Mechanobiology of fluid mechanics and instability of kapista pendula.

Sara Watson*

Department of Applied Mathematics, University of Washington, United states.

Abstract

The emergence and development of instabilities is one of the central problems in fluid dynamics. We develop a relationship between the free-fluid interface instability and the inverted pendulum. When an inverted pendulum is unstable because only gravity acts on it. This position is stabilized by the Kapitsa phenomenon, which produces high-frequency, low-amplitude vertical vibration. The base creates an imaginary force that opposes gravity. By transforming the dynamic equations governing the fluid interface to the appropriate pendulum equations, we show how well-tuned oscillations can induce stability in a fluid system.

Keywords: Purification processes, Bioreactor design, Surface science, Fluid mechanics.

Introduction

Interfacial instabilities are the seeds of many pattern forming mechanisms in Nature. The ability to delay or entirely suppress these instabilities therefore represents a significant tool. In fluid mechanics, a number of important instabilities occur at one or more discrete interfaces between immiscible fluids with different material and flow properties. Much recent attention has been paid to potential methods of stabilizing these interfaces. Several mechanisms are available for example, stabilization of the canonical Rayleigh-Taylor instability has been proposed through the use of gyroscopic forces, magnetically-charged colloids, or heat and mass transfer across the interface. Similarly, capillary instabilities have been shown to be tunable in the presence of internal flows, external acoustic waves, and vibrations [1].

Tuning the properties of these instabilities is desirable, for example, in the design of fusion reactors. In such systems it can be desirable to find criteria for global stability which do not depend on feedback mechanisms, but rather depend on inducing a tenable external force which causes the unperturbed trivial solution to be stable for long times. In classical mechanics, an external agent can always induce such a force according to the principle, by accelerating the previously-inertial frame in which the desired solution was unstable [2].

A canonical example is the Kapitsa phenomenon, in which a pendulum in the inverted position can be stabilized by low-amplitude, high-frequency vertical vibrations of its base. This effect was predicted based on variants of the Mathieu equation. The stability of the trivial solution is determined by the material parameters and the parameters of the oscillator and several stable regions exist in this parameter space. Recent work has sought to explain and generalize this effect, using tools ranging from simplistic topology to differential geometry and classical mechanics. Using external vibrations to transform the equation of a simple harmonic oscillator into a Mathieu-type equation has several extensions [3].

The use of the effect to circumvent Earns haw's theorem, according to which any stationary collection of electric charges is inherently unstable, led to the development of the ion trap which earned its inventor the Nobel Prize. It is now known that all extreme of a potential become minima when the potential undergoes similar oscillations, leading to vast applications in conservative systems. These oscillations have been invoked as a stabilizing mechanism as far afield as economics [4].

They have also been known to stabilize a denser fluid atop a lighter fluid for many decades, presenting one method of dynamically stabilizing the Rayleigh-Taylor instability. A similar effect can levitate a rigid body by placing it in a small-amplitude high-frequency oscillating airflow; this is likely an important mechanism in insect flight. By reducing the local dynamics of the interface to a one-dimensional dynamical equation for the perturbation amplitude via standard techniques in the study of instabilities [5].

Conclusion

In this work we reviewed existing literature connecting an inverted pendulum to the Rayleigh-Taylor instability. Both systems can be stabilized by low-amplitude high-frequency external forcing in the vertical direction mathematically speaking, this equates to transformation from the equation of a simple harmonic oscillator to Mathieu's equation. We expand this initial correspondence by deriving similar equations for discrete planar and cylindrical interfacial instabilities of interest and pointing to further expansions known in the

***Correspondence to:** Joseph Stephen, Department of Applied Mathematics, University of Washington, United states. E-mail: sarawatson@uw.edu

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literature. In each case we use the penduluanalogies to invoke results from the vibrations and dynamical systems literature.

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