EXPERIMENTAL STUDY OF THE VIBRATIONS OF A FUEL PIN MODEL IN PARALLEL TWO-PHASE FLOW

F. HARA

Department of Mechanical Engineering,
Tokyo University of Science, Shinjuku-ku, Tokyo, Japan

SUMMARY

In the work of this paper are reported the results of experiments concerning the excitation mechanism of the vibrations of a fuel pin model in parallel two-phase (air + water) flow and it is experimentally concluded that the parametric excitation mechanism plays an important role in the vibrations of a fuel pin model which is inserted in air-water parallel two-phase flow.

The essential part of the experimental apparatus consists of an elastic flat strip made of stainless steel, which is clamped at its both ends in a cylindrical channel conveying the air-water two-phase fluid. The experiments are made for fifty cases of conditions of air and water flow rates and the following physical quantities are measured:

1. Vibrational strains of the fuel pin model at the point 100 mm away from its downstream end;
2. Pressure fluctuations of the two-phase flow on both surfaces of the fuel pin model at its midpoint;
3. Void-signals of the two-phase flow which distinguish the air from the water at the points 100 mm and 150 mm away from the downstream end of the fuel pin model, respectively.

From the statistical analyses of these time series data, the author obtains

1. the relation between the variance of the vibrational strains which denotes vibration intensity and the two-phase flow velocity,
2. the relation between the fundamental natural frequency ω_0 of the fuel pin model and the dominant arrival frequency ω_s of water slugs in the two-phase flow, and
3. the relation between the vibration intensity and the variance of the fluctuations of resultant pressure difference caused by the two-phase flow pressure acting on both surfaces of the fuel pin model.

The author experimentally finds the fact that there exists a simple relation such as 1/2, 2/2, 3/2,... between the fundamental natural frequency of the fuel pin model and the dominant arrival frequency of water slugs of the parallel two-phase flow when an extraordinarily strong vibration is produced in the fuel pin model by the parallel two-phase flow.

1. Introduction

The vibrations induced by parallel air + water two-phase flow in fuel pin systems are considered to cause the fretting between each fuel element or fuel elements and pressure tubes and also subsequent structural damages to them. This vibration problem is evidently very important not only in design of fuel assemblies but also in an academic field of flow induced structural vibrations. Because from practical view point, the investigation of excitation mechanisms of the flow induced vibrations can play an essential role in the design of vibration prevention devices and the evaluation of the responses is substantially useful to the assesment of frettings between the fuel pin elements, of subsequent erosion of their clad material and of the structural damages due to the vibrations. On the other hand, from scientific view point, the knowledge on the characteristics of air + water two-phase flow has been poorly understood and it is therefore said that the interaction between the two-phase flow and structural systems has become a new engineering problem to be intensively investigated.

Some papers [1] - [2] concerning the two-phase flow induced structural vibrations were presented at the previous SMiRT Conferences. They dealt with experimental evaluation of the vibration response of a fuel pin model or a fuel assembly in the parallel air + water two-phase flow. The investigation of the excitation mechanisms has not sufficiently been done in these papers. Concerning the piping systems, F.Hara studied the excitation mechanism of the two-phase flow induced vibrations and concluded that there exist two causes to excite the vibrations, that is, 1) periodical external force due to the fluctuations of the two-phase fluid density and 2) parametric excitations [3] - [4].

This paper deals with an experimental study on the excitation mechanisms of the vibrations induced by parallel air + water two-phase flow in a fuel pin model. The author will show the conclusions that there exist two causes to the excitation of the two-phase flow induced vibrations, 1) the pressure fluctuations acting on both surfaces of the fuel pin model, which play the role as a random external force, and 2) the virtual mass fluctuations due to the density fluctuations of the two-phase fluid, which produce the so-called parametric excitations to the vibration system of the fuel pin model in the two-phase flow.

2. Experimental Apparatus and Procedures

The general scheme of the experimental apparatus for investigating the vibrations of a single fuel pin model in the parallel air + water two-phase flow is shown in Fig.1. A fuel pin model (M) is made of stainless steel and has rectangular cross section (10 mm x 2 mm), both ends of which are fixed at inlet and outlet ends of the test section of the experimental channel. It locates in the central part with regard to the cross section. The cross section (L) is built up with an acrilic circular pipe with inner and outer diameters of 23.8 mm and 30.0 mm, respectively. The air pressurized by a small compressor (A) is supplied to an air-water mixer (K) through the air flow meter (C), which measures the air flow rate by using a floater. The static pressure of the air flow at the exit of the flow meter is indicated on a manometer (D). On the other hand, the water conducted from a reservoir (E), which is located at the height of 3,284 mm from the ground level, is also pressurized by a pump (G) and flows into a surging tank (I), where the pressure fluctuations can be reduced. The flow rate of the water is measured by an orifice and is indicated as pressure difference on another manometer (J). Then the water enters the mixer (K) and makes the mixture of air + water two-phase fluid. The air + water two-phase fluid flows up to the test section (L) and there it produces the vibrations in the fuel pin system (M). After travelling through the section, the two-phase fluid comes to the tank (E). The air can release to the air and only the water again goes down to the conduit (F).

The flow condition is specified by the flow rates of the air and water, which are regulated by two valves installed at the exits of the air compressor and the pump. The 56 combinations of each flow rate are employed in this experimental study and shown in Table 1.

(1) Photographic Observation of the Two-Phase Flow Patterns

The flow modes of the air + water mixture in a virtical circular pipe depend strongly upon the mixing ratio of both fluids, the flow velocity and the inner diameter of the pipe. In order to categolize the two-phase flow modes into several groups, the pictures of the flow patterns are taken by a camera at the midpoint of the test section. This experiment is done for the 56 cases of the flow condition.

(2) Void-Signals

Besides the photographic observation of the two-phase flow patterns, the essence of the flow modes can be extracted through the measurement of void-signals, which are two-valued signals and can distinguish the air from the water. A plutinum electroprobe having a sharp end and composing an bridge circuit can detect the difference of electric resistance between the both fluids. Consequently the void-signals can offer the information about whether or not a certain point in space indicated by the electroprobe is occupied with the air. Two sets of the electroprobes are installed at the points of 85 mm and 185 mm away from the down stream end of the test section. The electric signals obtained by these void meters are recorded on magnetic tape and converted into digital form in order to calculate their statistical measures such as variance, power spectral density and so on.

(3) Pressure Fluctuations

The pressure fluctuations of the two-phase flow are considered to play a role of stochastic loading in exciting the vibrations of the fuel pin model. Two small pressure gauges ($6^{\phi} \times 0.5^{t}$, 2 Kg/cm^2) are firmly attached on both surfaces of the pin model at its midpoint. The electric signals of these pressure fluctuations are amplified by DC amplifiers and recorded on magnetic tape for use of statistical data processes. After the transformation of these data into digital form, the pressure difference between the both sides of the fuel pin model is calculated and then the stochastic loading due to the pressure fluctuations is evaluated by using this pressure difference.

(4) Vibrational Strains

The vibrational strains produced by the two-phase flow fluctuations in the fuel pin model are the most important information for the study on excitation mechanisms of the vibrations. A strain gauge is pasted on each surface of the pin model at the point 80 mm away from the down stream end of the test section. These two pieces of strain gauges compose one set of a strain detecting senser, for one is active for measurement and another is dummy for compasating the temperature fluctuations of the two-phase fluid. After amplifing the electric signals of the strains, they are recorded on magnetic tape for the convienience of further processes of the data.

The void-signals and pressure fluctuations of the two-phase flow and the vibrational strains are quite random in nature. The author employs the following statistical procedures for extracting the essences out of those complicated and random data, which are available to the investigations on the excitation mechanisms of the two-phase flow induced vibrations:

1) The three kinds of these analog data obtained are transformed into digital data by an A - D converter, at which the sampling period is 0.02 sec. and the length of each data is 1,000 digits, which are considered to be sufficient for statistical calculations.

2) The power spectral densities are calculated by using auto-regression method developed by H.Akaike [5]. Simply explaining, when the obtained data are denoted as $x(k)$, $(k = 1, 2, ---, N)$ in discrete form and its estimate $\hat{x}(k)$ is introduced with the relation

$$\hat{x}(k) = \sum_{m=1}^{M} a(m)x(k-m) , \tag{1}$$

where $a(m)$, $(m = 1, 2, ---, M)$ and M are coefficients and a certain number expressing a time in past, respectively, they are determined so that the square sum of the error $e(k) = x(k) - \hat{x}(k)$,

$$\overline{E(\,a(m),\,M\,)} = \lim_{N \to \infty} \frac{1}{N} \sum_{k=1}^{N} e(k)^2 \tag{2}$$

may be minimized. Then the power spectral density of the data $x(k)$ is evaluated by the following

$$p(w) = \frac{h s_x^2}{\left| 1 - \sum_{m=1}^{M} a(m)\exp(-iwmh) \right|^2} , \tag{3}$$

where h is the sampling period.

3) The variance of the pressure difference and/or of the vibrational strains is a good measure of intensity. Assigning $x(k)$ to one of these data, the variance is calculated by the relation

$$s_x^2 = \frac{1}{N} \sum_{k=1}^{N} (\,x(k) - \bar{x}\,)^2 . \tag{4}$$

Here $\bar{x}$ is the average of the data.

3. Experimental Results

3.1 Flow Patterns of the Two-Phase Channel Flow

The result of classification of the photographs obtained at Experiment (1) is shown in Table 2. The typical flow patterns are also shown in Photo 1. In Table 2, the following can be discerned: There exist five typical flow modes in the case of the experimental conditions specified by the air and water flow rates; namely, bubble flow (B), fast bubble flow (B'), slug flow (S), bubble and slug coexisting flow (B + S), and bubble and slug coexisting fast flow (B' + S). In the range of lower volume quality, defined as the ratio of the air flow rate to the total flow rate, that is, of being less than about 0.4, the bubble flow is dominant; the bubble and slug coexisting flow becomes the predominant one in the band region of the volume quality from 0.4 to 0.55; and finally in the range of the quality being larger than 0.55, the slug flow is the prevalent flow mode.

3.2 Wave Forms of Void-Signals, Pressures and Vibrational Strains

The wave forms of the void-signals and pressure fluctuations of the two-phase flow and of the vibrational strains of a fuel pin model are shown in Figs.2 and 3, corresponding to the typical flow modes, the bubble flow and the slug flow, respectively. In the case of bubble flow, the void-signals contain so many spikes for unit time, each of which means an air bubble, and they are thinner and not fully developed. This record describes the following about the flow mode: The air is dispersed in the water flow in the form of small bubbles. Due to the random movement of air bubbles, the pressure fluctuations on both surfaces of the fuel pin model are quite stochastic as shown in this figure. However the vibrations are so periodical as to be recognized the fundamental one of them. On the other hand, Fig.3 can qualitatively show that the air and water slugs travel almost alternately along the channel and the pressure fluctuations are more intensive. The wave shapes of both pressure fluctuations are completely agreed. The strain signals have larger amplitudes and higher periodicity.

For the quantitative evaluation of the vibrations produced by the two-phase flow in the fuel pin system, the 18 cases of the experimental conditions are employed as shown in Table 3. For these experiments from A to R, the following physical quantities are evaluated:

1) Two-phase flow velocity U, which is calculated from using the time lag of the cross correlation function between the void-signals detected at two points shown in Fig.1 and the distance between them;
2) Variance of the vibrational strains S_s^2 , which is evaluated by eq.(4);
3) Variance of the pressure fluctuations S_p^2 ;
4) Variance of the differential pressure fluctuations evaluated from the pressures on both surfaces of the fuel pin model S_{dp}^2 ;
5) Fundamental frequency of the vibrational strain signals ω_0 , which is defined as the frequency corresponding to the highest peak of their power spectral density;
6) Dominant frequency of the void signals ω_s ;
7) Dominant frequency of the differential pressure fluctuations ω_p , in 6) and 7), they are obtained through the same procedure as in 5); and
8) Volume quality α_v , which is defined as $Q_a / (Q_a + Q_w)$.

3.3 Relations of Vibration Intensity with Flow Velocity, Differential Pressures and Volume Quality

In Fig.4, the relation between the variance of vibrational strains S_s^2 , which will be called as vibration intensity,and the flow velocity U is shown. It is found in this figure that there exists a tendency that the vibration intensity is getting stronger in accordance with the increase of the flow velocity. However attention should be paid to the points, A, B, F, M, and R. The first four points A, B, F, and M show an extraordinarily higher vibration intensity comparing with the points having the similar flow velocity as these points, and the point R takes rather lower intensity inspite of its higher flow velocity.

Fig.5 shows the relation between the vibration intensity and the differential pressure fluctuations. As far as the general tendency is concerned, the vibration intensity increases with along the differential pressures, however there exist several peculiar points A, B, F, M, and R as well as in Fig.4. The vibration intensity in point A is about eight times as strong as that of point O despite of its weaker differential pressures. The points B, F, and M show the some stronger vibration intensities than the points indicating the similar inensity of differential pressures.

The relation of the vibration intensity with the volume quality of the two-phase flow is desribed in Fig.6, where it can be recognized that the vibration intensity is getting stronger with the increase of the volume quality in each series of experiments in which only the air flow rate is increased under the condition of fixing the water flow rate at a certain rate.

3.4 Frequency Characteristics of the Vibration Intensity

The dependency of the vibration intensity on the frequency of the differential pressure fluctuations is shown in Fig.7, where the ordinate and the abscissa denote the ratio of two variances, S_s^2 / S_{dp}^2 and the one of the first or second dominant frequency of the pressure fluctuations ω_p to the fundamental natural frequency of the fuel pin model ω_0, ω_p / ω_0 , respectively. For comparison of the experimental results with the theoretical responses of a single mass - spring vibration system, three curves are described on the same graph, each of which is correspondent to the damping coefficient of 0.0, 0.2 and 0.3, respectively. The following can be discerned: Most of the experimental results are considered as the responses of the vibration system excited by some periodical external force due to the two-phase flow pressure fluctuations, however it should be noted again that there exist several outstanding points in Fig.7, that is, the points A, B, J, K, P, and Q. These experimental points can imply the other excitation mechanisms with regard to the vibrations of a fuel pin model in parallel air + water two-phase flow.

In order to subtract the effect of forced vibrations from the experimental results concerning the vibration intensity, the author introduces the following measure:

$$\hat{S}_s^2 = S_s^2 \frac{1 - (\omega_p / \omega_0)^2}{S_{dp}^2} \qquad \text{-----------------------------------} (5)$$

in which the term $1 - (\omega_p / \omega_0)^2$ means the resonance characteristics of the single mass - spring vibration system.

The relation between the newly defined measure $\hat{S}_s^2$ and the dominant frequency of the void-signals ω_s is shown in Fig.8. The very interesting feature can be disclosed by this figure, that is, the measure $\hat{S}_s^2$ takes the higher values at the ratios $\omega_0 / \omega_s = 0.5, 1.0$, and 1.5.

4. Discussions and Conclusions

As the differential pressure acting on the fuel pin model is considered as an external force to the vibration system of the fuel pin, its relation with the flow velocity is shown in Fig.9, where except the point A, the relation can be mathematically expressed by the line described as $S_{dp}^2 = 1.34\ U$. Furthermore the dependency of the differential pressure on the volume quality is also shown in Fig.10. This figure reveals two interesting features: 1) the intensity of the differential pressure fluctuations is getting stronger with the increase of the volume quality when the water flow rate is kept constant, and 2) on the other hand, under the condition of the air flow rate being fixed constant, it decreases with along the volume quality in the case when the slug flow mode is dominant, however it increases against the volume quality in the case of the bubble flow. From Figs.9 and 10, it can be discerned that the differential pressure fluctuations have a rather definite dependency on the flow velocity or the volume quality of the air + water two-phase flow.

The general trend of the vibration intensity against the flow velocity, the differential pressures and the volume quality was described in Figs.4, 5, and 6. In these figures, several distinguishable points were disclosed, which have extraordinarily stronger vibration intensity. However the reason why those points are deviated so much from the general trend is not made clear in those three figures. The attention should be here paid to the dependency of the vibration intensity on frequency characteristics of the two-phase flow and of the vibration system. As shown in Fig.7, most of the experimental points are considered as the result of responses of a single mass - spring vibration system model to a certain periodical external force due to the differential pressure fluctuations. Consequently it can be concluded that one of the excitation mechanisms of the two-phase flow induced vibrations is experimentally found as an external force produced by the two-phase flow pressure fluctuations. The reason why the peculiar points appeared in Fig.7 can be explained by Fig.8. These experimental points have an interesting characteristics that they show extraordinarily higher response ratio at the case when the ratio of the dominant frequency of the void-signals to the fundamental natural frequency of the fuel pin model is 1/2, 1/1, 3/2, and so on. The water slugs arround the fuel pin may play the role of virtual mass in the vibrations of the fuel pin system, then the periodical arrival of the water slugs may cause the so-called parametric excitation to the fuel pin vibration system when the above mentioned ratio takes a certain series of numbers such as 1/2, 1/1, 3/2, --- . In Fig.11, power spectral densities of the vibration strains, the differential pressure fluctuations and the void-signals are shown when the parametric excitation ($\omega_o / \omega_s = 1/2$) was experimentally observed.

The author can conclude the followings about the excitation mechanisms of the vibrations of a fuel pin model in parallel two-phase flow:

(1) There exist two excitation sources producing the vibrations in a fuel pin system; one is an external force due to the pressure fluctuations of the two-phase flow and the other is a periodical change of the virtual mass of the vibration system, which comes from the periodical arrival of water slugs in the two-phase flow.

(2) The pressure fluctuations cause the resonance to the vibration system, consequently the vibration intensity becomes stronger at $\omega_p / \omega_0 = 1.0$.

(3) The periodical arrival of water slugs causes the so-called parametric excitation to the vibration system, therefore when the ratio $\omega_o / \omega_s = 1/2, 1/1, 3/2, ---$, the vibration intensity becomes extraordinarily stronger.

(4) The general trend of the vibration intensity of the fuel pin model has been made clear against the flow velocity, differential pressures and volume quality of the two-phase flow.

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Table I Experimental flow conditions specified by the combination of air and water flow rates

Q_w (l/m)	15	19	25	30	34	38	41	
Q_a (l/m)	10	15	20	25	30	40	50	60

Table II Classification of air + water two-phase flow modes in case of virtical circular pipe

B --- Bubble flow; B' --- Fast bubble flow;
S --- Slug flow; B + S --- Bubble and slug coexisting flow;
B' + S --- Bubble and slug coexisting fast flow

Q_a l/m \ Q_w l/m	10	15	20	25	30	40	50	60
15	B+S	B+S	B+S	S	S	S	S	S
19	B	B+S	B+S	S	S	S	S	S
25	B	B	B+S	B+S	B+S	S	B+S	S
30	B	B	B	B+S	B+S	S	S	S
34	B'	B'	B'	B'	B'+S	B'+S	B'+S	S
38	B'	B'	B'	B'	B'	B'+S	S	S
41	B'	B'	B'	B'	B'	B'+S	S	S

Table III Experimental flow conditions specified by air and water flow rates for quantitative evaluation of the vibrations

Exp.	A	B	C	D	E	F	G	H	I
Q_w (l/m)	15	15	15	15	25	25	24	30	30
Q_a (l/m)	20	40	50	60	20	40	60	25	40
P_o (cmHg)	10.3	13.0	15.0	18.0	14.0	17.0	22.5	17.0	19.5

Exp.	J	K	L	M	N	O	P	Q	R
Q_w (l/m)	34	35	34	34	38	42	41	41	41
Q_a (l/m)	20	30	40	60	50	20	40	50	60
P_o (cmHg)	18.0	19.5	22.0	29.0	28.0	21.5	26.0	30.0	33.5

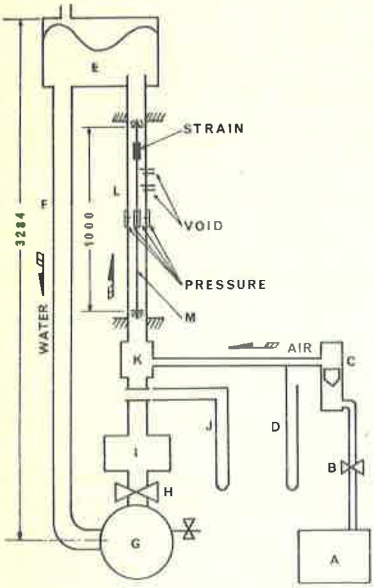
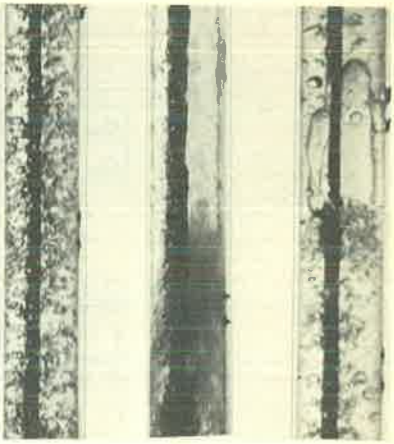


Fig.1 Schematic diagram of the experimental apparatus for studies on the vibrations of a single fuel pin model in parallel air + water two-phase flow



Bubble flow Slug flow Bubble + slug flow

Photo 1 Photographs of typical flow modes of air + water two-phase flow

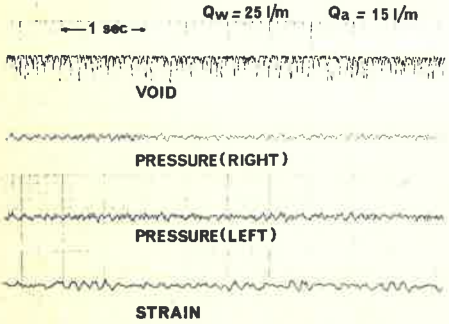


Fig.2 Wave forms of void-signals, pressure fluctuations and vibrational strains in case of bubble flow

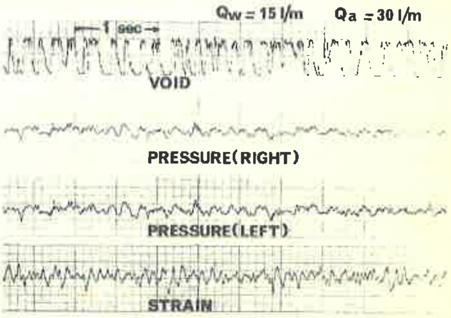


Fig.3 Wave forms of void-signals, pressure fluctuations and vibrational strains in case of slug flow

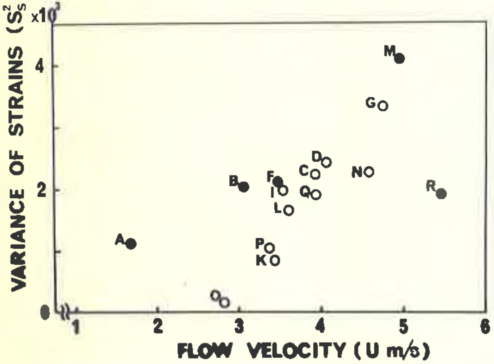


Fig. 4 The relation between vibration intensity and two-phase flow velocity

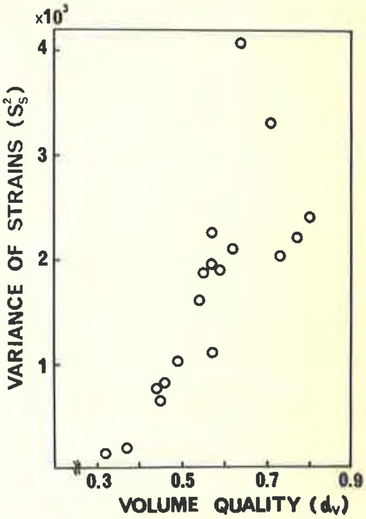


Fig.6 The relation between vibration intensity and volume quality

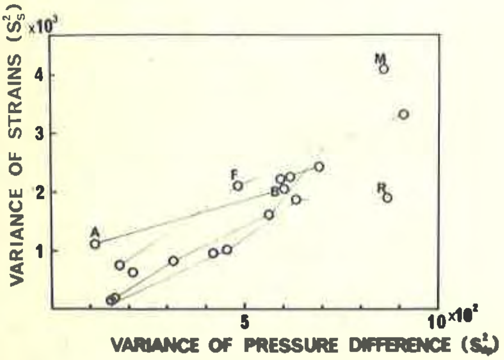


Fig.5 The relation between vibration intensity and differential pressure intensity

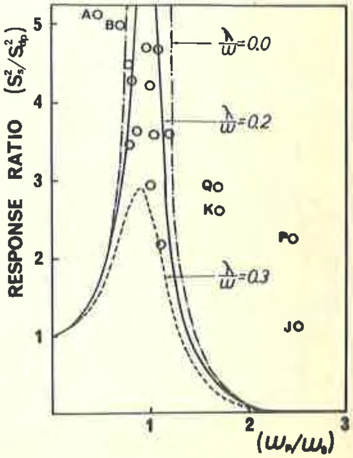


Fig.7 The dependency of vibration intensity on the dominant frequency of differential pressure fluctuations

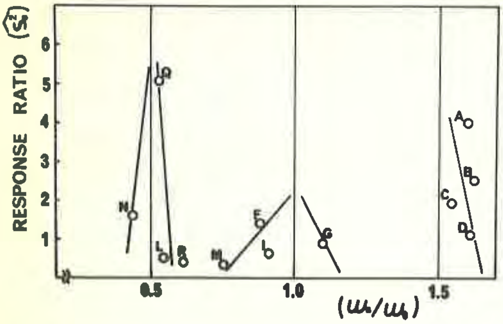


Fig.8 The dependency of vibration intensity on the dominant frequency of void-signals

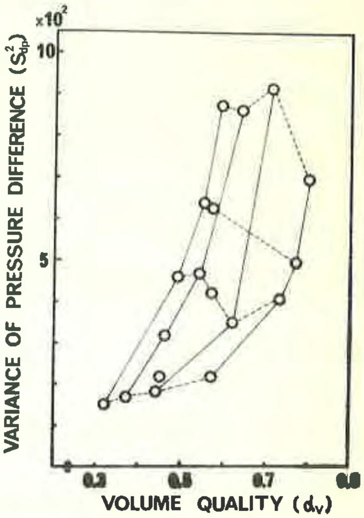


Fig.10 The relation between differential pressure intensity and volume quality

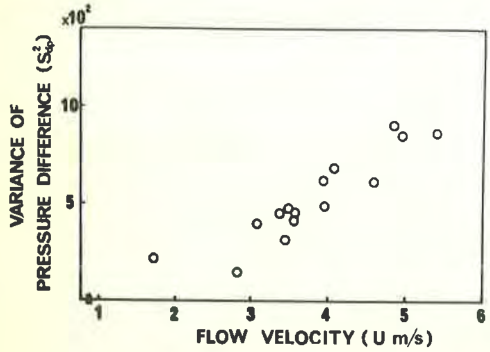


Fig.9 The relation between differential pressure intensity and two-phase flow velocity

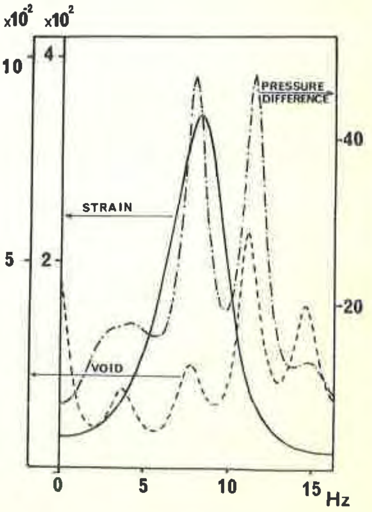


Fig.11 A typical example of power spectral densities of vibration strains, differential pressures and void-signals