CHAPTER 6

CONCLUSIONS AND DISCUSSIONS

6.1 Static Tests

6.1.1 Smooth Flow

Static tests were performed with the purpose of identification of static coefficients, including drag, lift and moment coefficients. The experiments were conducted under various wind velocities and it can be concluded that the Reynolds Number effects on static forces and moment are negligible since the coefficients are almost the same at differed wind velocities. This occurs because the normalization of static forces by squared wind velocities was always performed. At varied wind attack on bridge deck, the results show that all three coefficients increase, respect to angle of attack. It was moreover found that the flow separation occurs at 3°. This little angle of separation occurs due to sharp leading edge of bluff type section that generally causes the flow separation more easily.

The results of modified sections were found that, fairings intend to influence the drag force of the section. Drag coefficient was reduced up to 41% in high negative angle of wind attack. Since the original section is directly subjected to wind attack, separation of wind can cause more forces on the section. Fairings cause relatively small vortices sizes and very low turbulence. Hence, the wind is prohibited to frontally hit the bluff section. There is only little change in lift and moment coefficients. Some changes may caused by increasing of area of lifting wind on bridge, especially for fairing modified section. However, these changes are considered to be negligible.

6.1.2 Turbulent Flow

Static tests were furthermore conducted in turbulent wind condition, around 8% turbulence intensity, generated by grids. The static behaviors were slightly different from smooth flow. Turbulence tends to enhance the reattachment of the flow by increasing the angle where the flow separation occurs from 3° in case of smooth flow to that of 6° in case of turbulence flow, respectively.

The effects of three types of geometrical modification on bridge’s static behavior under turbulence flow condition. All types of modification gave very close results in lift and drag coefficient. Drag force was significantly decreased in case of fairings and combined sections. These two types of modifications prohibit the oncoming wind to directly hit the bridge section. For moment coefficients, fairings and combined sections resulted in a very close range to the original section. Flow separation had been observed at the angle of 6°. Therefore, it can be concluded that fairings and combined sections can effectively reduce the drag coefficients.

6.2 Dynamic Test

6.2.1 Smooth Flow

6.2.1.1 Critical Wind Speeds and Structural Responses: Smooth Flow

For original section, vortex shedding had been found in the original section at reduced velocity of 1.5 (equivalent to 41 m/s in full-scale). The phenomenon was perfectly exterminated by any type of modifications since they prohibit the generation of vortices which periodically attack and cause bridge exhibit in unstable behavior. Flutter was found under torsional single degree-of-freedom instability. Critical wind speed had been observed at reduced velocity of 4.5 (118 m/s in full-scale). This states that the bridge section is susceptible to flutter phenomenon at high wind speed. However, the tests of aerodynamic appendages modified sections were further conducted to increase that velocity. On one hand, fairing-modified section is able to delay the critical wind speed up to reduced velocity around 5 (135 m/s in full scale) or around 16% increased. On the other hand, for soffit plate and combined section, flutter phenomenon was not found in testing velocity range.. This concludes the highly achievement of aerodynamic appendages modification to stabilize flutter phenomenon and vortex shedding responses in case of smooth flow.

Since the bridge section was clearly found the unstable under torsional direction, vertical TMD sections show a little effect on suppression of responses. Nonetheless, torsional TMDs are able to device effectively. They show reduction of vortex shedding response significantly and are observed gradually over mass ratios. Torsionally, critical wind speeds of 138 m/s and 148 m/s are identified for 1% and 2% mass ratios, respectively. For 4% mass ratios, the flutter was not clearly observed over a testing range. This occurs as a consequence of increasing of mass contributes high energy absorption. Torsional TMDs are then suggested in vortex shedding suppression and increase of critical wind speeds. Besides, it was found that vortex shedding phenomenon is perfectly suppressed by all aerodynamic appendages modified sections.

In conclusions, to suppress the vortex shedding responses in smooth flow, all aerodynamic appendages modified sections and torsional TMD are highly suggested. Fairings seemed to have less effect on flutter prevention. Meanwhile, the soffit plates and combined sections show highly increase in critical flutter wind speeds, these two types of modifications are then suggested for instabilities improvements.

6.2.1.2 Flutter Derivatives: Smooth Flow

In this study, IRR Bridge is an example of blunt type section that has a good cost performance, but at the same time the bridge cross-section is known as a section with aerodynamically unstable at high wind speed. For these types of sections, the most important terms are H_1* and A_2*, which refer respectively on vertical and torsional damping of the section, whose positive values indicate unstable conditions. Flutter derivatives play an important role to illustrate the behavior. All 8 derivatives were extracted by Covariance-driven Stochastic Subspace Identification (SSI-COV), developed by Janesupasaeree (2009).

For an original section, the sign reversal of the A_2* was observed as the reduced wind speed reached the value of 4.5, i.e. at velocity equals 118 m/s in full scale while H_1* remains in negative (stable) region. These indicate that this bridge section is susceptible to behave in torsional flutter at high wind speed.

The modification effects can be neglected on vertical aerodynamic damping coefficient related term, H_1*. All sections show this value in negative region. Besides, the section are influenced by the modifications in A_2* which is most considerable in long-span bridges. Fairings show some improvements on the torsional unstable behavior by delaying the unstable of bridge deck from reduced velocity of 4.5 to 5. This occurs since the eddies which generally formulated by the attachments to bluff section are postponed. Moreover, it was clearly found that soffit plates and combined sections produce more stable characteristics. Their sign reversals in A_2* are not clearly observed. Flutter derivatives H_2* term, cross derivatives to a torsional aerodynamic damping, are conversely agree well with A_2* results.

Results of H_1* and A_2* can be confirmed by comparing them with structural responses. For an original section, torsional flutter was observed at reduced velocity of 4.5, similar value to the sign reversal of flutter derivative A_2*. Moreover, for soffit plates and combined sections, no flutter had been observed from the responses tests, guaranteed with all their A_2* values presented in negative region. H_1* term for all sections presented in negative region and trend to be more negative when wind speed increases, the absence of vertical flutter phenomenon from the dynamic responses test is also confirmed.

6.2.2 Turbulent Flow

6.2.2.1 Critical Wind Speeds and Structural Responses: Turbulent Flow

Compared to the smooth flow, critical flutter wind speed of an original section was postponed by effects of turbulence. Reduced velocity of 4.5 in smooth flow extended its limit to 5.5 in turbulence condition (from 117 to 163 m/s in full-scale). It can be concluded that vibration under turbulence flow seemed to result in more stable in flutter behavior where eddies were not easily formulated. For dynamic responses, turbulence reduces the vortex shedding oscillations because the turbulence tends to enhance the reattachment of flow and weaken the vortex shedding formulation. However, it raises the amplitude of the bridge responses progressively over the speed range. Hence, buffeting responses shall become more significant in turbulence case.

For aerodynamic appendages modified sections, fairings cause little effects on improving buffeting responses and delaying the flutter instability. Nevertheless, soffit plates and combined sections can then be concluded as the satisfactory in postponing flutter instability since flutter phenomena were not been observed in this case. The result of critical flutter wind speed indicates the insignificance of fairings modification due to the wind speed results in the same value of an original section. Besides, buffeting responses are not affected by fairing modification. For soffit plates and combined sections, flutter phenomena were not observed during the test velocities. The recommendation for the great improvement in critical flutter wind speeds and reduction in buffeting responses can then be concluded.

6.2.2.2 Flutter Derivatives: Turbulent Flow

Under turbulent wind, the identified flutter derivatives, except A_2*, are generally in agreement with those in smooth flow. The most important and positive effect of the turbulence is that it tends to make the bridge more aerodynamically stable by delaying the sign reversal of the aerodynamic damping A_2*. This coefficient postponed its sign-reversal to positive values which can cause unstable oscillation from 4.5 to 5.5 in smooth and turbulence flow, respectively. This may reveal that for those bridges with bluff type sections similar to the IRR Bridge, the effects of turbulence can be significant. Hence, the wind tunnel tests of such bridges for flutter derivatives estimation should also be carried out in turbulent flow.

For modified sections, H_1* terms remain negative for all mounted sections and agree well in trend. However, fairing-modified section indicates the insignificance in delaying flutter where A_2*. It shows the sign reversal at reduced velocity 5.5, which are the same value as the original section. However, for soffit plates and combined sections, A_2* terms remain in negative region while the torsional flutter is not clearly observed from experiments and even from inspections. This sign-reversal phenomenon is the outstanding factor toward the flutter instability of bridge decks. The results show that the more streamlined bridge section exhibits more aerodynamic stability. Then, the streamlined bridge sections seemed to be an appropriate choice for the very-long span bridges design. Moreover, aerodynamic appendages resulted in efficiency in enhancing the structure’s aerodynamic behavior and represent a cost effective solution to a major safety and performance problem.

6.3 Discussions and Recommendation for Future Works

In this study, in order to reveal the vortex shedding-response phenomena, the low-inherent damping of model was selected. This vortex-shedding amplitude is well-known as damping dependence, and then tests may further be carried out in the case of higher structural damping of real bridge.

The modified sections were performed to compare with an original one in term of static coefficients, structural responses, critical flutter wind speeds and flutter derivatives. The results show that drag forces were reduced significantly in fairing modified case due to fairings can slice the wind that it prohibited to hit the bridge head on. Soffit plates show great improvements in increasing critical flutter wind speeds, which are confirmed by flutter derivatives results, especially A_2* term. Modified sections show a perfect reduction in vortex shedding responses as well. TMDs installed section can additionally improve the critical flutter wind speeds, with related to those mass ratios.

The effect of incident turbulence on the aerodynamic parameters should be further examined for a wide range of bluff sections and different turbulent intensities. The oscillation amplitude may limit the maximum reduced velocity that can be tested to identify flutter derivatives in this study, especially for high turbulence intensities where large amplitude of the buffeting response occurs. In order to identify flutter derivatives of a bridge deck under high turbulence intensities, a new experimental set-up or an additional artificial damping such as electro-magnetic may be required.

From this study, it is found that there are some limitations for the identification of flutter derivatives from the buffeting test. For example, it becomes more difficult to extract the flutter derivatives from the buffeting responses in the situation when a relatively heavy model is excited at a very low reduced wind velocity, i.e. low wind energy. The useful signal is in the same order as the measurement noises. Theoretically, this research attempts to extract the flutter derivatives with SSI-COV method. The most recently publish SSI-DATA may be applied to the problems and may extract flutter derivatives as well. Then, they may be applied further to experimentally determine all the derivatives for a wide range of bridge deck cross sections shapes to gain further insights into the complex phenomena of flutter and buffeting. Nevertheless, a more extensive experimental set-up is required. Besides, since the method is used for flutter derivatives extraction in this study in buffeting or ambient responses, it represents the great contribution in enhancement of the application in real structure where the similarities in bridge deck behavior to the real oscillations are then be established. With further mathematical and numerical investigations, it should overcome the difficulties in the extraction in ambient oscillations in real structures.

In this study, the effects of turbulence upon the aeroelastic and the aerodynamic phenomena of a blunt type bridge deck of IRR Bridge were investigated. Turbulence has positive effects when concerning bridge stability. On one hand, it delays the onset of flutter and reduces the vortex-shedding response when compared with the smooth flow. On the other hand, the turbulence raises the amplitude of response progressively over the wind speed range and may causes problem to the serviceability of the bridge. Modified sections were mounted to the model and resulted in great stabilities. However, high buffeting amplitudes were still observed. One should investigate regarding the optimum section modification for this section.