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A Study on the Coffee Spilling Phenomena in the Low Impulse Regime

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A B S T R A C T

When a half-full Bordeaux glass is oscillated sideways at 4 Hz, calm waves of wine gently ripple upon the surface. However, when a cylindrical mug is subject to the same motion, it does not take long for the liquid to splash aggressively against the cup and ultimately spill. This is a manifestation of the same principles that also make us spill coffee when we walk. In this study, we first investigate the physical properties of the fluid-structure interaction of the coffee cup; in particular, the frequency spectrum of each oscillating component is examined methodically. It is revealed that the cup's oscillation is not monochromatic: harmonic modes exist, and their proportions are significant. As a result, although the base frequency of the cup is considerably displaced from the resonance region, maximum spillage is initiated by the second harmonic mode of driving force that the cup exerts on its contents. Thus, we spill coffee. As an application of these experimental findings, a number of methods to reduce liquid spillage are investigated. Most notably, an alternative method to hold the cup is suggested; in essence, by altering the mechanical structure of the cup-holding posture, we can effectively suppress the higher frequency components of the driving force and thus stabilize the liquid oscillation. In an attempt to rationalize all we have investigated above, a mechanical model is proposed. Due to practicalities, rather than to construct a dynamical system using Newton's equation of motion, we choose to utilize the Euler-Lagrangian equations. Extensive simulation studies reveal that our model, crude in its form, successfully embodies the essential facets of reality. This liberates us to make two predictions that were beyond our experimental limits: the change in magnitude of the driving force and the temporal stabilization process.

Introduction

Rarely do we manage to carry coffee around without spilling it once (Fig. 1). In fact, due to the very commonness of the phenomenon, we tend to dismiss questioning it beyond simply exclaiming: “Jenkins! You have too much coffee in your cup!”

However, the coffee spilling phenomenon is deceivingly simple. As a counter-intuitive example, prepare two liquid containers with distinct geometrical structures; here, we consider a wine glass and a normal sized cylindrical mug. We first pour the same amount of coffee inside each container. Then, using a mechanical vibrator connected to a function generator (Fig. 2a), we impose a horizontal excitation $X = X_0 \cos(2\pi ft)$ to each liquid container, where X denotes the container's horizontal position and f is set to 2 Hz. This effectively simulates the human walking motion. Intuitively, since the amount of coffee is the same in each container, the amount spillage due to the oscillation should be fairly similar as well. However, this is not the case. As clearly shown in Fig. 3b, the liquid motion inside the wine glass is aggressive while that of the cylindrical cup is comparatively steady; consequently, the quantity of spillage is significantly different. When the driving frequency “f” is changed to 4 Hz, we are again surprised. Essentially, the liquid behavior inside each container is completely reversed: while the coffee inside the wine glass remains close to its equilibrium,

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Fig. 1. Rarely do we walk without spilling coffee.

the coffee inside the cylindrical cup oscillates violently (Fig. 3c and d). Such experiment results are enough to show that the amount of liquid may not be the sole reason behind spilling coffee.

Indeed, the spilling of coffee is a manifestation of multiple interactions, ranging from the body-hand coordination to the resonance properties of the cup-coffee interaction. Thus, in order to gain clearer insight, the coffee spilling phenomenon is divided into two regimes: the low impulse regime and the high impulse regime. The term "impulse" indicates the maximum magnitude of the impulse that the cup experiences. Not surprisingly, the physical properties of each regime are pronouncedly different. In the low impulse regime, the interaction between the cup and coffee is considered as a periodic function; thus, the oscillation properties are researched extensively. However, in the high impulse regime, the interaction between the cup and coffee is momentary and aggressive. Oscillation phenomena carry less importance in such a regime. Spilling from casual walking falls under the former regime; spilling after slamming into a colleague falls under the latter. In the present paper, the low impulse regime is set to be the main focus of study.

Also, the effective cup height (which is defined to be the height of the cup minus the liquid equilibrium level [Fig. 2b]) is not considered as a variable in this study for two reasons. First, the role of the effective height of the cup in spilling is rather straight forward. If the effective height of the cup is large enough, the coffee is unlikely to spill unless it is flipped over. On the other hand, if the effective height of the cup is close to zero, that is, if the cup is filled to its brim, the liquid is much more likely to spill. Thus, the taller the cup and lesser the coffee, the less you spill. Such a relationship is not investigated to further extent in this study. Second, as much as it is simple, the role of effective cup height is also absolute; due to the dominant role of the effective cup height, it is treated as a classification rather than a variable.

Thus, in this paper, we study the conditions that maximize the amplitude of coffee oscillation under the low impulse regime. In the Experiment Studies section, the liquid oscillation properties and the cup's motion properties are investigated. Here, a surprising feature of the hand (cup) movement during walking is realized from its frequency spectrum. Then, combining the results from each investigation, it will be revealed how the interplay between the cup and coffee leads to spilling. By applying this knowledge, a number of methods to reduce coffee spilling are presented as well. Next, in the Model Studies section, two mechanical models of the "normal hand" posture and the "claw-hand" posture are proposed. They are each modeled by the oscillating-pivot single pendulum and the oscillating-pivot double pendulum; both models are constructed upon the bold assumption that coffee, at least in this study, can be treated as a simple pendulum. Surprisingly, simulation studies reveal that both models successfully predict the important physical properties discovered through experiment. We then conclude the paper with a summary of our discoveries.

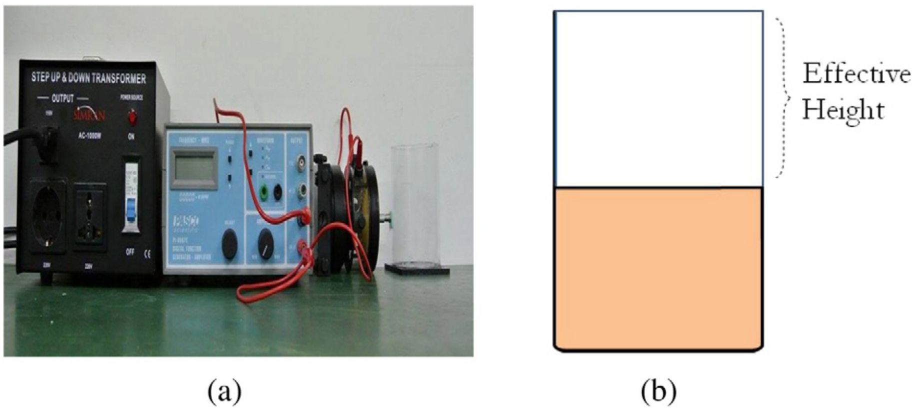

Fig. 2. (a) A mechanical setup to maintain a fixed frequency during oscillation. (b) A diagram of the effective cup height.