The Four-Ball Gyro and Motorcycle Countersteering

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Most two-wheel motorcycle riders know that, at highway speeds, if you want to turn left you push on the *left* handlebar and pull on the *right* handlebar. This is called *countersteering.* Countersteering is counterintuitive since pushing left and pulling right when the front wheel is not spinning would turn the wheel to the right. All good motorcycle instructors teach countersteering but few understand the physics of why it works, even though there is considerable discussion about it among motorcycle riders. This paper gives a simplified explanation of gyroscopic precession and then applies this to the front wheel of a motorcycle using two steps: 1) explaining how the wheel's lean is initiated, and 2) explaining how the lean will cause the wheel to turn. To assist with this discussion and to demonstrate the conclusions, a "wheel" was constructed using copper pipe, a bicycle wheel hub, and one pound of lead in each of four "balls" at the end of the spokes (see Fig. 1).

Fig. 1. The four-ball gyroscope.

Riders of bicycles and motorcycles perform both conscious and unconsciousness actions as they travel. The simple act of turning is started by one of these unconscious actions. When executing a stable turn, the center of mass of the rider and vehicle must lie inside the curve. A rider turning left is certainly aware of leaning slightly left throughout the turn. However, if the rider initiates a left turn by turning the front wheel left, his or her momentum will carry the center of mass to the outside of the curve, which is unstable. Thus a left turn cannot be initiated simply by turning the front wheel left. Let's take a closer look at what actually happens.

Physicists know that if a torque is applied perpendicular to the axis of a spinning wheel, the response will be for the axis to change direction. Research has been done and papers have been published that deal with the topic of torque and directional change of a spinning wheel[1,2] and, in particular, the spinning front wheel of a motorcycle or a bicycle.[3] Students encountering explanations involving torque and the angular momentum of the motion may remain puzzled, saying, "I understand the math, but where are the forces?" The following explanation illuminates the forces involved.

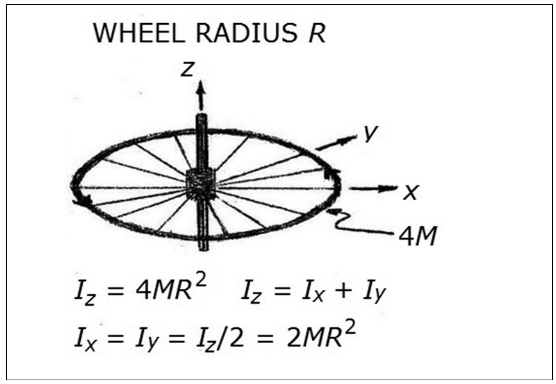

Fig. 2. Moments of inertia for a wheel.

Consider a wheel of mass $4M$ and radius R (neglecting the mass of the spokes and hub). Then consider a "wheel" with this same mass concentrated in four small but heavy (1 lb each) balls at the common radius R. Let us calculate the moment of inertia about the principal axes for both "wheels." For the actual wheel lying in the x-y plane (see Fig. 2), the z-moment of inertia is $I_z = 4MR^2$, and because $I_x = I_y$ by symmetry and $I_x + I_y = I_z$ by the perpendicular axis theorem, we have $I_x = I_y = 2MR^2$.

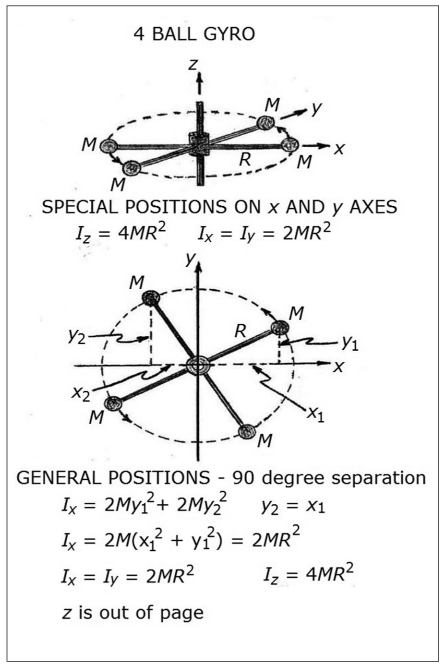

Fig. 3. Moment of inertia for the four-ball gyro.

Next, we calculate the moments of inertia for the four-ball "wheel" in the "aligned" orientation shown at the top of Fig. 3. By inspection, we obtain the same results as those for the actual wheel.

Finally, we calculate the moments of inertia for the four-ball "wheel" with an arbitrary orientation, as shown at the bottom of Fig. 3. Note that $y_2 = x_1$. We have $I_x = 2My_1^2 + 2My_2^2 = 2M(y_1^2 + x_1^2) = 2MR^2$ and, similarly, $I_y = 2MR^2$, so $I_z = 4MR^2$.

 DOI: 10.1119/1.4978726

Therefore a common torque about any axis will give the same dynamical result for a four-ball gyro according to the equation $\tau = I\alpha$.[4]

We are now prepared to investigate the torque on our spinning wheel in terms of the forces applied. First, we imagine holding the rotating four-ball gyro as shown in Fig. 4. The initial angular velocity vector $\boldsymbol{\omega}$ is in the positive z-direction. Let's exert a torque about the y-axis (so the torque vector is in the positive y-direction) while the center of the gyro remains at rest. To do this, the left hand pushes in the positive x-direction and the right hand pulls in the negative x-direction. Ball 1 is forced down as it moves left (from the person's point of view) and the left half of the gyro tilts down toward the vertical x-z plane. This forces the left hand to move left and downward. Similarly, ball 3 is forced up as it moves right (from the person's point of view) and the right half of the gyro tilts up toward the vertical x-z plane. This forces the right hand to move right and upward. Thus an applied torque about the y-axis produces a rotation of the gyro about the x-axis. This argument is equivalent to applying the vector equation $\boldsymbol{\tau} = d\boldsymbol{L}/dt$, but involves only forces.

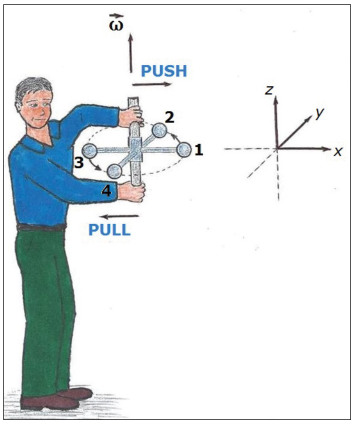

Fig. 4. The torque on a four-ball gyro.

We are now ready to apply this to provide a simple explanation of the motorcycle left turn. The first thing the rider must do is to move the center of mass to the left, that is, to the inside of the curve. To do this, the rider must turn the front wheel slightly to the right, so his or her forward momentum will carry the center of mass slightly to the left of the bike. The turn of the front wheel to the right also causes a gyroscopic action that leans the wheel left. As before, think of the front wheel of the motorcycle as consisting of four heavy balls attached to four strong "massless" rods and rolling, as shown, on a smooth "massless" rim (Fig. 5). The left hand pushes forward in the positive y-direction and the right hand pulls back in the negative y-direction. Ball 1 spins to the top position while being forced to the left (negative x-direction), and, similarly, ball 3 spins to the bottom position while being forced to the right (positive x-direction). This causes the wheel and the motorcycle to tilt downward to the left. Now that a left lean has been initiated, the resulting gravitational force on the center of mass causes the bike to continue to lean more to the left, as desired.

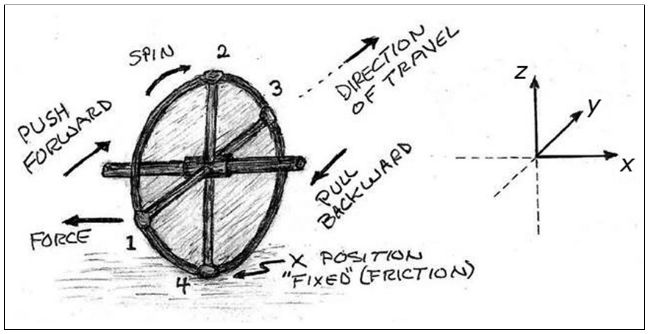

Fig. 5. The front wheel of the motorcycle as a four-ball gyro, showing the initial right turn.

As the front wheel leans farther left, gyroscopic action plays an important role in steering the front wheel from the right to the left. The situation is like hanging the wheel (or four-ball gyro) from a rope at the end of the right grip. In the absence of rotation, gravity would pull the wheel down to the left (as is happening with the motorcycle), but for a spinning wheel gyroscopic motion adds another effect. As the motorcycle leans to the left, it is like pushing down on the left grip of the hanging wheel while the rope pulls up on the right grip. As a result, mass 2 in Fig. 5 is forced left as it moves forward (from the rider's point of view), and the front side of the wheel pivots to the left. Similarly, mass 4 is forced right as it moves backward (from the rider's point of view), and the back side of the wheel pivots to the right. Thus, while the bike is in the process of leaning farther to the left, gyroscopic action is responsible for turning the wheel from the initial right turn back to the left. At this point the rider's center of mass is on the inside of the curve, and the wheel is leaning left and turned left. The motorcycle can now proceed with a stable left turn.

A word of caution: It is important for the motorcycle rider to employ this countersteering only for a fraction of a second to *initiate* the turn. Once into the turn, the motorcycle will follow the desired path through the turn, and the proper lean will be achieved with experience and "feel" for stability.[3,5]

Using the four-ball gyroscope to present this argument in terms of forces, rather than torques, provides the student with an answer to "Where are the forces?" Students can use their understanding of the underlying forces as a bridge to the more elusive description involving torques and angular momentum.

Conclusion

Pushing forward on the left grip and pulling back on the right grip of a motorcycle turns the wheel slightly to the right, taking the rider's center of mass to the left of the bike. The right turn causes a gyroscopic action that initiates a leftward lean, which is then enhanced by gravity. The increase of the leftward lean itself produces another gyroscopic action that turns the wheel from the right to the left, and the left turn proceeds.

Acknowledgments

The authors wish to thank the referees for their helpful comments.

References

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2. Harvey Kaplan and Andrew Hirsch, "Gyroscopic motion: Show me the forces!" *Phys. Teach.* **52**, 30–33 (Jan. 2014).
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4. A demonstration wheel with four masses added is available from http://www.pasco.com.
5. Personal experience and observation of the authors.