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Bio-mimicry inspired tall buildings: The response of cactus-like buildings to wind action at Reynolds Number of 10^4

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ABSTRACT

Applying bio-mimicry intelligence to the aerodynamic performance of tall slender buildings has potential to lead to not only improved response to wind loading, but generate savings in material and construction costs, affect energy consumption by providing self-shading and controlling local air flow to promote local wind energy generation and ventilation strategies. To this end, the alongwind and crosswind responses of high aspect ratio (15:1) cylinders, (smooth, roughened and grooved) were obtained from wind tunnel tests in simulated smooth and rough atmospheric boundary layer flows. The influence of top, flat or domed was also studied. The *Saguaro* cactus-inspired cylinder with 24 circumferential grooves was seen to have large reductions (~20%) for mean and fluctuating alongwind base shear (drag) and overturning moments in comparison with smooth cylinders and is in agreement with 2D studies in uniform low turbulence flow. Domed tops also led to reduced drag over flat tops. Differences in fluctuating crosswind base shear (lift) and overturning moment were much less marked. In spectral terms the amplitudes of response near the pronounced vortex shedding frequency were almost unchanged, however the cactus-shape had a higher Strouhal Number indicating a shift to a higher frequency as might be attributed to a narrowing of the wake.

1. Introduction

Urbanization is seen as the key feature of population change over the next 40 years (United Nations, 2012). Clearly the density of cities must increase if commuting and work days are to be kept to sustainable levels. This implies that the average building height must rise in most large urban areas around the world rather than in just a few select cities and given typical plot sizes in developed cities, it is not necessarily that the buildings will become exceptionally tall, but rather more slender and consequently prone to aerodynamic effects. Currently typical urban tall buildings have height aspect ratios (Height/Plan dimension) well below 10:1, the original World Trade Center twin towers were 7:1. While building developments are now being planned with height aspect ratios exceeding 20:1, it is timely that the response of such slender buildings is evaluated from a generic viewpoint.

The need to build densely implies not only building higher but also building faster, safer and lighter. New construction techniques such as modular off-site construction may render slender buildings more sensitive to wind due to their reduced weight which could imply that in order to build slender, lighter structures within a densely populated urban area, reduced cross-wind response without losses of significant floor area is required for an efficient solution. For such cases, large geometric gestures, the traditional approach to improve aerodynamic response, such as tapering, chamfering or stepping the building shape might result in substantial floor area loss and reduced ability for repetitive modular construction. Local small scale changes to the plan, potentially introduced within the depth of the envelope, could be more cost effective both for floor area efficiency and ability to construct repetitively. Another implication of the projected urban growth would be an increase in energy consumption in cities and greater mechanical efficiency of buildings through self-shading and natural ventilation will become increasingly important.

To ensure that these taller, more slender buildings remain economically sustainable, nature through evolution provides examples of tall and slender structures with clear economy. One such example is the Saguaro Cactus (*Carnegiea gigantea*). Found in the US desert south west and growing to 15 m or more in height, with aspect ratios (height/diameter) well over 20 (Hodge, 1991), these cacti typically grow as isolated 'structures' and evolution has developed an efficient system to resist environmental loads

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without relying on the shelter of forests. This cactus suggests a potential bio-mimicry inspired solution to future urbanization. Approximately circular in cross-section but with deeply grooved trunks, these cacti have inspired several studies, many focused on drag reduction (alongwind response) and with very limited attention paid to crosswind response which is more often the critical design issue to be addressed in tall building design. This paper presents the results from a recent wind tunnel study to better understand the impact of the grooved circumference on the aerodynamic response of tall slender cylinders under typical wind loading scenarios. In the following section background research on flow around cactus-like shapes are presented. Next the experimental program is described in detail and the results presented and discussed for mean and fluctuating loads. Comparisons are made with earlier studies on wake interaction and drag reduction. Finally conclusions are drawn concerning the effectiveness of bio-mimicry inspired tall slender structures to address the pressing demand of urbanization. Additionally, our ability to learn from nature should extend to holistic design which addresses more than just the aerodynamic performance of tall buildings, but simultaneously the impact on heating loads, and local flows thus promoting wind energy generation and enhancing the potential for natural lighting and ventilation strategies.

2. Background

Bio-mimicry in aero- and hydro-dynamics is not novel. Drag reduction on moving and stationary bodies immersed in a flow has inspired much research particularly as the cost of energy becomes more significant. In reviewing this topic, Bushnell and Moore (1991) details nature's success stories in evolving low drag devices, from surface treatments (roughness), 'turbulizing' features to 'bleed flow' through feathers. Bushnell indicated that cactus shapes result in reductions in drag but did not quantify this observation. Hodge (1991) reports on the desert south west Saguaro cactus that grow to height aspect ratios (H/D) of well over 20:1 and with 10–30 grooves around the circumference depending on age with typical groove depth to diameter ratios (e/D) of around 7%. In a longitudinal study (Pierson and Turner, 1998), where wind speed was monitored, saguaro cacti were exposed to monthly winds in excess of 22 m/s with limited failure, indicating a potential aerodynamic advantage evolved by this species of cactus. Table 1 summarizes recent research specifically on cactus-shaped objects, and some individual studies are described in more detail in the following.

In research at Stanford in the early 2000's Talley (Talley et al., 2001; Talley and Mungal, 2002) studied the drag reduction of cactus shapes on 2D cylinders in uniform flow. Undertaking both physical and numerical studies, they noted large reductions, ~25%, in mean drag, with cavity depth having a strong effect (reduction) on the drag and a '…substantial dampening effect on the unsteady motion', although this was not quantified. In the range of Reynolds numbers studied, $4–20\times10^4$, the grooved cylinders showed no Reynolds Number dependency unlike the sandpaper roughened smooth cylinders which showed clear drag crises. The attempt at studying cross-wind forces was somewhat unsuccessful because of poor choice of force balance, with low natural frequency and undocumented damping.

Yamagishi and Oki (2004, 2005) undertook wind tunnel and computational studies on the effect of groove shape and number around 2D circular cylinders. The flow was uniform with very low turbulence. Mean surface pressures were measured and drag forces computed. Increasing the number of grooves lead to earlier drag crisis as a function of Reynolds Number, while triangular grooves led to lower drag than arc grooves.

Babu and Mahesh (2008) also undertook numerical studies on a cactus shaped cylinder similar (number and depth of grooves) to that studied here. However their Reynolds Number was extremely low ~100–300, well below full scale values and their results are difficult to compare to other work at 10^4 or higher Reynolds Numbers.

Liu and coworkers (Liu et al., 2011; Levy and Liu, 2013), undertook extensive Time-Resolved Particle Image Velocimetry (TR-PIV) measurements in a water flume. The TR-PIV was able to resolve the flow field in detail, and specifically shear layer

Table 1
Previous studies of flow around cactus-like cylinders.

Source	Experiments	Flow type	Reynolds No.	Model details	Groove depth	Other
Talley et al. (2001)	Drag (wake traverse – with pitot) CFD-RANS (v^2-f)	Uniform	$2–20\times10^4$ $2–10\times10^4$ (CFD)	2-D, 24 grooves $L/D=7.1$ 13% blockage	$e/D=0.035$, 0.07, 0.105	Smooth and rough $ks/D=2.5\times10^{-3}$ (sand paper)
Talley and Mungal (2002)	Surface pressures, base forces (Drag and Lift) (highly damped)	Uniform		2-D and 3-D flat topped 24 grooves, $L/D=7.1$ (2-D), $L/D=5.47$ (3-D) blockage 13% (2-D) 10% (3-D) corrections applied	$e/D=0.035$, 0.07, 0.105	Smooth and rough $ks/D=1.7$ and 8.4×10^{-3} (sand paper)
Yamagishi and Oki (2004)	Pressures, drag (wake traverse), CFD-RANS(k-ε)	Uniform, 0.65% turbulence	$1–10\times10^4$	2-D, 32 grooves, $L/D=8.75$, 12% blockage	$e/D=0.01$ Triangular or Circular Arc grooves	
Yamagishi and Oki (2005)	Pressures, drag (wake traverse), CFD-RANS(k-ε)	Uniform, 0.65% turbulence	$1–10\times10^4$	2-D, 20, 26, 32 grooves, $L/D=8.75$, 12% blockage	$e/D=0.01$	
Babu and Mahesh (2008)	CFD – DNS Pressure, viscous and pressure drag		20, 100, 300	2-D, 24 grooves	$e/D=0.105$	Smooth cylinder as well
Abboud et al (2011)	Surface pressures	Uniform	$6.8–21\times10^4$	2-D, 8 grooves, $L/D=6.6$, 15% blockage	$e/D=0.08$ U-shaped grooves	
Liu et al. (2011)	TR-PIV (water tunnel)	Uniform, 2% turbulence	1.5×10^3	2-D, 24 grooves $L/D=10$, 7.5% blockage	$e/D=0.07$	
Levy and Liu (2013)	TR-PIV (water tunnel)	Uniform, 2% turbulence	$0.4–2.4\times10^3$ (Water tunnel)	2-D, Spines NOT Grooves $L/D=10$, 7.5% blockage	$s/D=0.1$, 0.2	Smooth cylinder as well
ElMakdah and Oweis (2013)	PIV	Uniform	$5–17\times10^4$	2-D, 8 grooves, $L/D=6.5$, 15% blockage	$e/D=0.08$ U-shaped grooves	