

Title:	<b>Interactive Aerodynamic Design of Supertall Buildings</b>
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Subjects:	Sustainability/Green/Energy Wind Engineering
Keywords:	Aerodynamics Structure Wind Tunnel Testing
Publication Date:	2012
Original Publication:	CTBUH 2012 9th World Congress, Shanghai
Paper Type:	<ol style="list-style-type: none"><li>1. Book chapter/Part chapter</li><li>2. Journal paper</li><li>3. <b>Conference proceeding</b></li><li>4. Unpublished conference paper</li><li>5. Magazine article</li><li>6. Unpublished</li></ol>

# Interactive Aerodynamic Design of Supertall Buildings

## 超高层建筑的交互式空气动力设计



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## Abstract

In order to maximize the benefit of early stage wind tunnel tests, the authors of this paper have developed tools which enable dynamic wind tunnel testing workshops that allow rapid optimization of building aerodynamics and structural performance. They allow derivation of meaningful performance information within minutes of wind tunnel data acquisition and rapid modifications can be made to the structural properties of the building and to the wind tunnel model geometry to allow responsive re-testing. This makes the full integration between architecture and supertall building aerodynamics a reality, enabling the generation of building envelopes specifically tuned to optimize the performance of the lateral-stability system to wind loading excitation. This paper presents case studies which show the development of this process.

**Keywords: Aerodynamics, Wind tunnel testing, HFFB, dynamics, mode shape, structural frequency.**

## 摘要

为了最大化早期风洞测试的效益,本文作者在他们各自的专业领域,共同开发了让动态风洞试验研讨会得以实现的工具,从而使得建筑空气动力特性和结构特性得以快速优化。这些工具能在几分钟的风洞数据采集时间里,获得丰富且有价值的性能信息。据此对建筑的结构特性以及风洞模型的几何外形作快速修改,使其能在研讨会时立刻进行相应的再测试,使建筑学与建筑空气动力学的交互设计变得现实,有针对性地调整建筑外形以优化建筑结构抗风横向稳定系统的性能。本文列举了数个分析案例来说明建筑空气动力学交互设计研讨会到目前为止的开发进程。

**关键词: 空气动力学, 风洞试验, 高频测力天平, 动力学, 模态振型, 结构自振频率**

## Introduction

As modern tall and supertall buildings (often of non-orthodox architectural forms) are becoming taller and more slender they also become more sensitive to dynamic wind-induced excitation, especially in the cross-wind direction which is often driven by vortex-shedding excitation. The importance of such cross-wind excitation and its intimate relation to the architectural form of a tall building is well known [Shimada et al. (1989), Hayashida and Iwasa (1990), Dutton and Isyumov (1990), Miyashita et al. (1993), Kareem et al. (1999), Tamura et al. (2011)] and has now also been considered in the current draft of the new Chinese Building Code (GB 50009-201x). It is however difficult to intuitively predict the impact of building form on vortex-shedding, and so lateral wind loading and wind-induced accelerations, which are often critical factors for the structural efficiency of a tower, cannot always be appropriately considered and addressed.

In the last decade, technical developments in the design and construction of high-frequency force balance (HFFB) models have allowed compound wind tunnel model / balance frequencies in the excess of 100Hz to be achieved even for supertall and very

## 引言

随着现代高层与超高层建筑(通常是非传统建筑形式)建得越来越高,建筑形态越来越纤细,使得这些建筑物对动态风致激励更加敏感。特别对由漩涡脱落引起的横风向激励。横风向激励的重要性及其与高层建筑外形的紧密联系是众所周知的[Shimada et al. (1989), Hayashida and Iwasa (1990), Dutton and Isyumov (1990), Miyashita et al. (1993), Kareem et al. (1999), Tamura et al. (2011)],新的中国建筑设计规范送审稿中已对横风向激励予以考虑。但是想直观地预测漩涡脱落对建筑的影响还是比较困难的,横风向荷载和风致加速度通常是影响高楼结构效率的重要因素,难以总是得到适当的处理和考虑。

在过去的十年里,对高频测力天平模型在设计与制作上的技术提升,让即使是非常高而细的建筑,都可以使风洞模型与天平的组合体固有频率超过100Hz。在模型频率比约为1:100时,模型强度使测试速度超越雷诺数 $\sim 2 \times 10^5$ 成为可能,同时保持在设计风速范围内足尺高层建筑结构频率的良好独立性。本文作者已在一些高层建筑项目的早期阶段进行了风洞试验,这使风荷载和动力响应的风险能在设计初期得到控制,但这也要基于对已定建筑造型中关键问题的检验方式。

slender buildings. At typical frequency scales of the order of 1:100, the stiffness of these models made testing speeds in the excess of Reynolds number  $\sim 2 \times 10^5$  possible, while still retaining a very good separation from the full-scale structural frequencies of the tall building at the design wind speeds of interest.

Working together, the authors of this paper have carried out wind tunnel testing in the early stages of several tall buildings projects. This has enabled the risk in terms of wind forces and dynamics to be managed early on, but it has tended to be based on the approach of checking predetermined architectural forms for critical problems.

This work has shown to the team that it would be much more advantageous in terms of design progression to be able to run a series of interactive tests early in the design process and within a workshop environment where results can be produced almost in real time and, in reaction to this data, designs altered and re-tested. Ideally this would be carried out in a fashion similar to wind environment testing where the architect and other members of the design team can be directly involved.

The ultimate aim is to help define a process that ensures a better integration between the architectural form and the resulting structural design, which in turn allows for the shape of the tower to be developed on the basis of reducing the demand on the structure and therefore saving material by aerodynamically optimising the building form. In order to make such workshops possible, the authors of this paper have trialled a number of analysis tools and procedures to help make the data from such testing reliable and useful. Presented in this paper are a number of projects which have followed such a workshop approach and some initial details of an experimental and fully interactive workshop which has been carried out.

## Building Blocks To Interactive Testing

### Al Khozama Centre – Riyadh

This proposed development, located in the Middle East, included a 400m tall building with 42 office floors in the lower portion, a luxury hotel occupying the next 20 levels and a tower-top spa (see Figure 1).

The structural stability of the tower was to be provided by three reinforced concrete shear cores disposed at 120 degrees to each other. These were connected rigidly up their height via five double-height steel coupling trusses at plant levels, which make the three cores behave more like a braced framed system rather than three individual cantilevers. The rotational symmetry of the design led to an omnidirectional fundamental translational mode with a period of 11.8s and a torsional period sitting at 7s for ultimate limit state (ULS) calculations. These respectively reduced to 10.8s and 6.5s for the serviceability conditions (SLS). For the wind tunnel test post-processing, a damping of 1.5% was used for ULS and a figure of 1% was selected for SLS.

It was clear that the main and driving mechanism of wind excitation was alternate vortex-shedding from two of the three structural mega cores that protruded beyond the façade cladding line. The edges of these two cores were almost perfectly facing the most critical wind sector (see Figure 2a which shows the directional variation of the site-specific design wind speed at a reference height of 400m for the 50- and 10-yr return period wind events). Vortex-shedding was in this case mainly governing the strength design at the 50-yr return period design wind speeds, as well as the wind-induced peak accelerations at the relatively more frequent 10-yr return period winds. Wind tunnel testing was engaged very early on in the design process, but in the traditional



Figure 1. Al Khozama Tower (Source: Foster + Partners)

图1. 描库扎玛酒店 (资料来源: Foster + Partners)

这一工作证实, 通过研讨会在设计早期阶段进行一系列交互式风洞试验对推进设计是非常有益的。结果数据几乎是即时得到的, 而根据这些数据可以修改设计并进行再测试。理想状态下, 这一过程类似于风环境测试, 即建筑师和设计团队的成员都能直接参与其中。

其终极目标是帮助确定一个能保证建筑造型与结构更好结合的流程。通过建筑外形的空气动力学优化, 使塔楼外形能降低结构需求并节约材料。为了让这样的研讨会成为可能, 本文的作者已尝试了许多不同的分析工具和分析程序, 使得收集到的数据有用且可信。本文列举了运用此种方法的一些项目和已实施的试验性交互式研讨会的初步细节。

## 交互试验的基础

### 库扎玛酒店 - 利雅得

此开发项目位于中东, 其中包括一幢400米的高层建筑。低区是42层的办公区、高区为20层的豪华酒店以及顶楼的水疗会所(见图1)。

塔楼结构的稳定性是由三个互成120度的钢筋混凝土剪力核心筒提供的, 并通过五个两倍高的钢连桁架在设备层位置牢固地联接起来。这使三个剪力核心筒更像一个支撑框架体系而非三个单独的悬臂。轴对称的设计造成了一个全向平动的基本模态。对于承载极限状态(ULS)的计算, 其平动周期和扭转周期设置分别为11.8秒和7秒。而对于正常使用极限状态(SLS), 平动周期和扭转周期分别降为10.8秒和6.5秒。在风洞测试的后期处理中, 承载极限状态使用的是1.5%的阻尼比, 而正常使用极限状态则是1%的阻尼比。

很明显, 风激励的主要驱动机制是三个突出在立面外墙覆盖层外的结构巨型核心筒中其中两个的交替漩涡脱落。这两个核心筒的边缘几乎是完全面对主导风向(见图2a, 其中显示了在该场地上参考高度为400m处50年和10年重现期强风在方向上的分布)。在这种情况下, 漩涡脱落激振控制了50年重现期的强度设计, 并主导了更频繁出现的10重现期风致加速度峰值。风洞试验在设计初期就被考虑, 但在传统方法中, 则主要是作为检验塔楼加速度和确定结构设计风荷载的工具。

初步试验的评审结果是建议将塔楼逆时针旋转 $30^\circ$ 以减小漩涡脱

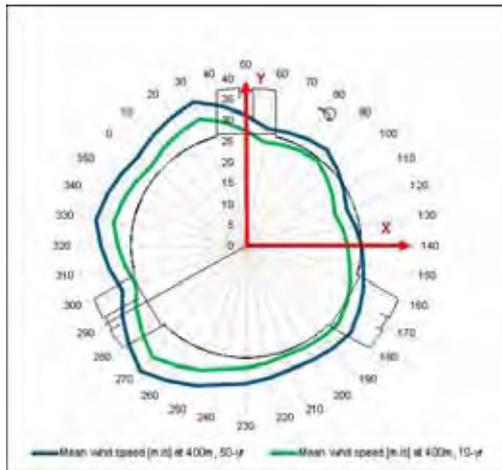


Figure 2a. Original core plan (Source: BMT Fluid Mechanics)  
图1. 原核心筒平面 (资料来源: BMT Fluid Mechanics)

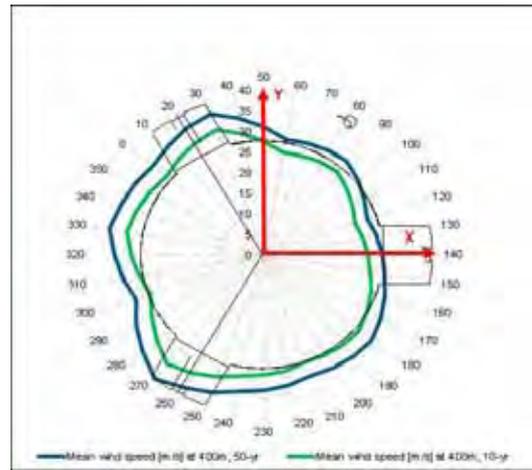


Figure 2b. Rotated core plan (Source: BMT Fluid Mechanics)  
图2b. 旋转后核心筒平面 (资料来源: BMT Fluid Mechanics)

approach was primarily used as a tool to check the accelerations in the tower and to establish the applied wind loads for structural design.

A post testing review of the initial results suggested that rotating the tower by approximately 30° counter-clock wise would reduce the vortex-shedding excitation (see Figure 2b). This new orientation aligned one of the three structural mega cores towards the most critical wind sector which allowed the form to create enough disturbances in the flow to significantly reduce the strength of the flow separation (and associated vortex-shedding) now happening much more downstream where the two other mega structural cores were now located.

Initial tests showed that the level of reduction achieved in the peak cross-wind base overturning moment ("My" load component, see Figure 3) and wind-induced peak acceleration were respectively ~30% and ~20%. The achieved ~20% reduction in wind-induced peak acceleration was able to bring the level of wind-induced peak acceleration within the criteria (15-milli-g for the 10-yr return period wind events) set for the highest occupied level of the tower (a luxurious spa). It should be noted that in order to achieve the same level of occupant comfort with the initial tower orientation, an increase of ~15% of the first mode frequency would have been required.

This re-test of the tower was carried out a few weeks after the original testing, but it was an example to the authors of this paper of something that could have been picked up if the original testing had been carried out in a more interactive manner.

Although the development of this design was not continued, it was evident to the team that further improvements in the wind performance of this tower could be gained by slight modifications to its form, with particular emphasis on the prominence of the structural cores and the open top section of the tower. With this in mind, and based on the collective knowledge that the structural and wind engineers had on this tower, as the idea of interactive testing developed it was clear that the team could use this tower as the basis to undertake a workshop test day to trial the interactive testing process as described later in this paper.

### Istanbul Tower

The site in the Levent district of Istanbul was particularly long and narrow, of which architects Foster + Partners were keen to make the best use. The proposed tower was to be in the order of 250m tall, but no more than 22m wide due to the site constraints. With this level of slenderness, the wind-induced dynamic excitation could be critical for the structural design of the building. However, with the site

落激励响应 (见图2b)。新的朝向让三个巨核中的一个对准主导风向, 使其在形态上能生成足够的流动干扰, 从而有效地减小常发生在气流下游另两根巨型结构核心筒处的流动分离强度。

初步测试显示横风向倾覆力矩峰值 ( $M_y$ 分量, 见图3) 与风致加速度峰值可达到的最大减少量分别为~30%和~20%。这减小的~20%的风致加速度峰值使塔楼最高使用层也能符合风致加速度峰值的设定标准。应当注意的是, 在原来的塔楼朝向下, 为了达到居住者与目前相同程度的舒适度, 第一固有模态的频率需要提升~15%。

塔楼的再测试是在原测试完成几周后进行的, 但若原测试能以一种更交互的方式实施, 则可更早地提供某些有用的信息。当然这只是本文作者的举例说明。

虽然此设计项目没有继续, 但整个设计团队都已知晓此塔楼的抗风性能可以通过对其外形作细微修改得到改善, 特别是可以通过对结构核心筒和塔楼顶部开洞区的优化而得到进一步的提高。综合上述考虑, 基于对此建筑结构与风工程的综合认知, 并随着交互试验想法的开发, 团队认识到可用这座塔楼作为基础尝试交互试验研讨会的流程与方法。具体内容见本文以下章节。

### 伊斯坦布尔大楼

伊斯坦布尔的勒文特区, 其形长而窄, 因而Foster + Partners建筑事务所希望能在本项目中充分利用其特性。计划的塔楼约250m高, 但受场地限制宽度不超过22m。对这样纤细的建筑, 风致动态激励就可能成为建筑结构设计中最重要的部分。由于建址还位于高烈度地震区, 地震荷载主导强度设计。但由总体刚度来控制与风致振动有关的居住环境舒适度也是主要的设计目标。因

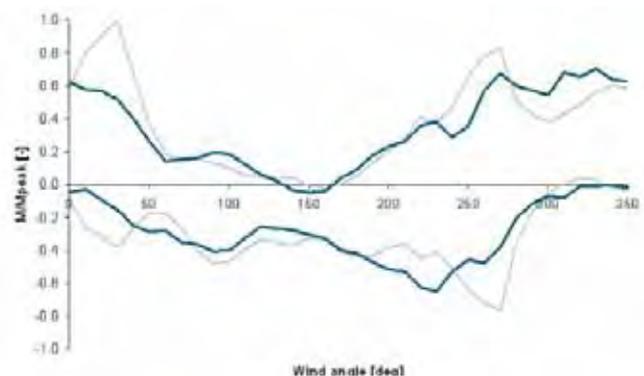


Figure 3. Normalised peak dynamic wind base overturning moments for the original tower orientation (grey curve) and the final tower orientation (blue curve) (Source: BMT Fluid Mechanics)  
图3. 最初塔楼朝向和最终塔楼朝向下基底倾覆力矩的归一化峰值 (资料来源: BMT Fluid Mechanics)

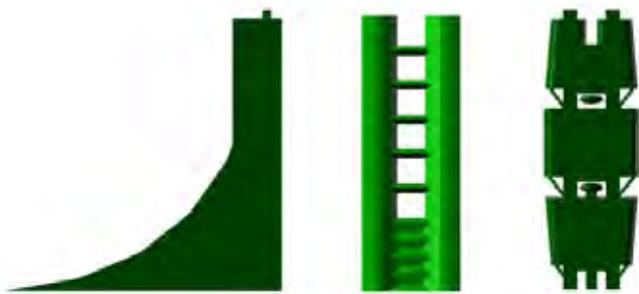


Figure 4. Istanbul Tower: initial forms tested (Source: Buro Happold)  
图4. 伊斯坦布尔大厦：测试的初始外形（资料来源：Buro Happold）

being in a high seismic zone, it was found that the earthquake design forces drove the stress design, but overall stiffness to control wind-induced occupant comfort was the main design driver. Thus, the wind tunnel investigations were primarily focused on wind-induced peak accelerations.

The wind tunnel testing for this project was ultimately carried out in four stages. In the first stage, a number of single and twin tower arrangements were initially conceptualised by the architect. In order to de-risk the project from the very start (concept stage) wind tunnel testing was conducted on each of these to explore, from an aerodynamic point of view, the merits and flaws of the different architectural solutions. Three very different basic shapes (see Figure 4) were tested (in isolated condition) and analysed on-line in the wind tunnel. In traditional manner the structural properties of mass distribution, natural frequency and mode shape were analysed in advance of the wind tunnel testing. For each of the three schemes the fundamental period was in the range of ~9-10s. Following the wind tunnel testing and data processing of the original designs, the twin-tower scheme was chosen to be investigated further and progressed in more detail.

In the next stage of wind tunnel testing a number of geometrical variations were made to the twin-tower scheme, including different spacing between the two towers as well as different vertical spacing between the sky-bridges (see Figure 5). These changes were tested and re-analysed on-line to try to aerodynamically reduce the wind-induced accelerations. These were also fully coupled with specifically tuned adjustments introduced by the structural engineers in the structural system. It was found that, as the response of the structure was vortex-controlled, a careful re-shaping of the corners of the towers was able to improve the level of wind-induced accelerations by ~30%.

At this stage the design was being further developed and a number of different corner solutions were prepared by the architect: two of these were selected for a third phase of wind tunnel testing (see Figure 6). Again, these two newly developed shapes were tested and analysed in conjunction with permutations of two potential structural solutions, which included a fully eccentrically braced steel solution and a reinforced concrete one.

The final scheme was then subsequently tested with an accurate representation of the surrounding area. The performance finally achieved by the twin tower scheme, with regard to wind-induced acceleration at the highest occupied level, was ~15milli-g (10-yr return period winds) for 1.5% structural damping.

This testing process showed the team that the wind tunnel can be used very effectively as a design tool running in parallel with the early conceptual architectural scheme and engineering design process. However, it also highlighted a number of issues that kept wind tunnel testing apart from being an integral and easily enmeshed part of the

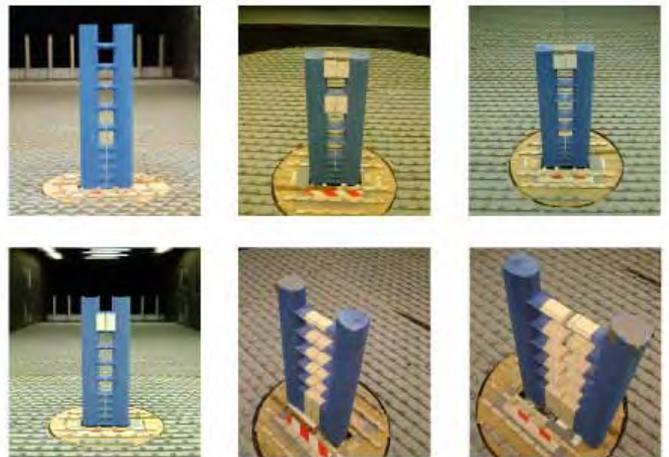


Figure 5. Istanbul Tower: twin tower studies (Source: BMT Fluid Mechanics / Buro Happold)

图5. 伊斯坦布尔大厦：连体塔楼研究（资料来源：BMT Fluid Mechanics / Buro Happold）

此风洞试验主要关注风致加速度峰值。

这个项目的风洞测试最终是通过四个阶段得以实施的。在第一阶段，建筑师对一些单个和成对塔楼的排列进行初步的概念设计。为了能在最开始的概念设计阶段就考虑降低项目的风险，对每个概念设计都进行了风洞试验，从空气动力学的角度去探测不同建筑方案的优点与瑕疵。分别测试了三种完全不同的基本建筑形态（见图4）并即时在风洞中进行了分析。与传统方法相同，质量分布、固有频率和振型等结构特性都在风洞测试之前提前分析。这三个方案中的基本周期都在9秒至10秒范围内。根据原设计的风洞测试和数据处理，最终选择了双塔连体方案进行下一步的研究和细节处理。

在接下来的风洞测试阶段，对双塔连体方案进行了一些几何外形更改，包括两塔之间不同的间隔和天桥之间垂直间隔（见图5）。这些更改经过测试与即时的再分析试图从空气动力学途径进一步降低风致加速度。同时结构工程师对结构系统也进行了与这相应的调整。可以发现，在结构响应由漩涡激振控制的情况下，通过细致研究对塔楼楼角部分的外形修正可将风致加速度降低约30%。

在这一设计深入阶段，建筑师同时也准备了一些不同楼角的解决方案：其中两个被选中进入第三阶段的风洞测试（见图6）。这两个新的楼角方案会再一次进行测试并结合两种可能的结构布置方案进行分析，其中包括一个完全偏心支撑刚框架的和一个钢筋



Figure 6. Istanbul Tower: twin tower corner variations (Source: BMT Fluid Mechanics / Buro Happold)

图6. 伊斯坦布尔大厦：连体塔楼的楼角变化（资料来源：BMT Fluid Mechanics / Buro Happold）

process. This was primarily due to the time taken to work through the testing process which included:

- Confirmation of building form for target model;
- Preparation time for structural data required for assessment of dynamics and forces;
- Wind tunnel testing time to run all wind angles;
- Time taken for post-processing of wind tunnel results.

It was felt that though useful to test while experimenting with building form, it would be beneficial to be able to condense the time taken for this process, which led to the progression of the interactive testing process.

### Interactive Testing To Aerodynamically Optimise Tall Building Envelopes

The projects presented herein demonstrated to the authors of this paper that it would be beneficial to use a more interactive approach to wind tunnel testing to better integrate the architectural and structural design of tall buildings. In these projects the authors of this paper had used the wind tunnel testing to bring gradual design improvements, but this had taken a number of testing sessions over a period of weeks. The authors of this paper were particularly keen to define a process that would help optimise the form of the building over a period of one or two days of interactive wind tunnel testing.

Following the framework very well described by the Davenport wind loading chain ([www.iawe.org/about/Wind>Loading\\_Chain.pdf](http://www.iawe.org/about/Wind>Loading_Chain.pdf)), the wind loading on a building is determined by the combined effects of:

- Wind climate;
- Aerodynamic characteristic of the building shape;
- Structural system / arrangement adopted for the building.

From this it is clear that to enable effective experimental testing to be carried out rapidly, one would need to be able to not only rapidly modify the shape of the target model being tested, but combine this with revised assessments of the structural performance in a short space of time. Critically one would need to output tunnel test data within minutes. All of this needed to be carried out with enough accuracy to differentiate the different performances of the tower.

In order to make this possible, the wind engineers developed a more streamlined method of post-processing the raw data from the wind tunnel testing to reduce analysis time and present the critical data of base forces / moments and accelerations within a matter of minutes. Similarly, the structural engineers have reviewed the level of detail required within the structural analysis model and, for this testing, were able to develop simple analysis models that could be both adapted and re-run very quickly, but also give comparable analysis results to more detailed models.

Using the previously described Al Khozama Tower, the wind and structural engineers carried out a sample interactive test day. A number of preparations were made for the test day to help it run as smoothly as follows:

- A base target wind tunnel model was designed and constructed;
- Appropriate but simple structural analysis models were prepared;

混凝土的解决方案。

随后测试了最终方案，试验中包括精确的周边地区模型。双塔方案最终达到了性能要求，即在结构阻尼比为1.5%时，最高居住层的10年重现期风致加速度为~15milli-g。

这个测试过程显示出风洞能被非常有效地用作设计工具并与早期的建筑概念方案和工程设计过程平行进行。但也有一些突出的问题使风洞测试难以成为流程中完整且易融入的部分。这主要是因为测试过程中所需的时间，其中包括：

- 确定测试模型的建筑外形所需要的时间
- 评估动力响应与风荷载时需要的结构数据的准备时间
- 测试所有风向角需要的风洞试验的时间
- 风洞试验数据后期处理所需要的时间

虽然在尝试不同建筑形式时进行风洞试验是有用的，但如果能缩短此过程所需的时间将会更有利于进入交互试验过程。

### 运用交互测试优化高层建筑空气动力学外形

本文作者以此处所举项目来说明，通过与设计交互沟通更好的方式进行风洞测试来整合高层建筑的建筑设计与结构设计是有益的。在这些项目中，本文作者已通过使用风洞测试来逐步完善设计，但这是在几周时间内通过一系列测试研讨后完成的。本文作者希望能建立一个流程，能在一至两天时间内通过与设计交互的风洞试验来优化建筑外形。

根据达文波特风荷载链所描述的构架，([www.iawe.org/about/Wind>Loading\\_Chain.pdf](http://www.iawe.org/about/Wind>Loading_Chain.pdf))，建筑的风荷载主要由下列因素的联合效应决定：

- 风气候
- 建筑体型的空气动力学特点
- 所采用的建筑结构体系与布置

很明显为了进行快速有效的试验研究，不仅要能迅速修改试验模型的外形，还需在短时间内与修改后的结构性能相结合。更重要的一点是，需在几分钟之内输出风洞测试数据。上述所有这些都需要足够的精确度以便识别不同的塔楼性能。

为了做到这一点，风工程师们开发了一种更为顺畅的后期处理风洞测试原始数据的方法来减少分析时间，同时在几分钟之内给出基底力/力矩和加速度的关键数据。同样的，结构工程师对所需的结构分析模型的细致程度进行了评估，对本项目开发出了简易结构分析模型，不但能迅速适应调整和重新运行，还可以给出与更详细的模型作比较分析的结果。使用之前所述的库扎玛酒店，风工程师和结构工程师安排了一次作为样本的设计交互试验日。为此做了以下各种准备以便交互试验能顺利进行：

- 设计并制作了基准风洞试验模型
- 准备了简化且适用的结构分析模型
- 准备了质量分布与/重分布计算所需的简易数据表。
- 进行风气候分析并明确了主导风向及其标准

结构模型通过特定方式设置，从而易于根据建筑外形的调整改变质量分布、或改变核心筒及稳定刚度，而且能进行快速计算给出风洞测试数据后期处理所需要的主要结构特性（质量分布、固有频率和模态振型）。根据对风气候和原试验结果的审阅，确定较少的但起控制作用的风向用于试验。

在风洞试验日，每一组工况的试验分析是一个比较简易的过程，如下所述：

- 风洞测试只侧重于选定的起控制作用的风向；

- Simple spreadsheets for mass distribution / re-distribution calculations were prepared;
- A review of wind climate and identification of most critical wind directions and criteria were undertaken.

The structural models were set up in such a manner that they could easily be adapted to mirror a change in form with an appropriate change in mass distribution or have simple changes in core and / or stability stiffness made, and they were built to perform quick analyses and output structural properties (mass distribution, natural frequencies and mode shapes) essential for the wind tunnel data post-processing. From reviewing the wind climate and the original tests, a limited number of critical wind directions were identified and used for testing.

On the test day, a fairly simple process was followed for each set of explored / tested configuration. The process was identified as follows:

- The wind tunnel test is only focused on the identified / selected critical wind directions;
- The wind tunnel data is processed using structural properties to provide peak floor accelerations and base forces and moments within minutes;
- The output data is quickly reviewed and proposed changes to the form are considered;
- Physical adjustments to target model are made;
- If required, adjustments to the structural models are also made in order to produce structural properties fully consistent with the adjusted architectural form;
- Further wind tunnel tests are carried out on the new target model geometry.

The use of smoke visualisation was also utilised to help understand the impact of changes. Using this process a total of 12 variations were able to be investigated on the test day and led to some recommendations to optimising the aerodynamic behaviour of the building. Initial investigations focused mainly on the very top portion of the tower (related to the spa) and the exposed core sections.

Initial results from the testing showed that the cross-wind excitation was not particularly sensitive to the shape of the spa or the exposed core sections. On this basis, focus then turned to the hotel section, which is the upper portion of the main tower body. A number of variations were carried out (see Figure 7) which showed that cross-wind excitation was sensitive to the core shape over this zone and a number of possible improvements were proposed.

Within the day, it was possible to make a number of conclusions:

- The spa geometry and form was not critical to the cross-wind performance of the tower;
- The shape of the exposed sections of the core was not critical to the wind performance of the tower;
- The core shapes in the hotel floors of the tower were critical and variation of these cores could improve the performance of the tower by reducing the peak accelerations and cross-wind forces;

More specifically:

- A mesh façade around the hotel was able to reduce the spectral energy around the frequency of interest: this reduced the wind-induced peak accelerations by ~2-3milli-g (10-yr return period wind events) and cross-wind forces by ~5% (50-yr return period wind events);

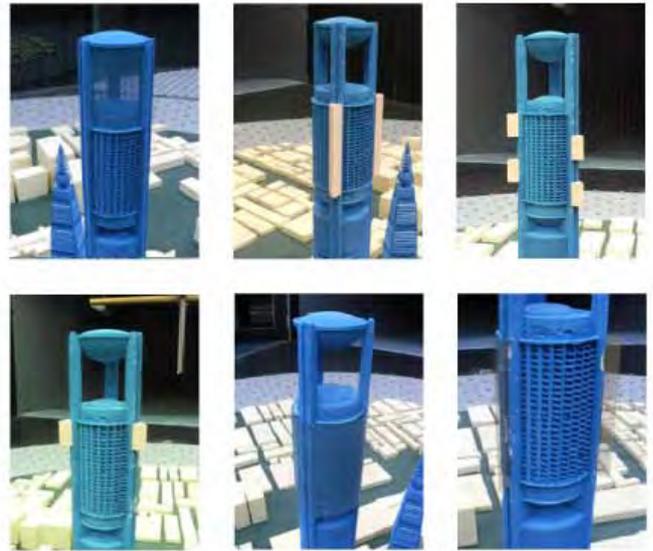


Figure 7. Sample investigations for Al Khozama Tower (Source: BMT Fluid Mechanics / Buro Happold)

图7. 库扎玛酒店样本调查 (资料来源: BMT Fluid Mechanics / Buro Happold)

- 风洞数据结合结构特性进行处理, 在几分钟之内提供楼层加速度峰值和基底力及力矩数据;
- 对输出数据进行快速审评并考虑外形更改;
- 对测试模型作相应的修改;
- 为了使结构特性与调整后的建筑形式保持完全的一致, 结构计算模型会根据需要作相应调整;
- 对外形修改后的测试模型进行下一轮风洞测试。

采用烟雾显形方法有助于了解外形更改所产生的影响。用此方法在测试日内共可研究12种建筑外形变化, 并且得到一些可优化建筑空气动力特性的建议。初步考察的重点主要是在塔楼的最顶部(即水疗会所部分)和楼顶开敞段的核心筒截面。

测试的初步结果显示横风向激励对于水疗会所部分外形或开敞段核心筒截面外形不是特别敏感。基于此, 研究重点转到酒店部分, 即塔楼主体的上部。在实施的一些外形变化中(见图7)显示出横风向激励对这一区域的核心筒外形很敏感, 同时提出了一些可能的改进方案。在一天之内, 就可得到以下一些结论:

- 水疗会所部分的几何形状对于塔楼的横风向响应不是很关键。
- 开敞段核心筒的形状对塔楼抗风性能不是很关键。
- 塔楼酒店楼层核心筒的形状非常关键。这些核心筒的外形改变能减小加速度峰值和横风向荷载, 从而提高塔楼的性能。

更具体来说:

- 酒店周围的网状立面能降低响应频率段的风谱能量, 从而降低风致加速度峰值~2-3milli-g (10年重现期)和横风向荷载~5% (50年重现期)。
- 酒店区域顶部核心筒形状的不同变化可造成斯托罗哈数有利的改变, 这能降低风致加速度~3-5milli-g (10年重现期)和横风向荷载~10-15% (50年重现期)。

为使这些方案实际可行, 建筑方面还需要作进一步的工作。但测试结果证实了这些方案确实能带来效益。如果没有测试考察中的交互部分, 塔楼形状的修改方案很可能会局限在塔楼最顶部, 以及其它基于经验假设的修改方案。这对能否带来设计效益存在不确定性, 可看作是一种带有碰运气性质的办法, 因为实际效果

- A variation to core shape at the top of the hotel section was able to produce a favourable shift in the Strouhal number: this reduced the wind-induced peak accelerations by ~3-5milli-g (10-yr return period wind events) and cross-wind forces by ~10-15% (50-yr return period wind events);

Architectural input would be needed to develop these options further to make them viable, but the testing clearly gave confidence that the changes would provide benefits. Without the interactive element to the tests investigations, changes to the tower form would likely have been proposed to the shape of the very top of the tower, as well as other changes that would have been the subject of experienced assumptions. These may or may not have yielded much design benefit, and this approach would be seen as an opportunistic approach to wind engineering, with its findings perhaps only ever verified late in the design process when changes are more difficult to adopt.

## Conclusions

As experienced engineers, the authors of this paper are able to advise architects and clients on ways to develop and improve the shape of towers to help their aerodynamic performance. However, this tends to be in general terms through the use of discontinuities in shape, tapering forms, introduction of porosity etc. Once a form has been pre-defined by the architect, it is very difficult without the use of wind tunnel testing to be specific on ways to improve its aerodynamic performance in a way that would provide real values of potential savings to the structure.

Using the interactive process, it is possible to carry out wind tunnels tests to compare up to ~15-20 variations of the form within a single day. Importantly, the tests and investigations do not need to be predetermined: a team of model makers enable additions, subtractions and changes to be made to the wind tunnel HFFB model, and a flexible / easily-adaptable structural analysis model can allow tests to be timely reactive to the results that are found as the wind tunnel testing progresses. Since the process has been set up to enable the structural analysis to be linked with geometrical changes, it is possible to account for considerable changes in form with reasonable accuracy. It is of course also possible after the testing day to continue to post-process the wind tunnel test data for different structural properties. As such, the authors of this paper are confident they could facilitate interactive aerodynamic optimisation days that can provide positive changes to the form of tall buildings during various stages of the design process.

只能在之后的设计过程中予以证实，而那时再考虑外形修改将会很困难。

## 结语

作为经验丰富的工程师，本文作者可以建议建筑师和客户去开发与改善塔楼形状从而提高其空气动力性能。但是这通常是通过采用上下不连贯的外形、由下至上收缩的外形、局部开孔等方式来实现的。一旦建筑师预先确定了建筑物形状，在没有进行具体的风洞测试情况下，很难能提供改善其空气动力学性能的具体方法以达到节约结构成本的目的。

运用交互过程，使风洞测试有可能在一天中对15至20个不同建筑外形作比较研究。最重要的是，试验研究对象不需要预先决定：即模型制作团队可加减和修改风洞试验的高频测力天平模型，灵活易用的结构分析模型可跟随风洞测试结果进行及时反馈。由于结构分析随几何外形更改的步骤已经预设，在结构分析中可以考虑外形较大的改变并使结果保持合理的精度。当然还可在测试日之后针对不同的结构特性继续风洞测试数据的后期处理。由此本文作者有足够的自信主持建筑空气动力特性优化的交互试验，在不同设计阶段为高层建筑外形提供积极的修正方案。

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