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A phenomenological model for the aerodynamics of the knuckleball

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ABSTRACT

The movement of a knuckleball depends on the seams of the baseball strongly, as a consequence a lift force proportional to the square of the ball velocity is occasioned. In this work we develop a model as a function of the position of the seams to compute the lift coefficient that appears in the lift force acting in upward direction, for four-seam (4S) and two-seam (2S) orientations of the ball. The result of the model is consistent with experimental data. In addition, deviations caused by lift force are calculated for all angles in the 4S and 2S orientations and some trajectories are generated.

1. Introduction

Baseball pitchers have a wide repertory of throws, which can be divided by the relative motion to its center of mass in two types: rotating and non-rotating balls. Majority of pitches belong to rotating (or spinning) balls, as examples: curveball, slider, change-up, and varieties of fastball; whereas the unique throw without initial spin is known as knuckleball. Both types of balls have a deflection on their trajectory, however, forces that cause these motions are not the same. On the one hand, changes on trajectory in spinning pitches are caused by a difference of pressure on the sides of the rotating ball giving rise to the well-known Magnus force [1–5]. On the other hand, when a knuckleball is thrown, the pattern of the baseball seams can produce an asymmetrical turbulence and laminar boundary layers on different sides of the ball, which lead to cross (lift and lateral) forces [6–8].

In this way, cross forces in a knuckleball depend on the asymmetry of the ball seams. This means that for a baseball traveling without rotation and with an orientation in which it is perfectly symmetric on both sides of the front view, as both orientations in Fig. 1, it will only experience a change in the upward-direction. Now, if the ball spins at a frequency low enough (<50 rpm) to remain as a non-rotating ball, the lift force will be changing over time and a more erratic trajectory will be produced [8,9]. Trajectories like those are commonly seen in real knuckleballs since pitchers have a tendency to

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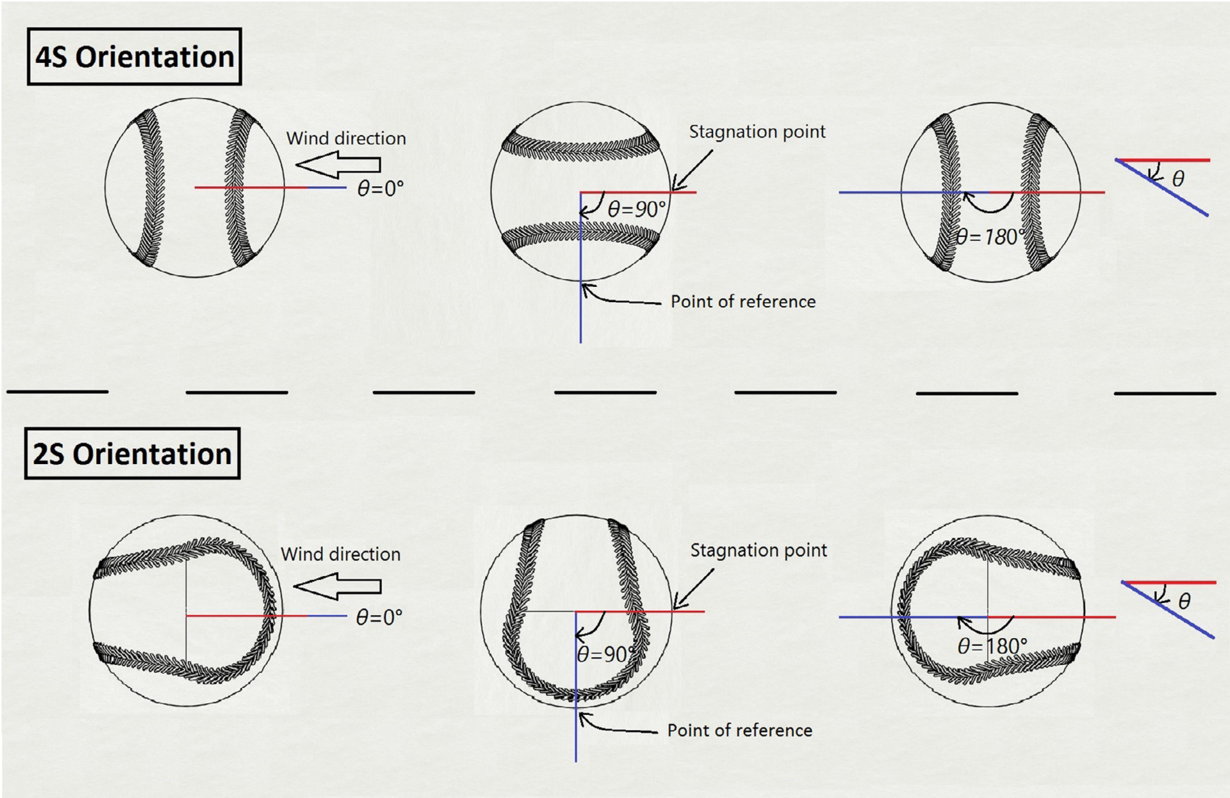

Fig. 1. Knuckleball orientations at different attack angles θ. The angle is measured from the point of stagnation (red line) to the point of reference of the ball (blue line). Up: Four-seam (4S) orientation. Bottom: Two-seam (2S) orientation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

throw two specific ball orientations, namely, four-seam (4S) and two-seam (2S), in accord with the number of seams that pass through the front of the ball [8,10].

Since the phenomenon was not qualitatively well understood, for many years pitchers experiences were the main way of information about knuckleball trajectories, so that speed changes, unusual movements and diverse final positions of the ball with apparent similar initial conditions led to the popular belief that the knuckleball motion was a random process [11,12]. Only a few studies in attempt to describe cross forces have been reported. Most of them are compiled in the mathematical model for the lift force $\mathbf{F}_L$ proposed by Nathan [12]:

$$\mathbf{F}_L = kC_L V^2 (\hat{\alpha} \times \hat{\mathbf{V}}), \tag{1}$$

where $\mathbf{V}$ is the ball velocity, $\boldsymbol{\alpha}$ is a vector perpendicular to both the lift force and the velocity determining the orientation of the ball, C_L is an adjustment constant coefficient, and k is a numerical factor that involves the air density ρ, the mass m and the area A of the ball.

Model (1) is consistent with Watts and Sawyer [9] measurements on the quadratic relationship between cross forces and ball speed, $F_L \propto V^2$, however, it does not consider the dependence of lift/lateral force on the attack angle θ of the ball. In spite of this, Nathan suggested such dependence can be added to the model by means of the lift coefficient C_L. Moreover, both Watts and Sawyer [9] and recently Borg and Morrisey [8] measurements indicate that cross forces are periodic, therefore they can be related to the attack angle in an approximately sinusoidal behavior. In detail, the expression

$$F_L = F_0 \sin(\omega t) \tag{2}$$

has been used for describing the magnitude of the lateral force F_L, when considering a steady-state system in which the baseball spins at low angular velocities ω, and F_0 is the force at time $t = 0$. Borg and Morrisey data about the lift coefficient for 4S and 2S orientations are shown in Fig. 2.

As mentioned before, there are a few studies describing the knuckleball dynamics; however, nowadays technology measures in a better way the dynamics of a ball in different sports and thus opens the possibility of developing more accurate models taking into account more detailed experimental data. In an effort to contribute to the understanding of this phenomenon, in this work we construct a model to describe the lift force acting upon upward-direction for 4S and 2S orientations based on (1) with a lift coefficient as a function of the position of the ball seams. The structure of this paper is