regime is established. This flow regime is presumably less turbulent and the vibration amplitude reaches a minimum. As the quality is increased further, the flow velocity and consequently the vibration amplitude increases again to reach another maximum. This maximum corresponds to the transition between annular flow and dispersed/fog flow regime. The vibration amplitude decreases again to a minimum as fog flow regime is established. Further increase in quality resulting in higher flow velocity would likely cause a further increase in amplitude until 100% quality is reached.

3.4 Effect of Nucleate Boiling Noise

The cylinder was heated in an attempt to investigate the contribution of nucleate boiling noise as a vibration excitation mechanism. The cylinder heat flux was varied from 0 to 500 x 10^3 BTU/h.ft^2. For constant values of mean* qualities greater than 10%, the effect of bulk nucleate boiling at the surface of the cylinder is negligible. This is shown on Figure 9 primarily for a mass flux of 0.350 x 10^6 lb/h.ft^2. The same behaviour was observed at higher mass fluxes (see Figure 9 and also appropriate data points on Figure 4).

Some tests were done to study the effect of subcooled nucleate boiling and bulk nucleate boiling at low quality. The mean quality was varied from -6.5% to 3% while keeping the inlet subcooled at -6.5%. The results were not clear since at such steam qualities part of the signal could be attributed to deformation of the strain gauge structure due to bubble collapse or boiling occurring underneath the weldable strain gauge flange. Whatever the origin of the signal, the maximum measured amplitude of the cylinder under subcooled nucleate boiling conditions was not larger than the maximum amplitude observed in two-phase adiabatic flow.

3.5 Relevance of the Results to the Designer

Under the conditions existing in the axial flow region of a typical steam generator (i.e., 600 psia and 0.35 lb/h.ft^2), the amplitude of vibration is relatively independent of steam quality. The maxima in vibration amplitude observed at certain steam qualities are small from a practical point of view and are mainly interesting from a fundamental point of view.

The effect of nucleate boiling noise appears to be small at steam qualities greater than 10%. Under subcooled nucleate boiling conditions, the vibration amplitude should be no greater than in two-phase flow.

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* The mean quality is defined by the average of inlet and outlet qualities.

Some of the results may also apply to the design of nuclear fuel for CANDU-BLW* type reactors. Although we were not able to attain the high mass fluxes of BLW fuel channels (i.e., 3×10^6 lb/h.ft^2) we were able to simulate realistic heat fluxes. The maximum heat flux in BLW fuel elements is 310×10^3 BTU/h.ft^2(100 W/cm^2). The vibration response of the elements is probably not much affected by nucleate boiling noise.

The designer should bear in mind the limitation of the above results. The results were obtained on a 48 Hz single cylinder whereas actual components are bundles of cylinders of various frequencies. Fortunately the natural frequencies of fuel elements and of steam generator tubes are not too different from 48 Hz (i.e. 45 Hz and > 30 Hz respectively). In large multi-cylinder bundles, mass transfer between subchannels is likely. This may be caused by non-uniform heat fluxes. Transverse flow velocity components would result. Possible vibration excitation due to transverse flow components are not at all considered here.

4. CONCLUSIONS

The results of an exploratory vibration experiment on a 48 Hz heated cylinder in axial two-phase flow show that:

1) The vibration response of the cylinder appears highly dependent on flow regime. Two maxima in vibration amplitude occur; the first and more prominent one at steam qualities between 10 and 25% and the other between 40 and 50%. The maxima appear to be related to the transition between bubbly/slug flow and annular flow, and to the transition between annular flow and dispersed/fog flow respectively.

2) The amplitude of the vibration maxima is roughly proportional to mass flux. The vibration amplitude generally decreases with increasing system pressure.

3) At qualities greater than 10%, the contribution of nucleate boiling to vibration excitation is negligible. Subcooled nucleate boiling does not excite the 48 Hz cylinder more than adiabatic two-phase flow at the quality corresponding to maximum amplitude.

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* BLW: Boiling Light Water.

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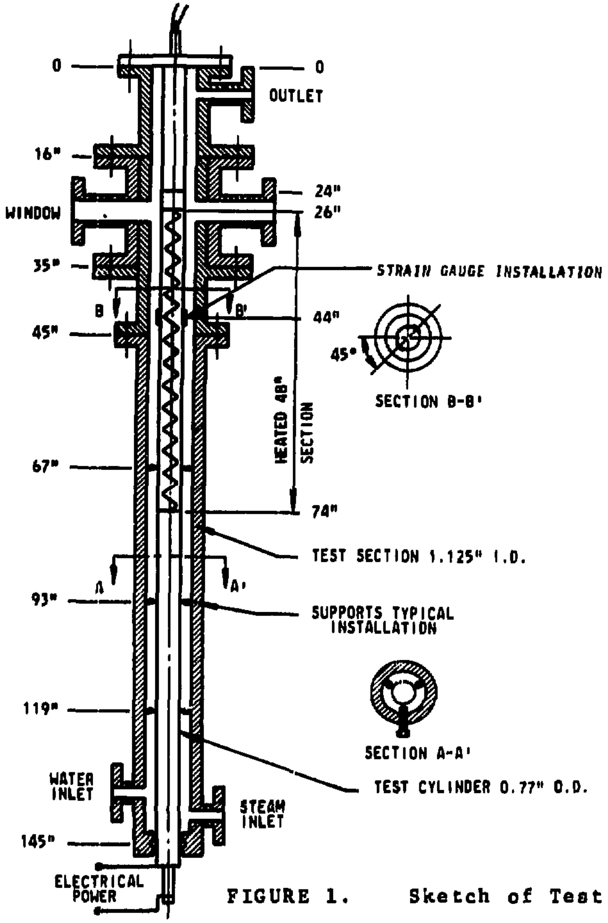
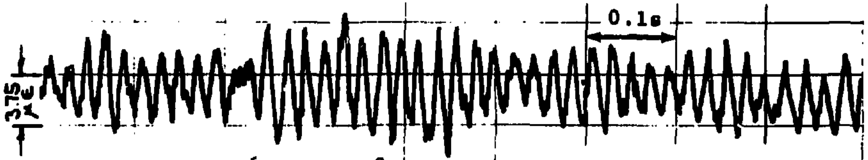


FIGURE 1. Sketch of Test Section.



Flow: 1.3 x 10^6 lb/h.ft^2 X_{in}: 10% X_{out}: 20%

Flow: 1.3 x 10^6 lb/h.ft^2 X_{in} = X_{out}: - 6.5%.

FIGURE 2. Typical Vibration Induced Dynamic Strain Traces.

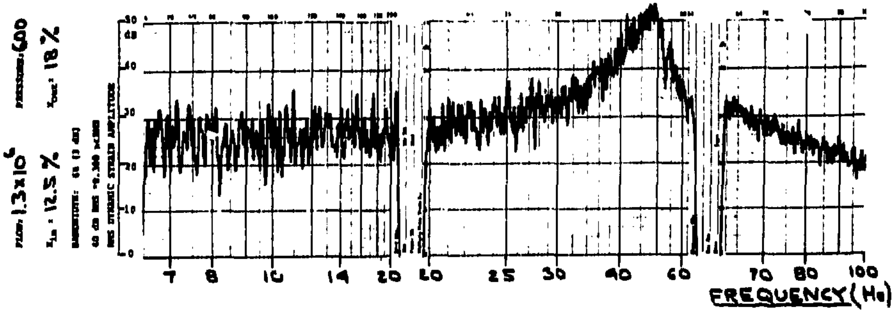


FIGURE 3. Selected Frequency Spectrum.

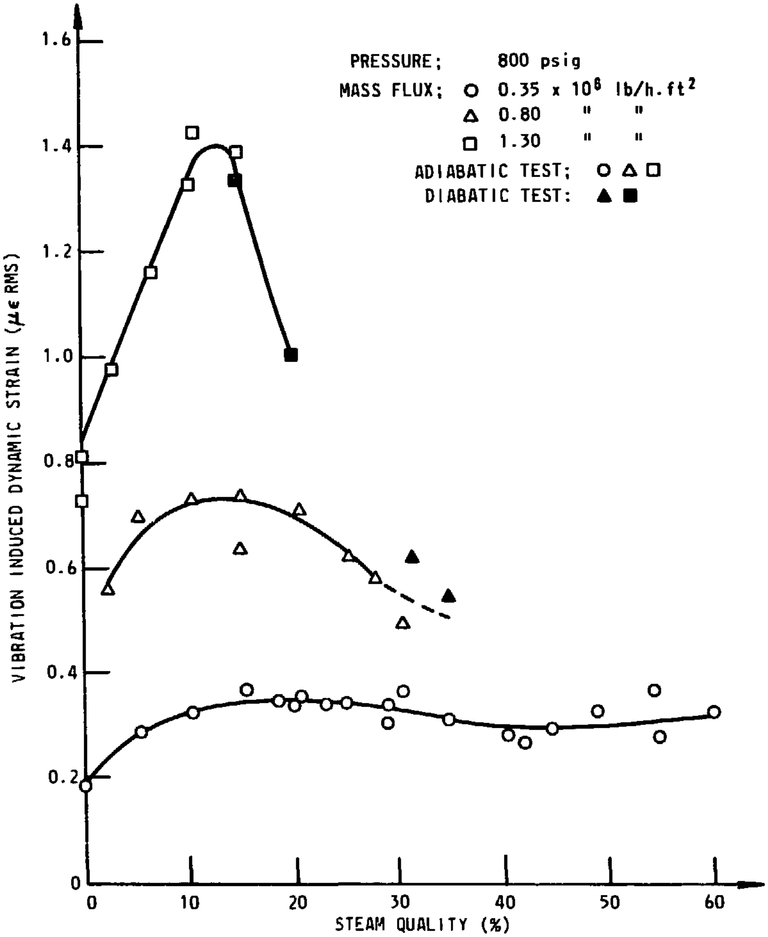


FIGURE 4. Effect of Steam Quality and Mass Flux on Cylinder Vibration.

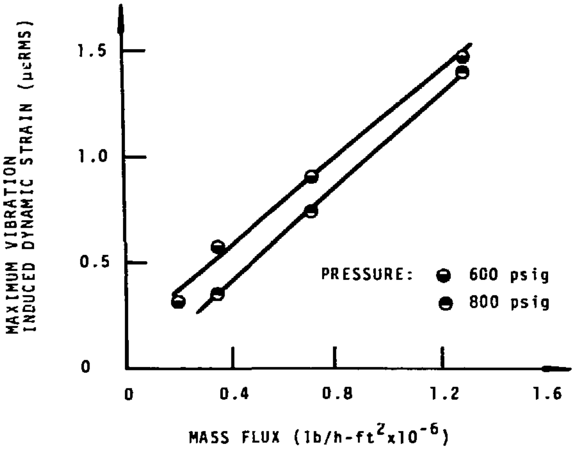


FIGURE 5. Effect of Mass Flux and Pressure.

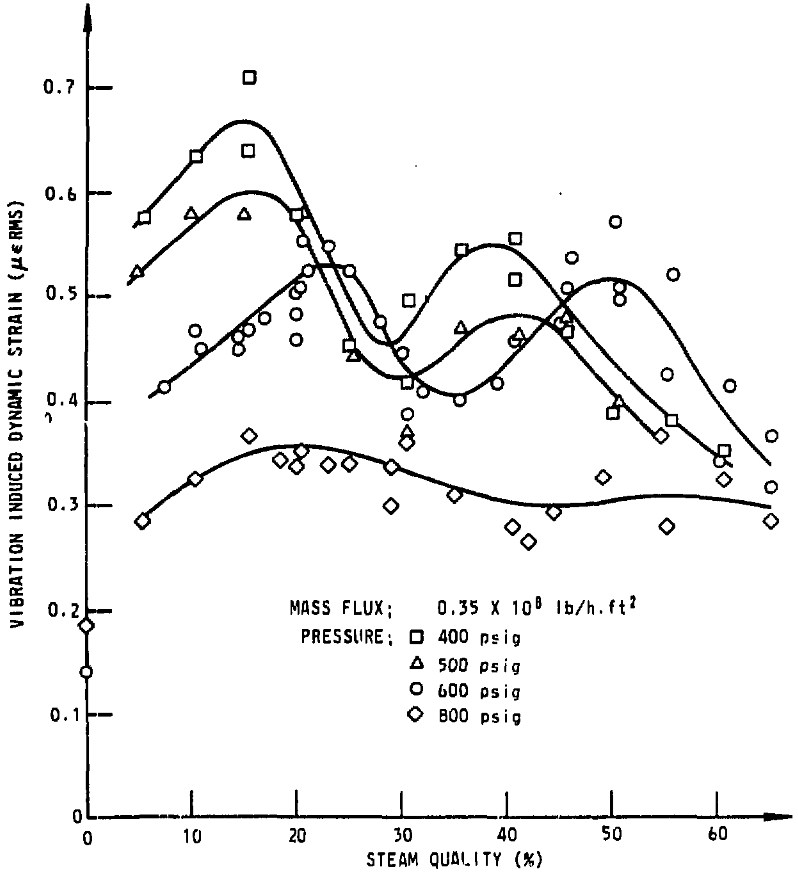


FIGURE 6. Effect of Steam Quality and Pressure.

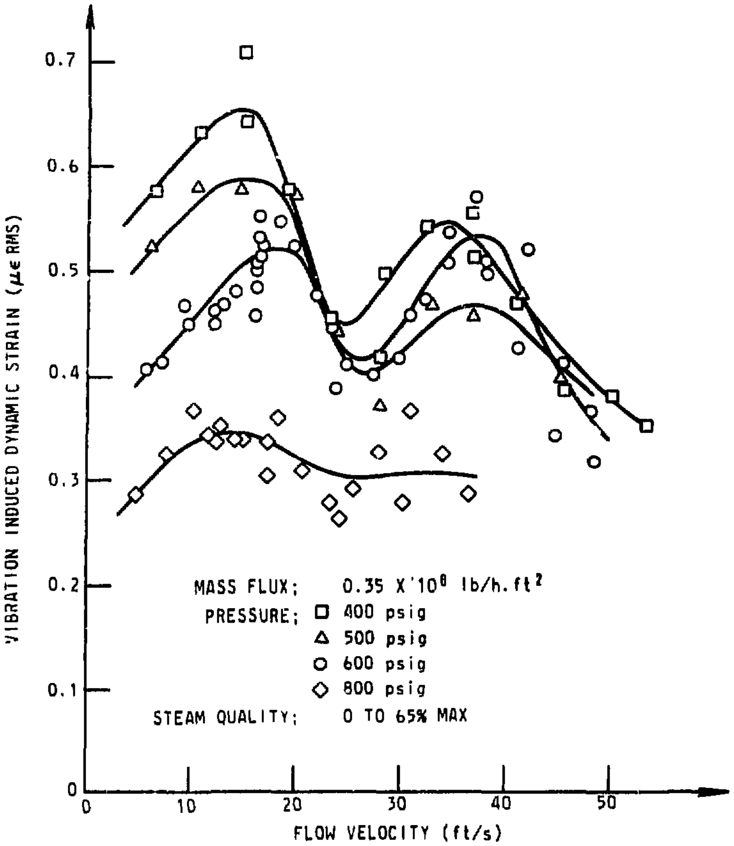


FIGURE 7. Effect of Flow Velocity and Pressure.

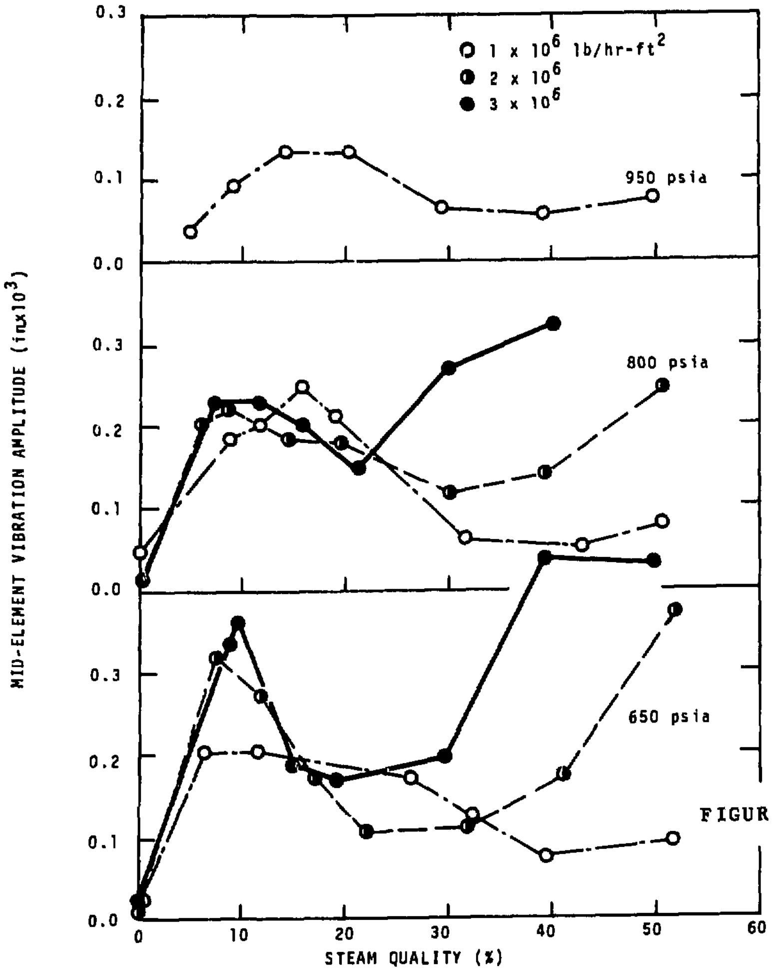


FIGURE 8. Forrest and Sandig's Results$^{(10)}$: Effect of Steam Quality, Mass Flux and Pressure on the Vibration Response of a Single 68 Hz Cylinder.

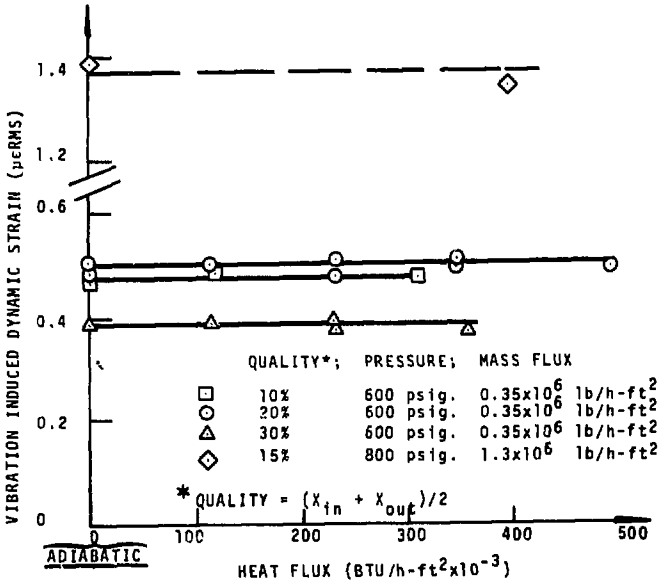


FIGURE 9. Effect of Nucleate Boiling on Cylinder Vibration.

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