Resonant Frequencies in Piping Systems with a Gapped Support

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ABSTRACT

Resonant frequencies in piping systems with a gapped support are discussed through the experiments. A simple estimation method for resonant frequencies is proposed and the results are compared with both the experimnts and calculations using equivalent spring constants.

1 INTRODUCTION

Piping systems in nuclear power plants and other facilities often have some clearance at the supports. These clearances cannot be ignored if low-amplitude vibrations occur and they affect the vibration chracteristics such as resonant frequency, damping factor and, consequently, response of the piping system. An iterative algorithm using an equivalent linearization technique to compute the response of a piping system with gapped supports has been proposed (M.S.Yang et al. 1989). Steady forced vibration in continuous systems with clearance has been analyzed by applying a piecewise-linear method (T.Watanabe 1978). The response of a three-dimensional multi-gap piping system has been calculated by reducing it to a single degree of freedom system (J. P. Vayda 1981). The response of piping support systems with gaps and friction has been calculated from that of a linear piping support system by using a reduction factor (A.Sone and K.Suzuki 1989). Although the response calculation for piping systems with gapped supports is important, it is more important to calculate the resonant frequencies of such systems,in order to avoid resonant vibration. However, hardly any investigations of the resonant frequency of such systems have been carried out by experiments. In this paper, the effects of support parameters on the resonant frequency of a piping system with a gapped support were investigated through experiments using simple piping models. The parameters evaluated were: clearance, eccentricity of the clearance, and piping diameter. A simplified method of estimating resonant frequency is also proposed.

2 EXPERIMENTS

In order to investigate the resonant frequencies in piping systems with a gapped support, simple piping models were tested. A schematic view of the test model is shown in Fig.1. Three different sizes 1/2B,1B, and 2B, were

SMiRT 11 Transactions Vol. J (August 1991) Tokyo, Japan, © 1991

tested. The dimensions of the piping models are given in Table 1. All these piping models were simply supported at one end, A, and fixed at the another end, B. Additional masses were mounted on the pipes at locations D and E. In addition, there was a restraint C with some clearance between the pipe and the support. This clearance was varied in the test. The first natural frequency of these three piping models was designed to be about 6 Hz without support C, and about 10 Hz with a pinned support at location C. So, these were similar to each other. Shaking direction was Y-direction in Fig.1. These were one dimensional model. In the parametric calculations in latter section, it was also calculated about the case of a gapped support at location F.

The models were placed on a shaking table and sinusoidal sweep up tests were carried out. The input acceleration level was kept constant during sweep tests. Strain gauge type accelerometers were used to measure the response of the piping models at the elbow. Load cells were also used to measure the reaction force at the gapped support, C. In this paper, the resonant frequency is defined as the frequency at which the response of the piping was a maximum during the sinusoidal sweep up test.

The response acceleration curves of a piping model with linear boundary conditions are shown in Fig.2. The solid line in Fig.2 represents the response of a piping model without gapped support, C, and the dashed line shows the response without clearance at a support C. Fig.3 shows typical response acceleration curves with some clearance at the gapped support C. Input acceleration level was varied in Fig.3. Hardening system characteristics are seen in Fig.3.

The relationship between resonant frequency and input acceleration divided by clearance is shown in Figs.4, 5, and 6. In these figures, f_L is the first natural frequency of the piping model without support C, and f_H is that with a pinned support at location C. These relationships are linear in a semi-logarithmic plot. The effects of clearance on resonant frequency are shown in Fig.4. The effects of pipe diameter are shown in Fig.5. The resonant frequency remains constant if either the clearance or the pipe diameter changes, as long as the ratio of input acceleration to clearance is constant.

Even if the total clearance of the gapped support is constant, the pipe can be placed in various positions inside the restraint; initialy contacting one side of the restraint or biased towards one side of the restraint. The effects of these eccentricities on the resonant frequencies are shown in Fig.6. This shows that the resonant frequency depends on total clearance and is not affected by the eccentricity.

The relation between resonant frequency and equivalent spring constants is shown in Fig.7. In this figure, experimental equivalent spring constants are also plotted. The experimental equivalent spring constants were calculated as measured load divided by clearance. It was shown that using equivalent spring constants, the resonant frequency can be calculated approximately.

3 CALCULATIONS

As already mentioned, the resonant frequency can be calculated approximately using equivalent spring constants. However, in these calculations several iterations are necessary. In this paper, a simplified method is proposed.

3.1 Estimation method

Modelling the piping by an equivalent single-degree-of-freedom-system, the vibration equation can be expressed as follows:

$$M_p \ddot{x} + C_p \dot{x} + K_p x = -\beta M_p \ddot{z} \quad (1)$$

where

x :Relative displacement
z :Input displacement
K_p:The equivalent stiffness of the piping model at the gapped support.
C_p:Viscous damping coefficient
M_p:The equivalent mass of the piping model without a gapped support.
β :Modal participation factor

The equivalent stiffness K_p of the piping model at the gapped support can be calculated easily using static analysis. Using the equivalent stiffness K_p and the first natural angular frequency ω_p of the piping model without a gapped support, the equivalent mass M_p of the piping model without a gapped support can be obtained as follows:

$$M_p = \frac{K_p}{\omega_p^2} \quad (2)$$

When the input motion is a harmonic function, the relative displacement can be expressed as follows:

$$x = x_0 \cdot \sin \omega t \quad (3)$$

where

x_0:Relative displacement amplitude
ω :Input angular frequency

When the response displacement of the piping model at the gapped support is less than the clearance, the resonant frequency is ω_p. On the other hand, when the response displacement of the piping model at the location of the gapped support is larger than the clearance, the actual response displacement is equal to the clearance if the support is rigid enough. Therefore, considering only the first natural vibration the equivalent stiffness of the whole piping model including the effect of the gapped support can be expressed as follows:

$$K = \frac{x_0}{\delta_g} K_p \quad (4)$$

where

K: The equivalent stiffness of the whole piping model
x_0:Relative displacement amplitude of the piping model at the location of the gapped support
δ_g:Clearance at the gapped support

So natural frequency can be written as follows:

$$\omega = \sqrt{\frac{K}{M_p}} = \omega_p \sqrt{\frac{x_0}{\delta_g}} \quad (5)$$

3.2 Parametric calculations

Using the equivalent spring constant method, the resonant frequencies of several piping models, shown in Figs. 1 and 8, were calculated. These models are as follows:

Case I : Tested piping model supported with clearance at location C(Fig.1).

Case II: Tested piping model supported with clearance at location F(Fig.1).
Case III: Cantilever piping supported with clearance at two-thirds of its length(Fig.8).
Case IV: Straight piping clamped at both ends and supported with a clearance at the mid-point(Fig.8).

The relationship between resonant frequency and response displacement without a gapped support is shown in Fig.9. For case I, the experimental results are also shown in Fig.9. The calculated results coincide with the experimental ones. The estimation error in resonant frequency using Eq.(5) comparison with the results of the equivalent spring constant method, is shown in Fig.10. The estimation of the resonant frequency is acceptable as long as the response is small. The error may be due to vibration mode changes as the response becomes large. In case I in particular, the effect is thought to be large because of the small modal amplitude at the location of the gapped support. The applicable limit of this method will be considered in future.

Furthermore, more simplified estimation of the resonant frequency may be considered using the linear relationship seen in the semi-logarithmic plot of resonant frequency against ratio of the input acceleration to clearance. For example, straight lines connecting the two points; $x_0/\delta_g=1$ and $x_0/\delta_g=10$ in Fig.9, provide good estimations of the resonant frequency for all these cases.

4 CONCLUSIONS

Simple piping model with a gapped support were tested to investigate the resonant frequency. The experiment proved that the resonant frequency remains constant even if either the clearance or the pipe diameter changes, as long as the ratio of input acceleration to clearance is constant. It became clear that the resonant frequency depends on total clearance and not on eccentricity. It was also confirmed that the relationship between resonant frequency and input acceleration divided by clearance is linear in a semi-logarithmic plot.

A simplified estimation method for resonant frequency based on the equivalent stiffness of the piping was proposed. Results using the proposed method agree with the analytical results as long as the response of the piping is small. A simpler estimation of resonant frequency may be considered using the linear relationship seen in the semi-logarithmic plot of resonant frequency against ratio of the input acceleration to clearance.

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Table 1. DIMENSIONS OF PIPING MODELS

PIPE SIZE INCHES	2 B	1 B	1/2 B
L_1 (mm)	2400	1770	1392
L_2 (mm)	2000	1475	1160
L_3 (mm)	600	442	348
L_4 (mm)	200	147	116
L_5 (mm)	292	215	169
L_6 (mm)	600	442	348
M_1 (Kg)	6. 4	1. 9	0. 7
M_2 (Kg)	6. 5	2. 0	0. 8

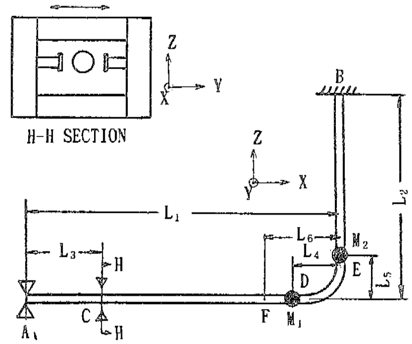

Fig. 1 A SCHEMATIC VIEW OF TEST PIPE MODEL

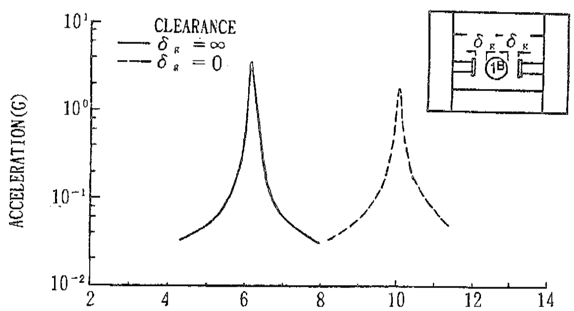

Fig. 2 RESPONSE CURVES

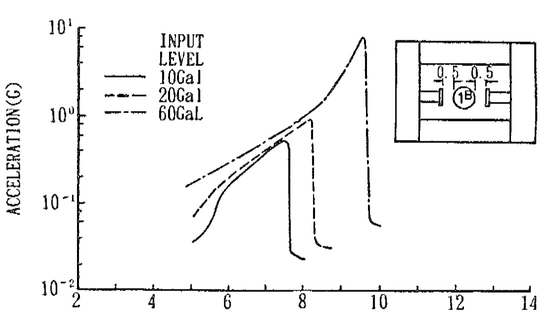

Fig. 3 RESPONSE CURVES (EFFECT OF INPUT LEVEL)

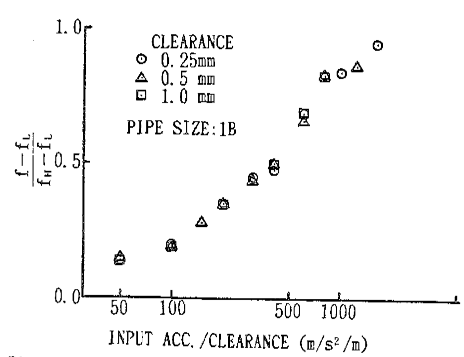

Fig. 4 EFFECT OF CLEARANCE ON RESONANT FREQUENCY

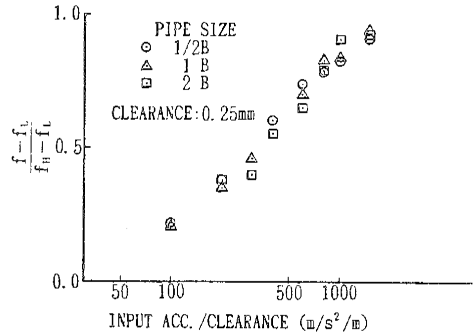

Fig. 5 EFFECT OF PIPE SIZE ON RESONANT FREQUENCY

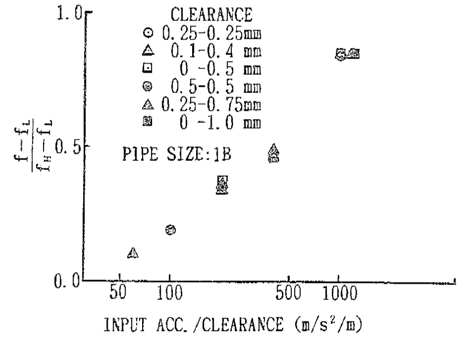

Fig. 6 EFFECT OF GAP ECCENTRICITY ON RESONANT FREQUENCY

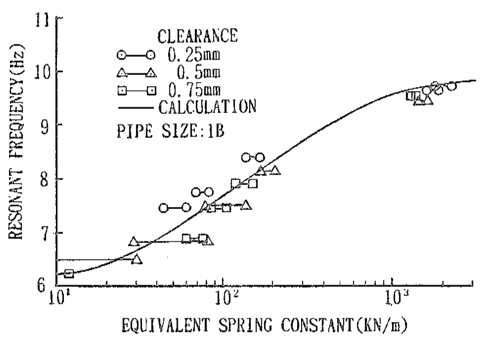

Fig. 7 RESONANT FREQUENCY VS. EQUIVALENT SPRING CONSTANT

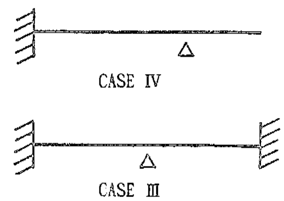

Fig. 8 PIPING MODELS

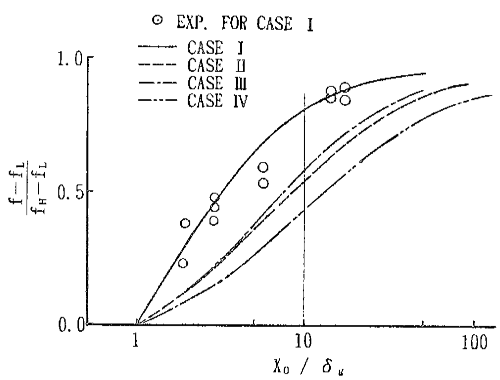

Fig. 9 RESONANT FREQUENCY VS. RESPONSE DISPLACEMENT OF PIPING SYSTEM WITHOUT GAPPED SUPPORT

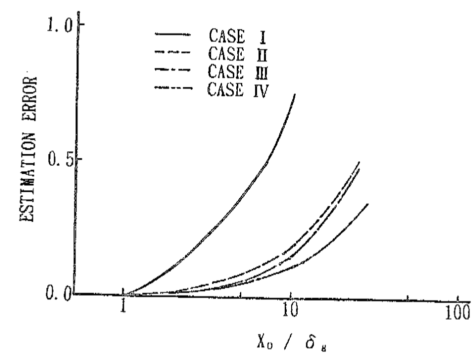

Fig. 10 ESTIMATION ERROR VS. RESPONSE DISPLACEMENT OF PIPING SYSTEM WITHOUT GAPPED SUPPORT