United States - Japan Benchmark Study of Flutter Derivatives of Selected Bridge Decks

by

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ABSTRACT

The motivation for this work emerged from the U.S.-Japan Benchmark Study on Bridge Flutter Derivatives that was initiated in 2002. Aeroelastic coefficients (flutter derivatives) of bridge decks are routinely extracted from wind tunnel section model experiments for the assessment of their performance to wind loading. Two distinct methods, developed over the years, are usually employed for this purpose (free or forced vibration). Even though advantages and disadvantages of each technique are known, few examples of a systematic comparison of laboratory techniques exist in the literature. This paper focuses on the systematic comparison of the experimental results obtained via the two methods at two distinct laboratories (ISU and PWRI) and within the same laboratory (ISU) and provides interpretation of this comparison for cross sections ranging from bluff (rectangular prisms) to streamlined. Other data sets derived from previous experiments on rectangular cross sections, performed in Japan and available in the literature, were employed for the interpretation of the data. It was concluded that while the trends of the various data sets for the bluff cross section were very similar, there were some differences that could be possibly associated with the effects of amplitude dependency. The data sets for the streamlined sections compared very well showing lesser dependency on technique used or initial amplitude.

KEYWORDS: bridge aerodynamics, free and forced vibration, bridge flutter-derivative benchmark study, aeroelasticity of long-span bridges.

1.0 INTRODUCTION

Aeroelastic coefficients (i.e., flutter derivatives) of bridge decks are routinely extracted from wind tunnel section model experiments for the assessment of the bridge performance to wind loading. Two distinct methods are usually employed for this purpose: free or forced vibration methods. Information on each method can be found, for example, in (Sarkar et al., 1992) and in (Matsumoto, 1996), respectively. Even though advantages and disadvantages of each technique have been highlighted by numerous researchers, few examples of systematic comparison of the experimental results are available in the literature. This paper summarizes the latest results of the research that was conducted within the framework of the United States–Japan benchmark study on bridge flutter derivatives. This research was initiated by Iowa State University (ISU) in the US and the Public Works Research Institute (PWRI) in Japan in 2002. At a later stage, Northeastern University in the US joined the investigation. Some of the results presented in this paper...
complement those presented at the 39th meeting of the UJNR Panel on Wind and Seismic Effects (Sarkar et al., 2007).

The significance of this study is associated with the systematic comparison of a comprehensive set of experimental data on flutter derivatives for bridge decks of various cross sections as measured in different laboratories using two distinct methods – free and forced vibration.

Aeroelastic characteristics of both streamlined and bluff deck sections were investigated. The PWRI data used here for comparison were taken from a past study conducted by Sato et al. (2004). In addition, data published in the literature (Matsumoto, 1996; Matsumoto et al., 1996; Washizu et al., 1978; Washizu et al., 1980), and those recently made available to the co-authors of this study (Matsumoto, 2007) were used for comparison.

Active collaboration between the US and Japanese researchers led to this benchmark study which includes comparison of flutter derivatives and a discussion on the implications of the differences found between the data sets on the estimated aeroelastic response of long-span bridges. This comprehensive study is described in detail in Sarkar et al. (2008).

2.0 DESCRIPTION OF MODELS AND EXPERIMENTS

In the proposed study, five bridge cross sections were selected for investigation: (1) Rectangle \( B/D = 2:1 \) aspect ratio, with \( B \) width, \( D \) depth of the model, (2) \( \Pi \)-section (or edge girder section), (3) Streamlined Box Girder (labeled as “B2”), (4) Slotted Box Girder (labeled as “B3”), and (5) Original Tacoma Narrows. More information on the cross sections can be found in previous studies (Sarkar et al., 2007; Sarkar et al., 2006). Later, one additional cross section (rectangle with \( B/D = 5:1 \) was added to this list for investigation.

In this study, experimental data derived from the tests conducted at ISU and PWRI during 2002 to 2007 are presented. In particular, the results from experiments conducted in the Summer 2007 at ISU are included for comparison with previous data (Sarkar et al., 2007).

Figures 1 and 2 show the cross sections that were considered in this study. Dimensions of the models, tested at ISU, are also given. In particular, the cases discussed in this study are:

- “B2” streamlined cross section with triangular-type fairings (Figure 1) with aspect ratio \( B/D = 17:1 \);
- “B3” streamlined cross section with central slot, derived from B2 (Figure 1);
- “R2_1” rectangular cross section with aspect ratio \( B/D = 2:1 \) (Figure 2);
- “R5_1” rectangular cross section with aspect ratio \( B/D = 5:1 \) (Figure 2).

Each model had a span of 0.533 m. Two Plexiglas end plates were used to reduce aerodynamic end effects for all models.

All tests at ISU were conducted in the Bill James Wind Tunnel (see Figure 3), which is a low-speed open-circuit facility located in the Wind Simulation and Testing Laboratory (WiST). The Bill James Wind Tunnel has a 0.91m by 0.76m test section and a wind speed capacity of 80m/s. The ISU experimental rig employed in the forced vibration tests is also shown in Figure 3. For description of the operation of this rig, the reader is referred to previous work by Haan (2000).

The 2007 experiments at ISU used the free-vibration technique for the extraction of flutter derivatives. For description of the free-vibration test set-up and apparatus the reader is referred to Sarkar et al. (2007).

3.0 EXPERIMENTAL EXTRACTION OF FLUTTER DERIVATIVES

This section summarizes the main aspects associated with the extraction of flutter derivatives from section model tests.

The formulation of aeroelastic forces employed in the study (lift and moment per unit length of the deck model, Figure 1) is:
where $B$ is the bridge deck width, $U$ is the mean wind velocity, $\rho$ is the air density, $h$ (defined as positive downward) and $\alpha$ represent heaving and pitching motion components and $\dot{h}, \dot{\alpha}$ are time derivatives. Flutter derivatives $H_1^*$ and $A_2^*$ are a function of the reduced frequency $K = \omega B/U$ where $\omega = 2\pi n$ is the circular frequency of vibration of the model (rad/sec) and is proportional to the reciprocal of the reduced velocity $U_r = U/nB = 2\pi/K$. Lateral force component (drag) was not considered.

In the free vibration method, a rigid section model, supported by a set of springs, is allowed to vibrate freely in the wind tunnel. From the comparison of free-decay time response of the model displacement, with and without wind, the flutter derivatives can be extracted. The Iterative Least Squares (ILS) method (Chowdhury and Sarkar, 2003) was used to find the flutter derivatives at ISU. The lateral degree of freedom and drag force can be easily included in the analysis, if needed, because the method allows the derivation of all eighteen flutter derivatives associated with three degrees of freedom (DOF). One or two DOF can be considered at a time, by appropriately restraining the section model (either the $h$ or $\alpha$ component or both as in Figure 1). It is recommended to perform three different sets of two-DOF testing, namely, vertical-torsional, vertical-lateral, and lateral-torsional, instead of three-DOF testing for accurate extraction of all the derivatives (Chowdhury and Sarkar, 2003).

In the forced vibration method (Haan, 2000; Matsumoto, 1996), the model is driven by a motor in a prescribed sinusoidal motion with given constant amplitude, indicated as $h_0$ or $\alpha_0$. For example, if the prescribed motion through the rig (Figure 3) is torsional and $\alpha(t) = \alpha_0 \cos \omega_0 t$ (with $t$ time and $\omega_0$, circular frequency of vibration), aerodynamic lift and moment forces can be calculated, for example, by integrating the surface pressures on the model. Forces can be expressed as (Figure 1):

\[
L^*_{sw} = \frac{1}{2} \rho U^2 B \left[ \frac{KH_1^* \dot{h}}{U} + \frac{KH_2^* B \dot{\alpha}}{U} \right] + K^2 H_3^* \alpha \left( \frac{\dot{h}}{B} \right),
\]

\[
M^*_{sw} = \frac{1}{2} \rho U^2 B^2 \left[ \frac{KA_1^* \dot{h}}{U} + \frac{KA_2^* B \dot{\alpha}}{U} \right] + K^2 A_4^* \alpha \left( \frac{\dot{h}}{B} \right),
\]

where $L_0$ and $M_0$ are the amplitudes of the fluctuating lift and moment, respectively. The quantities $\phi_L$ and $\phi_M$ are the phase lags of the lift and moment coefficients with respect to the angular position, $\alpha(t)$, respectively.

From Eqs. (2a) and (2b), the flutter derivatives related to the torsional, i.e., pitching motion are:

\[
H_2^* = \frac{-L_0}{\alpha_0} \sin \phi_L, \quad H_3^* = \frac{L_0}{\alpha_0} \frac{qBK^2}{qBK^2},
\]

\[
A_2^* = \frac{-M_0}{\alpha_0} \sin \phi_M, \quad A_4^* = \frac{M_0}{\alpha_0} \frac{qBK^2}{qBK^2}.
\]

Similar expressions can be derived in the case of heaving motion.

4.0 FORCE COEFFICIENTS ADOPTED BY WASHIZU ET AL. (1978) IN RELATION TO FLUTTER DERIVATIVES

An alternative formulation of aerodynamic forces (Washizu et al., 1978; Washizu et al., 1980) for single-DOF forced-vibration measurements is reviewed in this sub-section because experimental data from these studies were also employed in the current comparisons. Unsteady coefficients associated with this formulation can be related to $H_1^*$, $H_4^*$ for lift and $A_2^*$, $A_3^*$ for moment.

For example, lift per unit length ($L_{sw}$, positive upward, Figure 1) can be defined in terms of unsteady coefficients ($C_{L_{sw}}$) in frequency domain as either an in-phase or an out-of-phase
component with respect to the vertical displacement \( y(t) = \text{Re}[y_0 e^{i \omega t}] \) (Figure 1) at circular frequency \( \omega_{m,y} = 2\pi n_{m,y} \) and constant amplitude \( y_0 \) (Washizu et al., 1978) as

\[
P_m^w(t) = \frac{1}{2} \rho U^2 B \text{Re} \left[ C_{LmR}(U_{r,y}) e^{i \omega_{m,y} t} \right] + i C_{LmR}(U_{r,y}) e^{i \omega_{m,y} t} \right]. \tag{4}
\]

In Eq. (4) \( i = \sqrt{-1} \) and \( \text{Re}[\cdot] \) is the real part of a complex number. The dimensionless quantities \( C_{LmR} \) and \( C_{Lml} \) are experimentally recorded at different velocities \( U \), i.e., represented as a function of \( U_{r,y} = U/(n_{m,y} D) \). If \( y(t) = y_0 e^{i \omega_{m,y} t} = -h(t) \) is inserted into Eq. (1a) and the real part only is retained, the definition of lift in accordance with Eq. (1a) as a function of lift in \( \text{Re} \left[ \frac{\text{H}_t^1(U_{r,y}) e^{i \omega_{m,y} t} + i H_1^1(U_{r,y}) e^{i \omega_{m,y} t}}{B} \right] \text{Re} \left[ \frac{C_{LmR}(U_{r,y}) e^{i \omega_{m,y} t} + i C_{LmR}(U_{r,y}) e^{i \omega_{m,y} t}}{B} \right] \right] \]. \tag{5}

From the comparison between Eqs. (5) and (6), the conversion between \( C_{LmR}, C_{Lml} \) and \( H_1^*, H_4^* \) turns out to be

\[
H_1^* = \frac{C_{LmR}(U_{r,y}) B}{K^2 y_0^*}, \quad H_4^* = \frac{C_{LmR}(U_{r,y}) B}{K^2 y_0^*}, \tag{6a, 6b}
\]

with \( K = 2\pi U_{r,y} \). Similarly, unsteady aerodynamic moment per unit length, \( M_m^w \), for one-DOF forced-vibration (Figure 1) with \( \alpha(t) = \text{Re}[\alpha e^{i \omega_{m,\alpha} t}] \) is given in terms of two dimensionless coefficients as a function of \( U_{r,\alpha} = U/(n_{m,\alpha} D) \) (Washizu et al., 1980) as

\[
M_m^w(t) = \frac{1}{2} \rho U^2 B^2 \text{Re} \left[ C_{MlR}(U_{r,\alpha}) e^{i \omega_{r,\alpha} t} \right] + i C_{MlR}(U_{r,\alpha}) e^{i \omega_{r,\alpha} t} \right]. \tag{7}
\]

The comparison of Eq. (7) with Eq. (1b) yields the relation between \( C_{MlR}, C_{Ml} \) and \( A_2^*, A_5^* \), i.e.,

\[
A_2^* = \frac{C_{MlR}(U_{r,\alpha})}{K^2 \alpha_0^*}, \quad A_5^* = \frac{C_{MlR}(U_{r,\alpha})}{K^2 \alpha_0^*}. \tag{8a, 8b}
\]

5.0 ERROR ANALYSIS OF FLUTTER DERIVATIVES

The error in the flutter derivatives extracted through free vibration technique depends on a number of parameters including but not limited to the number of degrees of freedom, upstream turbulence, type of bridge section, sampling rate and sampling time, instrumentation and the system identification method used. Numerical simulation shows that the ILS method (Chowdhury and Sarkar, 2003), as used here, usually produces a maximum error of 1.7% for one-DOF tests and 5% for two-DOF tests for the damping-related indirect flutter derivatives \( (H_2^*, A_1^*) \) and 0.02% for one-DOF tests and 1% for two-DOF tests for the stiffness-related indirect flutter derivatives \( (H_3^*, A_4^*) \) corresponding to 20% noise-to-signal ratio. The uncertainty in the direct flutter derivatives in two-DOF tests \( (H_1^*, H_4^*, A_2^*, A_5^*) \) was shown to be almost half of these errors for the same level of noise-to-signal ratio. The robustness of the system identification method plays an important role in minimizing the errors but irrespective of the method used as the number of DOF and the noise levels in the recorded time histories increase the errors in the flutter derivatives will increase. The noise level is expected to be higher for bluff sections compared to the streamlined sections as a result of turbulence produced by the body itself.

The error in the flutter derivative, derived through the forced vibration method, was discussed in a recent study (Sarkar et al., 2008). The measurements of the phase angles between the model motion and the self-excited forces (e.g., \( \phi_L \) and \( \phi_p \) in Eqs. 3a and 3b), play a major role in the final value of the aeroelastic coefficients. These angles are derived from the lift and moment time histories by integration of the pressures on the surface of the model (Haan, 2000).

Three contributions to phase angle uncertainty were identified in the ISU apparatus. First, there are effects of the flexible tubing that connects the pressure taps to the pressure scanner/sensors
which are responsible for phase and magnitude distortion of the pressure signals. The errors are usually estimated as +/-0.5 degrees.

A second contribution arises from the finite sampling rate of the pressure scanner. The time delay, from which a phase angle error can be computed and associated with this effect, was estimated as \(1/n_{SS}\), where \(n_{ss}\) is the sampling rate of the pressure scanner (430 Hz at ISU). The phase error \(\phi_e\) is usually derived from the time delay \(\tau_e\) as 
\[
\phi_e = 360n\tau_e,
\]
with \(n\) as the frequency of oscillation of the model.

The third contribution originates from the non-simultaneous sampling of the pressure sensors, i.e., a skew in time between one sensor sample and the next one. A conservative upper-bound of the time delay can be estimated as the inverse of the inter-channel rate of the pressure scanner (i.e., the ratio between the scan rate of the multiplexer, 50,000 Hz) and the total number of pressure channels (64) specified for the pressure transducer at ISU.

### 6.0 RECENT COMPARISONS BETWEEN ISU AND PWRI DATA

#### 6.1. Streamlined cross sections B2 and B3

In this sub-section, the results of recent comparisons associated with the ISU and PWRI experimental data of streamlined box girders are reported. The cross sections for the streamlined box girder deck (B2) and streamlined slotted box-girder deck (B3), as shown in Figure 1, were considered. Analyses included the evaluation of the two flutter-derivative extraction techniques: ISU free-vibration method and PWRI forced-vibration method. This latest comparison was intended to complement the preliminary investigation (Sarkar et al., 2006).

The B2 and B3 flutter derivatives are depicted in Figures 4 and 5, respectively. All the flutter derivatives except \(A_1^*, A_3^*, A_4^*, H_3^*, H_4^*\) for B2 and \(A_1^*, A_2^*\) for B3 have slight differences but well within the error bounds that were previously estimated. The difference might have resulted, in part, because of the difference in the amplitudes of oscillation between ISU and PWRI. Normalized amplitudes of vibration employed at ISU were \(h_0/B=0.05\) for heaving motion and \(a_0=0.049\) rad for pitching motion, whereas those used at PWRI were \(h_0/B=0.01\) and \(a_0=0.017\) rad.

It was found that generally the flutter derivatives associated with moment for the slotted box girder (Figures 5c and 5d) were of smaller magnitudes than those of the solid box girder (Figures 4c and 4d). The difference can be attributed to the slot in the cross section that reduces the moment originating from heaving and torsional motions. Good comparison was observed between the ISU and PWRI data sets, especially for \(A_1^*\) and \(A_2^*\) (Figures 4c and 5c).

#### 6.2. Rectangular cross sections R2_1 and R5_1 prisms (vertical DOF)

Figure 6 show the analysis of flutter derivatives \(H_1^*\) (a) and \(H_4\) (b) for the R2_1 deck model. The main purpose of this study was the analysis and comparison between the one-DOF (vertical) free-vibration tests conducted at ISU and forced-vibration experiments at PWRI. The data sets from ISU include the dependence on \(h_0\). For the R2_1 section, ISU amplitudes normalized with deck width varied from \(h_0/B=0.07\) (9 mm) to \(h_0/B=0.20\) (large amplitude, 26 mm). Amplitudes employed at PWRI were much lower than ISU with \(h_0/B = 0.01\). Comparison with published results, reproduced from the literature, is also included (Matsumoto, 1996; Matsumoto, 2007; Washizu et al., 1978). In the figures different symbols and line types are used to highlight distinct sets.

The higher values of \(h_0/B\) adopted for the ISU tests are possibly larger than the expected levels of oscillations in full-scale bridges, and were chosen purely for academic interest assuming that these amplitudes may be observed in the vicinity of the flutter speed.

The actual values of the heaving-motion amplitudes employed by Matsumoto (1996) for the rectangular sections with \(B/D = 2\) and 5 was 5 mm \((h_0/B=0.05)\), while the prescribed amplitudes...
reported by Washizu et al. (1978) on the $B/D = 2$ model varied between 2 mm and 20 mm ($B=200$ m). The latter correspond to a normalized amplitude $h_0/B$ between 0.01 and 0.10.

The analysis of the ISU sets in Figure 6(a) for R2_1 reveals evident dependence on the initial amplitude for the $H_1^\ast$ curve. In particular, in Figure 6(a) and for large amplitude $h_0/B=0.20$ (26 mm) the negative magnitudes of $H_1^\ast$ decreased in comparison with the other two ISU cases. The general trend of the $H_1^\ast$ graphs show a shift towards lower $U_r=U/(nB)$ at the zero crossing point with decreasing amplitudes. Matsumoto’s forced-vibration data with a corresponding normalized amplitude $h_0/B=0.05$ are consistent with the ISU results for $h_0/B=0.07$ with respect to both the trend and the location of the zero crossing of $H_1^\ast$. However, the negative and positive magnitudes of $H_1^\ast$ are greater than the ISU case.

With regards to Figure 6(b) for $H_4^\ast$ values of R2_1, a similar trend was observed in the ISU cases. In particular, the positive peak value of $H_4^\ast$ corresponding to different amplitudes does not change but the curves tend to shift toward lower $U_r$ at zero crossing point for smaller amplitudes, similar to the trend of $H_1^\ast$. The first zero crossing of the ISU $h_0/B=0.07$ case compares well with other investigators (Matsumoto, 1996). The positive peak values of ISU $H_4^\ast$ somehow differs from other experimental records (Matsumoto, 1996). This is consistent with the one observed for $H_1^\ast$ in Figure 6(a).

Differences between ISU and PWRI data are evident from Figures 6(a) and 6(b). Amplitude dependency had been an issue for the experiments by Washizu et al. (1978) for both $H_1^\ast$ and $H_4^\ast$. The largest amplitude in Washizu et al. (1978), $h_0/B=0.10$, was close to the smallest $h_0/B$ amplitude employed at ISU.

In Figure 6, the data set of Washizu et al. (1978) for $h_0/B=0.10$ compared well with ISU data for a similar $h_0/B$ ratio of 0.07, whereas the data set of Washizu et al. (1978) with $h_0/B=0.01$ compared well to the PWRI data at the same $h_0/B$.

In Figures 7(a) and 7(b), the moderately streamlined cross section R5_1, is analyzed for $H_1^\ast$ and $H_4^\ast$, respectively. The comparison is performed between the ISU tests and Matsumoto (1996). No examples were available from PWRI for this $B/D$ ratio. The correspondence between these two sets is good apart from some difference in $H_1^\ast$ at higher reduced velocity. As anticipated, since this cross section is intermediate between a bluff section and a streamlined section, the influence of the initial amplitude on the flutter derivatives is negligible.

6.3. Scruton Number effects on $H_1^\ast$, $H_4^\ast$ derivatives of the R2_1 prism

To further investigate the effects of the testing procedure on flutter derivatives of bluff cross sections, one-DOF free-vibration tests were conducted at ISU at a constant $h_0/B$, where the potential effects of the mass/damping parameter were accounted, especially in the proximity of the zero crossing for $H_1^\ast$ at reduced velocities of 6 to 11 (Figures 6). This range of reduced velocities was in fact associated with the onset of heaving-mode instability.

Figures 8(a) and 8(b) show the $H_1^\ast$ and $H_4^\ast$ derivatives, respectively, for the R2_1 section, derived from free-vibration tests for constant initial amplitudes $h_0/B=0.06$ and variable Scruton number $Sc=m\overline{\zeta}\rho B^2$. The quantity $m$ denotes the mass of the model per unit length, $\zeta$ the structural damping ratio of the experimental apparatus and $\rho$ the air density. The quantity $m$ was varied in the wind tunnel by adding weights to the section model. The damping was measured for each case of added mass and the Scruton number was estimated.

As anticipated, some evidence of $Sc$ dependence was observed during the free-vibration tests at ISU as shown in Figures 8. While the curves are in very good agreement in the interval $0<U_r<6$ corresponding to an aeroelastically stable regime, a general shift of the $H_1^\ast$ and $H_4^\ast$ was observed towards larger $U_r=U/(nB)$ at higher $Sc$. This fact may confirm the presence of nonlinear effects
during the onset of heaving-mode instability for this bluff section.

Larger peak values in the curves, both positive and negative, are observed for larger Sc. The asymptotic behavior at large \( U_r \) is not affected by Sc. This comparison tends to confirm the importance of Sc in addition to the initial amplitude, for the free-vibration method applied to bluff sections.

6.4. Comparison of the aerodynamic moment coefficients for R2_1 and R5_1 prisms

Free-vibration one-DOF experiments in torsion with initial condition \( a_0=0.030 \text{ rad} \) (1.5 deg) were conducted at ISU to identify \( A_2^* \) and \( A_3^* \) derivatives for rectangular prisms R2_1 and R5_1. Figures 9(a) and 9(b) summarize the results of these experiments for R2_1 in comparison with the forced-vibration data derived at PWRI for \( a_0=0.017 \text{ rad} \).

Data sets from literature of other Japanese researchers (Matsumoto, 1996; Washizu et al., 1980) were also used for comparison for amplitude \( a_0 \) compatible with the ISU and PWRI data. As an example, \( a_0=1.9 \text{ deg} \) (0.033 rad) corresponding to Washizu et al. (1980) was included in these analyses.

In relation to \( A_2^* \), a relatively good agreement was found between ISU and PWRI along with the asymptotic behavior at large \( U_r \) for \( B/D = 2:1 \). Some discrepancy is evident with respect to Matsumoto (1996, 2007) at \( U_r=9 \) \( (a_0=0.035 \text{ rad} \), two-DOF tests).

The torsional galloping \( (A_2^* > 0 \text{ as } U_r \to +\infty) \) is only evident from the data in Washizu et al. (1980) in contrast with other derivative sets that do not show the same behavior revealing that \( A_2^* \) behavior at large \( U_r \) seems to be dominated by either initial amplitude or experimental method.

Finally, the experimental comparison is more complicated for \( A_3^* \) in Figure 9(b). Further analyses are required at this stage.

In Figures 10(a) and 10(b) the \( A_2^* \) and \( A_3^* \) flutter derivatives corresponding to \( B/D = 5:1 \) are depicted. Comparison was performed between the ISU one-DOF torsional free-vibration experiments at \( a_0=0.030 \text{ rad} \), and the two-DOF forced-vibration (FV) tests by Matsumoto (1996) for \( U_r<12 \). No data were available from PWRI. The study was restricted to \( U_r<12 \) since in this range of \( U_r \) the cross section exhibits torsional flutter with \( A_2^*>0 \). Therefore, free-vibration tests at ISU had to be interrupted at higher speeds to avoid damage to the apparatus.

While good correspondence was found between the two data sets for \( A_3^* \), \( A_2^* \) data reported by Matsumoto (1996) \( (a_0=0.035 \text{ rad} \) tend to show lower positive values for \( U_r<12 \).

7.0 SUMMARY

This paper presents some recent results associated with a research activity aimed at the comparison between different wind tunnel measurements and techniques for the extraction of flutter derivatives for bridge aeroelastic analyses. This research was motivated by a benchmark study initiative initially promoted by Iowa State University in the United States and Public Works Research Institute in Japan, and subsequently extended to include Northeastern University at a later stage of the study.

This study completes the previously reported research activities, presented by the investigators at previous meetings of the UJNR Panel on Wind and Seismic Effects.

In this paper, a systematic analysis of laboratory results was conducted for free and forced-vibration wind tunnel methods for two bluff rectangular prisms and two streamlined deck models. Data from two different laboratories, ISU and PWRI, were analyzed. Comparisons were also extended to other experimental results available in the literature.

Dimensional parameters such as reduced velocity and reduced amplitude of vibration were used for the interpretation of different sets of data.
It was concluded that while the trends of the various data sets for the bluff cross section were very similar, there were some differences that could be possibly associated with the effects of amplitude dependency. The data sets for the streamlined sections compared very well showing lesser dependency on technique used or initial amplitude.

8.0 ACKNOWLEDGMENTS

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9.0 REFERENCES


Figure 1: Streamlined deck models B2 and B3 used for comparing free and forced vibration methods in the ISU wind tunnel (aeroelastic forces are also shown in the figure)

Figure 2: (a) Rectangular box girder section model, R2_1; (b) dimensions for the B/D = 2 (R2_1) and B/D = 5 (R5_1) models.
Figure 3: Bill ISU Wind Tunnel with forced-oscillation system installed on overhead frame.
Figure 4: Comparison between the ISU (free vibration) and PWRI (forced vibration) flutter-derivative results of the B2 streamlined box girder deck section.
(a) $H_1^*$ and $H_4^*$; (b) $H_2^*$ and $H_3^*$; (c) $A_1^*$ and $A_4^*$; (d) $A_2^*$ and $A_3^*$. 
Figure 5: Comparison between the ISU (free vibration) and PWRI (forced vibration) flutter-derivative results of the B3 streamlined slotted box girder deck.
(a) $H_1^\ast$ and $H_4^\ast$; (b) $H_2^\ast$ and $H_3^\ast$; (c) $A_1^\ast$ and $A_4^\ast$; (d) $A_2^\ast$ and $A_3^\ast$. 
Figure 6: $H_1^*$ (a) and $H_4^*$ (b) flutter derivatives of the rectangular cross section R2_1 ($B/D = 2:1$). Comparison between the ISU 1-DOF vertical free-vibration experiments ($h_0/B$: normalized amplitude; $h_0/B=0.07$, 0.13, 0.20) and the data from PWRI (Sato et al., 2004, 1-DOF, $h_0/B=0.01$), Matsumoto (1996, 2007, 1-DOF, $h_0/B=0.05$) and Washizu et al. (1978) (1-DOF, $h_0/B=0.01$ and 0.10).
Figure 7: $H_1^*$ (a) and $H_4^*$ (b) flutter derivatives of the rectangular cross section R5_1 ($B/D = 5:1$). Comparison between the ISU 1-DOF vertical free-vibration experiments for variable $h_0/B$ and the 1-DOF forced-vibration (FV) tests by Matsumoto (1996)
Figure 8: Rectangular cross section R2_1 ($B/D = 2:1$). Analysis of the Scruton number, $Sc=mζ/(ρB^2)$, dependence for the $H_1^*$ (a) and $H_4^*$ (b) flutter derivatives recorded at ISU during 1-DOF vertical free-vibration tests with initial amplitude $h_0/B=0.06$. 

- Reduced Velocity, $U/nB$
- $Sc=2.82$
- $Sc=3.24$
- $H_1^*$
- $H_4^*$

(a) and (b)
Figure 9: $A_2^*$ (a) and $A_3^*$ (b) flutter derivatives of the rectangular cross section R2_1 ($B/D = 2:1$). Comparison between the ISU 1-DOF torsional free-vibration experiments ($\alpha_0=0.030$ rad), the 1-DOF PWRI experiments ($\alpha_0=0.017$ rad), the 1-DOF forced-vibration (FV) tests by Matsumoto (1996) for $\alpha_0=0.035$ rad, and by Washizu et al. (1980) (1-DOF, $\alpha_0=0.033$ rad)
Figure 10: $A_2^*$ (a) and $A_3^*$ (b) flutter derivatives of the rectangular cross section R5_1 ($B/D = 5:1$). Comparison between the ISU 1-DOF torsional free-vibration experiments ($\alpha_0=0.030$ rad) and the 1-DOF forced-vibration (FV) tests by Matsumoto (1996) with $\alpha_0=0.035$ rad.