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Study of Dynamic Similarity Law of an Experimental LMFBR Tank with Fluid-Structure Interaction

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ABSTRACT

The use of shaking table tests to study the earthquake response of a LMFBR vessel is an effective way. This paper discusses the dynamic similarity law of fluid-structure interaction by using the domain dynamic control equations for both the liquid and the solid, and the contact conditions at the interface. Because major loading members of the reactor vessel are plates and shells, different similitude ratios are assigned to overall dimension and thickness, respectively, so as to cancel the gravity distortion effect. Nominal density of model material can be contented by dummy weight. The proposed method has been applied to the shaking table test of an experimental LMFBR vessel.

1. INTRODUCTION

A LMFBR vessel contains large amount of sodium coolant. Since most reactor internal components, such as intermediate heat exchangers and pumps, are submerged in the sodium coolant, hydrodynamic effects induced by fluid-structure interaction are of great importance in the design of reactor components. Under seismic excitation it is a typical non-linear random dynamic problem. It is difficult to theoretically analyze the liquid pressure on the structure and the non-linear sloshing of the liquid sodium. Other methods such as FEM (finite element method) and semi-analysis method have same difficulties and limitations to solve this kind of problem. On the other hand, the shaking table test is effective on this kind of problem. Model experiment requires the model and the prototype contents the second law of similarity principle, which means that the model contains the similar conditions of the essential problems of the prototype. Maintaining similarity between the actual reactor and the test model with respect to the fluid-structure interaction when designing a test model.

This paper deals with the similarity ratio for CEFR (China Experimental Fast Reactor), which is approximately 12m in high, 8m in diameter and 1300 tons in weight. The thickness of the cylindrical vessel wall is 25mm. The specifications of the shaking table used in the experiment has 6 d. o. f. with the dimension of 4m×4m, the frequency range of 0.1~100Hz, and the maximum loading capacity of 15 tons. The scale of the model adopted was 1/8 because of the limitations of the shaking table.

2. DYNAMIC SIMILARITY LAW OF FLUID-STRUCTURE IN INTERACTION

Two methods are usually used to obtain the similarity law: (1) the method of dimensional analyses; (2) the method of domain control equations analyses. Parameters can not be omitted if using method (1) while method (2) can grasp the main variables. The method (2) is adopted in this study. There are three kinds of domain dynamic control equations of fluid-structure interaction and listed below:

(1) Fundamental Motion Equation for Structure (Lame equation):

$$\frac{\partial^2 u}{\partial t^2} = \frac{(\lambda + \mu)}{\rho_s} graddivu + \frac{\mu}{\rho_s} \nabla^2 u + F_s \tag{1}$$

Where, ρ_s stands for structure density, F_s for gravitational acceleration, and λ and μ are Lame coefficients.

From Eq. (1), two non-dimensional parameters can be obtained:

$$\pi_1^* = \frac{Et^2}{\rho_s l^2} \qquad \pi_2^* = \frac{u}{F_s t^2} \tag{2}$$

(2) Fundamental Motion Equation for Fluid (Navy-stocks equation):

$$\frac{\partial V}{\partial t} + (V \cdot grad)V = F_f - \frac{1}{\rho_f} gradp + \nu \nabla^2 V \tag{3}$$

Where, ρ_f is the fluid density, F_f gravitational acceleration, P fluid pressure and ν kinetic viscosity coefficient.

From Eq. (3), four non-dimensional parameters can be obtained:

$$\pi_3^* = \frac{Vt}{l} \qquad \pi_4^* = \frac{V^2}{lg} \qquad \pi_5^* = \frac{p}{\rho_f V^2} \qquad \pi_6^* = \frac{Vl}{\nu} \tag{4}$$

(3) Boundary Conditions on Fluid-structure Interfaces:

$$-p = (\sigma_{ij})_n \tag{5}$$

$$(V_x, V_y, V_z)_n = -(\frac{\partial u_x}{\partial t}, \frac{\partial u_y}{\partial t}, \frac{\partial u_z}{\partial t})_n \tag{6}$$

From Eq. (5) and (6), we obtain other two non-dimensional parameters:

$$\pi_7^* = \frac{Eu}{pl} \qquad \pi_8^* = \frac{u}{Vt} \tag{7}$$

For the LMFBR model, only four of the eight non-dimensional parameters that mentioned above are independent, they are:

$$\pi_1 = \frac{V^2}{lg} \qquad \pi_2 = \frac{\rho_s}{\rho_f} \qquad \pi_3 = \frac{E}{\rho_s V^2} \qquad \pi_4 = \frac{Vl}{\nu} \tag{8}$$

where, π_1 is the Froude number of structure and equals to π_4^*,
π_2 is the ratio of Euler number of structure and fluid, and equals to π_1^*,
π_3 is the Cauchy number of structure and obtained from π_1^* and π_5^*,
π_4 is the Reynolds number of fluid and equals to π_6^*.

The objective of the shaking table test is to study the responses and destructive states of LMFBBR main vessel under earthquake excitation. Thus parameters $\pi_1 \sim \pi_4$ of the model should be equal to the prototype. Because of the limitation in selection of fluid material properties the density and viscosity of fluid has to be adjusted, similarly because $\pi_1 \sim \pi_3$ are independent to π_4, the equation of Reynolds number for model and prototype has to be loosened.

Generally, the test model can not conforms $\pi_1 \sim \pi_3$ at the same time because of the effect of gravitational distortion. In order to conform the similitude law of gravitational acceleration, different scales for overall dimension and thickness are adopted. For a LMFBR vessel with plates and shells as its main loading members, the following results can be obtained:
From π_1, we have

$$\frac{V_m}{V_p} = \sqrt{\frac{L_m}{L_p}} \tag{9}$$

from π_2,

$$\frac{\rho_{sm}}{\rho_{sp}} = \frac{\rho_{fm} L_m l_p}{\rho_{fp} L_p l_m} \tag{10}$$

and from π_3,

$$\frac{E_m}{E_p} = \frac{\rho_{sm} V_m^2}{\rho_{sp} V_p^2} \tag{11}$$

in which, the subscript p is for prototype, m for model, L for overall dimension and l for thickness.

If material properties of the liquid and the scale for overall dimension of the model are determined, then the scale for the model thickness and density of structure can be obtained by using Eq. (9)~(11), that is

$$\frac{l_m}{l_p} = \frac{E_p L_m^2 \rho_{fm}}{E_m L_p^2 \rho_{fp}} \qquad \frac{\rho_{sm}}{\rho_{sp}} = \frac{E_m L_p}{E_p L_m} \tag{12}$$

3. DYNAMIC SIMILITUDE RATIOS OF MODEL

Water is commonly available and convenient to simulate the liquid sodium. Its density is close to liquid sodium. Acryl, stainless steel and aluminum alloy may all be possibly used as the material for the model structure of LMFBR, but aluminum alloy is finally adopted because it is easy to manufacture, its material property is more stable, and conforms the requires of this test (see Table. 1). The scale of model's overall dimension is chosen as 1/8 according to the conditions of shaking table facility, and other parameters are listed in Table.2.

4. CONCLUSIONS

(1) The dynamic similarity law of fluid-structure interaction obtained in this paper by considering dynamic control equations and boundary conditions is general for all of these kinds of problems;

(2) In order to cancel the effect of gravitational distortion, different scales for overall dimension and thickness are adopted since the mainly loading members of LMFBR are plates and shells. This may reduce the dummy weight comparing to the model using same scales for three dimensions.

References

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Table 1. Material Properties of Actual Reactor and Model

Material	Reference Temperature [° *C*]	Specific Weight [*kg/m³*]	Youngs Modulus [*Mpa*]	Poissons Ratio	Viscosity Coefficient [*kg-s/m²*]
Stainless Steel	400	7860	1.68×10^5	0.295	—
Aluminum Alloy	25	2700	7.25×10^4	0.34	—
Liquid Sodium	500	820	—	—	2.51×10^{-5}
Water	25	1000	—	—	1.02×10^{-4}

Table 2 Similarity Ratio of the Aluminum-Made 1/8 Scale Test Model

	Similarity formula	Similarity ratio	Note
Density of fluid ρ_f	S_{ρ_f}	0.82	Sodium/Water
Density of structure ρ_s	S_{ρ_s}	0.29	Stainless steel/Aluminum
Length L	S_L	8	
Shell thickness I	S_I	22.6	Stainless steel/Aluminum
Stiffness K	$S_E\,S_I$	52.5	
Period T	$\sqrt{S_L}$	2.83	
Frequency f	$1/S_t$	0.354	
Energy e	$S_E\,S_I\,S_L^2$	3362	
Velocity V	$\sqrt{S_L}$	2.83	
Acceleration a	1	-	
Gravitational ACC. g	1	-	
Pressure P	S_a	1.0	
Inertia force I	S_a	1.0	