Study on the Influence of the Inflow Angle on the Vortex-Induced Vibration Characteristics of a Tip-Shaped Wide Submerged Floating Tunnel Section

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Abstract

The pointed cross-section is a multilaned wide cross-section of a submerged floating tunnel tube that is favorable for fluid-structure interaction in wave-current environments, and its angle of attack is directly related to the fluid load. To reveal the intrinsic relationship between the angle of attack and the vortex-induced vibration characteristics of a wide pointed cross-section submerged floating tunnel, this study designed seven wide pointed cross-sections with different angles of attack. A two-dimensional scaled numerical model under unsteady flow was established using FLUENT, and the incompressible viscous N-S equations were solved using the two-dimensional Reynolds-Averaged Navier-Stokes (RANS) SST k-ω turbulence model. Runge-Kutta method code was embedded in FLUENT UDF to solve the structural vibration response, and dynamic mesh technology was used to simplify the submerged floating tunnel as a mass-spring-damping system for numerical simulation. The vibration response, wake vortex-shedding modes, and motion trajectories of submerged floating tunnels with different angles of attack and natural frequencies under ocean currents were investigated. The results show that: 1) the maximum transverse amplitude of the structure decreases with increasing angle of attack, the drag increases with increasing angle of attack, and the maximum streamwise amplitude increases with increasing flow velocity; 2) the amplitude-limited motion of the submerged floating tunnel in water is dominated by transverse reciprocating vibration, while the streamwise direction deviates from the original position; 3) an angle of attack of 80° is an appropriate angle for the pointed cross-section when comprehensively considering force conditions and space utilization; 4) changes in the natural frequency of the structure have a significant effect only on lift and do not alter the vortex-shedding mode of the structure.

Full Text

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Abstract: The tip-shaped section is a multi-lane wide section of a submerged floating tunnel tube that is conducive to fluid-structure coupling interaction in wave-current environments, and the magnitude of its inflow angle is directly related to the fluid load. To obtain the intrinsic relationship between the inflow angle and the vortex-induced vibration characteristics of a tip-shaped wide submerged floating tunnel section, seven tip-shaped wide sections with different inflow angles were designed in this study. A two-dimensional scaled numerical model under unsteady flow was established using FLUENT, and the incompressible viscous-fluid N–S equations were solved using the two-dimensional Reynolds-averaged Navier–Stokes (RANS) SST k-ω turbulence model. Runge-Kutta method code was embedded into the FLUENT UDF to solve the structural vibration response, and dynamic mesh technology was used to simplify the submerged floating tunnel into a mass–spring–damper system for numerical simulation. The vibration response, wake vortex-shedding modes, and motion trajectories of submerged floating tunnels with different inflow angles and natural frequencies under ocean-current action were investigated. The results show that: 1) the maximum transverse amplitude of the structure decreases as the inflow angle increases, the drag increases as the inflow angle increases, and the maximum streamwise amplitude increases with increasing flow velocity; 2) the limited-amplitude motion of the submerged floating tunnel in water is dominated by transverse reciprocating vibration, while the streamwise direction deviates from the original position; 3) an inflow angle of 80° is a suitable angle for the tip-shaped section when both loading and space utilization are considered comprehensively; 4) changes in the structural natural frequency have a relatively large influence only on lift and do not change the vortex-shedding mode of the structure.

Keywords: submerged floating tunnel; tip-shaped wide section; inflow angle; vortex-induced vibration; numerical simulation

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Influence of the inflow angle on the vortex-induced vibration characteristics of the tip-shaped wide submerged floating tunnel section

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Abstract: The tip-shaped section is a kind of multi-lane wide section of the submerged floating tunnel (SFT) tube that is conducive to the fluid-structure coupling interaction in the wave and current environments. Its inflow angle is directly related to the fluid load value. To obtain the intrinsic relationship between the inflow angle and the vortex-induced vibration characteristics of the tip-shaped wide SFT tube

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section, seven tip-shaped wide cross-sections with different inflow angles were designed in this paper. A two-dimensional scaled numerical model under unsteady flow was established using FLUENT. The two-dimensional Reynolds-averaged Navier–Stokes (RANS) shear-stress transport (SST) $k-\omega$ turbulence model was used to solve the N–S equations for an incompressible viscous fluid, and Runge–Kutta code was embedded in a FLUENT UDF to solve the structural vibration response. The dynamic-mesh technique was used, and the SFT was simplified as a mass–spring–damping system for numerical simulation. The vibration responses, wake patterns, and motion trajectories of tip-shaped SFT structures with different inflow angles and different natural frequencies under current action were investigated. The results show that: 1) the maximum transverse amplitude of the structure decreases as the inflow angle increases, the drag force increases as the inflow angle increases, and the maximum amplitude in the flow direction increases with flow velocity. 2) The bounded-amplitude motion of the SFT in water is dominated by lateral reciprocating vibration, while the vibration in the flow direction deviates from the original position. 3) Considering both force and space-utilization efficiency, 80° is an appropriate inflow angle for the tip-shaped section. 4) Changes in the natural frequency of the structure have a significant effect only on the lift force and do not change the vortex-shedding mode of the structure.

Key words: submerged floating tunnel; tip-shaped wide cross-section; inflow angle; vortex-induced vibration (VIV); numerical simulation

Submerged floating tunnels, as a new type of potential transportation structure for crossing deep straits and long waterways[1], were listed in 2018 by the China Association for Science and Technology as one of the 60 major scientific problems and major engineering-technology challenges. Compared with conventional bridges, immersed-tube tunnels, and subsea tunnels, submerged floating tunnels have the advantages of being more economical, causing less pollution, reducing the energy consumption of passing vehicles, and requiring no large-scale excavation; moreover, they have greater crossing capacity and are less affected by extreme weather[2-3]. Submerged floating tunnels remain in the underwater environment for long periods, and wave and ocean-current loads are their main external loads. Different cross-sectional forms of submerged floating tunnels exhibit considerable differences in force characteristics and vibration responses under wave–current loads, and the determination of the cross-sectional form plays a pivotal role in the design and practice of submerged floating tunnels[4-5]. Increasing numbers of scholars have begun to focus on the dynamic responses of submerged floating tunnels under wave–current loads, using numerical simulations and experimental methods to study the fluid–structure interaction characteristics of different cross-sectional forms.

LI et al.[6] studied the spatial structure of submerged floating tunnels, proposed cross-sectional dimensions and spatial requirements, and compared the hydrodynamic characteristics of elliptical and polygonal sections. MANDARA et al.[7] established a mathematical model of a submerged floating tunnel based on CFD and compared the hydrodynamic characteristics of circular and elliptical sections with the same layout under dynamic and static conditions; the results showed that the elliptical section had more favorable hydrodynamic characteristics. Gu Zhen et al.[8], using the FLUENT module of ANSYS and the RNG $k-\varepsilon$ turbulence model, studied the force conditions of a submerged floating tunnel with inflow velocity as the variable. Zeng Fanxu et al.[9-10] compiled a UDF to add transverse and streamwise constraint conditions to the submerged floating tunnel tube, and established a flow domain using the two-dimensional Reynolds-averaged N–S equations and the SST $k{-}\omega$ turbulence model; they comparatively analyzed the vortex-shedding characteristics and vorticity values of polygonal and curved sections under fluid–structure coupling conditions. Chen Zhiwei et al.[11] used FLUENT to study the complex flow-around characteristics of wide sections with different shapes and different scale ratios under ocean currents. Guo Xiaoling et al.[12], based on the Reynolds-averaged equations with the SST $k-\omega$ turbulence model, used numerical simulation to study vortex-induced vibration of submerged floating tunnel tubes at different Reynolds numbers and different natural frequencies.

As a new type of underwater crossing transportation structure, model tests of submerged floating tunnels have also been continuously carried out by scholars around the world[13-14]. JAUVTIS et al.[15] conducted underwater tests of a submerged floating tunnel (SFT) and studied the vortex-induced vibration of SFT tubes under different incoming-flow velocities. DROST[16] carried out hydrodynamic and kinematic experimental research on rectangular cylinders, analyzing the acceleration dynamic response under combinations of different mooring angles and submergence depths under wave–current action. DENG et al.[17] studied the transverse vortex-induced vibration characteristics of a twin-tube submerged floating tunnel model by conducting self-oscillating model tests. JIANG et al.[18] carried out dynamic response tests in a water tank on the overall structure of a submerged floating tunnel under pure-current, pure-wave, and coupled wave–current environments.

Although existing studies have achieved abundant results, most studies by scholars on cross-section selection for submerged floating tunnels have used numerical simulation to select streamlined or smooth curved sections, such as circular, elliptical, and ear-shaped sections, while tip-shaped sections similar to hexagons have been selected less often. Wang Guangye et al.[19] used the FLOTRAN module of the finite-element software ANSYS to study the hydrodynamic characteristics of several typical submerged floating tunnel sections under uniform-flow action, pointing out that designing a polygonal section can greatly reduce …

low flow resistance. Luo Gang et al.[20] used a large-eddy turbulence model in FLUENT to calculate the flow-around characteristics of submerged floating tunnels with four cross-sectional forms: auriform, circular, hexagonal, and octagonal. The results showed that, considering the combined circumferential pressure and the amplitude of the lift force, the hexagonal section exhibited good performance and was subjected to smaller forces than the other section types. Zeng Fanxu et al.[9] used FLUENT UDF to establish vortex-induced motion models for submerged floating tunnels with different characteristic transverse sections in a uniform flow field, investigated the motion characteristics of different sections, and found that, compared with other conventional sections, the pointed-end section had the smallest transverse vibration amplitude. The above studies indicate that the pointed-end section has advantages in terms of hydrodynamic force and vibration amplitude in water[9,19-20]. However, relatively few studies have examined how the inflow angle affects the vortex-induced vibration characteristics of pointed-end SFT sections. As a type of flow-induced vibration, the influence of wind fairing angle on bridge vortex-induced vibration performance has been investigated by many scholars, showing that changing the wind fairing angle has different vibration-suppression effects for bridges[21-23].

In summary, the influence of the inflow angle on the vortex-induced vibration characteristics of pointed-end SFT sections deserves further investigation. In this study, a pointed-end section is selected as the numerical simulation cross-sectional form. By changing the tip expansion angle of the pointed-end section, the dynamic response of submerged floating tunnel pipe segments under different incoming-flow velocities is simulated and calculated, and the influence of different inflow angles on the intrinsic vortex-induced vibration characteristics of the pointed-end submerged floating tunnel pipe section is analyzed.

1 Governing Equations and Model Establishment

1.1 Governing Equations

The following assumptions are made for the calculation process: 1) the fluid is an ideal two-dimensional incompressible viscous fluid, and the motion is irrotational[19]; 2) structural deformation of the submerged floating tunnel pipe is not considered, and only overall displacement is considered; 3) the flow direction is perpendicular to the pipe axis, and the vibration is a combination of the streamwise and transverse directions; 4) under the same simulation condition, the geometric dimensions, stiffness, and material properties of the submerged floating tunnel remain unchanged along the longitudinal direction. A wide submerged floating tunnel is exposed to a turbulent environment for a long time. Owing to fluid instability and the presence of separated flow, many vortices are generated as the fluid flows past; these vortices gradually shed as time advances. Let f_s denote the vortex-shedding frequency and f_n the natural frequency; then $f^* = f_s/f_n$ is the frequency ratio. A two-dimensional SST $k-\omega$ turbulence model is established for simulation[12]. The governing equations, namely the continuity equation and momentum equations of the Navier-Stokes equations, can be simplified as

$$\frac{\partial u}{\partial X} + \frac{\partial v}{\partial Y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial X} + v\frac{\partial u}{\partial Y} = -\frac{1}{\rho}\frac{\partial p}{\partial X} + \mu\left(\frac{\partial^2 u}{\partial X^2} + \frac{\partial^2 u}{\partial Y^2}\right) \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial X} + v\frac{\partial v}{\partial Y} = -\frac{1}{\rho}\frac{\partial p}{\partial Y} + \mu\left(\frac{\partial^2 v}{\partial X^2} + \frac{\partial^2 v}{\partial Y^2}\right) \tag{3}$$

where u and v are the velocity components in the X and Y directions, respectively; p is the water pressure; μ is the kinematic viscosity coefficient of the fluid; and ρ is the fluid density.

The cross section of the submerged floating tunnel pipe is simplified as a mass-spring-damper system, and the vibration equations for its two degrees of freedom can be written as

$$\ddot{X} + 2\xi\omega_n\dot{X} + \omega_n^2 X = \frac{F_d}{m} \tag{4}$$

$$\ddot{Y} + 2\xi\omega_n\dot{Y} + \omega_n^2 Y = \frac{F_l}{m} \tag{5}$$

where ξ and ω_n denote the damping ratio and natural circular frequency of the vibration system, respectively; m denotes the pipe mass per unit length; F_d and

F_l are the drag and lift generated when the fluid acts on the pipe; $\ddot{X}$, $\dot{X}$, and X denote the streamwise acceleration, velocity, and displacement of the pipe, respectively; and $\ddot{Y}$, $\dot{Y}$, and Y denote the transverse acceleration, velocity, and displacement of the pipe perpendicular to the flow direction, respectively.

The flow field is solved using the segregated solver in FLUENT. In the momentum equations, the coupling between velocity components and pressure is handled using the SIMPLEC algorithm; pressure interpolation adopts the Standard scheme, and a second-order scheme is used to reduce numerical dissipation. The above vibration equations are solved by compiling a user-defined function (UDF). The Runge-Kutta method[24-25], a highly efficient and high-precision single-step iterative calculation method, is compiled into the UDF as the computational rule; it requires only the calculation data from the previous time step to compute the result for the current step, and the calculation results are obtained through this cycle.

For some complex boundary-motion problems, the problem cannot be input directly into FLUENT through interactive processing and must be completed using a UDF. By combining the initial structural velocity and initial displacement, the equations can be iterated and solved. The flowchart of the complete calculation process is shown in Fig. 1.

Text in Fig. 1 flowchart

Start
↓
Compile and load UDF
↓
Use the SST $k-\omega$ turbulence model to solve the N-S equations
↓
`DEFINE EXECUTE AT END` macro calls UDF
↓
`Compute Force And Moment` function obtains the force on the section
↓
Runge-Kutta method solves the differential vibration equations
↓
`DEFINE CG MOTION` macro passes the structural velocity to Fluent
↓
End of calculation for one time step
↓
Are the calculation results stable?
–No: return to solving the N-S equations
–Yes: End

Fig. 1 Flowchart of numerical calculation for VIV

When an actual fluid flows past a submerged floating tunnel, an interaction force is generated between the fluid and the structure. The component of this force in the flow direction is the drag F_d, and the transverse component is the lift F_l. The drag and lift are nondimensionalized using the following method:

$$\begin{cases} C_D = \dfrac{F_d}{\frac{1}{2}\rho U^2 B} \\ \\ C_L = \dfrac{F_l}{\frac{1}{2}\rho U^2 B} \end{cases} \tag{6}$$

where C_D is the drag coefficient, and C_L is the lift coefficient.

1.2 Model Establishment

For practical engineering considerations of submerged floating tunnels, the choice of cross-sectional form is of primary importance. Depending on regional conditions, a variety of cross-sectional forms have been proposed for submerged floating tunnel projects at home and abroad (Table 1).

Table 1 Cross-sectional forms of some proposed SFT projects at home and abroad

SFT project	Qiandao Lake [26]	Korea [27]	Jintang Strait [28]	Mexico [29]
Cross-sectional form	Circular	Elliptical	Hexagonal	Rectangular

Considering traffic and safety requirements, submerged floating tunnels are generally designed with wide, multi-lane cross sections. Referring to existing design schemes and relevant literature, this study analyzes a tip-shaped cross-sectional form with an angle of attack α (Fig. 2), where α ranges from 70° to 130°. It should be noted that, for vortex-induced vibration characteristics of a tip-shaped cross section, the profile design is crucial, and α is an important parameter. The design of the tip-shaped cross section includes the dimensions of the traffic lanes, emergency spaces, and other components, and must satisfy the requirements for road traffic clearance. In Fig. 2, m and n denote the width and height of the traffic lane cross section, while a and b denote the width and height of the emergency space; the two cross-sectional areas can be roughly expressed as $S_1 = m \times n$ and $S_2 = a \times b$. The design of the tip-shaped cross section must account for both flow-induced vibration characteristics and traffic clearance requirements, in order to determine the optimal angle of attack α.

Fig. 2 Scheme of SFT tip-shaped cross-section
(a) Schematic diagram of the tip-shaped cross section. Visible labels include: emergency space $a \times b$, emergency space, traffic lane, X, Y, m, and n.

(b) Section dimensions at a 1:100 scale. Visible labels include: 135 mm, 375 mm, and α.

The cross-sectional vibration model of the submerged floating tunnel segment is simplified as a mass–spring–damping system (Fig. 3, where B is the cross-sectional width and H is the cross-sectional height). The model is established at a geometric scale of 1:100. The two-dimensional, two-degree-of-freedom model simultaneously considers vibration of the submerged floating tunnel segment in the streamwise direction (X) and transverse direction (Y). The tunnel mass is taken with reference to the experiment [15], and, according to the area ratio of the simulated section, is input into the UDF in the form of the dimensionless parameter mass ratio M^* (for example, when $\alpha = 80^\circ$, the value is 90.95). The tunnel stiffness is represented by the equivalent stiffness K, and the damping is represented by the equivalent damping C. K_x and K_y, and C_x and C_y, are respectively the streamwise and transverse components of the stiffness coefficient and damping coefficient. Their values are obtained from $K = (2\pi f_n')^2 M^*$ and $C = 2\sqrt{KM^*}\xi$, and are automatically calculated by the software [30]. The fluid computational domain is modeled in Workbench [31]. The computational domain is a rectangle with dimensions $14B \times 8B$. The boundary conditions are set as follows: the left boundary is the velocity inlet, the right boundary is the pressure outlet, and the upper and lower boundaries are walls. The section center is located $4B$ from the velocity inlet, $10B$ from the outlet, and $4B$ from the upper and lower walls (Fig. 4).

Fig. 3 Spring-mass-damping system of SFT section
Visible labels include: B, H, C_x, K_x, K_y, and C_y.

Fig. 4 Layout of calculation area division
Visible labels include: stationary mesh region, wall, dynamic mesh region ($3B \times 3B$), velocity inlet, rigid mesh region ($2B \times 2H$), outlet, $3B$, $4B$, $4B$, and $10B$.

To solve problems such as mesh distortion and entanglement in dynamic-mesh simulations, the method of "rigid-motion region + dynamic-mesh region + stationary-mesh region" [32] is adopted to establish the mesh partitioning regions for vortex-induced vibration of the hexagonal section. The "dynamic-mesh region" is set as a square with side length $3B$, and the "rigid-mesh region" is set as a rectangle of $2B \times 2H$. In the modeling tool DM provided by ANSYS Workbench, the Add Frozen method is used to add a frozen body and establish the submerged floating tunnel model. ICEM is used for mesh generation. In the rigid-motion region, the mesh near the wall must first be refined. Owing to the presence of sharp edges at the tip of the section, the number of mesh layers in the near-wall region of the tube should not be set too high; otherwise, twisting and deformation of the mesh shape will occur.

shape. In this model, the near-wall region has 15 grid layers, with a minimum size of 0.1 and an expansion ratio of 1.15. This part of the mesh moves synchronously with the structure during structural motion, so no smoothing or remeshing treatment is required. Triangular elements are selected for the dynamic-mesh region, while quadrilateral elements are selected for the stationary-mesh region. This not only effectively solves the problems of mesh distortion and negative cell volumes during the calculation process, but also improves the computational speed and efficiency. Figures 5(a) and 5(b) show, respectively, the overall mesh of the flow-field region around the pointed-end section and a local schematic diagram.

(a) Overall mesh schematic

(b) Local mesh schematic

Fig. 5 Grid division diagram

1.3 Parameter-independence verification

Mesh resolution is the key to ensuring the accuracy of numerical simulations. To ensure the validity of the numerical simulation results and eliminate adverse effects of different parameter settings on the computational results, an independence verification was carried out for the computational time step Δt and the number of mesh cells in the numerical model [11]. Taking the pointed-end wide-section suspended tunnel section at $\alpha = 80^\circ$ as the reference, nine different cases were established by changing only the mesh size and the computational time step. The total calculation duration was 180 s (time step $\times$ number of calculation steps). The compiled comparison of the computational results is shown in Table 2.

Table 2 Calculation-model parameter-independence verification
Tab. 2 SFT model parameter independence verification

Simulation case	Number of grids	Computational time step / s	$C_{\mathrm{D,mean}}$	$C_{\mathrm{L,AM}}$
Case 1	148 263	1×10^{-2}	0.406	1.212
Case 2	89 260	1×10^{-2}	0.408	1.215
Case 3	45 352	1×10^{-2}	0.418	1.225
Case 4	148 263	2×10^{-3}	0.401	1.206
Case 5	89 260	2×10^{-3}	0.402	1.208
Case 6	45 352	2×10^{-3}	0.412	1.217
Case 7	148 632	5×10^{-4}	0.401	1.205
Case 8	89 260	5×10^{-4}	0.403	1.207
Case 9	45 352	5×10^{-4}	0.406	1.210

Note: $C_{\mathrm{D,mean}}$ denotes the mean drag coefficient; $C_{\mathrm{L,AM}}$ is the lift-coefficient amplitude.

As can be seen from Table 2, when $\Delta t \leq 2 \times 10^{-3}$ s, except for Case 6, the calculated lift and drag coefficients are already quite close. If the time step is further reduced, the improvement in calculation accuracy is limited, while the computation time is extended. For the two cases with grid numbers of 148 632 and 89 260, the computational results are only slightly affected by the time step. The larger the number of grids, the lower the computational efficiency. In summary, the computational scheme with a total of 89 260 grids in the entire computational domain and a time step of $\Delta t = 2 \times 10^{-3}$ s is selected. It satisfies the accuracy requirements while also maintaining relatively high mesh quality and computational efficiency.

1.4 Model validation

To verify the capability of the numerical model in this study for simulating the vortex-induced vibration characteristics of a suspended tunnel, this section establishes a two-dimensional numerical model with the same parameters as the classic experiments in Refs. [15, 33], conducts numerical simulations of the experimental cases, and compares them with the experimental results. In the experiment of Ref. [15], the cylinder diameter was $D = 0.0381$ m, the damping ratio was $\xi = 0.0036$, the mass ratio was $M^* = 2.6$, and the natural frequency of the cylinder vibrating in water was $f_n = 0.4$ Hz. In the experiment of Ref. [33], the cylinder diameter was $D = 0.0381$ m, $f_n = 0.4$ Hz, the damping ratio was $\xi = 0.0013$, and the mass ratio was $M^* = 2.4$; streamwise vibration was not recorded. By compiling a UDF, the numerical simulation parameters were made consistent with the experimental parameters, and the comparison between the simulation results and the experimental results is shown in Fig. 6. In the figure, the horizontal coordinate $U_r = U/(f_{nD})$ denotes the reduced velocity, where U is the incoming-flow velocity. The vertical coordinate A_x/D or A_y/D denotes the dimensionless amplitude of the tunnel segment in the streamwise or transverse direction, respectively, at a given flow velocity.

It can be seen from Fig. 6 that, for both the classic experiments and the numerical simulations, within the reduced-velocity range of 0–16, as the flow velocity increases, both the streamwise and transverse amplitudes of the suspended-tunnel segment first increase and then decrease. The maximum relative difference between the transverse amplitude and the experimental result of Ref. [15] is 5.56% (Fig. 6a), and the maximum relative difference from the experimental result of Ref. [33] is 7.5% (Fig. 6b). The maximum relative difference between the streamwise amplitude and the experimental result of Ref. [15] is 8.69% (Fig. 6c). Thus, the numerical simulation agrees well with the experimental results, indicating that the method used in this study can effectively simulate the dynamic response of the structure and can be used for further dynamic-response analysis. The structures, materials, and other parameters selected for an actual suspended tunnel need to be determined through experiments; the model parameter values in this study can also provide a reference for subsequent model tests.

Fig. 6. Comparison of dimensionless amplitude between the present method and referenced experiments

- **(a)** Comparison of transverse amplitude with experiment [15].
Vertical axis: A_y/D; horizontal axis: reduced velocity U_r.
Legend: experiment [15] results; present calculation results.
- **(b)** Comparison of transverse amplitude with experiment [33].
Vertical axis: A_y/D; horizontal axis: reduced velocity U_r.
Legend: experiment [33] results; present calculation results.
- **(c)** Comparison of streamwise amplitude with experiment [15].
Vertical axis: A_x/D; horizontal axis: reduced velocity U_r.
Legend: experiment [15] results; present calculation results.

2 Numerical Simulation Results and Analysis

Based on the numerical model described above, this section calculates the vortex-induced vibration behavior of the submerged floating tunnel under different cross-sectional forms and different incoming-flow velocities.

2.1 Analysis of Numerical Simulation Results for the Pointed Cross-Section

When fluid passes around a structure, the dynamic characteristics of the structure are related to the fluid density and viscosity, as well as to the natural frequency and characteristic length of the structure. In flow-induced vibration analysis, the value of the reduced velocity also depends on the interaction between the structure and the fluid. Therefore, taking the pointed cross-section as the research object, and referring to the simulation procedures and observed laws in the literature [15, 33], the reduced velocity U_r was varied within the range $0 \sim 8$, while the angle of attack of the pointed cross-section was also changed. The maximum dimensionless streamwise and transverse amplitudes of the cross-sections at various angles, as shown in Fig. 7, were obtained, together with the variations of the mean drag coefficient $C_{\mathrm{D,mean}}$ and the lift-coefficient amplitude $C_{\mathrm{L,AM}}$ with the reduced velocity U_r. At the same time, the analysis results for the pointed cross-section were compared with the existing round-ended and octagonal cross-sections previously studied by the research group [11], with the fixed-flow-around model therein changed to a two-dimensional vortex-induced vibration model.

It can be seen from Fig. 7(a) that the maximum transverse vibration amplitude of the pointed cross-section with $\alpha = 80^\circ$ is relatively close to that of the round-ended cross-section, while the maximum transverse vibration amplitude of the pointed cross-section with $\alpha = 130^\circ$ is relatively close to that of the octagonal cross-section. According to Figs. 7(b) and 7(c), in the process of successively analyzing the round-ended, octagonal, and pointed cross-sections, the streamline shape at the two ends of the cross-section changes from a curved profile to one with protruding corners, and the mean drag coefficient and lift-coefficient amplitude decrease successively, namely: pointed cross-section < octagonal cross-section < round-ended cross-section. As shown in Fig. 7(d), over-

Figure 7: Three force coefficients and amplitudes of a tip-shaped section with different inflow angles and other sections

Figure 1: Figure 7: Three force coefficients and amplitudes of a tip-shaped section with different inflow angles and other sections

all, the streamwise vibration amplitude increases with increasing incoming-flow velocity and also increases with increasing angle of attack. From Fig. 7(e), it can be seen that, for the pointed cross-section, the maximum transverse vibration amplitude decreases as the angle increases. Among them, the maximum dimensionless vibration amplitude of the pointed cross-section is $A_y/B = 0.119$, corresponding to the reduced velocity $U_r = 2$ and the angle of attack $\alpha = 70^\circ$. After the maximum transverse vibration amplitude is reached, as the reduced velocity U_r increases, the transverse vibration amplitudes of the pointed cross-sections with different angles of attack all decrease. According to Figs. 7(f) and 7(g), when α lies in the range $70^\circ \sim 130^\circ$, the variations of the mean drag coefficient $C_{\mathrm{D,mean}}$ and the lift-coefficient amplitude $C_{\mathrm{L,AM}}$ of the pointed cross-section with U_r show similar patterns: as U_r increases, they first increase and then decrease, and the variation trend eventually tends to become gentle; in addition, the reduced velocities corresponding to the maximum values are not identical. Furthermore, Fig. 7(h) gives the variation laws, with angle of attack, of the maximum values of A_y/B, $C_{\mathrm{D,mean}}$, and $C_{\mathrm{L,AM}}$ under different flow velocities. It can be seen that the maximum values of A_y/B and $C_{\mathrm{D,mean}}$ exhibit approximately linear decreasing and increasing trends, respectively, as α increases. The maximum value of $C_{\mathrm{L,AM}}$, however, follows a more complex pattern of increasing first, then decreasing, and then increasing again, with $\alpha = 80^\circ$ being a local minimum. At this point, the maximum values $C_{\mathrm{D,mean}} = 0.402$ and $C_{\mathrm{L,AM}} = 1.208$ are respectively 75.4% and 25.0% smaller than the corresponding values at $\alpha = 130^\circ$, namely $C_{\mathrm{D,mean}} = 0.705$ and $C_{\mathrm{L,AM}} = 1.51$. This indicates that $\alpha = 80^\circ$ provides a certain advantage in terms of the force-bearing performance of the pointed cross-section.

On the basis of the known relationship between the hydrodynamic coefficients of the structure and the angle of attack, and by comprehensively considering the force-bearing performance and spatial utilization of the pointed submerged floating tunnel cross-section, it can be seen that α should not be set too large, such as 130°; otherwise, the drag on the structure will increase and the lift will not be optimal. Nor should it be set too small, such as 70°; otherwise, the transverse vibration amplitude will increase, and at the same time, for the same width, the cross-sectional area will decrease, the controllable areas S_1 and S_2 will be reduced, and the spatial utilization of the structure will decline. Considering both force-bearing performance and spatial utilization, $\alpha = 80^\circ$ is an appropriate angle of attack and can provide a reference for the design of pointed cross-section submerged floating tunnels.

(a) Maximum transverse amplitudes for different cross-sectional forms

(b) Mean drag-coefficient values for different cross-sectional forms

(c) Lift-coefficient amplitudes for different cross-sectional forms

(d) Streamwise amplitudes of tip-shaped sections with different inflow angles

(e) Transverse amplitudes of tip-shaped sections with different inflow angles

(f) Mean drag-coefficient values of tip-shaped sections with different inflow angles

(g) Lift-coefficient amplitudes of tip-shaped sections with different inflow angles

(h) Variation of the maximum values of lift, drag, and amplitude with inflow angle

Fig. 7 Three force coefficients and amplitudes of tip shape section with different inflow angles and other sections

2.2 Time-history curves and vortex-shedding mode analysis

To further describe the temporal variation of the vibration characteristics of the tube body when water flows past the submerged floating tunnel, Fig. 8 presents the time-history curves of the dimensionless transverse vibration displacement Y/B, drag coefficient C_D, and lift coefficient C_L at the corresponding reduced velocities when the tip-shaped-section tube segments with different α reach their maximum transverse amplitudes. Fig. 9 shows the vorticity contours of the wake vortex-shedding modes after the vibration of the submerged floating tunnel tube body has stabilized when the inflow angle α of the tip-shaped section varies within the range 80°-130°. Table 3 gives the reduced-velocity values corresponding to the occurrence of the maximum transverse amplitude for tip-shaped sections with different inflow angles.

According to the variation trend of the lift-coefficient amplitude in Fig. 7(c) and the data in Table 3, the selected reduced velocities U_r are 1.33, 1.73, 2, and 4, respectively.

Fig. 8 Time-history curves of the tip-shaped section at maximum transverse amplitude for different inflow angles

In each panel: legend Y/B, C_D, C_L; horizontal axis t/s; left vertical axis C_D, C_L; right vertical axis Y/B.

(a) $\alpha = 70^\circ,\ U_r = 2$

(b) $\alpha = 80^\circ,\ U_r = 1.73$

(c) $\alpha = 80^\circ,\ U_r = 1.73,\ f_n = 0.15$ Hz

(d) $\alpha = 90^\circ,\ U_r = 1.73$

(e) $\alpha = 100^\circ,\ U_r = 1.33$

(f) $\alpha = 110^{\circ},\ U_r = 1.33$

(g) $\alpha = 120^{\circ},\ U_r = 1.73$

(h) $\alpha = 130^{\circ},\ U_r = 1.73$

Table 3 Reduced velocity at which the maximum transverse amplitude occurs for the tip-shaped section

$\alpha/(^{\circ})$	70	80	90	100	110	120	130
U_r	2.00	1.73	1.73	1.33	1.33	1.73	1.73

As can be seen from Fig. 8, the variation trend of the dimensionless transverse amplitude A_Y/B is consistent with that of the lift coefficient C_L. This indicates that, after a certain time, the lift acts on the submerged floating tunnel tube in the form of a periodic force. Under the excitation of lift, the transverse vibration of the tube also exhibits periodic up-and-down reciprocating motion. The drag coefficient fluctuates only within a small range around a certain value.

It can be seen from Fig. 9(a) and Fig. 9(b) that, when the inflow angles of the tip-shaped section are $\alpha = 70^{\circ}$ and 80°, the wake vortices of the submerged floating tunnel tube exhibit irregular shedding at reduced velocities of $U_r = 4$ and 1.33, respectively. This is because the flow field after the fluid passes the submerged floating tunnel tube becomes disordered, and the fluid motion is unstable. When the reduced velocities are $U_r = 2$ and 1.73, respectively, the transverse amplitude of the submerged floating tunnel tube reaches its maximum. Fast Fourier transform analysis of the lift-coefficient variation curves in Fig. 8(a) and Fig. 8(b) gives wake-vortex shedding frequencies f_s of 0.235 Hz and 0.314 Hz, respectively, which are lower than the prescribed natural frequency of the structure, $f_n = 0.4$ Hz. At this time, after the fluid flows past the submerged floating tunnel tube, two pairs of counter-rotating vortices with obvious differences are formed successively and shed; four vortices are released within one period, producing a relatively stable 2P (Pair) shedding mode. In Fig. 9(c), when $\alpha = 90^{\circ}$ and the reduced velocities are $U_r = 1.73$ and 2, the wake-vortex shedding presents a P+S mode: one positive vortex and one pair of negative vortices appear within one period. The amount of vortex shedding caused by the larger flow velocity is also greater; the spacing between shed wake vortices decreases, and the vortices shift downward.

(a) Wake vortex shedding contours at $\alpha = 70^{\circ}$

Color bar: vortex shedding quantity / s^{-1}, from 1.0 to -1.0.

- $U_r = 1.33$, 2S
- $U_r = 1.73$, 2S
- $U_r = 2$, 2P
- $U_r = 4$, irregular

(b) Wake vortex shedding contours at $\alpha = 80^\circ$

Color bar: vortex shedding quantity / s^{-1}, from 1.0 to -1.0.

- $U_r = 1.33$, irregular
- $U_r = 1.73$, 2P
- $U_r = 2$, 2P
- $U_r = 4$, 2S

(c) Wake vortex shedding contours at $\alpha = 90^\circ$

Color bar: vortex shedding quantity / s^{-1}, from 1.0 to -1.0.

- $U_r = 1.33$, 2S
- $U_r = 1.73$, P+S
- $U_r = 2$, P+S
- $U_r = 4$, 2S

(d) Wake vortex shedding contours at $\alpha = 100^\circ$

Color bar: vortex shedding quantity / s^{-1}, from 1.0 to -1.0.

- $U_r = 1.33$, P+S
- $U_r = 1.73$, 2S$→$2P
- $U_r = 2$, 2S
- $U_r = 4$, 2S

(e) Wake vortex shedding contours at $\alpha = 110^\circ$

Color bar: vortex shedding quantity / s^{-1}, from 1.0 to -1.0.

- $U_r = 1.33$, 2P
- $U_r = 1.73$, 2S
- $U_r = 2$, 2S
- $U_r = 4$, 2S

(f) Wake vortex shedding contours at $\alpha = 120^\circ$

Color bar: vortex shedding quantity / s^{-1}, from 1.0 to -1.0.

- $U_r = 1.33$, 2P
- $U_r = 1.73$, 2S
- $U_r = 2$, 2S
- $U_r = 4$, 2S

(g) Wake vortex shedding contours at $\alpha = 130^\circ$

Color bar: vortex shedding quantity / s^{-1}, from 1.0 to -1.0.

- $U_r = 1.33$, 2S
- $U_r = 1.73$, 2P
- $U_r = 2$, 2P
- $U_r = 4$, 2S

Fig. 9 Wake vortex shedding contours of tip-shaped sections with various inflow angles at different reduced velocities.

When the reduced velocity is $U_r = 4$, the wake-vortex shedding mode has already transformed into the $2S$ (Single) mode; that is, after the fluid passes the pointed suspended-tunnel section, vortices are shed alternately and detach in the flow direction. Compared with the wake-vortex shedding modes at the previously lower flow velocities, the position where vortices in the flow field shed is farther from the section. In Fig. 9(d), when the reduced velocity is $U_r = 1.33$, within one period, one side of the structure sheds a pair of opposite vortices, while the other side sheds a single positive vortex, forming another $P + S$ mode. When the reduced velocity is $U_r = 1.73$, the wake initially exhibits a $2S$ mode as the water first passes the structure, and then changes to a $2P$ mode. From Fig. 9(e) and Fig. 9(f), it can be seen that when the reduced velocity is $U_r = 1.33$, the wake-vortex shedding mode is already a stable $2P$ mode; as the flow velocity increases, it changes to a $2S$ mode, the amount of vortex shedding increases, and the streamwise spacing of the wake vortices decreases. From Fig. 9(g), it can be seen that when the inflow angle of the pointed section is $\alpha = 130°$, under the four reduced velocities, the symmetrically distributed flow-field pattern alternately produces a relatively regular periodic vortex-street phenomenon after passing the pointed tube, and the wake-vortex shedding mode follows the variation pattern "$2S \rightarrow 2P \rightarrow 2S$." When the reduced velocities are $U_r = 1.33$ and 4, the wake-vortex shedding mode of the section is close to that under the fixed flow-past condition [11], showing a stable $2S$ shedding mode. For the former, because the fluid velocity is smaller, the vortices generated by the fluid motion gradually diminish and disappear in the far field owing to energy dissipation, and the streamwise spacing between vortices is larger. When the reduced velocity is $U_r = 1.73$, a fast Fourier transform analysis of the variation curve of the lift coefficient in Fig. 8(g) gives a wake-vortex shedding frequency of $f_s = 0.26$ Hz, which is also much smaller than the prescribed natural frequency of the structure, $f_n = 0.4$ Hz. At this time, the wake-vortex shedding mode changes to the $2P$ mode, indicating that the vibration of the tube itself increases and has a certain influence on wake-vortex shedding.

In summary, as the incoming-flow velocity and inflow angle of the pointed suspended tunnel increase, the wake-vortex shedding mode also changes accordingly. When the inflow angle α of the pointed section varies within the range of 70°–130°, the vortex-shedding mode of the suspended-tunnel tube becomes more stable and more regular at larger inflow angles and higher flow velocities, such as $\alpha = 120°$ and $U_r = 2$. None of the above analyses shows the phenomenon of "frequency lock-in."

2.3 Analysis of Mass-Center Motion Trajectories

Figure 10 presents the motion trajectories of the mass center of the two-degree-of-freedom pointed-section model. At this time, the tube motion has reached the maximum lateral amplitude corresponding to each flow velocity. As can be seen from Fig. 10, the vortex-induced vibration of the two-dimensional pointed suspended-tunnel tube in water is a bounded-amplitude vibration; that is, its motions in both the streamwise and transverse directions remain within certain ranges. The transverse displacement is larger than the streamwise displacement. During the calculation time, the streamwise displacement spends a larger proportion of time deviating in the flow direction, whereas the transverse motion is an up-and-down reciprocating motion. When $\alpha = 70°$–$100°$, the mass-center motion of the pointed suspended-tunnel tube can be roughly divided into two forms. The first is a divergent reciprocating motion combining left–right and up–down movements; after stabilization, the motion trajectory presents a vertical "figure-eight" shape at the center, and the "figure-eight" in the trajectory is most obvious when $\alpha = 80°$. As the angle increases, the motion of the pointed suspended-tunnel tube diverges toward the left and right ends in the streamwise direction, and the "figure-eight" shape gradually disappears. When $\alpha = 130°$, even when the tube vibration reaches the maximum lateral amplitude, the mass-center trajectory presents a relatively regular cylindrical spiral-type reciprocating motion. The motion of the pointed suspended tunnel in water changes under the influence of the inflow angle.

Fig. 10 Mass-center trajectories when tube sections with different inflow angles reach their maximum lateral amplitude ($f_n = 0.4$ Hz except for Fig. 10c).

Subfigures:

- (a) $\alpha = 70°,\ U_r = 2.0$
- (b) $\alpha = 80°,\ U_r = 1.73$
- (c) $\alpha = 80°,\ U_r = 1.73,\ f_n = 0.15$ Hz
- (d) $\alpha = 90°,\ U_r = 1.73$
- (e) $\alpha = 100°,\ U_r = 1.33$
- (f) $\alpha = 110°,\ U_r = 1.33$
- (g) $\alpha = 120°,\ U_r = 1.73$
- (h) $\alpha = 130°,\ U_r = 1.73$

2.4 Influence of Natural Frequency on Structural Vortex-Induced Vibration

As is known from the preceding discussion, tip-shaped sections with different angles α have different vibration characteristics. When α varies within the range of $70°$–$130°$, the lift and drag coefficients at $\alpha = 80°$ are the smallest among the several angles. Therefore, the tip-shaped section with $\alpha = 80°$ was selected as the representative section, and the vibration of the suspended tunnel tube under ocean-current action was simulated for different natural frequencies. According to the formula $U_r = U/(f_{nD})$, when the prescribed natural frequency of the tube is changed, the actual fluid velocity input into FLUENT must also be changed in order to keep U_r unchanged. Based on existing experience from suspended-tunnel experiments and simulations $[4-5, 12, 15-18]$, the natural frequency range is taken as 0.1-1.0 Hz. Figure 11 presents the variations of the dimensionless amplitudes A_x/B and A_y/B, the mean drag coefficient $C_{D,\text{mean}}$, the lift-coefficient amplitude $C_{L,\text{AM}}$, and the frequency ratio f^* for the tip-shaped section with $\alpha = 80°$, when the natural frequency f_n varies within this range and $\xi = 0.0036$, $M^* = 2.6$, and $U_r = 1.73$.

Figure 12 shows the wake vortex-shedding contours for the tip-shaped section with $\alpha = 80°$ at four natural frequencies. These four frequencies correspond to four typical lift values that undergo the process of increasing from small to large to a peak and then decreasing and tending to level off. It can be seen from Fig. 11 that the change in the natural frequency of the tip-shaped suspended-tunnel section has the greatest influence on lift, while its influence on amplitude, drag, and frequency ratio is relatively small. The minimum lift-coefficient amplitude is $C_{L,\text{AM}} = 0.894$, corresponding to $f_n = 0.1$ Hz; the maximum is $C_{L,\text{AM}} = 1.297$, corresponding to $f_n = 0.15$ Hz, which is 44.93% larger than the former. In sharp contrast, for the variation of f^*, when $f_n < 0.55$ Hz, f^* fluctuates slightly as f_n increases; the maximum value ($f^* = 0.781$) is 1.1 times the minimum value ($f^* = 0.701$). When $f_n \geq 0.55$ Hz, as f_n increases, the value of f^* under the same U_r remains almost unchanged. It is worth noting that when f^* approaches 1, vortex-induced resonance may occur in the structure, causing large deformation and stress and leading to structural damage; this should be avoided as far as possible in engineering practice.

Fig. 11 Effects of natural frequencies on VIV characteristics of the tip-shaped section with $\alpha = 80°$

Comparing the results in Fig. 12 with the numerical simulation results for $f_n = 0.4$ Hz discussed above shows that, when only the structural natural frequency is changed, the wake vortex-shedding mode of the structure ($2P$) does not change, whereas the trajectory of the centroid changes. When the natural frequency is relatively small, such as 0.1 Hz, the flow velocity is low and the amount of vortex shedding is small; when the natural frequency is relatively large, such as 0.8 Hz, the flow velocity is high and the amount of vortex shedding is large. In addition, when $f_n = 0.15$ Hz, the "figure-eight" shape of the centroid trajectory is not obvious. A fast Fourier transform of the lift-coefficient variation curve in Fig. 8(c) gives a vortex-shedding frequency of $f_s = 0.105$ Hz, which is lower than the structural natural frequency and far from the lock-in region; from the perspective of vortex-induced resonance, the structure is relatively safe.

Fig. 12 Wake vortex shedding contours of different natural frequencies
(Panel labels: $f_n = 0.1$ Hz*,* $f_n = 0.15$ Hz*,* $f_n = 0.4$ Hz*, and* $f_n = 0.8$ Hz*; color bar: vortex-shedding quantity* $/\text{s}^{-1}$*.)*

In summary, changing the structural natural frequency can cause relatively large changes in the amplitude as well as in the lift and drag. Changing the structural mass and the buoyancy-weight ratio is one of the methods for adjusting the natural frequency.

3 Conclusions

In this study, numerical simulations of vortex-induced vibration using a two-degree-of-freedom model were carried out for several tip-shaped wide suspended-tunnel sections. The influence laws of the inflow angle and natural frequency were investigated, and the following conclusions were obtained.

1) When the inflow angle α is within the range of 70°–130°, the motion parameters and hydrodynamic coefficients of the tip-shaped section exhibit similar trends with increasing U_r. The streamwise amplitude increases with increasing U_r, while the transverse amplitude, the mean drag coefficient, and the lift-coefficient amplitude first increase and then decrease with increasing U_r, and their trends eventually become gradual.

2) Considering comprehensively the relationship between the force performance and the space utilization of the tip-shaped suspended-tunnel section, it can be seen that when α is too large, the drag on the section increases and the lift is not optimal; when α is too small, the transverse amplitude increases and the space utilization of the section decreases. Considering both the section force performance and space utilization, $\alpha = 80^\circ$ is the tip-shaped

a suitable incident-flow angle for the cross section.

3) Under different flow velocities and different incident-flow angles, the vortex-shedding modes and shedding amounts of the pointed-end tubular body differ, and both variations affect the motion of the structure. For the two-degree-of-freedom model, when the maximum transverse vibration amplitude is reached, the "figure-eight" trajectory of the centroid is most pronounced at $\alpha = 80^\circ$.

4) The natural vibration frequency lies within a parameter interval that can excite relatively large lift on the pointed-end tubular body, but no "lock-in" phenomenon occurs. This natural-frequency interval should be avoided in structural design.

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