Pickleball Flight Dynamics

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Abstract

This paper considers the flight dynamics of the ball in the sport of pickleball. Various simplifications are introduced according to the features of the game. These simplifications and some approximations enable straightforward coding to study aspects of the game such as the trajectory of the ball and its velocity. In turn, strategic questions may be addressed that have not been previously considered. In particular, our primary research question involves the preference between playing with the wind versus against the wind. It is demonstrated that playing against the wind is often preferable than playing with the wind.

Keywords: pickleball, projectile motion, strategy.

1 INTRODUCTION

Pickleball is a relatively new sport. It was invented in 1985, and in recent years its popularity has taken off. Pickleball was the fastest growing sport from 2022 to 2023 in the United States with over 8.9 million participants (SFIA 2024). According to a 2023 report from the Association of Pickleball Players (APP), nearly 50 million Americans have played pickleball at least once in the previous year (https://www.theapp.global). The game is popular across wide age cohorts at the recreational level. Pickleball also has various professional leagues and tours including Major League Pickleball (MLP).

Despite the popularity of the sport, there has been little quantitative research on pickleball. Gill and Swartz (2019) consider the impact of strong and weak links on success in doubles pickleball. It is the intention of this paper to add to the sparse literature with a specific aim of gaining a better understanding of pickleball flight dynamics. Albert et al. (2017) consider problems in sports analytics across major sports.

The topic of projectile motion has a long and well-studied history (Lubarda and Lubarda 2022). The details are complex, especially when considerations are given to air resistance and wind. Projectile motion models typically involve special functions and differential equations. Such work is important to serious investigations such as ballistics. In sport, Chudinov (2022) considers issues of approximate projectile motion in the sports of golf, tennis and badminton. However, there does not seem to be any literature on pickleball flight dynamics; this paper attempts to provide insights on this topic.

In the problem considered here, we take features of the sport of pickleball into account. This, together with additional assumptions simplifies our projectile motion model. The final model is straightforward to code so that various investigations involving pickleball may be undertaken. In particular, we look at the impact of the wind in pickleball. Pickleball is often played outdoors where the choice of ends, and understanding how to play in the wind become questions of strategy. Our primary research question involves the preference between playing with the wind versus playing against the wind where it is demonstrated that playing against the wind is preferable in many contexts. This problem in pickleball strategy does not seem to have been previously addressed.

In Section 2, we provide a description of the relevant details of the pickleball court, and features of interest. We also define the relevant input variables to the projectile motion

model. In Section 3, the basics of the pickleball motion model are described. In particular, we explain how features of the sport allow us to calculate input variables that are not immediately available. In Section 4, we look at various pickleball applications. In particular, we investigate pickleball trajectory and pickleball velocity under various conditions. We then discuss a question of strategy in terms of whether it is better to play against the wind or with the wind. The work indicates that a strategic advantage is often conferred when playing against the wind. We conclude with a short disscussion in Section 5.

2 PROBLEM FORMULATION

Figure 1 provides the relevant details of the pickleball court and our features of interest. The pickleball court is 44.0 feet long which is divided into two equal halves by a net. The net is 3.0 tall at the ends although this detail is not important for our motion model.

In Figure 1, a launch point is depicted on the left side of the court. This is the location from which the player of interest strikes the pickleball. The location is marked x_0 feet from the left endline and serves as an input variable for our investigation. We have the constraint $x_0 \in (0, 15.0)$ feet where we note that the 15.0 foot mark denotes the beginning of the non-volley zone (i.e. the closest point to the net that the player should approach). The player strikes the ball at height y_0. We consider $y_0 \in (0, 7.0)$ feet as a realistic range for the height at which the pickleball is struck. Note that 7.0 feet is 1.0 foot over the head of a 6-foot player. Further, the ball is struck at launch angle θ. For our purposes, we consider $\theta \in (0, 30°)$. An angle larger than 30° either represents a lob shot or a mishit, two shots that are not relevant to this investigation.

In Figure 1, we also depict the opponent (i.e. the point of interest) on the right side of the court whose horizontal position is given by z_0 feet from the left endline. Later, we are interested in the opponent's ability to hit the struck ball. Since the opponent is not advised to stand in his non-volley zone, we have the constraint $z_0 \in (29, 44)$.

There are two quantities that are relevant to our investigation that are not depicted in Figure 1. First, the wind is a characteristic of interest. We make the assumption that it blows in a strictly horizontal direction. Personal experiences in pickleball suggest that playing in winds less than 10mph are largely inconsequential. On the other hand,

playing in wind speeds exceeding 20mph are extreme and are situations that many players avoid. Therefore, we are interested in wind velocities w (i.e. speed and direction) in the intermediate intervals $(-20, -10)$mph and $(10, 20)$mph.

Second, we require the initial velocity v_0 that the pickleball is struck at the launch point. In the related sport of tennis, the average serve in men's professional tennis (e.g. the ATP tour) is estimated at 120mph. Unlike tennis, pickleball has a rigid paddle (without strings) and a ball which is hard and compresses only negligibly. Therefore, the fastest pickleball shots reach speeds of only 60mph. We emphasize that the velocity v_0 corresponds to the direction of the launch angle θ.

Therefore, to summarize, the input variables that are relevant to pickleball flight dynamics are $(x_0, y_0, \theta, z_0, w, v_0)$.
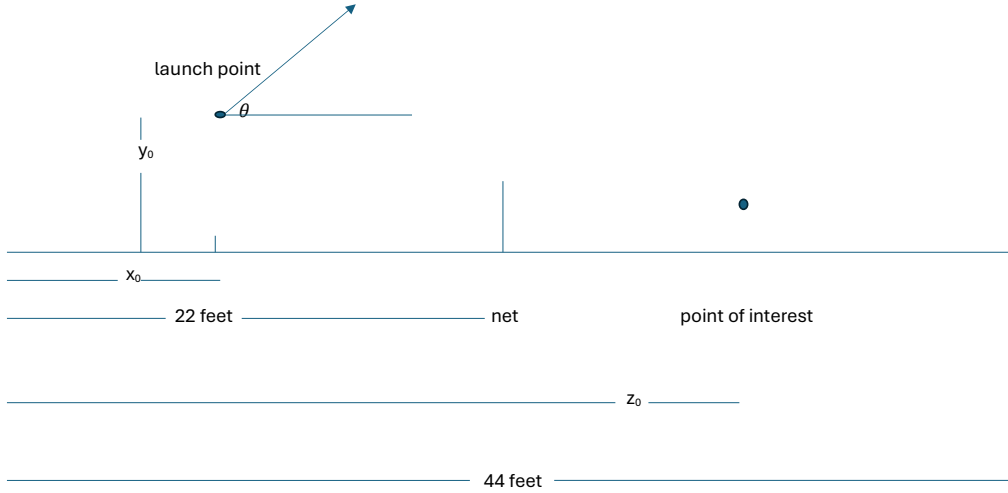

Figure 1: Configuration of the court and the variables related to the flight of the pickleball.

3 PICKLEBALL MOTION MODEL

This section describes the basics of the pickleball motion model. More details including the associated physics of the model are provided in the Appendix.

For this investigation, it is convenient to consider pickleball motion separately in the x and y coordinates. We are primarily interested in the location and speed of the pickleball which we denote by x and x' in the horizontal direction, and by y and y' in the vertical direction.

Referring back to the discussion and the notation in Section 1, the coordinate speeds are expressed more fully as

$$x'(t, \theta, w, v_0) \tag{1}$$

and

$$y'(t, \theta, w, v_0) \ . \tag{2}$$

The arguments of the speeds in (1) and (2) have common terms, namely the time from launch t, the launch angle θ, the wind velocity w and the initial velocity v_0. Of course, and as described in the Appendix, (1) and (2) are complex functions that also depend on the features of the pickleball (e.g. weight, size and surface) which determine the impact of air resistance. Also, the force of gravity comes into play in the vertical speed but not in the horizontal speed. In our model, we ignore the impact of spin.

In (1) and (2), we note that the speed functions depend on the launch angle θ and the initial velocity v_0. In fact, there is a simplification that occurs since coordinate speeds only depend on θ and v_0 through the initial coordinate speeds. Therefore, using trigonometry, we may replace θ and v_0 in (1) by $v_0 \cos\theta$ and we may replace θ and v_0 in (2) by $v_0 \sin\theta$. However, we retain the excessive notation in (1) and (2) which is helpful in future considerations.

For the coordinate locations, these are expressed more fully as

$$x(x_0, t, \theta, w, v_0) \tag{3}$$

and

$$y(y_0, t, \theta, w, v_0) \ . \tag{4}$$

The functions (3) and (4) have the same arguments as in (1) and (2) except that the initial locations x_0 and y_0 also influence location at time t.

It may be noted that the relationship between location and velocity allows us to express the locations functions as $x(x_0, t, \theta, w, v_0) = x_0 + \int_0^t x'(t, \theta, w, v_0) \ dt$ and $y(y_0, t, \theta, w, v_0) = y_0 + \int_0^t y'(t, \theta, w, v_0) \ dt$. However, these expressions do not assist our development since the integrands are intractable functions.

3.1 A Pickleball Simplification

A primary interest in our research concerns the issue of playing in the wind; should you prefer to play with the wind or play against the wind? To simplify the problem, we consider some standard pickleball strategy. Referring to Figure 1, we assume that the player on the left hand side of the court (i.e. the launch point) hits the ball as hard as possible such that the ball remains in bounds. This assumption is widely applicable in pickleball (excepting drop shots, for example). Players hit the ball hard because high speed shots pose difficulty for the opponent; in particular, the opponent has less time to react. Hitting the ball as described, means that the ball, if left untouched, would land on the endline on the right hand side of the court. Therefore, hitting the ball in this manner may be considered an optimal shot in pickleball.

We denote t_b as the hypothetical time that it would take the hard hit ball to *bounce* on the right endline. Because the length of the court is 44 feet, we can express this constraint as

$$y(y_0, t_b, \theta, w, v_0) = 0.0 \tag{5}$$

and

$$x(x_0, t_b, \theta, w, v_0) = 44.0 \ . \tag{6}$$

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In equations (5) and (6), we are going to investigate various cases involving the input settings x_0, θ and w. In other words, x_0, θ and w are values that are determined in advance. Therefore, (5) and (6) represent two equations in two unknowns, t_b and v_0. Using the model described in the Appendix and the associated numerical methods, we are able to solve for t_b and v_0. This is particularly helpful since these are two quantities for which little is known apriori.

Having solved for v_0, we can then consider the equation

$$x(x_0, t, \theta, w, v_0) = z_0 \tag{7}$$

for an unknown time t. Equation (7) addresses the time that it takes the ball from when it is struck to reach the opponent (i.e. the location of interest in Figure 1 which is z_0 feet from the left endline).

From (7), we are able to solve for t. When t is small, this means that there is little time for the opponent to react with their return shot. Therefore, the shot would be a very good shot. Consequently, for opposing wind velocities w and $-w$, we can assess whether it is better to play with or against the wind. This problem is studied in Section 4.3.

4 APPLICATIONS

4.1 Pickleball Trajectory

Using the motion model described in the Appendix and the associated numerical methods, we are able to compute both the horizontal location $x(x_0, t, \theta, w, v_0)$ and the vertical location $y(y_0, t, \theta, w, v_0)$ given the input variables. The resulting (x, y) coordinates taken over a sequence of times t allow us to produce trajectory plots. Note that our code allows us to do this over any set of input variables.

In Figure 2, we provide plots for input values $x_0 = 11$ feet (which corresponds to the middle of the left court), $y_0 = 3$ feet (which is a typical height from where the ball is hit) and $\theta = 20$ degrees (which is a typical launch angle). Four plots are provided; for wind speeds $w = -10$mph, $w = 0$mph (no wind), $w = 10$mph and $w = 15$mph. The initial velocity input v_0 is evaluated according to the optimality conditions described in Section 3.

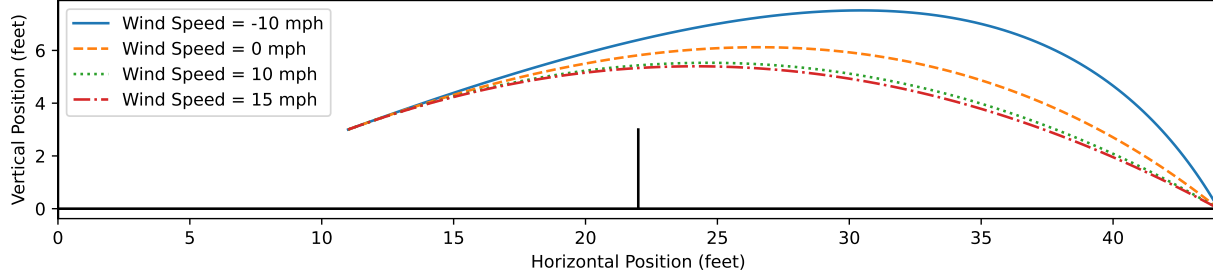Figure 2: Trajectory of an optimally hit pickleball in four wind conditions $w = -10$mph, $w = 0$mph, $w = 10$mph and $w = 15$mph. Other input values are set at $x_0 = 11$ feet, $y_0 = 3$ feet and $\theta = 20$ degrees.

In Figure 2, we observe that the trajectories for wind speeds $w = 0, 10, 15$mph do not differ greatly. However, when playing against the wind (i.e. $w = -10$mph), the pickleball flight has greater curvature with a higher arc. It appears that the pickleball which is light gets held up by the wind. Towards the end of the path when playing against the wind, the pickleball is moving more in a downward direction than horizontally.

4.2   Pickleball Velocity

We now consider an exercise with the same input values as given in Section 4.1. However, this time we calculate the velocity functions $x'(t, \theta, w, v_0)$ and $y'(t, \theta, w, v_0)$. We evaluate the coordinate velocities x' and y' for increasing times t. Then, the overall velocity v is calculated via $v = [(x')^2 + (y')^2]^{1/2}$. In Figure 3, we plot v versus the horizontal location x under the wind conditions $w = -10$mph, $w = 0$mph, $w = 10$mph and $w = 15$mph.

In Figure 3, we again observe that the condition of playing against wind (i.e. $w = -10$mph) is significantly different from the other three cases. For example, the initial velocity v_0 is greatest when playing against the wind. This is necessary in order for the shot to reach the right endline. When playing against the wind, we also observe greater initial deceleration (i.e. the slope of the velocity curve is steeper). On the other hand, when
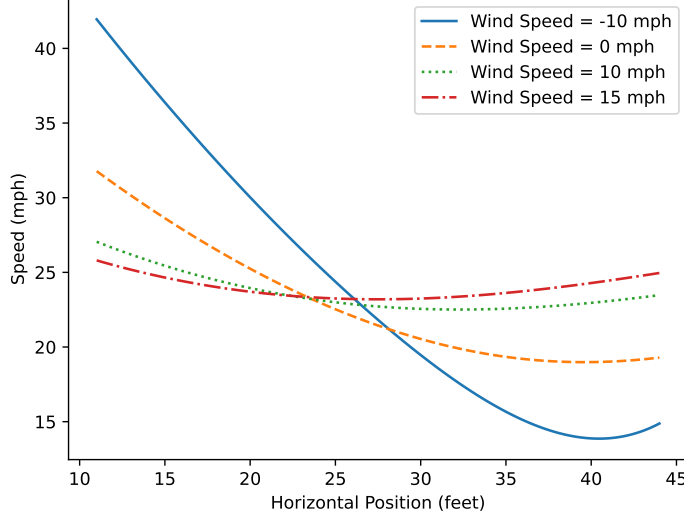
Figure 3: Velocity of an optimally hit pickleball in four wind conditions, $w = -10$mph, $w = 0$mph, $w = 10$mph and $w = 15$mph plotted against the horizontal location. Other input values are set at $x_0 = 11$ feet, $y_0 = 3$ feet and $\theta = 20$ degrees.

playing with the wind, the ball maintains a similar velocity throughout its path. Under all four wind conditions, we see that the pickleball velocity is similar (approximately 24mph) at horizontal location 27 feet. This point is close to the non-volley zone (NVZ) on the right hand side of the court. From a playing perspective, it is interesting that the NVZ position which is widely regarded as being most strategic is the position where the ball is passing the fastest.

4.3   Strategy - Playing in the Wind

Here we address the question: is is better to play with the wind or against the wind? Again, we assume that the player of interest has played optimally in the sense that the ball is hit hard enough to bounce on the right baseline.

   We use the general approach described in Section 3.1 to evaluate the time that it takes the ball to reach the opponent (i.e. point of interest in Figure 1). If it takes less time to reach the opponent playing with the wind, then playing with the wind is preferred. If it takes

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less time to reach the opponent playing against the wind, then playing against the wind is preferred. Table 1 calculates time differences under the following conditions: $x_0 = 0, 11, 15$ feet (corresponding to endline, mid-court and non-volley zone) for the player executing the shot, $z_0 = 29, 33, 44$ feet (corresponding to non-volley zone, mid-court and endline) for the opponent, launch angle $\theta = 20$ degrees and launch height $y_0 = 3$ feet. We note that the time difference results in Table 1 are not greatly sensitive to minor modifications in the values of θ and y_0.

Letting t_w denote the time in seconds that it takes the ball to reach the opponent with an assisting wind $w \geq 0$, we consider the excess time difference $D_w = t_w - t_{-w}$ that it takes for the ball to reach the opponent when playing with the wind compared to when playing against the wind. This is evaluated for the wind conditions $w = 10$mph, $w = 15$mph and $w = 20$ mph.

x_0	z_0	D_{10}	D_{15}	D_{20}
0	29	0.097	0.200	0.346
0	33	0.056	0.166	0.348
0	44	-0.302	-0.490	0.089
11	29	0.082	0.150	0.242
11	33	0.058	0.133	0.255
11	44	-0.230	-0.375	-0.568
15	29	0.075	0.131	0.203
15	33	0.059	0.124	0.223
15	44	-0.203	-0.332	-0.505

Table 1: Excess time difference in seconds D_w that it takes the ball to reach the opponent when playing with the wind compared to when playing against the wind where w is recorded in mph. The calculations are carried out using 9 combinations of x_0 and z_0, and using typical settings $\theta = 20$ degrees and $y_0 = 3$ feet.

From Table 1, we observe that most of the D_w entries are positive. This suggests that there is a competitive advantage to playing against the wind. The ball reaches the opponent faster and there is less time for the opponent to react when playing against the wind. The only situations where D_w is negative correspond to the setting $z_0 = 44$ feet (i.e. the opponent is located on the right endline). This is noteworthy since it is generally

accepted pickleball strategy to approach the non-volley zone, and not sit back at the right endline.

It is also interesting to look at the row with input settings $x_0 = 15$ feet and $z_0 = 29$ feet. This corresponds to the common situation where both players have approached the non-volley zone and are as close as possible. Here, we see that as the wind w increases, D_w increases. That is, the advantage of playing against the wind becomes greater as the wind blows harder. In fact, this same phenomenon is observed in all situations in Table 1 whenever $z_0 \neq 44$ feet.

We need to verify the sensitivity comment in the second paragraph of Section 4.3 related to θ and y_0.

5   DISCUSSION

This paper appears to be the first serious investigation of flight dynamics in the sport of pickleball. The work is based on a detailed physical model that takes into account relevant inputs including air resistance and wind. Python code is provided in a github page (see the Appendix) that allows researchers to graph pickleball trajectories and velocities under various conditions. By taking into account standard pickleball strategy we are also able to address research questions such as the impact of playing with and against the wind.

Although the results provided in this paper correspond to our intuition and were derived from existing knowledge of projectile motion, it would be good to verify some of the results against video taken from pickleball matches. In future research, it may also be useful to consider additional wind environments such as crosswinds.

6   REFERENCES

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7 APPENDIX

This section provides details regarding the pickleball motion model. It includes discussion of air resistance, the Reynold's number, the ODEs, possible references. We also describe how model computations are handled numerically. Probably we refer to a github page that provides code?