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An Introduction to Analogy Vibrational Behavior of Celestial Bodies and Asteroids

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Abstract

Understanding the vibrational behaviour of celestial bodies and asteroids is crucial for advancing our knowledge of their structural integrity, composition, and potential hazards they pose to Earth. This study presents a comprehensive modelling approach to investigate the vibrational dynamics of these objects using numerical simulations and analytical techniques. By employing analogies method, the examination of the effects of various parameters, such as size, shape, and material properties, on the vibrational modes of selected asteroids is investigated. The findings reveal distinct vibrational characteristics that can inform impact risk assessments and contribute to the design of spacecraft missions for asteroid exploration. This research not only enhances he understanding of the physical processes governing celestial bodies but also provides valuable insights into planetary defence strategies and the geological evolution of these objects.

Keywords: Analogy Modelling, Vibrational Behaviour, Celestial Bodies, Asteroids

1. Introduction

The vibrational behaviour of celestial bodies and asteroids is a complex topic involving their internal and external dynamics. These vibrations, or oscillations, are typically caused by various forces and physical processes. Here's an overview of the key concepts involved. Tidal Forces and Oscillations, celestial bodies like planets, moons, and stars are subject to gravitational interactions with other bodies in their vicinity. This gravitational pull leads to tidal forces, which can induce oscillations or deformations (vibrations) in their structure. These tidal forces cause phenomena like tidal bulging and energy dissipation, leading to changes in rotational behaviour and surface deformations over long periods [1].

Moons (like Earth's Moon) or planets close to their stars can experience tidal locking, where their vibrational energy leads to a synchronization of their rotation period with their orbital period. Seismic vibrations (Asteroseismology and Planetary Seismology), stars, including our Sun, vibrate due to internal processes. These vibrations can be studied using asteroseismology, where oscillations on the star's surface are analysed to learn about its internal structure. These oscillations are caused by the movement of plasma and energy inside the star. Planets and moons can experience seismic activity (such as Earthquakes or Moonquakes). This is due to internal stresses, such as tectonic activity or impacts from meteorites, and is studied through seismology [2].

In 2019, NASA’s Insight mission detected Mars quakes, showing Mars has seismic vibrations that may provide insights into its internal structure and geologic history. Asteroids and Small Body vibrations, asteroids and other small celestial bodies can experience vibrations due to impacts from other objects or internal stresses. Because they lack atmospheres and have irregular shapes, their vibrations may differ significantly from those of larger celestial bodies. Asteroids' vibrational behaviour is often influenced by their rotational dynamics, internal composition, and structural integrity [3].

YORP effect: Over time, sunlight can cause rotational changes in asteroids due to asymmetric heating, leading to gradual increases or decreases in their spin rate, which might induce internal stresses and vibrations. Large impacts can cause entire asteroids to vibrate like a bell for extended periods, especially if the asteroid has a loose rubble-pile structure [4].

Normal modes of vibration, celestial bodies, particularly large ones, can vibrate in specific patterns called normal modes. These are distinct frequencies at which the body oscillates naturally, much like how musical instruments resonate at particular notes. For Earth, normal modes were detected following large earthquakes. Similarly, a large enough asteroid collision could excite normal modes of an asteroid, allowing us to study its internal structure [5]. Moonquakes detected by Apollo missions revealed that the Moon has natural vibrational modes, providing insights into its internal composition and layering.

Resonances, orbital resonances can cause vibrational interactions between celestial bodies. When two orbiting bodies have gravitational interactions and their orbital periods are related by a simple ratio (e.g., 2:1), energy can be transferred between them, leading to periodic oscillations. For example, Jupiter's moons Ganymede, Europa, and Io are in a Laplace resonance, where their orbits influence each other's vibrational and rotational behaviour [6].

External forces and excitations, external factors like solar radiation, magnetic fields, or even the passage of a celestial body through a dense region of dust or gas can cause a body to experience vibrational effects. Comet nuclei, for example, may undergo vibrations or rotational shifts due to outgassing (jets of material ejected from the comet), which can alter the body's spin or cause surface stresses [7].

Artificial impacts and probes, in several space missions, controlled impacts have been used to study the vibrational response of celestial bodies. For example, NASA's LCROSS mission intentionally crashed a spacecraft into the Moon to study the ejecta, and ESA's Rosetta mission studied the surface vibrations of comet 67P/Churyumov-Gerasimenko. Future missions might use similar techniques to analyse the vibrational response of asteroids to learn more about their internal structures, which is crucial for planetary defence strategies[8]. For more implementation of asteroids behaviour, see Figure (1). Modelling the vibrational behaviour of an asteroid using a mass-spring-damper system is an interesting approach. This simplification allows us to analyse the dynamics of the asteroid's oscillations under certain assumptions. Here's how to conceptualize and set up this model in the main body. The vibrational behaviour of celestial bodies and asteroids is governed by internal processes (like tectonics and composition), external forces (like impacts and gravitational interactions), and resonances from orbital dynamics. Studying these vibrations offers key insights into the internal structures, compositions, and evolution of these bodies, and it plays a significant role in fields like planetary defence, astrobiology, and astronomy. The mentioned simple mass-spring-damper model provides insights into the vibrational behaviour of an asteroid is demonstrated in this study. The actual behaviour of an asteroid can be significantly more complex, influenced by its shape.

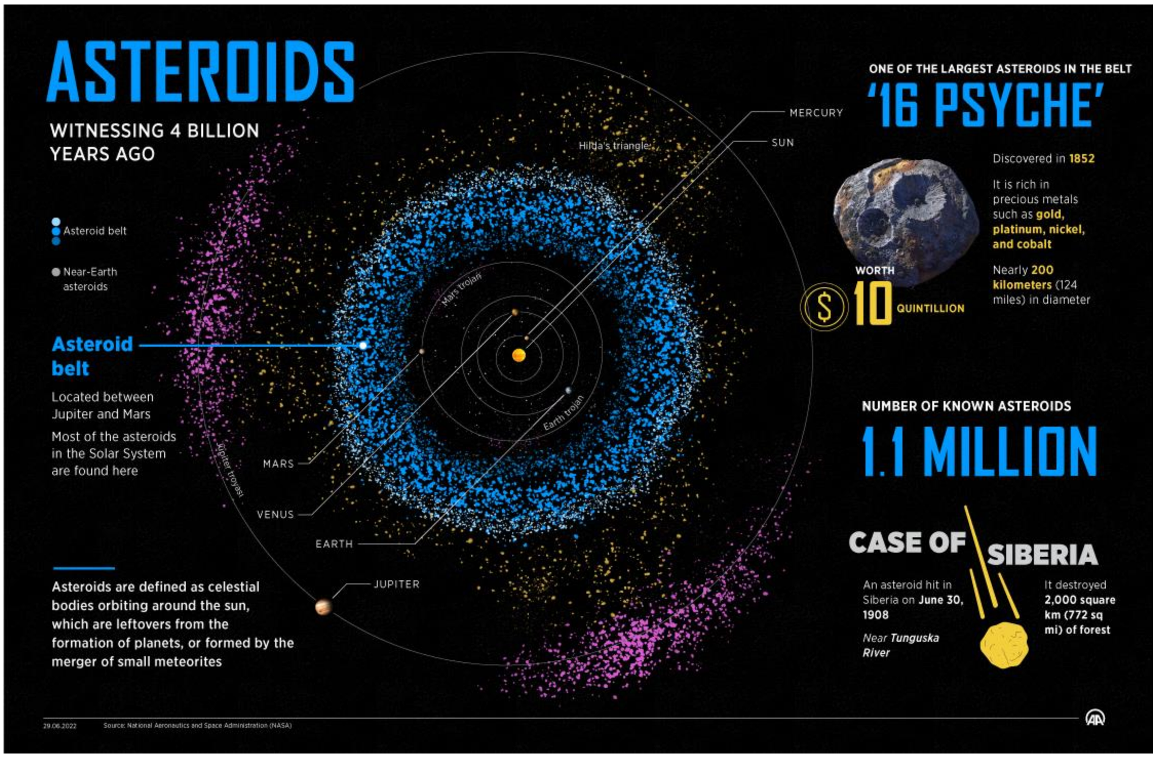

Figure (1). Implementation of asteroids behaviour [4]

Near-Earth Objects (NEOs): Asteroids and Comets

Near-Earth Objects (NEOs) are asteroids and comets that are gravitationally influenced by nearby planets, causing them to enter orbits that bring them into Earth's vicinity. Typically, comets consist of ice and dust particles, and they often form in the inner solar system, particularly between the orbits of Jupiter and Mars. The scientific interest in comets and asteroids stems from their preservation of primordial materials dating back to the early solar system, around 4.6 billion years ago. The larger planets (Jupiter, Uranus, Neptune, and Saturn) formed from the accumulation of billions of comets, and the leftover particles are the comets we see today. In contrast, asteroids represent the remnants of the formation of the inner planets, such as Mars, Venus, Earth, and Mercury.

Importance of NEOs

As these objects preserve the chemical structures from the early solar system, studying them can help us understand the composition of planets. If we want to determine the elemental makeup of the planets, we need to analyse the chemical composition of the dust in these leftover bodies, i.e., comets and asteroids. In recent years, the potential threat posed by asteroid collisions with Earth has become a serious topic of discussion among scientists. Smaller celestial bodies, such as NEOs, have become a focal point of research due to their significance in uncovering secrets about the formation, evolution, and composition of the solar system. NEOs are of particular concern because of their higher likelihood of colliding with Earth. Many of them could reach Earth more easily than other celestial objects, making them a significant threat [7].

Asteroid Impact Frequency and Risk

On average, a 10-kilometer asteroid strikes Earth every 26 to 30 million years, while Tunguska-level events (100-meter asteroids) occur every few hundred years. Each impact has the potential to drastically alter Earth's environment

t, prompting the scientific community to focus on NEOs as a significant threat to the planet's ecosystem [6].

Current Efforts in Asteroid Deflection

Numerous asteroid detection programs and space missions have been launched in the past decade, such as Deep Space 1, Deep Impact, Stardust, and ongoing missions like Rosetta, Hayabusa, and Dawn. Future missions like Don Quijote aim not only to study asteroids but also to test the ability to deflect them through rapid impact techniques. In terms of deflection strategies, several studies have utilized both analytical methods and numerical simulations based on n-body models to predict the effectiveness of these strategies. Researchers have conducted comparative evaluations of deceleration strategies, categorizing them based on asteroid-spacecraft pairings, technological innovation, and response time [2].

Analogous Vibrational System for Asteroid Reorientation

Introduction to Vibration Concepts

To establish a comprehensive analogy between space reorientation systems and mechanical vibrational systems, we begin by utilizing basic concepts of vibrations, assuming that the reader has a background in this area due to the engineering focus of this paper. More detailed explanations will be provided in subsequent sections. A common approach in scientific research is to create analogies with more tangible systems to better understand complex phenomena. Thus, this paper aims to establish an analogy between the reorientation behaviour of an asteroid, specifically Asteroid, and a vibrational system composed of a mass, spring, and damper.

Basic Vibrational Systems

Mechanical systems are often influenced by external forces, which may come in the form of initial displacements and velocities or external forces that act for a specific period. These forces can be harmonic, non-harmonic but periodic, non-periodic, or random. The vibrations caused by such external stimuli are known as forced vibrations, and the system's response is called a forced response. Even harmonic vibrations may arise due to the inherent properties of the system, in which case they are referred to as self-excited vibrations. Consider a single-degree-of-freedom damped system subjected to a harmonic external force. The equation of motion for such a system is as follows:

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{1}$$

Where:

m is the mass,

c is the damping coefficient,

k is the stiffness of the system,

x represents displacement.

This second-order linear non-homogeneous differential equation has a solution composed of a general solution and a particular solution, which is the response to the non-homogeneous term.

Key Parameters in Asteroid Reorientation

The key parameter in reorientation around an asteroid is analogous to the non-dimensional ratio seen in vibrational systems, represented as:

$$\mu = \frac{k}{m} \tag{2}$$

Three cases arise for the analysis of this key ratio:

1. When $k/m < 1$,
2. When $k/m = 1$,
3. When $k/m > 1$.

The ratio k/m, characterized by the dimensionality S^{-2}, serves as a fundamental descriptor of the system's dynamic behavior and can be effectively employed in the spatial reorientation of asteroids. This parameter correlates with the asteroid's angular velocity ω, quantified in radians per second, which is derivable from astrophysical datasets. Consequently, the critical parameters for analytical modeling are computationally determinable.

The stiffness coefficient k encapsulates the intrinsic elastic properties of the system, governed by the interplay of cosmic elastic forces and the asteroid's gravitational field. Considering the asteroid's substantially larger mass compared to the spacecraft, k inherently reflects the dynamic equilibrium established by these forces. Within this framework, the parameter k is rigorously defined by the gravitational-elastic interactions intrinsic to the cosmic environment, providing a robust basis for dynamic modeling and analysis.

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Vibrational Absorbers in Space Reorientation

To mitigate or eliminate oscillations during specific mission phases, a vibrational absorber can be employed, especially when the parameter k/m approaches unity, a scenario reminiscent of resonance in vibrational systems. This approach is particularly useful when dealing with rotational motions where oscillation amplitudes become significant.

Conclusion

This paper presents an analogy between the vibrational behaviour of an asteroid in space and a mechanical vibration system consisting of mass, spring, and damper. The primary objective of this analogy is to provide a clearer understanding of the dynamic behaviour of space asteroids, particularly in relation to asteroid redirection missions such as those involving Asteroid. By employing this analogy, the complex dynamics of asteroids can be modelled and analysed through well-established vibration systems in mechanical engineering. The analogy highlights the key parameters governing the asteroid's behaviour, which correspond to the spring constant, damping coefficient, and mass in a vibration system. This allows for a deeper exploration of the effects of gravitational and elastic forces within a space environment, especially when considering asteroid deflection missions. Through this approach, we are able to predict critical behaviours, such as resonance, which could impact the success of a mission. Finally, by incorporating additional systems like a secondary spacecraft, the model expands to a two-degree-of-freedom system, increasing the mission's reliability. This ensures that the mission's critical performance criteria, such as avoiding resonant conditions, are met. The analogy thus provides a robust framework for designing and evaluating asteroid deflection strategies with greater confidence.

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