Dynamic Behavior of a Submerged Structure Affected by Neighboring Structures

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1. Introduction

The dynamic behavior of a submerged structure is of interest to various engineering applications such as the nuclear industry. Typically, the dynamic effect of fluid on a submerged structure is modeled as added-mass terms in the structure mass matrix. This approach is quite effective for a simple structure, where the added mass term is known analytically and the well-developed analysis techniques for the dry structure can be applied. However, the dynamic behavior of a submerged structure can be significantly affected by neighboring structures, and this is not an uncommon case for a general structural system. In this work, using concentric pipes, it will be shown that the added-mass approach is invalid and the FSI (fluid-structure interaction) analysis is practically the only viable option for such a structural system.

2. Response of a Submerged Structure

In this section, the dynamic equation of motion will be reviewed for the structure subject to support excitation.

2.1 Dry Structure

The response of a dry structure is represented by the following differential equation of motion:

$$\mathbf{M}\ddot{U}(t)+\mathbf{C}\dot{u}(t)+\mathbf{K}u(t)=-\mathbf{M}U_b\ddot{u}_g(t) \quad (1)$$

where U_b is the influence vector, the displacement vector of the structural system when the support undergoes a unit displacement in the direction of the excitation. Note that the same mass matrix is present in both the inertia term and driving term.

2.2 Submerged Structure

The equation of motion of a submerged structure[1, 2] is

$$\begin{aligned}&\mathbf{M}_V\ddot{U}(t)+\mathbf{C}\dot{u}(t)+\mathbf{K}u(t)=-\mathbf{M}_W U_b\ddot{u}_g(t)\\&\mathbf{M}_V=\mathbf{M}+\mathbf{M}_E+\mathbf{M}_H\\&\mathbf{M}_W=\mathbf{M}+\mathbf{M}_E-\mathbf{M}_D\end{aligned} \quad (2)$$

where the virtual mass matrix $\mathbf{M}_V$ includes structural mass matrix $\mathbf{M}$, entrapped fluid mass matrix $\mathbf{M}_E$, and hydrodynamic(added) mass matrix $\mathbf{M}_H$. The wet mass matrix $\mathbf{M}_W$ in the driving term includes displaced mass matrix $\mathbf{M}_{DS}=\mathbf{M}-\mathbf{M}_D$ and entrapped fluid mass matrix $\mathbf{M}_E$. Note that the submerged structure has a virtual mass matrix in the inertial term and wet mass matrix in the driving term, whereas a dry structure has the same mass matrix in both terms (see (1)). If a finite element code for dry structures is used to analyze a submerged structure, the equation of motion becomes

$$\mathbf{M}_V\ddot{U}(t)+\mathbf{C}\dot{u}(t)+\mathbf{K}u(t)=-\mathbf{M}_V U_b\ddot{u}_g(t) \quad (3)$$

and thus one should adjust the results obtained [2].

2.3 Remarks

The added-mass approach has been widely used for analyzing submerged structures. Once the added mass has been determined reasonably, finite element codes developed for dry structures can be applied to the submerged structure. As the driving term in (3) is larger than that in (2), the results from the finite element analysis yield conservative results, which can be regarded as the margin in the design.

However, for a general structural system in fluid, the dynamic behavior of a structure can be significantly affected by neighboring structures. For such a structural system, one cannot count on the added-mass approach as the added mass term cannot be estimated, and the structural response obtained unrealistic. These will be illustrated in the following section.

3. Finite Element Analysis of Concentric Pipes

Consider the two concentric pipes shown in Fig. 1 and Table 1. The lower end of the inner pipe is clamped while the upper end is free. The annular space in between the pipes is filled with water. For simplicity, the outer pipe is assumed to be rigid and held fixed.

If the annular space containing water is wide enough, the dynamic behavior of the inner pipe is not affected by the outer pipe, and the conventional added-mass approach is effective. Its first wet frequency is calculated to be 43.94Hz. But if this is not the case, the dynamics of the inner pipe can be significantly affected by its neighboring structure, which is the outer pipe for this example. For other structural systems except the two concentric pipes dealt with in this work, there are no quantitative estimations for the effects of neighboring

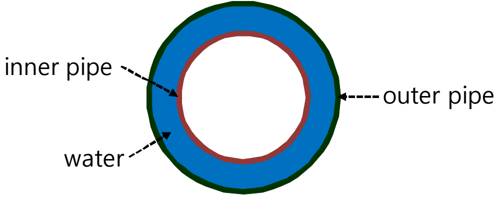

Fig. 1. Two concentric pipes.

Table 1: Specifications of Two Concentric Pipes

	Dimensions			Material Properties		
	ID (m)	OD (m)	Height (m)	Density (kg/m^3)	E (Gpa)	Sound speed (m/s)
Inner pipe	0.24	0.26	2	7850	200	-
Water	0.26	0.265	2	998.23	-	1484

Structures, as their effects are strongly dependent on the spatial proximity to the structure of interest. An FSI modal analysis has been performed for the two concentric pipes in Fig. 1 and Table 1, and its first natural frequency yields 10.22Hz. Note that the dynamic characteristics of the inner pipe has changed drastically due to the adjacent outer pipe.

An FSI transient analysis was conducted for the two concentric pipes. The damping was assumed to be 2%. The acceleration input shown in Fig. 2 is applied at the support (base). Fig. 3 and Table 2 show the time histories at the top and mid-span of the inner pipe. Note that the FSI analysis is equivalent to solving the equation of motion (2).

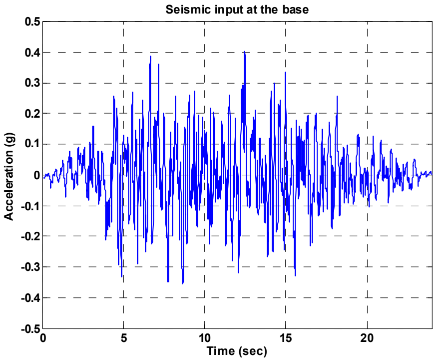

Fig. 2. Acceleration Input.

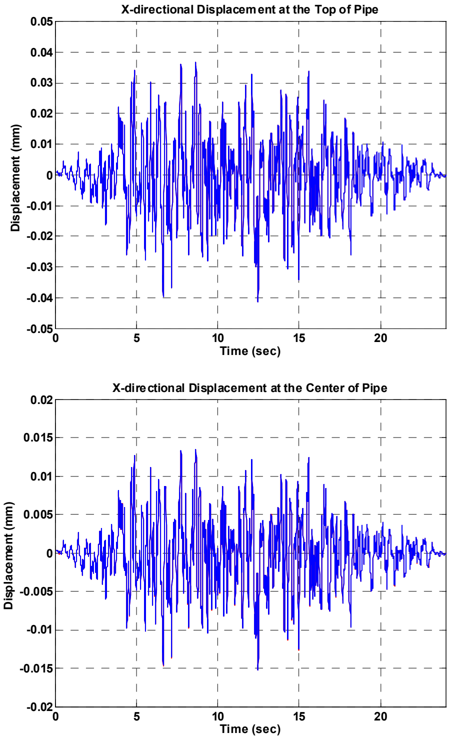

Fig. 3. FSI Analysis; Displacement Time Histories at the Top (upper) and the Mid-span (lower) of the Inner Pipe.

Table 2: Summary of Analysis Results

			FSI Module	Structural Module
Modal Analysis		Wet frequency (Hz)	10.22	12.49
Transient Analysis	Top	Max. deflection (mm)	0.0366	1.9544
		Min. deflection (mm)	-0.0414	-2.2981
	Mid-span	Max. deflection (mm)	0.0135	0.6943
		Min. deflection (mm)	-0.0153	-0.8169

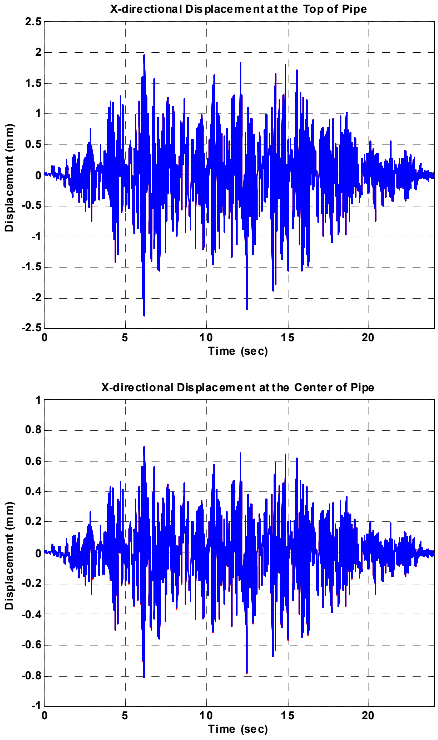

Fig. 4. Structural Analysis; Displacement Time Histories at the Top (upper) and the Mid-span (lower) of the Inner Pipe.

As stated, an analytic formula of added mass is available for this specific example. Applying this, the wet frequency is calculated to be 12.49Hz, which is similar as the FSI result. Also, a transient analysis has been performed using an FE code for dry structures. The added mass is reflected as the surface load on the inner pipe. Note that it is equivalent to solve the equation of motion (3). The same excitation and damping value were applied as the FSI analysis. The time histories are plotted in Fig. 4. Compared with the deflection results from the FSI analysis, the results from the add-mass approach give about 55-times larger responses, which is quite incorrect and absurd.

Through an illustrative example, we have shown that the dynamic behavior of a submerged structure can be significantly affected by neighboring structures. For such structural systems, FSI analysis is the only viable option, although it is computationally expensive.

REFERENCES

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[2] B. L. Ly and Y. An, Response Spectrum Method for Submerged Structures, Proceedings of 2008 ASME Pressure Vessels and Piping Division Conference, July 27-31, 2008.