The Equivalence Principle and the Dynamics of an Accelerated Helium-Filled Balloon

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The Equivalence Principle and the Dynamics of an Accelerated Helium-Filled Balloon

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In an interesting recent article, V.M. Aguilella et al.[1] analyzed the dynamics of a helium-filled balloon tied by a string to the seat of a car that is moving at constant speed in a horizontal curve. To achieve their goal, the authors carefully apply Newton's laws of motion to a situation involving a noninertial frame of reference.

This note, whose purpose is twofold, is meant to complement the article by Aguilella and his colleagues. To begin with, I will stress that the type of problem considered by Aguilella et al. provides an ideal opportunity to introduce Einstein's principle of equivalence to young students, at a time when they are beginning to understand the links between the world they live in and the basic laws of physics. Then, I will consider a simplified version of the accelerating helium-filled balloon and show how easy it is to explain its behavior by using the principle of equivalence and very simple mathematics. The physical context of this problem is familiar to most beginners, through their own background of experience with accelerating systems.

Accelerating systems are very much a part of our modern world, and most people have experienced their peculiarities on numerous occasions, often since birth. Examples of accelerating reference frames are available aplenty in amusement parks throughout the world and in numerous sports. It is probably fair to expect, however, that the passengers of amusement park rides or of sports activities focus more on the excitement of the occasion itself than they do on the more objective conditions of acceleration under which they are being placed. Fortunately, there is the common automobile! Indeed, a car is without doubt the best and most frequent provider of situations when a passenger is given enough time to feel the experience of acceleration itself *as it is happening.* This will then enable the passenger to draw from that feeling or intuitive reflection and to relate the experience to the laws of physics if prompted to at a later stage.

According to Serway et al.,[2] the principle of equivalence enunciates, "In the vicinity of any point, a gravitational field is equivalent to an accelerated frame of reference in the absence of gravitational effects." This basic formulation obviously has a converse, and I formulate that converse here in order to use it later: "In the vicinity of any point, an accelerated frame of reference is equivalent to a gravitational field in the absence of acceleration effects."

The principle of equivalence is one of the two basic postulates used by Albert Einstein to derive his general theory of relativity from first principles. This principle is the cornerstone of general relativity, and it provides a deep insight into the phenomenon of gravitation. I suggest that such a powerful principle can and should be introduced at the early stage of a student's scientific development, but that it is badly neglected in introductory science textbooks and in high school and college science curricula.

I now show how easy it is to understand the dynamical behavior of a helium-filled balloon attached by a string to the seat of an accelerating car. To make the situation a little simpler than that considered by Aguilella et al., I will assume that the car is accelerating at a constant rate along a straight horizontal road. The more general situation, including the one considered by these authors, can readily be discussed along lines similar to those presented below.

To begin with, and for the sake of later contrast, imagine what happens if the car is either at rest or moving at a constant velocity. Let us first look at the behavior of the helium-filled balloon. In the absence of acceleration, the balloon rises vertically upward *against* the downward pull of gravity. The balloon is held stationary by the tension in the string, whose value equals the product of the balloon's buoyant mass times the acceleration due to gravity, $a_G = 9.8$ m/s^2, as discussed by Aguilella et al. This behavior of the balloon arises because the density of helium in the balloon is smaller than that of the surrounding air, a fact that can simply be explained at the elementary level by invoking the law of buoyancy of Archimedes.[2] Now let us assume the same conditions of rest or uniform motion for the car, but this time let us examine the forces that act on a passenger, as seen from that passenger's perspective. For the passenger, a vertical downward pull is acting on her, that of gravity, and it presses her body against the bottom part of the car seat that keeps her stationary. This downward pull of gravity can be calculated from the mass of the passenger times the downward acceleration due to gravity, a_G.

Now when the car is accelerating forward at a constant rate a_C, the passenger experiences a new force that presses her against the back of the seat. In such a state of motion, the passenger would be entitled to conclude, by the second form of the principle of equivalence, that the situation is equivalent to having two simultaneous gravitational fields, one pointing downward and characterized by an acceleration a_G, the other pointing backward and characterized by an acceleration a_C. Consequently, the net *equivalent* gravitational field experienced by the passenger would have an associated acceleration of magnitude $a = \sqrt{a_G^2 + a_C^2}$ and would be oriented toward the back of the car, under the horizontal direction, at an angle $\theta = \tan^{-1}(a_G/a_C)$. Consequently, under these same conditions of acceleration, the helium-filled balloon will again *rise* because of the unbalanced force of buoyancy, as in the case of uniform motion, except that it would now do so against the net effective gravitational field. Furthermore, when the dynamical equilibrium of the balloon's motion has finally been reached, the string will come to rest at an angle $\theta = \tan^{-1}(a_G/a_C)$ pointing toward the front of the car and above the horizontal. Finally, the tension in the string will equal the buoyant mass of the balloon times the effective gravitational acceleration a.

References

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2. Raymond A. Serway, Robert J. Beichner, and John W. Jewett, *Physics for Scientists and Engineers,* 5th ed. (Saunders, New York, 2000), p. 1279.