Analysis of Influence Factors on Wind Resistance Stability of Long-span Bridges

Xunzhi Hou*

Chang'an Dublin International College of Transportation, Chang'an University

*Corresponding author: 2020905545@chd.edu.cn

Abstract. Long-span bridges (LSB) are common in the developed coastal areas, which is an important node of economic operation. However, LSB often has the problem, such as bridge stability with the condition of wind resistance, which is important for the bridge safety, service life and other important indicators. Therefore, it is meaningful to study and analyze the stability of bridges under wind resistance. This article will from the bridge structure deformation under calm wind load and wind resistance of bridge vibration under these two factors, the research status about the stability of LSB is expounded, and analysis of the specific image factor is applied to bridge structure, how in the end put forward using tuned mass damper (TMD) is used to reduce the influence of bridge vibration on the stability. The conclusion of this paper can be a reference for the design of the wind resistance and implementation of wind resistance measures of LSB.

Keywords: Long-span Bridges; wind resistance; tuned mass damper.

1. Introduction

The cross-sea bridge broke through the limitation of transportation networks, and promote the regional economic development and cultural exchanges. It is indispensable to the coastal city of backbone traffic, and for large span Bridges, the elements such as bridge stability is an important factor to ensure the security of the bridges and the traffic of the city logistics has important significance.

In recent years, the bridge length and compliance have a rapid growth, the dynamic problem of long-span bridges has become prominent, and wind load has become the main control load considered when designing the long-span bridges (LSB) [1]. The researches of Ma also pointed out that one of the main design loads for long-span spatial structures for bridges is the wind load [2]. In the research of Cheng et al. [3], a large number of arches, the basic units of arch Bridges were analyzed, and the relationship between the ultimate load and static wind load of steel arch Bridges was pointed out. The results of static wind load show that when the applied wind load increases, the ultimate bearing capacity will be significantly reduced, which seriously threatens the bridge safety. Therefore, it is very important and significant to study the influencing factors of the stability of long-span Bridges under the action of external wind. Normally, stability of the bridge is made by the influence of various factors, such as bridge type and bridge structure, and one of the most important is the influence of the external environment factors, which mainly refers to structural deformation of the bridge caused by constant static forces imposed by crosswinds and the bridge vibration under the weather. Previous literatures, such as the researches of Xing et al. [1], focused on wind-induced vibration control of Sutong Suspension Bridge with a main span of 1088 meters, but did not pay attention to the influence of static load caused by continuous wind. Many studies which research the stability of bridges only studied the two influencing factors separately and made case analysis of a specific bridge. That makes most of the experimental conclusions are not according to the universality, convenient to future researchers were analyzed.

In view of this, this paper introduces the common methods to determine the stability of long-span bridges and the concept of relevant important physical quantities. Then it focuses on the analysis and comparison of two factors on the bridge structure deformation caused by the constant static force imposed by the crosswinds and the bridge vibration under the action of weather. Finally, some suggestions are put forward to improve the existing measures of bridge stability.

2. Determination Methods of Long-span Bridge Stability

The stability of a bridge is determined by a variety of factors. When studying the influence of external weather, we should try to eliminate the influence caused by other factors. Since the influence of weather on Bridges is manifold, it is difficult to propose a perfect experimental method and consider all the situations. At present, most of the experimental methods can only focus on several aspects. There are two mainstream experimental methods: using finite element to analyze the bridge model, and using wind tunnel model to analyze the aerodynamic stability of the bridge.

2.1. Finite Element Analysis Methods

Finite element analysis (FEA) is rapidly developed for structural mechanics analysis as a modern calculation method. The first method in the field of continuous mechanics, dynamic characteristics of the application of an effective numerical analysis is it, then soon widely used in the solution of electromagnetic field, fluid dynamics and other problems, hydraulic engineering, civil engineering, bridges, nearly all the scientific research and engineering technology research need finite element method. And finite element analysis is one of the most common analysis methods in engineering modeling. It is easy to operate and can simplify the complex model and make it easy to deal with. In the study of bridge stability, finite element analysis is often used to research the bridge characteristics, such as linear and nonlinear stability [4]. Linear Elastic Stability (LES), Nonlinear Elastic Stability (NLES) and Nonlinear Inelastic Stability (NLIES) are common types of stability to research. In the research of Cheng [4], the ANSYS program was used to establish a finite element model with three-dimensional for stability analysis of Yachi Bridge, and three linear and nonlinear stability were studied. The bifurcation stability theory could lead to the LSE, so geometric nonlinearity and material nonlinearity were ignored, due to their small influence. As for NLES and NLIES, these two kinds of stability are based on the theory of ultimate load stability. NLES could only consider geometric nonlinearities, while NLIES finite element analysis considers both geometric and material nonlinearities.

2.2. Wind Tunnel Experimental Methods

Wind tunnel analysis is mainly referring to measuring Bridges in wind tunnel model of the data, then analyze, this experiment is to compare the benefits of accurate control of experimental conditions, such as air flow rate, pressure and temperature, etc., and undertake experiments indoors, little impact on climate conditions, can offer a good experimental environment for scientific research workers. In this experiment, linear and nonlinear bridge stability still need to be considered to measure the aerodynamic stability. However, even though linear methods are the most widely used methods to study the aerodynamic stability of Bridges and their response to turbulent winds, they cannot deal with the important nonlinear effects inherent in aeroelastic problems [5]. As shown in Fig.1, The tunnel experimental methods of Hong Kong-Zhuhai-Macao Bridge has an active effect in the process of bridge design.

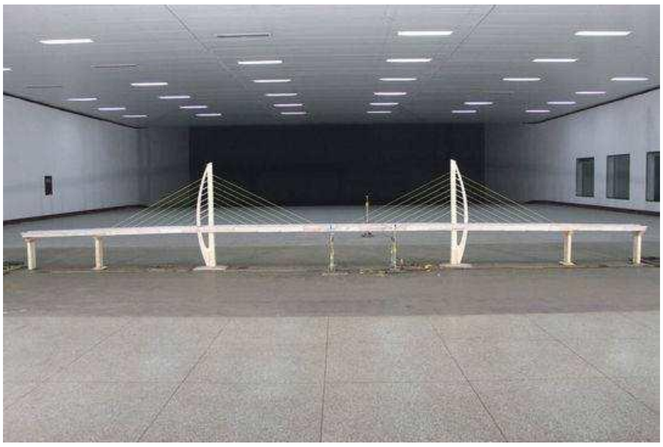

Fig. 1 The tunnel experimental methods of Hong Kong-Zhuhai-Macao Bridge [6]

3. Influence Factors on Wind Resistance Stability

3.1. Structural Deformation caused by Constant Static Forces

The large-span bridge with a large pillar is tall, soft and has a large contact area exposed to the weather. In the situation like wind load, it will have a significant vertical and horizontal displacement. The influence of this influence results in additional force and rail lateral displacement, resulting in an irregular initial rail and then damaging the lateral stability of the rail structure. However, if the windproof rail is laid on the large pillar and the LSB, the wind load in length has little influence on the structure of the rail. Since the wind load in length has no influence on the horizontal and vertical irregularity of the rail, only a stability analysis is carried out [7]. The contact area of the large bridge and the LSB is large, and under the vertical load of the wind, the displacement in the length of the bridge top pier is relatively large. Due to stresses on the steel column, the displacement of the column is transferred directly to beams, and the column has transferred the displacement to the track structure. The longitudinal line limits the ends of the rails and cannot move along the line, which causes additional forces that act on the main beam and are transferred to the upper pillar, thus the upper pillar is under the pressure force. The presser is transferred from the pillar to the column and then rail until the equilibrium point is reached. It is also emphasized that the lateral force of the wind does not create additional force on the rail, but reduces the linear stability, limited the lower value and does not become a key factor for lateral instability. And the longitudinal force of the wind mainly causes the rail supporting the extra force, which is negligible if comparing to the effect of the extra expansion force. With regard to the increasing of the linear stability by the force of the transverse wind, the stability can be ensured to meet the requirements by increasing the safety factor.

3.2. The Bridge Vibration under the Wind

The stability of the bridge should not only consider the static wind effect, but also the non-uniformity of the spatial distribution of the structure's large variable wind speed. This non-uniformity is generated by the large span structure, In particular, the tower height of long-span suspension bridges is generally large. According to the spatial distribution characteristics of the wind, the wind speed at different positions along the bridge tower height and the main cable will be significantly different, which makes the wind speed show obvious non-uniform distribution characteristics in space. In the study of Zhang [8], the increase of flutter critical wind speed is mainly caused by the negative Angle of attack caused by the torsional deformation of the bridge deck girder under the action of static wind, and the other part of the increase comes from the change of the dynamic characteristics of the structure. However, when the lift load applied on the bridge deck beam is downward, the axial tension in the cable increases, so that the gravity stiffness and vibration frequency of the structure are increased. At the same time, when the wind speed increases, the shape of each order mode of the structure also changes, the similarity between the modes decreases, and the multi-mode coupling vibration is promoted. It is the increase of vibration frequency and the positive effect of multimodal coupling that finally improves the aerodynamic stability of the structure.

4. Methods for Controlling Wind-induced Vibration

For common Bridges, due to the vertical and horizontal stiffness of piers are quite large, and the contact area to bear the wind load is too small to consider, so the wind load has no obvious influence on the stability of Bridges. Pier Bridges with high pier and long-span have a higher height than ordinary bridges, and will have greater vibration influence under the same wind load. In order to reduce the vibration influence of wind resistance on the stability of Bridges, many methods have been studied. One of the components called tuned mass damper (TMD) has a good stabilizing effect on the stability of Bridges.

In the study of Xing [1], the TMD was used to reduce the impact of vibration on the bridge. The advantage of TMD counterweight is that under the condition that the function of the original counterweight structure is unchanged, the response of the structure under dynamic loads such as wind is weakened to a certain extent. In the case of Sutong Bridge [1], the control characteristics of TMD counterweight of the measuring span with or without auxiliary piers was studied respectively. This system consisting of a mass block, spring and damper is the TMD system. When the system is properly tuned on the main structure of the bridge, the mass part of the TMD system will produce a vibration direction opposite to the vibration direction of the main structure. Through the link of the spring, an inertial force opposite to the motion direction of the main structure can always be provided by the inertial force in the system. As a result, the dynamic response of the structure will be greatly weakened, especially in long-span cable-stayed Bridges. In long-span cable-stayed Bridges as Fig.2 shown, when the side/main span ratio is small, counterweights are always used at the side spans.

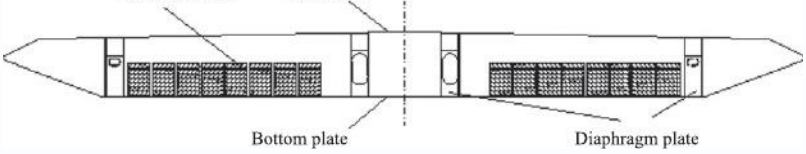

Fig.2 Counterweight distribution in long-span cable-stayed Bridges [1]

The TMD counterweight designed in this paper is proved to be an effective method to control chattering response of Sutong bridge, and can also be used as counterweight. TMD counterweight scheme is widely used in the future design of long-span cable-stayed Bridges. According to the experiment, the control ability of TMD on the main deck and side span of the bridge is significantly improved after removing the auxiliary piers. Obviously, the presence of auxiliary piers inhibits the effectiveness of the TMD system. Therefore, better control effects of TMD can be expected on cable-stayed Bridges without piers. In other aspects, similar to the situation of the bridge deck, in the TMD system, the longitudinal displacement of the bridge tower top without the auxiliary pier is much smaller than that with the bridge auxiliary pier [9]. This may be because the vertical displacement of the tower top is closely related to the vertical displacement of the bridge deck. However, the transverse displacement of the main tower of the bridge is not affected by the TMD system because the stiffness of the bridge tower is large [10].

5. Conclusion

In this paper, the wind resistance stability factors of long-span Bridges are analyzed, and the influence mechanism of bridge structural deformation caused by static wind load and bridge vibration under wind resistance on bridge stability is proposed. The effect of static wind on the aerodynamic stability of long-span suspension Bridges is very important, so it should be fully considered in the analysis. Factors such as spatial non-uniform distribution of wind speed and cable wind load have little influence on the aerodynamic stability of long-span suspension Bridges, so their influence can be ignored in the main analysis. As for TMD counterweight, this system is an effective method to control bridge vibration and maintain bridge stability. For long-span Bridges without piers, TMD counterweight has good vibration reduction ability, and it has a broad application prospect in the design of LSB in the future. The future research direction can be biased towards the study of wind vibration resistance scheme similar to TMD type, and more parameters should be considered as the analysis basis for the stability analysis of LSB.

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