# Experimental Study of Flow Induced Vibration of a Model Fuel Assembly

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1. Introduction

The flow induced vibration of fuel assemblies is an important problem in reactor technology. A lot of research works had been performed at home and abroad. The object of our experiment is to measure the natural frequencies and amplitudes of multispan fuel rods in the test loop directly.

For understanding the different factors which affect the flow induced vibration of the fuel assembly, several preliminary tests have been arranged.

2. Static and dynamic behaviour of the fuel assembly

2.1 Static stiffness test of the fuel assembly

The test rig is shown in Figure 1. Based on the measurement of deflections and weights for different cross sections, the mean value of static stiffness ($2.22*10^5 N-m^2$) of the fuel assembly is obtained.

2.2 Natural vibration test and analysis of the fuel assembly, fuel rod and guide tube

(1) The natural vibration test of the fuel assembly is performed in the test rig of static stiffness. The experimental value of the fundamental frequency for the fuel assembly is 5.5 Hz and the damping ratio is 0.4%. The theoretical fundamental frequency of the fuel assembly using the above stiffness is 5.47 Hz.

In the calculation the effective length, the mass per unit length and the static axial force are 3.367m, 135kg/m and 9378N respectively.

(2) Measurement of the natural frequencies of the fuel rod and the guide tube

The measurement system of the natural frequencies for the fuel rod and the guide tube is shown in Figure 2. The structural parameters and the experimental and theoretical values(Han, 1982)are given in Table 1 and Table 2.

2.3 Virtual mass test of the zircaloy tube in stagnant water

Using single span zircaloy tubes instead of the fuel rods, the experimental data of the natural frequencies for the zircaloy tubes are obtained as thown in Table 3.

The experimental values of the virtual mass ratio approximately equal to the theoretical values (Chen, 1972) and the constrained conditions have no significant effect on the natual frequencies of zircaloy tubes in water.

3. Experimental study of the flow induced vibration of the fuel assembly

The test loop is shown in Figure 3. The amplitude of the vibration of the test rig without the model fuel assembly is lower than 0.12mm.

Table 1 Structural parameters of the fuel rod and the guide tube

| component | mass per unit length (kg/m) | outside diam. (cm) | inner diam. (cm) | spring constant tens. or comp | torsional |
|---|---|---|---|---|---|
| | | | | N/m | N-m |
| fuel rod | $m_1=0.300, m_2-m_7=0.697$ | 1.00 | 0.86 | $1.07*10^7$ | $3.32*10^2$ |
| guide tube | 0.154 | 1.29 | 1.19 | $\infty$ | $5.14*10^4$ |

Table 2. The natural frequencies of the fuel rod and the guide tube

| No. of mode | fuel rod | | guide tube | |
|---|---|---|---|---|
| N | experimental | theoretical | experimental | theoretical |
| 1 | 59.5 | 60.3 | 372 | 322.1 |
| 2 | 64.3 | 65.3 | 379 | 375.4 |
| 3 | 68.4 | 71.7 | 384 | 377.2 |
| 4 | 78.1 | 80.0 | 388 | 379.5 |
| 5 | 92.8 | 89.1 | 395 | 381.9 |
| 6 | 98.4 | 96.7 | 406 | 383.7 |
| 7 | 130.7 | 144.3 | 409 | 482.9 |
| 8 | 185.1 | 184.1 | 1006 | 888.0 |

Table 3. The natural frequendies and the mass ratios of the zircaloy tube

| end condition | mode 1 | | | mode 2 | | | mode 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | F(Hz) | | mass ratio | F(Hz) | | mass ratio | F(Hz) | | mass ratio |
| | A | W | $m_w/m_r$ | A | W | $m_w/m_r$ | A | W | $m_w/m_r$ |
| free end | 252 | 207 | 56% | 679 | 554 | 52% | 1326 | 1079 | 52% |
| elastic-supported | 277 | 217 | 63% | 785 | 624 | 58% | 1509 | 1209 | 56% |

A: in air
W: in water

The strain gauge locations for the fuel rods and the measurement system are shown in Figure 4 and Figure 5. The waterproved and insulated strain gauges had been preliminarily checked in a water tunnel with high flow rate. The flow rates are 3.43, 4.73, 5.68, 6.61 and 7.57m/s. Based on the readout of the dynamic frequency spectrum meter, the root mean square value of the strain corresponding to a central frequency is obfained for different flow rates, i.e.

$$\left.\begin{aligned} \epsilon(f_i) &= \epsilon_0 10^{\frac{dB}{20}} \\ W(f_i) &= \frac{\epsilon^2(f_i)}{\Delta f_i} \\ \bar{\epsilon}^2 &= \Sigma W(f_i)\Delta f_i = \Sigma \epsilon^2(f_i) \end{aligned}\right\} (1)$$

where dB—decibel number
$\epsilon(fi)$ —rms of the strain with central frequency fi

$\epsilon_0$ — calibrated value of strain with zero dB

$W(f_i)$ —experimental power spectrum density of strain with central frequency $f_i$

$\bar{\epsilon}$—rms of the strain in reading range

The distribution of the experimental power spectrum densities are shown in Figure 6. The peak values of $W(f_i)$ are located at 60Hz. This demonstrates that virtual mass has no significant effect on the natural frequencies of the fuel rods which have smaller mass ratio than that of empty zircaloy tube. For pertubing pressure with white noise the following relations are established.

$$\left.\begin{aligned} \bar{Y}^2 &= \sum_{N=1}^{\infty} \frac{\pi S_{PN}}{2\zeta_N \omega^3{}_{WN}} Y_N^2 \\ \bar{\ddot{Y}}^2 &= \sum_{N=1}^{\infty} \frac{\pi S_{PN}}{2\zeta_N \omega^3{}_{WN}} \ddot{Y}_N^2 \end{aligned}\right\} \qquad (2)$$

$$\left.\begin{aligned} S_{PN} &= \lim_{\Delta f \to 0} \lim_{T \to \infty} \frac{1}{\Delta f T} \int_0^T Q_{N,\Delta f}^2 (t)\, dt \\ Q_N(t) &= \frac{\sum_1^n \int_0^{L_i} q(x,t) Y_{Ni}\, dx_i}{\sum_1^n (m_i + m_{wi}) \int_0^{L_i} Y_{Ni}^2\, dx_i} \\ 2\zeta_N \omega_{WN} &= \frac{c \sum_1^n \int_0^{L_i} Y_{Ni}^2\, dx_i}{\sum_1^n (m_i + m_{wi}) \int_0^{L_i} Y_{Ni}^2\, dx_i} \end{aligned}\right\} \qquad (3)$$

Where $\bar{Y}$ and $\bar{\ddot{Y}}$ are the amplitude and its second derivative with respect to the axial Coordinate respectively. "i" denotes the ith span, and N the mode number, W means water, C means Viscous damping factor, $\zeta$ the damping ratio, $\omega$ the circular frequency, q(x,t) the pertubing pressure, and n the span number of elastic-supported Continuous beam. If the difference in damping ratios between the different modes is neglected and only the dominant frequencies of the fuel rods with flow induced vibration are considered, the approximate relations are obtained.

$$\bar{Y}/\bar{\ddot{Y}} \approx Y_1(x_i)/\ddot{Y}_1(x_i)$$

$$\epsilon \approx \ddot{Y} \frac{D_2}{2}$$

$$Y_i(x_i) \Big|_{\text{experimental}} \approx \frac{Y_1(x_i)}{\ddot{Y}_1(x_i)} \cdot \frac{2\bar{\epsilon}_{\text{experimental}}}{D_2} \qquad (4)$$

For example, the theoretical values of $Y_i(x_i)/\ddot{Y}_i(x_i)$ for the middle point of the 7th span are 187.9, 177.2, 164.2, 148.3, 133.5, 122.5, 64.4 etc. It shows that the rms value of the amplitude calculated with Formula (3) is conservative. The relations between the strain and velocity are shown in Figure 7. The amplitude is proportional to 1.63th power of the flow velocity. The corresponding one-dimensional stresses are smaller than the endurance limit of the zircaloy tube by two orders of magnitude. Therefore, the effect flow induced vibration on the fuel rod life would be negligible.

## 4. Conclusion

Analyzing the experimental data, we can summarise as follows:

(1) The fundamental natural frequencies of the fuel assembly, the fuel rods and the guide tubes differ by orders of magnitude from each other, Coupling phenomenon of the fuel rods with the fuel assembly or the guide tubes has not been discovered.
(2) The flow velocities and the virtual masses have no significant effect on the natural frequencies of the fuel rods.
(3) The effect of the flow induced vibration on the fuel rod life would be negligible.
(4) The flow induced vibration of the fuel assembly is an ergodic process and the components of lower natural frequencies of the fuel rods are dominant.


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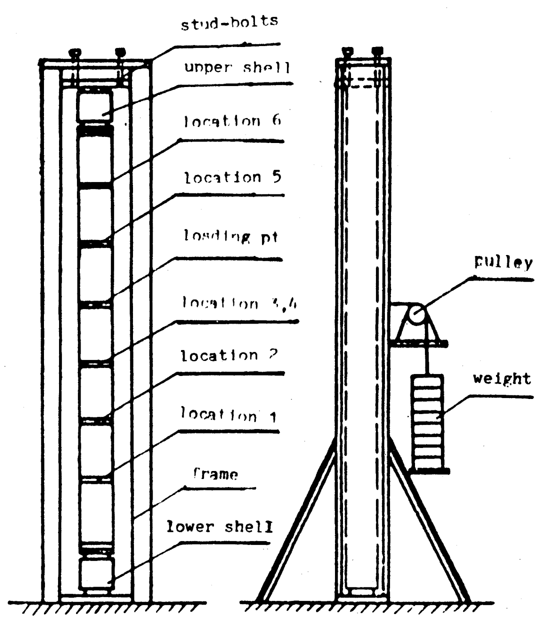


Fig.1 test rig of static stiffness.

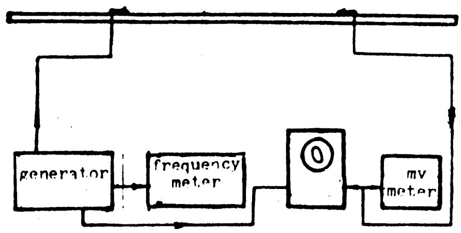


Fig.2 measurement system for natural vibration.

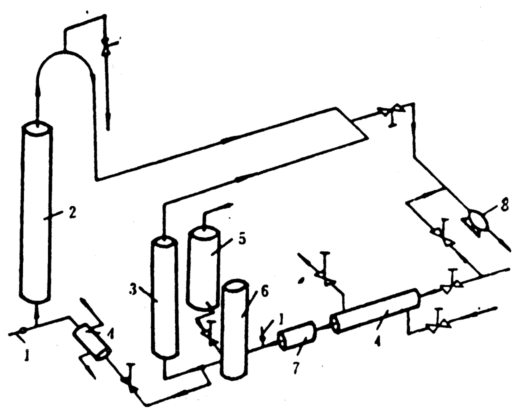


Fig.3 test loop of flow induced vibration for fuel assembly.

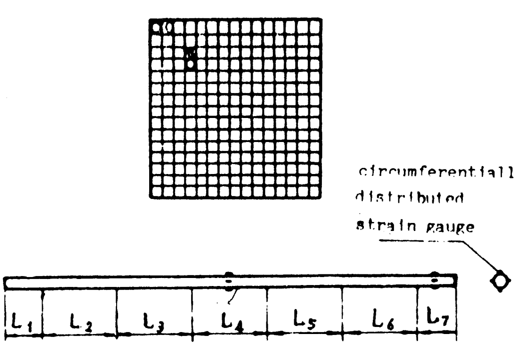


Fig.4 strain guage location.

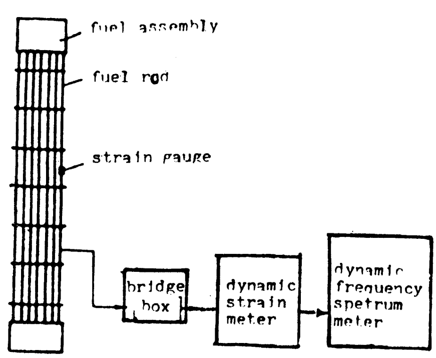


Fig.5 measurement system for flow induced vibration.

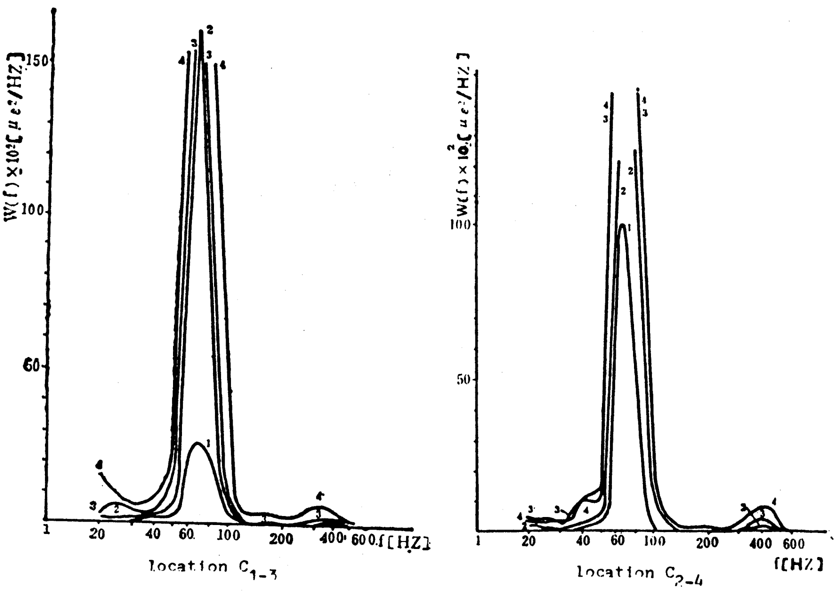


Fig.6 strain power spectrum density curves.

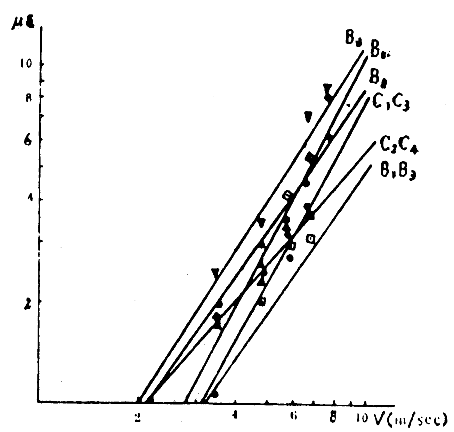


Fig.7 relation between strain and velocity.