Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division VI, Paper ID 173
(include assigned division number from I to X)

Vibration Suppression Support Using Added Mass of Fluid

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ABSTRUCT

Piping systems crossing between isolated and non-isolated structures need to be supported without restraining the response displacement of the isolated structures. As a support that is suitable for these piping systems, a vibration suppression support using the added mass of fluid is proposed in this paper. The support force of this support is generated by inertia of fluid. This support force is small against low-frequency responses due to movement of the isolated structure and is large against high-frequency responses due to the resonance of the piping system. A test support was manufactured, and the support force was examined experimentally. Additionally, the effect of the vibration suppression support was examined by eigenvalue analysis with a two-degrees-of-freedom analytical model. Finally, earthquake response analysis was carried out. The results showed the effectiveness of the proposed support.

INTRODUCTION

Piping systems crossing between isolated and non-isolated structures are designed to have a relatively long length so as not to restrict the displacement of the isolated structure during an earthquake. Therefore, the natural frequencies of these piping systems are not high enough to avoid resonance due to earthquake movements. In such cases, supports are required not to restrain the displacement of the isolation, and to suppress the resonance of the piping systems.

In this paper, a support using the added mass of fluid is proposed. This support is composed of a cylinder, a piston, and a tube. The tube connects two spaces in the cylinder partitioned by the piston. The cylinder is filled with a fluid, and the fluid flows through the tube when the piston moves. The support force is generated by the inertia of the fluid flowing through the tube. Therefore, the support force is proportional to the acceleration of the piston. The support force is small enough for the piston to move almost freely against the low-frequency response displacement of the isolated structure due to an earthquake. On the other hand, it is large enough to suppress the resonance of the piping systems during an earthquake.

A test prototype of the proposed support was manufactured, and an experiment was carried out to examine the characteristics of the support forces. The experimental results of the support force were confirmed to be in agreement with the theoretical values. Also in this paper, the effects of the proposed support for the piping system response were analysed. From these analyses, it was shown that the participation factor of the target vibration mode was minimized by optimizing the parameters of the supports. Additionally, from an earthquake response analysis, it was confirmed that the resonances of the piping systems were suppressed without restraining the response displacement of the isolated structure.

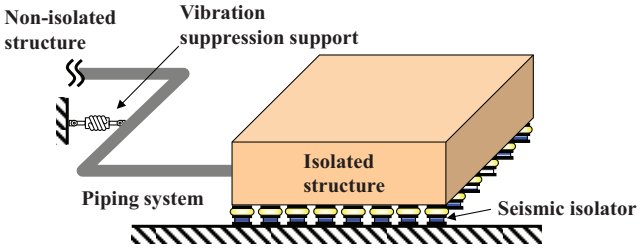

Figure 1. Piping system crossing between isolated and non-isolated structures.

COMPOSITON OF THE VIBRATION-SUPPRESSION SUPPORT

The composition of the vibration suppression support is shown in Fig. 2. The support is composed of a cylinder, a piston, and a tube. The tube connects two spaces in the cylinder partitioned by the piston. The cylinder is filled with a fluid, and the fluid flows through the tube when the piston moves. The support force is generated by the inertia of the fluid flowing through the tube. The support force is given by the following equation reported by Matsuoka and Sunakoda (2009):

$$F_m = \rho L A_b \left(\frac{A_p}{A_b} \right)^2 \frac{dV}{dt} \tag{1}$$

where F_m is the support force due to the inertia of the fluid, ρ is the density of water, L is the length of the tube, A_b is the cross-sectional area of the tube, A_p is the cross-sectional area of the piston, V is the velocity of the piston, and t is time. The force F_m is proportional to the acceleration of the piston, dV/dt. The coefficient of the acceleration dV/dt has the dimension of mass. This coefficient is called *added mass* and expressed by

$$m_s = \rho L A_b \left(\frac{A_p}{A_b} \right)^2 . \tag{2}$$

The added mass m_s increases as the length of the tube L and the ratio of cross-sectional areas A_p/A_b increase.

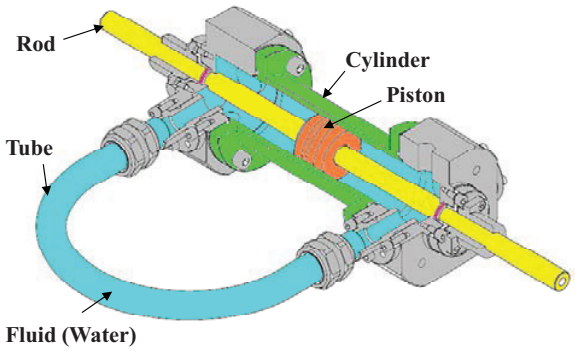

Figure 2. Composition of a vibration suppression support.

EXPERIMENT

A test support was manufactured, and an experiment was carried out to examine the characteristics of the support forces. The experimental apparatus is shown in Fig. 3. The experimental apparatus consisted of the test support and a vibrating system. One side of the test support was fixed to a shaking table, and the other side was attached to the vibration system, which was composed of a weight and a coil spring. The support force was generated by vibration of the weight. The load cell was set between the rod of the piston and the weight, and the support force was measured. The displacement of the weight was measured by a laser sensor.

The test support is shown in Fig. 4. The total mass of the weight, the piton, and the rod of the piston was 11.45 kg. The stiffness of the coil spring was set so that the natural frequency of the system in the case without a support force was 10 Hz. The dimensions of the test support are shown in Table 5. The

length of the tube was set depending on the added mass, which ranged from 12.3 to 100 kg, as shown in Table 3.

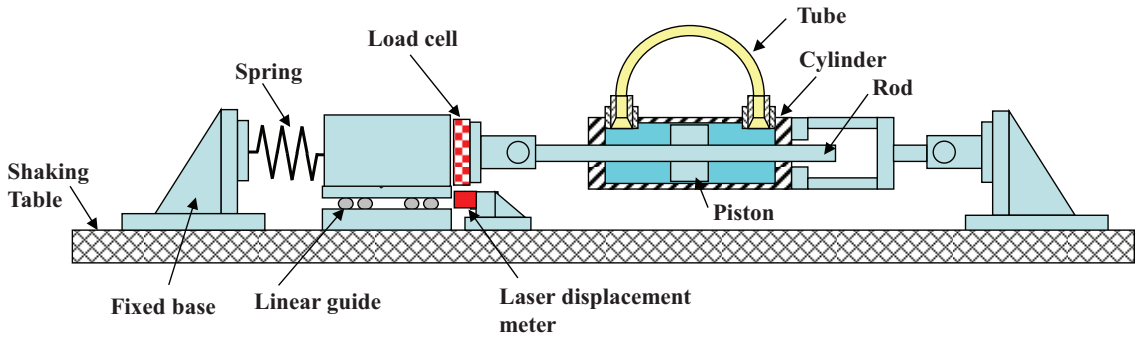

Figure 3. Experimental apparatus.

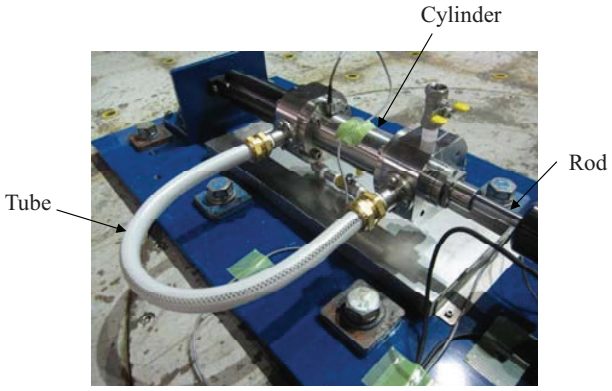

Figure 4. Test support.

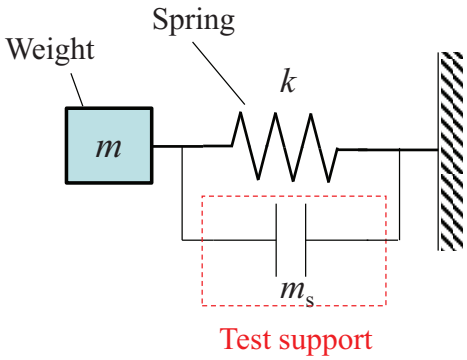

Figure 5. Vibration model of the experimental apparatus.

Table 2: Main dimensions of the test support.

Diameter of the cylinder [mm]	$50\ \binom{+0.08}{0}$
Diameter of the piston [mm]	$50\ \binom{-0.05}{-0.1}$
Diameter of the tube [mm]	15
Diameter of rod [mm]	16
Maximum stroke [mm]	±50

Table 3: Length of the tube, *L*.

Added mass, m_s [kg]	Length of the tube, *L* [mm]
12.3	699
25	1422
50	2845
75	4267
100	5689

The vibration model of this experimental apparatus is shown in Fig. 5 . In this model, m and k constitute a one-degree-of-freedom system composed of a weight and a coil spring, and m_s is the added mass of the test support. The support force obtained by equation (1) is the product of the added mass m_s and the relative acceleration between the weight and the shaking table. Therefore, the equation of motion is expressed as

$$(m + m_s)\ddot{z} + kz = -m\ddot{u} \tag{3}$$

where z is the relative displacement between the weight and the shaking table. The natural frequency of this model is given by

$$\omega_n = \sqrt{\frac{k}{m + m_s}}\ . \tag{4}$$

From this equation, the added mass m_s is calculated by

$$m_s = \frac{k}{\omega_n{}^2} - m\ . \tag{5}$$

The frequency response curves obtained in sine-wave sweep tests are shown in Fig. 6. The input acceleration was 700Gal. It was confirmed that the resonance frequency decreased as the added mass m_s increased. The natural frequency obtained from Fig. 6 is shown in Fig. 7. Fig. 8 shows the added mass m_s calculated by substituting the natural frequency into equation (5). It was confirmed that the experimental results are in good agreement with the theoretical value. Experimental results of the added mass were lower than the theoretical value for large m_s. It is possible that the added mass decreased due to a change of the cross sectional area caused by the high pressure in the tube.

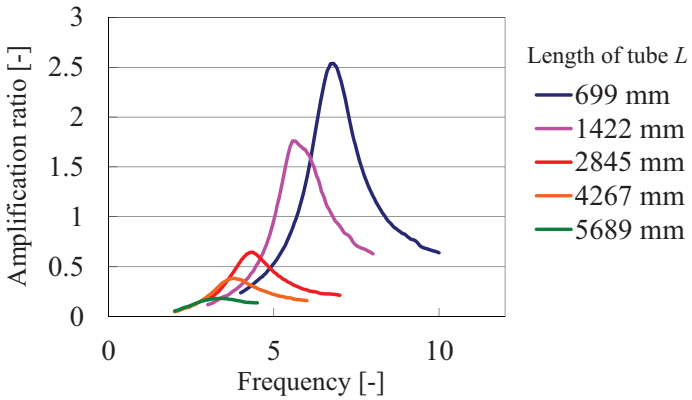

Figure 6. Frequency response curve obtained by experiment.

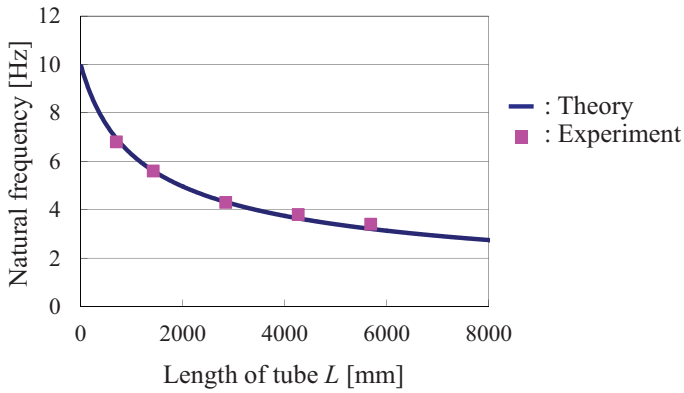

Figure 7. Natural frequency obtained by experiment and fitted with theoretical calculation.

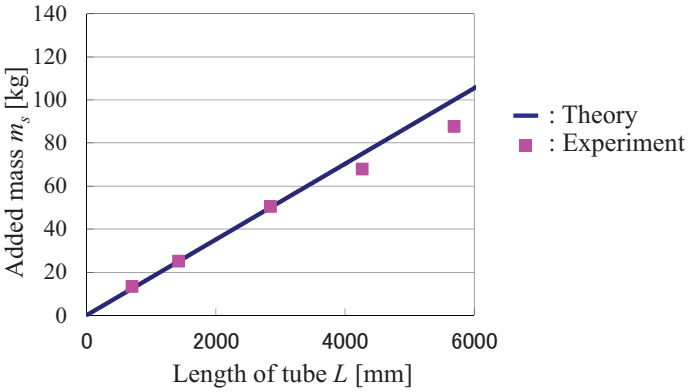

Figure 8. Added mass obtained by experiment and fitted with theoretical calculation.

ANALYSIS OF 2DOF VIBRATION MODEL

This section discusses eigenvalue analysis using a two-degrees-of-freedom (2DOF) model. The analytical model is shown in Fig. 9. In this model, the vibration suppression support is set between the piping system and the non-isolated structure. The isolated structure and the piping system are represented as a 1DOF vibration system. Only one mode of the piping system is targeted in this model. In this 2DOF vibration model, the vibration of the isolated structure is dominant in the 1st vibration mode. On the other hand, the vibration of the piping system is dominant in the 2nd vibration mode. The 2nd vibration mode is the target of the vibration suppression support. In the model, m_I is the mass of the isolated structure, m_p is the equivalent mass of the piping, k_{p1} is the equivalent stiffness of the piping system connected to the non-isolated structure, k_{p2} is the equivalent stiffness of the piping system connected to the isolated structure, k_I is the stiffness of the isolated structure, and m_s is the added mass of the vibration suppression support.

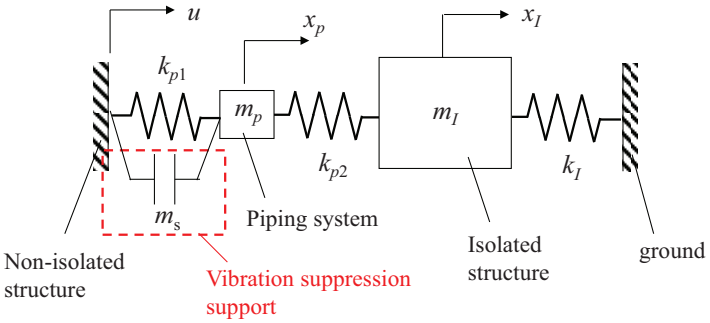

Figure 9. 2DOF analytical model.

The equation of motion of this model is expressed as

$$[M]\{\ddot{z}\}+[K]\{z\}=-[M^*]\{e\}\ddot{u} \tag{6}$$

where the matrices and vectors are expressed as follows:

$$[M]=\begin{bmatrix} m_p+m_s & 0 \\ 0 & m_I \end{bmatrix},\ [K]=\begin{bmatrix} k_{p1}+k_{p2} & -k_{p2} \\ -k_{p2} & k_I+k_{p2} \end{bmatrix},\ [M^*]=\begin{bmatrix} m_p & 0 \\ 0 & m_I \end{bmatrix} \tag{7}$$

$$\{z\}=\begin{Bmatrix} z_p \\ z_I \end{Bmatrix},\ \{e\}=\begin{Bmatrix} 1 \\ 1 \end{Bmatrix}. \tag{8}$$

Here, z_p and z_I are the relative displacements of the piping system and the isolated structure, respectively. The participation factor of the j-th mode is calculated by

$$\beta_j=\frac{\{\phi_j\}^T[M^*]\{e\}}{\{\phi_j\}^T[M]\{\phi_j\}}=\frac{1+\mu_I\dfrac{1-\nu_{nj}{}^2(1+\mu_s)}{\alpha}}{1+\mu_s+\mu_I\left\{\dfrac{1-\nu_{nj}{}^2(1+\mu_s)}{\alpha}\right\}^2} \qquad (j=1.2) \tag{9}$$

Here, $\{\phi_j\}$ is the mode vector of the j-th vibration mode, which is normalized so that the displacement of the piping system is 1. The non-dimensional parameters in the above equation are expressed as follows:

$$\mu_s=\frac{m_s}{m_p},\ \ \mu_I=\frac{m_I}{m_p},\ \nu_I=\frac{\omega_I}{\omega_p},\ \nu_{n1}=\frac{\omega_{n1}}{\omega_p},\ \nu_{n2}=\frac{\omega_{n2}}{\omega_p},\ \alpha=\frac{k_{p2}}{k_{p1}+k_{p2}} \tag{10}$$

where ω_{nj} is the natural frequency of the j-th vibration model, and ω_p and ω_I are the natural frequencies of the piping system and non-isolated structure, which expressed as

$$\omega_p=\sqrt{\frac{k_{p1}+k_{p2}}{m_p}},\ \omega_I=\sqrt{\frac{k_I}{m_I}}. \tag{11}$$

The participation factors of the 1st and 2nd vibration modes calculated by equation (8) are shown in Fig. 10. The horizontal axis is the ratio, μ_I, of the added mass m_s and the piping system mass m_p. The mass ratio μ_I is set to 1000 since the mass of the isolated structure is much larger than the mass of the piping system. Assuming a case where the natural frequency of the piping system is ten times larger than that of the isolated structure, the ratio of the natural frequencies, ν_I, is set to 10. Also, assuming a case where the vibration mode of the piping system is symmetric about the point at which the vibration suppression support is connected, k_{p1} and k_{p2} are set to the same value. Because of this assumption α is set to 1/2. The value of the participation factor of the 2nd mode becomes 0 by setting μ_s to 1. Therefore, it is possible to minimize the high-frequency response of the piping system by tuning the added mass of the vibration suppression support. The participation factor of the 1st vibration mode is nearly constant despite the added mass of the vibration suppression support. Therefore, the vibration suppression support has little effect on the low frequency response of isolation.

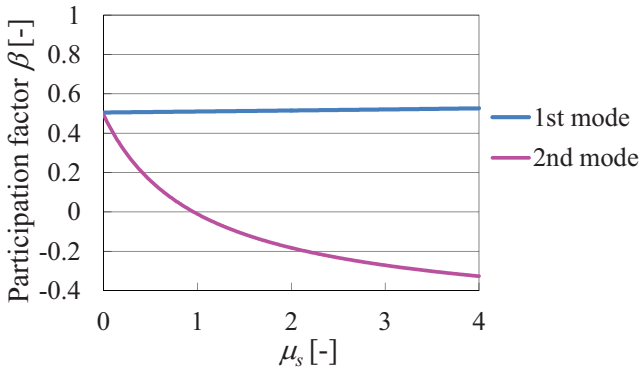

Figure 10. Participation factor of 1st and 2nd modes.

SIMULATED SEISMIC RESPONSE USING PIPING SYSTEM MODEL

Finally, the seismic response analysis by the piping system model is shown. An outline of the piping system used for analysis is shown in Fig. 11. This piping system crosses between the non-isolated structure and the isolated structure. This piping system has the two elbow parts so as not to restrain the displacement of the isolation. The vibration suppression support is attached between the centre of the straight part and the non-isolated structure. The natural frequency of the 1st vibration mode is 3 Hz, and the natural frequency of the isolated structure is 0.3 Hz. Taking account of the analytical results shown in the above section, the added mass of the vibration-suppression support is set equal to the equivalent mass of the piping system calculated by modal analysis. This equivalent mass, m_p, is calculated by

$$m_p = \{\phi\}^T [M]\{\phi\} \tag{12}$$

where $[M]$ is the mass matrix, and $\{\phi\}$ is the mode vector of the target vibration mode, which is normalized so that the displacement of the point supported by the vibration suppression support is 1. The displacement of the piping system obtained by earthquake response analysis is shown in Fig. 12. In the case without the vibration suppression support, the response wave contains both the low-frequency response of isolation and the high-frequency response of the piping system resonance. On the other hand, in the case with the vibration suppression support, the high-frequency response of the piping system is suppressed, and the low-frequency response of isolation is not influenced by the vibration suppression support.

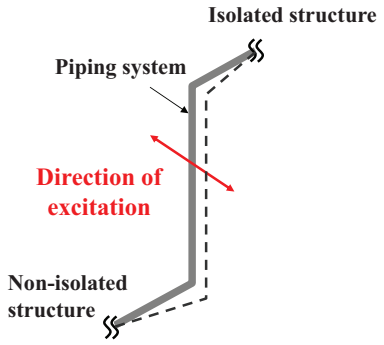

Figure 11. Outline of piping system.

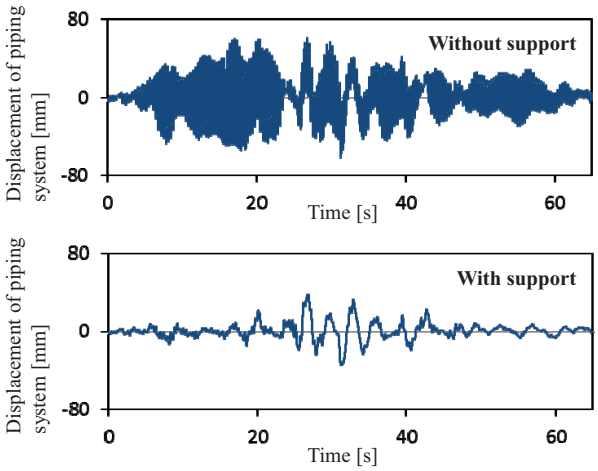

Figure 12. Results of earthquake response analysis.

CONCLUSION

A vibration suppression support using the added mass of fluid is proposed for restraining the vibration of a piping system crossing between isolated and non-isolated structures. The composition of this support and the support force were shown. A test support was manufactured, and an experiment was carried out to evaluate the support force. It was confirmed that the experimental results of the support force were in good agreement with theoretical values.

Next, eigenvalue analysis using a 2DOF vibration system composed of the piping system and the isolated structure was carried out. It was shown the participation factor of the target vibration mode becomes zero by adjusting the added mass of the vibration suppression support. That is to say, the earthquake response of the target vibration mode was minimized by optimizing the added mass.

Finally, earthquake response analysis using a piping system model crossing between non-isolated and isolated structures was carried out. From this analysis, it was confirmed that the high-frequency response of the piping system was suppressed without restraining the displacement of the isolation. The results show that the vibration suppression support is effective for suppressing the response of the piping system crossing between non-isolated and isolated structures. However, in the method shown in this paper, the number of target vibration modes was limited to only one. Development of a method for minimizing the response of several target vibration modes will be the subject of future work.

NOMENCLATURE

F_m	force of the vibration suppression support
m_s	added mass of the vibration suppression support
ρ	density of water
L	length of tube
A_b	cross-sectional area of the tube
A_p	cross-sectional area of the piston
V	velocity of the piston
t	time
m	mass of the weight
k	stiffness of the coil spring
z	relative displacement between weight and shaking table
m_p	equivalent mass of the piping system
m_I	mass of the isolated structure
k_{p1}, k_{p2}	equivalent stiffness of the piping system
k_I	stiffness of the isolated structure
x_p	absolute displacement of the piping system
x_I	absolute displacement of the isolated structure
z_p	relative displacement of the piping system
z_I	relative displacement of the isolated structure
u	displacement of the base
ω_p	natural frequency of the piping system
ω_I	natural frequency of the isolated structure
ω_{nj}	natural frequency of j-th vibration mode
μ_s	ratio of masses m_s and m_p
μ_I	ratio of masses m_I and m_p
α	ratio of k_{p1} and sum of k_{p1} and k_{p1}
ν_I	ratio of natural frequencies ω_I and ω_p
ν_{nj}	ratio of natural frequencies ω_{nj} and ω_p
β_j	participation factor of j-th vibration mode

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