ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Dynamic Response of Submerged Floating Tunnel

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Abstract:
Cables are critical bearing components of the submerged floating tunnel (SFT). As the accidental cable-breakage incident will seriously threaten the public safety, this paper investigates the global dynamic response of a SFT subjected to an abrupt anchor-cable failure by focusing on the post-breakage behavior. Firstly, an approximate theoretical approach is proposed, in which the analysis model of SFT is simplified and the alternate load path method (AP method) is adopted to simulate the cable-breakage process. Then, the differential equations of the SFT tube are established based on the Hamilton principle, and solved through the fourth order Runge-Kutta method. A finite element analysis in ABAQUS is also performed as a verification of the theoretical results, in which the VUSDFLD subroutine and ABAQUS/Aqua is employed to simulate the stiffness loss of the cable and apply the fluid loads respectively. A good agreement exists between the simplified theoretical model and FE simulation. Finally, the effects of some key parameters are discussed, such as the gravity-buoyance ratio and the damping ratio of the SFT, the breakage time and position of the broken cable, etc.

The results show that the structural vibration is intensive after the sudden cable breakage. Also, the remaining anchor-cables close to the cable-loss position are most affected by the cable rupture. The change of gravity-buoyance ratio and damping ratio have notable effects on structural deformation. The SFT is most unfavorable when the cable breakage happens at the mid-span or near the two ends of the tunnel. The vibration amplitude attenuates significantly with the increase of the failure time of anchorcable.

Introduction

Submerged Floating Tunnel (SFT), is a new transport facility for crossing waterways. A typical SFT is composed of three major parts:
(1) the hollow tunnel tube suspended in the water;
(2) the supporting devices like anchor-cables or pontoons to balance the redundant buoyancy of the SFT tube;
(3) the offshore connections between the tunnel and mainland on the ends.
Compared with other traditional ways crossing straits, such as long-span bridges or subsea tunnels, the SFT with anchor-cables is regarded as with the greatest potential in the 21st century.

It has such advantages as:
(1) strong adaptability of underwater foundation;
(2) lower construction cost rise with the increase of span length;
(3) negligible effects on the normal navigation and other water production activities even under severe climatic conditions [1] [2]. Schematics of a typical SFT and a traditional cable-stayed bridge, as well as their main bearing load styles are shown in Fig. 1.

Since the late 1980s, the researches on SFT have been thriving around the world. In the past 10 years, scholars had begun to pay more attention to the dynamic problems of SFT during accidental situations, such as earthquakes, harsh wave conditions, impacts, and other extreme loads.

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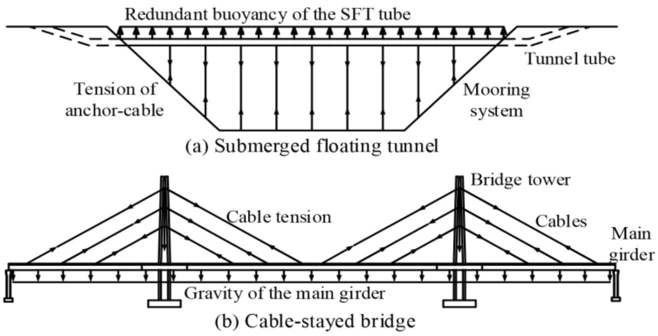

Fig. 1. Schematics of a typical SFT and a cable-stayed bridge.

Di Pilato et al. [3] studied the nonlinear dynamic performance of the Messina strait SFT under multiplesupport seismic excitation and hydrodynamic load. Sun [4] carried out model experiments of the SFT under seismic excitations on the underwater shaking table. Martinelli et al. [5] analyzed the non-linear dynamic response of SFT based on the EN 1998 pseudoacceleration elastic response spectrum. Besides, Martinelli et al. [6] reviewed the latest research developments on seismic response of SFT, with a case study in ANSYS to verify the effectiveness of two kinds of passive control devices against seismic excitations. Moreover, Lu et al. [7] studied the potential slack phenomena in anchor-cables of a rigid SFT segment caused by harsh wave loads. Seo et al. [8] calculated the deformations and internal forces of the SFT tube subjected to an underwater explosion based on the energy conservation law and compared the obtained results with FEM. Xiang et al. [9] investigated the spatial dynamic characteristics of the SFT under external impact loads. The above studies promoted the understandings of the mechanical characteristics for SFTs and established scientific basis for the later design and construction.

Since 09/11/2001 event, the structural safety and the robustness against progressive collapse has been more and more emphasized. More research achievements started to focus on the impact on the long-span cable-supported bridges from the abrupt cable failure [10–16]. In the design guideline for the cable-stayed bridges, Post-Tensioning Institute [10] stated that the sudden failure of any single cable should not lead to the zipper-type collapse, and two load application methods were given for dynamic calculations. Mozos et al. [11] studied the effects of the failure duration of the broken cable on the structural dynamic response. Cai et al. [12] compared four approaches for the cable-loss simulations considering the initial state of a cable-supported bridge.

Zhou et al. [13] [14] established a time-progressive dynamic analysis framework for a cable-stayed bridge suffering the cable-breakage incident. However, up to now, the explorations of the SFT with the similar bearing load form as these long-span bridges have not involved yet.

In a marine environment, the anchor-cables and the joints between the tunnel tube and cables are regarded as the weakest components of the SFT. Once the breakage of anchor-cable suddenly occurs, it can cause strong vibration and large deformation, which will certainly endanger the social security. Therefore, during the early research phase, the dynamic response analysis of the SFT suffering from this accidental disaster, as well as the corresponding prevention and countermeasures should be given more attention.

The objective of this paper is to understand the global response in post cable-breakage stage of a seabed anchored SFT. On the one hand, a theoretical model is presented, where the SFT is treated as a beam on discrete elastic supports, meanwhile, the process of abrupt cable failure is simplified according to the AP method. Then, the governing differential equations of the SFT tube are established through the Hamilton principle, and solved by the corresponding numerical method. On the other hand, FE analysis inside ABAQUS is conducted to verify the theoretical results. Finally, some key parameters affect the structural dynamic response are discussed, which can be useful for determining the basic parameters of the actual structure.

Mechanism of excited Motion and control equation of cable

The influence of SFT on the cable simplified as parameter excitation

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The SFT cable is similar to tendons of tension, so it can be simplified as a beam. The midpoint of the span is selected to be a reference point. Assuming that

- The cable tension is much larger than the gravity, so the change of the tension along the length direction can be neglected. Namely, the tension of cable equals everywhere;
- The material properties, stiffness and geometric properties of the cable are not changed along the length;
- The current is a linear current, and the bottom velocity is zero.
- The Z axis is the axial direction of the cable, the Y axis is the direction of the tunnel, the X axis is the direction of the sea floor, and the direction of flow is positive direction of X axis.
- Only considering the transverse vibration of the cable, that is, the vibration in the plane of Y-Z.

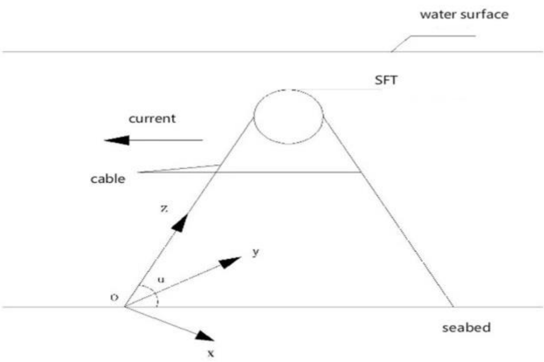

Fig. 2 Schematic diagram of SFT

Because the influence of SFT is simplified as the parameter excitation, the transverse vibration equation of the cable is

$$EI\frac{\partial^4 y}{\partial z^4}-T_0(1+\varepsilon cos\omega t)\frac{\partial^2 y}{\partial z^2}+C\frac{\partial y}{\partial t}+m\frac{\partial^2 y}{\partial t^2}=F_y(z,t) \quad (1)$$

$T0$ is static tension; ω is ratio of static and dynamic tension; ω is parametric excitation frequency.

$$F_y(z,t)=F_l-F_d \quad (2)$$

$$F_l=\frac{1}{2}\rho_w DC_L V^2 sin^2\alpha cos\omega_v t \quad (3)$$

F_l is lift force generated by vortex induced vibration;

ρ_w is density of seawater; D is diameter of cable; C_L is lift coefficient; V is current speed; α is inclination angle of cable; ω_v is discharge frequency of vortex.

F_d is water body damping force and additional mass force [26] per unit length.

$$F_d=\frac{1}{2}\rho C_D D\dot{y}|\dot{y}|+C_m\frac{\pi D^2}{4}\rho\ddot{y} \quad (4)$$

C_D is drag coefficient; C_m is coefficient of added mass.

According to formula (1), (2), (3) and (4), we can get

$$\ddot{y}_n+[\omega_{Mn}^2+\omega_{An}^2(1+\varepsilon cos\omega t)]y_n+\frac{C_n}{\bar{m}}\dot{y}_n+\frac{2D_n}{l\bar{m}}=\frac{\rho DC_L}{l\bar{m}}cos\omega_v t\int_0^l v_c^2 sin\frac{n\pi z}{l}dz \quad (5)$$

Where: $D_n=\frac{1}{2}\rho DC_D\int_0^l \dot{u}|\dot{u}|\,sin\frac{n\pi z}{l}dz$; $C_n=2\bar{m}\omega_n\xi$; ξ is cable damping ratio; $\omega_n=({\omega_{Mn}}^2+{\omega_{An}}^2)^{1/2}$; ${\omega_{Mn}}^2=(\frac{n\pi}{l})^4\frac{EI}{\bar{m}}$; ${\omega_{An}}^2=(\frac{n\pi}{l})^2\frac{T_0}{\bar{m}}$; ω_n is N-order vibration frequency of cable.

After using Galerkin's method to simplify formula (5), we can get

$$\ddot{y}+\left[\omega_n^2+\frac{EA(n\pi)^2Z}{\bar{m}L^3}\right]y+\frac{C}{\bar{m}}\dot{y}+\frac{2D_n}{L\bar{m}}+\frac{EA\pi^4}{4\bar{m}L^4}y^3=\frac{2}{\pi\bar{m}}\rho DC_L(vsin\theta)^2cos\omega_v t \quad (6)$$

According to the formula (6), the vibration displacement-time response curve of the anchor cable can be obtained.

Cable-tunnel coupled nonlinear vibration

According to the environment of SFT, the load can be divided into five kinds, such as environmental load, permanent load, functional load, deformation load and accidental load. The specific load classification and causes are shown in table 1.

Table 1 Load on SFT

Load Type	Causes
environmental load	wave, current, eddy current, tide,
permanent load	etc. structure weight and
functional load	hydrostatic pressure
deformation load	transportation, construction,
accidental load	ballast load, etc.
	Temperature changes, uneven
	settlement, creep, shrinkage,
	residual stress caused by
	construction, etc.
	Earthquake, traffic accident,
	sinking ship, explosion, collision
	of ships, etc.

In all kinds of load of SFT, in addition to the weight of the structure and the hydrostatic pressure that must be taken into account, environmental loads, such as wave, flow and eddy, are much larger and more destructive than those of automobiles and often the most important control load in the design of SFT. Therefore, the permanent load, wave force and flow force are the basic loads that must be considered in the design of SFT.

ISSN No: 2348-4845
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In practical engineering, because of the complicated current environment, the simulation calculation of cable should be as accurate as possible. The lateral vibration of cable is not limited to the parameter excitation. The model does not fully reflect the actual vibration of cable. Therefore, the establishment of the cable-tunnel coupled vibration model better reflects the lateral vibration response of cable under actual sea conditions.

The tube of SFT is simplified as the concentrated mass M of the end part of the cable. The stiffness of tube body is simulated by the spring K, and the damping is simulated by the damper C. Coupling vibration model [27] of cable and tube in SFT, shown in fig. 2, is used to research on the response of the cable under the excitation of parameters.

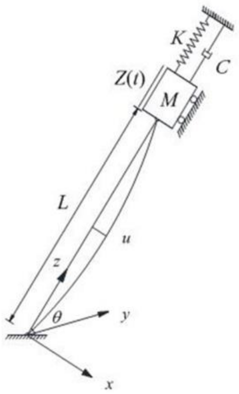

Fig. 3 Schematic diagram of cable-tunnel coupling model

The motion equation of mass block M is

$$M\ddot{Z} + C\dot{Z} + KZ + \frac{EA}{L}\int_0^L \varepsilon\, dz = 0 \qquad (7)$$

The dynamic strain of the anchor cable can be written by the Taylor formula as

$$\varepsilon = \varepsilon_z + \varepsilon_l = \frac{Z}{L} + \frac{1}{2}{u_z}^2 \qquad (8)$$

According to formula (7) and (8), the vibration differential equation of tube section is

$$\ddot{Z} + 2\omega_M \xi_M \dot{Z} + \omega_M^2 Z + \frac{EA\pi^2}{4ML^2} y^2 = 0 \qquad (9)$$

Where: ω_M is the natural frequency of a single SFT; ξ_M is the damping ratio of tunnel.

So cable and tube coupling vibration equations are

$$\begin{cases} \ddot{y} + \left[\omega_n^2 + \frac{EA(n\pi)^2 Z}{\bar{m}L^3}\right] y + \frac{C}{\bar{m}}\dot{y} + \frac{2D_n}{L\bar{m}} + \frac{EA\pi^4}{4\bar{m}L^4} y^3 = \frac{2}{\pi\bar{m}}\rho D C_L (v\sin\theta)^2 \cos\omega_v t \\ \ddot{Z} + 2\omega_M \xi_M \dot{Z} + \omega_M^2 Z + \frac{EA\pi^2}{4ML^2} y^2 = 0 \end{cases} \qquad (10)$$

Parametric excitation is expressed as the change of the cable stiffness [28] caused by the vibration of the tunnel in formula (10).

Though there is no time item in formula (10), the vibration of mass M can cause the periodic variation of the cable tension. The change of tension can change the stiffness of the anchor cable, which can change the amplitude of the vibration equation of the cable, so the cable is equivalent to the parameter excitation. According to the internal resonance properties of second order nonlinear systems, when the vibration frequency of the cable is close to the half of natural frequency of mass block M, the vibration of mass block M along axial direction will lead to a large transverse vibration of anchor cable, which is called parametric resonance. Formula (10) is a nonlinear coupled vibration system. There exist both linear and nonlinear terms in the system and the influence of the additional inertia force and damping force of the water body caused by the vibration of the cable is considered. Therefore, it can reflect the mechanical nature of the coupling vibration of the cable and the fact with parametric excitation and vortex excitation.

For a coupled nonlinear system with both square and cubic terms, it is possible to generate an internal resonance when the nature vibration frequency is equal to one or two times of the parametric excitation frequency [29]. So the quality and rigidity of the tube are adjusted to meet the conditions above. Through the Simulink module of MATLAB, the displacement response of cable and mass block can be obtained under different conditions.

The excitation of the cable of SFT is simplified as parametric excitation frequency model, which can significantly reflect the law of VIV and parameter of vibration; Tunnel-cable coupled model is more consistent with the actual situation, and the results are more accurate.

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Example analysis

In the specific calculation process, the basic parameters of SFT are shown in table 2.The cross section of SFT is elliptical and 5 pairs of oblique cables are used. First order natural frequency is related to the static tension T_0, that is, the natural frequency is different under different flow velocity

Table 2 Basic parameter

	Length (m)	69.284
	Diameter(m)	0.489
	Mass per unit length (kg/m)	1037.4
	Additional mass per unit length(kg/m)	193.06 7850
	Density (kg/m^3)	2.1h10^{11}
	Elastic modulus (ု□)	60º
	Angle	2.572h10^7
	Initial tension (*N*) damping ratio	0.0018 0.01
	Initial disturbance (m)	0.432
Cable	Ratio of static and dynamic tension	
Tube body	Mass (kg)	1.5h10^7
	Initial disturbance (m)	0.05
	Long half shaft (m)	22.5
	Short half shaft (m)	9.5
Water body	Density (kg/m^3)	1028

Effect of simplified model on cable

According to theoretical knowledge, when parametric vibration of cable happened, whether vortex induced vibration happened has little effect on the modal response. The vortex induced vibration only provides a constant disturbance for the parametric vibration. The response of the first order parameter is the biggest, and the response of the second and third order parameter is gradually reduced. For the high order response of SFT's cable, the vibration amplitude is small, less than 1% of the first order response due to the current environment and the tunnel frequency are not in the coupling region; when the high order vortex induced vibration and parametric excitation vibration happened at the same time, the vibration response of cable also differs by one order of magnitude compared to the first order vibration amplitude. Therefore, the influence of parameter excitation on the first order vibration of cables under different flow velocity is mainly analysed in this paper.

Taking the flow velocity ့ൗ့ഋ ŢGɴ• Ầ• , the relationship between the first order displacement response amplitude of the cable and the parameter excitation frequency is shown in fig. 4.

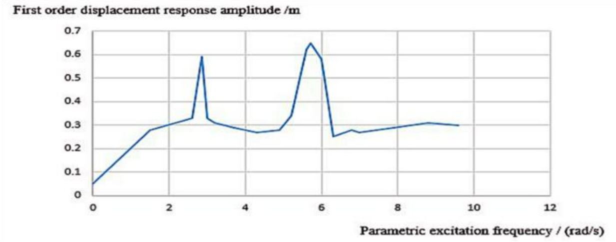
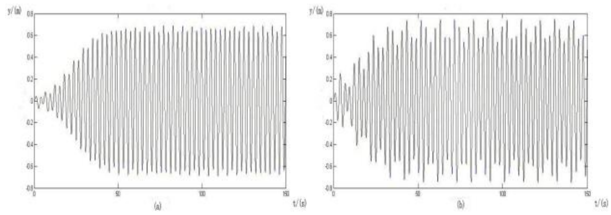


Fig. 4 The relationship between the first order displacement response amplitude and the parameter excitation frequency

It can be seen from the figure that when the parameter excitation frequency is one or two times of the first order natural frequency of cable, the first order displacement response amplitude of the cable has a local peak value and when the parameter excitation frequency is two times of its first order natural frequency, the maximum value of the first order displacement response amplitude is obtained.

Taking that the parameter excitation frequency is two times of the first order natural frequency, the first order vibration displacement response of the cable is calculated when the flow velocity is 2m/s, 3m/s, 4m/s and 5m/s respectively.



(a) (b)

Fig. 5 (a) The first order vibration displacement response of cable when 2m/s; (b) The first order vibration displacement response of cable when 3m/s

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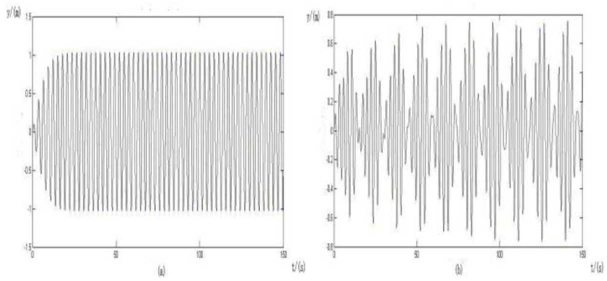


(a) (b)

Fig. 6 (a) The first order vibration displacement response of cable when 4m/s; (b) The first order vibration displacement response of cable when5m/s

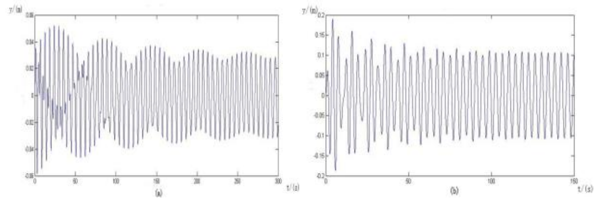
As can be seen in the figures, the vibration of the cable increases with the increase of the flow rate, but the vibration of the cable in figure 6 is obviously increased. The calculated results show that the vibration amplitude of the cable is increased with the increase of the flow rate when the geometric deformation, the stiffness difference and the difference of the material of the cable are neglected. When the flow rate reaches 4.2m/s, the discharge frequency of vortex is equal to the first natural frequencies of cable, which will lead to resonance and result in a significant increase in the amplitude of vibration; when the parameter excitation frequency is 2 times of the natural frequency of the cable, the same resonance occurs. At this time, the maximum amplitude of cable can reach 1.1m.

On the whole, the influence of parameter vibration is greater than that of vortex induced vibration.

A. Coupled nonlinear vibration of cable and SFT

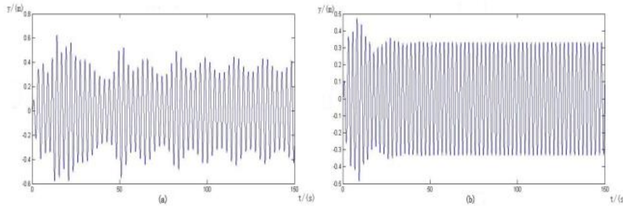
The natural frequency of SFT has a great influence on the cable. Taking the natural frequency of pipe section ω ω*M* = 2 1, tha is, parametric resonance phenomenon of system is produced, the vibration amplitude of cable and the displacement response of SFT are calculated. Assuming that the mass of the pipe segment is constant, ◌ด◌ is adjusted by changing the stiffness.

Fig. 7 and Fig. 8 show the vibration amplitude of the cable under the coupling action when the flow velocity is 2m/s, 3m/s, 4m/s and 5m/s respectively.



(a) (b)

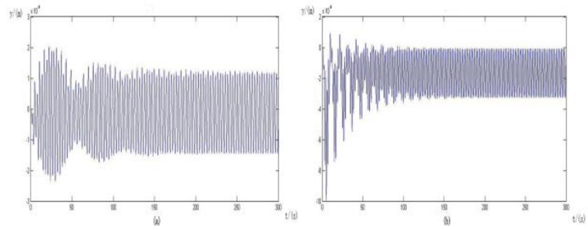
Fig. 7 (a) The vibration amplitude of cable under the coupling action when 2m/s; (b) The vibration amplitude of cable under the coupling action when 3m/s



(a) (b)

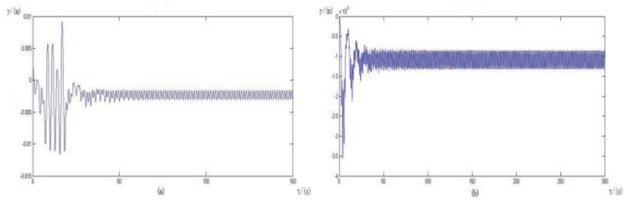
Fig. 8 (a) The vibration amplitude of cable under the coupling action when 4m/s; (b) The vibration amplitude of cable under the coupling action when 5m/s

Fig. 8 and Fig. 9 show the displacement response of SFT under the coupling action when the flow velocity is 2m/s, 3m/s, 4m/s and 5m/s respectively.



(a) (b)

Fig. 9 (a) The displacement response of SFT under the coupling action when 2m/s; (b) The displacement response of SFT under the coupling action when 3m/s



(a) (b)

Fig. 10 (a) The displacement response of SFT under the coupling action when 4m/s; (b) The displacement response of SFT under the coupling action when 5m/s

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As can be seen from the figures, the frequency of the tunnel and the cable meets $\omega \ \omega_M = 2 \ _1$, so the vortex induced resonance excited system parameters resonance, and energy transfers between the cable and the tunnel. In the initial period of vibration, the amplitude of the cable and the tunnel appeared fluctuation, and then the amplitude gradually stabilized. The amplitude of the cable is increased with the increase of the flow velocity, and the vortex excited resonance of the cable occurs at the 4.2m/s velocity. On the whole, when the coupling of the SFT and the cable, the vibration of the cable is greatly suppressed, and the vortex induced vibration and parametric excitation vibration are the main factors that cause the vibration of the cable.

Conclusions

In this paper, the cable of SFT is considered as a beam, and the motion response of cable is analyzed by using the vortex induced vibration equation. Meanwhile, the effects of parametric excitation are discussed, and the differences between non-coupling and coupling of tunnel and cable are compared. The following conclusions can be obtained:

- The vortex induced vibration of the cable can be used to excite the parametrical vibration of the system, and finally to the vibration of steady state. Vortex induced vibration and parametric excitation vibration are the main factors of cable vibration and parametric excitation vibration is dominant. The instantaneous amplitude of the anchor cable under the interaction of the vortex excited resonance and the parametric vibration is larger than that of any single action.
- When the ratio of the vibration frequency of the cable and the pipe body is satisfied with [illegible] or [illegible], there will be a parametric resonance, and the anchor cable will produce a large amplitude vibration. In other cases, there is no obvious coupling effect between the cable and tube.
- The additional inertia force of the water body can make the amplitude of the anchor cable become smaller, but the amplitude is not large. It can be considered to use the hollow section to increase the additional inertia force, so that the amplitude of the cable is decreased.
- The damping force of water can reduce the amplitude of the transient vibration of the cable to a certain extent, but transient parametric vibration phenomenon is still very obvious. As time goes on, the anchor cable will gradually stop vibration due to the effect of the damping force of water.
- The pipe section has a significant inhibitory effect on the vibration of the cable, but the displacement response of the cable is still large when the vortex induced resonance and the parameters excitation vibration occur at the same time.

The characteristics of the tube, the traffic flow and the roughness of the road surface will have a great impact on the parametrical excitation frequency. Therefore, in the preliminary design process, all possible parametric excitation frequency should be fully considered to try to avoid the situation that parametric excitation frequency is 2 times than the natural frequency of cable, which could cause a large displacement response of cable and structural damage.

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