The Effects of Turbulence on the Aerodynamics of Oscillating Prisms

Fred L. Haan, Jr [a], Ahsan Kareem [b]

[a]*Iowa State University, Ames, Iowa, USA*
[b]*University of Notre Dame, Notre Dame, Indiana, USA*

ABSTRACT: This experimental study, focusing on the effects of turbulence on long-span bridge aerodynamics, examined the anatomy of turbulence effects on the self-excited forces responsible for flutter and the spanwise correlation of the overall aerodynamic lift and moment. This examination was conducted by measuring pressure distributions around an oscillating prism. A forced-vibration system was used with a model of rectangular cross section instrumented with 64 pressure transducers. Spanwise coherence measurements were made on both stationary and oscillating models in a series of smooth and turbulent flows. Unsteady pressure distributions were examined to observe turbulence-induced changes in the self-excited forces. This allowed a clearer understanding of turbulence effects than was possible by observing only integrated quantities such as flutter derivatives.

KEYWORDS: turbulence; bridge aerodynamics

1 INTRODUCTION

The role of turbulence in the aerodynamics of stationary bluff bodies has been extensively documented in the literature. Studies have shown that the flow about bluff bodies is governed by the separation and reattachment of the shear layers and by vortex shedding. The shear-layer thickness and the body size are length scales associated with these two phenomena, respectively. Turbulent eddies on the order of these scales are most effective at altering flow structure. The main effect of small-scale turbulence is to cause earlier reattachment of the flow through enhanced mixing in the shear layers. Turbulence in the range of the body scale can enhance or weaken vortex shedding depending on the body geometry.

While most of the work has been done for stationary prisms, work related to oscillating prisms is rather elusive. Experimental studies focusing on the effects of turbulence on bridge aerodynamics have typically noted an increase of critical wind velocity with added turbulence. However, several studies have reported destabilizing trends associated with turbulence (e.g., Huston, 1986). The cause of these disagreements remains to be conclusively determined and signifies the limitations in current understanding of the problem (e.g., Scanlan, 1997).

More recent studies investigating the effects of turbulence on rectangular sections have focused on both stationary and/or oscillating prisms with applications to improved understanding of building and bridge aerodynamics to turbulence (e.g., Haan 2000, Cheung and Melbourne, 2005). These studies investigated the distribution of pressure around the prism in both chordwise and spanwise directions including their correlations and, in bridge related studies, the correlation of the pressure field in comparison with that of the upstream turbulence. This paper presents observations and findings of a recent study (Haan, 2000) which brings out some useful observations and important ramifications for the current state of the art of aerodynamic analysis of long span bridges.

2 EXPERIMENTAL

This study was conducted at the NatHaz Modeling Laboratory, utilizing grid generated turbulence to study the effects of both turbulence intensity and turbulence scale on aerodynamic forces. Turbulent flows were generated using conventional biplane, square-mesh grids. The suite of inflow conditions included flows with turbulence intensities of 6 and 12 percent, with two length scales at each intensity. Flows with 6% turbulence intensity are referred to as Case 6a and Case 6b, where the "a" case had a turbulence integral scale, L_{ux}, of approximately 1.8*D* and the "b" case had a scale of 4.9*D*. The "a" and "b" cases of the 12% flows had scales of 1.3*D* and 4.9*D*, respectively. The model had a depth of 38mm, streamwise dimension of 254mm, and a span of 1.07m. A picture of the model set up in the motion driving mechanism and a closer view of the model surface with pressure taps and the associated embedded transducers are shown in Fig. 1. Sixty-four pressure transducers were utilized to measure the pressures distributions about the model and their integral effects for stationary and oscillation cases. The data were statistically analyzed to derive space-time correlations of the pressure field and the associated aerodynamic forces.

Figure 1: Model with motion driving mechanism and close-up of pressure tap installation.

3 RESULTS AND DISCUSSION

By examining the unsteady pressure distributions over the bridge model rather than the flutter derivatives alone, a clearer understanding of how turbulence affects the unsteady forces was obtained. Both increasing turbulence intensity and increasing turbulence scale decreased the amplitudes of self-excited pressure fluctuations. As shown in Figure 2, the basic shape of the chordwise distributions of pressure amplitude was a single hump shape. This shape shifted upstream with increasing intensity of the free stream turbulence, and amplitudes increased somewhat with increasing turbulence scale.

Phase values of the self-excited pressure (with respect to the body motion) were found to have several regimes in the streamwise direction. Figure 3 shows phase plots for the smaller scale turbulent flows and a reduced velocity of 20. Near the leading edge, phase was nearly constant. Downstream of this locale was a region where phase increased more rapidly. Beyond this rapidly increasing phase zone was a region where the phase values leveled off and even decreased in some cases. While scale had little discernible effect on these phase values, turbulence intensity tended to shift the region of rapidly increasing phase toward the leading edge.

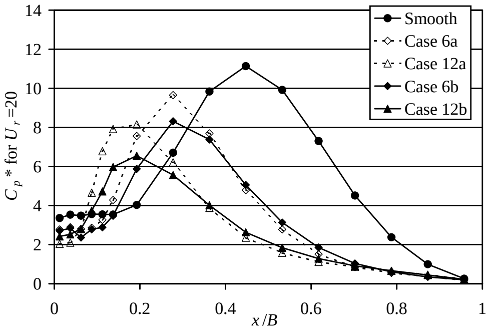


Figure 2 Pressure amplitude distributions for a reduced velocity of 20.

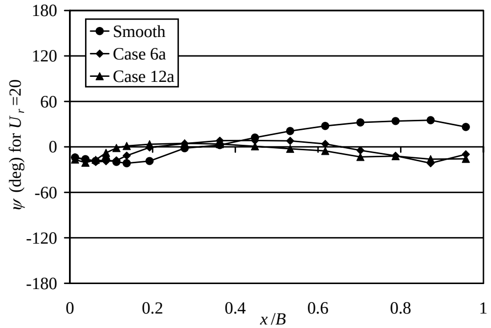


Figure 3 Pressure phase distributions in smooth flow and small-scale turbulent flows at a reduced velocity of 20.

Turbulence was observed to have a stabilizing effect on the flutter derivatives, most obviously with A_2^* as shown in Figure 4. An expression relating the amplitude and phase distributions shown above to A_2^* can be shown to be:

$$A_2^* = \frac{1}{8K^2}\int_{-1}^{1} x^* 2C_p^*(x^*)\sin\psi(x^*)dx^* \tag{1}$$

where $x^* = x/(B/2)$ is the streamwise position ($x^* = 0$ corresponds here to midchord), B is the streamwise dimension of the model (the "deck width"), and $K = \omega B/U$ is the reduced frequency. The relationship of equation (1) can be used to relate the turbulence-induced shifts in the pressure amplitude and phase distributions to the changes in A_2^*. By tracking the integrand, specific changes in pressure amplitude and phase were linked to flutter derivative modifications. The integrand of equation (1) is plotted in Figure 5. Values of the integrand within the shaded regions on the plot contribute to a positive (destabilizing) value for A_2^*. Turbulence effects in this case tended to shift the integrand out of both of the shaded regions.

In addition, this upstream shifting in the unsteady pressure on the oscillating models was found to be similar to the behavior observed in distributions of fluctuating pressure over stationary models. This suggests that the large amount of research done in bluff body aerodynamics on stationary bodies may aid in the understanding of oscillating body problems as well.

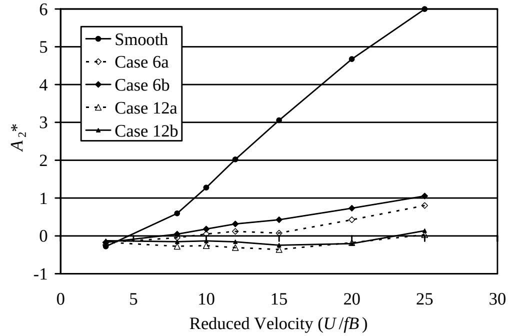


Figure 4 Flutter derivative A_2^* in smooth and turbulent flow.

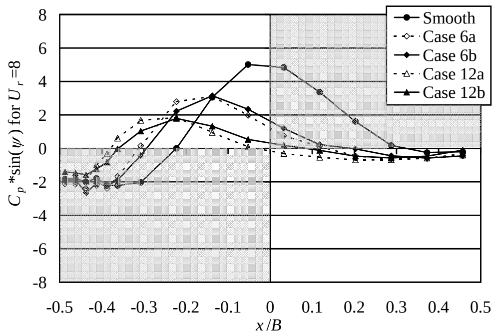


Figure 5 $C_p^*(x)\sin(\psi(x))$ plotted versus streamwise position for all flow cases at $U_r = 8$.

Prior to this study, no experimental study had justified the conventional assumption (often used in long-span bridge analysis) that aerodynamic forces could be decomposed into flutter and buffeting components and analyzed independently. Pressure measurements made on oscillating models allowed experimental assessment of this assumption. Overall, the assumption is quite close. Examination of the lift and moment spectra showed close agreement in the broad band throughout the frequency range considered. Figure 6 shows example moment spectra for the 6% turbulence intensity cases and reduced velocity of 20. Where the stationary and oscillating model spectra did not agree, the oscillating model values were typically larger. This oscillation-induced increase in the broad band energy occurred mainly for frequencies above $fD/U = 0.1$ although some differences were observed for lower frequencies as well.

Quantitative analysis of these differences showed that oscillating model buffeting forces could have RMS values as much as 10% higher than their stationary model counterparts. This difference decreased for increased turbulence intensity and increased turbulence scale. For the flow with the highest intensity and scale considered, these differences were only around 2-3%. Observation of the streamwise distribution of such differences revealed that the location of oscillation-induced increase in broad band energy was upstream of reattachment (typically this means upstream of the location of the maximum RMS pressure value). This implies that bodies which experience separation over smaller portions of their surface may exhibit less significant differences between stationary and oscillating model buffeting levels.

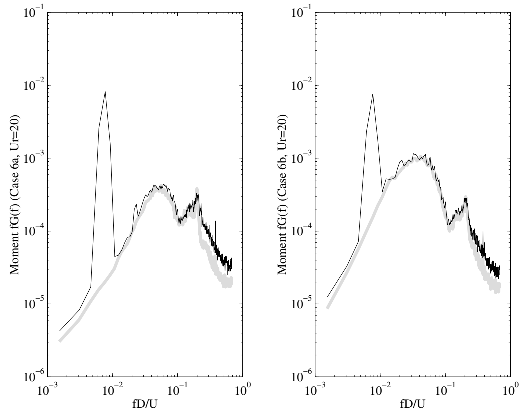


Figure 6 Moment spectra for $I_u = 6\%$ for both stationary and $U_r = 20$ tests (stationary results shaded).

A decomposition of flutter and buffeting components was utilized for examining the spanwise correlation of aerodynamic forces on the cross section. Figure 7a shows the separation of self-excited and buffeting components (i.e. the remaining broad-band components) of lift force. Correlation and coherence calculations were performed on each of these components separately. Figure 7b shows an example case for correlation of lift force at a separation distance of 1.2B and reduced wind velocity of 20. The cross-correlation function of the total lifting force signals is shown on the left and correlation functions of the decomposed components are shown on the right. The self excited components are far more highly correlated than the broad band buffeting components. Figures 8 and 9 show the correlation values for broad band and self-excited forces, respectively. As has been observed by numerous past researchers, the broad band force correlations are significantly higher than the correlation of the incident turbulent flow.

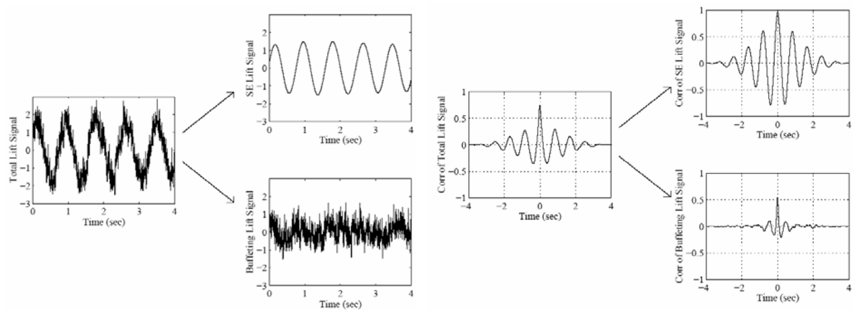
Haan (2000) provides detailed results of the correlation for a wide range of configurations. A key observation from this exercise was that the correlation structure for the broad band buffeting components is essentially the same as that for the stationary prisms. Correlation values for buffeting forces increased with increasing turbulence scale for both oscillating and stationary models. Self-excited force correlations were found to be very high (values of 0.96 or above) for every incident flow, every reduced velocity, and nearly every separation. Only in two cases of $\Delta y = 2.4B$ did the correlation value get below 0.96 to a value of 0.90. One consistent observation was that larger turbulence scales resulted in lower self-excited force correlation values.

The plots of Figure 10 show trends in the total lift correlation values on the oscillating models (for reduced velocity of 20). The trends showed lower spanwise correlation for greater turbulence intensity and for larger turbulence integral scale. These trends reflect what was observed for the self-excited force correlations (and not what was observed for buffeting force correlations) and may reflect the fact that the self-excited force components dominate the overall force in these experiments.

Spanwise force correlation measurements on dynamic models were also made by Cheung and Melbourne (2005) on a full-bridge model in a boundary layer wind tunnel. They concluded that the spanwise correlations exhibited strong dependency on turbulence and leading edge vortex separation. Their results showed an increase in spanwise correlation with increasing turbulence intensity (and decreasing turbulence scale). The different trends between the current results and these may be due to the difference in model oscillation amplitude. In the current results, the self-excited forces have a rather dominant role in the overall forces. It is possible that the organizing effects of the separated and reattaching shear layers *when driven by the body motion* resist perturbations by small turbulence scales. It is possible that larger, more energetic turbulent velocity fluctuations are required to reduce spanwise correlations such self-excited forces. This may explain why the broad band forces behave as expected with respect to turbulence length scale (in general good agreement with stationary prism studies such as Larose (2003) and Matsumoto et al. (2003)) but the self-excited forces exhibit a different trend.

Force coherence was also considered. In both coherence and correlation calculations of self-excited force components, the self-excited forces were found to have near unity coherence over the entire spanwise separation range considered. It was noted that cases with larger turbulence length scale showed a slightly lower correlation than those of smaller scales, the estimated 95% confidence intervals of ± 0.03 puts all results within the statistical spread of the others suggesting no influence of length scale. The conventional assumption of self-excited forces being fully correlated in the spanwise direction was thus partially supported by the results of this study. Of course, this also means that the often-suggested hypothesis that a decrease in spanwise correlation of the self-excited forces causes the turbulence-induced increase in the critical flutter velocity was not supported by the current results. A conclusive investigation of self-excited force coherence would requires much longer span lengths to observe whether appreciable changes occur for longer spanwise separations.

Coherence calculations also showed that the broad band coherence of the oscillating model matched that of the stationary model to within the uncertainty of the experiment. This supports current analytical practice as well. Extracting the buffeting components of the oscillating model forces for calculation of buffeting correlation on oscillating models also showed close matches between stationary and oscillating model results.



(a) (b)

Figure 7: For turbulence case 12b, a reduced velocity of 20 and a spanwise separation of 1.2*B*: (a) Separation of self-excited and buffeting components of the lift force and (b) an example case for correlation of the lift force.

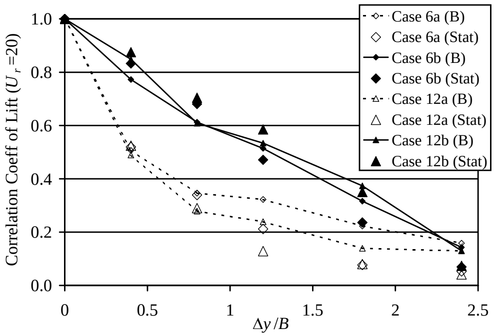


Figure 8 Cross correlation coefficients ($\tau = 0$) of stationary model lift (Stat) and of the buffeting components (B) of lift with the model oscillating at $U_r = 20$.

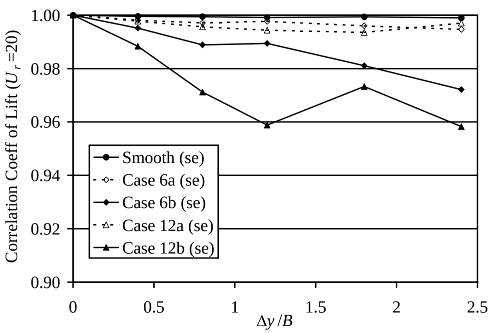


Figure 9 Cross correlation coefficients ($\tau = 0$) of the self-excited components (se) of lift with the model oscillating at $U_r = 20$.

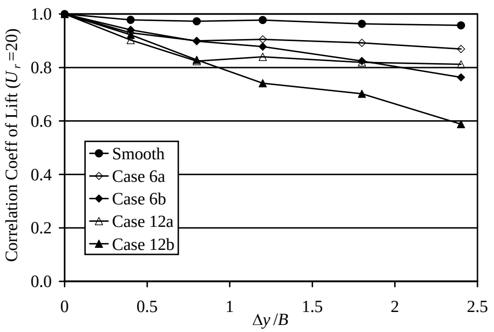


Figure 10 Cross correlation coefficients ($\tau = 0$) for total lift with the model oscillating at $U_r = 20$.

4 CONCLUDING REMARKS

For the cross section studied, turbulence stabilized the self-excited forces. Regions of maximum pressure amplitudes were observed to shift toward the leading edge with increasing turbulence intensity, similar to the behavior observed in pressure distributions on stationary bodies. This upstream shifting was responsible for the bulk of the changes in the overall stability characteristics. Spanwise correlation was quantified for both total aerodynamic forces and for self-excited and buffeting components separately. Self-excited forces showed essentially unity coherence for the entire spanwise separation range studied (2.4B). This supports the assumption common in analytical estimates of fully correlated self-excited forces. However, it does not support the hypothesis that the stabilizing effect of turbulence observed in full aeroelastic tests is due to a turbulence-induced decrease in the spanwise coherence of the self-excited forces. In the future, greater spanwise separations need to be tested for full understanding of this behavior. Spanwise correlation of the buffeting force components showed exceptional similarity between stationary and oscillating model tests.

5 ACKNOWLEDGEMENTS

The authors acknowledge the support provided in part by NSF Grants CMS 0324331 and CMS 0239070.

6 REFERENCES

1 J.C.K. Cheung, W.H. Melbourne, Spanwise deck sectional force correlation of bridge in motion in turbulent flow, *Proc. of Sixth Asia-Pacific Conf. on Wind Eng.*, Seoul, Korea (2005).
2 F.L. Haan, The effects of turbulence on the aerodynamics of long-span bridges, University of Notre Dame Dissertation (2000).
3 D.R. Huston, The effects of upstream gusting on the aeroelastic behavior of long suspended-span bridges, Princeton University Dissertation (1986).
4 G.L. Larose, "The spatial distribution of unsteady loading due to gusts on bridge decks," *Journal of Wind Engineering and Industrial Aerodynamics*, v. 91 (2003) 1431-1443.
5 M. Matsumoto, H. Shirato, K. Araki, T. Haramura, T. Hashimoto, "Spanwise coherence characteristics of surface pressure field on 2-D bluff bodies," *Journal of Wind Engineering and Industrial Aerodynamics*, v. 91 (2003) 155-163.
6 R.H. Scanlan, Amplitude and turbulence effects on bridge flutter derivatives, *Journal of Structural Engineering*, 123 (1997) 232-236.