# A Comparison of Force Balance and Pressure Integration Techniques for Predicting Wind-Induced Responses of Tall Buildings

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## ABSTRACT

Both High Frequency Force Balance (HFFB) and High Frequency Pressure Integration (HFPI) studies of the CAARC standard tall building were carried out at RWDI's boundary layer wind tunnel facility in Guelph, Canada. The results described in this paper are part of an ongoing detailed investigation aimed at quantifying the advantages and limitations of the HFFB and HFPI methods.

## INTRODUCTION

In the past few decades, wind tunnels have been widely used for reliably predicting wind-induced structural loads and responses of tall buildings. With the exception of unusually tall or slender structures, it is generally considered adequate to conduct the wind tunnel tests using a rigid model, with the dynamic characteristics of the full-scale structure accounted for in the analysis. The two main measurement methods, which use rigid models for this purpose, may be referred to as the High Frequency Force Balance (HFFB) and High Frequency Pressure Integration (HFPI) techniques.

Each method offers advantages as well as limitations. Although both methods are commonly used for wind load predictions on tall buildings, the choice of method for a project is typically made based on engineering judgment and experience, without the benefit of detailed comparisons. There are examples where both methods have been compared for the same project, although the primary purpose was to illustrate how these methods can supplement each other [Steckley et al., 1992; Flay and Vickery, 1997; Isyumov et al. 1999; Flay et al., 2003; Lin et al., 2005]. It would appear that extensive comparisons are lacking, which quantify where one method would be clearly superior. This is the main objective of the investigation currently underway at RWDI.

This paper will focus on comparisons of the load and response results for the standard CAARC building [Melbourne, 1980] derived using both methods.

## HIGH FREQUENCY FORCE BALANCE (HFFB) METHOD

The HFFB method is based on measuring the overall wind-induced forces acting at the base of a rigid model, using a high frequency force balance. To allow predictions of the dynamic responses of the structure to be made, the model must be light and stiff (i.e., nominally rigid) so that the measurements reflect the fluctuations in the applied wind loading only, and not the vibrations of the model itself. The requirement for a light, stiff model is in contrast to an aeroelastic model, which would be carefully designed to vibrate as the actual structure would. The HFFB method, when it was first introduced, allowed a simple model to be constructed and tested, generating data with which various sets of structural dynamic information (e.g., mass, stiffness and damping) could be analyzed without altering the model and repeating the wind tunnel tests. For this reason, the HFFB method has proven to be a cost-effective tool.

Inherent in the HFFB approach is the fact that only the total loading at the base is known. The prediction of the dynamic response to wind requires knowledge of the wind-induced generalized forces, which are related to the pressure distribution over the height of the building. For a building with a linear mode shape, it is possible to use the base moments directly to represent the generalized forces. For the general case of non-linear mode shapes, various refinements are possible, both in the physical test set-up as well as in the analysis.

The overall shear force and overturning moment acting on a building can be expressed as

$$F(t) = \int_0^H f(z,t)dz \qquad M(t) = \int_0^H f(z,t)zdz \tag{1}$$

where, F(t) and M(t) are the shear force and overturning moment measured at the base. The challenge is to deduce the load distribution f(z,t) from measurements of F and M, so that the generalized force can be calculated. In the method proposed by Xie and Irwin [7], a linear pressure distribution is chosen which satisfies both base moment and shear force simultaneously. In general, the true distribution of loading f(z,t) cannot be obtained from the HFFB method, particularly for complex geometries where assumptions on the drag properties of various elements introduce additional uncertainty.

The torque measured at the base using a force balance can be expressed as

$$T(t) = \int_0^H t(z,t)dz \tag{2}$$

where t(z,t) is the aerodynamic torque per unit height. Whereas the base overturning moment is representative of the generalized force associated with a linear mode shape, which is approximately correct, the measured base torsion represents a uniform mode shape with height. Empirical factors are therefore introduced, based on the geometry and mode shape, to scale the measured torsion down to the appropriate generalized torque. As an aside, one novel approach used by RWDI, for wider buildings where torsion is a concern, is to split the model into two halves, each tested simultaneously on an HFFB. The torsional mode is therefore described by linear pressure distributions calculated from the moments and shears on each half.

Note that HFFB method always measures overall responses. To generate effective load distributions over the height of the building requires similar assumptions to those discussed above. This appears to be adequate in many cases of practical significance; however, there are obvious limitations should the designer wish to focus on individual structural elements higher up in the building.

## HIGH FREQUENCY PRESSURE INTEGRATION (HFPI) METHOD

The HFPI method is based on the simultaneous measurement of pressures at several locations on a building. Simply put, if the pressure taps are installed at a fine enough resolution over the building surfaces, then integrating the data should provide the same output as from an HFFB test. In fact, the measurement of the generalized forces is greatly improved as assumed pressure distributions based on measured base forces are replaced with instantaneous pressure distributions over the entire building surface. This method also allows for flexibility in isolating components or substructures for which loads can be determined in detail. The measurements also allow higher modes to be considered, and ultimately can allow the designer to focus on individual structural elements in detail.

A practical benefit is that such pressure measurements are typically required to begin with, for the prediction of cladding loads. Therefore, some testing time may be saved. It is worth noting that the ability to sample pressures *simultaneously*, at the hundreds of locations required for this task is a relatively recent development. The current state of data storage as well as pressure scanning technology has virtually eliminated this obstacle.

In general, the HFPI approach is more labor-intensive with respect to the determination of tap tributary areas, moment and torsion arms, as well as the physical installation of the pressure taps. Again, advances in graphics and modeling technology continue to help this process.

There remain some physical constraints with conducting HFPI studies. Slender structures provide limited space in which to run the instrumentation from the building face and out to the data acquisition system. Close proximity to nearby buildings seemingly requires more taps to deal with the complexity of the flows compared to those affecting an isolated building. Installation of pressure taps on balconies and architectural facade details may be difficult or impossible. Frames, trellis work or other kinds of screens pose similar challenges. Addressing such details requires engineering judgment usually in assigning tributary areas and pressures to such features. Alternatively, this is often justification for using the HFFB technique where one can be certain that the integrated effect of such details will be embedded in the measured based loads.

The above issues are the primary focus of the ongoing study by RWDI. The effectiveness of pressure integration methods is often illustrated on simple isolated, rectangular buildings. It would be beneficial to see, for example, how much additional tap coverage may be needed for a building in complex terrain, compared with an isolated one.

## COMPARISON BETWEEN HFFB AND HFPI METHODS

### Experimental Details

The data presented here were collected from wind tunnel studies of the standard CAARC tall building model using the HFFB and HFPI techniques. These tests were conducted on a 1:400 scale model of the building in the presence of three different surrounding scenarios, as shown in Figure 1, in RWDI’s 2.4m x 2.0m boundary-layer wind tunnel. A

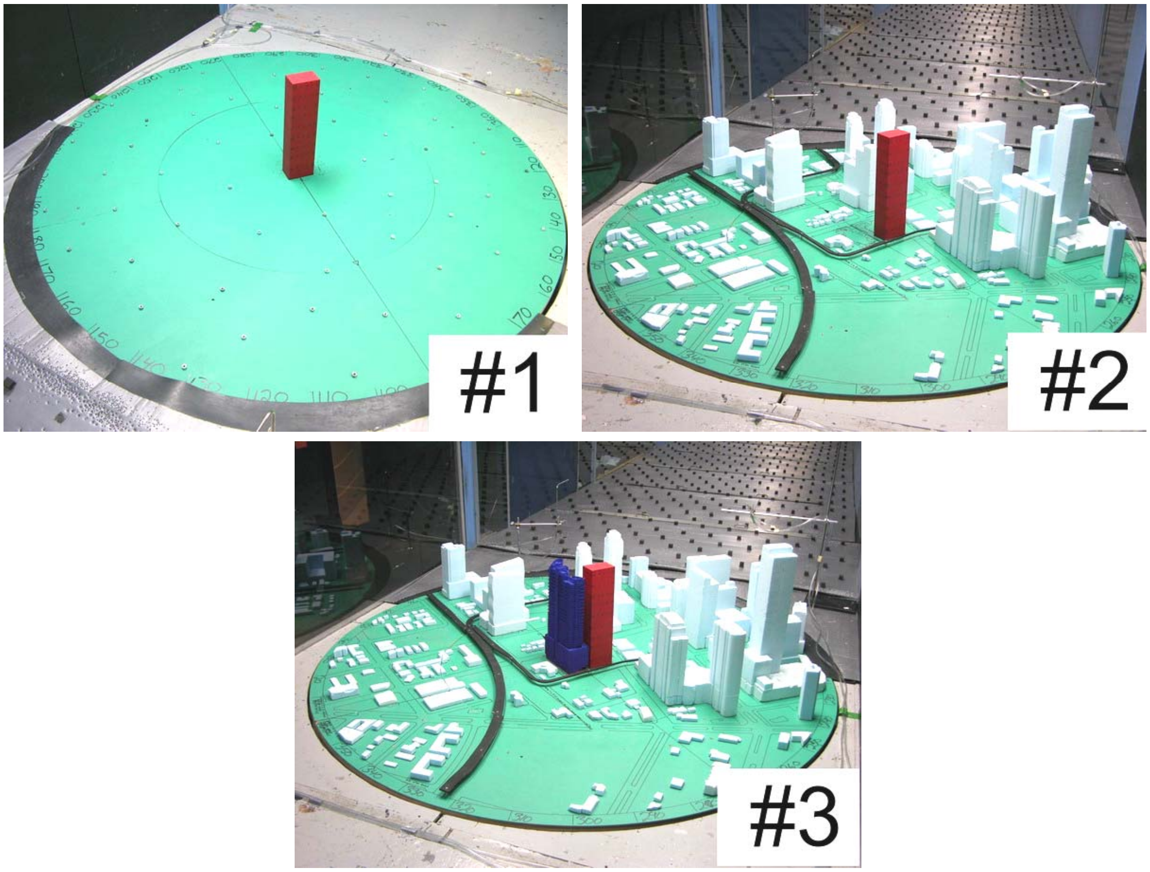


FIGURE 1
WIND TUNNEL TEST CONFIGURATIONS

rural upwind terrain condition ($z_o$ = 0.1m, corresponding approximately to a power law exponent of 0.17) was simulated for all wind directions by means of floor roughness and upwind spires. The first configuration was without any immediate surroundings and the second configuration was with similar size surroundings on one side of the study building. The third configuration was the same as the second but with a similar sized tower immediately adjacent to the study building.

For the HFFB tests, a balsa model was constructed and mounted on a balance consisting of a stiff rectangular sway flexure on top of a stiff torsional flexure. Instantaneous overturning and torsional moments were read directly from strain gauges attached to the force-balance flexures, and the instantaneous shear was computed from the difference in strain gauge readings at two levels on the sway flexure. The time series of the base loads were used to estimate the generalized forces assuming linear mode shapes in the two sway directions and torsion. Mean, root-mean-square (rms) values and spectra of the moments and generalized forces were calculated. Maximum and minimum values of the moments about the X and Y direction (Mx, My), shear in the X and Y direction (Fx, Fy), and torsional moment Mz could then be predicted.

For the HFPI tests, the building was instrumented with 280 pressure taps, including the standard CAARC locations, plus additional taps near the building edges. Time series of the pressures at these locations were collected and stored for post-test analysis. The individual pressure time series were used to form time series of the base loads and generalized forces, from which statistics and spectra could be calculated. The peak base moments, shears and torsion could then be determined.

Figure 2 provides the pressure tap locations for the HFPI study, along with the overall equivalent full-scale dimensions, axes system and wind flow angle. The wind tunnel tests were conducted for 36 wind directions at $10^{o}$ intervals.

For the analysis, the natural frequency of the building was taken as 0.2 Hz in both sway directions and 0.3 Hz in the torsional direction. The structural damping was taken as 1% of critical and the mass distribution of the building was taken to be 160 $kg/m^3$. These above values were the same as used by other studies [Melbourne, 1980] for the CAARC building for comparison purposes.

## Results

The comparison between wind-induced responses by the HFFB and HFPI methods with respect to wind direction are shown in Figure 3 for Configuration 1. This figure presents the mean and rms of the base overturning moments (Mx and My) as well as the base torsional moment (Mz) for a reduced velocity ($U_H/nD_y$) of 4.7, where $U_H$ = reference velocity at roof height, n = natural frequency (0.2 Hz) and $D_y$ = wide dimension of building cross section (45.72 m). This reduced velocity was selected for consistency with the published data. All the mean and rms moments in this figure are normalized by

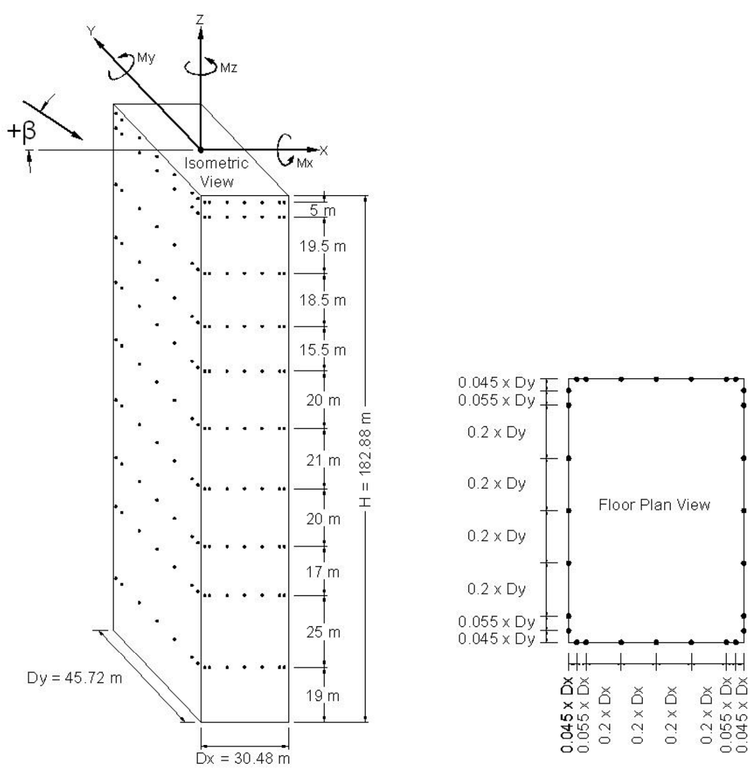


FIGURE 2

CAARC BUILDING MODEL: DIMENSIONS, HFPI PRESSURE TAP LOCATIONS AND COORDINATE SYSTEM

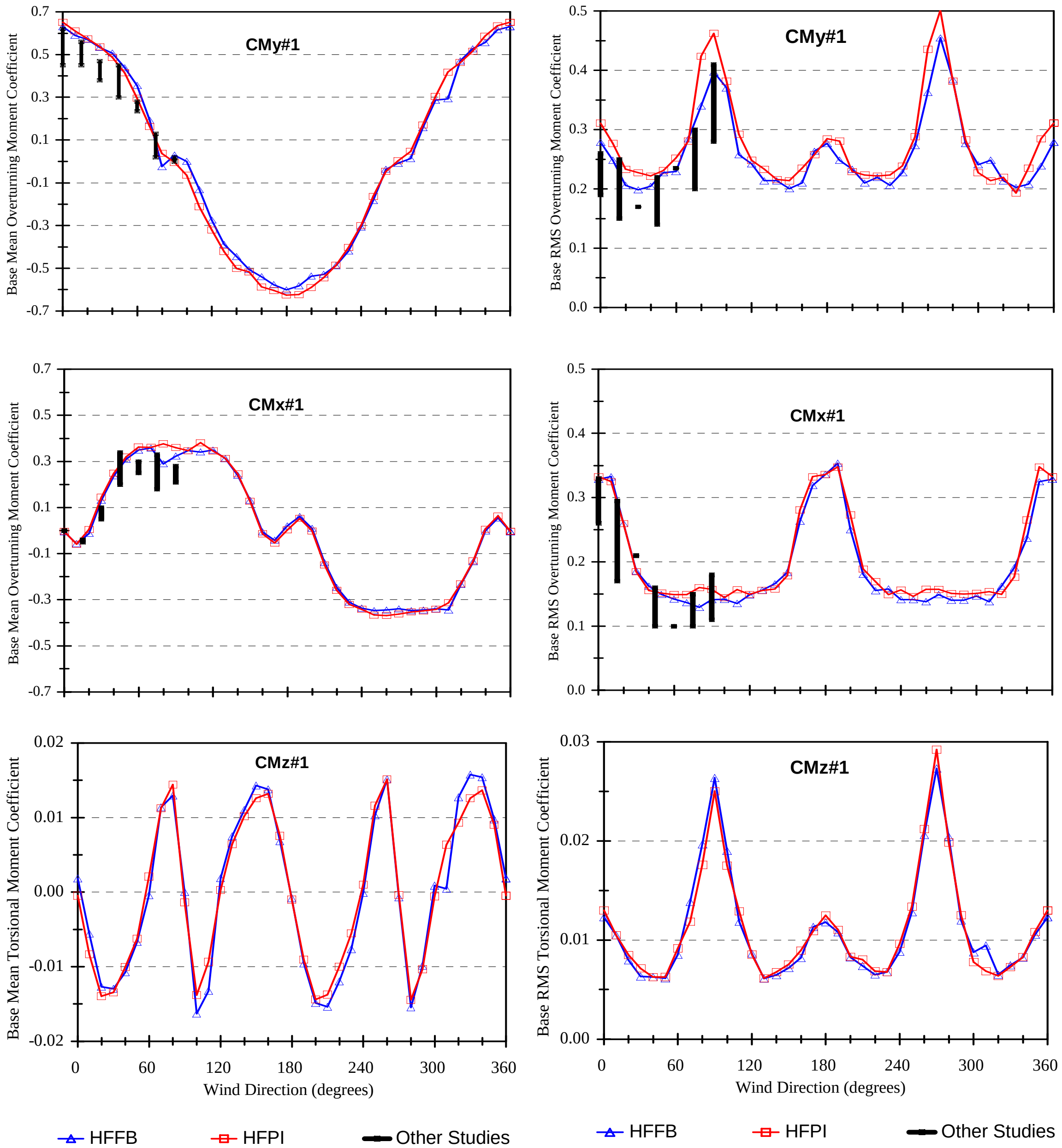


FIGURE 3

COMPARISON OF WIND-INDUCED RESPONSE OF CAARC BUILDING USING HFFB AND HFPI METHODS CONFIGURATION #1, $U_H/nD_y$=4.7

$\frac{1}{2}\rho U_H^{2}H^{2}D_y$ .

It can be seen that there is generally good agreement between the predictions from the HFFB and HFPI methods. One possible exception is the fluctuating My for 90° and 270°. These are across-wind responses and the variation between symmetric angles even for the same test suggests that they are very sensitive to angle of attack, particularly without buffeting effects from surrounding buildings. The plots also show the

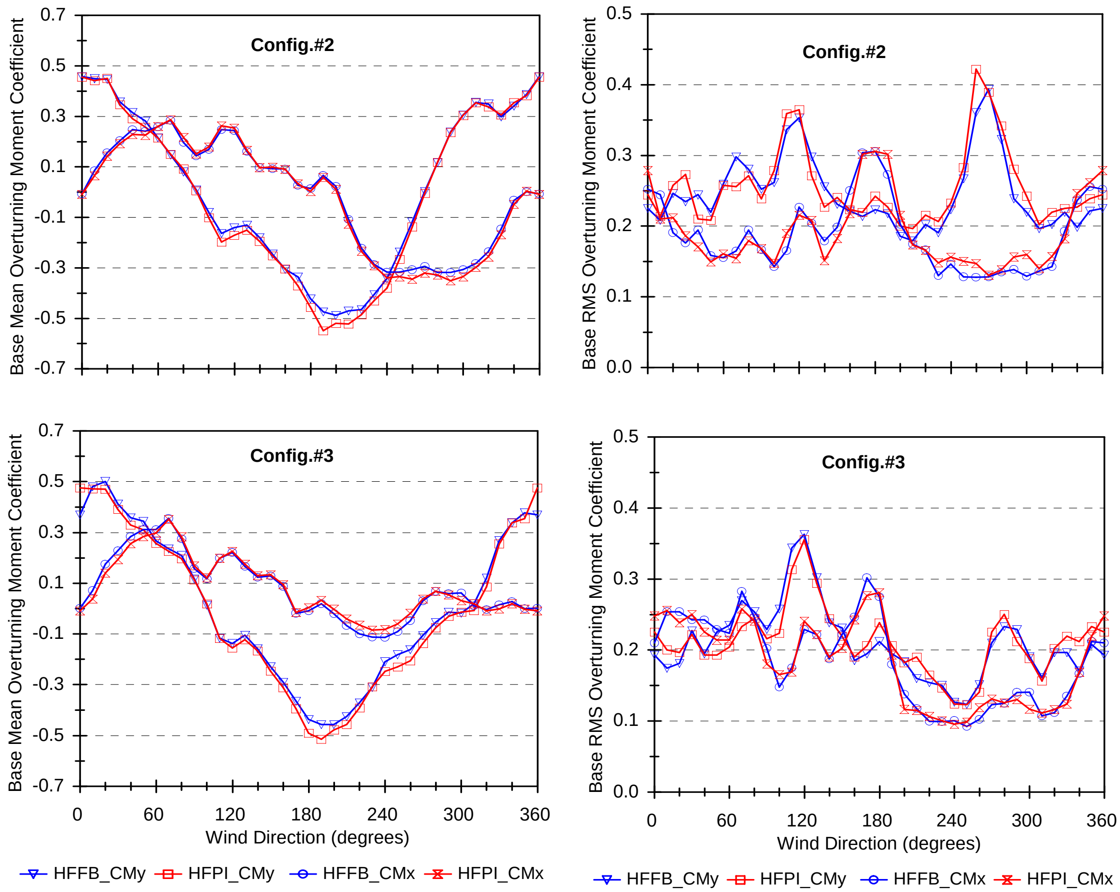


FIGURE 4

COMPARISON OF WIND-INDUCED RESPONSE OF CAARC BUILDING USING HFFB AND HFPI METHODS CONFIGURATIONS # 2 AND 3, $U_H/nD_y$=4.7

corresponding range of results from other studies [Melbourne, 1980]. The present results from RWDI on the standard CAARC model compare reasonably well with results predicted by others in the past. Part of the variation would be the result of differences in the flow simulations. The previous studies were conducted in rougher terrain (suburban or rougher) simulations compared to the rural type terrain condition used for this study.

Figure 4 presents the comparisons for Configurations 2 and 3. The agreement between HFFB and HFPI is good even with the presence of complex surroundings. The differences appear again to be more pronounced for the across-wind responses, where there could have been slight variations in the angle of attack.

Along-wind, across-wind and torsional base moment spectra corresponding to selected wind directions, from the three test configurations, are shown in Figure 5. The abscissa of the plots represents reduced frequency, $fD_y/U_H$ and the ordinate represents normalized spectral energy fS(f)/sigma^2, where f = frequency, S(f) = spectral energy and sigma = rms of fluctuations. Note that regardless of the wind direction, type of response and configuration, the spectra obtained by HFFB and HFPI methods are in good agreement.

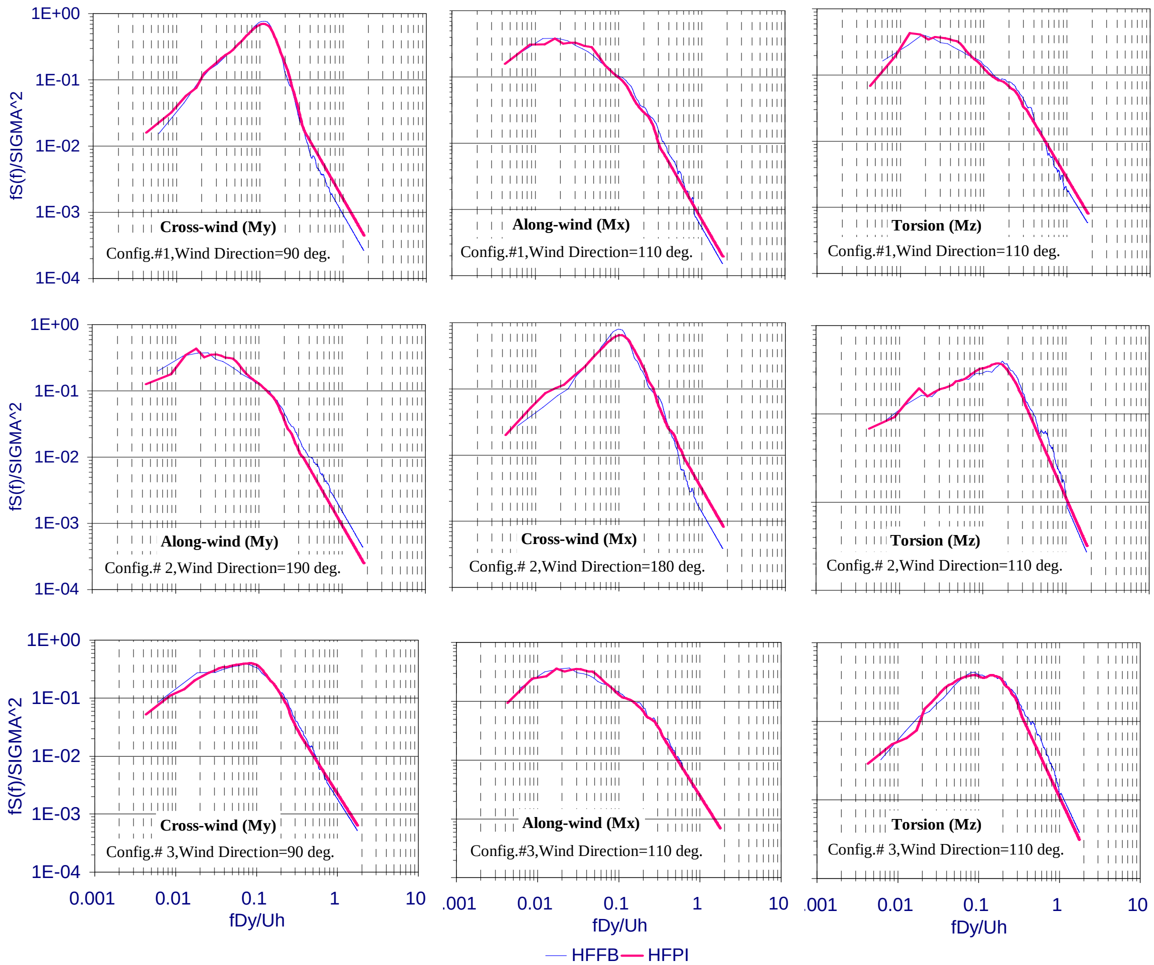


FIGURE 5

COMPARISON OF SELECTED SPECTRA PREDICTED BY HFFB AND HFPI METHODS, $U_H/nD_Y$=4.7

The mean and rms of the base moments Mx and My predicted by HFFB and HFPI methods as a function of reduced velocity for 90$^o$ and 180$^o$ are presented in Figure 6 for Configuration 1. The quality of the comparisons in this figure suggests that the results are independent of the design speed and building frequency, as expected. Similar results have been noted in other configurations.

## CONCLUDING REMARKS

The results shown indicate that the two test methods can give similar results for a simple, flat-faced building situated in complex surroundings. This is expected as the CAARC building is ideal for both methods. For a building such as this, the HFPI would therefore appear to be a preferred method particularly if pressures are already required to obtain design information for the cladding. The theoretical advantages with regards to mode

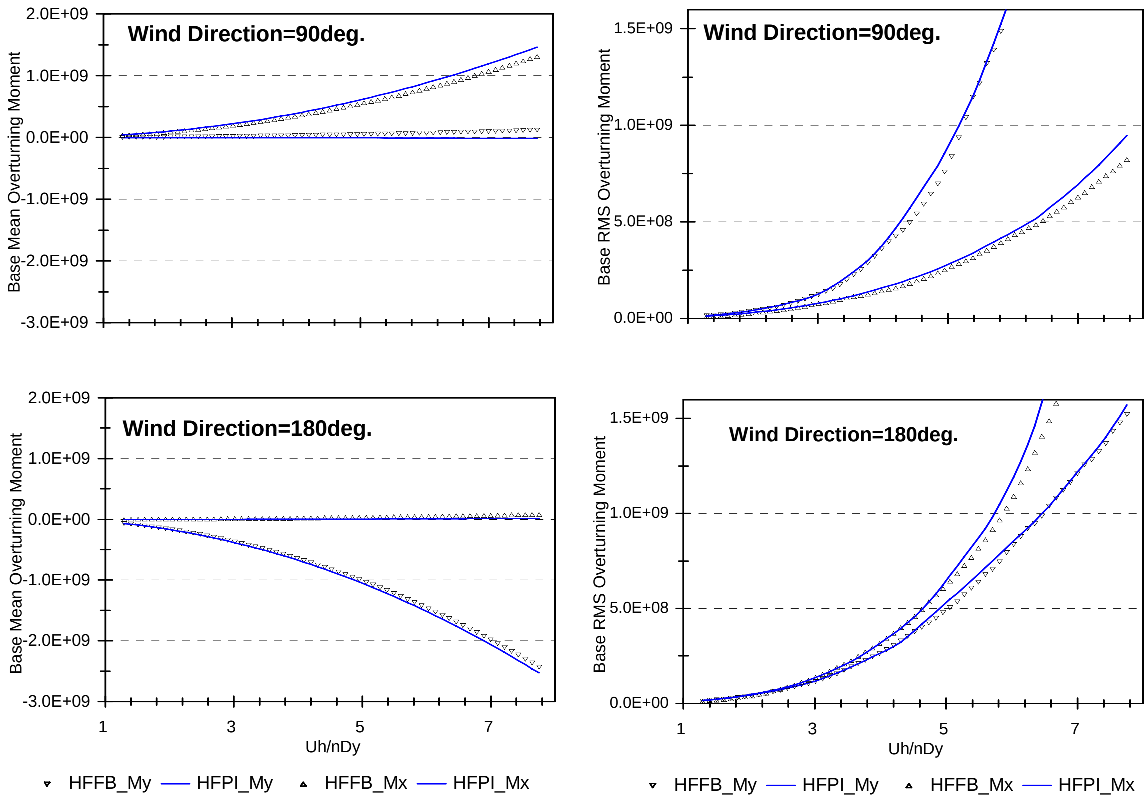


FIGURE 6

COMPARISON OF BASE MOMENTS PREDICTED BY HFFB AND HFPI METHODS AS A FUNCTION OF REDUCED VELOCITY, CONFIGURATION #1

shape are not apparent in this example, although analysis with curved mode shapes may start to show some differences. HFPI tests would permit higher modes to be investigated as well as the loading on upper portions of the building. It is worth noting however that, with a few exceptions, these issues have not been critical to the design of typical buildings and are generally not reflected in code procedures. In fact, higher modes tend to become significant only in very tall slender structures where aeroelastic effects also come into play. In such cases the HFPI approach may not be adequate either.

The HFFB method offers the advantage that the total loading on complex geometries will be reflected in the measured base loads. Future plans for this study include conducting more comparison tests to increase the level of comfort in applying the HFPI approach on buildings with balconies and other complex surface details. The model construction and analysis of more complex structures is being aided by technological advances so that the HFPI approach is becoming a more practical option. Complex developments where loading information is required on individual substructures, and combinations thereof, are more suited to an HFPI approach as well.

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