Aerodynamics of a knuckleball

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(Received 30 July 1974; revised 2 December 1974)

The nature of the forces causing the erratic motion of a knuckleball has been investigated by measuring the lateral force on a baseball in a wind tunnel. We have identified two possible sources of a lateral force imbalance that can give rise to the observed erratic changes in the direction of a knuckleball as it moves through the air. One of these results because the nonsymmetrical location of the roughness elements (strings) gives rise to a nonsymmetrical lift (lateral) force. A very slowly spinning knuckleball will have imposed upon it a lateral force that changes as the positions of the strings change. A knuckleball whose spin is identically zero has a constant lateral force unless a portion of the strings is precisely at a location where boundary layer separation occurs. If this happens, the point of boundary layer separation switches alternatively from the front to the rear of the strings, shifting the wake from one position to another, and thereby giving rise to a second possible alternating force imbalance. A two-dimensional analysis of the trajectory of the baseball indicates that the measured force can cause a deflection of the baseball's trajectory of more than a foot. An effective knuckleball should be thrown so that it rotates substantially less than once on its path to home plate.

INTRODUCTION

The knuckleball is the name given to a type of pitch in the game of baseball. The ball is held with the first knuckles or the fingernails (hence, the name knuckleball). As it is thrown, the fingers are extended in such a fashion as to inhibit the backspin normally possessed by a thrown ball. Indeed, it is commonly believed that a properly thrown knuckleball should have no spin at all. As a knuckleball approaches home plate, it changes directions erratically in an apparently random manner.

The lateral deflection of a spinning ball (curve ball) has been studied by Briggs[1] and others and appears to be well understood. It results when the spin of the baseball causes boundary layer separation to occur further upstream on the portion of the ball's surface that has relative motion against the flow of air past the ball. The wake then shifts towards that side of the baseball and the ball is deflected towards the opposite side.

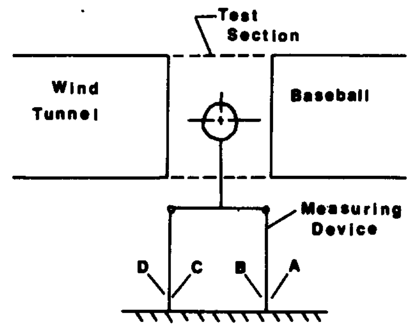

Fig. 1. Schematic of apparatus. The measuring device is in the position used to measure drag.

In an effort to determine precisely the nature of the forces that cause the erratic motion of the knuckleball, we sought to model the situation as nearly as we could in the fluid mechanics laboratory. The results of these experiments are described herein.

APPARATUS AND EXPERIMENTS

The experimental arrangement that we used consisted of a subsonic wind tunnel, a device for measuring lift and drag, and a strip chart recorder for measuring and recording the lift and drag forces.

A drag and lift measuring device was used to measure the forces on the baseball in the wind tunnel. The device (Fig. 1) consisted of two beams rigidly attached at the base and pinned at the top. Foil strain gauges located at A, B, C, and D were placed on each side of the beams and were connected to a Baldwin–Lima–Hamilton micro strain indicator in such a fashion that the total strain output was four times the strain measured by one of the gauges.

A system of known weights was attached by a pulley to the test stand in order to calibrate the measuring device. The resulting curve confirmed that the strain was directly proportional to the force component.

A baseball mounted on this device and placed in a wind tunnel will experience the same flow history as a knuckleball moving through still air at the velocity of the

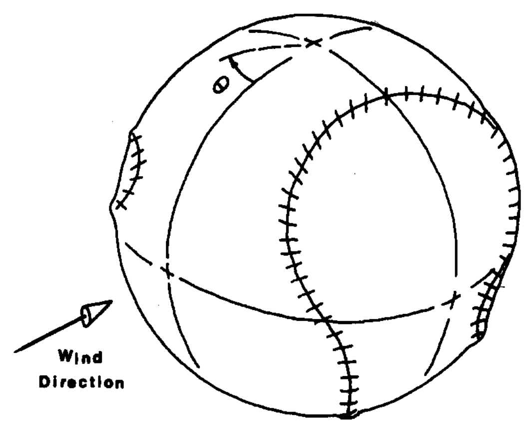

Fig. 2. Position of baseball at $\theta = 0°$. The ball can be rotated in the direction θ to a new position.

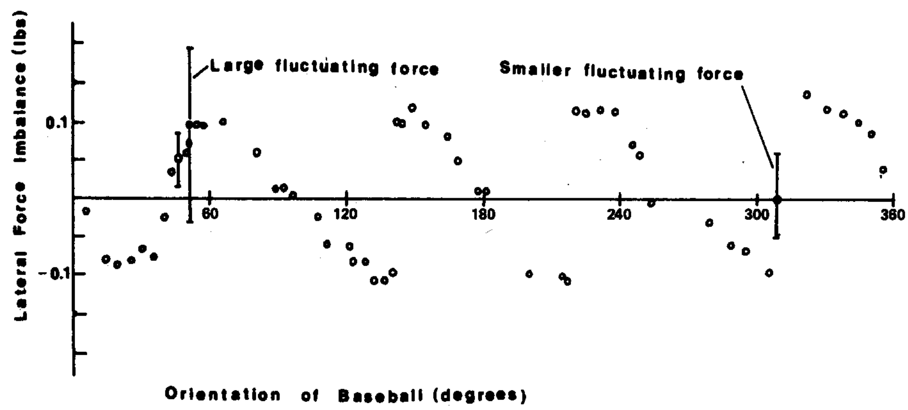

Fig. 3. The variation of the lateral force imbalance with orientation of the baseball. (See Fig. 2 for definition of θ.)

air in the wind tunnel. The velocity profile across the duct of the wind tunnel was measured by using a static Pitot tube. The velocity at a distance 3 in. from the center line of the test section was within 1% of the center line velocity. The velocity across the test section was therefore assumed to be independent of radial position.

With the ball in place and the tunnel velocity at about 50 ft/sec, the chart recorder indicated a lateral force with high-frequency noise superimposed. The frequency of the noise was at least 10 cycles/sec. The noise was probably associated with the turbulence in the wind tunnel. By inserting grids of various sizes in the wind tunnel upstream of the baseball, we were able to decrease the magnitude of the noise by a factor of 2 or 3. In any case, the frequency of the noise was so high that it could cause no measurable deflection of the baseball. We shall give an estimate of this in a later section of this paper. The constant lateral force that we measured was of sufficient magnitude (~ 0.05–0.1 lb, the same order of magnitude as the drag) to cause a significant deflection of the baseball in the distance of 60.5 ft from the pitcher's mound to home plate. However, the force was *constant.* If the ball did not spin, it could give rise to a laterally curved trajectory, but not to the erratic motion associated with the knuckleball.

The lateral force that we measured resulted from the fact that the strings on the surface of the ball form a roughness pattern that is nonsymmetric. The flow pattern about the ball (including the wake) will therefore be nonsymmetric. This will naturally cause a nonsymmetric lateral force distribution and result in a net force in one direction or another. This explanation seems to be justified intuitively. Furthermore, by changing the orientation of the baseball, we were able to change the measured drag force by as much as 50% and to cause the lateral force to change sign.

While we were investigating the effect of the location of the strings on the drag and lateral forces, we discovered that when the ball was oriented in a certain way the strip chart began to record a randomly changing lateral force with a frequency low enough (< 1 cycle/sec) to cause a significant lateral deflection of the baseball. This only occurred for certain special orientations, and we concluded rather quickly that these orientations place a portion of the strings of the baseball at approximately the position where boundary layer separation occurs, at an angular position about 105°–115° from the front stagnation point.

We suspected that the oscillatory force resulted from the point of boundary layer separation changing from the front to the back of the stitches, thereby causing an oscillating wake. In order to check this theory, fine wool threads were individually glued to the rear portion of the ball (in the wake). The ball was then reinserted in the wind tunnel. The location of the wake could be detected as that portion of the rear of the ball where the wool threads indicated backflow.

As we expected, one could clearly detect the fluctuation of the edge of the wake as it moved from the front edge of the stitches to the rear edge and back again.

LATERAL FORCE

It now remained to obtain quantitative measurements to be sure that the forces we observed could cause the ball to deflect as much as a foot or two as they are observed to do for real baseballs. We also wanted to find out how the magnitude and frequency of the fluctuating force varied with velocity, and how the constant lateral force varied with velocity and with the orientation of the baseball.

A standard 2.88-in.-diam baseball was inserted in the wind tunnel in the position shown in Fig. 2. An isometric sketch is shown in order to establish the initial position of the strings. With the ball oriented in this way the lateral force was zero. The ball was then turned about the vertical axis. The lateral force was recorded for various values of the angle θ between 0 and 2π rad. The velocity was

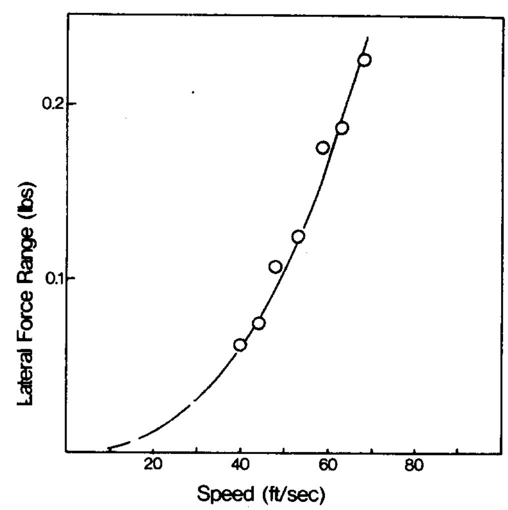

Fig. 4. Variation of difference between the maximum and minimum lateral forces.

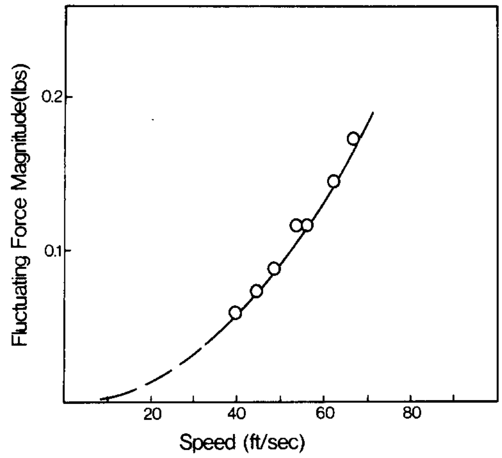

Fig. 5. Variation of the magnitude of the fluctuating force.

68 ft/sec. The results are shown in Fig. 3.

Figure 3 reveals several interesting features, some of which we did not anticipate. The lateral force varied between about 0.1 lb towards the left and 0.1 lb towards the right. At angles of approximately $\theta = 140°$ and 220° there was a nearly discontinuous jump in the lateral force from about 0.08 lb in one direction to a similar value in the opposite direction. Also, at approximately $\theta = 52°$ and 310° there was an instability that caused the lateral force to alternate from left to right with an amplitude of about 0.18 lb and a frequency of 0.5–1 cycle/sec. This alternating force occurred when a portion of the strings was located just at the point where boundary layer separation takes place. As we pointed out above, it resulted when the point of separation changed from one side of the strings to the other. *It did not always occur* when the strings lay at the edge of the wake. For example, at $\theta = 140°$ and 220°, there occurred a practically discontinuous change in the lateral force, indicating that the separation point had moved from the front to the rear of the strings (or vice versa) and remained there. The data near all four of the positions $\theta = 52°$, 140°, 220°, and 310° were quite repeatable.

Figures 4 and 5 give an indication of how the various forces change with velocity. In the Reynolds number range in question (Re $\approx 10^5$) the drag *coefficient* for a sphere is approximately constant.[2] The drag *force* therefore increases as the square of the velocity. It is therefore not too surprising that the magnitudes of the various lateral forces increased as approximately the square of the velocity. Figure 4 shows such a variation in the difference between the maximum and minimum lateral forces on the baseball for a given velocity. Figure 5 shows how the magnitude of the *fluctuating* force near $\theta = 52°$ and 310° varied with the velocity. The frequency of this fluctuating force did not appear to vary appreciably with velocity, nor did the value of θ for which it occurred.

THE TRAJECTORY

We now wish to compute possible deflections in the trajectories of thrown balls in response to the forces measured, and to draw some conclusions about the possible origin of the erratic motion of knuckleballs. We begin with a simple force balance on the baseball in the direction mutually perpendicular to the original direction of level flight of the ball and the gravitation vector. Although the lateral force is actually perpendicular to the instantaneous direction of flight of the ball, it serves our present purpose best to use the approximation, accurate for small deflections,

$$F = m\frac{d^2x}{dt^2}, \tag{1}$$

where F is the lateral force, m is the mass of the baseball, and d^2x/dt^2 is the lateral acceleration of baseball. The steady-state solution that results when F is a periodic force $F_0 \sin(\omega t)$ is

$$x = \frac{F_0}{m\omega^2}\sin(\omega t + \pi). \tag{2}$$

The magnitude of the displacement from the undisturbed trajectory of the baseball therefore varies inversely with the square of the frequency of the imposed force. Taking the mass of the baseball to be 10^{-2} slugs and the force to have a magnitude of 0.05 lb, we find that a deflection of 1 ft or more can be obtained only if the frequency is less than about 0.2 cycle/sec. In particular, the high-frequency force that we attributed to wind tunnel noise could cause a deflection of only about 5×10^{-4} ft if we assume its frequency is 10 cycles/sec and its amplitude is 0.02 lb.

If a lateral force $F(t)$ is suddenly applied to a ball whose initial lateral velocity and displacement are zero, the lateral displacement after a time t will be approximately

$$x(t) = m^{-1}\int_0^t \int_0^\tau F(\lambda)\,d\lambda\,d\tau. \tag{3}$$

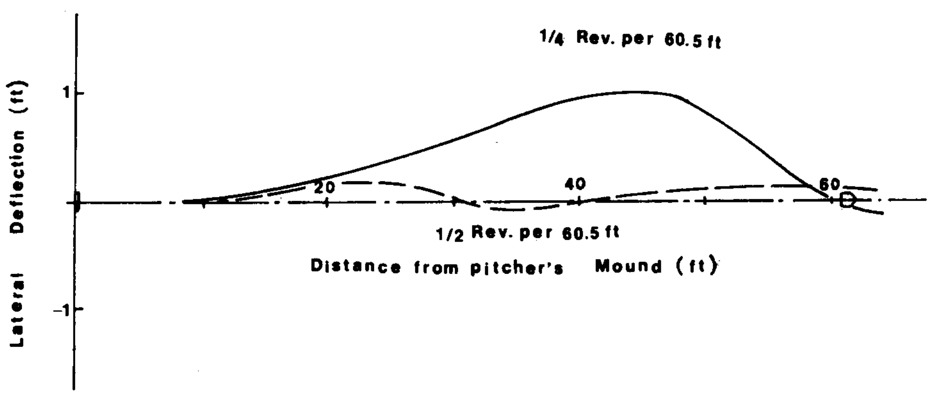

Fig. 6. Typical trajectories, v = 68 ft/sec.

In particular, if $F(t)$ is a constant, F_0,

$$X(t)=\tfrac{1}{2}(F_0/m)t^2. \tag{4}$$

If the forward speed of the ball is constant, the time to reach home plate will be D/V, where D is the distance traversed by the ball and V is its speed. Hence, the distance the ball will curve by the time it reaches home plate is

$$X=\tfrac{1}{2}(F_0/m)(D/V)^2. \tag{5}$$

When we recall that the lateral force F_0 is (roughly speaking) proportional to the square of the velocity, we obtain the somewhat surprising result that the lateral deflection does not vary with speed.

If the knuckleball is thrown in such a fashion that it has no spin at all, it can only curve laterally in one direction. The maximum deflection will be dependent only on the initial orientation of the baseball (i.e., the initial locations of the strings). The single exception can occur in the remote possibility that the strings are initially positioned so that they disturb the point of boundary layer separation and bring about the oscillating wake phenomena described above. This could cause the erratically fluctuating lateral motion that is actually observed to occur with real knuckleballs.

A much more plausible argument is that the ball spins very slowly as it approaches the plate, thereby exposing the ball to a varying lateral force depending on the orientation of the ball at any given instant. If the ball spins too fast, we can see from Eq. (2) that the deflection will be small. For example, if we approximate the curve in Fig. 3 by a sine wave of amplitude 0.08 lb and we assume the baseball is thrown at 60 ft/sec and undergoes two complete revolutions before reaching home plate, the amplitude of the deflection is only 0.048 ft. The spin of the ball should therefore be substantially slower than this.

An important feature of Fig. 3 is the nearly discontinuous change in the lateral force at $\theta = 140°$ and $220°$. If the ball should move through this orientation at some time during its flight towards home plate, the induced slow curvature caused by the slowly varying lateral force will suddenly become a very sharp "break," that is, a sudden change in curvature.

We have numerically integrated Eq. (3) using our data for the cases where the ball is initially oriented such that $\theta = 90°$ and the spin is such that the ball undergoes a quarter- and a half-revolution, respectively, during the time required to reach home plate. The results are shown in Fig. 6. Clearly, the first is the better pitch.

We wish to make one additional remark regarding the physical nature of curving baseballs. It is frequently stated by those who actually play the game that a curving baseball "breaks" rather than simply deflecting with constant curvature. If a lateral force $F(t)$ is applied to a baseball so that it is always perpendicular to the instantaneous direction of flight, the baseball will curve in such a fashion that $F(t)$ is equal to the instantaneous centripetal acceleration $mv^2\kappa(t)$, where $\kappa(t)$ is the instantaneous curvature of the path of the baseball. Thus, a constant lateral force would give rise to a constant curvature

$$\kappa = F_0/mv^2. \tag{6}$$

No "break" occurs. From the batter's vantage point, however, things appear quite different. As the approximate solution given as Eq. (4) shows, what the batter sees is a projectile whose lateral deflection is *changing at an accelerating rate*. How much worse if the deflecting force is erratic!

SUMMARY AND CONCLUSIONS

We can summarize our most important results as follows:

(i) There are two possible mechanisms for the erratic lateral force that causes the fluttering flight of the knuckleball. A fluctuating lateral force can result from a portion of the strings being located just at the point where boundary layer separation occurs. A far more likely situation is that the ball spins very slowly, changing the location of the roughness elements (strings), and thereby causing a nonsymmetric velocity distribution and a shifting of the wake.

(ii) An effective knuckleball should have a slight spin. Too much spin could prove disastrous, however, since the inertia of the ball would not allow a significant deflection.

(iii) The magnitude of the lateral force increases approximately as the square of the velocity. This results in a total lateral deflection that is independent of the speed of the pitch.

[1]L. J. Briggs, Am. J. Phys. **27**, 589 (1959).

[2]L. Prandtl, *Essentials of Fluid Dynamics* (Hafner, New York, 1952), p. 191.