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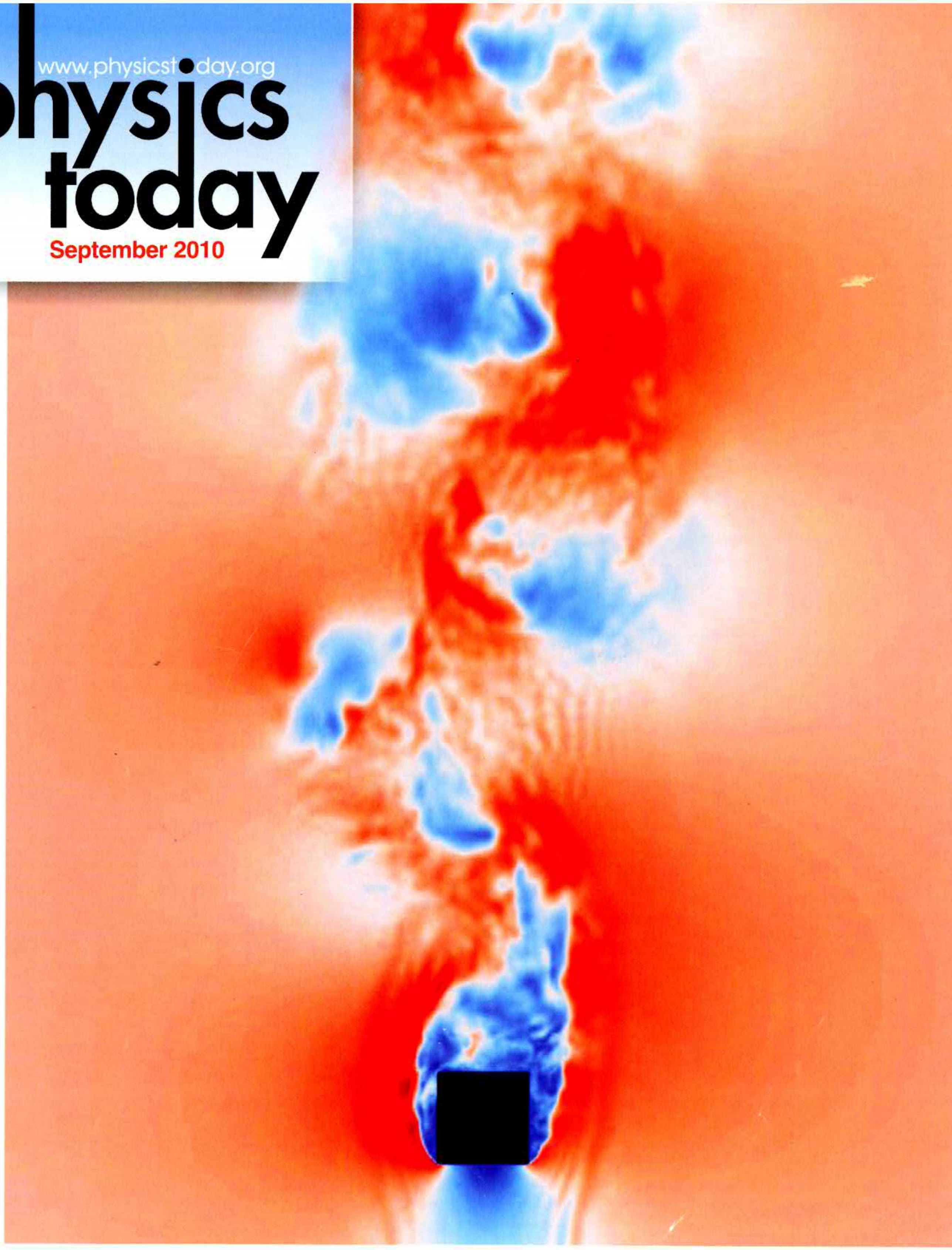
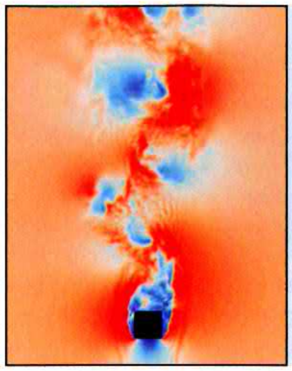


Building against the wind

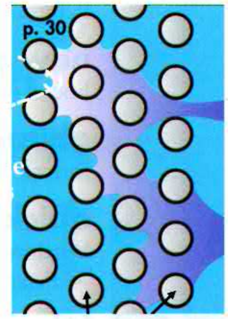
A publication of the American Institute of Physics

volume 63, number 9
www.physicstoday.org
physics today
September 2010



cover: This image from a simulation of wind blowing past a building (black square) reveals the vortices that are shed downwind of the building; dark orange represents the highest air speeds, dark blue the lowest. As a result of such vortex formation and shedding, tall buildings can experience large, potentially catastrophic forces. To learn how building designers and engineers tame those forces, turn to the Quick Study by Peter Irwin beginning on page 68. (Courtesy of the computational fluid dynamics group at Rowan Williams Davies and Irwin Inc.)

feature articles



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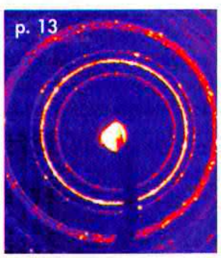

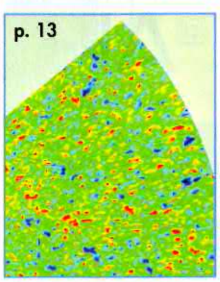

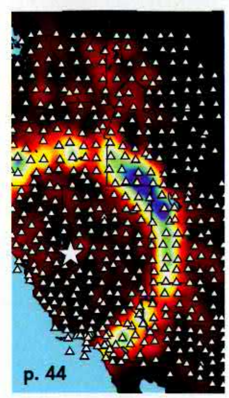

PHYSICS TODAY (ISSN 0031-9228, coden PHTOAD) volume 63, number 9. Published monthly by the American Institute of Physics, 2 Huntington Quadrangle, Melville, NY 11747-4502. Periodicals postage paid at Huntington Station, NY and at additional mailing offices. POSTMASTER: Send address changes to Physics Today, American Institute of Physics, Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502. Canada subscriptions: Canada Poste Agreement Number 40034526. Send change of address information and blocks of undeliverable copies to PO Box 1051, Fort Erie, ON L2A 6C7.

quick study

Vortices and tall buildings: A recipe for resonance

Peter A. Irwin

Structures buffeted by steady winds experience pushes and pulls in the direction perpendicular to the wind flow. If those forces were to organize coherently, the results could be disastrous.

Peter Irwin is the chairman of Rowan Williams Davies and Irwin Inc, a Canadian consulting firm of engineers and scientists who have been involved in the wind engineering of many of the world's tallest buildings.

Look carefully at a flagpole or streetlight on a windy day and you may see the structure oscillating in the breeze. Imagine the phenomenon scaled to the height of an urban skyscraper and you can appreciate that at a minimum, life for the inhabitants on the upper floors would be uncomfortable; and should the building fail due to the forces exerted on it, life would be in peril. How, then, do the designers of tall buildings mitigate against the effect of winds that routinely have velocities of 50–150 km/hr near the tops of tall city buildings? The key phenomena that building engineers need to worry about are the vortices—swirling flows of air—that form on the sides of a building as the wind blows by it and the forces that arise as those vortices form and subsequently detach from the building.

Street savvy

Most people have an intuitive sense of vortices from observations of swirling flows in rivers or streams, or even flows down a bathtub drain. When vortices form in a turbulent environment, the turbulence can break them down by transferring kinetic energy to successively smaller eddies until viscous effects convert the energy to heat. On the other hand, the tight rotation of fluid around a vortex core actually suppresses turbulence. As a result, a vortex's high and rapidly varying velocities can be maintained for a long time. Indeed, the vortices that form at and detach from tall buildings can persist long enough to affect nearby buildings.

When a vortex forms on the side of a building, it creates a suction force. The force generated by an individual vortex is not great. The potential problem is that vortices tend to form in well-organized patterns and rock the building as they shed alternately from each side as shown in figure 1; the resulting wake of shed vortices is called a Kármán vortex street in honor of physicist Theodore von Kármán.

A tall building will generate a Kármán street if it has a uniform shape along its height and is in a steady wind—that is, one with little turbulence. For many city buildings, the Kármán street is not a significant worry: Densely packed urban structures lead to turbulence that impairs the initial formation of coherent vortices and rapidly breaks up those that do form. But turbulence may not be significant near very tall buildings that stand apart from their neighbors or structures near the edge of town where the upwind terrain is open country. In those environments, buildings are able to shed a well-structured Kármán street. Architects and engineers must design the buildings to withstand the associated forces that, for many of the world's tallest skyscrapers, are the highest forces they will encounter—even greater than those caused by earthquakes.

A tall building is like a swing

To know whether a tall building is in danger of being adversely affected by vortex shedding, one needs to ascertain two important frequencies. The first is the fundamental frequency of vibration for the building, f_b, and the second is the frequency f_v with which vortices are shed from the building into the vortex street. When the two are equal, a resonance phenomenon sets in: Just as you build up the amplitude of a child on a swing by pushing at the natural pendulum frequency of the swing, so the formation and shedding of vortices shakes the building at its most vulnerable frequency. The structure can thus experience large crosswind oscillations.

A building's fundamental frequency depends on its structural system and mass distribution, and structural designers of large buildings typically use specialized software to help them accurately compute that frequency. For a 50-story building, f_b is typically about 0.2 Hz, corresponding

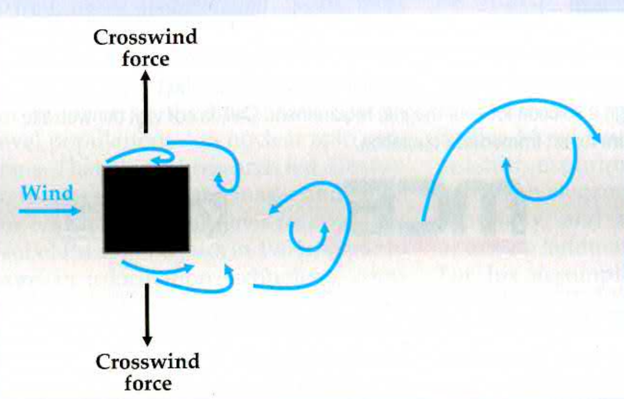

Figure 1. Vortices can form coherently on the sides of a building buffeted by steady winds, exert alternating forces on the structure (black arrows), and, once detached, form a so-called Kármán street downwind of the building. If the coherent vortex shedding is not mitigated, the resulting forces on the building can grow dangerously large.

Figure 2. The Burj Khalifa in Dubai, United Arab Emirates (UAE), is, at 828 m, the tallest building in the world. Opened in January 2010, it took more than five years to build. The design includes a variation of cross section with height to help ensure that vortices are not shed coherently along the entire height of the structure. Khalifa bin Zayed Al Nahyan, for whom the burj (tower) is named, is the president of the UAE. (Photo by Nicolas Lannuzel.)

to a period of 5 seconds. For a 100-story building, f_b is in the range of 0.1–0.125 Hz, corresponding to a period of 8–10 seconds, but some super-tall structures have been conceived for which the frequency is as low as 0.05 Hz, corresponding to a 20-second period.

The frequency of vortex shedding is given by the Strouhal relationship, $f_v = SU/w$, where U is the wind speed, w is the width of the building that faces the wind, and S is the Strouhal number, which is often treated as a constant that depends on only the cross-sectional shape of the building. For buildings with sharp corners, the approximation of constant S is reasonably good. For rounded shapes, S also depends on the Reynolds number $R = Uw/\nu$, where ν is the kinematic viscosity of air, that is, the ratio of air's viscosity to its density. Even in that case, though, S is often reasonably constant over the range of interest for R.

The critical wind speed U_{crit} for which $f_b = f_v$ is readily calculated to be $f_b w/S$. If, for example, $f_b = 0.1$ Hz; $w = 50$ m; and $S = 0.14$, a typical value for the Strouhal number; then $U_{crit} = 36$ m/s, or 130 km/h. That is a high wind speed, and it would need to be sustained for several minutes for the motions induced by vortex shedding to build up. Still, the calculated critical speed falls well within range for winds that impinge on very tall buildings in many parts of the world. Moreover, because of a phenomenon called vortex lock-in, a building, once it begins to move, can actually lock the frequency of the vortex shedding to the fundamental frequency of the building even if the wind speed subsequently moves away from U_{crit}.

One approach to reducing the loads caused by vortex shedding is to stiffen the building. That increases the natural frequency (think of a Hooke's-law spring), which in turn increases the critical velocity at which resonance occurs. In principle, the critical velocity can be made high enough that resonance is too rare an event to be a concern. Increasing the stiffness can work on buildings that are not too tall and slender, but making a super-tall building stiff enough requires so much steel and concrete as to be costly and impractical. Therefore, design engineers need to adopt other strategies.

Confusing the wind

If vortex shedding is to be effective in exciting a building into motion, the vortices must be shed coherently; that is, they must be sloughed off rather uniformly along the building height. Turbulence in the wind can inhibit or disrupt such uniformity, as discussed above. But engineers need not rely on turbulence; they can employ a number of techniques to frustrate coherent shedding. One technique is to have the structure's cross section vary with building height. Then w and S also change with building height, which makes f_v a function of height as well. As a result, the wind "becomes confused" and vortices lose their coherence. That tiering strategy, backed up by wind-tunnel tests, was used successfully on the world's tallest building, the Burj Khalifa in the United Arab Emirates, shown in figure 2. Other effective shaping strategies are softening sharp corners, creating openings in the building for the wind to bleed through, and adding spoilers that break up the vortices much as do the spiral bands, or strakes, seen on many chimney stacks.

A complementary strategy for controlling the response to vortex excitation is to draw the energy out of the building's crosswind oscillations with special damping systems. Every building dissipates some of the oscillation energy through the natural damping of its materials and through friction at joints and partitions.

The inherent damping of tall buildings, however, is not very high. The usual measure of damping is the so-called damping ratio, essentially the fraction of the total vibrational energy in the building that is dissipated in each half cycle of motion, divided by 2π; typical values for tall buildings are in the 0.01–0.02 range. By adding various types of dampers, design engineers can multiply that value severalfold. Some of those dampers can be very impressive indeed: The 101-story Taipei 101 tower in Taiwan uses a damper weighing more than 600 metric tons.

As the world's population becomes increasingly concentrated in large cities, the pressure to build taller buildings will also increase. Thus super-tall buildings will become more common, and so will the need to deal with the consequences of the Kármán vortex street.

The online version of this Quick Study includes the animation from which the cover image was extracted.

Additional resource

▶ W. F. Baker, D. S. Korista, L. C. Novak, "Engineering the World's Tallest—Burj Dubai" (2008), http://www.som.com/resources/content/5/0/4/3/9/0/1/8/documents/SOM_EngineeringtheWorldsTallest.pdf. ■