EFFECT OF A RIGID VALVE AND A FLEXIBLE VALVE ON VALVE ACCELERATION, PIPE MOMENT AND SUPPORT REACTIONS

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SUMMARY

A simple method is developed to study the change in valve rigidity. Numerical results are presented to compare a rigid valve and a flexible valve on valve acceleration, pipe moment and support reactions.

INTRODUCTION

Valves are generally required to be designed rigid, i.e., with frequencies at least 33 Hz. This requirement is imposed to insure that valves will not be further amplified by the piping motion. Also, for a rigid valve, the model needs only be represented as an eccentric mass in a piping system model. This information is readily available from the equipment vendor.

In a rare event when a valve is flexible, the valve flexibility tends to increase its own response acceleration and affects the pipe movement and support reactions. As a result, the valve model to be included in a piping analysis should have all flexible valve modes and at least the first rigid frequency mode. The effect of such a flexble valve model on piping analysis can be assessed with a complete piping analysis. However, this is very time-consuming and costly.

In this paper, a simple method is developed to study the change in valve rigidity, based on a dynamic model with one degree of freedom valve supported by a one degree of freedom pipe. Once the dynamic response is known, the effect on pipe moment and support reaction is determined using a one span beam model with the valve mass supported at the center of the span. This model is particularly suitable for analyzing valves supported by Class 2 and Class 3 piping where it is usually designed by support spacing tables based on a one span beam model.

Numerical results are presented for different valve and pipe mass ratios for the following four difference cases:

1. When the valve is supported in close proximity such that the pipe frequency is substantially higher than the valve frequency,
2. When the valve is substantially more rigid than the pipe,
3. When valve and pipe are close to resonance, and
4. When valve and pipe relation is not in any of the cases above.

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FORMULATION

In order to evaluate the effect of valve flexibility on its own response and the supporting pipe response, a simple two degrees of freedom model shown in Figure 1 is used. This model in effect limits the study to one piping mode only. For valves which are supported by Class 2 and 3 piping, which is designed according to support spacing table developed from simply supported one span beam, the two degree of freedom model is sufficient. This is because this model is not intended for determining the exact response value of the piping design, but to evaluate the increase in response from the original design basis. Therefore, it is appropriate to use a model consistent with the original model used in developing the support spacing table.

For valves which are supported by piping system designed by complete piping analysis, the model in Figure 1 only addresses the effect on one piping mode. However, the maximum percentage increase in response from the initial value where the valve is assumed rigid is applicable also to a complete piping analysis. This is because the mode by mode increase in response should not be more than the maximum percentage increase computed. Therefore, the final response combined from all modes should not be more than the maximum percentage response computed for any mode.

The natural frequency equation for the combined model can be shown as the following (Ref.1):

$$\left(\frac{\pi_{1,2}}{\omega_1}\right)^2 = \frac{1}{2}\left\{(1 + R_K + R_f^2) \mp \left[(1 + R_K - R_f^2)^2 + 4\, R_K^2/R_m\right]^{\frac{1}{2}}\right\} \qquad (1)$$

where $\pi_{1,2}$ represents either first or second mode of the coupled model corresponding to the values calculated by taking either "-" "+" sign in the right hand side equation, respectively. In addition, R_K, R_f, and R_m are the stiffness ratio, frequency ratio, and the mass ratio represented by the following:

$$R_K = \frac{K_c}{K_1} \qquad (2)$$

$$R_f = \omega_2/\omega_1 \qquad (3)$$

and

$$R_m = m_2/m_1 \qquad (4)$$

where

$$\omega_1 = (K_1/m_1)^{1/2} \qquad (5)$$

$$\omega_2 = (K_2/m_2)^{1/2} \qquad (6)$$

are the decoupled frequencies for mass 1 and mass 2, respectively.

The mode shape coefficients for the two masses have the following ratios (Ref. 1):

$$\frac{\phi_{1i}}{\phi_{2i}} = R_K/(1 + R_K - \frac{\pi_i^2}{\omega_1^2}) \tag{7}$$

$$i = 1,\ 2$$

where subscript i represents the i th mode, and ϕ_1 and ϕ_2 are the mode shape coefficients for masses 1 and 2, respectively.

The participation factors can be written in the form as follows:

$$P_i = \frac{1}{\phi_{2i}} (\frac{\phi_{1i}}{\phi_{2i}} + R_m)/[(\frac{\phi_{1i}}{\phi_{2i}})^2 + R_m] \tag{8}$$

Or, one may write

$$P_i\ \phi_{2i} = (\frac{\phi_{1i}}{\phi_{2i}} + R_m)/[(\frac{\phi_{1i}}{\phi_{2i}})^2 + R_m] \tag{9}$$

Finally, the acceleration response ($\ddot{x}$) for both masses can be written in the following form:

$$\ddot{x}_j = [(P_1\ \phi_{j1}\ S_1)^2 + (P_2\ \phi_{j2}\ S_2)^2]^{\frac{1}{2}}\quad ,\ j = 1,\ 2 \tag{10}$$

Here subscript j represents the mass number 1 or 2, S_1 and S_2 are the response spectral acceleration values for modes 1 and 2, respectively.

Once the response acceleration has been determined, piping moment and support reactions can also be computed. To do so, the model in Figure 2 is used, which is a more realistic model for computing reaction on each support and pipe moment at the center of span where the valve is located.

Using this as the basis, the support reaction can be written as the following:

$$V = \frac{1}{2} (m_1\ \ddot{x}_1 + m_2\ \ddot{x}_2) \tag{11}$$

and the pipe moment at the mid span is

$$M = \left(\frac{1}{8} m_1 \ddot{x}_1 + \frac{1}{4} m_2 \ddot{x}_2\right) \ell \tag{12}$$

The change in both support reaction and pipe moment can be derived directly from Equations (11) and (12) with the following results:

$$\Delta V = \frac{1}{2} (m_1 \Delta\ddot{x}_1 + m_2 \Delta\ddot{x}_2) \tag{13}$$

$$\Delta M = \frac{\ell}{8} (m_1 \Delta\ddot{x}_1 + 2 m_2 \Delta\ddot{x}_2) \tag{14}$$

where Δ represents the increment.

By dividing Equation (13) with Equation (11), and Equation (14) with Equation (12), one arrives at the following ratios for support reaction and pipe moment, respectively:

$$\frac{\Delta V}{V} = \frac{\Delta\ddot{x}_1}{\ddot{x}_1} \; \frac{1 + R_m \Delta\ddot{x}_2/\Delta\ddot{x}_1}{1 + R_m \ddot{x}_2/\ddot{x}_1} \tag{15}$$

$$\frac{\Delta M}{M} = \frac{\Delta\ddot{x}_1}{\ddot{x}_1} \; \frac{1 + 2R_m \Delta\ddot{x}_2/\Delta\ddot{x}_1}{1 + 2R_m \ddot{x}_2/\ddot{x}_1} \tag{16}$$

where

$$R_m = m_2/m_1 \tag{17}$$

It is seen from Equations (15) and (16) that the ratio of change for both support reaction and pipe moment is directly proportional to the ratio of increase on pipe acceleration response, but it is a function of mass ratio, the incremental acceleration ratio of both masses, and the ratio of acceleration response of both masses. Therefore, the ratio can only be evaluated on a numerical basis.

NUMERICAL EXAMPLES

In order to properly evaluate Equations (10), (15) and (16) for acceleration response, support reaction, and pipe moment, respectively, the valve and pipe system can be better classified into the following four categories:

1. $R_f < 0.9$
   In this case, the valve frequency is less than the pipe frequency. That is, the valve is actually being supported at a close proximity. Therefore, any change in valve rigidity will have a direct impact on the response computed.

2. $R_f \geq 2$
   The valve is considered to be far more rigid than the supporting pipe. Therefore, the valve can actually be considered as decoupled from the pipe. Any change in valve rigidity should have a minimal impact on the overall response.

3. $1.1 \geq R_f \geq 0.9$
   In this case, the valve is assumed to be close to resonance with the pipe. Therefore, the effect in the change of valve rigidity should have an important impact on the overall response. However, the effect would clearly depend on the amount of change. Should the change be so large that the new frequency ratio is outside of the resonance range, then clearly some reduction in response may actually occur.

4. $2 \geq R_f \geq 1.1$
   This is a case where frequency of the valve is in between Cases 2 and 3.

Also, to provide as realistic inputs, Figure 3 shows two different envelop response spectra used in the present study. Both spectra have one g zero period acceleration (ZPA) and a 3 g flat peak at and below 10 Hz. The first spectrum converges to ZPA at 33 Hz and the second at 20 Hz. Since it is unlikely to encounter very low frequency modes in the cases studied, the peak is not truncated and the value does not go to zero at zero Hz as it should. The use of these inputs should yield very conservative results.

CONCLUDING REMARKS

In order to provide a general assessment, different valve and pipe mass ratios have been studied. Tables 1 and 2 show the results thus obtained for the valve and pipe mass ratio from 1 to 5. However, it should be noted that the percentage change in response shown for each case only represents a range.

Results in Table 1 are based on an envelop spectrum with a 3 g peak at and below 10 Hz and a 1 g ZPA at and above 33 Hz. In this example, Case 1 has the largest impact. That is, when the valve is supported at close proximity, the reduction in valve rigidity means a corresponding increase in valve acceleration; and the largest increase can be as much as 206 percent, whereas the pipe reaction has very little increase. In the mean time, both support reaction and pipe moment could be increased by as much as 60 percent and 61.7 percent, respectively. On the other hand, it can be noted that the actual response could either decrease slightly or increase slightly. Therefore, the reduction in valve rigidity does not imply an automatic response increase.

In Case 2, the valve frequency and pipe frequency show the least amount of change. Therefore, it may be concluded that in this case there is essentially no change in response effects.

For Case 3 where valve and pipe are close to resonance, the largest increase in response is still in the valve acceleration which reaches a maximum of 61.2 percent. For support reaction and pipe moment, the increase is 21.1 and 30.6 percent, respectively. On the other hand, pipe response acceleration shows very little change.

Finally, Case 4 is a case in between Cases 2 and 3. However, the results are not in between the two cases. This is primarily because that for a valve pipe frequency ratio initially between 1.1 and 2, the new ratio after the valve frequency reduction could actually be close in resonance. Therefore, the response changes could also be quite large.

In order to evaluate the effect of a different type of response spectra, a second load case (Fig. 3) is studied. In this load case, the ZPA is changed from 33 Hz to 20 Hz from Load Case 1. With such a shift in frequency content, one may feel that the response effect should be less than those computed for Load Case 1. However, this is not the case, since the results are computed for the ratio of change vs. the initial value. The slope of Load Case 2 between 10 Hz and 20 Hz is larger than that of Load Case 1. This simply means that the change could also be larger if the frequency is in that range. This is verified by the results shown in Table 2.

Table 2 shows, in addition to possible large effect due to the steeper slope in the response spectrum input, similar conclusions reached for load case 1. That is, 1) the maximum acceleration response is about the same as the peak response spectral value, 2) except for case 2 (where valve is substantially more rigid than pipe), all other cases shown important response effects. However, the response increase is no more than 70 percent in all cases studied. Also, the reduction in valve frequency does not mean the response will automatically be increased. In fact, reduction in responses is a very possible result.

As a result of this study, the following conclusions can be made:

1. The response increase due to valve flexibility is limited to about the same as the applied response spectral peak value.
2. The maximum valve acceleration, pipe support reaction, and pipe moment increase occur in all cases, except in the case where valve is substantially more rigid than pipe.
3. The change in response depends very much on the type of input used. In particular, it depends on the change of the response spectrum in the peak region and whether the pipe frequency is also in this region.
4. The increase in pipe moment and support reaction is shown to be less than 70 percent in all cases.

REFERENCE

1. Lin, C.-W., "A Discussion of Coupling and Resonance Effects for Integrated Systems," 3rd Smirt Conference, London, August 1975.

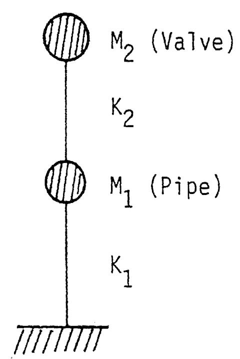

Figure 1. Dynamic Model for Acceleration Response

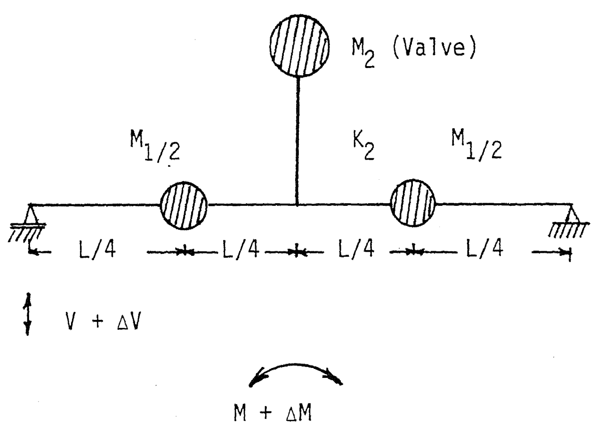

Figure 2. Static Model for Support Reaction and Pipe Moment

TABLE 1

RANGE OF RESPONSE CHANGE (LOAD CASE 1)

Case	R_m	$\Delta\ddot{x}_1/\ddot{x}_1$	$\Delta\ddot{x}_2/\ddot{x}_2$	$\Delta V/V$	$\Delta M/M$
1	1	-0.085	0.200	0.140	0.152
($R_f < 0.9$)	5	0.391	2.063	0.600	0.617
2	1	-0.057	0.003	-0.0018	0.0013
($R_f \geq 2$)	5	-0.015	0.112	0.045	0.064
3	1	-0.072	0.007	-0.0016	0.0028
($1.1 \geq R_f > 0.9$)	5	0.100	0.612	0.262	0.306
4	1	-0.044	0.090	0.063	0.072
($2 \geq R_f > 1.1$)	5	0.133	0.999	0.362	0.415

TABLE 2

RANGE OF RESPONSE CHANGE (LOAD CASE 2)

Case	R_m	$\Delta\ddot{x}_1/\ddot{x}_1$	$\Delta\ddot{x}_2/\ddot{x}_2$	$\Delta V/V$	$\Delta M/M$
1	1	0.833	1.281	0.087	0.136
($R_f < 0.9$)	5	2.191	3.050	0.649	0.657
2	1	0.943	1.003	-0.002	0.0013
($R_f \geq 2$)	5	1.051	1.191	0.108	0.126
3	1	0.931	1.007	-0.0017	0.0029
($1.1 \geq R_f > 0.9$)	5	2.227	3.194	0.632	0.652
4	1	1.051	1.198	0.148	0.156
($2 \geq R_f > 1.1$)	5	2.208	3.150	0.639	0.656

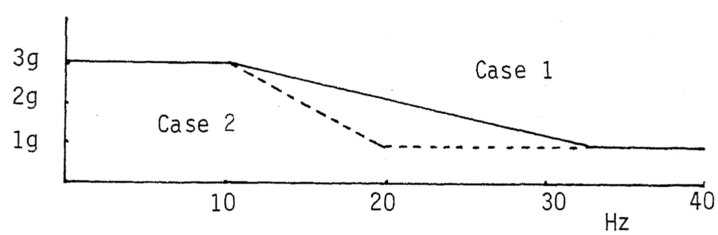

Figure 3. Input Response Spectra