Chapter 4

Wind-Induced Vibrations to Tall Buildings and Wind Turbines

Abdel Rahman Elbakheit

Additional information is available at the end of the chapter

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Abstract

While wind generated noise maybe limited in magnitude and effect, wind-induced structures' vibrations could be a devastation (i.e., Tacoma Bridge Collapse 1940). This occurs with just above moderate wind speed increase, if it can excite a structure with its natural frequencies. When this occur, structures enter a phase of oscillations until collapse. However, with proper understanding of vibrations in structures these vibrations can be eliminated. Studying vibrations can be experimental through wind-tunnel and or by simulations. Wind in buildings can induce two types of motions: static or sustained; as building drift and oscillatory or resonant vibration. Motion is composed of three contributions: sway in two horizontal or perpendicular directions and torsion. This vibration would considerably affect the habitability and stability of building spaces gauged through a life cycle assessment study, habitability perception and determination or acceleration measurements and estimation. The novelty of aerodynamic design and optimization in providing vibration free tall buildings and wind turbines with added savings that otherwise be incurred by adoption of costly structural and/or supplementary damping technologies highlighted. Better habitability, safety and comfort without added costs. State of the art in wind vibrations reviewed, together with factors influencing control vibration in tall buildings and wind turbines.

Keywords: wind vibrations in tall buildings, vertex shedding in tall buildings, aerodynamic optimization of tall buildings, habitability and vibration conception in buildings, wind turbine integration in tall buildings, wind vibrations in turbines

1. Introduction

1.1. Building's aerodynamic performance to control wind induced vibrations

Generally speaking Wind affects buildings with two distinct effects, Buffeting and vertex shedding [1, 2] (i.e., Drift and oscillation as mentioned above). The first happens in the along wind direction force producing drag or overturning. If we consider a wind boundary layer acting on a tall square plan buildings with an angle α to the horizontal axis X, **Figure 1**. Wind velocity would be gradient along the Z-axis that is to say the highest wind speed would occur in the upper most position of the boundary layer and the lowest wind speed would be close to the ground. The building would experience a drag along all major axes X, Y, that are measured using local mean force coefficient CfD, and overturning or torsional moments over the X, Y and Z direction measured using overturning moments coefficients over the X-axis CML, over the Y-axis CMD, and over the Z-axis CMT, such as Shown in **Figure 1**. The second wind induced effect (i.e., Oscillations) is rather more complex in its cause, but usually happens perpendicular to the direction of wind flow and can be measured using fluctuating moments coefficient CFL presented in **Figure 1**.

As an aerodynamic reaction, wind induced vibrations or oscillations always triggered by the shape and form of the object subjected to wind flow [3]. The more uniform and symmetrical the form is, the more likely for it to oscillate in wind flows. Therefore, considering these factors first would lead to permanent passive solutions to vibrations in structures due to wind. There has been growing evidence from research of wind-induced vibration that symmetrical cross sections of structures may produce vibrations to structures at one of their natural frequencies.

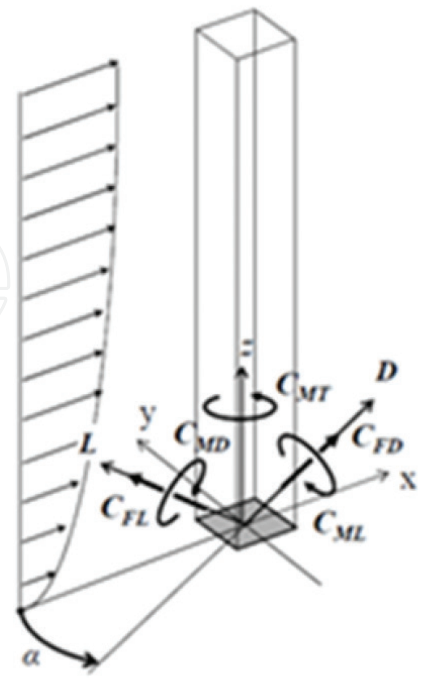

Figure 1. Aerodynamic forces acting on a basic square tall building.

As the expression of Strouhal gives the natural frequency N as a function of wind speed and width of the building as follows:

$$N = S\frac{u}{b} \tag{1}$$

where S = Strouhal number, U = wind speed, b = building width.

Having established that, this is generally have little effects on low-rise buildings. But the effect is highly pronounced in tall Buildings. With the new advancement in tall building structures, where high strength material coupled with reduced weight, it is made possible to design even more slender, more taller buildings quite easily and the trend is on the rise. These conditions makes high-rise buildings more prone to be excited by winds in the upper layers of the atmosphere that are usually with higher wind speed magnitudes.

On the other hand, only very specific wind speeds would cause the vertex shedding effect for any given tall structure by virtue of its three dimensional form and/or cross sectional plans. As mentioned above uniform plans of square **Figure 2**, rectangular **Figure 3**, circular **Figure 4** and similar shapes are more susceptible to trigger vertex shedding. This happens as wind approaches a high-rise structure it separated into two streams along the sides of the building by the plan shape creating equal vertices along each side faces of the building that are identical in shape and size **Figure 2**.

However, only at certain wind speeds the vertices would be greater in size and stronger in velocity magnitude to force its way on one side of the tube. Thus forcing the structure to

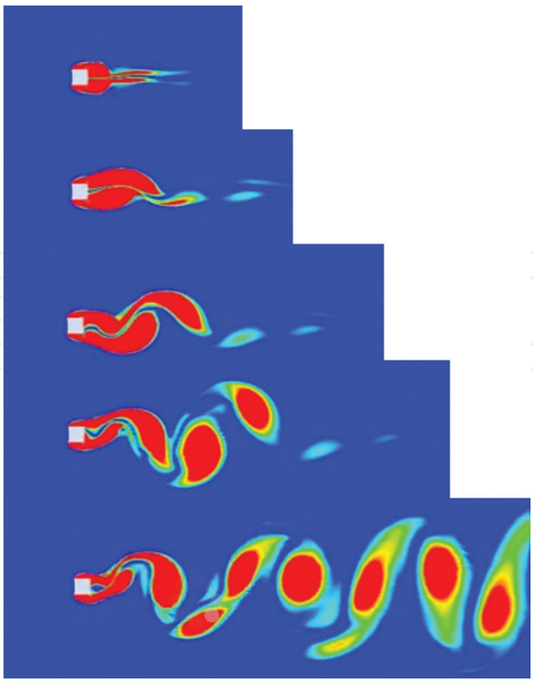

Figure 2. Computational fluid dynamics image for air flow around a square tube under vertex shedding effect, with stages of vertex formation.

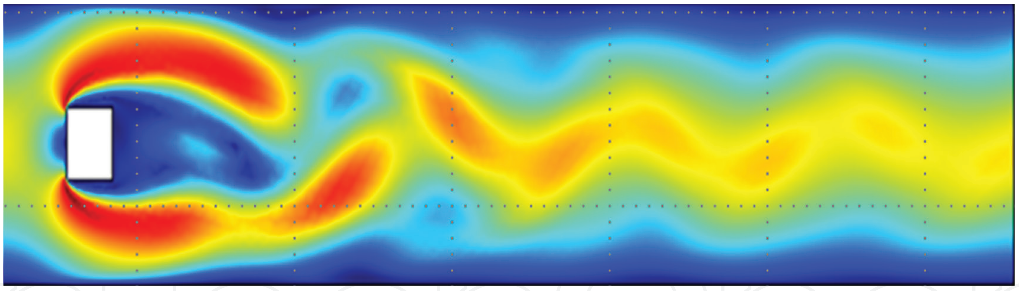

Figure 3. Computational fluid dynamics image for air flow around a rectangular tube under vertex shedding effect.

sway to the other side. The structure would sway back to position and beyond by virtue of its elasticity. Then comes the succeeding vertex to push the structure further to the opposite side. This is where the Oscillation process would typically starts. The oscillations would be sustained by the differences in wind pressures along the opposite sides of the building swept across that eventually cause the tall structure to continue to sway in the direction perpendicular to the wind's main stream. This phenomena has been experienced widely in some industries such as factory's Chimney stacks, undersea cables, bridges, tall buildings and so forth and whenever a main stream fluid passes across a uniform geometrical object.

These oscillations of structures/objects caused by vertex shedding because of wind speed produce air pressures similar in behavior to the sinusoidal waves of sound. However, opposite in its process to the normal process of sound generation. Sound is generated whenever an object moves in air causing a succession of higher and lower pressure regions, which can be presented (i.e., heard) as a sound wave. Therefore, we can expect noise produced accompanying vertex shedding of structures or objects.

Nevertheless, with the right building three-dimensional design configuration and cross sections of it plan, it would be possible to totally control any possible wind induced vibrations in tall buildings. Thus providing great savings that otherwise needed to increase the mass (concrete), stiffness (reinforcement) and damping (restraint) needed to stabilizing structures against excessive wind vibrations.

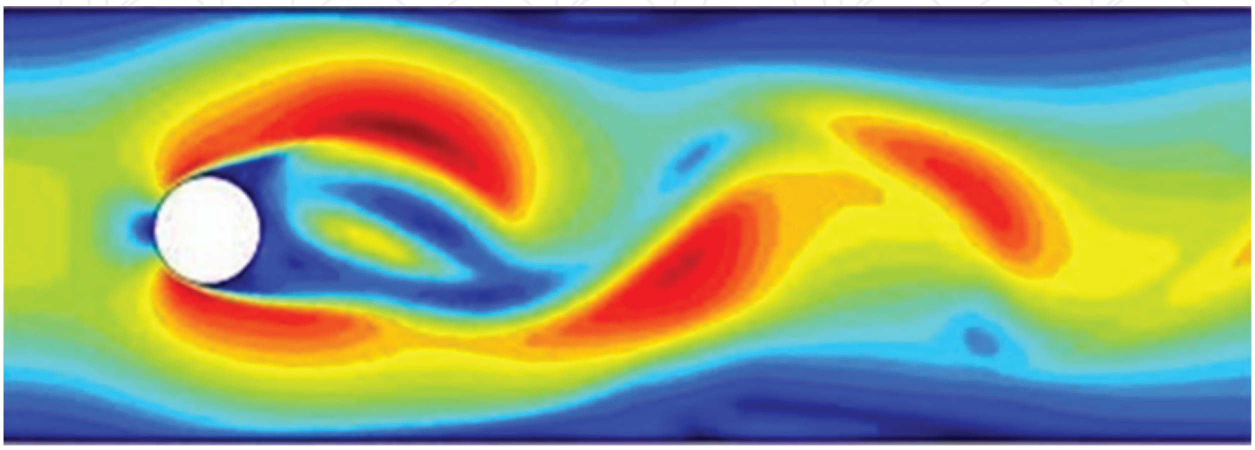

Figure 4. Computational fluid dynamics image for air flow around a circular tube under vertex shedding effect.

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To arrive at a building form or shape that is vertex shedding free can involves computational Simulations and or wind tunnel experimentation trying to break the symmetry of the buildings plans and forms. Mooneghi and Kargarmoakhar [4], proposed minimal intervention to any proposed buildings forms by the additions of small fins and corner modifications that help considerably reduce the shedding effect. Several studies have been conducted on this subject in the past (e.g., Gu and Quan [5], Irwin [6], Irwin et al. [7]) but each case study should be carefully evaluated to avoid unfavorable effects in building behavior. This is identical to what would typically be applied in manufacturing industries exhaust or stack chimneys, undersea cables previously mentioned examples of industries. However, these solutions may not always be practically or technically feasible to integrate into building's facade systems, **Figure 5**.

A more efficient approach for dealing with this issue in buildings is to Further modify forms three dimensionally in what is known as aerodynamic design modification of building forms based on combinations of the cross sections and their combinations three dimensionally compared to basic square tall buildings. A good example for this point is Burj Khlifa Tall building in Dubai, where the building have tapering plans being reduced with height, as well as breaking the uniformity of form plans 2-dimenstionally and 3-dimensionally, **Figure 6**.

Tamura et al. [8], presented a systematic study of building forms subjected to wind influence ranging from simple forms to more complex combinations under direct wind and cross winds using wind tunnel's scaled models as well as computational fluid dynamics. Among the figures tested are basic forms include Square, rectangle, Circle and ellipse, Tilted and snaked or winded three dimensional tubes. Corner modifications, tapered, bulged, helical, top-openings all in different modifications and finally composite forms of several basic shapes, **Table 1**. Totaling 31 models in 7-categories.

The study compared values of overturning moments co-efficient CMD, CML, fluctuating overturning moments co-efficient CFL, Local mean wind force co-efficient CfD, in the along

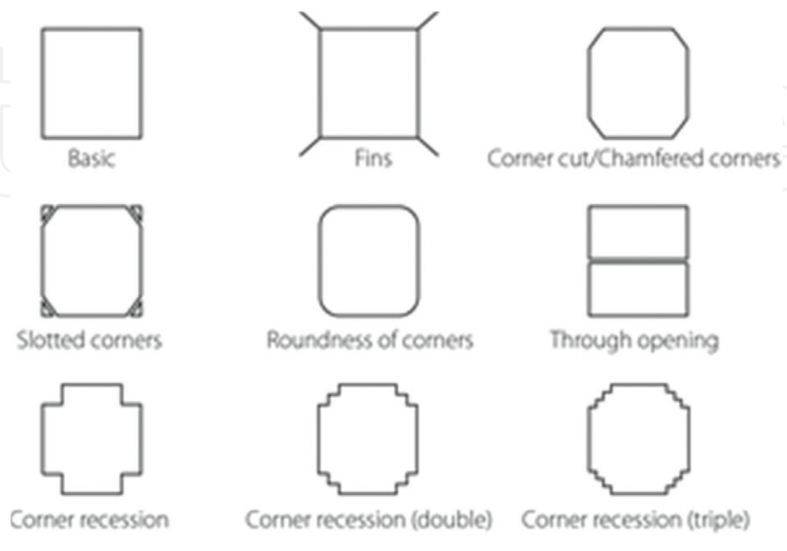

Figure 5. Minor aerodynamic modifications [4].

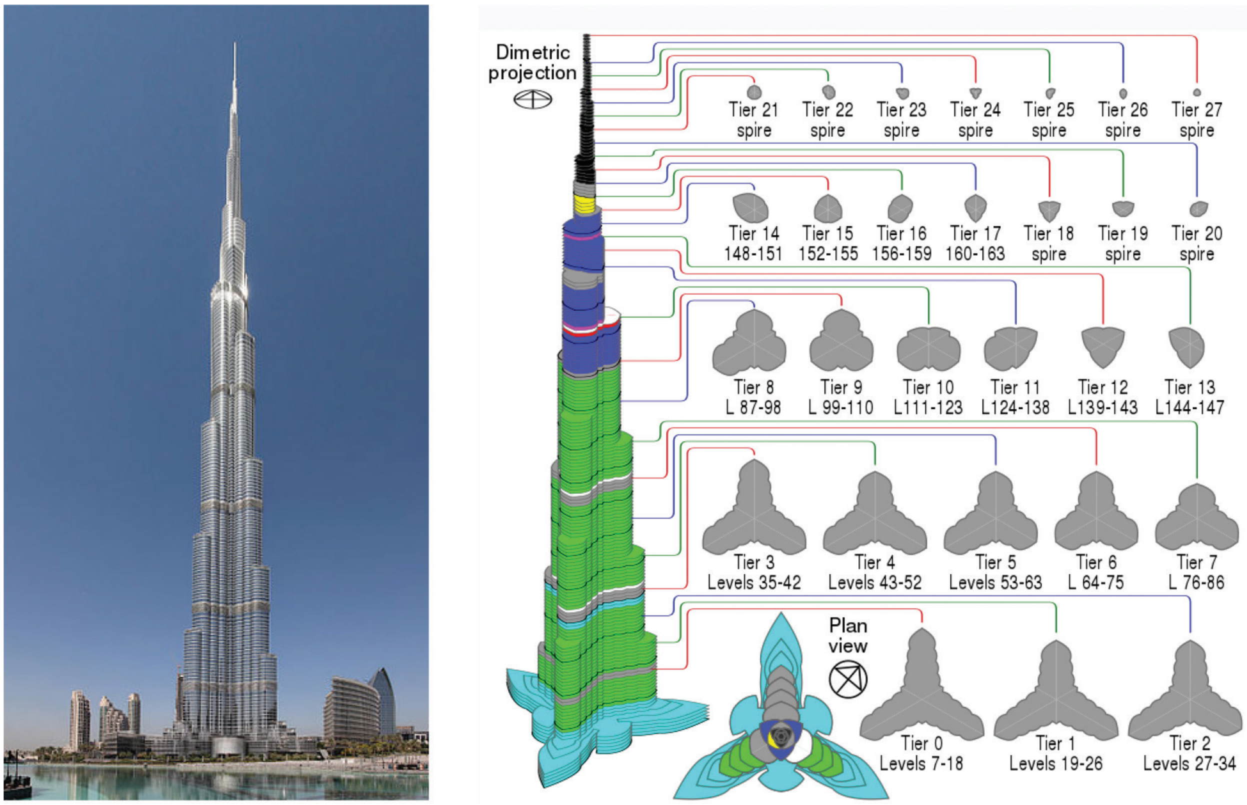

Figure 6. Burj Khalifa tower in Dubai. Modifications in plans shape and sizes with height.

wind, cross wind and torsional directions CMT, **Figure 1**. Distribution of wind pressure coefficient Cp and response analysis is also evaluated for these models. In order to determine the habitability of the studied models eigenvalue analysis and response analysis were conducted.

Corner cut and helical square models were the lowest in design values for spectral wind speed for one-year return period, which is far better than the response of the basic square model.

Basic	Corner Modified	Tilted	Tapered	Helical	Opening	Composite
Square	Chamfered	Tilted	Setback	Helical square 90°	Cross void	Helical +Setback
						

Table 1. Possible modifications in three-dimensional tubes to reduce vertex shedding effect.

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Meaning that they are the safest in terms of habitability and design safety. This was echoed with even better results for the models with extra-helical angles. Setbacks produced the minimal wind pressures because of reduced surface area with height; however, they experienced larger excitations of spectral wind speed than the original basic square form. Rendering it with worst expected habitability. This means that aerodynamic modifications can generally improve or eliminate vertex-shedding excitations.

1.2. Occupant's perception to wind induced vibrations

Undoubtedly that vibrations to structures would produce uncomfortable sensations to occupants especially in the highest floor due to more excessive vibrations. However, people perceive motion quiet comfortably, but it is the rate of motion (i.e., accelerations) that causes uneasy or discomfort. Therefore, vibrations are normally expressed as fractions of acceleration due to gravity in the form of (milli-g). Human perception to vibration is a complex sensation that encompass subjective and objective factors. The former is dealing with issues that may be subject to individual's age, culture, experience and so forth, while the latter is well-established physical phenomena that is measured, determined and occur with consensus among humans.

To give some indication what certain levels of "milli-g" actually mean for a human being (i.e., Objectively), the following extract from a monograph on wind-induced motion of tall buildings, published by the American Society of Civil Engineers [9], is provided:

5 milli-g: perceptible to some occupants but, provided that such building motion does not occur frequently or continuously for an extended period of time, unlikely to cause significant adverse occupant response or alarm;

10 milli-g: perceptible to the vast majority of occupants;

35–40 milli-g: a fear and safety threshold, sufficiently severe enough to cause some occupants to lose balance;

Occupant's response (i.e., subjectively) to wind vibrations come in different symptoms grading according to the severity of the motion – from concern, anxiety, fear, vertigo, dizziness, headaches and nausea. Some of these symptoms are often enhanced by the presence of audio stimulus, such as, wind noises, creaking noises due to building sway and/or visual stimulus, which is particularly relevant in the case of a tall building exhibiting highly three-dimensional modes of vibration.

It should also be noted that perceptibility of wind-induced motion is inversely proportional to the square root of the product of mass, stiffness and damping; this means that, in order to halve the perceptibility, the "mass × stiffness × damping" quantity needs to be increased by a factor of 4.

$$perceptibility = \frac{1}{\sqrt{(mass) \times (stiffness) \times (dampness)}} \tag{2}$$

1.3. Habitability in some international building codes

In 2004 the Architectural Institute of Japan (AIJ), produced a guideline to the levels of wind-induced accelerations that is relating to the natural frequencies of buildings. Focusing on 1 year return period (i.e., the maximum acceleration for a structure that can happen in a single year). The process involves determining buildings spectral response for a year and plotting it into a graph of a relationship between building's natural frequencies and acceleration. The position of the building's plotted response will determine the percentage of people who would be affected by the ensued acceleration. **Figure 7**, depicts the graph from the AIJ.

The graph lines in **Figure 7** denotes 5-levels of percentages of people perceiving the acceleration effect. (i.e., AIJ H-10, H-30, H-50, H-70, H-90) were the number denotes the percentage of people perceived the effect. The higher the plotted position of a building's response on **Figure 7**, the worse is peoples experience inside it.

Following the AIJ recommendations, back in 2007, the International Organization for Standardization (ISO) published a set of guidelines, which have now become the most widely adopted criteria for habitability design internationally [ISO 10137, 2007] also in **Figure 7**. The acceleration limits (again set against a 1-year return period) vary with the natural period of the structure and they are more stringent for residential developments than for office buildings, **Figure 7**.

1.4. Intrinsic damping

Intrinsic damping is the natural properties of building materials and construction processes of withstanding wind effects without extra-means or supplementary damping. It is normally required for a yearly return period (the highest wind occurring within a year), however, longer periods would be favorable but very rear. The exact estimation of intrinsic damping can only be determined through actual measurements due to the many factors contributing to it. According to [8] main sources of intrinsic damping are:

- Material damping;
- Friction between members and connections;
- Structural system and joint types;
- Foundation and soil types (soil-structure interaction);
- Interior partitions;
- Exterior cladding;
- Other nonstructural members;
- Vibration amplitude.

Many completed buildings are been monitored globally trying to establish intrinsic damping magnitudes under wind service periods (yearly, 10-year, 50-year…).

1.4.1. Wind deflection criteria

Wind deflection in buildings is due to both the drag and oscillations wind forces. Is it very limited to negligible in low-buildings. However, in tall buildings, it is dependent on the type

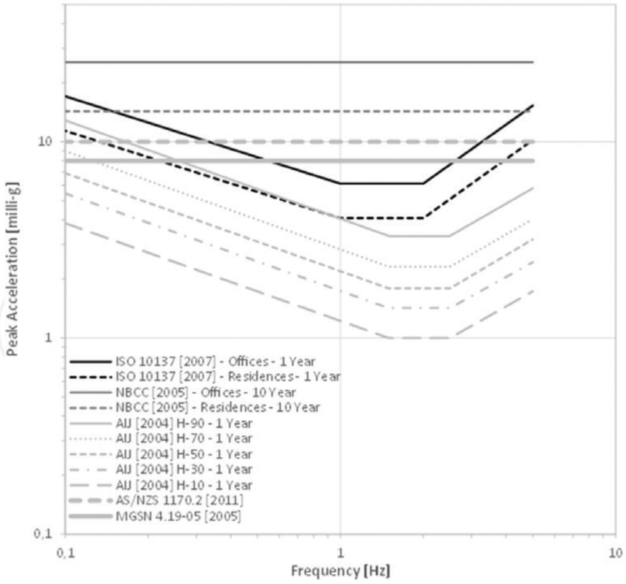

Figure 7. Comparison of average perception thresholds (where not indicated the return period is not specified by the relative code.

of building's structures and the wind forces applied to it. With outrigger systems, diagrid, bundle tubes having the most stable and least deflection while, framed systems having the highest deflections due to wind.(details of these systems is outside the scope of this publication).

We can generally measure two types of deflections due to wind in buildings. Overall deflection over the whole height of the building, which recommended being in the region of H/500 to H/300, Smith [9]. This normally perceived in the acceleration and habitability of buildings. The second is in plane or story deflection to individual units like doors, windows, cladding and similar systems from normal vertical and often affects the services, operations as well as soundness within buildings. With greater deflection of this type, building components like doors windows, etc. may lose operation and stick in frames.

For example, if we consider a 200 m residential tall building with a natural frequency of 0.25 Hz exhibiting a total building drift of 0.35 m under 50-year return period winds, this would meet the widely used H / 500 limit. If the corresponding total drift under 10-year return period winds is, say, 0.25 m and assuming that 50% of this is governed by dynamic behavior (i.e., vertex shedding) - which, in the across-wind direction, is not untypical – then the resulting wind-induced peak acceleration would move toward a rather undesirable 30 milli-g (50% × 0.25 m × $[2 \times \pi \times 0.25\ \text{Hz}]^2$).

2. Wind induced vibrations in wind turbines

Wind turbines come in different shapes and sizes, but they all convert wind power into electricity by converting wind motion into a mechanical movement and eventually into electricity. The conversion into mechanical movement can be partly converted into vibrations that reduces the efficiency of conversion to electricity. Besides, generating noise as well as faults due to vibrations.

With modeling of vibrations the failure of key components such as tower post, drive train, gear and blades can be greatly reduced if not eliminated. The main causes to vibrations can be varied according to each particular part of the turbine, however, almost all causes are due to aerodynamic behavior. Yet till different components have different types of vibrations and vibration causes. Tower's vibration, for instance, has a low frequency magnitude from 0 to 200 Hz, while the gear and drive train have high frequency (3–20 kHz). We can distinguish between these cases for the different components as follows:

Tower Post: the main support of the turbine, which is normally towering high to capture more wind speed. Its geometrical uniform cross section can cause considerable aerodynamic vibrations in the same manner discussed in point 1.1 and subsection above. It worth mentioning here that tall buildings can function as supports to wind turbines in the same manner.

Turbine blade: Turbine blades can cause vibrations in the turbine, associated gear and tower post if they or anyone of them has different pitch angles. This will cause unsteady rotational angular speed. Vibrations may be sever in above rated wind speeds (normally 12 m/s and above). According to Peng Guo and David Infield [10], "increasing the blade pitch angle beyond stall point may lead to aerodynamic lift coefficient decreases and the drag coefficient increases leading to increased thrust causing tower to deflect and vibrations to increase."

Because of the strong connectivity of the different parts together it may be difficult from start to distinguish the source of vibration in wind turbines. Not even with close monitoring, therefore, Peng Guo and David Infield [10] proposed a simulation depending on nonlinear state estimation technique NSET whereby it would be easily to compare turbine vibrations, wind speed, angle of blade, power generated and torque at normal and specific time steps. This will relate the positions of the blade pitch of the turbine, the conditions of the wind speed with the ensued aerodynamic response of power generation, stalling or vibrations. Therefore, potentially identifying the cause of vibration. NSET would also predict the magnitude of these vectors in a given timeframe, when comparing the prediction to the normally monitored data, any discrepancies may indicate a possible cause of failure including vibrations. However, NEST involves a mathematical modeling of the parameters simulated (i.e., turbine vibrations, wind speed, angle of blade, power generated and torque) and establish its validity to the actually recorded values from active monitoring beforehand. Only when the validity of the simulation is established the comparison process my take place. This process has not been used on many cases so its validity at large is not that solid. In addition to having, to distinguish between different operational modes (i.e., below rated wind speeds or above rated wind speeds); would mean making a simulation for each mode separately to be able to compare the results.

3. Wind turbines integration in tall buildings

The integration of wind turbine technologies in tall buildings poses great potential to harness the resources, which is abundant around tall buildings. This can be either on the top or

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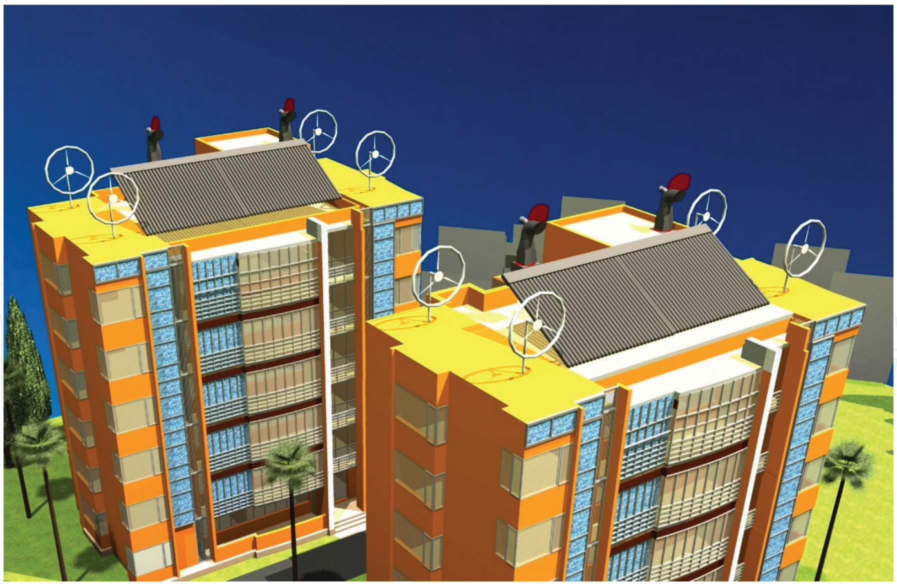

Figure 8. Wind turbines integration in tall buildings.

along the sides of buildings. Buildings can in fact provide the structural support as well as the continuous and sustained flow of wind needed to generate the required power, Elbakheit [11]. The acceptable process involves further optimization to tall buildings aerodynamic form as well as buildings structural loadings. Adding wind turbines to buildings (especially tall buildings) or existing buildings after construction may render the structure under vertex shedding effect, as it will change totally the aerodynamic response of the building as well as the resulting wind speeds around buildings.

Nevertheless, there are many models of wind turbines that are more quiet with less vibration such as Vertical axis wind turbines that can be integrated with tall buildings with little draw backs. In addition, using a number of small capacity wind turbines of less than 100 kW would break wind aerodynamic forces into small manageable portions compared with the option of using large turbines of over 100 kW. This also reduce the burden of maintenance and provide backup should any single turbine fails. **Figure 8**.

4. Conclusions

A high level of vibration control is achievable with the right aerodynamic design solutions in buildings, wind turbines and any industry establishments.

Vertex shedding is an aerodynamic phenomenon that triggers oscillations and vibrations in various fields of construction as well as industries. Symmetrical plans' cross-sectional configurations are the most susceptible to wind induced vibrations.

Introducing transformations in plans, horizontally and vertically is the key to control wind-induced vibrations in both buildings and various industry establishments. Corner modification, fins, torsional or spiral additions are among the favorable solutions in chimneystacks, undersea cables and similar structures.

Three-dimensional form modifications are the more efficient solutions for tall building structures.

Corner cut and helical and spiral plan modifications in various angles and configurations can considerably reduce or eliminate the vertex shedding effect in tall buildings. Setbacks, although it is a form of three-dimensional plan modification, yet due to the reduced mass at the top of tall buildings might trigger vibrations more severe than the standard uniform plans.

The recommended limit for wind vibrations or oscillations for a structure is in the range of H/300 to H/500 were, H is the height of the buildings.

Human perception to vibration varies and depends on acceleration (rate of motion) related to gravity acceleration g. Alarming vibrations occurs above 30 milli-g.

Tall buildings provide a promising building type for wind energy integration. Furthermore, the addition of wind turbines into building either new or retrofitting can render the building under vertex shedding. Exercise extreme caution to optimize wind flows around buildings to enhance power generation as well as to avoid vertex shedding.

Wind Vibrations in wind turbine caused either by turbine tower cross-sectional symmetry and/or by, the unbalanced pitch angles of turbine blades. Therefore, checking turbine blade angles first would assures of turbine's stability, if vibration still exists, then it will be the symmetrical cross section of the supporting post.

Further aerodynamic optimizations research in tall buildings' 3-dimensional configuration and/or aerofoils for integration of sizable small-scale wind-harnessing technologies can add to the safety, habitability of tall buildings with renewable energy at hand.

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Author details

Abdel Rahman Elbakheit

Address all correspondence to: abdel.elbakheit@hotmail.com

Department of Architecture and Building Science, King Saud University, Riyadh, Saudi Arabia

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