Extension of MINE6D to General Mine-Shaped Bodies

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LONG-TERM GOALS

The ultimate goal is to develop an effective physics-based simulation model that is capable of reliably predicting the motion of a three-dimensional mine-shaped object impacting water surface from air and subsequently dropping through water toward the sea bottom. This deterministic model provides the velocity and orientation of mines as the key input for bottom impact/burial prediction and is an essential building block in stochastic model development for mine impact/burial prediction.

OBJECTIVES

In our previous work, we developed a deterministic physics-based model, MINE6D, which is capable of predicting the motion of a cylindrical-shaped mine impacting the water surface and subsequently dropping through the water toward the sea bottom (Mann *et al* 2007). MINE6D accounts for six-degree-of-freedom motions of the body and employs physics-based modeling of key hydrodynamic effects such as viscous drag, air entrainment, and water surface impact. The main objective of this work is to extend the capabilities of MINE6D for cylindrical mines to general mine shapes. The focus of the study is on the developments in the following three key areas:

1. Expand the capabilities of MINE6D to general mine shapes and obtain the motion characteristics for different classes of mine shapes for which qualitatively different motion features (from those of cylindrical mines) might be expected.

2. Incorporate the new generation of bluff body drag treatment into MINE6D for general mine shapes and obtain deterministic and stochastic datasets as well as model coefficients to support expert systems for predicting the motions and bottom burial of different classes of mines.

3. Improve physical modeling in MINE6D in key areas that affect the reliability of motion predictions: viscous drag due to three-dimensional flow separation and vortex shedding, water surface impact, and air entrainment behind and/or around the body.

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APPROACH

MINE6D is a deterministic tool predicting the motion dynamics of a mine-shaped object impacting the water surface from air and subsequently dropping through the water toward the sea bottom. The general equation of motion governing the six-degree-of-freedom body dynamics is solved deterministically through a numerical procedure. The added mass effect associated with unsteady fluid-body interactions and the environmental forcing due to ambient waves/currents are evaluated exactly using a boundary-integral-equation method. The physics-based models are employed to account for the hydrodynamic effects due to other complex processes involved in the problem such as water surface impact, flow separation, vortex shedding, air cavity and entrainment.

Water surface impact: To account for the large range of physical/geometrical parameters, we develop a two-level approach utilizing theoretical and semi-analytic tools in the respective regimes in which they are valid and most efficient. Specifically, we develop: (i) an analytic model based on the theory of von Karman without the inclusion of spray effects for water impact of arbitrary three-dimensional bodies; and (ii) an effective semi-analytic model using the generalized Wagner's approach with the inclusion of spray effects for water entry of mine-shaped bodies at arbitrary entry velocity and angle.

Viscous drag: The viscous effect of a bluff body due to vortex shedding and flow separation is accounted for based on the use of empirical quasi-static drag coefficient. The exact distribution of the drag along the body depends on the Reynolds number, yaw angle, and aspect ratio of the body. The parameterization of the viscous drag model is obtained through sensitivity studies and comparisons to available experimental data.

Air entrainment: Proper modeling of the effect of air entrainment behind a dropping object is challenging. Two major physical processes are typically involved in the development and evolution of air cavity associated with a dropping body: air trapping during water entry of the body before cavity pinch off; and bubble oscillation and collapse after cavity closure. To properly model these processes, we carry out experimental, analytical, and numerical studies. Specifically, at the first stage, experimental tests and asymptotic/computational analyses are used to determine the basic time and length scales of air trapping. At the second stage, numerical computations are used to analyze the bubble formation and collapse and to parameterize the modeling of the induced drag effect on the motion of falling mines.

MINE6D is calibrated and validated by direct comparisons to the tank and field drop tests, which were conducted by the other research teams also funded by the ONR mine burial research program.

WORK COMPLETED

- **Understanding of stochastic characteristics of cylindrical mine motions:** Continued to apply MINE6D to conduct Monte-Carlo simulations to better understand statistical features and sensitivities of cylindrical mine motions in water for various releasing conditions, mine geometry/material properties, and environmental factors.

- **Extension to general mine-shaped bodies:** Generalized MINE6D to arbitrary mine-shaped bodies. The major extension is the generalization of computation of the added mass matrix and physics-based modeling of viscous drag, water impact, and air entrainment for arbitrary three-dimensional bodies.

- **Investigation of motion characteristics of manta-shaped mines:** Performed systematic MINE6D simulations for Manta-shaped mines and made comparisons to those of cylindrical mines for understanding the basic features of key characteristic motions of Manta-shaped mines dropping in water.

- **Understanding of water-entry cavity dynamics:** Theoretically and computationally investigated the formation and evolution of air cavity in water entry of three-dimensional bodies at relatively low/intermediate Froude numbers relevant to mine drops. We developed an asymptotic solution based on the slender-body theory for the description of key characteristics of air cavity before pinch off occurs. We performed fully-nonlinear computations to understand the physical effects neglected in the asymptotic theory such as body geometry and nonlinear boundary conditions on the free-surface and cavity. Both theoretical and computational solutions are compared to experimental data from laboratory dropping tests of disk and sphere (Yan *et al* 2007).

RESULTS

While we continued to validate MINE6D and characterize the motion dynamics of manta-shaped mines dropping in the water, we focused on the study of air cavity development and its effect on the motion of mines (which drop into the water from air). In particular, we developed an asymptotic theory based on the slender-body assumption for the prediction of the shape and size of air cavity in the water entry of a three-dimensional body (such as mine). To verify the effectiveness and identify the limitations of the theory, we also developed a computational method, based on a boundary-integral equation panel method, for fully-nonlinear simulation of cavity development and interaction with the dropping body. Both theoretical solution and fully-nonlinear computational result are validated by direct comparisons to available experimental data in the dropping tests of disk and sphere.

Figure 1 illustrates a sketch of cavity development in the water entry of a three-dimensional body. The main interests of the problem include the shape of the cavity, maximum height of the cavity (H_c) before pinch off, and the time (T_c) when pinch off occurs or the distance form pinch off point to the mean water surface (D_c). These quantities are critical in the determination of initial cavity size/shape attached on the body after pinch off.

In this study, both asymptotic theory and fully-nonlinear computation are developed in the context of potential flow; and the body and cavity are assumed to be axisymmetric about the vertical center axis. The evolution of the cavity and its interaction with the body are governed by the initial boundary-value problem for the velocity potential. On the free-surface and cavity wall, the nonlinear free-surface kinematic and dynamics boundary conditions are applied. On the body surface, the impermeable boundary condition is imposed. For the asymptotic theory, we applied a slender body assumption for the cavity, i.e. the width of the cavity is much smaller than the height of the cavity. The body is replaced by a point source located at its center. Consistent with this assumption, the nonlinear boundary conditions on the free surface and cavity wall are also linearized. With these assumptions, a closed-form asymptotic solution to the initial boundary-value problem can be derived. For the fully-nonlinear solution, the nonlinear initial boundary-value problem is solved directly in the time domain using the boundary integral equation method. The boundary conditions are satisfied at the exact instantaneous boundary positions during the time evolution of the problem.

Figure 2 shows a sample comparison between the theoretical prediction and the fully-nonlinear computation for the shape of air cavity at four different time (before pinch off occurs) in the water entry of a thin circular disk. The disk drops at a constant velocity with the Froude number Fr = V_0/(gD)1/2 =5.0, where g is the gravitational acceleration. The asymptotic theory compares well with the fully-nonlinear computation except in the region near the free surface where the slender-body assumption is invalid, as expected. Figure 3 shows the theoretical prediction and fully-nonlinear computational result of the cavity closure time T_c and cavity closure height Dc as a function of the Froude number in the water entry of a circular disk and a sphere. For the disk, the experimental data of Glasheen and McMahon (1996) for T_c is shown. The comparison indicates that asymptotic theory compares well with the fully-nonlinear computation, and both are in good agreement with the experimental data. For the sphere, the experimental data of Kominiarczuk (2007) for both T_c and D_c is shown. Note that in the experiment, the dropping velocity of the sphere varies due to the effect of drag while the constant dropping velocity is used in the theory and fully-nonlinear computation. The fully-nonlinear solution compares very well with the experimental data for D_c, but is a bit smaller for T_c than the experimental data. The asymptotic theory cannot account for the effect of body geometry. Thus it somewhat overestimates both T_c and D_c for the sphere.

IMPACT/APPLICATIONS

Proper modeling of the hydrodynamics of mines impacting the water surface and dropping through the water to the bottom is an essential building block in mine burial prediction. Our work provides a robust, reliable, and accurate model to predict the motion dynamics of cylindrical mines. Such accuracy and reliability cannot be achieved using the existing tools such as IMPACT 25/28.

TRANSITIONS

The present model developed in this study will be incorporated into a global prediction system of mine burial prediction. In particular, the hydrodynamic model will be used for the stochastic prediction of velocity and angle at ocean bottom, which is an essential input of soil-penetration prediction.

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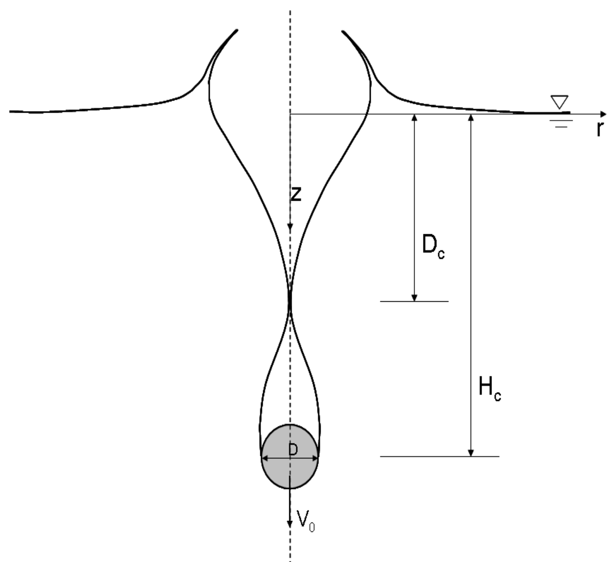

Figure 1. Definition sketch of air cavity developed in the water entry of a three-dimensional body. D and V_0 are the characteristic length and dropping velocity of the body, respectively; H_c is the maximum height of the cavity before pinch off occurs, and D_c is the distance from the pinch off point to the mean water surface.

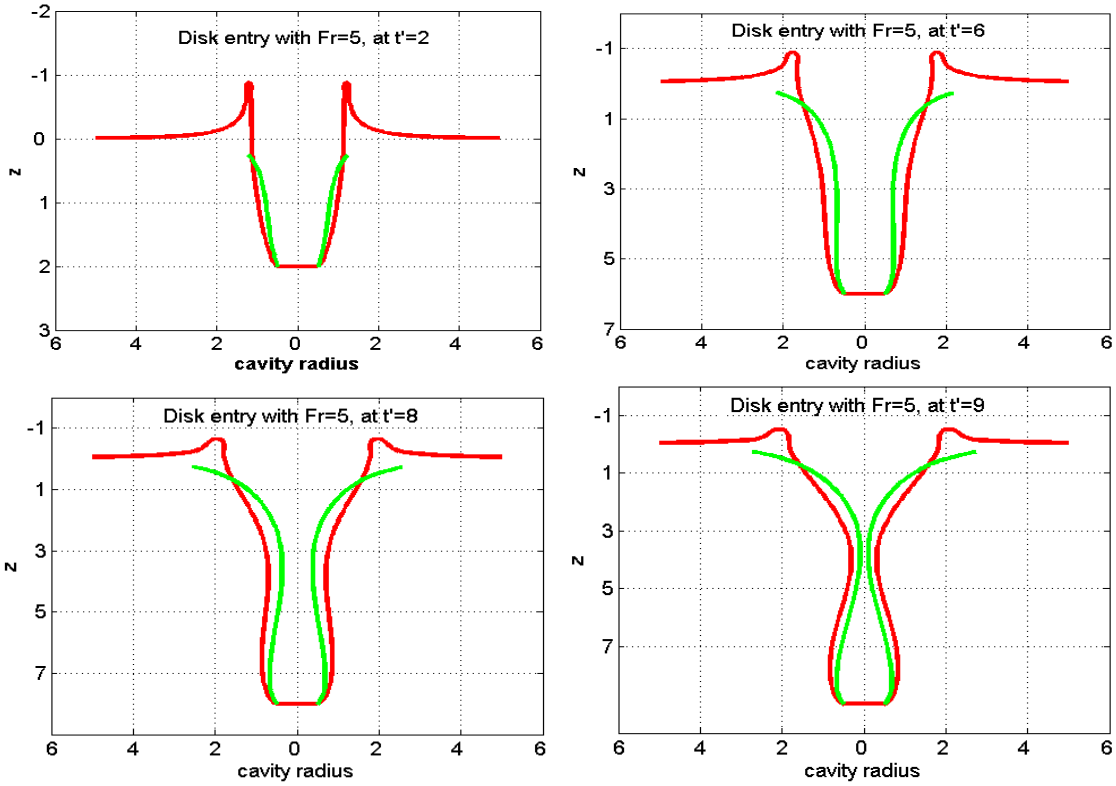

Figure 2. Comparison of the asymptotic theory prediction (——) and fully-nonlinear computation (——) for the shape of air cavity at four different time during the water entry of a circular disk. The disk drops at a constant velocity with Froude number Fr=5.

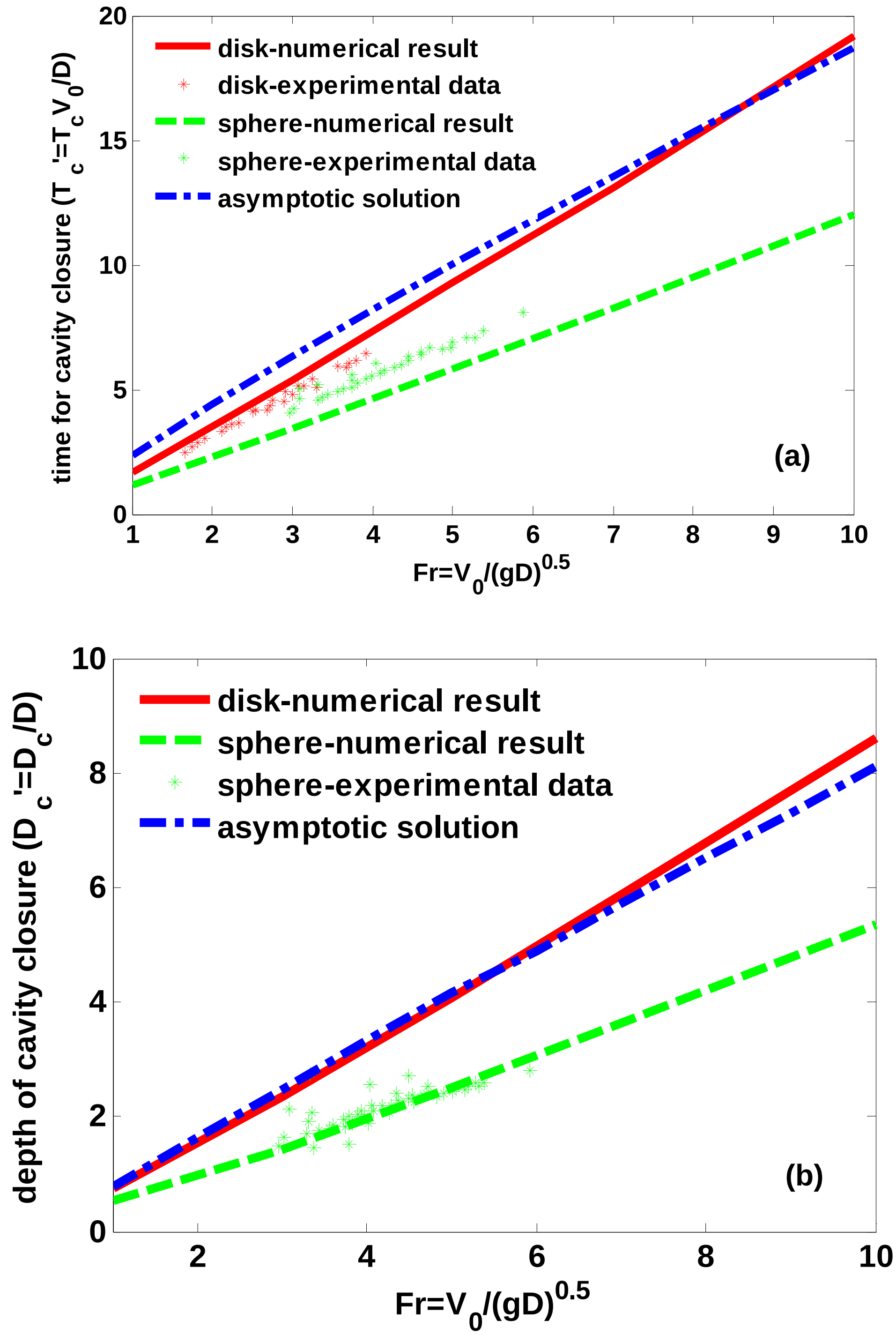

Figure 3. Normalized (a) time (T_cV_0/D) and (b) depth (D_c/D) for cavity closure as a function of Froude number Fr in the water entry of a circular disk and a sphere. The plotted are the asymptotic theory (– • – • –), fully-nonlinear computation for disk (——) and for sphere (– – –); and experimental data for disk (*) and for sphere (*).