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The Physics of Motocross

Jeffrey R. Giles
Longwood University

Charles D. Ross
Longwood University, rosscd@longwood.edu

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Jeffrey R. Giles and Charles D. Ross
Department of Natural Sciences, Longwood College, Farmville, VA 23909; cross@longwood.lwc.edu

Motocross is a sport in which participants race motorcycles on a track containing man-made and/or natural obstacles. Some of the obstacles encountered are steep hills, sudden drop-offs, and jumps of various sizes. Naturally a racer seeks the fastest way around the track. In motocross this often means jumping the motorcycle off of and over obstacles, sometimes remaining airborne for great distances (often reaching over twenty feet in height and ninety feet in distance). A successful racer must know how to control the flight of the motorcycle in order to clear these jumps. We tell here how the laws of physics allow the rider to control the flight of a motorcycle.

A motorcycle jumping an obstacle is an example of projectile motion (see Fig. 1). Therefore, the height achieved, time of flight, and horizontal distance traveled may be calculated by projectile-motion equations. Vertical acceleration, a_y, is –9.80 m/s^2 due to gravity. By multiplying the original velocity, v_0, by the sine of the angle θ from which the motorcycle was launched, the motorcycle's initial vertical velocity, v_{0y}, can be found:

$$v_{0y} = v_0 \sin \theta \qquad (1)$$

Once the vertical component of the velocity is known, the height achieved, y, may be calculated by:

$$y = (v_0^2 - v_{0y}^2)/2a_y \qquad (2)$$

After determining v_{0y} and y, the time of flight, t, may be calculated:

$$y = v_{0y}t + ½a_y t^2 \qquad (3)$$

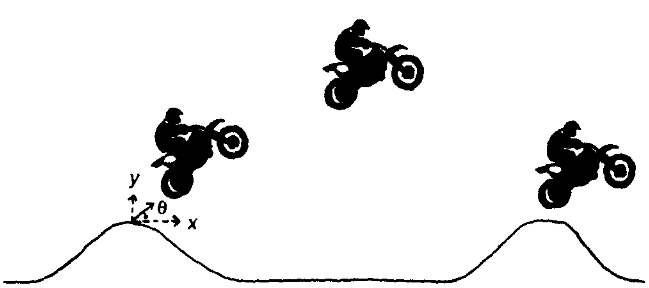

Fig. 1. Parabolic flight of a motorcycle from one obstacle to the next showing *x*, *y*, and θ.

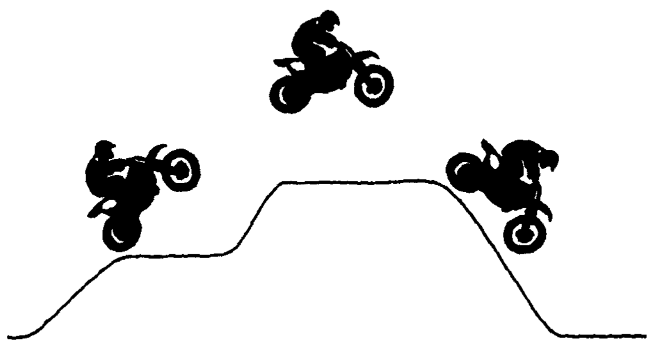

Fig. 2. Jumps such as this "tabletop" jump require a rider to achieve more height and less distance in order to land on the second obstacle.

Air resistance is assumed here to have a minimal effect; therefore, horizontal acceleration will be taken as zero. Horizontal velocity, v_{0x}, is found by multiplying the original velocity by the cosine of the angle from which the motorcycle was launched. Horizontal distance, x, traveled during the jump may be calculated:

$$x = v_{0x}t \qquad (4)$$

Riders use many techniques on the face of a take-off ramp to change the pattern of flight of the motorcycle. In most cases, the rider accelerates toward the ramp (to achieve high enough velocity to land on the downside of the next obstacle), lets off the throttle before the base of the ramp (to avoid "preloading" the suspension, as explained below), and gives a short burst of throttle before the rear wheel leaves the ramp (to keep the front wheel from dropping). However, sometimes the rider desires more height and a shorter distance in order to land on the down-ramp of the next obstacle (see Fig. 2). To obtain more height, a rider will compress the motorcycle's suspension on the face of the ramp. This is commonly referred to as "preloading" the suspension. Two methods are commonly used to preload the suspension. The first method is to accelerate at a greater than normal rate into the base of the ramp. This large acceleration increases the motorcycle and rider's momentum in the horizontal direction towards the base of the ramp. When the front wheel encounters the upward slope of the ramp, the ramp causes the springs in the motorcycle's front forks to compress. The rear suspension also

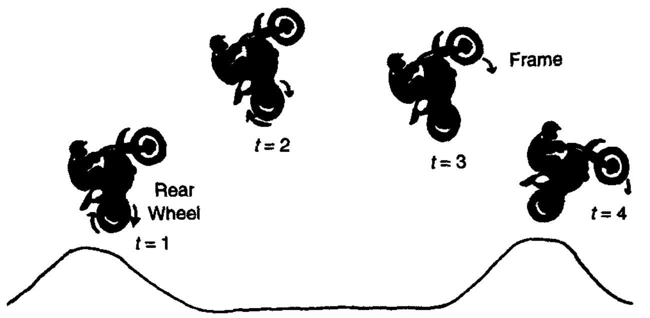

Fig. 3. To correct "looping out," the rider can stop rotation of the rear wheel to bring the motorcycle to a more stable position. At t = 1, the rider has just left the ramp and the front wheel is beginning to lift too high. The front wheel is too high for a safe landing at t = 2. At t = 3, the rider has locked the rear wheel and the motorcycle frame is beginning to rotate downward. At t = 4, the frame is continuing to rotate downward for a safe landing.

compresses as the rear wheel meets the base of the ramp due to the force being applied.

The second method of compressing the suspension is to press downward on the handlebars and footpegs at the base of the jump. The rider's upper body is positioned above the handlebars by leaning forward. This position allows the rider to press downward on the handlebars. The rider also presses downward on the footpegs with his legs. The resulting downward acceleration of the motorcycle frame compresses the suspension. The suspension rebounds as a result of this initial compression. This is similar to the behavior of a pogo stick. As the motorcycle is about to leave the ramp, this rebounding of the suspension provides a force on the frame of the motorcycle in the vertical direction. This extra force causes a greater v_{0y}, providing the desired gain in height.

Many times a rider will make a mistake on the ramp of a jump that causes the motorcycle to become unstable in the air. The way riders solve these problems and avoid crashing can also be explained by the laws of physics. One of the most common mistakes is known as "looping out." Looping out occurs when the front wheel is too high above the center of mass of the motorcycle (see Fig. 3). This often causes the motorcycle to flip over backwards before landing. Even in the slightest cases, looping out causes a very rough landing, which slows the forward momentum of the motorcycle. To counteract looping out, a rider can do one of two things: shift his body weight forward, or lock the rear wheel. The center of mass of the motorcycle and rider (as a single unit) is following a parabolic path. Shifting the rider's weight to the front of the bike changes the location of the center of mass of the bike/rider unit to a more forward location on the motorcycle. Since the center of mass follows the parabolic path, the new center of mass causes the motorcycle to rotate forward, thus lowering the front wheel.

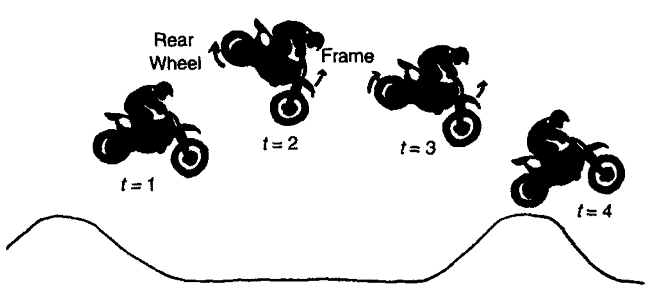

Fig. 4. To correct "endoing," the rider can accelerate rotation of the rear wheel to lift the front wheel for a safe landing. At t = 1, the rear wheel has begun to drop too low for a safe landing. At t = 2, the rider is accelerating the rear wheel, which begins to rotate the frame upwards. At t = 3, the frame is continuing upward rotation until a safe position is achieved at t = 4.

By locking the rear brakes, the rider may stop rotation of the rear wheel. The resulting change in the motorcycle's orientation is explained by conservation of angular momentum. Before the rider locks the rear brakes, the rear wheel spinning around the rear axle exhibits angular momentum, as does the entire motorcycle. Once the rear wheel is locked, the angular momentum originally in the rear wheel must be transferred to another part of the motorcycle in order for angular momentum of the entire motorcycle to be conserved. Thus, the frame of the motorcycle rotates downward, bringing the front wheel down. These two methods are used by racers to resolve front wheel loft and often prevent disastrous crashes.

"Endoing" is another case where the motorcycle is unstable in the air. Endoing occurs when the front wheel drops too far below the motorcycle's center of mass (see Fig. 4). This often results in the front wheel not clearing the next obstacle on the track. Riders solve this problem by revving the engine

Fig. 5. "Pancaking" is a crowd-pleasing maneuver in which the motorcycle is leaned to a horizontal position during flight between obstacles.

in midair. The rear wheel spins faster due to the application of the throttle and gains angular momentum. The axis of this additional angular momentum is the rear axle. Angular momentum must be conserved within the system. The result of the added angular momentum to the rear wheel is that the frame of the motorcycle rotates upward around an axis through the center of mass, providing the needed lift for the front wheel.

Riders could resolve endoing by leaning towards the back of the motorcycle to change the center of mass. However, riders prefer to be positioned over the front of the motorcycle to maintain proper control of the motorcycle. Therefore, leaning over the rear of the motorcycle is not an efficient means of resolving endoing.

The last case to be discussed is known as "pancaking" the motorcycle. This is an aerial maneuver often done to impress the crowd watching the race (see Fig. 5). While in the air, the rider rotates the motorcycle from its normal vertical plane to a horizontal position. The rider then returns the motorcycle to the vertical position before landing, making jumps much more spectacular to watch. If a rider wants the right side of the motorcycle to be above the left side, he will shift his weight from the right footpeg to remove the downward force of his weight from the footpeg. This is accomplished by simply lifting the right leg off the footpeg, removing the weight that was pressing directly on the footpeg and transferring it to the left footpeg. Pressure is applied to the left side of the frame by rotating the body below the hips in a counterclockwise direction and from above the hips in a clockwise direction. This motion is similar to that of a cat falling and landing on its feet. The twisting motion of the rider rotates the right side of the motorcycle upward. Once the motorcycle is in the horizontal position, shifting the body and weight in the opposite sense returns the motorcycle to a vertical position for landing.

Motocross is currently gaining much popularity and attracts a young audience, both in person and on cable television. One of the largest attractions for spectators is watching the motorcycles jump for great distances. Explaining how the laws of physics allow riders to control a motorcycle in these jumps is an interesting way to grab the attention of your students. This will also demonstrate how classroom theory applies to real-world situations.

et cetera...

Column Editor: **Albert A. Bartlett**
Department of Physics, University of Colorado, Boulder, CO 80309-0390

▼ Tethered Satellite

In the recent flight of the Space Shuttle a satellite was released that was attached to the Shuttle by a wire 20 km long. The wire, moving through the Earth's magnetic field was designed to generate an emf of 0.25 volts per meter or about 5 kilovolts. "For the eastward-moving shuttle, the satellite will charge positive, while the shuttle will be negative with respect to the ambient ionospheric plasma. The induced emf will lead to collection of electrons at the satellite and electron emission at the orbiter (the shuttle)." The electron emission was to be achieved by the use of electron guns in the shuttle cargo bay. The objective of the mission was to see how the tether could draw current from the ionosphere and thus generate useful electric power.[1,2] [As we all now know, the tether broke and the satellite was lost.]

1. D. Papadopoulos, A.T. Drobot, and N. Stone, *Transactions of the American Geophysical Union* **73**, 1 (July 28, 1992).
2. I am indebted to my colleague David Bartlett (no relation) for giving me a copy of this article after I had asked him how the tether system was going to generate useful electric currents.

▼ Check Your Arithmetic!

In a NASA educational newsletter, the headline said, "Langley Student Teams Create and Fly World's Largest Paper Airplane."[1] One photo showed a student launching a glider by hand, and the caption said, in part, the student "flies a prototype glider with a 27,432-meter (9-foot) wing span..." and he "tossed the plane about 137,160-meters (45 feet)...during preliminary flight tests."[1]

NASA's conversion factor is off by a factor of 10^4, and in each case the conversion from feet to meters resulted in an increase of four in the quoted significant figures. The origin of this added accuracy is not explained.

I wonder if anyone in NASA would catch this conversion error when they convert the specifications for the Space Station from American units to SI?

1. *NASA Educational Horizons* **1**, 10 (Spring 1992).

▼ What Physical Laws of Nature?

Howard Voss sent me a copy of an ad for an upscale car that carried the headline, "Inertia. Gravity. Centrifugal Force. These Things Mean Nothing To Our Engineers." This sounds a bit like a few of the students who did not make it in our introductory courses for engineers.

But then in the body of the ad we read, "While it stands to reason that all automobiles are subject to the physical laws of nature, [our car] appears to have been singularly exempted."

Beam me up, Scotty!

A²B