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The Transport of Non-Spherical Particles In a Simulated Ocean Environment

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Abstract

Plastic particles contaminating the world's oceans and accumulating in oceanic gyres has become a ubiquitous problem and the solution involving how to clean up the debris efficiently has still not been found. One particular issue is understanding where the greatest densities of debris may be. It is known that floating trash will tend to accumulate in large circular systems of ocean water called gyres, however these areas span thousands of miles of ocean. The present study aims to understand the transport of anisotropic particles in conditions similar to an oceanic environment using experimental methods in an effort to better predict the regions of ocean in which the highest densities of plastic pollution reside, and to investigate the effect of particle size and shape on such motion.

1. Introduction

Many equations for the motion of a solid sphere in different situations have been validated through experimentation and theory, however these equations are usually only valid for one or a small class of unique situations. If a small sphere is neutrally buoyant and fully submersed in laminar flow of a single fluid, then one can use already existing equations and theories to understand its motion. If one looks at a situation that is much more complicated than the aforementioned situation, then the motion of the object may be almost entirely chaotic and impossible to predict.

An instance in which this problem is very prominent is that of the plastic pollution floating in the world's oceans. These plastic particles do not follow a linear path until they happen upon land once again; rather, they are influenced by two main factors: the surrounding wind and water. The strengths of these forces are dependent on multiple factors, such as the surface areas, volumes, and masses of the particles, as well as the directions and strengths of the wind and water currents. Adding in the fact that there are a multitude of additional factors influencing the directions and strengths of the wind and water currents leads to a problem that can really only be modeled through experimental data.

While there has been much research already performed on the individual relationships between these factors, very few researchers have investigated such dynamic relationships in a more holistic approach. The present study aims to understand the motion of anisotropic particles when partially submersed in water and subjected to gravity waves in the water as well as turbulent air flow.

2. Background Information

A particle semi-submersed in wavy water and subjected to turbulent airflow has many forces acting on it at any given time; some of which may not be estimated as constant with time. Each of these forces are influenced by a variety of factors relating to the particle, wave, and turbulent air characteristics. Besides the force of gravity, the major forces affecting the motion of the particle are the buoyant force, the drag forces from the wind and water, and the culmination of these forces that results in a mean Stokes drift velocity.

1.1 Buoyant Force and Floating Orientation

The buoyant force acts upon any object residing in any fluid. This force always acts upwards in a gravitational field and is equal to the weight of the fluid displaced by that object, as defined by Archimedes' Principle. A particle with positive buoyancy in a fluid will float to the fluid surface while a particle with negative buoyancy has a mass that is greater than the mass of the fluid it displaces while fully submersed in the fluid and will sink to the bottom.

The strength of the buoyant force relative to the particle's mass will affect the motion of the particle upon which it is acting through its determination of how much of the particle's volume and surface area will be submersed in the fluid. The density of an object does not affect the buoyant force applied to that object, so as the density increases, the object will sink further into the fluid as the weight of the object begins to outgrow the buoyancy. In the case of the present experiment, this means that less of the object's volume and surface area will be subjected to the drag force associated with the turbulent airflow above the water surface.

It is very simple to predict whether a particle will float in a given fluid, as long as the density of the fluid and mass and volume of the particle are known. Predicting the stable orientation of a floating body, however, is a much more complicated task. This orientation depends not only on the buoyant force, but also the three-dimensional shape of the body. Because there are infinitely many shapes, the determination of such an orientation for most floating bodies can only accurately be known through experimental techniques.

There are, however, a few principles that are omnipresent in these situations. As explained by Erdös et al., for any object in a stable floating equilibrium, the sum of the gravitational potential energies of the object and the displaced fluid must be at a minimum, if one assumes that the displaced fluid will be displaced to the surface layer (1992).

The second principle involves the analysis of the metacenter and metacentric height. For any equilibrium position (stable or unstable), the center of buoyancy, or the center of gravity of the displaced fluid, will be directly below the center of gravity of the object. If the object is rotated slightly, the center of gravity of the object will remain in the same position relative to the orientation of body, but the center of buoyancy will shift. The point of intersection of the vertical line that passes through the new center of buoyancy and the line that passes through the center of gravity and old center of buoyancy is termed the metacenter and the distance between the metacenter and the center of gravity is called the metacentric height, as shown in Figure 1. If the metacentric height is positive, and the metacenter lays above the center of gravity, the aforementioned equilibrium is considered stable, and the body will return to that position when released. If the metacentric height is negative, then the equilibrium was unstable and the body will not return to that orientation when released.

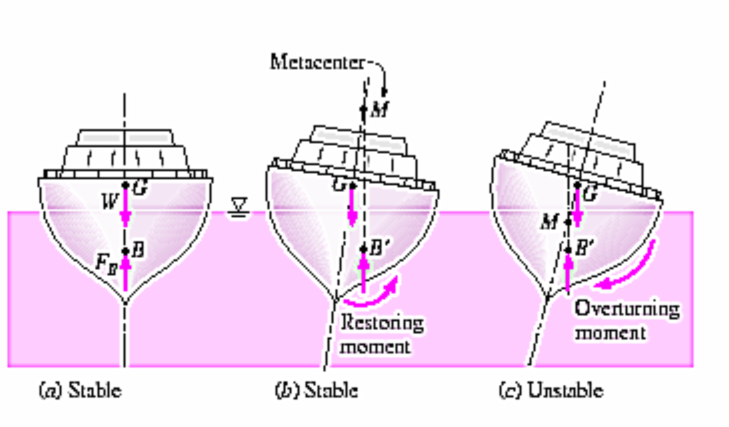

Figure 1: The position of the metacenter M depends on the positions of the center of gravity G, original center of buoyancy B, and new center of buoyancy B'. From "The Rotational Stability Criteria for Floating Bodies," 2015, https://propertiesoffluids.wordpress.com/2015/05/04/stability-of-immersed-and-floating-bodies/.

Using these two principles and a general knowledge of Archimedes' Principe, one can make generalized predictions about the stable and unstable floating equilibrium positions of most shapes of particles.

2.2 Drag Force

The drag phenomenon occurs when there is a velocity difference between a fluid and either an object or another fluid that is in direct contact with it. The friction produced by this velocity difference creates a shear force on the object or fluid surface. Additionally, a pressure difference will occur between the upstream and downstream segments of fluid in the case of a three-dimensional object being present, which will add to the magnitude of the drag force. This force will always act opposite to the motion of the object or second fluid in the inertial reference frame of the first fluid, and in the case of the object, will force the object to move in the direction of the fluid flow if no other forces are present.

There are two different applications of the drag force that are important to take into consideration when predicting the transport of particles in a simulated ocean environment: the drag force that is directly exerted upon a particle by the wind and water, and the drag force that is exerted by the wind onto the water, which affects the characteristics of the water waves.

The drag force exerted on an object is a complicated force that is dependent on a multitude of variables, but is most dependent on the particle Reynolds number, or Re_p. This dimensionless number describes the flow of fluid around a particle. A particle with a higher Re_p is more likely to produce a turbulent fluid flow around it compared to that with a lower Re_p. The particle Reynolds number is proportional to the particle's diameter and the fluid's density and relative velocity, and is inversely proportional to the fluid viscosity.

Other factors that affect the drag force on an object is the orientation of the object and its degree of deviation from a perfect sphere. The drag force is fairly easy to predict when the object is a sphere, but for irregular and asymmetric shapes, oftentimes the drag force is predicted by assuming the object to be a sphere and then just experimentally determining the drag coefficient for performing subsequent drag calculations. The best way to determine a drag coefficient without experimentation, however, is still fairly disputed (Loth 2008).

The drag force exerted on the water by the airflow in the present experiment does not directly affect the motion of the floating particles, but this drag force often leads to an alteration in wave patterns, according to Miles' theory of wave generation (1957). Without any wind present, waves were still present in some of this project's experiments due to the wave generator used, but the wave heights of these waves are oftentimes increased when turbulent air flow is introduced due to the new drag force. This is an important factor to take into account when making predictions because the wave characteristics greatly influence the air-water boundary layer characteristics, such as the velocity field, which will subsequently affect the motion of the particles floating in that boundary layer.

2.3 Stokes Drift

When predicting the motion of a particle floating in surface gravity waves, the Stokes drift phenomenon must be taken into account. According to linear wave theory, small amplitude waves can be fairly accurately modeled using a sinusoidal function. This model shows how the crests and troughs of the waves seemingly move in the direction of wave propagation, but the individual fluid particles making up the waves only oscillate in the vertical direction; therefore, any tracer particle floating on the surface of these waves should also only oscillate vertically unless acted upon by another force.

This is not what is seen in the real world, however. For both inertial and inertialess particles subjected to this type of environment, a mean Stokes drift velocity in the horizontal direction of wave propagation is seen. This is due to the fact that the fluid particles actually trace out orbitals—counter clockwise for waves propagating to the left and clockwise for those to the right—that become distorted in wave amplitudes greater than what can be considered small perturbations of the surface. These distortions lead to open orbitals which in turn lead to the Stokes drift phenomenon. Such particle paths have been rigorously modeled using nonlinear equations in situations that involve classic Stokes waves and tracer or fluid particles (Constantin 2006).

Inertial particles also experience a mean Stokes drift velocity, but the modeling or predicting of such particles' motions is much more complicated. For particles of finite size and non-negligible inertia, the Stokes velocity depends on both the Stokes and Reynolds numbers of the given particle. The Stokes number, like the Reynolds number, is a dimensionless number, but the Stokes number describes how well a particle will act as a tracer of the fluid flow around it. Whether an inertial particle will experience a greater or lesser mean Stokes drift velocity depends on the ratio of particle density to fluid density (Santamaria et al., 2013).

3. Methodology

A tank with approximate dimensions of 5 meters long, 1.2 meters wide, and 0.3 meters deep was placed inside the test section of a closed-circuit wind tunnel with inner test section dimensions of 5m x 1.2m x 0.8m. The wind tunnel was capable of varying wind speeds from 2 m/s to 20 m/s. The upstream entrance of the test section was comprised of small, rotatable, metal winglets.

A remote-controlled motorized flap acting as a wave generator spanning the inner width of the tank was installed inside the bottom of the tank on the upstream side. This wave generator was capable of producing variable wave frequencies in the same direction as the flow of turbulent produced by the wind tunnel.

The tank was then filled with 0.2 meters of water. The tank was equipped with a particle recycle system so that once a particle traveled to the downstream end of the tank, it would automatically be returned back to the upstream side of the tank.

A number of small particles were 3D printed using the Ultimaker 3 FDM 3D Printer and/or the Formlabs Form 2 SLA 3D Printer. The particles printed by the Ultimaker 3 were printed using polyactic acid (PLA) printer filament in a variety of colors. The default settings on

Cura were used to create the gcode files for the prints. These particles had an approximate maximum length of one inch. A certain number of prolate spheroids with polar radius to equatorial radius ratios of 2, cubes with lengths of one inch, cylinders with heights and diameters of 0.75 inches, and tetrahedrons with lengths of 0.75 inches were printed. These objects were sanded down by hand and then sealed using XTC-3D epoxy in order to waterproof the prints.

Inside the wind tunnel, two or three cameras were used to track the particles' translational and rotational motion in either two- or three-dimensional space. Using these video clips, data tracking software coded using OpenCV and Python was used to collect and store the path data of each of the particles over a certain amount of time. Background subtraction and color tracking techniques were implemented in the code, as well as the use of the Kalman Filter Prediction Step in order to distinguish individual particles from each other.

Multiple experiments were conducted in the wind tunnel with this setup. Initially, particle image velocimetry (PIV) was used to describe the motion of the wind at different speeds and at different heights above the water surface, with a focus on attempting to characterize the boundary layer between the fluids. Diethylhexyl sebacate particles were used to seed the tunnel for the various PIV tests. The motion of the particles was also observed without the addition of wind at all. The number of particles used in an experiment ranged from 5 to 30 particles in the tank at a single time. Some experiments involved the use of only one type of shape in the tank at a time while others involved a mixture of shapes. Additionally, the frequency of the wave generator will be varied as well.

The accumulated data were analyzed using R and/or MATLAB to investigate statistical significances with respect to changes in particle geometry and fluid properties. Correlations between particle paths and wave type/size, air flow, and particle shapes were all examined. If a strong correlation existed between variables, the corresponding data were plotted to produce an image depicting the particle motion trends.

4. Results (Predictions)

Because this project is centered around experiments that involve many moving parts, it is hard to develop any strong predictions about what relationships may be found between particle characteristics and fluid or air flow characteristics. At the moment, a thorough review of the literature relevant to this subject area has not yet been conducted due to the infancy of this project.

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