Investigation on a Shallow Water Annular Tuned Liquid Damper for Suppressing Vibration of Wind Tower

Youlin Zhang, Huaxiang Li, Yiqing Xu

Dep. Technology Innovation Center, Shanghai Electric Wind Power Group Co., Ltd., 115 Caobao Rd., Shanghai, PRC.
sir.zhyl@163.com

Abstract. Although the annular tuned liquid damper (ATLD) filling with shallow water is helpful in mitigating the vibration response of wind tower, it’s challenging in predicting the interface force between the ATLD and its supporting system and evaluating the damping contribution of the ATLD to the dynamic response of tower. In this study, we developed an approach to investigate the damping performance of the ATLD base on the cooperation between the smoothed particle hydrodynamics method (SPH) and the equivalent tuned mass damper (TMD). Herein the SPH method is employed to numerically investigate the non-linear behaviour of sloshing waves in the damper and calculate the interface force, while the TMD method is used to express the TLD properties. Based on this approach, a series of numerical simulations of liquid sloshing in a shallow water ATLD with different excitation periods are carried out. The equivalent damping ratios of ATLD are calculated to quantitatively analyse the suppression effect of ATLD on the vibration response of a wind tower.

1. Introduction

As the progressing of wind energy technology, more flexible slender wind towers are installed to obtain high-quality wind resource. Since the low natural frequency and lightly damped features of wind tower, the vibration of the tower induced by the wind load becomes more and more obviously, which reduces the fatigue life of wind turbine. To suppressing the oscillation of the wind turbine system, vibration control devices can be used to increase the structural damping of tower. In the near few years, tuned liquid damper (TLD), which is widely utilized to introducing higher damping and absorbing the kinetic energy of high-rise buildings, is also employed by original equipment manufactures (OEMs) of wind energy to mitigate the vibration responses of wind tower. Due to its low natural frequency feature, the annular tuned liquid damper (ATLD) filling with shallow water is capable in suppressing the first mode vibration of wind tower.

For the application of an ATLD in practical engineering, there are still two main challenges to be overcame during the structure designing stage. First, the interface force between an ATLD and wind tower, which is closely effected by the evolution of free surface in the tank, needs to be predicted accurately. Till to now, some grid-based approaches [1][2] cooperating with free surface catching techniques have been proposed to simulate the dynamic behaviors of sloshing waves in a liquid tank. However, the nonlinear phenomena, such as wave breaking, splashing and fusion of fluid, are difficulty to be described by those approaches. Recently, the smoothed particle hydrodynamics (SPH) method, which disperses the fluid space by particles and represents the flow with the movements of particles, is
utilized in many studies of violent free surface flow [3]-[5]. In view of its flexibility in simulating the evolution of liquid surface, the SPH method is employed to numerically investigate the non-linear behaviors of sloshing waves in the damper and predict the interface force between ATLD and wind tower. For the second challenge, a method for quantitatively evaluating the damping contribution of a shallow water ATLD to the wind tower need to be developed. Since the nonlinearity of fluid behaviors, the damping ratio of shallow water TLD is hard to be predicted directly by theoretical approaches. In the studies [6][7], the equivalent tuned mass damper (TMD) method is used to express the TLD properties in view of the similarity between TMD and TLD in aspect of the basic mechanism.

In this study, we aim to investigate the performance of an ATLD in suppressing the vibration of wind tower. The cooperation between the SPH method and equivalent TMD model is introduced. An approach to calculate the equivalent damping ratio, which is considered as the Key Performance Indicator (KPI) of the ATLD, is proposed. Then, a series of numerical simulations of liquid sloshing in a shallow water ATLD with different excitation periods are carried out. The suppression effect of ATLD on the vibration response of a wind tower is quantitatively analyzed.

2. Methodology

2.1 SPH method for simulation of fluid motion

The SPH technique discretises a fluid domain using a set of material points or particles where physical quantities are known [8]. These properties carried by each particle are calculated by the integration of variables regarding neighbouring particles which are determined by the smoothing length often denoted as $h$.

$$ F(r) = \int F(r')W(r-r', h)dr' $$

(1)

Here, $F(r)$ is the function of any physical quantities such as position, velocity, density and pressure, $r-r'$ represents the distance between a neighbouring particle and the target particle, the interpolation or weighting function $W$ is referred to as the kernel function. Typically, the following approximation of the integration formula is popular for the discretization of governing equations [8].

$$ F(r_a) \approx \sum_b F(r_a) \frac{m_b}{\rho_b} W(r_a-r_b, h) $$

(2)

where $a$ and $b$ denote the target particle and its neighbouring particle, $m$ and $\rho$ are the mass and the density of particle respectively. In this paper, the Quintic kernel function [9] $W$ is employed and expressed as

$$ W(r,h) = \alpha_D \left(1 - \frac{q}{2}\right)^4 (2q+1) $$

(3)

where $q=r/h$, $r$ is the distance between any two given particles, $\alpha_D$ is equal to $7/4\pi h^2$ in 2-D and $21/16\pi h^3$ in 3-D.

In the Lagrange system, the evolutions of fluid field are governed by the Navier-Stokes formulas expressing as

$$ \frac{d\rho}{dt} = -\rho \nabla \cdot v $$

(4)

$$ \frac{dv}{dt} = \frac{1}{\rho} \nabla P + \mu \nabla^2 v + g $$

(5)

where $v$ is the velocity field, $P$ is the pressure, $\mu$ is the kinematic viscosity, $g$ is the body force.
According to the contributions of laminar viscous stresses from [10], and the concept of the Sub-Particle Scale (SPS) proposed by [11], the momentum conservation equation (5) in a continuum can be rewritten by the following discrete scheme

$$\frac{dv_a}{dt} = \sum_b m_b \left( \frac{P_b + P_a}{\rho_b \rho_a} \right) \nabla_a W_{ab} + g $$

$$+ \sum_b m_b \left( \frac{4v_0 r_{ab} \nabla_a W_{ab}}{(\rho_b + \rho_a)(\gamma + \eta^2)} \right) v_{ab}$$

$$+ \sum_b m_b \left( \frac{\tau_{ij}}{\rho_b^2} \frac{\tau_{ij}}{\rho_a^2} \nabla_a W_{ab} \right)$$

where the superscripts refer to particles a and b.

By discretizing the continuity equation with the delta-SPH form [12], the density changes of fluid particles can be computed by

$$\frac{d\rho_a}{dt} = \sum_b m_b v_{ab} \nabla a W_{ab} + 2\delta_T c_0 \sum_b (\rho_b - \rho_a) \frac{r_{ab} \nabla a W_{ab} m_b}{\rho_b}$$

where $c_0$ is the speed of sound at the reference density, $\delta_T$ is the delta-SPH coefficient and set as 0.1 in this paper.

Following the work of [13], the fluid is treated as weakly compressible, an equation of state is used to establish the relationship between the fluid pressure and density.

$$P = \frac{c_0^2 \rho_0}{\gamma} \left( \left( \frac{\rho}{\rho_0} \right)^\gamma - 1 \right)$$

where $\gamma=7$, $\rho=1000\text{kg/m}^3$ is the reference density.

2.2 Equivalent damping ratio calculation method

Though the numerical or experimental approaches may provide details of non-linear sloshing phenomena inside the tank of ATLD, they are incapable to quantitatively evaluate the performance of TLDs for the preliminary design. In this paper, a TMD analogy is employed to study the properties of ATLD, and a method to calculate the equivalent damping ratio is proposed as the Key Performance Indicator (KPI) of the ATLD.

In engineering, the equivalent damping ratio of an ATLD needs to be comprehensively evaluated in conjunction with the wind turbines it serviced. For simplicity, the system of wind tower, rotor, and nacelle with an ATLD damper installed inside, is considered as the model shown in figure 1. Here the tower is idealized as a cantilever beam with the height H and the mass $M_T$. The rotor and nacelle assembly (RNA) components are simplified as one block with the mass $M_{RNA}$, and attached with the ATLD.

Under the excitation of wind load, the vibration of the system is governed by

$$M \ddot{x} + Kx = F_w - F_i$$

where $K$, $M$ is the stiffness and mass of the system. $F_i$, which is produced by the liquid motion in the ATLD tank, is the interface load between the damper and the RNA, and will be calculate by the previous mentioned SPH approach.

According to structural mechanics, the natural frequency of the system in figure 1 is
\[
\omega_0 = \sqrt{\frac{K}{M}}
\]  

(10)

where

\[
K = \omega_0^2 (M_{RNA} + \frac{33}{140} M_T)
\]  

(11)

\[
M = M_{RNA} + \frac{33}{140} M_T
\]  

(12)

In view of that the TLD is the same as the TMD with respect to its basic mechanism, the property of TLD is expressed using a TMD analogy. Following [6], the response of system in figure 1(b) is assumed to be same as that in figure 1(c), and the interface load \( F_i \) can be expressed using the virtual mass \( M_{VTLD} \) and damping \( C_{VTLD} \) of ATLD:

\[
F_i = M_{VTLD} \ddot{x} + C_{VTLD} \dot{x}
\]  

(13)

then

\[
M_{VTLD} = \int_0^T f(t) \dot{x}(t) \, dt / (\pi \omega^3 A^2)
\]  

(14)

\[
C_{VTLD} = \int_0^T f(t) \dot{x}(t) \, dt / (\pi \omega A^2)
\]  

(15)

where \( x \) is the displacement of the damper, \( T = 2\pi / \omega_0 \) and \( A \) is the period and amplitude of structural vibration, respectively.

Based on the formula (9) and (13), the vibration of the structure-ATLD composite system is governed by

\[
(M + M_{VTLD}) \ddot{x} + C_{VTLD} \dot{x} + Kx = F_w
\]  

(16)

Then, the equivalent damping ratio of the composite system can be calculated by

\[
\xi = \frac{C_{VTLD}}{2 \sqrt{K(M + M_{VTLD})}}
\]  

(17)

\( \xi \)

Figure 1. Simplification of tower-RNA-ATLD system
2.3 Procedure of performance analysis of the ATLD

In this study, the SPH method is used in cooperation with the equivalent TMD approach to evaluate the damping effectiveness of an ATLD following the analysis procedure shown in figure 2. The SPH method is employed to investigate the complex dynamic behaviors of sloshing wave in a shallow water ATLD. For a simulation work based on the SPH method, the fluid continuum is discretized by a set of particles. The motion of the particle is governed by the Navier-Stokes equations in the Lagrangian system. With the help of smoothing kernel function, the particle’s physical quantities in the governing equations can be locally integrated according to the physical properties of surrounding particles. According to this calculation idea, the evolution of shallow water can be reproduced and the bottom shear force of liquid tank can be calculated in time domain.

To quantitatively describing the damping feature of a shallow water TLD, the equivalent TMD analogy is carried out following the SPH simulations. By the integration of shear force and structure motion within one vibration period of wind tower, the equivalent damping and mass can be calculated and the damping contribution of ATLD to a wind turbine can be obtained.

Figure 2. Analysis procedure of the ATLD for suppressing vibration of wind tower

3. Numerical conditions

In this paper, the damping effect of ATLD on the vibration of a wind tower with the height 120 m is numerically investigated. The mass of tower and RNA are set to 300 t and 350 t, respectively. The first order frequency of the tower is 0.189 Hz. Four ATLD dampers are mounted in the nacelle, and each damper is consisted of 10 annular tanks. The tank has an outer diameter of 1.26 m, an inner diameter of 0.57 m and a height of 0.08 m. A mixture of glysantinG30 and water is filled in the tank with the height of 0.03 m, and the two are in a volume ratio of 1:2. The density and viscosity of glysantinG30 are 1.125 g/cm$^3$ and 26 mm$^2$/s, while those of the water are 1.0 g/cm$^3$ and 1.01 mm$^2$/s, respectively.

Based on the performance evaluation process of ATLD, the sloshing behaviors of liquid in ATLD under shallow water loading condition will be numerically analyzed by the SPH approach firstly. The spatial discretization of ATLD model with particles is shown as figure 3. The total number of particles
is 313000 while the number of fluid particles is 238000. The mixed liquid used has a density of 1.075 g/cm³ and a viscosity of 10 mm²/s.

To study the performance of the ATLD based on the KPIs, for instance the working frequency and damping performance, the behaviors of shallow water in the annular tank under a series of excitation frequencies are simulated. The ATLD tank is forced to move harmoniously in the horizontal direction. The amplitude of motion is 0.1 m, while the excitation frequencies vary from 0.1 Hz to 0.46 Hz.

![Figure 3. Particle model of ATLD tank](image)

**Table 1. Parameters of ATLD and its support structure.**

| Parameters of tower and RNA | Values | Parameters of ATLD | Values |
|-----------------------------|--------|--------------------|--------|
| States                      | Park   | Number of ATLDs    | 4      |
| Wind speed (m/s)            | 2.5    | Outer diameter of tank (m) | 1.26 |
| Height of hub (m)           | 120    | Inner diameter of tank (m) | 0.57 |
| Mass of rotor (ton)         | 110    | Height of tank of tank (m) | 0.08 |
| Mass of nacelle (ton)       | 240    | Liquid depth (m)     | 0.03  |
| Mass of tower (ton)         | 350    | Density of liquid (g/cm³) | 1.075 |
| 1st order frequency of tower (Hz) | 0.189 | Viscosity of liquid (mm²/s) | 10 |

4. **Performance evaluation of shallow water ATLD**

In traditional researches, the liquid sloshing load is usually considered as a key factor to judge the energy dissipation effect of a TLD, and the excitation frequency corresponding to the maximum sloshing load is regarded as the resonance frequency of liquid. Figure 4 shows the time histories of interface forces between the annular tank and the turbine tower. For the cases of sloshing with low-frequency excitation, such as $f = 0.14$ Hz and $f = 0.16$ Hz, the time history curves of interface loads presents the harmonic characteristic. As the excitation frequency increases from $f = 0.14$ Hz and $f = 0.25$ Hz, the curves show the non-linear characteristic due to the presence of higher order load components, and the peak values of the interface loads increase from 7 N to 14.5 N. For high-frequency excitation conditions such as $f = 0.28$ Hz and $f = 0.34$ Hz, although the high-frequency load components of the interface load curves still be observed, the amplitudes of the loads together with the instantaneous variety of the curves gradually decrease.
Figure 5 shows the evolution of free surface in the tank with an excitation frequency of 0.25 Hz. The nonlinear phenomena including the sloshing wave propagation in an annular tank, the slamming event on the wall, the variation of flow velocity and vortex around the affiliated obstacle structures are observed.

According to the equivalent TMD analogy method, the interface force includes the components concerning the virtual mass $M_v$ and damping $C_v$. In this study, the virtual mass and damping regarding different excitation frequencies are calculated based on equation (14) and (15), and plotted in figure 6. For the virtual mass $M_v$, the trend of the curve consists of three segments, i.e., the ascending section with the excitation frequency less than 0.16 Hz, the descending section with the excitation frequency between 0.16 Hz and 0.28 Hz, and following with the gentle section. For the virtual damping $C_v$, the trend of the curve is more moderate than that of virtual mass curve, and the peak presents at the excitation frequency 0.25 Hz which is same with that regarding the amplitude of interface force.

To quantitatively evaluating the damping performance of the shallow water ATLD, the equivalent damping ratios are investigated. The related trend versus excitation frequencies is shown as figure 7, and similar to that regarding the virtual damping $C_v$, which indicates that the equivalent damping ratio is closely effected by the virtual damping. As the peak of the damping ratio curve presents around the frequency 0.22 Hz, the interval between 0.18 Hz and 0.25 Hz is recommended as the operating frequency of ATLD.

![Figure 4. Time histories of interface forces of one ATLD tank](image-url)
In addition, the vibration of a tower with or without ATLD installed is analyzed. The initial structural damping ratio is set to 0.5% for the tower without ATLD, while an additional damping ratio of 0.14% is considered for the case with ATLD. For simplicity, the wind load $F_w$ is assumed as a sinusoidal force with an amplitude of 109 kN which represents the aerodynamic load under the low wind speed of 2.5 m/s, and a frequency 0.189 Hz which is consistent with the natural frequency of tower. Under this load, the vibrations at the top of tower with/without ATLD installed are shown in Figure 8. For the case with ATLD, the vibration amplitude is 0.462 m, which is 35.4% lower than that without ATLD.

**Figure 5.** Evolution of free surface in ATLD tank ($f_e=0.25$ Hz)
5. Conclusions
In this study, the SPH method in cooperation with an equivalent TMD analogy approach is employed to evaluate the damping performance of a shallow water ATLD to suppress the vibration of wind tower, and a series of numerical simulations of liquid sloshing in a shallow water ATLD with different
excitation periods are carried out. According to the numerical results, the following conclusions can be derived:

1) The interface load between the ATLD and tower shows the non-linear characteristic due to the presence of higher order load components. The frequency $f=0.25\text{Hz}$ regarding the maximum amplitude of the interface loads can be considered as the sloshing resonance frequency.

2) The equivalent damping ratio is closely effected by the virtual damping $C_v$, and the interval between 0.18 Hz and 0.25 Hz is recommended as the operating frequency of the present ATLD.

3) The vibration response of tower with four ATLDs installed inside the nacelle is mitigated by the amplitude of 35.4%.

Generally, the proposed method shows good capability in handling the challenges about reproducing the nonlinear phenomenon of wave-structure interaction in ATLD and evaluating the damping contribution of ATLD to the wind tower.

6. References

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