Bouncing steel balls on water

2007 Phys. Educ. 42 466

(http://iopscience.iop.org/0031-9120/42/5/003) www.iop.org/journals/physed

Bouncing steel balls on water

Michael de Podesta

National Physical Laboratory, Hampton Road, Teddington TW11 0LW, UK

E-mail: michael.depodesta@npl.co.uk

Abstract
The 'skimming' of stones on water is a subject of perennial fascination for children and adults alike. In this article I describe the construction of an apparatus for safely and reproducibly demonstrating a similar phenomenon: the bouncing of 25 mm diameter steel balls from a water surface. The 'bouncing' is technically known as a ricochet and the article recounts the use of the effect in the Second World War in the 'Dam Busting' air raids of 1943. A number of calculations are made which allow an estimate of the projectile speed and energy, and the use of simple experimental techniques for validating these estimates is suggested. The role of spin is discussed, and a literature review collates the available empirical and theoretical results concerning the incident angle and speed for successful ricochet of spinning and non-spinning projectiles.

Introduction

In June 2004 I spent several weeks preparing for a demonstration in which I bounced 25 mm diameter steel ball bearings at a shallow angle across the surface of a 20 m pond. Over the course of their flight, the balls bounced three or four times before striking an end wall at considerable speed. The demonstration was part of a local commemoration of the 60th anniversary of 'D-Day', which marked the beginning of the end of the Second World War in Europe. The public who watched this activity in the High Street of Teddington seemed to enjoy it greatly, and my purpose in describing this activity here is threefold. Firstly, during the construction I learned a great deal, and I feel that many teachers or students could be inspired by carrying out similar investigations. Secondly, the phenomenon in which a dense object can bounce off a less dense fluid is one which often fascinates children 'skimming' stones, and is relevant to other physics, such as how a meteorite can 'bounce' off the Earth's atmosphere. And finally, readers above a certain age from the United Kingdom may recognize this as a 'bouncing bomb' apparatus. The story of the 'bouncing bomb' is in itself a tremendous story, and it is worth pausing for just a moment to tell it.

Background

One of the most famous exploits of the Second World War, in Britain at least, was an air raid which employed a 'bouncing bomb' to attack several dams. Nowadays guidance systems permit missiles to land within a metre or so of their intended target. In 1943, this was not possible. Bombs were dropped from aircraft at high altitude and only 50% of the bombs fell within 5 miles of their target. If they fell within 500 m of their target they would be considered accurate. To destroy a dam, a large bomb had to explode underwater within a few centimetres of the wall of the dam, and there was no conventional way of achieving this with a heavily guarded dam. Inspired by the experience of 'skimming stones', the aeronautical engineer Barnes Wallis conceived of a 4 tonne bomb which would bounce along the surface of

 0031-9120/07/050466+12$30.00

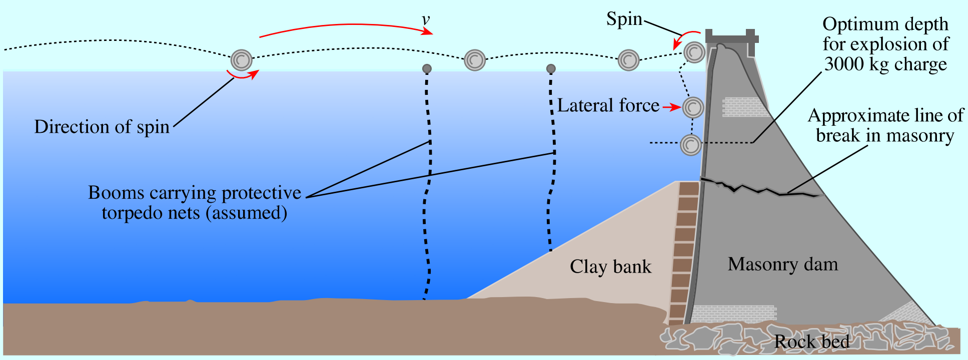


Figure 1. Schematic of the Dam Busting Weapon as conceived by Barnes Wallis.

the lake behind the dam, hit the wall of the dam, sink against the wall of the dam and explode at a predetermined depth.

The exploit was carried out on the night of 16 May 1943, and two dams were destroyed. The ingenuity of the weapon and the bravery of the air crew inspired a film, *The Dam Busters*, which kept images of wartime heroism alive for a generation of post-war children, of whom I am one.

In order to construct such a device, a team lead by Wallis carried out extensive studies at the ship-testing tanks at the National Physical Laboratory (NPL), where I now work. Although the 'ship tanks' no longer exist, the collective memory of the research lives on at the laboratory, and it was this which inspired me to see if I could recreate some of his earlier experiments. Factors that Wallis investigated would have included the effect of launch speed, launch height, launch angle and spin. The studies would have shown how the optimal values for these parameters varied with the speed size and density of the projectile, allowing the experimental results with models to be scaled up to the real thing.

The apparatus

Even though the phenomenon of 'skimming stones' is well known, it still seems surprising that dense objects can bounce off water. The fundamental explanation of this phenomenon is discussed in the section 'The literature', but at its simplest, objects will bounce off a water surface if they are a simple shape which will not 'tumble' after the first bounce and are travelling quickly nearly parallel to the surface

I began my research by firing a marble from a catapult out over the River Thames and these experiments indicated that it would not be hard to get spheres to bounce. I considered several options for reproducibly firing a 25 mm diameter sphere, but in the end settled on an 'air-powered' gun.

The 'gun'

The gun (figures 2 and 3) was constructed from standard plumbing fixtures connected to a piece of brass pipe with an internal diameter slightly larger than 25 mm. The gun had several important features designed to ensure safety during public demonstration. A pressure-limiting valve prevented the pressure rising more than 3 bar above atmospheric pressure, and the valve could be key-locked in the open position to prevent pressurization by unauthorized persons. In use the barrel pointed downwards, and so the steel ball was held in place during pressurization by a magnet taped to the barrel. The system was pressurized using a standard car-tyre foot pump connected to the system through a modified end-cap.

The 'ship tank'

I constructed a preliminary 'ship tank' in my back garden using a combination of light (6.2 kg) and heavy (13.2 kg) building blocks, each 0.45 m × 0.1 m × 0.21 m with polythene laid over them.

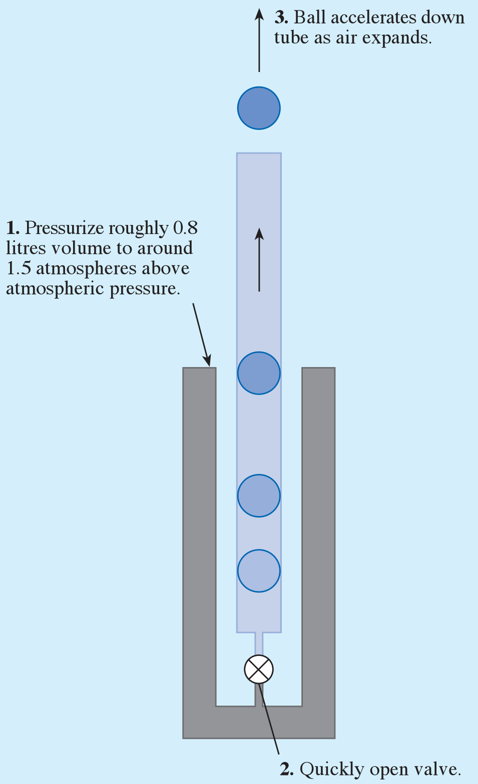


Figure 2. Schematic diagram of the air powered gun.

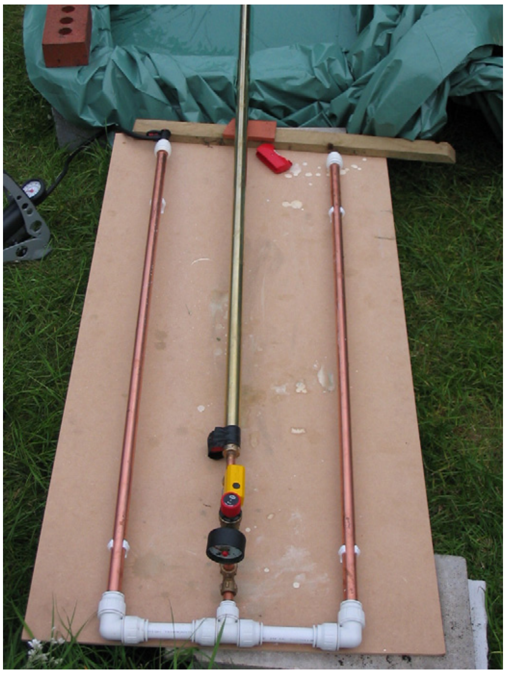


Figure 3. Photograph of the gun in place at the end of the 'ship tank'. The air storage tubes (22 mm outside diameter copper tube) are each around 1.1 m long and the 25 mm bore barrel is approximately 1.6 m long.

This confirmed the feasibility of the project, but only permitted a single bounce, so for the public demonstration the tank was lengthened to 20 m to permit multiple bounces to be more easily observed (figures 4 and 5).

Public demonstration and safety

Getting the balls to bounce reproducibly

It was possible to make the balls bounce over a wide range of speed and launch angles. However, for a public demonstration I settled on a single set of standard firing conditions (figure 6).

Firing pressures were typically in the range from 1.0 to 1.5 bar above atmospheric pressure, corresponding to a maximum projectile energy in the range 60–70 J, and maximum projectile speeds in the range 40–50 m s^{-1}. I conducted extensive tests outside this range to ensure that there was no possibility of the ball bouncing outside of the enclosure. Lower pressures consistently failed to produce any bounces, with the ball sinking directly underwater. Pressures greater than 1.5 bar typically produced bounces, but their increased projectile speed caused them to land rather close to the back wall. The pressure was increased to 3.0 bar and the safety release valve was observed to operate, and at this pressure the balls still landed safely in the pond. I created waves on the surface in an effort to induce unusual bounce dynamics, but waves always seemed always to cause a ball to sink immediately at the first bounce. In pre-demonstration tests 60 shots were fired over a 1 h period: three shots went straight underwater; 12 shots bounced once and then dived underwater; 45 shots displayed two or more bounces and hit the end wall with a resounding sound; zero shots left the pool.

Public demonstration

While building the apparatus in my garden provided a diversion for my children, I was comforted by the fact that no safety officer would

Figure 4. The arrangement of bricks for the public demonstration pond.

allow such an apparatus to be demonstrated in public. I was wrong. The NPL safety officer thought this would make a fantastic demonstration and so I found myself faced with the task of working with the safety officer to make sure that the demonstration could be carried out safely. This was no minor consideration: the kinetic energy of the balls is roughly equivalent to a golf ball being hit from a tee, which is a serious hazard. The safety case then rested on separating balls and people, i.e. ensuring the balls could not leave the pond, and that people could not get into the pond. I ensured this by a combination of specified operating conditions, safety barriers, trained operators, and a key interlock that prevented the gun being fired by anyone else.

In this demonstration I had no choice in the position of the ship tank and the public had access to the entire length of the ship tank. I placed barriers along the side of the pond to keep the public a distance of 0.75 m from the edge of the pond. (If I were to repeat this I would definitely make sure that the gun was arranged to point directly away from any audience members.) Additionally, the final 1 m of the pool was covered with weighted polycarbonate sheet to capture any stray bounces off the end wall of the pond.

Happily, the public demonstration passed without any incidents: the trained operators always fired the gun with the same operating parameters; each shot was announced with a warning klaxon; the gun was locked in an un-pressurizable state for the short times it was left unattended; and during the day over 200 balls were fired down the pond, and almost all behaved exactly as expected. Except for two.

At the end of the day, a ball fired in the standard conditions bounced in an extraordinary way—backwards!—and left the side of the pool. Although the ball was travelling slowly when it left the pool and no one was hurt, I was stunned that, after our extensive testing, any such event was possible. We tried again and observed the same strange behaviour, and at that point we stopped the demonstration.

The rogue ball

At the time I was perplexed by the behaviour of the rogue ball, but the explanation of its behaviour occurred to me a few days later: it was caused by *spin*. In normal operation I did not expect the ball to spin significantly about any axis and so I could not see how anything had changed during the day to make the 200th ball spin when the 199th had not. However, as the demonstration day wore on, I became rather casual about the reloading of the gun. The procedure was to fire ten balls, then collect them from the pool, dry them and fire them again. Late in the day I skipped the drying step, and placed the balls back in the gun while they were still wet. After a while this must have created a pool of water in the lower part of the tube which would have caused extra drag on the lower part of the ball, and could have initiated a significant top spin.

When I began the experiments I had thought that creating a reproducibly spinning ball would be one of the main challenges, and so it is somewhat ironic that the introduction of spin should have caused a halt to the demonstration. The role of spin is discussed in the section 'Spin?'.

Calculations and measurements

There are many simple calculations that can be made about this experiment, that can allow students and teachers to appreciate more fully some of the simple physics underlying gas expansions and particle kinematics.

Calculation 1: stored energy

The energy to actuate the device is the excess pressure of gas stored in the 22 mm diameter copper pipe. The pipe has wall thickness 1 mm and so the pipe has an internal *radius* of 10 mm. The storage pipe consists of 2×1.1 m lengths and 1×0.35 m length. The volume is therefore

$$\begin{aligned} \text{volume} &= \text{length} \times \pi r^2 \\ &= (2 \times 1.1 + 1 \times 0.35) \times \pi 0.01^2 \\ &= 8.0 \times 10^{-4}\,\text{m}^3 \end{aligned} \tag{1}$$

i.e. just under 1 litre. At a typical gauge pressure of 1.2 bar (1.2×10^5 Pa) the stored energy (*pressure*$\times$*volume*) is $1.2 \times 10^5 \times 8.0 \times 10^{-4}\,\text{m}^3 = 96$ J. The volume of the barrel is similar to the volume of the storage tubes:

$$\begin{aligned} \text{volume of barrel} &= \text{length} \times \pi r^2 \\ &= (1.65) \times \pi 0.0125^2 \\ &= 8.1 \times 10^{-4}\,\text{m}^3. \end{aligned} \tag{2}$$

If the ball completely seals the barrel, then on firing the gas will have expanded by a factor of approximately two. The expansion will be adiabatic, i.e. so quick that the gas will cool as it expands. The cooling reduces the pressure of gas below what it would otherwise be, and a 'simple calculation' (below) indicates that for this gun only approximately 60% of the stored energy could conceivably be utilized in the expansion, i.e. at 1.2 bar the maximum utilizable energy is $96\,\text{J} \times 0.6 = 58$ J.

Calculation 2: available energy

During an adiabatic expansion the quantity PV^γ is a constant, K. In this expression P is the absolute pressure (i.e. one atmosphere more than the gauge pressure), V is the volume of the gas, and γ is the ratio of the principal heat capacities of a gas. The work done on the gas during an expansion from V_1 to V_2 is given by

$$\begin{aligned} \text{work} &= -\int_{V_1}^{V_2} P\,\mathrm{d}V \\ &= -\int_{V_1}^{V_2} \frac{K}{V^\gamma}\,\mathrm{d}V. \end{aligned} \tag{3}$$

Removing K from the integral and integrating we find

$$\begin{aligned} \text{work} &= -K\int_{V_1}^{V_2} V^{-\gamma}\,\mathrm{d}V \\ &= -\frac{K}{-\gamma+1}\left[V^{-\gamma+1}\right]_{V_1}^{V_2}. \end{aligned} \tag{4}$$

If we rewrite V_2 as a factor f of V_1 we find

$$\begin{aligned} \text{work} &= -\frac{K}{-\gamma+1}\left[V^{-\gamma+1}\right]_{V_1}^{fV_1} \\ &= -\frac{KV_1^{-\gamma+1}}{-\gamma+1}\left[f^{-\gamma+1}\right]_1^f. \end{aligned} \tag{5}$$

If we remember the value of K then this equation simplifies

$$\begin{aligned} \text{work} &= -\frac{\left[P_1V_1^\gamma\right]V_1^{-\gamma+1}}{-\gamma+1}\left[f^{-\gamma+1}\right]_1^f \\ &= -\frac{[P_1V_1]}{-\gamma+1}\left[f^{-\gamma+1} - 1^{-\gamma+1}\right] \\ &= -\frac{[\text{stored energy}]}{-\gamma+1}\left[f^{-\gamma+1} - 1^{-\gamma+1}\right]. \end{aligned} \tag{6}$$

Using $\gamma = 1.4$ (appropriate for air) and an expansion factor $f = 2$, we find

$$\begin{aligned} \text{work} &= -\frac{[\text{stored energy}]}{-0.4}\left[2^{-0.4} - 1\right] \\ &= -\frac{[\text{stored energy}]}{-0.4}\left[2^{-0.4} - 1\right] \\ &= -0.60 \times [\text{stored energy}]. \end{aligned} \tag{7}$$

The minus sign indicates that in fact during the expansion the gas does work on the environment, most of which is transferred to the ball. However, only approximately 60% of the stored energy could conceivably be accessed in this expansion.

Calculation 3: projectile speed

If all the accessible energy of the gas is converted to kinetic energy of the ball bearing (mass $m = 0.065$ kg) the velocity leaving the barrel will be

$$v = \sqrt{\frac{2E}{m}}. \tag{8}$$

At 1.2 bar (accessible energy = 58 J) the maximum speed possible is 42 m s^{-1} (100 mph). In practice we would expect that not all the gas compression energy would be converted to kinetic energy of the ball bearing. There is friction in the barrel, and some of the air leaks around the side of the ball. Also the rapidity with which the valve is opened makes a significant difference to the speed of the ball. Additionally, projectiles travelling at such speeds suffer rapid deceleration from air resistance.

Experiments can determine the exit velocity (technically known as the muzzle velocity) fairly accurately. The technique described below (figure 7) requires no sophisticated apparatus, but nowadays a frame-by-frame analysis of a digital video will provide a superior and more accessible analysis that could be used by students and teachers.

First, make sure that the barrel is horizontal and then measure the distance, d, to the first bounce. Although the ball moves quickly, the position of the first bounce can be seen fairly clearly for a few seconds after the ball has been fired as the epicentre of a set of ripples.

Assuming the ball falls under gravity and starts with zero initial vertical component of velocity, the ball hits the water after a time $t = \sqrt{2h/g}$, and the downward speed at impact is

$$\begin{aligned} v_y &= gt = g\sqrt{2h/g} \\ &= \sqrt{2hg}. \end{aligned} \tag{9}$$

In a time t the ball travels distance d with uniform horizontal velocity v. So

$$\begin{aligned} v_x &= \frac{d}{t} = \frac{d}{\sqrt{2h/g}} \\ &= \sqrt{\frac{d^2 g}{2h}} \end{aligned} \tag{10}$$

and from measurements of d and h it is possible to determine the exit speed of the ball. From these two calculations we can also find the angle of impact as $\tan^{-1}[v_y/v_x]$

$$\begin{aligned} \text{angle} &= \tan^{-1}\left[v_y/v_x\right] \\ &= \tan^{-1}\left[\sqrt{2hg}\Big/\sqrt{\frac{d^2 g}{2h}}\right] \\ &= \tan^{-1}\left[\frac{2h}{d}\right] \\ &\approx \frac{2h}{d} \qquad \text{if } h \ll d. \end{aligned} \tag{11}$$

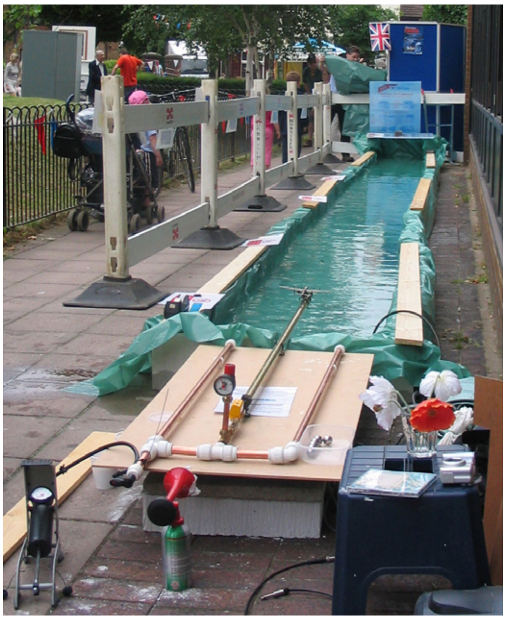


Figure 5. The ship tank as finally constructed. Notice the polycarbonate enclosure at the far end, the klaxon and foot pump, and the poppies in remembrance of those who died in the original action.

Table 1. (a) Theoretical and experimental values of some key parameters compare modestly well with each other. (b) Typical values for the parameters in the bouncing balls demonstration compared with those used for bouncing bombs.

(a)

Pressure (bar gauge)	Stored energy (J)	Available energy (J)	Theory KE (J)	Theory Speed (m s^{-1})	Experimental KE (J)	Experimental Speed (m s^{-1})
1.2	96	58	58	42	14 (24%)	21 (50%)
1.5	120	72	72	47	27 (38%)	29 (60%)
3.0	240	144	144	66	No data	No data

(b)

	Dam busters	Demonstration	Factor
Projectile	Back-spinning cylinder 1.27 m diameter × 1.52 m length mass 4100 kg	Non-spinning sphere 0.025 m diameter mass 0.065 kg	63 000 (in mass)
Launch height	60 feet (18.3 m)	3 in (0.075 m)	244
Launch speed	250 mph (111 m s^{-1})	65 mph (29 m s^{-1})	4
Distance to first bounce	214 m	3.5 m	61
Angle of incidence	10°	2.4°	4

Experiments indicate that at 1.2 bar the muzzle velocity is approximately 21 m s^{-1} (54 mph), which corresponds to an energy of 14 J or approximately 38% of available energy.

If the barrel is pointed down, this formula will overestimate the time to the first bounce, and underestimate the speed of the ball. Also the viscous resistance of the air will cause a rapid decline in speed of the ball after it has left the muzzle of the gun, so we can consider this experimental estimate of the muzzle velocity as a definite lower bound for the muzzle velocity of the ball.

Table 1 shows (a) how the theoretical and experimental values of some key parameters compare with each other, and (b) typical values for the demonstration bouncing balls, and the actual bouncing bombs.

Spin?

One of the most persistent questions asked by members of the public during the demonstration concerns the role of *spin*. Indeed, before carrying out any experiments I had been concerned about how I would impart a reproducible spin to the balls. The implicit assumption that I had made was that spinning the projectile was somehow associated with the bouncing phenomenon. This is a natural enough assumption: it is essential to spin a stone when skimming it, and Wallis arranged for the bouncing bombs to be spun about their cylindrical axis at 500 rpm. However, experiments quickly showed that spin was simply not necessary. After puzzling and calculating about this for several days, understanding eventually dawned. My understanding was later confirmed by a literature review described in the section 'The literature'.

The stones used for 'skimming' are ideally flat-bottomed stones in the shape of extremely oblate ellipsoids. These are spun about their short axis, and bounce off their large flat surface. In this case, the role of spin is to stabilize the angle of the impact of the stone from one bounce to the next. If the stone is not spun, then after the first bounce it is likely to tumble, strike the water at a random angle and sink at its next bounce. In this sense the spinning amounts to gyroscopic stabilization of the attitude of the stone (figure 8).

In the bouncing bombs situation, the spinning of the cylinder performed two functions: one to do with the bouncing, and the other to do with the bombs. As with skimming stones, the spinning of the bombs caused them to gyroscopically maintain their attitude relative to the water from one bounce to the next. After the final construction of full-

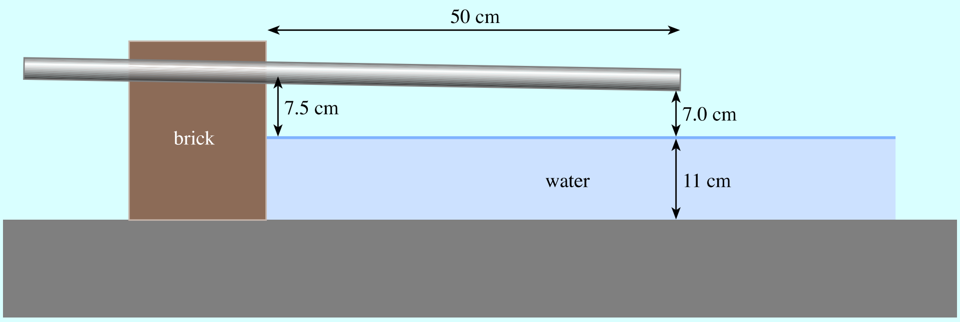


Figure 6. The general arrangement of the barrel over the pond. The barrel was tilted downwards at an angle of approximately 0.01 rad (0.6°).

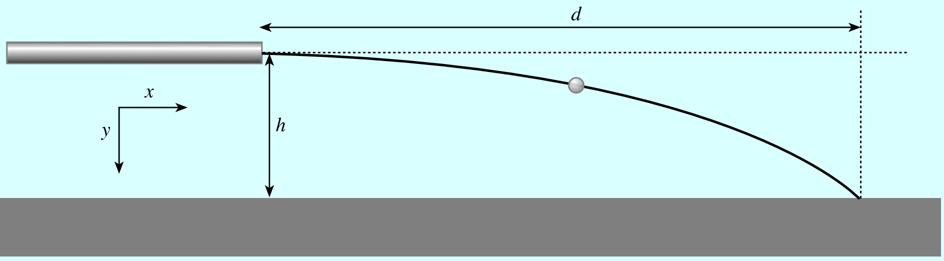


Figure 7. Diagram showing how to estimate the muzzle velocity from measurements of the distance d to the first bounce.

scale bombs, the key step in Wallis's achievement of making a 4200 kg cylinder bounce was not the spin, but his ability to persuade pilots to fly at 250 miles per hour at a height of just 18.3 m above the water (rather than 80 m in previous trials). This was done in order to stop the bomb casing disintegrating when it hit the water, and it also reduced the angle of incidence on the water to around 10°. But although the spin was not the key parameter in causing the bounces, it did have another effect. When the forward motion of the bombs was stopped (by, for example, a dam wall), the spinning caused the bomb to roll down the wall surface (figure 1) increasing the effectiveness of explosive which was triggered at a predetermined depth.

For the steel balls in this demonstration, no matter whether the balls spin or not, the spheres still hit the water with the same attitude because the spheres are homogeneous, and lacking in any asymmetry. Thus even if the balls tumble or begin to spin after the first collision, they still hit the water in the same way. So for a perfect sphere, no gyroscopic stabilization of attitude is required.

The final question concerning spin is why (if spin is not important) the flight of the balls was so affected when I *did* induce spin on them. Here I have to confess that I have over-simplified the discussion above. It is well known that in many ball sports spin plays a minor, but significant, role in ball dynamics, and the dynamics of the bouncing balls is no different. And as in sport, on occasion, spin can play an extremely important role.

The literature

This experiment was embarked upon lightly, was performed quickly, and it was not until

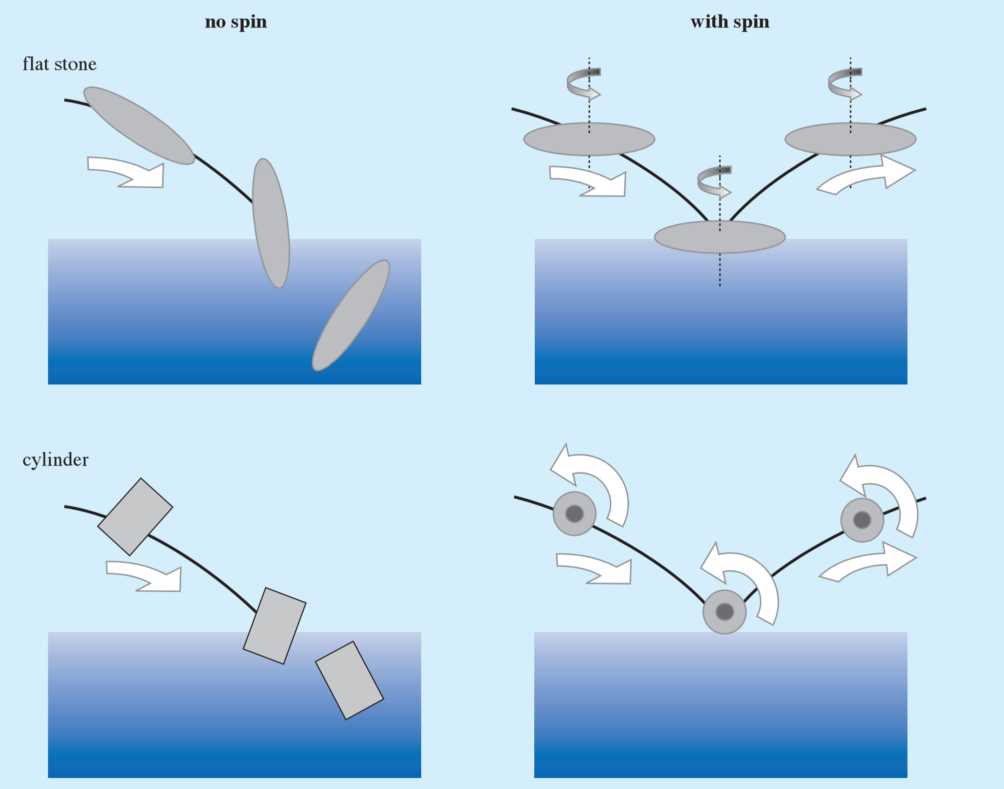


Figure 8. Diagram illustrating the gyroscopic stabilization of the attitude of a projectile.

writing this paper that I consulted the scientific literature. In additional to the semi-technical [1] and educational publications [2] I quickly learned from the sparse and sophisticated literature on this topic.

Ricochet

Johnson and Reid [3] point out that the correct term for this phenomenon is not bouncing but *ricochet*. This describes the case in which the water surface is 'ploughed' by the sphere for a short distance which transiently leaves a 'furrow' behind it, and piles water up in front of it (figure 9).

Johnson and Reid also point out that the phenomenon of ricochet has been well known for a *very* long time. They include a table from *Naval Gunnery* [4] published in 1855, which describes extensive tests by H.M.S. *Excellent* including one in which a hollow cannonball (20 cm in diameter and weighing 25 kg) ricocheted 32 times over a range of 2.5 km. The *Oxford English Dictionary* contains references to the word *ricochet* in this context dating back to 1769, and thus the practice certainly predates Admiral Nelson, to whom its invention has been ascribed.

Historically the empirical relationship of the largest angle (the critical angle) θ_C at which a ricochet can occur has been known to be given by

$$\theta_C \approx \frac{18^\circ}{\sqrt{\sigma}} \tag{12}$$

where σ is the ratio of the density of the material of the ball to the density of the liquid, in this case water. For solid steel balls, σ takes the value of roughly 8, yielding a critical angle of roughly $\theta_C \approx 6.4^\circ$. For the bouncing bombs (table 1), σ took the value 2.17, yielding a critical angle of $\theta_C \approx 12.2^\circ$, just larger than the 10° angle of incidence.

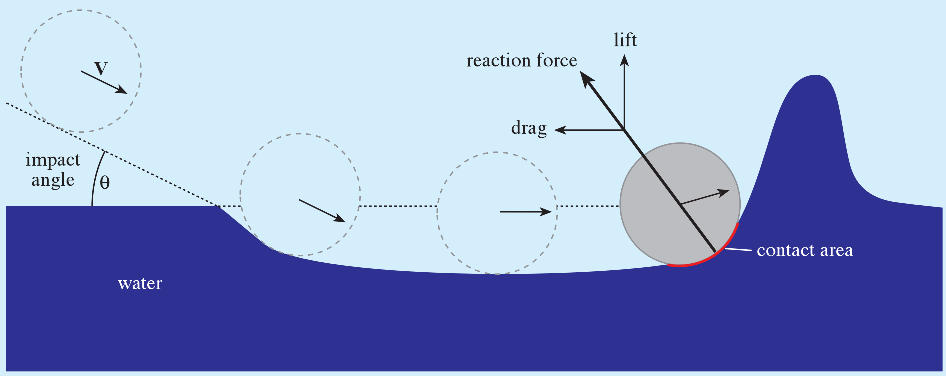


Figure 9. The trajectory of the ball in the water.

Theory

From a theoretical point of view, the ricochet problem consists of trying to estimate the forces exerted on the sphere as it strikes the water surface, and then 'ploughs its furrow' through the water (figure 9). Summing all the forces is complex, and even then estimating the pressure forces and contact area between the ball and the water depends on several assumptions. Despite this, early works by Birkhoff [5], modified by Johnson and Reid [3] and Hutchings [6] were all able to yield an expression similar to equation (12). More recently, Miloh and Shukron [7] have developed an approach which allows the calculation of previously unpredicted quantities of interest: the variation of the critical angle with projectile velocity; the minimum velocity required to ricochet; and the dependence of the critical angle on spin.

One feature which all the theories share is that rather than calculate directly in terms of the sphere speed, v, its radius a, and the acceleration due to gravity g, they calculate the problem in terms of a dimensionless parameter called the Froude number, F, given by

$$F \approx \frac{v}{\sqrt{ga}}. \tag{13}$$

Use of the Froude number allows results obtained with spheres of one diameter to be simply scaled to spheres with different diameters: if the sphere size is doubled, its speed must be increased by a factor $\sqrt{2}$ in order to maintain equivalent ricochet characteristics.

Miloh and Shukron do not produce a specific formula for the dependence of the critical angle θ_C on speed, but they do show that equation (12) is essentially the limiting case for a large Froude number (i.e. high speed). Miloh and Shukron calculate that the Froude number must fall below about 50 before θ_C is significantly reduced. For 12.5 mm radius spheres travelling at 30 m s^{-1}, the Froude number is around 85, so equation (12) should apply to these bouncing steel balls.

Miloh and Shukron calculate that the minimum velocity for a ricochet of any kind at essentially glancing incidence is given by

$$v_{MIN} \approx \sqrt{ga}\left[\frac{20}{\pi}\sqrt{\sigma} + 2.5\right] \tag{14}$$

which for these bouncing steel balls evaluates to a plausible 7 m s^{-1}. Finally, *Miloh and Shukron* develop an expression for the dependence of θ_C on spin, albeit for a cylinder rather than a sphere, and find

$$\theta_C \approx \frac{18.7°}{\sqrt{\sigma}}\sqrt{1 + \frac{1.6a\omega}{v}} \tag{15}$$

where the rotation rate ω (measured in rad s^{-1}) is defined as positive for a sphere with back spin. Equation (15) is clearly similar to the empirically derived equation (12), but it includes an extra

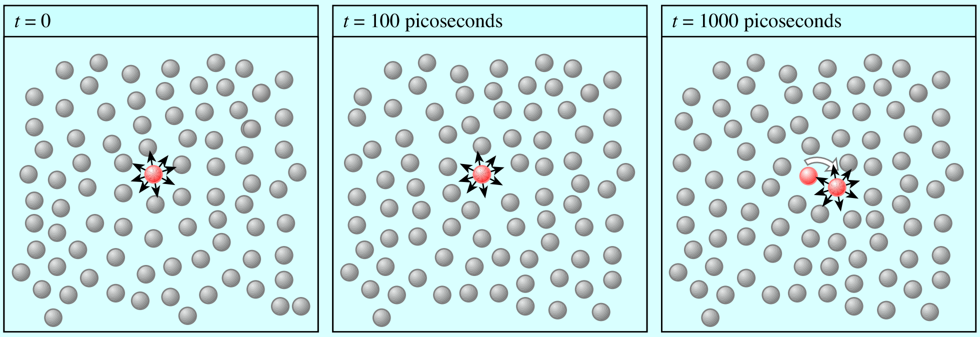


Figure 10. Illustration of the dynamic structure of a liquid. Three snapshots show how one particular molecule vibrates within a cell for typically 1000 vibrations, and then the random vibrations of its neighbours allow it to hop to a neighbouring 'cell'. In this way a liquid is able to change its shape.

factor which reduces to unity in the limit of extremely fast projectiles, but which can become large at lower speeds and high spin rates.

For the bouncing bombs, which were back-spun at a rate of 500 rpm ($\approx$52 rad s^{-1}), the critical angle would have been enhanced from roughly 12.2° to approximately 15°. Given that the actual impact angle was around 10°, this would have increased the chances of a successful first bounce, but it seems the bombs would have bounced (at least once) whether they had been spun or not.

My final discovery in the literature was the most personally astounding. Schlien [8] reports that when extreme spin ($>$20 000 rad s^{-1}) was accidentally introduced in their ricochet experiments, they observed that the critical angle for a ricochet could exceed 45°, and in one case (recorded on video) the sphere left the surface travelling backwards, i.e. back towards the gun! This was exactly the kind of anomalous behaviour that I had observed during my demonstration. From a safety point of view this confirms that (as far as public demonstrations are concerned) uncontrolled spinning of the projectiles is to be avoided.

But how can steel bounce off water?

So given that spin does not somehow 'magically' cause bouncing, we now need to understand the basic phenomenon we observed: the bouncing of steel balls off water. The physics of this phenomenon is known as fluid dynamics, and is as complicated as physics can get. However, one can gain some understanding by considering the microscopic arrangement of water molecules in the liquid state.

In a liquid the molecules are arranged in a manner similar to that in a solid. Indeed, if one could take a snapshot of a liquid structure (figure 10) one would be unable to distinguish it from a disordered solid. Each molecule in the liquid is trapped by its neighbours and vibrates within its available space typically every 0.1 ps (10^{-13} s). However, after typically 1000 oscillations, the molecules surrounding a particular molecule (let us call it 'Stephanie') rearrange themselves and allow Stephanie to hop to a new space. Thus naturally the liquid can change its structure. Stephanie (who is typical of the molecules in the liquid) can move roughly one molecular spacing (100 pm) in a time of 1000 $\times$ 0.1 ps, i.e. 100 ps. In other words, molecules in a liquid can naturally rearrange their positions if they can move at a speed of slower than 100 pm per 100 ps, i.e. 1 m s^{-1}. This fact is very familiar to us. If we try walking through a swimming pool (i.e. rearranging the positions of water molecules around our legs) it is easy if we walk slowly, but running is almost impossible.

Similarly, when steel balls (or stones or bombs) hit the water at a speed much faster than (say) 10 m s^{-1}, then the liquid is unable to easily flow out of the way and it resists the passage of the sphere strongly, giving rise to a transient reaction force which has an upward component and a 'drag' component. If this upward force is sufficient to lift the sphere then it can ricochet. If the ball is moving too slowly horizontally, then the reaction force is never sufficiently large and the sphere sinks.

Acknowledgments

A great many people helped with the original public demonstration and I should particularly like to thank Stephanie Bell; Maxwell, Christian and Charles de Podesta; Jacquie Elkin; John Makepeace; Janine Avison; Stephan Schöttl, Gavin Sutton; Angela Dawson; David Griffiths; and Fulwell Fire Brigade. Additionally, I should like to thank NPL and Fiona Auty for the resources and flexibility which made the event possible. Finally, I am grateful to Fiona Auty and Stephanie Bell for carefully reading the manuscript.

Received 19 June 2007
doi:10.1088/0031-9120/42/5/003

References

[1] Johnson W 1998 The ricochet of spinning and non-spinning spherical projectiles, mainly from water. Part II: an outline of theory and warlike applications *Int. J. Impact Eng.* **21** 25–34

[2] Stinner A 1989 Physics and the bouncing bomb *Phys. Educ.* **21** 260–7

[3] Johnson W and Reid S R 1976 Ricochet of spheres off water *J. Mech. Eng. Sci.* **17** 71–81

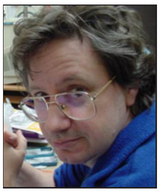
[4] Douglas H 1855 *Naval Gunnery* 4th edn

[5] Birkhoff G, Birkhoff G D, Bleick W E, Handler E H, Murnaghan F D and Smith T L 1944 Ricochet off water *A.M.P. Memo 42.4 M*

[6] Hutchings I M 1976 The ricochet of spheres and cylinders from the surface of water *Int. J. Mech. Sci.* **18** 243–7

[7] Miloh T and Shukron Y 1976 Ricochet off water of spherical projectiles *J. Ship Res.* **35** 91–100

[8] Shlien D J 1994 Unexpected ricochet of spheres off water *Exp. Fluids* **17** 267–72



Michael de Podesta gained a PhD in low-temperature condensed matter physics from Sussex University, and was a lecturer at Birkbeck College and University College until 2000. Since then he has worked on a variety of thermometry projects at the National Physical Laboratory. Currently he is working to redetermine the Boltzmann constant. He is an NPL Science Ambassador and runs the popular 'Protons for Breakfast' introductory course for people interested in science and its impact on society.