Flutter instability is a flow-induced and self-excited divergent aerodynamic instability phenomenon, resulted from interaction between fluid flow and elastic body. In long span bridges, deck element could experience flutter due to wind flow. This research aims to study the effects double slot, that is a relatively narrow slot placed near leading edge and trailing edge of the deck, for stabilization of coupled flutter. It is found that double slot can reduce absolute value of $A_1^*$, which is favorable for coupled flutter stability, but also can produce positive $A_2^*$, which change flutter characteristics from coupled flutter to torsional flutter with lower onset velocity. Optimum configuration which has almost zero $A_1^*$ and negative $A_2^*$ is possible, but the high sensitivity of aerodynamic derivatives value to the position of slots implies that another countermeasure or modification is needed to ensure the $A_2^*$ always negative.

1. INTRODUCTION
Since the failure of Old Tacoma Narrow bridge in 1940, the study of aerodynamic and aeroelastic has become more important in design of long span bridges. Old Tacoma Narrow bridge experienced torsional flutter, which is characterized by positive value of $A_1^*$ at low reduced velocity (Zhou et al., 2006). Modern long span bridges adopted slender and streamlined box girder deck section, which has negative $A_1^*$ so torsional flutter can be avoided, but still prone to coupled flutter if used in super long span bridge due to close value between natural heaving and torsional frequency. Matsumoto et al. (2002) used Step-by-step (SBS) analysis method to clarify the mechanism of flutter, and showed that $A_1^*$ and $H_1^*$ play major role in coupled flutter excitation. Therefore, reducing absolute value of $A_1^*$ and $H_1^*$ is the appropriate strategy to avoid coupled flutter. In this study, the unsteady pressure characteristics, unsteady pressure amplitude $\bar{C}_p$ and phase difference $\psi$, are used as the basis to modify aerodynamic derivatives value. The basic deck section is rectangular prism with side ratio B/D=20 (B=deck width [m], D=depth of deck [m]).

2. UNSTEADY PRESSURE CHARACTERISTICS
Unsteady pressure characteristics consist of unsteady pressure amplitude $\bar{C}_p(x^*)$ (peak to peak value of pressure fluctuation at point $x^*$) and phase difference $\psi(x^*)$ (lag of maximum negative pressure at point $x^*$ from maximum angle of attack of the body), $x^*$ is non-dimensional position from mid-chord (normalized by half-width $b$[m]). Aerodynamic derivatives can be expressed with unsteady pressure characteristics on the surface of the deck, since the total lift and moment are the results of integration of surface pressure along the width. One advantage of using pressure as variable for aerodynamic derivatives is that physical phenomena regarding the instability can be explained more clearly. For symmetric section, aerodynamic derivatives can be calculated by:

$$H_1^* = \frac{1}{2k_1^2 \eta_0} \int_{-1}^{1} \bar{C}_p(x^*) \cos(\psi(x^*)) \, dx^*$$  (1a)
$$H_2^* = -\frac{1}{2k_1^2 \eta_0} \int_{-1}^{1} \bar{C}_p(x^*) \sin(\psi(x^*)) \, dx^*$$  (1b)
$$A_1^* = -\frac{U}{2k_1^2 \eta_0} \int_{-1}^{1} x^* \bar{C}_p(x^*) \cos(\psi(x^*)) \, dx^*$$  (1c)
$$A_2^* = -\frac{U}{2k_1^2 \eta_0} \int_{-1}^{1} x^* \bar{C}_p(x^*) \sin(\psi(x^*)) \, dx^*$$  (1d)

Where $U$= wind velocity [m/s], $k$= b/0.8U (reduced frequency [rad/s]), $\omega_0$= frequency of heaving [Hz], $\omega_0$= frequency of pitch [Hz], $\eta_0$= amplitude of heaving [m], $\varphi_0$= amplitude of pitching [rad].

$\bar{C}_p(x^*)$ and $\psi(x^*)$ diagram for basic section, rectangular prism with B/D=20, are presented in Fig. 1. It can be seen that maximum pressure occurred near leading edge, and contribute predominantly to the value of aerodynamic derivatives. This is also related with the occurrence of separation bubble. Therefore, it is logical that manipulation of pressure in this zone will change the aerodynamic derivatives values significantly. Based on this condition, the introduction of narrow slot in this zone is expected to be able to change the flow and manipulate $\bar{C}_p(x^*)$ and $\psi(x^*)$ to produce more stable deck section.
3. WIND TUNNEL TESTS AND ANALYSIS

In order to study the effects of double slot, 15 models with variation position and width of slot are studied in wind tunnel tests. Forced vibration tests were conducted for each model, both heaving and torsional motion with frequency 2 Hz, \( \eta_0 = 1 \) cm and \( \phi_0 = 2 \) deg.

Results show that almost all of the model have positive \( A_2^* \) value even at low reduced velocity. Only model 4A has negative \( A_2^* \). Model 1B, 2B, 4A and 6 have very low value of \( A_1^* \). The values of \( H_3^* \) are not affected significantly with slot. From flutter onset velocity calculation, model 4A, which has very low \( A_1^* \) and negative \( A_2^* \) is the most stable section (no flutter occurred up to wind velocity 30 m/s, while basic section model F has flutter onset velocity around 10 m/s, with data : \( B=0.3 \) m, \( m=2.42 \) kg/m, \( I=0.0181 \) kg.m\(^2\)/m, \( f_\eta=4.0 \) Hz, \( f_\phi=5.2 \) Hz, \( f_\phi/f_\eta = 1.3 \)). But its relatively wide slot is considered not economically favorable to be applied for real bridge deck structure. More attention is given to model 1B, which has narrow width slot, very low \( A_1^* \) but positive \( A_2^* \).

From \( \tilde{C}_p \) and \( \psi \) data, time history of pressure distribution during one cycle of motion can be evaluated. Low absolute value of \( A_1^* \) means low moment induced by heaving motion.

4. CONCLUSION

Double slot has the potential to be an effective countermeasure for slender bridge deck against coupled flutter. But its effectiveness is very sensitive to position and width of the slot. Optimum configuration which produces very stable section is possible, but require relatively wide slot. Therefore, next step is combining double slot with other countermeasures to ensure value of \( A_2^* \) always negative.

REFERENCES
