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Numerical study on the trajectory of dropped cylindrical objects

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ABSTRACT

Dropped objects are among the top ten causes of fatalities and serious injuries in the oil and gas industry (DORIS, 2016). Objects may be dropped during lifting or any other offshore operation. Concerns for health, safety, and the environment (HSE) as well as possible damage to structures require the prediction of where and how a dropped object moves underwater. In this paper, the authors propose a new three-dimensional (3D) theory which considers the effect of axial rotation on dropped cylindrical objects. The 3D method is based on a modified slender body theory for maneuvering. A numerical tool called Dropped Objects Simulator (DROBS) has been developed based on this 3D theory. Firstly, simulated results of a dropped drilling pipe model using a 2D theory by Aanesland (1987) are compared with results from 3D theory when rolling frequency is zero. Good agreement is found. Further, factors that affect the trajectory, such as drop angle, normal drag coefficient, binormal drag coefficient and rolling frequency are systematically investigated. It is found that drop angle, normal drag coefficient and rolling frequency are the three most critical factors determining the trajectories. Finally, a low rolling frequency case is studied. Plots of landing points at the bottom of a 5 m deep water tank are obtained by investigating a series of simulations with different drop angles from 0° to 90° .

1. Introduction

Dropped objects are one of the principal causes of accidents in the oil and gas industry and increase the total risk level for offshore and onshore facilities (DORIS, 2016). ABS guidance (2010) proposes a general evaluation process for the assessment of damages due to dropped objects which may result from failed lifting operations from a supply boat or unsecured debris falling overboard during storms. However, this guidance does not address deep water structures (either fixed jackets or floating hull systems) and subsea equipment. The reason is that we lack specialized techniques to predict the trajectory of *dropped objects and the subsequent likelihood of striking additional structure and equipment* as well as predicting the consequences of such impacts (ABS, 2010). Therefore, the trajectory of objects falling into the water and their landing points are of interest for the protection of oil and gas production equipment resting on the seabed.

Aanesland (1987) experimentally and numerically investigated falling drilling pipes. Two model tests were presented. The first test was performed in order to investigate the entire history of events from a drop at the platform deck until the object lands on the seabed. The second drop test was intended to verify a computer program which was developed to calculate the motion, velocity, and acceleration of falling drilling pipes and to predict the impact load. A number of different trajectories were observed in the tests and are as illustrated in Fig. 1 (Aanesland, 1987). His program solves a set of two-dimensional (2D) maneuvering equations which describe the motions of drilling pipes, in which the trailing edge effect for a long slender body has been considered and further corrected for viscous effects (Newman, 1977).

Luo and Davis (1992) also simulated the 2D motion of falling objects by solving the differential equations of motion. Illustrative parametric studies are carried out in a computer program called DELTA. It was found that the horizontal excursion at the seabed level is greatly affected by the drop angle. In addition, the maximum horizontal velocity of the object is dependent on both the drop height and angle. Also, the tangential drag coefficient seemed to have little impact on the trajectory. Meanwhile, Colwill and Ahilan (1992) performed multiple numerical studies of trajectories of two dropped drill casings by using the same computer program, DELTA. These studies confirmed that drop height above waterline and the initial drop angle were key parameters influencing the horizontal velocity. Reliability-based impact analysis successfully established the relation between impact velocity and the probability of its exceedance.

Kim et al. (2002) focused on the study of characteristic motions of 3D bodies freely falling through water. The time-domain six degree-of-freedom motions of general 3D bodies dropping in water has been solved by a direct numerical scheme. In addition, the viscous effect on

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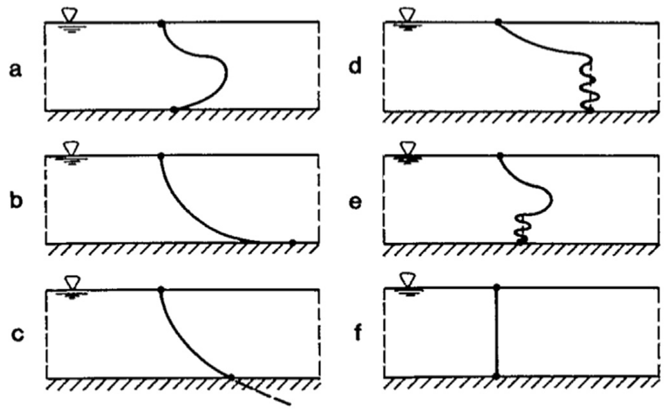

Fig. 1. Sketches of observed trajectories (Aanesland, 1987).

the cylindrical bodies have been considered by estimating the drag coefficients of the bodies for various body aspect ratios, end shapes, and orientations to incoming flow from laboratory experiments. A comparison between numerical results and experimental tests showed that the simulated motion pattern depends significantly on initial drop angle, body aspect ratio, and mass center.

Chu et al. (2005) and Chu and Fan (2006) developed a 3D motion program, IMPACT35, to simulate objects falling through a single fluid (e.g, air, water, or sediment) and through the interface of different fluids (air-water and water-sediment interface). In the equations of motion, apparent torque was ignored due to the use of a rotating coordinate system. Drag, lift force, and moments were linearized with temporally varying coefficients in time domain. Chu et al. (2005) reported the trajectories of falling cylinders from experiments with variation of mass center, initial velocity, and drop angle. IMPACT35 has been validated by comparing its results with the experimental data.

Yasseri (2014) experimentally investigated the fall of model-scale cylinders through water with low initial entry velocity and concluded that the landing location of free-falling cylinders is within 10% of the water depth with 50% of probability, within 20% of the water depth with 80% of probability, within 30% of the water depth with 90% of probability, within 40% of the water depth with 95% of probability, and within 50% of the water depth with 98% of probability.

Awotahegn (2015) performed a series of model tests to investigate the trajectory and seabed distribution of two drill pipes with diameter: 8″ and 12″ falling from defined heights above the water surface. He plotted and analyzed the maximum excursion points and the seabed landing points. After comparing them with the results from a simplified method by DNV (2010),Awotahegn (2015) concluded that the methodology recommended by DNV (2010) is generally conservative.

In this paper, the authors propose a new three-dimensional (3D) theory to consider the effect of axial rotation on dropped cylindrical objects by modifying the maneuvering equations for a slender rigid body. A numerical tool called Dropped Objects Simulator (DROBS) has been successfully developed based on this 3D theory. Simulated results of a dropped drilling pipe model using 2D theory by Aanesland (1987) are compared with 3D theory results when rolling frequency is zero. Simulated results agree well with data from model tests in Aanesland (1987). Then DROBS is used to investigate various factors that may affect the trajectories, including drop angle, normal drag coefficient, binormal drag coefficient, and rolling frequency. Finally, plots of landing points at 5-meter water depth are obtained from numerical simulations by tentatively changing the drop angle.

2. A two-dimensional (2D) theory for dropped cylindrical objects

Two coordinate systems are used in the two-dimensional (2D) theory as shown in Fig. 2. ***OXZ*** is the global coordinate system, where

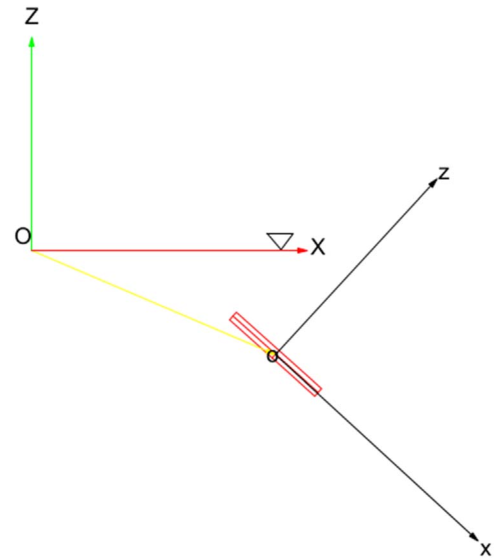

Fig. 2. Coordinate systems for equations of motion in two dimensions.

X-axis represents the still-water surface and Z-axis points vertical upwards. The other coordinate system is a local coordinate system - ***oxz*** which is fixed to the cylinder. Its x-axis is aligned with the cylinder's axis. Its origin ***o*** is assumed to be located at the center of gravity of the cylinder. Both coordinate systems ***OXZ*** and ***oxz*** coincide when the cylinder is horizontally situated on the water surface at the beginning of the drop.

In this paper, the cylinder is assumed to be rigid and slender. Its mass distribution is uniform. Therefore, its mass center and geometric center coincide. Aanesland (1987) simplified the problem into a 2D problem where only motions in the x-z plane are considered. The velocity components are U_1 (surge), U_3 (heave), and Ω_2 (pitch). The equations of motion are given in:

$$(m-\rho\nabla)g\sin(\beta) + F_{dx}=m\dot{U}_1 \tag{1}$$

$$-(m-\rho\nabla)g\cos(\beta)+F_{dz}=\{U_1 m_t U_3-U_1(x_t m_t)\Omega_2+m_{33}\dot{U}_3\} + m(\dot{U}_3-U_1\Omega_2) \tag{2}$$

$$M_{dy}=\{-U_1(m_{33}+x_t m_t)U_3+U_1 x_t^2 m_t\Omega_2+m_{55}\dot{\Omega}_2\} + M_{55}\dot{\Omega}_2 \tag{3}$$

where the parameters are defined as follows:

β : the instantaneous rotational angle between x-axis and X-axis.
m: the mass of the cylinder
M_{55}: moment of inertia in pitch direction
m_{33}:added mass for heave motion from strip theory
m_{55}: added mass for pitch motion from strip theory
m_t: 2D added mass coefficient for heave direction at the trailing edge
x_t: longitudinal position of effective trailing edge
g: acceleration of gravity
ρ: the density of water
∇: the volume of the cylinder

It should be noted that the motions in the above equations are stated in the body-fixed coordinate system ***oxz***. Longitudinal position of effective trailing edge x_t is introduced because the ends of the cylinder are not pointed. Slender body theory assumes smoothly varying geometries but the abrupt ending of the cylinder does not satisfy this condition. An additional force component is included to consider this trailing edge effect for a long slender body as shown in curly brackets on the right side of Eqs. (2) and (3) (Newman, 1977). The other terms on the right hand side represent the inertial forces and moments.

In addition, viscous forces and moment, F_{dx}, F_{dz}, and M_{dy} are evaluated with