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Improving aerodynamic performance of tall buildings using Fluid based Aerodynamic Modification

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ABSTRACT

A novel approach is proposed to integrate active air flow control into the assembly of building envelopes in order to affect the interaction between tall buildings and surrounding air flow. The potential benefits of the proposed approach include reduction of embodied energy contained within the building structure, improvement of the overall life-cycle of building materials, and increased access to natural daylight by shallow lease spans. To date, the trend towards light-weight and high-strength materials in tall buildings, compounded with the emerging inclination towards modular prefabrication of structural assemblies, increasing flexibility and reduced damping, and greater slenderness ratios, has increased the susceptibility of the structural performance of tall buildings to dynamic wind load effects. Currently, mitigating wind loads relies on either changing structural or geometric characteristics such as the building's shape or through the addition of auxiliary damping systems. Furthermore, market driven pressures on increasing the slenderness ratios of tall buildings have been at odds with the socio-economic viability of the corresponding deep lease spans that tall buildings have required at their base. The proposed Fluid-based Aerodynamic Modification (FAM) approach is fundamentally different: instead of re-shaping the solid material to improve the aerodynamic 'shape' of the structure, fluid-based active flow control is used to manipulate the separating boundary layer in order to improve the building's aerodynamic performance and thus reduce the wind excitation.

1. Introduction

The goal of this work was to demonstrate through wind tunnel tests the feasibility of FAM to improve the aerodynamic performance (specifically those governing the crosswind response) of a bluff body through a controlled introduction of momentum into the separated region over a tall rectangular prism having 15:2:1 height to plan dimensions immersed in a turbulent boundary layer.

The use of light-weight, high-strength materials in tall buildings has produced structures which are increasingly susceptible to dynamic response under wind loads. The greater flexibility and reduced mechanisms to dissipate energy along with increasingly detailed comfort criteria tend to limit the gains afforded by incorporating these new materials.

For many new tall buildings, occupancy acceleration criteria govern the structural design. Of the alongwind, crosswind and torsional responses, frequently it is the crosswind response, driven by wake excitations, which causes the greatest accelerations and thus influences the comfort driven design (Kwok et al., 2014). That is, strength design for peak predicted base moment or shear is not the governing criteria; rather, it is a wind event that occurs perhaps only once a year, which does not affect safety, only serviceability that is most critical. It is with this in mind that the authors pursue a method to directly modify the 'critical' wind event(s) rather than increase the resistance. This knowledge also offers a great opportunity to increase the sustainable and economic viability of tall building topology.

Currently, reducing crosswind response relies on a Solid-based Aerodynamic Modification (SAM), either by changing structural properties such as damping (Kareem et al., 1999) or by modifying the building's shape in plan (Kwok, 1988) or elevation (Tamura et al., 2010). The effect of these changes has been mostly studied in isolation from other parameters in the design of tall building such as their implication on material consumption, usable floor area ratio (FAR) and related construction costs.

While this approach has merit, it has two shortcomings: first, the loss of rentable areas and increase in construction costs due to increased structural complexity and requirements, which further contribute to high consumption of non-renewable resources by

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the building sector. For example, an aerodynamically efficient plan shape comes at the expense of usable, and therefore valuable, floor area that may require additional compensatory stories, resulting in an increase in wind loads and construction costs (Tse et al., 2009). Second, a limited ability to adaptively respond to local fluctuating environmental conditions such as changes in wind direction or velocity over the height of building due to the 'rigidity' of the SAM solution.

1.1. A Fluid-based Aerodynamic Modification (FAM)

The proposed Fluid-based Aerodynamic Modification (FAM) is a fundamentally different approach: instead of adjusting the solid material to improve the aerodynamic 'shape' of the structure, fluid-based flow control is used to manipulate the flow field around the building. The physical shape of the building is virtually modified such that the local flow 'sees' a different shape, one that experiences induces reduced wind excitation (Fig. 1).

The rationale behind the FAM approach relies on concepts developed in the research field of Active Flow Control (AFC). The ability to manipulate a flow field actively or passively to affect a desired change is of immense technological importance, and this undoubtedly accounts for the subject being more avidly pursued by scientists and engineers than any other topic in fluid mechanics (Gad-El-Hak, 2000). Within the scope of this work the main goal is to disrupt flow separation in order to reduce the coherence and impact of the shedding vortices, thereby decreasing pressure fluctuations across the building envelope and reducing wind loads.

Central to the problem is the existence of the time varying turbulent flow field formed downstream of the building. The complexity of this flow regime, even in the presence of predictable incoming flow conditions, is the result of interaction between four unstable shearing regions: incoming atmospheric boundary layer (ABL), the boundary layer over the surface of the building, the separated shear layer and the wake. With this in mind, it is understandable that the literature has focused on simplified flows and geometries, mainly of 2-D circular and square cylinders at low Reynolds Number in a uniform approach flows. This has limited applicability to the built environment but has provided fundamental insight into the physics and the stability of wakes, which may be advantageous during studies with greater parametric freedom.

The desire to actively control boundary layer separation and the resulting wake instabilities has prompted considerable experimental, numerical and theoretical study, with the goal of understanding

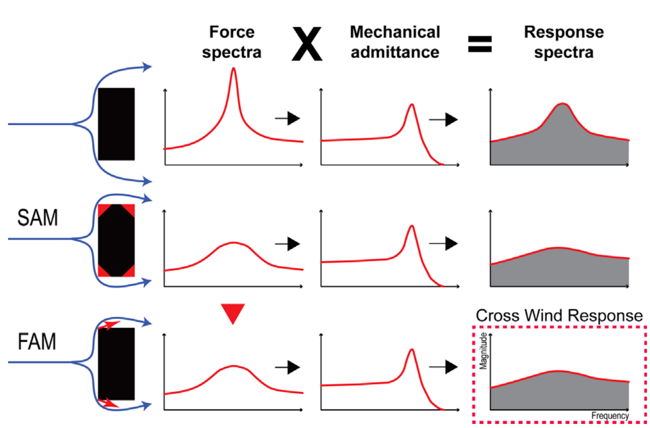

Fig. 1. In the FAM approach, the force spectrum is directly modified by manipulating the fluid structure interaction using flow control actuators. This approach enables the desired serviceability response criterion to be met without alteration to the building geometry (SAM) or by auxiliary damping (which would change the mechanical admittance).

the origin and evolution of the vortex shedding. The two strategies to actively control the boundary layer are steady and unsteady actuation. The first strategy uses a steady addition or removal of fluid momentum to/from the flow (blowing, suction or their combination or rotating cylinders mounted on a bluff body next to separation regions). The second strategy uses periodic addition or removal of momentum to/from the flow either by tuning to naturally occurring frequencies within the flow, and structures associated with them, or at frequencies that are much higher than any characteristic frequencies of the flow. This strategy includes various techniques and devices such as fluidic oscillatory blowing, suction or their combination, acoustical excitation, vibrating and shape changing surfaces. A further advanced unsteady technique (using devices such as synthetic jets) employs very high frequency periodic actuators, which decouple the actuation frequency from frequencies in the flow in order to create virtual aeroshaping.

In their theoretical and numerical work with steady actuation, Patnaik and Wei (2002) described a locale of absolute instability in the near wake dominated by temporal disturbances (amplitude insensitive) and a convective instability sensitive to all fluctuations. Suppression of the oscillating lift force was achieved by the introduction of angular momentum (by way of rollers) in the wake, increasing the size of a 'recirculation-free-zone' behind the body, which increases the base pressure (less negative). This ultimately led to reduction in the absolute and convective instability, dislocation and obliteration of vortex structures. This was preceded by a narrowing of the wake and an increase of the oscillation's frequency. Koutmos et al. (2004) used steady air injection into the base region and observed two distinct flow states: prior to, and after the jet penetrated through the vortex formation region such that it acted as a pseudo-splitter-plate. The vortex formation region elongated and pressure recovery were observed in the first state, while in the second, the jet prevented direct shear layer interaction, weakening the oscillating forces. A significant increase in the Strouhal number was observed for increasing quantities of momentum; this phenomenon, reported elsewhere (Patnaik and Wei, 2002; Munshi et al., 1999), is attributed to wake narrowing and irregular formation of smaller and larger vortices. In a similar study, Akansu and Firat (2010) reported similar findings but also identified the presence of a bi-stable mode for intermediate injection ratios.

Researchers have also employed unsteady flow control techniques with promising results. Zhang et al. (2005) used piezo-ceramic actuators to perturb the upstream surface of a square cylinder and alter the interactions between vortex shedding and structural vibrations. With actuation frequency at the order of the vortex shedding frequency, a 71% reduction in vortex strength was achieved when actuation was out-of-phase with the vortex shedding and 152% amplification when in-phase. Despite the fact that actuation was only imposed on one surface, the shed vortices appeared impaired (or amplified) on both sides equally. Actuators, such as synthetic jets (Glezer and Amitay, 2002), with actuation frequencies an order of magnitude higher than the shedding frequency, have also had great success. These jets do not take advantage of naturally occurring flow instabilities, as was done by, for example Nagib et al. (2004) and Greenblatt and Wygnanski (2000), who targeted wavelengths associated with naturally occurring flow instabilities. Rather, synthetic jets impose a virtual change to the shape (due to their high actuation frequency). Most recently, studies of the effect of a synthetic jet on a low aspect ratio, finite span cylinder showed that the interaction of the jets with the downwash from the free-end resulted in a global change to the flow field, yielding reduction in drag, and narrowing of the wake that persisted some distance downstream (DeMauro et al., 2012).

At the heart of any high frequency actuation method is the concept of virtual aerodynamic modification of surfaces