



Rigid dynamic performance simulation of an offshore pipeline plough



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ABSTRACT

Offshore pipeline ploughs are used for laying pipelines in seabed trenches; these devices primarily consist of a plough body and skid and steering systems. Research on the virtual dynamic analysis of this system is essential for predicting the dynamic performance of the plough during trenching and steering. In this work, a 3-D rigid body dynamic simulation model is developed to investigate the performance of the simulated plough under different operating conditions. To verify this simulation model, an onshore field trenching study with a prototype plough was carried out. In terms of the tow force, the simulation results of the plough performance agree with the onshore field results and laboratory data within a certain range of simulation tolerance. We also present the effects of sandwaves and steering adjustment on the plough tow force. In addition, this paper addresses the development process and the dynamic results of the simulation model with a flexible towline.

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1. Introduction

Offshore pipelines on the seabed laid by a vessel are prone to damage by unexpected artificial and natural disturbances caused by fishing nets, anchors, wave oscillations, and other seabed features and seism. Hence, pipelines are normally buried in trenches using offshore trenchers to prolong their service life and increase the pipeline stability in the sea environment.

Mechanical trenching equipment has been developed based on different pipeline installations and backfill methods in a variety of sea areas and conditions. Consequently, three types of mechanical trenchers are classified according to their mode of trenching as ploughing mode, jetter mode, or cutting mode. Each type of trencher offers mechanical advantages for laying different dimensions of pipelines, optical and electrical cables, and umbilical cables. The jetter and dredge were the original offshore trenching methods, as used in the European coastal oil and gas area in the 1940–1960 periods (Wilson and William, 2008). During the development of the North Sea Oilfield, jetter and cutting trenchers were first used in pipe-laying and trenching projects at the end of the 1960s. By the late 1970s, plough and advanced cutters were used in deep and rough sea conditions in the North Sea Oilfield. Plough-trenching technology subsequently began to develop in a rapid and practical manner. Recently, SMD Ltd. (2013) designed a series of trenchers known as the Advanced Pipeline Plough and Variable

Multi-Pass Pipeline Plough. The Advanced Pipeline Plough has been used in many projects in Europe since 1990 and first successfully trenched and laid pipelines with maximum diameters of 1200 mm under the supervision of CTC Marine Project Ltd. and COOEC in the China South Sea in 2009, a project that gathered a variety of working data for research (Deng et al., 2010). However, comparisons of these three types of trenchers indicate that the plough can be widely used across a large range of soils from high-shear-strength clays to sands and at high velocities ranging from 20 to 800 m/h in deep ocean areas (Trevor Jee Associates, 2004). The other notable merits of plough trenchers include simpler structural design, greater operational reliability, and lower initial investment costs.

The plough tow force calculation is important for specifying the required structural design and strength of the plough. Three calculation methods exist for calculating the plough tow force. The first method is the use of classical soil mechanics theory. For example, Coyne and Lewis (1999) introduced a methodology for calculating the plough tow force for a finite-width blade that considered passive earth pressure with pore water effects. The second calculation model applied soil mechanics theory calibrated with laboratory data. For instance, Cathie and Wintgens (2001) developed a calculation model that predicts the tow force using the in-situ soil coefficients based on the trenching depth which are determined by the assessment of standard offshore site investigation techniques, as calculated from Grinsted and Reece's (1985) theoretical model and laboratory data. By adopting this model, Lauder et al. (2008, 2012a, 2012b) and Lauder (2010) carried out a series of tow tests using 1/50-, 1/25-, and 1/10-scale plough models. The tests were performed in a soil container in which the tow force was measured across a number

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of different types of soils. A model of the tow force was developed with these laboratory data based on three calibration factors and the velocity. However, the values of these factors for each soil type in practice are required to be specified or suggested from multiple sets of tests or in-situ field tests. Third, little research has been conducted to calculate the plough tow force using the finite element and other numerical methods, while more projects have checked the structural strength. Using the plane-strain theory, Peng and Bransby (2011) investigated a simplified 2-D finite element model of a share and soil. White and Cathie (2010) carried out 3-D finite element method (FEM) analysis of a share to simulate the dynamic plough shearing resistance using a Mohr–Coulomb (M–C) model with the addition of a cap yield surface which provides an inelastic hardening mechanism and control volume dilatancy when the material yields in shear. And Wang et al. (2013) simulated a share shearing a linear Drucker–Prager soil model using smoothed particle hydrodynamics in ABAQUS. In these studies, the numerical calculation of shearing resistance was considered; however, because of the lack of a complete plough model, the forces of certain components of the plough were not considered. In this respect, the forces of other plough components (such as the forces in the skid arm) are also important in the calculations because they affect the value of the tow force as well as the plough's structural strength design. Using the laboratory models (Lauder et al., 2008; Hatherley et al., 2008), the effects of plough tow force and plough stability on loose and dense sand under complex sand wave conditions were comprehensively observed. Bransby et al. (2010b) explored the plough kinematics (including the share, beam, and skid) in regions with a non-uniform seabed, and Lauder et al. (2012a, 2012b) analysed the forecutter installation impact on the plough tow force. However, these researchers did not establish a valid rigid-body dynamic simulation model of the plough to analyse the dynamic performance under different types of soil conditions in a time and cost saving way.

This paper aims to develop and experimentally validate a 3-D rigid body dynamic simulation model of the offshore pipeline plough. It is developed to simulate a trenching process in the surface soil layer at a depth of 0.8 m in an onshore field study. This model is further verified using laboratory data from a plough in a flat bed and in sandwaves beds based on the work of Lauder et al. (2008). This paper also investigates the extent of variation of tow force and joint force in the skid arm arising from the rigid-body simulation model, the dynamic performance of the steering system and how a flexible towline affects the tow force of offshore pipeline ploughs. This simulation model could further serve as a reference for project designs in different working conditions.

2. Rigid-body kinematic equations of the plough

The offshore pipeline plough consists of six components, as shown in Fig. 1. To analyse the rigid-body performance of the key components of the plough, i.e., the force in the skid arm, the steering force, and the tow force, it is important to establish a virtual simulation model. This virtual simulation model can improve engineering efficiency and reduce product development costs by analysing the dynamic performance of the plough under different soil conditions. In this paper, MSC.ADAMS (ADAMS) is applied to calculate the rigid-body kinematic and dynamic performance, with a "friendly" interface of 3D modelling (e.g., SOLIDWORKS) and data post-processing capabilities (e.g., MATLAB). MSC. ADAMS is well known as the multibody dynamics software to assist engineers to understand and evaluate the complex interactions in the true system performance between disciplines including motion, structures, actuation, and controls to better optimise product designs for safety and comfort (MSC Software, 2014). This

section presents and analyses the kinematic equations used in ADAMS for the skid, steering system, and plough.

2.1. Brief introduction of plough modelling

In this research, the plough modelling method is adapted from the design concepts of agricultural ploughs. The plough is divided into two parts: share and mouldboard. The Cartesian coordinate system as shown in Fig. 2 is defined such that the ploughing direction is taken as the x -axis, the y -axis is vertical to the x -axis in the Oxy plane which is parallel to the ground horizontal plane. And the perpendicular to the Oxy plane which is along the soil rising direction as the z -axis. The share surface is a space plane formed by the plough share penetration angle a , surface angles b , c , with the trenching depth H and the initial mouldboard side angle α_0 . The mouldboard is approximated by a series of planes formed by functional lines and curves. A number of horizontal contour lines in horizontal planes are built through the derived curve in varied mouldboard side angles with a certain trend so that the mouldboard is formed along the derived curve gradually. The mouldboard side angle is a function of the height of mouldboard. The derived curve controls the position of the horizontal contour line which is parabolic to model a semi-spiral surface. The main design parameters of the derived curve include the mouldboard lift angle ε , the angular variation of the tangent line $\Delta\varepsilon$, spanning length of the derived curve l , and the height of soil lifted for inversion h_m specified by the design requirements. The mouldboard equation is given by (Gong et al., 2012). The shearing resistance on the share and mouldboard can be obtained using the mathematical equations of the plough shown in Section 2.4.

2.2. Kinematic equations of the skid

The skid is designed such that it adjusts the trenching depth and pitch in response to the soil topography via the action of two hydraulic cylinders in two degrees of freedom. The adjustable-depth hydraulic cylinder acts to modify the skid angle, and therefore the height of the skids relative to the plough body. The results in the plough share reach a steady ploughing depth due to the setting of the skid height. Fig. 3 presents the forces on the adjustable-depth hydraulic cylinder, and the axial thrust is given as follows:

$$F_h = (F_y l_a [\sin(\beta_0 + \theta_0) - \mu_s \cos(\beta_0 + \theta_0)] - G l_{cm} \sin(\alpha_{cm0} + \theta_0)) \times \left(l_c \sin \left(\arctan \left(\sin(\gamma_0 - \theta_0) (l_c l_d^{-1} - \cos(\gamma_0 - \theta_0))^{-1} \right) \right) \right)^{-1} \quad (1)$$

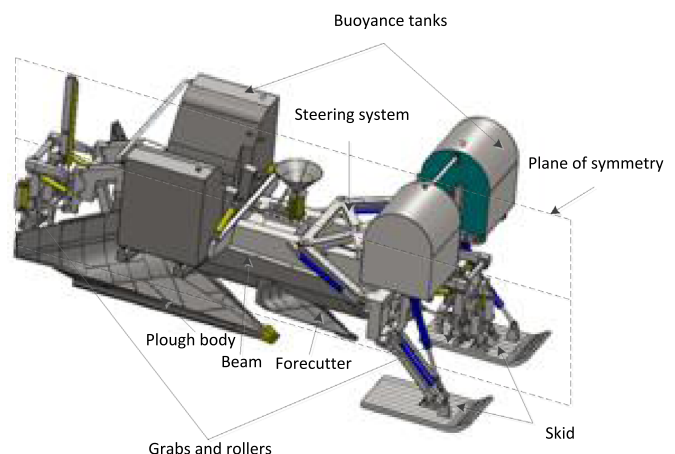


Fig. 1. 3-D overview of the offshore pipeline plough.

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