Understanding coffee spills using a smartphone

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The SpillNot® is an ingenious and effective device that aims to solve the everyday problem of transporting an open cup of hot beverage like tea or coffee without spilling. It not only avoids spills under the normal conditions in which a drink is usually carried, but also remains effective in extreme conditions such as giving full turns in a vertical or a horizontal plane. To help explain the operation of this device, instead of a cup, a smartphone was placed on the base of a SpillNot. The acceleration components, parallel and perpendicular to the base, were obtained using the built-in accelerometer. The analysis of these measures sheds light on the physical mechanisms of the SpillNot.

The physics of the SpillNot

Everyone has experienced the problem of carrying a cup containing a hot beverage like coffee or tea. Common knowledge suggests that one must be especially careful to avoid spills. One possible solution is to use a SpillNot,[1] a simple device aimed at solving this daily problem. It consists of an anti-slip pad placed on a base that is attached by a handle, which in turn is held by a ribbon. When someone carries a SpillNot held by the ribbon with a cup placed on its base, it is possible to oscillate the device with large amplitudes and even to give full turns in a vertical or in a horizontal plane, as shown in Fig. 1.

Let us consider a simple model of the SpillNot as a pendulum. On one hand, defining θ as the angle with the vertical from the lowest position, the vertical and horizontal acceleration components are given by

$$a_y = \frac{T}{m}\cos\theta - g$$

and

$$a_x = \frac{T}{m}\sin\theta,$$

thus the angle of the pendulum with the vertical verifies

$$\tan\theta = \frac{a_x}{g + a_y}.$$

On the other hand, in general, a fluid cannot sustain a force that is tangential to its surface. As a consequence, the free surface in a system subject to a constant acceleration forms an angle with the horizontal, whose tangent is given by

$$\frac{a_x}{g + a_y},$$

Fig. 1. Snapshot showing a cup on a SpillNot giving full turns in a vertical plane; the surface of the liquid can be appreciated.
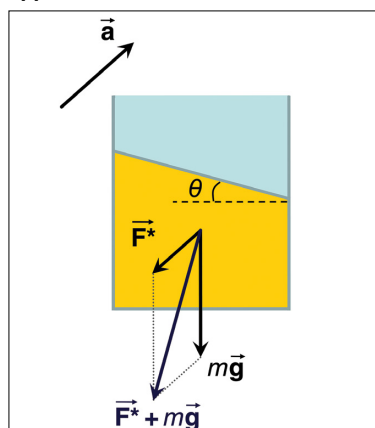

Fig. 2. The slope of a free surface in a container moving with uniform acceleration a is perpendicular to direction of the sum of the gravitational and the fictitious force F*.

where a_x and a_y are the horizontal and vertical acceleration components, as indicated in Fig. 2.

Putting these facts together, we see that, if we want no spilling, the angle of the SpillNot with respect to the *vertical* needs to be the same as the angle of the liquid with respect to the *horizontal*. So, if the acceleration is approximately perpendicular to the base, the liquid will remain roughly parallel to the base. This analysis is approximate in several factors; transient effects, the motion of the hand, or the finite size of the device, among others, are neglected. However, the key point, i.e., that the radial acceleration should be considerably larger than the tangential acceleration in order to limit spilling, is revealed.

Experimental results

To verify this conclusion, instead of a cup of hot beverage, a smartphone was placed on the base of a SpillNot and the system set in motion oscillating with a large amplitude in a vertical plane. An Android smartphone (Samsung GT-I9100) furnished with a three-axis accelerometer (ST-Microelectronics K3DH, 0.005 m/s^2 resolution and 16 Hz sampling rate) was used. The Androsensor application[2] was used to record sensor readings. The radial acceleration is given by the sensor along the z-axis while the vectorial sum of the values corresponding to the x- and y-axis is the tan-
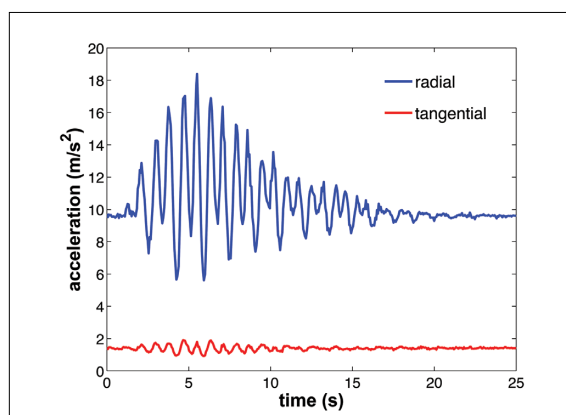
Fig. 3. Acceleration components as functions of time. During the interval between approximately 3 s and 15 s, the system is performing large oscillations in a vertical plane.

gential component.

The temporal evolution of the acceleration is shown in Fig. 3. It can be appreciated that the magnitude of the radial component is much greater than the tangential component. It must be highlighted that acceleration sensors measure, in fact, an apparent acceleration,[3-4] resulting from the vectorial sum of the real acceleration and the acceleration associated with a gravitational field in the opposite direction to that of the real gravitational field. As a consequence, the radial acceleration is centered about 10 m/s^2, instead of about a null value. In addition, the tangential component also oscillates around a non-zero value. This is due to the fact that the Spill-Not is asymmetric and, when hanging at rest held from the ribbon, the base is not horizontal but inclined at an angle of approximately 8°.

Final remarks

In this contribution a simple experiment using a smartphone helps to analyze a daily problem and discuss the underlying mechanisms of a device that, at first sight, appears to be magic. It is worth noting that, far from trivial, sloshing dynamics is a problem that goes beyond the carrying of hot beverages and has received considerable attention in physics and engineering.[5] For instance, one important application is the control of large liquid-filled structures such as rocket fuel tanks.

References
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2. See http://www.fivasim.com/androsensor.html.
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5. Raouf A. Ibrahim, *Liquid Sloshing Dynamics: Theory and Applications* (Cambridge University Press, 2005).