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Research on the automatically trajectory control of a spherical isolation plug in subsea pipeline

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A B S T R A C T

The rapid growth demanding for oil and gas resources has gradually driven the fossil energy exploitation from the land to the ocean. Technology shifts from manually operated oil fields to the remotely operated oil fields is necessary, and robotic assistance to human cognition is essential. Hot tapping and line stop techniques, as a great method for the replacement of the risky pipelines without disrupting the service to customers, demands for the automation to improve the efficiency and reliability. In this paper, automatically trajectory control of a spherical isolation plug in subsea pipeline was investigated. Mathematical model for the spherical plug head insertion was presented, and two control algorithms for the automatically insertion of the plug were proposed, named the rotation angle based control algorithm and the vertical displacement based control algorithm. Simulation was conducted and the results indicate that the vertical displacement based control algorithm owes better performance than the rotation angle based control algorithm. The accuracy and efficiency of the vertical displacement based control algorithm was then experimentally researched. The results in this paper can provide references for the automatically trajectory control of an isolation plug, as well as improve the accuracy and reliability of offshore hot tapping.

1. Introduction

The rapid growth demanding for oil and gas resources has gradually driven the fossil energy exploitation from the land to the ocean. With several decades, the exploration and production of offshore oil and gas resources have become important means of meeting global energy need (Bai and Bai, 2012; Lindøe et al., 2013; Shukla and Karki, 2016a, 2016b). As the great performance of onshore pipeline, offshore pipeline is also considered to be the safest and most economical way to transport oil and gas to terminals (Canavese et al., 2015; Nazari et al., 2015; Ramella et al., 2015; Zhu et al., 2015a, 2015b). However, due to the complicated environmental condition, subsea pipeline has encountered serious challenges, such as corrosion, buckling or pipeline damage due to external loads (Zeng et al., 2014; Nazari et al., 2015; Seo et al., 2015; Tian et al., 2015). In order to guarantee the safety of the subsea production system, emerging repair needs to be conducted for the replacement of the risky pipeline before the serious accidents occurred. Besides the emergency repair, routing maintenances like bypassing the pipeline product, tie-ins and facilitating chemical injection are frequently demanded in ocean engineering (Lim, 2012).

The oil and gas industry has used hot tapping and line stop techniques to provide localized isolation of a "live" section of pipe for many years (Bowie, 2015). This technology can ensure that the pipeline remains in service during operation, avoiding the disruption of the service to customers. Spherical isolation plug, an innovative structure proposed by Angus George Bowie (Bowie, 2015), is an important device for achieving localized isolation of the pipeline. Self-pressure test can be fulfilled between two compressed rubbers on the plug head when in operation and the sealing pressure is much higher than the traditional plug (double block and bleed plug or line stop tool). (Yeazel et al., 2012). The reliability of the sealing ability has been greatly improved due to the self-pressure test.

As offshore oil and gas operations take place in a much more difficult natural environment than onshore operations (Managi et al., 2006; Lim, 2014). Technology shifts from manually operated oil fields of the shallow-waters to the remotely operated deep-water oil fields is necessary, and robotic assistance to human cognition is extremely essential. As a result, in this paper, automatically trajectory control of a spherical isolation plug in oil and gas pipeline was investigated.

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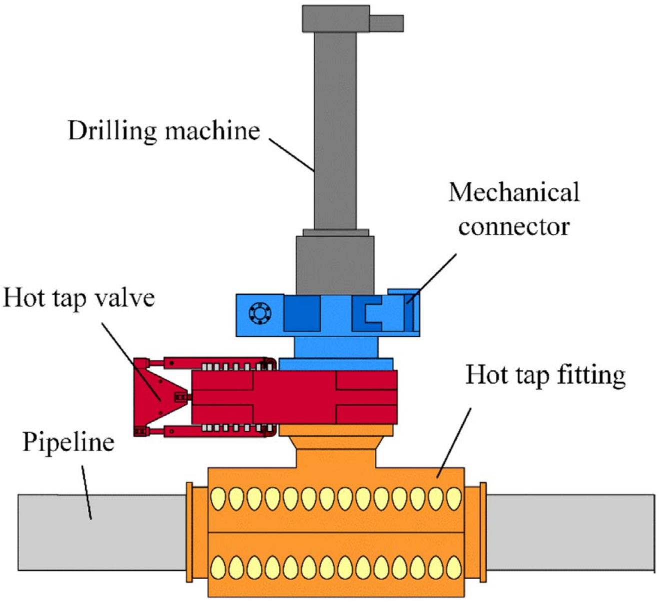

Fig. 1. Schematic diagram of hot tap and pipeline isolation procedure.

2. Mathematical modeling

2.1. Structure of the isolation plug

Hot tapping involves the fitting of a branch or tee connection to a live pipeline containing fluid at pressure. Installable tap or welded tap can be mechanically secured or welded to the pipe, and a valve being subsequently fitted to the connection, as shown in Fig. 1. A tapping or drilling machine being activated can pass through the open valve and drill through the pipe wall to create the branch (Lindholm et al., 2013). Once the branch is accomplished, an isolation plug can be connected and inserted into the pipeline for isolation. This is a single stop application. With the use of two plugging machines, a double stop with bypass can be achieved to isolate a section of pipeline while keeping both upstream and downstream of repairs in service. On completion of the isolation process, the fluid between these two plugging machines can be drained out and the defective pipeline can be replaced.

The primary structure of the spherical isolation plug is shown in Fig. 2. It consists of the hydraulic cylinder 1, hydraulic cylinder 2, support beam and spherical plug head. Hydraulic cylinder 1 and hydraulic cylinder 2 are responsible for the control of the rotational displacement and vertical displacement of the spherical plug head

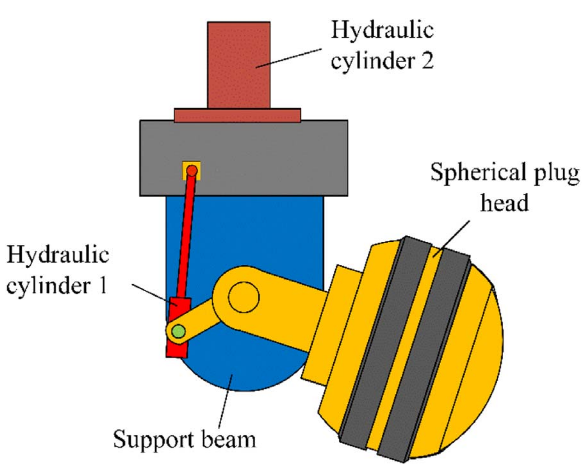

Fig. 2. Structure of the isolation plug.

respectively. A safe access into the pipeline of the spherical plug head without any collision with the pipeline inner wall can be achieved, according to the corporation of these two hydraulic cylinders.

2.2. Trajectory of the spherical isolation plug

The typical trajectory of the spherical plug head during operation is shown in Fig. 3. When on the initial state, the axis of the spherical plug head is perpendicular to that of the pipeline. After the completion of insertion, the axes will be parallel to each other, and can even be coincide at ideal condition.

In order to guarantee the sealing ability, the diameter of these two soft rubber (usually made of polyurethane) should be large enough, so that the rubbers can contact the pipeline as soon as possible, which means a small compression can reach a large contact pressure between the rubbers and the pipeline. As a result, the steel structures of the spherical plug head besides the rubbers have to be large enough as well for the anti-extrusion of the rubbers. Since the diameter of the plug head is close to that of the pipeline, collision between the plug head the pipeline will be a potential hazard, and any potential problems may lead to an unpredictable damage to the whole operation, especially under the sea. As a result, a control algorithm with high efficiency and reliability for the displacement coordination of two hydraulic cylinders is urgently needed, and can greatly increase the reliability of the pipeline maintenance.

2.3. Geometry modeling

According to the structure of the isolation plug described above, the geometry model can be proposed and shown in Fig. 4. Points O, O_1, O_2, A and B are all hinge points. The initial distance between point O and A is L_2, and AB = L_0, BO_1 = L_1, OB = L_3. The initial angle between AB and OB is β, which can be expressed in Eq. (1).

$$\beta = arccos\frac{L_0^2 + L_3^2 - L_2^2}{2 \times L_0 \times L_3} \tag{1}$$

It can be obviously found that the optimal control algorithm for the insertion of the spherical plug head is to keep its center point B staying on the axis of the horizontal pipeline during operation. Simultaneous movement of hydraulic cylinder 1 and 2 is not preferred at this stage, as the unavoidable overshoots exist due to the unstable flowrate in hydraulic system. Consequently, alternating movement of these two hydraulic cylinders is recommended, which means the vertical displacement and rotatable displacement are controlled alternatively. In order to achieve the automatically control of the spherical isolation plug, two kinds of control algorithms were presented and compared with each other to investigate the performance of the spherical plug head insertion.

2.3.1. Rotation angle based control algorithm

In this control algorithm, a constant rotation angle of the spherical plug head was achieved for each step, according the displacement control of hydraulic cylinder 1 (S1). After each rotation, the center of the spherical plug head will be above on the axis line of the horizontal pipeline, as shown in Fig. 5. A corresponding vertical displacement of hydraulic cylinder 2 (S2) was then given in the next step, to ensure the center of the spherical plug head can return to the axis line of the horizontal pipeline. Two steps comprised a cycle. After undergo dozens of cycles, 90° rotation angle will be finally achieved.

Since the rotation angle is constant (θ), the displacement of the hydraulic cylinder 1 varies at each step for achieving the constant rotation angle. If the rotated angle of the spherical plug head is θ, the center of the spherical plug head will move to point O'_1 from O_1, as shown in Fig. 5. The corresponding displacement of the hydraulic cylinder 1 (S_1) for achieving θ rotation can be described in Eq. (2).