Magnetic Levitation and Newton's Third Law

Horacio Munguía Aguilar, Universidad de Sonora, Hermosillo, Son. México

Newton’s third law is often misunderstood by students and even their professors, as has already been pointed out in the literature. Application of the law in the context of electromagnetism can be especially problematic, because the idea that the forces of “action” and “reaction” are equal and opposite independent of the medium through which they act can be muddied by the concept of “action at a distance.” While some experiments have been described illustrating Newton’s third law in magnetic situations, these do not offer the student a clear way of evaluating his/her own preconceptions. The experiment we present shows how easily the student, and even the graduate student, can fail to apply the third law correctly in an electromagnetic situation. The experiment described here employs a magnetic levitator and shows the difficulty in recognizing action and reaction forces.

The homemade levitator can maintain in suspension a 360-g steel ball at 5 mm from the end of the core of a vertical solenoid (see Fig. 1). Initially, the levitator without the ball is placed on a scale and weighed. We ask our students if after placing the ball under the solenoid in state of levitation the scale will indicate the original reading or if the reading will be altered due to the presence of the ball. Opinions vary because many students think that because the ball is “floating,” it does not add to the levitator mass, and so the weight remains unchanged. They do not take into account that in spite of the fact that the solenoid “acts at a distance” on the ball, it exerts a force of the same magnitude on the solenoid: the reaction force. This force adds to the weight of the levitator, which increases the scale reading. In our case, the mass of the levitator system (without ball) is 2.500 kg. With the ball levitating, the scale reading increases to 2.860 kg.

Fig. 1. Steel ball levitation system.

Fig. 2. Forces on the ball and the solenoid.
The forces for this situation are illustrated in Fig. 2, where $M$ is the mass of the levitator, $m$ is the mass of the ball, $F_m$ is the force exerted by the solenoid on the ball (action) and $F'_m$ is the reaction force acting on the solenoid. Therefore, the total weight of the system is given by

$$W_t = Mg + F'_m = Mg + mg.$$

We now continue the experiment under a new set of circumstances. The solenoid is disconnected from the control circuit and reconnected directly to a voltage source, which is adjusted so that the solenoid holds the steel ball in contact with its core. That is to say, we discontinue the levitation, and the solenoid is employed as a simple electromagnet. The current in the solenoid is adjusted in order to barely keep the ball from falling, 1.5 A in our experiment. It is clear to the students that the scale reading does not change from its earlier value. It remains 2.860 kg. At this point we observe that the force of attraction between the solenoid and the ball increases as the current rises. And then we offer our students the following argument: given that the weight of the system in the first experiment increases by virtue of the presence of the force $F'_m$ (the magnetic reaction force exerted by the ball), increasing the current will raise the total system weight, and therefore the scale reading should also increase. To some students’ surprise, when they increase the current the reading on the scale does not change. Misapplication of Newton’s third law is again the source of the confusion. One way to understand the new situation is to consider that the steel ball and the solenoid joined together form a new physical body with a mass $M + m$. The magnetic forces of action and reaction are still present, but now they are internal forces that cancel each other out without affecting the body’s weight. Therefore, the system’s weight is still

$$W_t = (m + M)g.$$

These internal forces are depicted in Fig. 3.

In order to carry out the first experiment, any attractive-force electromagnetic levitator of the sort described in the literature\textsuperscript{5,6} can be used. For the second part of the experiment it is important that the solenoid can be disconnected from the levitator in order to reconnect it to a voltage source as described. With respect to the scale, it is only necessary that it be capable to register the mass differences between the levitator and the steel ball.

References


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Horacio Munguía A. is a professor at the Departamento de Física at the Universidad de Sonora in Hermosillo, Son. México. He is involved in teaching Electronic Instrumentation and developing equipment and systems for measurement and control of physical variables. I also participate in a project in the design of physics education materials.

Departamento de Física, Hermosillo, Son. México; hmunguia@correo.fisica.uson.mx