

e-Analysis/Design of Tall Buildings Subjected to Wind Loads

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ABSTRACT

This paper presents re-designed NatHaz Aerodynamic Loads Database (<http://aerodata.ce.nd.edu>) which has served as an important first step in establishing an on-line experimental database for use in the preliminary design of tall buildings subjected to wind loads. Based on recent advances in data management, mining and software tools, this interactive database was revised to enhance, for the purposes of analysis and design, the accessibility, organization, dissemination and utility of wind tunnel data. The revised website offers more attractive and user-friendly features to allow on-line determination of equivalent static wind loads and accelerations for survivability and habitability designs, respectively. These changes were achieved using a combination of several web-based programming tools and popular softwares.

KEYWORDS: Aerodynamic Loads Database, On-line Analysis/Design, Tall Building, Wind Load

INTRODUCTION

One of the major challenges in any engineering discipline is the processing and archiving of large quantities of information. This is no exception in Structural Engineering, where such stores of data include those generated by wind tunnel studies, laboratory experiments, material testing and even full scale monitoring. Recent developments in information technology (IT) offer attractive solutions to these challenges, allowing efficient means to collect, store, analyze, manage, and even share large data sets with the worldwide community. For example, it is becoming a common practice to conduct web-based data retrieval from remote servers and to engage in on-line, on-the-fly analysis of data [1]. Not only do such approaches enable geographically dispersed members of a research project to share data and findings, but it also provides a venue in which this information can be shared with other members of the design community around the world.

The NatHaz Aerodynamic Loads Database (NALD), first established in the Fall of 2000, is an example of web-based archiving and distribution of wind tunnel test data for the determination of alongwind, acrosswind and torsional response [2]. This database has served as an important first step in establishing an online experimental database for use in the preliminary design of tall buildings. This interactive database provides users with the RMS base moment coefficients and the non-dimensional power spectra obtained from force balance measurements on rigid tall building models of varying aspect ratio and geometry, tested under varying boundary layers. One attractive feature was the use of JAVA-based applets to provide specific spectral values at a given non-dimensional frequency, negating potential errors associated with interpolation. However, the structure of this prototype site was rather archaic in light of recent advances in data management, mining and software tools. This study discusses the use of these advances to enhance, for the purposes of analysis and design, the accessibility, organization,

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dissemination and utility of wind tunnel data. The recently re-designed NatHaz Aerodynamic Loads Database (<http://aerodata.ce.nd.edu>) serves as the primary case study in the application of these new technologies. The revised site offers more attractive and user-friendly features to allow not only on-line determination of equivalent static wind loads for survivability, but also accelerations for habitability considerations. These changes were achieved using a combination of web-based programming tools and widely-used software, e.g., Apache HTTP servers, JAVA/JavaScript applets, Hypertext Preprocessors (PHP), Structured Query Language databases (MySQL), MATLAB.

WIND TUNNEL DATA

The aerodynamic database consists of 162 different data sets, including a combination of 9 cross sectional shapes, 3 model heights, 2 exposure categories and 3 response directions (alongwind, acrosswind and torsion) shown in Figure 1. Each of the balsa models was tested in a boundary layer wind tunnel with a 3 m (10 ft) x 1.5 m (5 ft) cross-section, of 18 m (60 ft) length. The turbulent boundary layers simulated in this study were generated by the natural action of the surface roughness added on the tunnel floor and the upstream spires. Two typical boundary layers were simulated in this experiment, BL1 ($\alpha=0.16$, where α = exponent of mean wind velocity profile) and BL2 ($\alpha=0.35$), similar to the conditions of open (Exposure C in the ASCE 7-98 [3]) and urban (Exposure A in the ASCE 7-98 [3]) flow environments, respectively. A high-frequency force balance was used in conjunction with each balsa wood model to determine the dynamic wind-induced structural loads. The output of the sensitive, multi-component force balance was analyzed, using the FFT, to determine the spectral and cross-spectral density functions, which were later non-dimensionalized. This analysis was carried out for all 27 model buildings, in both boundary layers, and at varying angles of wind incidence, though only the case of 0° is considered here. Additional building shapes and aspect ratios can be conveniently added in the database.

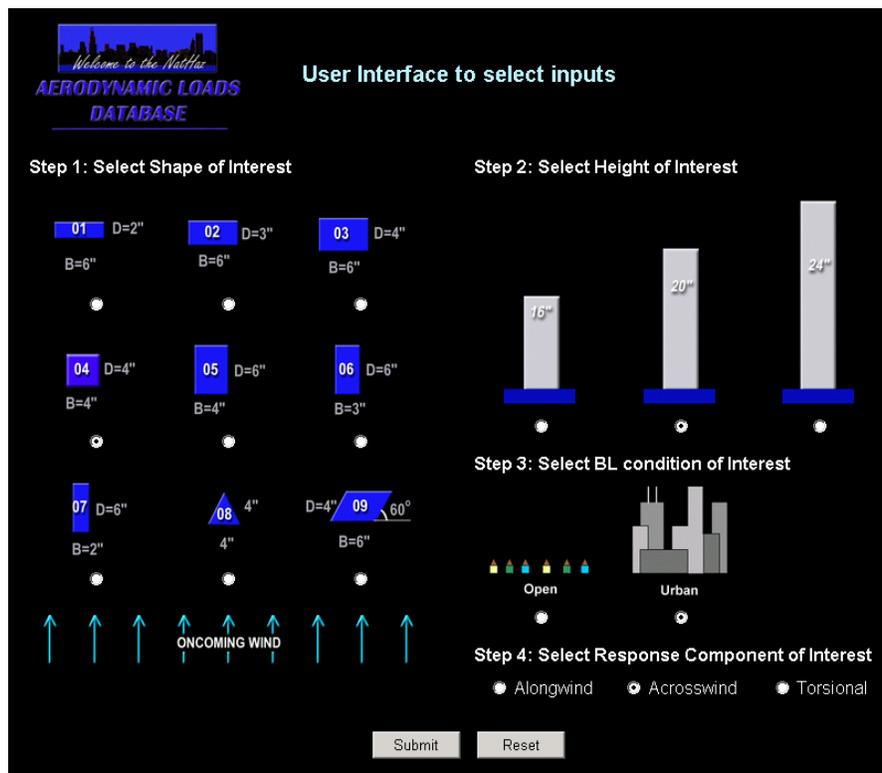


Figure 1. User-friendly interface for selection of wind tunnel data

REORGANAZATION OF PREVIOUS NALD

The previous NALD provided users with the RMS base moment coefficients and the non-dimensional power spectra obtained from force balance measurements on rigid tall building models of varying aspect ratio and geometry, tested under varying boundary layers. Upon entrance to the database, the user stepped through a series of HTML links to identify, with certainty, the data of interest. Once the desired building model was selected, the database recapped the selections and prompted the user to select the alongwind, acrosswind or torsional load results. JAVA programming was used to allow the retrieval of a building-specific value from the non-dimensional power spectrum. One attractive feature was the use of JAVA-based applets to provide specific spectral values at a given non-dimensional frequency, negating potential errors associated with interpolation. However, this previous version utilized an expansive hierarchy of directories with duplicate HTML files. This hierarchy required the user to step through the links at least five times to reach the desired JAVA applet.

To compensate above shortcomings, several web-based tools are utilized. The NatHaz Aerodynamic Loads Database desktop server is now operated by an Apache [4] web server program and available to the public at <http://aerodata.ce.nd.edu>. In particular, the archaic and sequential HTML structure of the original site was replaced with a database approach (MySQL) to archiving the 162 data sets. This change speeds the retrieval time and reduces the number of HTML files on the server. A combination of PHP [5], a kind of CGI (common gateway interface) language, and MySQL [6] makes it possible to reform the previous NALD interface. The new user-friendly interface shown in Figure 1 allows the selection of a desired analysis case in one step, which is then followed by the launch of the appropriate JAVA applet designed in the previous version of the site [2]. The digitized spectra made by JAVA applets removes the opportunity for human errors that result from picking off values from hardcopy spectra and eliminates the uncertainty associated with curve-fit expressions.

NEW FEATURE OF NALD: ON-LINE ANALYSIS/DESIGN OF TALL BUILDINGS

In the original NALD form, users would download relevant spectral properties for a given case and then perform off-line calculations of the building accelerations and equivalent static wind loads based on the procedure in Zhou et al. [2]. To improve the utility of this data and minimize the calculations required on the part of the end user, an on-line analysis module was developed to supplement the existing JAVA interface and provide these and other response quantities automatically. Therefore, the next component of the redesign was focused on the development on an on-line analysis module.

The new user interface developed for on-line analysis is shown in Figure 2. It is basically similar to reorganized interface (Fig. 1), but additional options for non-dimensional power spectral density (shortly, PSD) are newly introduced. At this time, three options are available for specifying a PSD for the analysis: PSD data from NatHaz experiments (default option), a user-defined PSD expression or user-supplied PSD data (X, Y pairs), as shown in Figure 2. The user selections are handled by a combination of PHP and MySQL as input for the next stage in the process. After selecting these basic inputs, the module requests additional inputs, including cross-sectional shape, height, exposure category, and fundamental dynamic characteristics (Fig. 3). Either Metric (SI) or English units may be specified for the structural inputs and calculated outputs. In addition, an on-line calculator is provided for unit conversion, e.g., converting meters to feet and vice versa (Fig. 4).

MATLAB [7] provides an attractive programming framework for more complicated computations and can be easily extended to more sophisticated numerical transforms owing to many pre-defined function capabilities. For these reasons, MATLAB 6.1 (R 12) is used as the computational framework for this study, and the MATLAB web server tool is internally utilized to interact between user inputs and the server-side MATLAB analysis. A MATLAB code, running on the server, determines the structural accelerations and equivalent static wind loads based on the procedure in Zhou et al. [2]. The end user then finds the following quantities displayed on the web portal: non-dimensional base moment spectrum (Fig. 5), RMS base moment coefficient, non-dimensional moment coefficient, base moment for survivability design, and acceleration at the top of the building for serviceability design (Fig. 6). These quantities are displayed for each of the three response components. Finally, this is supplemented by a plot of the mean,

background and resonant components of equivalent static wind loads on the building (Fig. 7). An option is available to provide the user the capability to save this information as an ASCII file and download it to their desktop for further analysis and application to an existing structural finite element model.

It should again be emphasized that one unique feature provided by this on-line analysis module is the user's non-dimensional PSD options. As mentioned earlier, new NALD provides user with three PSD options. Thus, the user can utilize not only PSD data provided by NatHaz test results or any arbitrary PSD expression or data set for the on-line determination of preliminary wind loads on tall buildings. Depending on the PSD option selected in Figure 2, additional inputs will be requested following the prompt for structural inputs. Figure 8(a) shows the interface for user-supplied PSD expressions, while Figure 8(b) shows the interface for supplying a PSD data set, i.e., X and Y pairs. Since this on-line analysis module is mainly achieved by MATLAB, inputs of these two user's PSD options should be MATLAB compatible. The on-line analysis module also includes an error-detection scheme with pop-up error message, which alerts users if input values are beyond the range of applicability of the NatHaz database.

It should be noted that the web-based tools used to originally establish the interface and analysis module listed herein are continuously and periodically updated as evolving security and vulnerability issues are identified. Due to this constant updating, the interfaces are likely to have evolved since the time of publication.

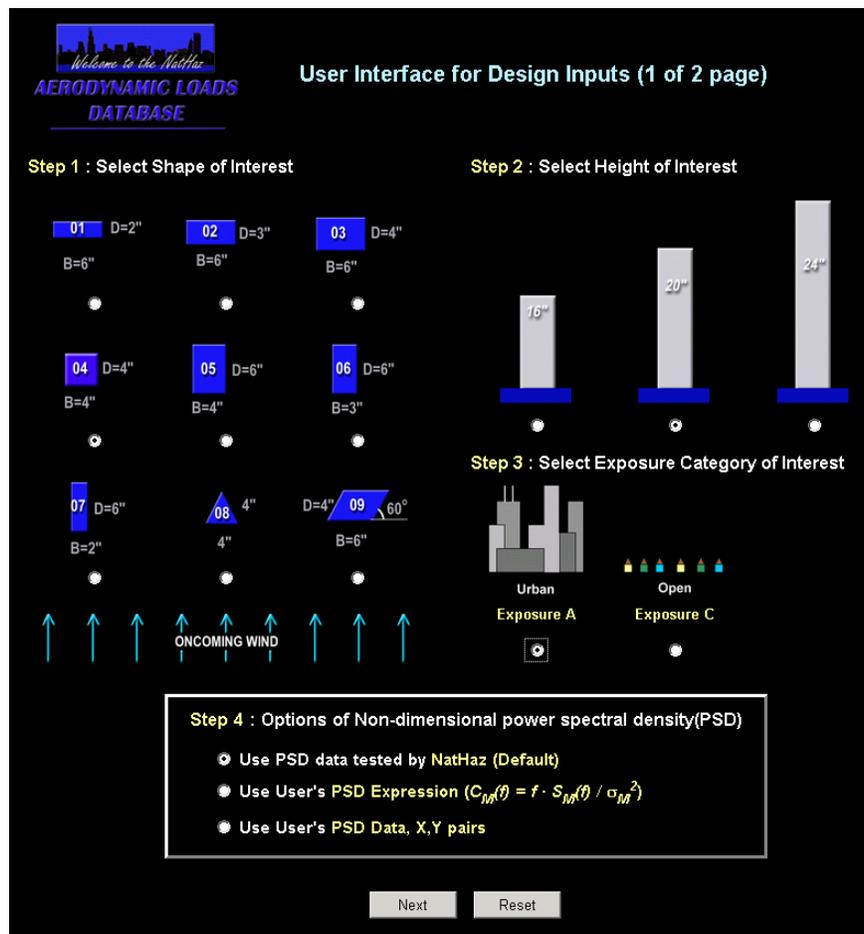


Figure 2. User interface to specify selections for on-line calculation of ESWL

Step 5 : Please select options and fill out input values. [On-line Unit Converter](#)

- Please select the unit of input values (default : Metric)
If user would like to see English unit output, please select checkbox (default : Metric)
 - Metric(SI) unit [kg, m, m/s]
 - English unit [lb, ft, mph]
 - Output : English unit
- Building width(B), depth(D) and height(H)

B [m, ft] : D [m, ft] : H [m, ft] :
- Natural frequencies of building for three directions; alongwind(f_x), acrosswind(f_y) and torsional(f_z).

f_x [Hz] : f_y [Hz] : f_z [Hz] :
- Mode shape exponents(β) for three directions, $(z/H)^\beta$ (default : linear mode shape, $\beta=1.0$)

alongwind(β_1) : acrosswind(β_2) : torsional(β_3) :
- Bulk Density(ρ_B), Average Radius of Gyration(γ) and Damping ratio(ζ) of Building

ρ_B [kg/m³, lb/ft³] : γ [m, ft] : ζ :
- Floor-to-floor height of building(ΔH), Air density(ρ_A), drag force coefficient(C_D)

ΔH [m, ft] : ρ_A [kg/m³, lb/ft³] : C_D :
- From ASCE standard 7-98 (Fig. 6-1)
3-second basic wind speed(U_{10}), file name(.dat) for wind force output (default : w_force),
select checkbox if this building is located in Alaska

U_{10} [m/s, mph] : file name : Alaska
- User selected to use NatHaz PSD data.

Figure 3. Interface for user-supplied structural inputs

On-line Unit Converter

<p>Length</p> <p><input type="text" value="20"/> <input type="text" value="m"/></p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 25%; border-right: 1px solid black;"><input type="text" value="20"/></td> <td style="width: 25%; border-right: 1px solid black;">m</td> <td style="width: 25%; border-right: 1px solid black;"><input type="text" value="2000"/></td> <td style="width: 25%;">cm</td> </tr> <tr> <td style="border-right: 1px solid black;"><input type="text" value="65.616"/></td> <td style="border-right: 1px solid black;">ft</td> <td style="border-right: 1px solid black;"><input type="text" value="787.392"/></td> <td>in</td> </tr> <tr> <td style="border-right: 1px solid black;"><input type="text" value="21.87200000"/></td> <td style="border-right: 1px solid black;">yd</td> <td style="border-right: 1px solid black;"><input type="text" value="0.012427272"/></td> <td>mile</td> </tr> </table>	<input type="text" value="20"/>	m	<input type="text" value="2000"/>	cm	<input type="text" value="65.616"/>	ft	<input type="text" value="787.392"/>	in	<input type="text" value="21.87200000"/>	yd	<input type="text" value="0.012427272"/>	mile	<p>Velocity</p> <p><input type="text" value="20"/> <input type="text" value="m/s"/></p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 25%; border-right: 1px solid black;"><input type="text" value="20"/></td> <td style="width: 25%; border-right: 1px solid black;">m/s</td> <td style="width: 25%; border-right: 1px solid black;"><input type="text" value="2000"/></td> <td style="width: 25%;">cm/s</td> </tr> <tr> <td style="border-right: 1px solid black;"><input type="text" value="65.616"/></td> <td style="border-right: 1px solid black;">ft/s</td> <td style="border-right: 1px solid black;"><input type="text" value="787.392"/></td> <td>in/s</td> </tr> <tr> <td style="border-right: 1px solid black;"><input type="text" value="72"/></td> <td style="border-right: 1px solid black;">km/hr</td> <td style="border-right: 1px solid black;"><input type="text" value="44.73872"/></td> <td>mph</td> </tr> </table>	<input type="text" value="20"/>	m/s	<input type="text" value="2000"/>	cm/s	<input type="text" value="65.616"/>	ft/s	<input type="text" value="787.392"/>	in/s	<input type="text" value="72"/>	km/hr	<input type="text" value="44.73872"/>	mph
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Figure 4. On-line unit conversion applet

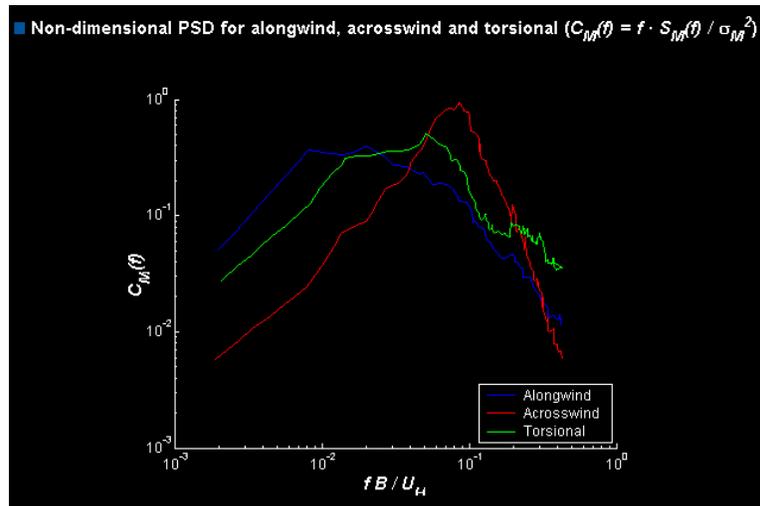


Figure 5. Non-dimensional base moment spectrum display

■ Survivability Design (50-year wind) : Base moments

	Base Moment (10^6 kN-m)			
	\bar{M}	\hat{M}_B	\hat{M}_R	\hat{M}
Alongwind	1.2828	0.9734	1.4828	3.0566
Acrosswind	-	1.1899	3.6403	3.8298
Torsional	-	0.0784	0.1386	0.1592

■ Serviceability Design (10-year wind) : Peak and RMS Accelerations

		Peak Accelerations at roof	
Alongwind		14.19 milli-g	
Acrosswind		23.50 milli-g	
Lateral Accelerations at Corner Induced by Torsion	0.00476 rad/s ²	Alongwind component : 9.70 milli-g	
		Acrosswind component : 9.70 milli-g	
Total Lateral Accelerations at Corner		Alongwind component : 17.19 milli-g Acrosswind component : 25.43 milli-g	

		RMS Accelerations at roof	
Alongwind		3.75 milli-g	
Acrosswind		6.21 milli-g	
Lateral Accelerations at Corner Induced by Torsion	0.00121 rad/s ²	Alongwind component : 2.47 milli-g	
		Acrosswind component : 2.47 milli-g	
Total Lateral Accelerations at Corner		Alongwind component : 4.49 milli-g Acrosswind component : 6.68 milli-g	

Figure 6. Display of calculated survivability and serviceability values.

EXAMPLE

The example building and wind environment used to illustrate the previous version of NALD in Zhou et al. [2] are utilized again in this study. Note that the previous version of the database provided users only with the spectral amplitude at a specified reduced frequency, thus requiring manual calculation of the desired response components following the procedure provided on-line, based on the work by Zhou et al. [2]. In the new version, all computations are automatically conducted by the on-line analysis module. The building's characteristics are summarized here for completeness: $B = 40$ m; $D = 40$ m; $H = 200$ m; average radius of gyration = 18 m; $f_x = 0.2$ Hz; $f_y = 0.2$ Hz; $f_\theta = 0.35$ Hz; bulk density = 250 kg/m^3 ; $\zeta = 0.02$; linear mode shapes. The 50-year and 10-year wind speeds at the building height are 51.30 m/s and 37.96 m/s, respectively for survivability and serviceability response estimates [2].

For these input conditions, the corresponding alongwind, acrosswind and torsional loading spectra based on the NatHaz experimental database are shown in Figure 5. A screen display of the corresponding response estimates automatically computed by the on-line analysis module is given in Figure 6. These include: survivability design quantities of mean, peak background, peak resonant and total peak base bending moments and serviceability design quantities of peak and rms accelerations at the roof level in the alongwind and acrosswind directions and the torsion-induced lateral accelerations at the building corner. The results match those computed manually in Zhou et al. [2]. The output also includes distributions of the equivalent static wind load components: mean, background and resonant for all response directions, as shown in Figure 7. These load distributions can be downloaded by the user for incorporation into models developed using various commercial software packages to allow for further analysis and design of structural members. This example illustrates the capabilities of the revised NALD — providing a user-friendly procedure to reliably estimate building dynamic response. The authors envision this capability to be particularly useful for those who may not be very familiar with the details of the analysis procedure typically employed in response estimation for dynamically wind-sensitive structures.

CONCLUDING REMARKS

The rapid development of internet technologies has revolutionized many engineering applications. This study discusses the use of these advances to enhance, for the purposes of analysis and design, the accessibility, organization, dissemination and utility of wind tunnel data. The re-designed NatHaz Aerodynamic Loads Database (<http://aerodata.ce.nd.edu>) serves as the primary case study in the application of these new technologies. The revised site offers more attractive and user-friendly features to allow on-line determination of equivalent static wind loads and accelerations for survivability and habitability designs, respectively. Several web-based tools such as PHP and MySQL are fused with MATLAB to create efficient yet computationally robust interfaces that process, convert and analyze wind tunnel data on-the-fly. The attractive feature of this on-line processing approach is that no human effort is expended in determination and display of wind loads for the preliminary design of tall buildings. Moreover, this on-line analysis module provides the flexibility to utilize not only the NatHaz experimental PSD data, but also user-specified PSD expressions or PSD data sets. The methodology used in this study can be easily extended to more sophisticated numerical analyses employing the many pre-defined function capabilities of MATLAB.

ACKNOWLEDGEMENTS

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