CHAPTER 2

LITERATURE REVIEW

Wind-induced vibration is the first important factor in the design of long-span bridges, especially for those located in the regions where typhoon often occurs (Gu, Zhang, & Xiang, 2000). Flutter is an aeroelastic self-excited oscillation of a structural system which may cause the structure vibrate continuously with increasing amplitude and it should be made sure that it does not occurs during the lifespan of bridges. The frequency-domain approach has been widely used for estimating flutter speed of structures.

This thesis mainly focuses on static and dynamic behavior, static coefficients, structural responses, critical flutter wind velocities and flutter derivatives. Among these parameters, the most complicated and problematical terms are flutter derivatives whereas the others can be straightforwardly obtained from the experiment. Many researchers have tried to extracted flutter derivatives particularly. The reviewed researches in this topic illustrates in section 2.1. Furthermore, to suppress this improper oscillation, the passive vibration control is going to be considered. The most practical and economical ways are tuned-mass dampers and aerodynamic appendages, which are mentioned in section 2.2 and 2.3, respectively.

The Danish Maritime Institute (DMI) had done the experiments of same bridge section of this thesis, Industrial Ring Road (IRR). The tests were performed at DMI wind tunnel during March and June 1997 by sectional model (DMI, 1997). The results of static coefficient show that lift and moment coefficients tend to be increased but drag coefficients tend to be decreased under turbulence effect. For dynamic tests, the results indicate that vortex-shedding responses were found for both vertical and torsional degree of freedom in smooth flow, but not in turbulence. For stability limit, all limits are larger than 65 m/s. The aerodynamic derivatives were identified by initial excitation method and were calculated for each wind speed as the average value of 10 tests at each velocity.

2.1 Flutter Derivatives

Gu et al. (2000) and Zhu et al. (2002) had proposed an identification method based on unifying least squares (ULS) theory to extract flutter derivatives of a two-DOF model. Though the ULS method could theoretically identify all 18 flutter derivatives using a three-DOF section model, only eight flutter derivatives were extracted due to lack of a more inclusive experimental set-up to accommodate the three-DOF section model.

Gu M. and Qin X. R. had studied the direct identification of flutter derivatives and aerodynamic admittances of bridge decks in 2004. They had introduced the previous studies on flutter derivatives estimations by system identification techniques and comment on the difficulties of both free and force vibration methods. Wind tunnel test of streamlined thin plate model and Hong-guang bridge sectional model were conducted in turbulent flow. The aerodynamic derivatives are identified by SSI (covariance-driven stochastic subspace identification) method. The identified parameters are compared with the theoretical ones. This thesis tracks this study's experimental setup, whereas a model was suspended by 8 springs, the piano wires were used for 2-DOFs-guaranteed and turbulence is generated by grids. However, Gu's research mounted 3 transducers to capture the acceleration signals but in this thesis installs only 2 transducers in the mid-span of model and non-zero velocity signals are captured from ambient vibration. Moreover, this thesis also identifies A_4^* and H_4^* which Gu's research didn't due to its extraction difficulties.

The free vibration method seems to be more tractable than forced vibration testing. However, at high reduced wind speeds, the vertical bending motion of the structure will decay rapidly. This occurs due to the effect of positive vertical bending aerodynamic damping, and thus the length of time history available for system identifications will decrease. Therefore, it leads to more difficulties to the system identification. In addition, the free vibration method regards the buffeting forces and the responses as external noises, and it is therefore confronted with great difficulties at higher wind speeds. In summary, most of the above mentioned methods are subsections of so-called output-only system identification (as input such as wind load are not exactly known and available parameters are output responses only). In a civil engineering context, the civil structures are the systems that is excited by a not measurable input force and that only output measurements (e.g. accelerations) are available.

Janesupasaeree T. (2009) had purposed the very fascinating measurement of flutter derivatives of bridge deck in wind tunnel test by covariance-driven stochastic subspace identification (SSI-COV) method. Thin flat plate was tested and compared with sectional model of Industrial Ring Road (IRR cable-stayed bridge), same sectional model of this thesis. The program written can extract the system matrices, $\mathbb{M}^{-1}\mathbb{K}$ and $\mathbb{M}^{-1}\mathbb{C}$. The results of this research showed that all of the flutter derivatives agreed well with the test results from DMI. The author of this study also suggested that the two methods, initial free vibration and ambient vibration gave the very close results to another, except a few sensitive and insignificant parameters. Thus, this study uses this method in ambient vibration to extract the flutter derivatives due to the convenience in testing procedure and its correspondence to real structure behavior.

Many stochastic system identification methods have been developed during the past decades, among which the stochastic subspace identification (SSI in short) technique has proven to be a method very appropriate for civil engineering. SSI declares many advantages as follow: (1) the assumptions of inputs are congruent with practical wind-induced aerodynamic forces, i.e. stationary and independent on the outputs; (2) identified modes are given in frequency stabilization diagram, from which the operator can easily distinguish structural modes from the computational ones; (3) since the maximum order of the model is changeable for the operator, a relatively large model order will give an exit for noise, which in some cases can dramatically improve the quality of the identified modal parameters; (4) mode shapes are simultaneously available with the poles, without requiring a second step to identify them.

2.2 Tuned-mass Dampers

Wind-induced instabilities such as flutter or buffeting responses are particularly important aerodynamic responses of long-span suspension bridges and long-span cable-stayed bridges. For increasing the levels of structural safety and occupant comfort of vehicle-running under common wind velocity, it is necessary to reduce the level of wind-induced responses in long-span bridges by using aerodynamic or structural control (Malhortra and Wieland, 1987). The aerodynamic method is usually an effective countermeasure for response suppression. Good aerodynamic performance of a bridge deck can be achieved by using shallow section, closed sections, streamline edges and other minor and more subtle change to the cross-sectional geometry which called aerodynamic appendages. Besides, the passive structural control method by using tuned-mass damper (TMDs) can further improve the responses. TMD had been widely investigated; both building and bridge design, and also applied to a real structure with minor change in overall structural mass.

Gu M. et al. had purposed the theoretically and experientially study the increase of critical flutter wind speed of long-span bridges by using tuned-mass dampers in 1998. The model of this study was Tiger Gate Bridge, a steel box deck suspension bridge with a main span of 888 m located in Southern China. The frequencies of TMDs were tuned neighborhood to the flutter frequency so as to increase the critical flutter wind speed. Several tests had been conducted and the results were shown in averaged. The results of this study showed that the most control efficiency came about at mass moment of inertia 5.6% and tended to saturate or even decrease when the mass moment of inertia ratio up to about 10%. For mass ratio of 0.9% and 2.5%, the control efficacy results were very close one to another. In case of effects of structural damping ratio, TMD was more effective for a bridge with a lower structural damping than for those with higher one. However, the authors also suggested that the TMDs damping ratio seems to have less effect on flutter control than frequency ratio did.

Boonyapinyo V. et al. (2007) had studied the suppression of aerodynamic response of Akashi Kaikyo Bridge, a 1990m main span bridge in Japan, during erection and after completion by using tuned-mass damper. This research analyzes both flutter instability and buffeting response by three-dimensional finite element model. The mass ratio of 1% and 3%, optimum damping ratio of 5% and 8.6% are used in the calculation which are similar ones used by many researchers. The results show that when wind velocity is low, about 20 m/s, the vertical and torsional TMD with 1% mass ratio in each direction and 1% mass moment of inertia ratio can significantly reduce the buffeting response in vertical, horizontal and torsional directions by 8.6-13%. When wind velocity increases to 40 m/s, the control efficiency in reducing torsional buffeting response increases greatly to 28%. However, its efficiency in vertical and horizontal directions reduces. They also suggested that the critical flutter wind velocity during erection significantly lower than the completed bridge.

Chen X. and Kareem A. had investigated the efficacy of tuned-mass dampers for bridge flutter control in 2003. New optimal TMD parameters are suggested with provided better performance than those in their literature. The dependence of TMD performance on structural damping is highlighted. Two example long-span bridges with different flutter characteristics are utilized to study the effectiveness and limitations of TMDs in controlling multimode coupled bridge flutter. It was clear that the performance of a TMD depended on the mass ratio, tuning frequency ratio, TMD and structural damping ratios. Optimal TMD designs for controlling the free vibration had been suggested. Mass ratios of TMD had been suggested to be not less than 0.0256, where the tuning ratio and optimal damping ratios were 0.9843 and 0.0992, respectively. Critical wind speed of bridge A increased from 67.7 to 74.5 m/s, and bridge B from 72 to 94.7 m/s. However, the suggested one and the optimal parameters gave very close result one to another.

Reduction of vortex-induced oscillations of Rio-Niteroi Bridge by dynamic control devices had been investigated by Battista R. C. et al. in 2000. The original bluff section experienced vortex-induced oscillations at sustained wind velocity close to 60 km/h which similar amplitude of oscillations. The bridge was having no upstream obstacles to generate oncoming turbulence and located in very calm water, so vortex had been produced predominantly by laminar flow. Some other aerodynamic appendages had been envisaged in order to improve this section, all of them having otherwise a penalty of adding substantial mass to the bridge. The sectional model had been experimented in wind-tunnel tests in both passive and active control. 1% mass ratio had been selected, distributed to 8 TMDs, and optimal tuning ratio and damping ratio were calculated. Passive control by TMD had taken as wholly satisfactory as it enabled a reduction of about 80-90% of the uncontrolled displacement amplitudes (from 34 cm to 2.1 cm). However, active control seemed to have better performance than the passive counterpart, nevertheless passive control was simple to design, construct and install, and its mechanical robustness demanded low maintenance.

The investigated on tuned-mass dampers had mainly focused on increase of critical flutter wind speed. Few had done on decreasing of vortex shedding and that used only 1% of mass ratio. Since the suppression in buffeting responses is based on different theoretical background, flutter and vortex are mainly investigated. Hence, this study moreover focuses on amplitude reduction of vortex responses of bridge section mounted with tuned-mass dampers with mass ratios of 1%, 2% and 4%. Optimal tuning ratios and damping ratios of tuned- mass dampers are identified from the formulae as literature appraisals. Besides, the critical flutter wind velocities are focused on either.

2.3 Aerodynamic Appendages

The investigation in aerodynamic appendages had been considered for a long time and many studies are used in an effort to suppress the oscillation in real structures. Bronx-Whitestone Bridge which had to use poor aerodynamic I-girder to keep construction in tight schedule, the stiffening systems including fairings are installed along bridge deck. Another illustration is Deer Isle Bridge, which is stated below. Some investigations had been reviewed as listed:

Wardlaw R. L. and Goettler L. L. (1968) had purposed the experimental study of the effects of aerodynamic appendages. They measured the amplitude of oscillation of Long’s Creek Bridge before and after installing aerodynamic appendages, which consisted of the soffit plates and various types of fairings, under the wind velocity of 8 to 18 m/s in wind tunnel test. The results of this study showed that the bridge responses via the vibration amplitude approached 11 cm of original section under 16 m/s wind speed. In the other hand, with fairings installed, the amplitude was decreased more and more following the fairings length. Since 3.0m fairings installed, the structure responded with amplitude less than 1 cm. The Long’s Creek Bridge is a representative of satisfactory performance of the triangular fairing on bridge aerodynamic instability. Many said that Long’s Creek Bridge is a representative of satisfactory performance of the triangular fairing on bridge aerodynamic instability.

The investigation of effects on geometry modification on aerodynamics of cable-stayed bridge deck had been carried out by Bienkiewicz in 1987. A 1:140 scale of Weirton-Steubenville cable-stayed bridge model was a case study which its original section behaved an unstable oscillation in torsional direction, including high vortex-induced response. The wind tunnel tests were carried out in smooth flow for four sections including original section, partially streamlined, enclosed lower cavity and fully streamlined section. Streamlining of deck resulted in improved aerodynamic performance, with an increase in the critical flutter wind speed for torsional flutter and decrease in vortex response.

Houston D. R. and Bosch H. R. had published the effects of fairings and of turbulence on the flutter derivatives of a notably unstable bridge deck in 1988. This study aimed to identify the flutter derivatives of Isle-Sedgwick Bridge by sectional model test in wind tunnel. Its deck had a same plate girder profile as the Tacoma Narrows Bridge, which was subsequently shown to have such poor aerodynamic characteristics. Like the Tacoma Narrows Bridge, the Deer Isle Bridge was built during the depression and has a relatively light and flexible stiffening structure. Almost immediately after its construction, the Deer Isle Bridge experienced large wind-induced oscillations. Therefore, the fairing-modified section was tested for comparison. The result of the torsional aerodynamic stability represented via flutter coefficient A_2^* as a function of wind speed whose positive values indicate unstable conditions. It is clear that the fairing modification produces a more stable section. Furthermore, the fairing coverage effects are also carried out where the section with 100% covered with fairing introduced the most stable section.

Nagao F. et al. had investigated the effects of triangular edge fairing on bridge box girder aerodynamic stabilities in 1993. Various angles of triangular fairings were mounted to different type of bridge deck sections. The results showed that fairing which the upper slope angle is 0° showed only a little increase in onset flutter velocities. Generally speaking, the modification of flow properties along the upper deck is effective in preventing the flutter. In addition, fairing effects on flutter increased with the slenderness ratio of cross section. Moreover, the results show that an inner angle of 60° fairing gave the most effects of flutter onset velocity. This type of fairing can furthermore execute almost vortex shedding. Nonetheless, this study was carried out in the uniform flow and due to no flutter derivatives were indentified from this study; hence the effects of turbulence on the aerodynamic instability for bridge deck and flutter derivatives should be clarified in the next place.

Fang F. et al. had investigated on the aerodynamic instability of a suspension bridge with a hexagonal cross-section in 2007. Measurements of the dynamic responses of a sectional bridge model in the cross-wind and torsional directions were firstly carried out in wind tunnel. Three sections were mounted and tested for a comparison including bluff rectangular 180^o side angle section, 90^o, 60^o, and 30^o side angle sections. Among the hexagonal decks studied, it was found that one with 30^o side angle leads to the greatest critical flutter speed. Beside wind tunnel model tests, the method of computational fluid dynamics (CFD) had also been used to examine the aerodynamic performance of the sections where the results of numerical predictions agreed well with those from the experiments.

From the investigations reviewed above, geometry modifications of cable-stayed bridges are suggested to mount on a considered section due to their efficiency in reducing static and dynamic responses. Fairings, soffit plates and combined sections are consequently first-rated. Most of previous studies had focused on the effects of geometry modifications on critical flutter velocities, where flutter derivatives were not widely judged due to lack of motivation on the simplicities and stabilities of extracted values. This thesis additionally carries out static responses, an overall response of bridge deck and all eight flutter derivatives which are affected by deck shape modifications as well.