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TECHNOTES

ISSUE NO. 7

HOW DOES A BASEBALL FLY?

By Michael J. Soligo, Principal

RWDI's involvement with baseball aerodynamics began with Comiskey Park in Chicago. During discussion about wind tunnel studies for the stadium, the team expressed an interest in comparing the wind impact on hitting characteristics between the old stadium and the new baseball park. As a result, RWDI developed a technique that uses velocity measurement of the flow field in the park as input for a computer model that predicts baseball trajectories. Since the work on Comiskey Park, major league ballparks have been studied in a similar way for Baltimore, Cleveland, Milwaukee and Seattle.

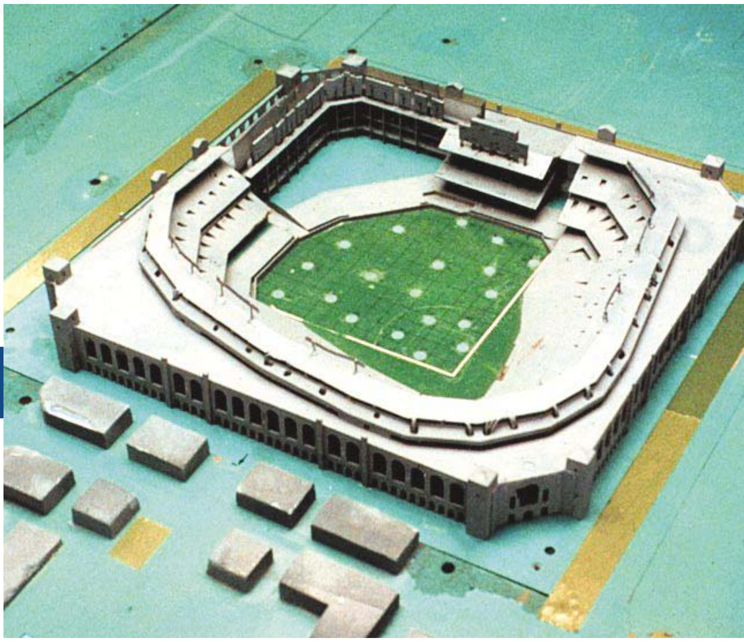

Figure 1: Scale model of Texas Rangers Ballpark

Prior to construction on the new Texas Rangers Ballpark at Arlington, a trajectory study was undertaken after the original design of the stadium was assessed by RWDI. This assessment showed that an opening behind center field would frequently channel wind into the ballpark and directly into batter's face. This effect would reduce the distance a batted ball would travel, as well as, create uncomfortable conditions in the seating bowl.

These conditions were first identified through testing of a scale model of the ballpark in RWDI's open channel water flume wind simulator. Coloured dye was injected into the flowing water to visually identify the wind flow characteristics of the stadium. The design team and Texas Rangers personnel participated in testing various building configurations to reduce unwanted wind impact. The building structure, as it was ultimately built, was determined to best mitigate the winds, while still maintaining a desirable design. However, the building structure alone was not sufficient, so RWDI designed and tested a unique placement of advertising boards and wind screens to intercept some of the disruptive winds. Figure 1 shows the scale model of the Texas Rangers Ballpark.

The effectiveness of the design was confirmed through wind tunnel testing where actual wind speed measurements and directionality were determined. These data were used in software developed by RWDI, that simulated the direction and distance a baseball travels under various external wind conditions for all types of hits.

The simulation takes into account the physics of the flight of a baseball, since it is affected by gravitational and aerodynamic forces that try to slow the ball's speed and deflect its flight path. Gravity is a constant force pulling the ball downward, but due to the effects of the local wind environment, as well as the baseball's speed, rate of rotation, and direction, aerodynamic force can vary throughout the flight.

Basically, there are three components of aerodynamic force acting on the baseball (see Figure 2): the drag force, F_d; the lift force, F_l; and the side force, F_S, acting lateral to the ball's flight path. The largest aerodynamic force acting on the ball is the drag component. The lift and side forces are caused by asymmetries in the stitch patterns, and by the so-called Magnus force, F_M, resulting from ball spin.

All of the forces are dependent on the speed of the ball. The aerodynamic force of drag is the sum of pressure drag and skin friction drag. The drag acts on the baseball in the direction opposite to the ball's velocity relative to the air.

The Magnus Effect is lateral deflection in the flight of the ball caused by its spin about an axis perpendicular to the direction of flight. This is the effect on which pitchers rely to cause their curve ball pitches to curve. Major league pitchers can achieve spin rates of up to 30 revolutions per second (ω=30Hz) with ball speeds up to 45 m/s (100 mph). The amount of deflection in the ball's flight path increases with the rate of spin.

Computations of the baseball's trajectory, including wind effects, require that the wind velocity field within the stadium be known. The wind velocity field is determined by a combination of methods: hot wire anemometer measurements in a scale model of the stadium in a wind tunnel and Computational Fluid Dynamics (CFD) modelling. The wind velocity vector, V_w, has three components V_{wx}, V_{wy}, and V_{wz}. These velocity components not only vary spatially, but also fluctuate with time due to the turbulent nature of wind. The wind tunnel tests allow a full simulation of both time averaged velocity field and the turbulent velocity components to be achieved.

To model the flight path of the baseball after it has been hit into the outfield, the basic equations of force acting on the baseball are broken down in a cartesian coordinate system and the effects of backspin are incorporated.

The effect of the wind's speed and direction acting on the flight of the baseball over a finite time interval is integrated as part of the study. The new position and velocity of the baseball is calculated every time interval. As the new positions are simulated, wind data determined through wind tunnel and CFD analysis are referenced, and the local wind velocity around the ball is updated. Also, for every time interval, the coefficient of aerodynamic drag, C_d, is updated according to the baseball's new Reynolds number.

To assess the aerodynamic quality of the park, the computer program launches baseballs over a range of vertical angles (angles at which the ball leaves the bat) in directions from first base through to third base. The program assesses the initial hit velocity required to just clear the home run fence with no wind present. This required hit velocity is compared between no wind conditions and representative wind conditions. In most cases, it is preferable to design ballparks to have limited deviation between the no wind and representative wind conditions, although this is often not easily achieved.

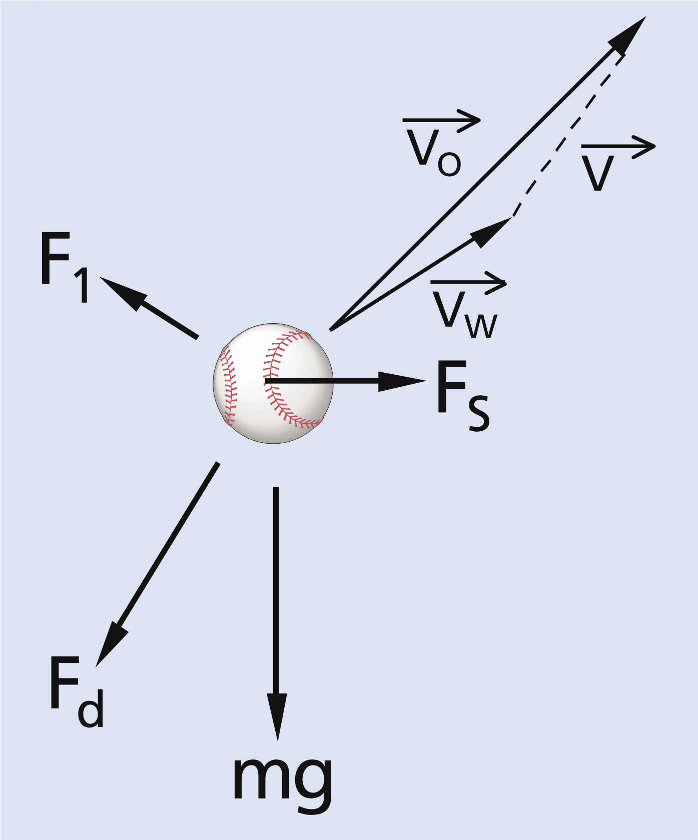

Figure 2: Aerodynamic force acting on the baseball.

The resulting simulation provides guidelines for the design and placement of outfield fences and information on home run potential. However, a home run hit depends on many other factors.

Robert Adair's book, The Physics of Baseball, (Harper & Row, Publishers, Inc., 1990) provides many interesting insights into baseball aerodynamics. For example, a typical long home run hit will almost certainly have a substantial amount of backspin (in order of 2000 rpm) that helps to lengthen the trajectory. Adair also discusses the effects of altitude, temperature, and humidity, factors which are accounted for in RWDI's simulation.

WIND LOADING OF LONG SPAN AND CANTILEVERED ROOFS

By Peter A. Irwin, Principal

The wind loading on the roofs of arenas and stadiums is often important in their structural design. These roofs are usually long span and quite flexible. Sometimes, as with tensioned fabric roofs, their shape is unusual. An increasing number of stadiums are being designed with retractable roofs which allow spectators to enjoy outdoor conditions when the weather is good and provide shelter when it is bad. Examples of retractable roof stadiums in North America are: SkyDome in Toronto, completed in 1987; Bank One Ballpark in Phoenix, currently under construction; the Pacific Northwest Stadium, under design for Seattle; and Miller Park, currently under design for Milwaukee. Long span roofs of any kind can be very susceptible to wind. Therefore, wind tunnel tests are commonly used to determine the wind loading on sports facility roofs.

The wind pressure patterns of a large roof continually fluctuate due to gusting of the wind. If you imagine the roof as a map and plot the contours of equal pressure on it for a given moment in time, the contours would resemble a complicated mountain range with many peaks and valleys. Now imagine the entire mountain range changing shape in a continuous way, with new mountains rearing up where there were valleys before and then shrinking as new peaks appear elsewhere. While the changing patterns may appear chaotic, there is a certain amount of order in that peaks will tend to reoccur in particular areas that are dictated by the roof shape. The task in wind tunnel tests is not only to measure the fluctuating pressure patterns, but to analyze them in such a way that the most critical load patterns can be selected for use in the roof design.

Using the cantilever roof in Figure 3 as an illustration, the pressures p_1, p_2, p_3, etc. are measured on the top surface at pressure taps 1, 2, 3, etc. At the same time pressures p_{b1}, p_{b2}, p_{b3} etc. are measures on the bottom surface of the roof at taps b1, b2, b3, etc. Each pressure tap is treated as giving the representative pressure for a selected area of roof. Therefore, tap 1 gives the pressure for area A_1 around tap 1. One quantity of interest for the structural design of the cantilever roof is the overall uplift. To obtain the instantaneous aerodynamic uplift on a segment of the roof we must sum the contributions from all the areas A_1, A_2, A_3, etc. on the top surface, and areas A_{b1}, A_{b2}, A_{b3}, etc. on the bottom surface. Adopting the convention that a positive pressure is one that pushes towards the roof surface and a negative pressure is one that sucks away from the surface, the uplift from area A_1 is $-A_1p_1$. Likewise, the uplift from the bottom surface area A_{b1} is $+A_{b1}p_{b1}$. Similar contributions come from all the other areas, so the total instantaneous total aerodynamic uplift Z is.

$$Z = -(A_1p_1+A_2p_2+A_3p_3+\ldots)+(A_{b1}p_{b1}+A_{b2}p_{b2}+A_{b3}p_{b3}+\ldots)$$

The pressures p_1, p_2, p_3, etc. vary continually with time, so it is important in the wind tunnel test to measure all terms simultaneously and to evaluate the above summation on-line on a continuous basis. Fortunately with modern integrated circuit pressure scanning equipment this can now be achieved in a routine manner.

Many other types of load or load effect can be measured directly in the wind tunnel using modern electronic pressure measuring systems. For example, another quantity of importance for the structural design of the cantilever roof in Figure 3 is the instantaneous aerodynamic bending moment M at the fixed end of the cantilever. This is measured on-line in the wind tunnel by multiplying each of the lift terms in the above expression by the appropriate moment arm about the cantilever's fixed end.

Flexible roofs tend to be excited into motion by the buffeting action of the wind. Therefore, in addition to the aerodynamic forces discussed above, there will also be inertial forces coming from the roof mass as it moves up and down. This may be treated as an amplification of the fluctuating wind forces. Using the total uplift as the example again, we first separate the uplift into its time averaged part Z and a fluctuating part with root-mean-square value σ_z. The peak uplift may then be expressed as

$$Z=Z+g_p\sigma_z F_{amp}$$

where g_p is a peak factor with typical value about 4.0 and F_{amp} is the so called dynamic amplification factor.

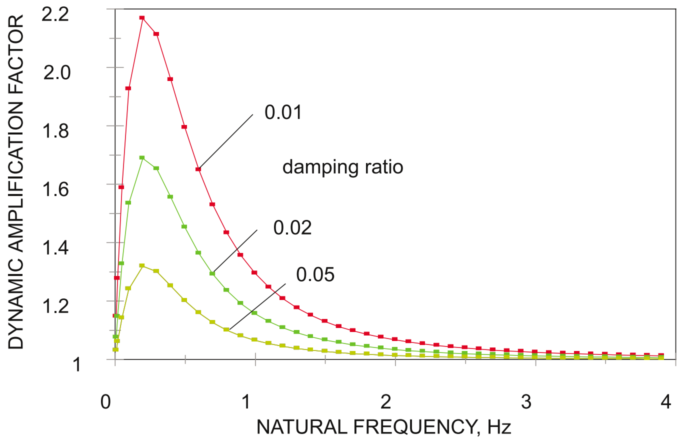

Figure 4: Typical Behavior of Dynamic Amplification Factor

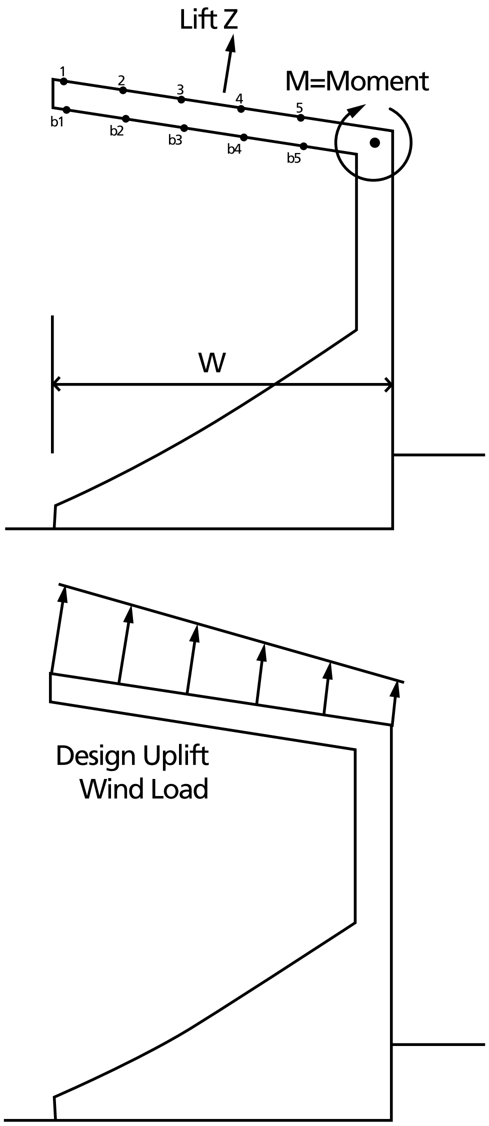

Figure 3: Cantilever Roof

The dynamic amplification factor depends on the natural frequency of the roof, its damping ratio and the details of the frequency spectrum of the uplift. A convenient expression for the dynamic amplification factor is

$$F_{amp} = \sqrt{1+\frac{\pi n_o S(n_o)}{4\zeta\sigma_z^2}}$$

where n_o is the natural frequency of the roof; $S(n_o)$ if the power spectrum of uplift at frequency n_o; and ζ is the damping ratio for the roof structure.

Figure 4 shows the typical behaviour of the dynamic amplification factor as a function of roof natural frequency and damping. It can be seen that as the natural frequency and damping of the roof become low the dynamic amplification factor becomes large. Most roofs have F_{amp} values not much above 1, values in the range 1.1 to 1.5 being typical, but very flexible roofs can have values above 2. The variation of F_{amp} can be seen in the above expression to depend on the spectrum S of wind uplift force which in turn depends on roof shape and the effects of surrounding structures.

Using the dynamic amplification factor method enables most dynamic effects to be effectively accounted for using only a rigid model. However, some roofs have the potential to undergo aeroelastic vibrations in very strong winds, i.e., the roof motion actually magnifies the fluctuating wind forces which then further magnify the motions in a vicious spiral. This is the type of instability that caused the well-known destruction of the Tacoma Narrows bridge in relatively modest winds in 1940. The most flexible roofs can experience similar aeroelastic phenomena to long span bridges.

To examine this possibility requires testing of an aeroelastic model which simulates not only the roof shape but its mass and flexibility, whereas the above discussion concerned wind tunnel testing using a rigid model on which pressures are measured. Most roofs have a lowest natural frequency in excess of 1 Hz and do not required an aeroelastic model study. However, for those roofs with unusual shapes, and a flexibility resulting in a frequency significantly less than 1 Hz, aeroelastic model studies are often undertaken to provide assurance that no hidden boundary of instability has been crossed.

Rowan Williams Davies & Irwin Inc. (RWDI) is a leading wind engineering and microclimate consulting firm - the result of more than 30 years of growth and development. From offices in Canada, the United States and the United Kingdom, our consultants meet the world's most complex structural and architectural challenges with experience, knowledge and superior service. In the early planning stages, careful attention to the effects of wind, snow, ventilation, vibration and related microclimate environmental issues on buildings and structures will save time, save money and reduce risk. Our capable and qualified staff uses advanced engineering tools and carefully defined consulting processes to deliver understandable and useful results.

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