NUMERICAL SIMULATION OF VIBRATION CONTROL OF THE STRUCTURES USING TLD

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ABSTRACT：

A finite element simulation of the structure with tuned liquid damper (TLD) is studied. The fluid-structure interaction (FSI) mode of TLD system is built with finite element analysis tool ADINA. The characteristics of vibration reduction of TLD, and transient fluid pressure distribution are simulated using the ADNIA FSI module. The results agree well with the date by simplified experimental mode. It is shown that the characteristics of TLD can be predicted accurately.

KEYWORDS： Tuned liquid damper, Fluid-structure interaction, Finite element analysis

1. INTRODUCTION

With the growth of construction industry, the structures develop towards tallness, light weight, mass bulk and high strength, which cause the reduction of stiffness and damping of structure, So it is very difficult for traditional seismic design to meet the comfort and safety requirements under strong ground motion. In order to overcome the deficiencies of traditional seismic design, the researchers suggest a new approach in relation to structure control. Tuned liquid damper is one of effective methods of structure control.

Vibration of TLD-structure by earthquake or wind loads will lead a movement of water tanks, and meanwhile the movement of water tanks will cause liquid sloshing and the surface of the waves. Dynamic pressure difference on the tank wall due to liquid sloshing and waves, and inertia force caused by the movement of structure and liquid, contribute to vibration control for structure. Equation [1] of motion for single degree of freedom structure - TLD system should be written as:

$$m\ddot{x} + c\dot{x} + ks = P(t) - P_{TLD} \tag{1.1}$$

Where m, c and k are, respectively, mass, damping and stiffness coefficient of structure; $P(t)$ is dynamic loads on structure; P_{TLD} is force caused by fluid sloshing and waves.

2 THEORY OF THE FINITE ELEMNT ANALYSIS ON FSI SYSTEM

2. 1 Kinematic and Dynamic Conditions

FSI analysis is mainly used for solving the nonlinear dynamic coupling between fluid and solid, its fundamental principle is that the fluid and solid are coupled by satisfying kinematic equilibrium equation and dynamic equilibrium equation on the FSI boundary, Its kinematic and dynamic conditions

$$\underline{d}_f = \underline{d}_s \tag{2.1}$$

$$n\underline{\tau}_f = n\underline{\tau}_s \tag{2.2}$$

Where $\underline{d}_f$ and $\underline{d}_s$ are, respectively, the fluid and solid displacements and $\underline{\tau}_f$ and $\underline{\tau}_s$ are, respectively, the fluid and solid stresses. The fluid velocity condition is resulted from the kinematic condition

$$\underline{v} = \dot{\underline{d}}_f \tag{2.3}$$

2.2 Separate Meshes of Fluid and Solid Models

Completely different elements and meshes can be used in fluid and solid models in the ADINA system [2], and the nodal point positions of the two models are therefore generally not the same on the fluid-structure interface as illustrated in the Figure 1

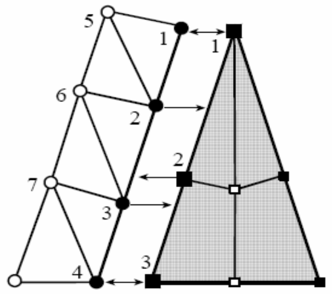


Figure 1 Coupling of fluid and solid nodes

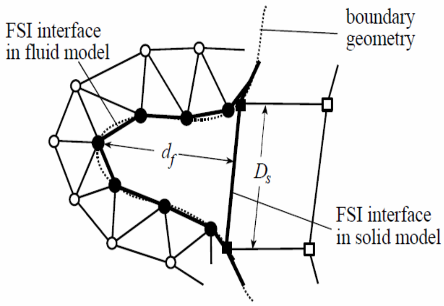


Figure 2 Measure of the distance between fluid and solid FSI boundaries

Since separate meshes are adopted in the fluid and solid domains, it is likely that the two meshes on the interfaces are not compatible. In order to overcome this incompatibility and ensure the two models fully coupling, the following two relative distances are define in ADINA.

$$r_f = \max\left\{\frac{d_f}{D_s}\right\} \tag{2.4}$$

$$r_s = \max\left\{\frac{d_s}{D_f}\right\} \tag{2.5}$$

Where d_f is the distance from a fluid node to the structural discretized boundary; d_s is the distance from a solid node to the fluid boundary; D_s is the length of the solid boundary element; D_f is the size of the fluid boundary element.

2.3 Consistent Time Integration for Fluid and Solid Models

The time integrations for both fluid and solid equations must be consistent. Although different coordinate systems are used in fluid and solid models, the two systems are the same on fluid-structure interfaces where the Lagrangian coordinate system is used. We therefore first focus on the time integration on the interface and then apply the results to the whole computational domain.

2.4 Finite Element Equations of the Coupled System

Let the solution vector of the coupled system be $X = (X_f, X_s)$, where X_f and X_s are the fluid and solid solution vectors defined at the fluid and solid nodes respectively. Thus, $\underline{d}_s = \underline{d}_s(X_s)$ and $\underline{\tau}_s = \underline{\tau}_s(X_s)$. The finite element equations of the coupled fluid-structure system can be expressed as

$$F(X) = \begin{bmatrix} F_f\left[X_f, \underline{d}_s(X_s)\right] \\ F_s\left[X_s, \underline{\tau}_f(X_f)\right] \end{bmatrix} = 0 \tag{2.6}$$

2.5 Solutions of the Coupled System

The iterative computing and direct computing are two solutions in ADINA system. These two solutions must ensure that time integrated points between the fluid and the solid are consistent in dynamic analysis. Because of FSI model being nonlinear, for these two solutions the finite element equation could be solved by iteration. The fluid and solid solution variables are also fully coupled in these two solutions. For direct solution, the fluid equations and the solid equations are linearzed in a matrix system. This matrix system can be written as

$$\begin{bmatrix} A_{ff} \; A_{fs} \\ A_{sf} \; A_{ss} \end{bmatrix} \begin{bmatrix} \Delta X_f^k \\ \Delta X_s^k \end{bmatrix} = \begin{bmatrix} B_f \\ B_s \end{bmatrix} \tag{2.7}$$

$$X^{k+1} = X^k + \Delta X^k \tag{2.8}$$

$$A_{ij} = \frac{\partial F_i^k}{\partial X_j} \quad (i, j = f, s) \tag{2.9}$$

3 THE FINITE ANALYSIS ON TLD-STRCTURE SYSTEM

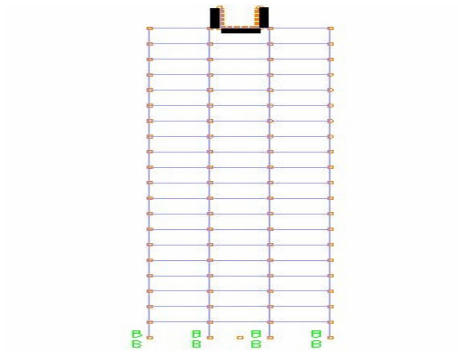
3.1 The Finite Element Models

A twenty story plane frame with the roof water tanks is modeled, and water tanks serves as tuned liquid damper. In ADINA, a fluid model and a structure model are defined respectively for fluid –structure interaction problems, so this 20-storey model is divided into a fluid model and a structure model shown in Figure 3 and 4. Because of research on dynamic response of TLD-structure system, the beam elements are used in structure model, and the 2D fluid elements in ADINA-F are used in fluid model.

In the establishment of fluid model, it is particularly important for installation of the boundary conditions, for this reason fifteen kinds of special boundary including FSI boundary can be used in ADINA-F. For this model, the upper surface of fluid should be set to free surface due to fluid sloshing, and the rest contacting with structure are set to FSI surface.

In transient analysis, in order to study the characteristics of vibration control for structure and flow, Tianjin wave, EI Centro wave and Taft wave serve as the dynamic loads on FSI model. In the process of solving, Newmark－β and α－implicit time integrations[3] are respectively adopted by solid equations and fluid equations, which can weaken the influence of time step on stability of calculation. For this model computing, Full Newton-Raphson iteration [4] is adopted, which is used to solve nonlinear fluid-coupling dynamic equation in ADINA. Although time step has great impact on convergence, a proper force relaxation factor and a displacement relaxation factor can improve stability of numerical convergence.

Condition number of linear equation coefficient matrix in Newton-Raphson iteration has great impact on the stability and efficiency, and large condition number will lead to computer rounding errors which finally result in calculation interrupting. By means of mesh optimization, appropriate unit and being dimensionless, diagonal element ratio of maximum to minimum may not exceed 10^{11}, thereby the condition number is reduced, which is very important for the direct FSI solution based on the assemblage of structure and fluid matrices.



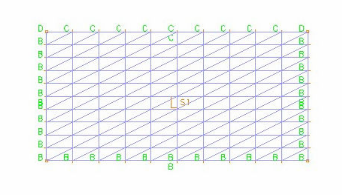


Figure 3 Structure model Figure 4 Fluid model

3.2 Analysis on Simulation

3.2.1 Model verification

In order to verify that this FSI model is correct, the solutions of simulation are compared with the results from simplify model [1] based on experiment. In figure 5, displacement time history by El Centro wave at the top of storey is plotted for these two models. It is obvious that two displacement time history curves are in good agreement. The control effect of peak displacement at the top of storey is 20.9 percent for simplify model, and the control effect of peak displacement at the top of storey is to reach 22.4 percent for FSI model, it can be seen that the effect of vibration control for FSI model is very close to simplify model, therefore the results of simulation for this FSI model have considerable credibility. Since there is different vibration sensitivity for both two materials, which consist of spring elements used by simplify model and fluid element used by FSI model, the response time history for these two models has certain phrase difference, but it can not change the basic characteristics of TLD.

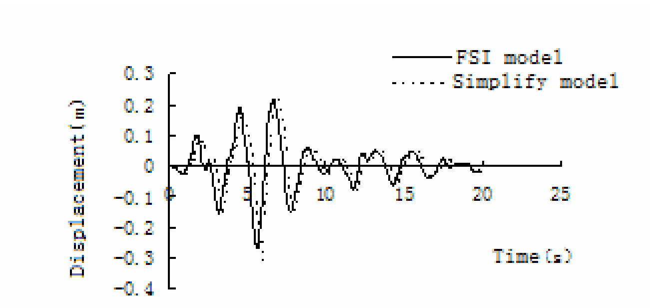
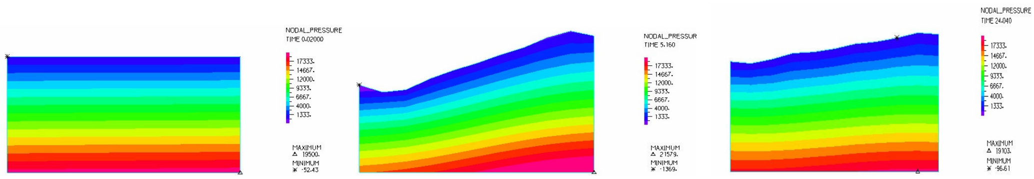


Figure 5 Displacement time history at the top of storey

3.2.2 The characteristics of flow for TLD-structure system

The fluid force at tank wall is integrated using the stress of the fluid boundary element where the solid node is located, and the pressure field decides the value of the fluid force at tank wall. Figure 6 indicate fluid pressure contours at different time by El Centro wave for the FSI model. The Fluid pressure contour at the beginning of structure vibration is in the figure 6(a), from the figure 6(b) the fluid pressure contour express that the displacement at the top of storey reaches peak value, and figure 6(c) shows the fluid pressure contour at the degeneration of structure vibration.

Because of smaller amplitude of vibration, it can be seen from the figure that fluid pressure field is relatively uniform at the beginning of structure vibration. With the increase of amplitude, the fluid pressure gradually shows local heterogeneity, and this heterogeneity becomes more and more obvious, finally local pressure concentration comes into being. The reason for this heterogeneity: after fluid sloshing at tank wall, the direction of flow has changed, stagnation effect appears, and local pressure increases; meanwhile, high pressure area occur at the bottom of water tanks away from the direction of structure vibration, and the fluid present state of low pressure along the he vibration direction.. The changes of fluid pressure is corresponding to the vibration of structure, it fully inflect coupling interaction between the fluid and the structure, in other words, the greater the fluid pressure has changed , the more significant the structure responses to fluid sloshing will be, thereby the good control for vibration of structure with TLD will be achieved



(a) t=0s (b) t=5.2s (c) t=24s

Figure 6 Fluid pressure

3.2.3 The characteristics of vibration control for TLD-structure system

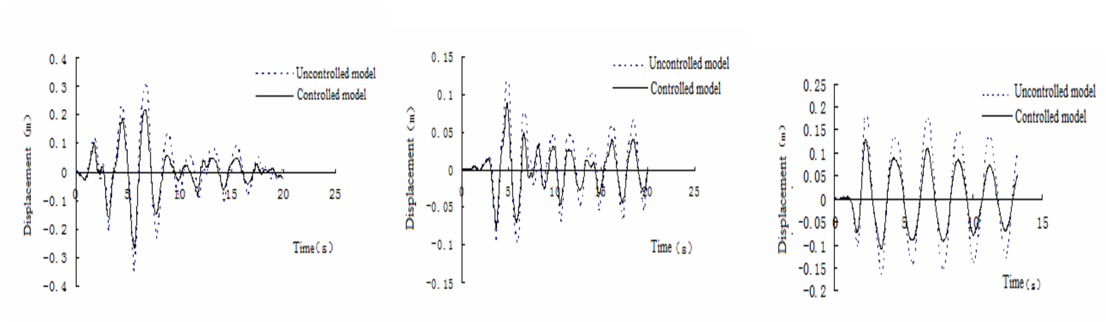
By means of analysis on the characteristics of flow, fluid sloshing is beneficial to constrain vibration of structure to a high degree, meanwhile, when the fluid sloshing frequency is corresponding to the natural frequency of structure, the amplitude of fluid sloshing will increase. Therefore, for improving the effect of vibration control, the size and depth of water tanks have been adjusted, and the ratio of fluid sloshing frequency to natural frequency of structure reaches 0.96. In addition, a suitable mass ratio is very important, because inertia force by fluid sloshing is a reason for interaction between fluid and structure. In this paper, the mass ratio is 4.13 percent.

Table 3.1 and figure 7~8 show that: when using adjusted model under three kinds of seismic waves, the results of acceleration and displacement at the top of storey before structure being control are compared with the results after structure being control. From the table, although the effects of vibration control are difference under three seismic waves, the vibration of structure with TLD is effectively controlled. Even if the effect of vibration control is lowest under the Taft waves, its ratio can also reach 22.4 percent. Therefore, TLD designed appropriately could make the best of its behavior of vibration control.

Table 3.1 The analysis results

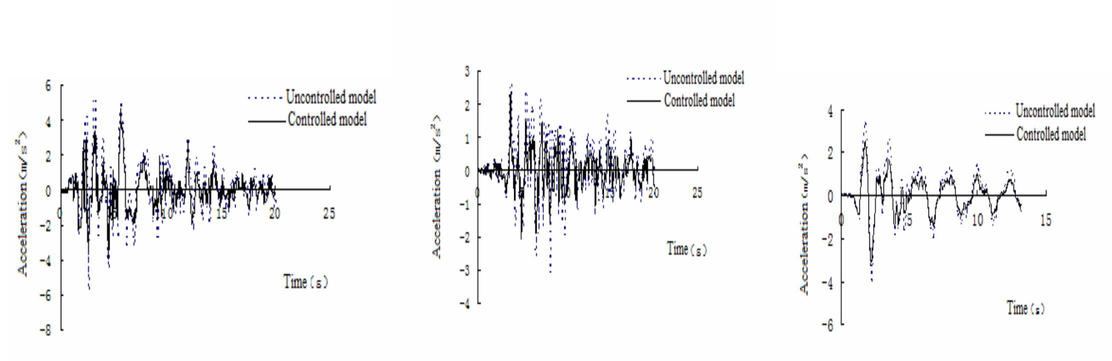
Waves	Displacement（m）			Acceleration（m/s^2）		
	Controlled model	Uncontrolled model	ratio（%）	Controlled model	Uncontrolled model	ratio（%）
Taft	0.1179	0.0915	22.4	3.0705	2.4902	18.9
Tianjin	0.1860	0.1298	30.2	4.1484	3.1403	24.3

El Centro	0.3469	0.2543	26.7	5.7429	4.4105	23.2



(a) El Centro wave (b) Taft wave (c) Tianjin wave

Figure 7 Displacement time history at the top of storey



(a) El Centro wave (b) Taft wave (c) Tianjin wave

Figure 8 Acceleration time history at the top of storey

4 CONCLUSIONS

In this paper, a finite element analytical method of the structure with tuned liquid damper (TLD) is studied. This method can effectively simulate the fluid-structure interaction, and accurately predict characteristics of vibration control for TLD-structure and flow. Furthermore, this method reduces the dependence on structure experiment and has benefit for application of TLD.

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