Characterising the Service Bounce using a Speed Gun

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Introduction

The angled bounce of a sports ball off a hard surface such as a typical tennis court has been the subject of many studies, for example Thorpe and Canaway (1986), Brody (1983), conferences and in-house reports. During play the tennis ball is hit at a variety of speeds, often with spin imparted to contact and bounce off the tennis court from a range of angles. The characteristics of these angled bounces, which depend on the physical properties of the ball and the court have a decided influence on the subsequent game. Perhaps of most importance is the nature of the ball's first bounce following service when maximum ball speeds are encountered.

The most reliable measurements of the angled bounce are those of Thorpe and Canaway who conducted high speed cinematic studies. They identified two important aspects that affect the playing of the game. These were the *Pace* of the court which was the player's perception of the change in horizontal component of velocity of the ball during impact – on a "slow" surface the ball comes through slower and vice versa. However the change in the horizontal component of velocity is often accompanied by changes in the vertical component of velocity, or the *Bounce*, and some players may have difficulty in distinguishing between the effects of *Pace* and *Bounce*.
Spin also has an influence but will be neglected in this study.

A theoretical analysis of the bounce process had been carried out earlier by Brody who derived mathematical relationships between the angles and speeds of a ball before and after the bounce. He distinguished two types of bounce – a low angle high speed bounce (such as the service) when the ball slides along the bounce contact without rolling. At higher angles and lower speeds (such as lobs, volleys etc) the ball rolls during the bounce contact with the surface and the characteristics of the bounce are quite different from the sliding bounce.

There have been more recent studies of these bounces, such as by Dunlop (1991), and many conference proceedings. This report describes an investigation of the kinematics of some typical tennis service bounces using a radar speed gun.

Speed Gun

The speed gun used in this investigation was based on a Doppler radar system of nominal primary frequency 34.7 GHz. The gun transmits radar waves and reflections of the radar waves off a moving target are then received and mixed with the primary frequency signal to produce a difference frequency signal related to the speed of the target towards or away from the receiver.
The Doppler equation yields the difference frequency Δf as follows

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$$\Delta f = 2 v f_0 / c$$

where v is velocity of target
f_0 is primary frequency
c is the velocity of microwaves (~300 Mm/s)

The calibration of the gun was first checked by measuring the primary frequency in the University's microwave laboratory and found to be accurate and stable.

This difference frequency is checked by holding a calibration tuning fork of 4188 Hz near the receiver and noting that the correct speed is displayed. To ensure that the gun was in calibration over a larger range of speeds a series of tuning forks was fabricated and the calibrations checked. The results of these measurements are shown in Figure 1, which confirms the linearity of the system.

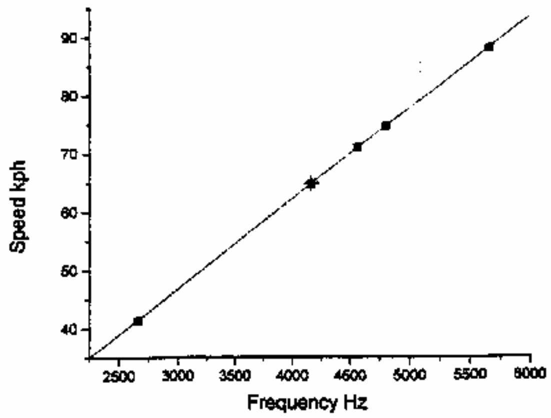

Fig. 1 Speed gun calibration

The speed measured is displayed on the gun or the data is transferred to a computer for storage and display. The sampling rate of the device is 30 Hz with a speed resolution of 1 km/hr. A higher resolution of 0.1 km/hr was also available at a lower sampling rate of 10 Hz.

Operation of Speed Gun

The speed gun produced continuous measurements of ball speed (towards the gun) as a function of time. The readings obtained for a typical service are shown in Fig. 2. For these measurements the ball was served normally into the court of play but also directly in line with the speed gun which was positioned 20 m behind the receiver's base line. These distances ensured that the direction of motion of the ball was less than 5 degrees from the straight line when the gun was oriented horizontally towards the server, reducing "cosine" errors to less than 0.5 %.
Fig 1. shows the horizontal speed of the ball soon after being struck by the racquet. The speed at the beginning is near 180 km/hr and decreases to about 130 km/hr

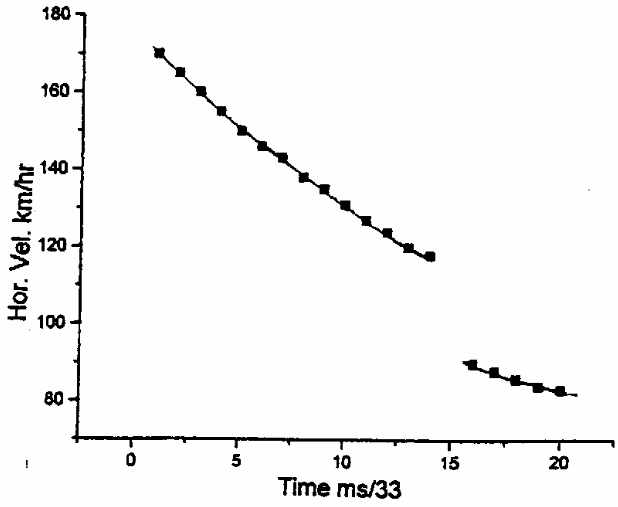

Fig. 2 Speed gun tracking of tennis ball (dots), theoretical values on solid line.

because of aerodynamic drag by the time it contacts the court. There is then a large discontinuity in speed during the bounce, the speed following contact being about 90 km/hr. There is a further decrease in speed due to drag during this second phase of the ball's trajectory.

Ball Trajectories

The ballistic trajectory of a struck tennis ball is affected by three forces – the force of gravity, G, the drag force D, due to its air resistance, and the Magnus force M, caused by rotation or spin of the ball. This latter force has been neglected in this study.
The trajectory of the ball can be described by the coupled differential equations, as per Stepanek (1988),

$$Mz'' = -mg - bv^2 \quad \text{and}$$
$$Mx'' = \quad -bv^2$$

where $v^2 = x'^2 + z'^2$

x and z represent the two defining coordinates and the primes the first and second derivatives.

The drag constant b is given by

$$b = C_D(\pi d^2/8mg)\rho$$

C_D being the drag coefficient being 0.508 for a typical tennis ball. Substituting values of 67 mm for d, 57.5 g for m and 1.29 kg/m^3 for ρ gives a value of b of 0.002.
Solutions of these equations can be adjusted to coincide with a typical tennis service as measured by the speed gun in Fig. 2. This was a minimum spin service from the base line contacting just inside the service line – a horizontal distance of 19 +/- 0.5 m.
To solve the equations, initial conditions must be supplied, in this case $x_0 = 0$, $y_0 = 2.9$ m, The velocities $y'_0 = 180$ km/hr and x'_0 are adjusted to give a contact at 19 m.
The calculated trajectory is plotted on Fig. 3. Further manipulation of the equations shows a grazing angle of contact of 10 degrees.

The equations can also be solved to yield the horizontal velocity y` versus time. This

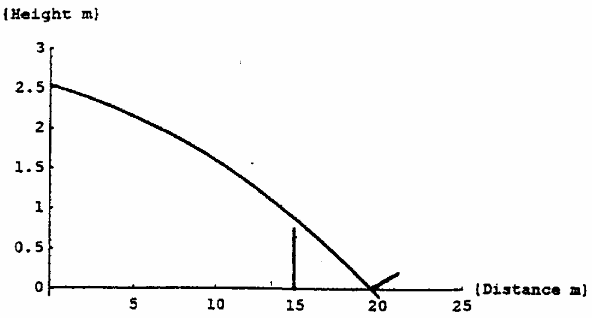

Fig. 3 Trajectory of typical tennis serve

is superimposed on Fig. 2 and shows a very close fit to the measured points.

Pace Determination

From Fig. 2 a direct determination of *Pace* can be made. The figure indicated that the ball contacts the surface with a horizontal velocity of 153 km/hr and leaves contact at 121 km/hr. This gives a *Pace* of the surface for this delivery of 0.79 or 79 %.
Brody's equations suggest that the pace is dependent on the angle of contact, so it should be noted that this *Pace* measurement relates to the angle made by the service.

Bounce Determination

For determination of *Bounce* or the vertical coefficient of restitution, it is necessary to track the trajectory of the ball to its second bounce. The time interval between the two contacts can then be measured and from this and trajectory theory the vertical velocity after the first bounce can be determined. The vertical velocity before the first bounce

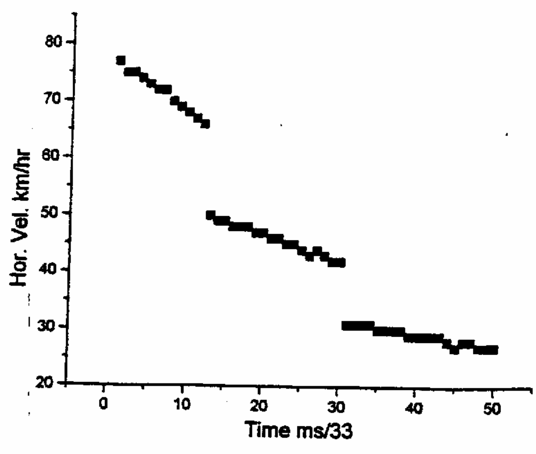

Fig. 4 Speed gun tracking of tennis ball showing second bounce

can be determined from solutions of the trajectory equations.
A typical trajectory using the ball projector is shown in Fig 4.

Results

Two professional tennis players were asked to strike their normal first services for measurement on three different tennis surfaces – grass, Rebound Ace and a sand filled synthetic tennis surface. The serving actions of both players were recorded on video camera to determine the heights of service for trajectory determination.
Fresh Dunlop "Hard Court " tennis balls which had first been tested to meet the rebound specifications and temperature conditioned to the temperature of the courts (22 degrees) were used. The services were tracked using the speed gun and various parameters as described above.
Similar measurements were carried out using a pneumatically operated ball projector to determine Bounce characteristics in an indoor environment.

The results are shown in Table 1.

Table 1: Measurement of pace parameters.

Source	V_{xi} kph	V_{xf} kph	Pace %	Average Pace
Dan	128	92	72	
	135	98	73	
	123	92	74	
	135	101	74	
	138	98	71	73 +/- 2
Ivan	113	78	69	
	108	74	69	
	93	66	71	
	113	81	73	
	111	81	73	
	113	85	75	72 +/- 2
Projector	66	48	73	
	66	48	73	
	66	48	73	
	66	47	71	73 +/- 1

Results of other surfaces are shown in Table 2.

Table 2 Measurement of Pace on several courts.

Surface	Source	Pace
Grass	Dan	76 +/- 2
	Ivan	78 +/- 2
	Projector	79 +/- 1
Sand turf	Dan	71 +/- 2
	Ivan	70 +/- 2
	Projector	69 +/- 1

The ball projector was used to determine the Bounce characteristics of various surfaces. It was set to project ball horizontally from a height of 1.00 m as before, striking the surface at 12.7 degrees with a vertical velocity of 4.22 m/s.
Results of measurements relating to the determination of Bounce are listed in Table 3.

Table 3: Measurement of Bounce parameters.

Surface	Δ T ms	V_{yf} m/s	Bounce %	Coef. Restitution
Rebound Ace	590	3.00	0.71 +/- 0.03	0.75 +/- 0.01
Grass	520	2.62	0.62 +/- 0.03	0.68 +/- 0.01

Discussion

The measurements show considerable variation in the Pace of the tennis service off any particular type of surface as perceived by the receiver. This is due to the variation in speed (and hence contact angle) and perhaps spin of each service from a particular player. The angle of contact was noted to range from 10.4 to 11.6 degrees for various typical serving parameters – ball off racquet speeds of 180 to 205 kph from heights of 2.54 to 2.9 m. The Pace values measured range from 70 % for a slow surface to 80 % for a fast one. The Pace measurements using a ball projector, albeit at lower speeds, were more consistent, and considering their precision might be used to distinguish one type of surface from another.
Bounce, which is essentially the coefficient of restitution for the angled rebound, can also be determined to a lesser precision than Pace, but sufficient to suggest that it very close to that measured from vertical rebound, supporting Brody's analysis.

Conclusion

The results of the measurements reported here indicate that the radar speed gun offers a simple and effective method for determining the Pace and Bounce characteristics of a tennis court surface.

References

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