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Numerical Simulation of Performance of TLD Device with a Ribbed Baffle

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Abstract. Tuned liquid damper(TLD) has been widely used to suppress structural vibration, and its combination with elastic components has become a research hotspot. In this paper, a TLD structure with a ribbed baffle is proposed, and the vibration damping performance of the normal baffle and the ribbed baffle has been compared when using rigid material and elastic material, respectively. The partitioned solution of fluid-structure interaction method is used to numerically simulate the horizontal vibration attenuation process of five TLD devices, which proves the superiority of vibration damping performance of ribbed baffles when using elastic materials. The vorticity contour of the two structures with different baffles when using elastic materials is compared, which confirms the superiority of the vibration damping effect of the structure with ribbed baffle.

Keywords. Tuned liquid damper, numerical simulation, fluid-solid interaction, elastic material

1. Introduction

Harmful vibration widely exists in engineering practice. Passive vibration reduction plays an important role in the field of vibration reduction due to its simple structure, convenient installation and low cost. The technology of passive vibration reduction by liquid sloshing has been applied in the field of marine ships and satellites for a long time. However, it was not until 1988 that Fujino's research team [1] formally proposed the concept of tuned liquid damper (TLD). The principle of TLD vibration reduction is as follows: in the process of liquid forced sloshing, the pressure difference, wave breakage and liquid viscous dissipation caused by sloshing liquid and wave are used to absorb and consume the vibration energy of the main structure and achieve the purpose of vibration reduction.

In recent years, many researchers have optimized TLD by using the methods of theoretical analysis, experimental research and numerical simulation.

Theoretical analysis is the most accurate method. Since TLD was proposed, many researchers have proposed Sun nonlinear sloshing model [2], potential flow theory [3], nonlinear shallow water wave theory [4], finite amplitude wave theory [5], and equivalent mechanical models [6]. However, if the shape of TLD is not a regular model, it is difficult to study its performance theoretically; In addition, the result derived from the equation is an analytical solution rather than a numerical solution.

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Recently, more researchers have chosen the combination of numerical simulation and other two modes to study the performance of TLD from the following aspects: using sloped bottom [6], using damping screen [7], improving the shape of liquid reservoir [8], etc.

Meanwhile, adding flow damping devices (FDD) to TLD has become a hot spot. This is because FDD can improve the disadvantage of low inherent damping of TLD. FDD is specially designed accessories of various shapes, sizes and forms. It is installed in TLD container to dissipate energy by interfering with the movement of shaking liquid. Common FDDS include iron mesh, screen, baffle, pole, floating object, bottom obstacle, etc. [9].

In the existing studies, most of the flow damping devices use rigid materials, and there are few studies on the combination of elastic materials and TLD. However, in recent years, the research on the fluid structure interaction between sloshing liquid and elastic materials has also attracted more and more attention due to the good performance of interaction effect between violent shaking of liquid and large deformation of elastic material. This characteristic can strengthen the energy consumption capacity of liquid and the energy absorption capacity of elastic device and also makes most flow damping devices made of elastic materials perform better in damping than rigid materials. Park et al. [10] proposed a new type of passive damper, TLCD with embossment (termed as ETLCD). The result shows that the structure with embossment is superior to the structure without it in vibration reduction performance, efficiency and stability. In view of the fact that the energy dissipation of the TLD device with baffle mainly comes from the vicinity of the baffle, a ribbed baffle similar to embossment is proposed, and the two-way fluid-structure interaction method of separation solution method is used to simulate and analyse it, and its vibration reduction performance parameters have been obtained.

In this paper, the performance of TLD devices with elastic material components or rigid material components is studied by numerical simulation. Through the attenuation process of structural vibration, the performance of the two is compared. Since TLD vibration reduction involves the process of fluid rotation, shear, vortex generation and fragmentation, and energy attenuation, this paper hopes to explore the corresponding vibration reduction mechanism combined with vorticity analysis, and seek the key design parameters. The numerical simulation work in this paper is realized on the two-way fluid-structure coupling platform of the commercial software ANSYS Workbench 2021R2, in which MECHANICAL software is used for numerical calculation in the solid domain and FLUENT software is used in the fluid domain.

2. Physical Model and Numerical Method

2.1. Physical Model

The physical model is a structural steel cube with four outer walls and exposed front and back. The inner cavity size is 100 mm ×100 mm × 100 mm, and the wall thickness is 5 mm, the volume is 210 cm^3 and the steel density is 7850 kg/m^3. The inner cavity is filled with water with a height of 50 mm; One end of the spring is connected to the fixed point, and the other end is connected to centre of the container wall, and the spring with a stiffness of 6508 N/M is compressed for 5 mm to give the structure an initial vibration. In order to ensure the high strength interaction between elastic materials and the swinging liquid, this case chooses the high elastic material with young's modulus of 6×10^6 Pa, density of 1100 kg/m^{3}and Poisson's ratio of 0.4, whose trademark is AXSONRE11820-(9) [11].

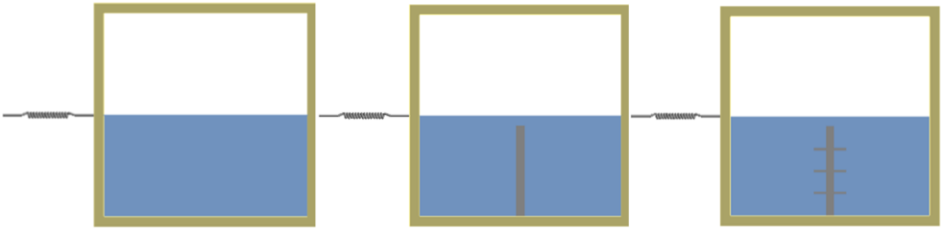


Figure 1. Device diagram of original structure, structure with baffle, structure with ribbed baffle

Figure 1 shows the diagram of original structure, structure with baffle, structure with ribbed baffle. The size of baffle is 90 mm × 4 mm × 45 mm and the size of the fins is 90 mm×6 mm×1 mm. In this paper, the fluid-structure interaction numerical simulation will be carried out, and the vibration reduction performance of five different cases will be obtained.

2.2. Numerical Method

Assuming that TLD works under normal temperature and pressure and ignoring the thermal effect, the calculation of energy conservation equation can be omitted, and the fluid viscosity coefficient can be regarded as constants. In this case, the working medium is liquid water, which can be regarded as incompressible fluid. Using the continuum assumption and Euler description, the fluid mass conservation equation and momentum conservation equation are expressed as follows:

$$\nabla \bullet \boldsymbol{u} = 0 \tag{1}$$

$$\rho \frac{D\boldsymbol{u}}{Dt} = -\nabla p + \mu \Delta \boldsymbol{u} + \rho \boldsymbol{f} \tag{2}$$

The conservation equation of solid domain can be derived from Newton's second law:

$$\rho_s \ddot{\boldsymbol{d}} = \nabla \bullet \boldsymbol{\sigma}_s + \boldsymbol{f}_s \tag{3}$$

Where, ρ_s is the solid density, $\ddot{\boldsymbol{d}}$ is the local acceleration vector in the solid domain, $\boldsymbol{\sigma}_s$ is the Cauchy's stress tensor and $\boldsymbol{f}_s$ is the solid volume force vector.

The numerical simulation of fluid solid coupling needs to follow the basic conservation equation, that is, at the interface of fluid solid coupling, it needs to meet the equivalence or conservation of various physical quantities of fluid and solid. If the influence of energy and heat transfer is ignored in this case, the stress and displacement shall meet the following fluid structure coupling equation:

$$\begin{cases} \boldsymbol{\tau}_f = \boldsymbol{\tau}_s \\ \boldsymbol{d}_f = \boldsymbol{d}_s \end{cases} \tag{4}$$

However, due to technical limitations, at present, the fluid structure coupling mostly adopts the separation method, that is, solving the fluid governing equation and solid governing equation respectively, and transmitting the calculation data of fluid domain and solid domain through the fluid structure coupling interface. This method has time lag and the physical quantities of the fluid structure coupling interface are not completely conserved, but its credibility has been verified in practical large-scale problems.

3. Results

This study compares the displacement changes of the horizontal vibration of the box in the following five cases. Table 1 shows the damping displacement, percentage of the maximum displacement and the time required when the damper displacement reaches the fifth wave peak. Figure 2 shows the change of displacement of five different types of shock absorbers with time.

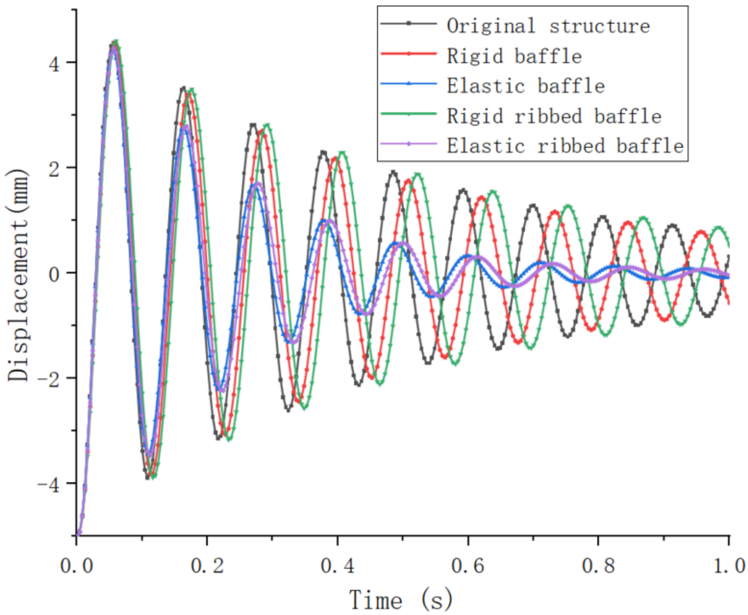


Figure 2. Vibration reduction horizontal displacement diagram of five TLD devices

As shown in figure 2, the built-in baffle can prolong the vibration period of the TLD devices, slow down the frequency, and improve the vibration reduction effect. This is because the baffle can block the motion of the liquid, making the liquid sloshing more intense, and greatly enhance the interaction of fluid and solid. The built-in elastic ribbed baffle structure has the best damping effect. Among them, when the structure is consistent, the frequency reduction effect of rigid material is slightly more significant than that of elastic material. The main reason is that the rigid material adopts structural steel and its density is higher than that of rubber, leading to the larger mass and slower frequency of the whole device. Compared with the rigid material, the elastic material has a better damping effect, because the elastic baffle can be bent and has a more intense interaction with the liquid than the rigid baffle, thus greatly increasing the wobbling motion of the liquid, which is expected to improve the damping capacity of the system.

Table 1. Performance parameters of five different types of TLD

Case	Peak displacement (mm)	Fifth peak (mm)	Percentage	Time (s)
Original structure	4.3844	1.9221	43.84 %	0.484
With rigid baffle	4.3781	1.7648	40.31 %	0.508
With elastic baffle	4.2549	0.5736	13.48 %	0.488
With rigid ribbed baffle	4.4198	1.880	42.54 %	0.520
With elastic ribbed baffle	4.2849	0.5761	13.44 %	0.500

In some TLDs, the energy dissipation occurred when there was relative motion between the liquid and the submerged object was caused by the pressure drop of the liquid on the object [12] , and the pressure drop was positively correlated with the density of the liquid and the square of the relative velocity between the liquid and the submerged object [13] .On both sides of the elastic baffle, the baffle bends to the right when the structure moves to the left; Conversely, as the structure moves to the right, the baffle bends to the left. This makes the relative velocity between the fluid and the elastic baffle higher than the rigid baffle, resulting in greater pressure drop and greater energy dissipation. At the same time, because of the larger contact area between the ribbed baffle and the fluid, the vibration reduction effect of the ribbed baffle with elastic material is better when the fluid-solid interaction is strong. However, the vibration reduction effect of the rigid fin baffle is not as good as that of the rigid fin baffle without fin, which is likely to decrease the volume of the fluid in the box due to the volume of the fin. When the fluid-solid interaction is not strong, the vibration reduction effect decreases instead.

On the other hand, the TLD device absorbs energy through the interaction between liquid and wall, and dissipates energy through liquid hitting the wall, wave breaking and internal shear flow, so as to achieve the purpose of energy dissipation and vibration reduction. Vorticity can represent the rotational and shear strength of fluid, so it can be analysed mechanically from the perspective of observing the microscopic changes of liquid vorticity in the process of vibration.

In order to simplify the process, representative moments will be selected to analyse the structure. As shown in figure 2, since the vibration reduction curves of each case have no significant difference before the first trough, four representative moments of motion state are selected from the second peak: ① the second peak, ② the spring fourthly reached the original length, ③ the second trough, ④the spring fifthly reached the original length. Due to the limited number of transient time steps in numerical calculation, only the moment closest to the above mentioned motion state in the recorded step size can be selected.

The specific time of the above 4 typical moments are shown in table 2:

Table 2. Specific time of 4 typical moments

Case/Time(s)	①	②	③	④
With elastic baffle	0.164	0.192	0.220	0.244
With ribbed elastic baffle	0.168	0.196	0.224	0.252

Figure 3 and figure 4 show the vorticity contour of structure with elastic baffle and structure with ribbed elastic baffle, respectively.

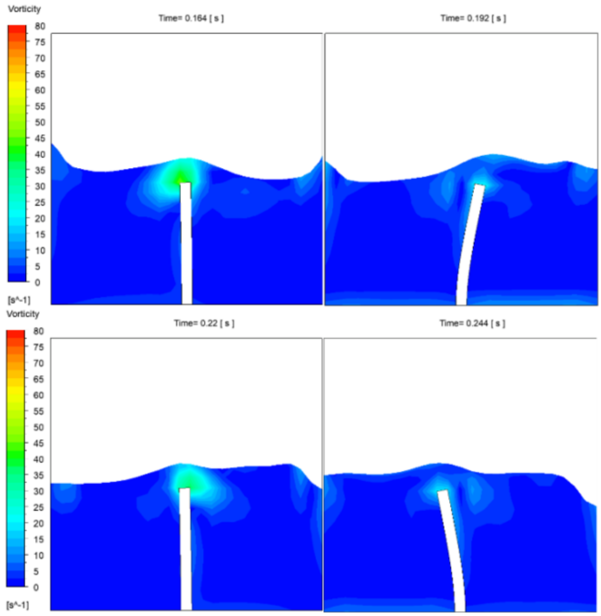
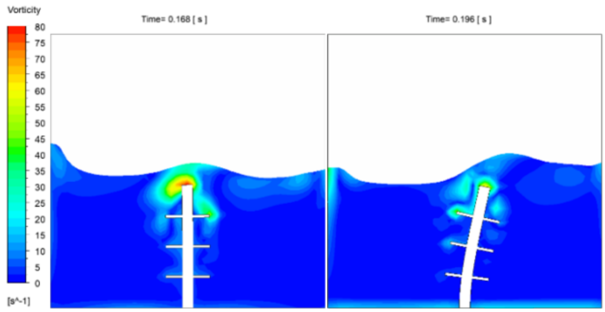


Figure 3. Contour of 4 typical moments of structure with elastic baffle



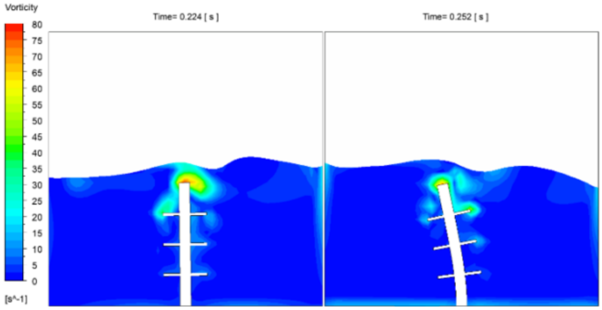


Figure 4. Contour of 4 typical moments of structure with elastic ribbed baffle

It can be observed that the places with large fluid vorticity are concentrated near the free surface, the top of the baffle and the top of the fins. Because the flexible baffle has a larger interaction area with the fluid, and the interaction between the fluid and the solid is stronger, this explains the reason why the elastic baffle with fins has better vibration reduction effect than the elastic baffle without fins. Among them, the rotation and shear motion of the fluid near the top of the baffle and the top of the fin are intense. On both sides of the elastic baffle, when the structure moves to the left, the baffle bends to the right, and the force generated by the baffle moves to the right, hindering the movement of the structure; At this time, the vortices near the left wall of the baffle are stronger, while in the fluid far away from the baffle, the vortices on the right are stronger. On the contrary, when the structure moves to the right, the baffle bends to the left, and the force generated by the baffle moves to the left, which also hinders the structure movement. At this time, the vortices near the wall on the right side of the baffle are stronger, while in the fluid away from the baffle, the vortices on the left are stronger. When the spring elongation (compression) is large, the rotation motion of the top of the elastic baffle is stronger and the disturbance is more intense; At this time, the shape variable of the elastic baffle is less than that when the spring is at the original length.

4. Conclusion

The damping effect of the structure with elastic materials is obviously better than the structure with rigid materials, and the damping effect of the structure with elastic ribbed baffle is the best. However, the frequency reduction effect of the structure with rigid materials is better. Under the condition that the frequency reduction requirements are high and the vibration reduction time is not high, it may be more appropriate to select the structure with rigid ribbed baffle.

The damping effect of the baffle with elastic fins is the best. The following are the reasons:

(1) the interaction area between the baffle with fins and the fluid is larger, and the area of pressure drop is larger. When the fluid structure coupling effect is strong, it is beneficial to damping.

(2) The fin intensifies the disturbance at the top of the fin, intensifies the fluid shear and vortex near the top, and accelerates the energy dissipation.

Besides, there are many kinds of elastic materials, and the selection of more appropriate elastic materials can further enhance the vibration reduction effect. Therefore, it is necessary to pay attention to the latest development of elastic materials.

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