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Deceleration of a Shuttlecock

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Abstract

The relationship between the velocity and the deceleration of a badminton shuttlecock was investigated. A shuttlecock was hit at a typical range of velocities and was filmed at 600 frames per second. The deceleration was found to be proportional to velocity squared over the range tested.

Introduction

Badminton is known to be the fastest racket sport, with the shuttlecock leaving the racket with speeds of up to 115 m/s[1]. But a badminton shuttlecock has a low mass and high cross sectional area so it decelerates very quickly as it moves through the air. In this research, the relationship between the velocity and the deceleration of a badminton shuttlecock will be investigated. The deceleration characteristic of a shuttlecock in air is important because it is needed to predict the path of the shuttlecock.

When a solid object travels through a fluid at high velocities, it is acted upon by a drag force. Drag is a mechanical force that is generated by the interaction of the solid body with the fluid. The factors that affect the magnitude of the drag force are the relative velocity of the object, the density of the fluid, the coefficient of drag and the cross sectional area of the object[2].

The equation for drag force for turbulent flow is given as

$$F_D = \frac{1}{2}\rho C_d A v^2 \quad [2] \qquad \text{(Equation 1)}$$

where F_D is the drag force, ρ is the density of the fluid, A is the cross-sectional area, and C_d is the coefficient of drag. The coefficient of drag is a number that is used to model the complex dependencies of shape, inclination and flow conditions. Equation 1 is generally applied to solid bodies, but a shuttlecock is not a solid body. There are spaces between the shafts of the feathers, and air flows between the feathers as it moves. This makes it impossible to reliably determine the cross sectional area of a shuttlecock. For the purposes of modeling drag in a shuttlecock, we propose to define a new constant, κ, replacing the quantity $C_d A$ in equation 1 and having units m^2.

Figure 1 The shuttlecock used.

The equation which we will use to model drag on a shuttlecock will be

$$F_D = \frac{1}{2}\rho\kappa v^2. \qquad \text{(Equation 2)}$$

Combining equation 2 with Newton's Second Law gives

$$a = \frac{1}{2m}\rho\kappa v^2 \qquad \text{(Equation 3)}$$

where m is the mass and a is the acceleration of the shuttlecock.

It is known that the coefficient of drag for a variety of solid balls does vary as a function of velocity. For a solid ball at high speeds, the coefficient of drag increases with increasing velocity approaching a maximum value[3].

The velocity and the deceleration of the shuttlecock will be measured and used to determine how the velocity affects the drag constant, κ, of the shuttlecock.

Methods

A high speed camera was set to record at 600 fps. A standard 4.82 gram badminton shuttlecock with a radius of 3.4 cm was used. The shuttlecock was 4 meters away from the camera and was hit perpendicular to the field of view of the camera at various speeds. The field of view of the camera was approximately 4 meters across. The temperature of the room was 27 degrees Celsius.

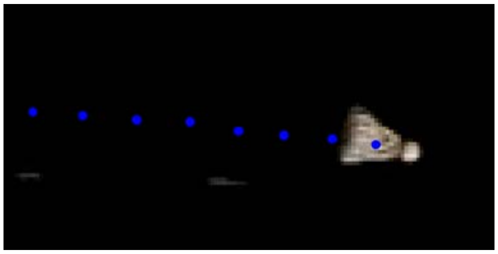

Figure 2 The position of the shuttlecock in each frame was analyzed.

Using Logger Pro Video Analysis, the velocity and the acceleration of the shuttlecock was determined. The position of the shuttlecock as a function of time was determined from the video as shown in figure 2. Only videos of shuttlecocks whose flight paths had stabilized and were within 10º of the horizontal were analyzed. The average velocity and acceleration were determined from the horizontal component of the position-time graph as shown in figure 3. The slope of a linear fit of the data was taken as the average velocity of the shuttlecock during that time. The acceleration was taken as twice the constant A for a quadratic fit of the data.

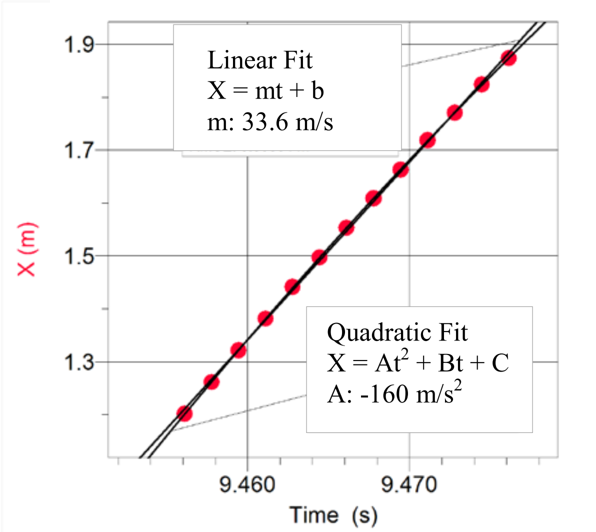

Figure 3 The slope of the linear fit is the average velocity, while 2A is the average acceleration.

Results and Discussion

From figure 4, the relationship between the velocity and the acceleration of a shuttlecock is given by the equation

$$a = 0.12 \cdot v^2 \qquad \text{(Equation 4)}$$

The velocity of the shuttlecock and its acceleration for velocities from 7 m/s to 55 m/s are directly proportional. The level of variation in the data is quite high but the relationship is valid within uncertainties.

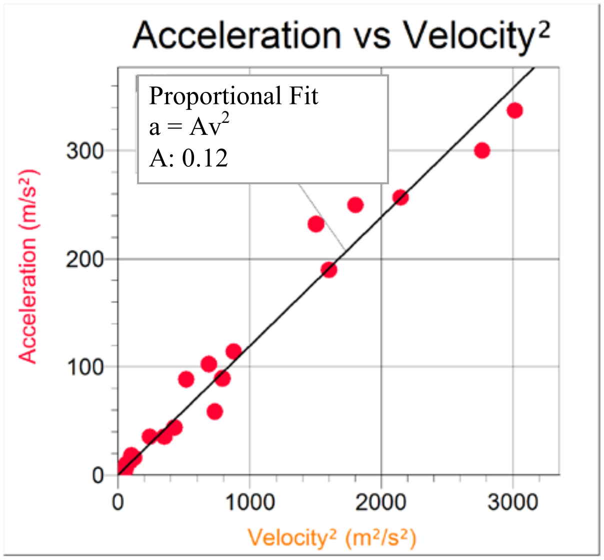

Figure 4 The acceleration of the shuttlecock is proportional to the square of its velocity.

Since the graph showed a proportional fit, the drag constant for the shuttlecock was found to be constant for all velocities within the range tested. Using equation 3, the drag constant, κ, for this shuttlecock was determined to be 9.7×10^{-4} m^2.

A solid cone with a 41° angle has been shown to have a coefficient of drag of 0.47 at low velocities[4]. Using equation 1, and assuming a solid body, the coefficient of drag of our shuttlecock was calculated as 0.27, which is significantly lower than the solid cone. This is a reasonable result since the shuttlecock is not a solid body. The air flowing through the spaces gives it a much lower effective cross sectional area making the application of equation 1 invalid.

As seen from figure 4, there are fairly high levels of uncertainties in the data. This is due to the difficulty in obtaining videos of the shuttlecock traveling horizontally and stabilized. The experiment could be repeated with the shuttlecock being hit vertically downward from a high location. While this might be more difficult to set up and analyze, the data would likely be more consistent.

It is suggested that research be conducted on shuttlecock velocities up to 115 m/s[1] to more clearly model game conditions. The drag constant, κ, can also be determined for a variety of shuttlecock brands and types.

Conclusion

The relationship between the velocity and the acceleration of a badminton shuttlecock was found. The acceleration of a shuttlecock is directly proportional to its velocity squared for velocities ranging from 7 m/s to 55 m/s. The drag constant, κ, was found to be 9.7×10^{-4} m^2.

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