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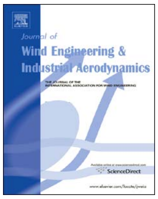

Mitigation of wind-induced accelerations using Tuned Liquid Column Dampers: Experimental and numerical studies

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ABSTRACT

During the early design stages of a relatively slender 42-storey high-end residential building located in the Middle East, a series of High Frequency Force Balance wind tunnel tests highlighted that the highest occupied floors could experience wind-induced motion which – depending on the inherent damping of the finished structure – had the potential to exceed standard industry occupant comfort criteria. In order to mitigate these excessive vibrations, a Tuned Liquid Column Damper solution was proposed for this building. The performance prediction and validation of the behaviour of such device involved: an initial campaign of full scale measurements to validate frequencies and inherent damping of the structure near completion; a series of shake table tests employing a 1:20 scale physical model; and a final full scale extrapolation study using Computational Fluid Dynamics. The damper study, which this technical paper is focused on, was part of a wider range of wind engineering consultancy services which included: wind climate study; pedestrian and terrace / balcony level wind microclimate study; overall wind loading study and façade pressure study.

1. Introduction

In order to enhance the capacity of a structure to dissipate energy, and therefore be able for example to mitigate any excessive wind-induced motion, auxiliary damping can be introduced within the structure itself. The simplest and more robust types of device that can be employed are the so-called passive dampers: these systems make use of a moving secondary mass capable to counteract the motion of the structure. Amongst these, Tuned Liquid Dampers (TLDs) have become very popular in tall building design, especially during the course of the last decades (Fujino et al. 1992; Kareem, 1990, 1993, Kareem and Tognarelli, 1994; Sakai et al. 1989); the main reasons for their success are:

i. The failure of such systems is virtually impossible;
ii. They are very effective in mitigating wind-induced motion;
iii. Their natural period is very easy to predict and relatively easy to adjust;
iv. They are inexpensive to build and virtually maintenance-free;

Before their first applications to ground-based structures (Modi and Welt, 1987; Tamura et al., 1988), dampers making use of properly tuned sloshing fluid in a container have been employed in other industries (Bhuta and Koval, 1966; Harris and Crede, 1987).

In civil engineering applications, two types of TLDs are commonly utilised: Tuned Sloshing Dampers (TSDs) and Tuned Liquid Column Dampers (TLCDs). TSDs can be either based around a deep or shallow water configuration: the shallow water ones dissipate energy through viscous action and wave breaking mechanism, whilst the deep water ones typically require baffles or screens to increase the energy dissipation of the sloshing fluid. Unfortunately, in deep water TSDs, not the entire mass of water actively participate as secondary mass (Kareem and Sun, 1987), a drawback that can be overcome by TLCDs. TLCDs comprise an auxiliary vibrating system consisting of a column of liquid often moving in a tube-like container: the restoring force is provided by gravity, whilst the energy dissipation is achieved through the baffles installed within the horizontal duct.

Whilst TSDs primarily utilise circular containers for shallow configurations and rectangular ones for deep water arrangements, TLCDs typically rely on U-shaped vessels.

Many analytical and experimental modelling techniques for the preliminary design of TLDs have been developed over the course of the last decades. The models which have been followed within the work presented in this technical paper are based on the

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equivalent Tuned Mass Damper (TMD) method, more specifically: the work of Kareem and Sun (1987) on the development and validation of equations that model the TLD behaviour as an equivalent linear TMD; the research of Sun et al. (1995) on the development of empirical amplitude-dependant parameters to be added to the linear TMD equations; the work of Yalla (2001), introducing a sloshing–slamming model that takes the effect of water slamming against tank walls into account; the experimental work of Tait et al. (2004), validating the coupling between the non-linear TMD model and the one of a Single Degree of Freedom (SDOF) structure; and the research work of Tait (2008) on the effect of submerged screens as a linearized equivalent damping ratio with subsequent integration within the equivalent non-linear TMD model he developed. With specific emphasis on the performance evaluation of TLCDs during their preliminary design phase, Di Matteo et al. (2014) recently proposed a new formula that allows the determination of the optimum parameters of a TLCD in a relatively quick and straightforward way.

With regard to existing installations, the sizes of TLDs can vary from relatively compact units – typically installed to mitigate wind-induced sway of air traffic control towers (e.g. the cylindrical multi-layered TSD units installed on the 42 m tall Nagasaki Airport Tower, totalling 950 kg, which reduced the structural response to wind of about 35% (Tamura et al., 1995), to much larger devices of several hundred tonnes (e.g. the two TLCDs installed at the top of the 52-storey Random House Tower in New York City of respectively 265,000 kg and 379,000 kg (Tamboli, 2005).

2. Background

2.1. Site characteristics

The location of the site of the proposed development considered within this technical paper was approximately 1 km from the Mediterranean coastline, with the immediate surrounding area consisting of densely populated low to mid-rise urban sprawl.

2.2. Wind climate analysis

When working in regions of the planet where little information is available with regard to design wind speeds – that is strength as well as directionality of the extreme wind events – purposely site-specific wind climate analyses need to be undertaken to inform and support the design process.

The first step in design wind speed prediction is the acquisition of long-term surface wind records: as part of the wind engineering work for the project presented within this technical paper, data from three weather stations within the region were considered. The length of the records of each station was in excess of 30 years and information about thunderstorm events were available: this allowed thunderstorms to be separated from the entire dataset and independently analysed from synoptic wind events. Once the records have undergone quality control checks and after they have been subjected to appropriate transposition to uniform terrain category (Engineering Science Data Unit, 2006), a mixed-climate extreme value analysis was performed.

While the origin of extreme value analysis is more than fifty years old (Gumbel, 1958), more sophisticated approaches that consider in greater detail the meteorological phenomena behind the different types of storm mechanisms have been developed during the course of more recent years (Lieblein, 1974; Gomes and Vickery, 1978; Cook, 1982; Harris, 1999; Cook et al., 2003). For the project presented within this technical paper, the analysis method of Cook et al. (2003) was utilised.

The 50-yr return period mean-hourly basic wind speed for the region was found to be ~25 m/s (10 m reference height in $z_0 = 0.03$ m), whilst the characteristic product of the local wind climate was found to be ~4.

2.3. Building characteristics

The height of the building was ~180 m, with a ~22 m × ~44 m rectangular typical floor plan (the slenderness ratio of the building in its weak axis was ~1:9). The unconventional massing of the building features four superimposed and zigzagging volumes rising between two existing tall buildings.

The structural stiffness, in relation to horizontal loading, was provided by a central reinforced concrete (RC) core. The structural frequencies of the three fundamental modes of vibration of the building predicted by the Finite Element (FE) model developed by the structural engineering firm working on this project were: 0.19 Hz, 0.26 Hz and 0.53 Hz, with the first two describing pure sway of the structure along the two principal axes of the central core (the exponent of these mode shapes was ~1.5) and the third one being torsional. In the investigation of the win-induced response of tall buildings only the first three fundamental modes of vibration of the structure are typically considered: higher order modes can become relevant – especially in the assessment of the wind-induced accelerations – only in the realm of super-tall buildings ($H > 300$ m), especially for tapered forms (Cammelli and Wyatt, 2011).

The density of the building was of the order of 400 Kg/m^3 and the level of eccentricity of the centre of gravity of each floor plate along the vertical development of the structure was contained within ±5 m.

3. On-site full scale measurements

When the construction of the super-structure of the tower approached its completion – and before commencement of the installation of the cladding, a campaign of on-site full scale measurements was conducted to detect some of the key structural parameters of the building, particularly structural frequencies and damping.

In order to achieve this, the 34th level of the tower was instrumented with a pair of tri-axial high performance accelerometers (measurement range: ±1.5 g and resolution: 0.00005 g) with the aim of acquiring a large number of ambient data records. Before commencement of post-processing, the different time-histories of recorded wind-induced accelerations was digitally low-pass filtered at a frequency of 1 Hz to remove high-frequency noise content which – due to the nature of the site – have inevitably been picked up during the measurements: as already pointed out in Section 2.3, this process is perfectly licit as the contribution of the higher modes of vibration of the structure to the total wind-induced acceleration of the building is negligible.

The different time-histories have then been analysed making use of the so-called random decrement (RD) technique (Tamura et al., 2000; Li et al., 1998, 2003), which enabled the random and chaotic part embedded in the actual measured signals associated with the excitation from the atmospheric turbulence to be fully removed, revealing the far more regular ‘signature’ left by the structure itself.

Subsequently, a time domain (output only) modal identification (MI) routine (Tamura, 2005) was applied to the RD signatures in order to identify the frequencies and damping of the building during construction. The first two modes of vibration of the structure have been found well aligned with the two principal axes of the structural core of the building and their frequencies (~0.30 Hz for the weak axis and ~0.43 Hz for the strong one) in