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Comparison of linear and nonlinear simulations of bidirectional pig contact forces in gas pipelines

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ABSTRACT

To predict the motion of a pig to estimate its velocity, position and required driving pressure is essential before pigging. The frictional force between a pig and the pipeline is a key determinant of the prediction accuracy, and a precise evaluation of the frictional force between the pig and the pipeline can enhance the prediction of pig motion. The contact between the pig and the pipeline is a soft interference of rubber and steel, and good performance of nonlinear simulation for evaluating the frictional force has been verified. However, due to some mathematical or technical limitations, the linear elastic behaviour of rubber has sometimes been used to simplify the prediction, greatly affecting the prediction accuracy. To determine the difference between these two cases in this paper, comparisons of linear and nonlinear simulation for predicting the bidirectional pig contact forces are presented. The effects of the elastic module (E), interference (δ), thickness (ξ), and clamping rate (ζ) of the sealing disc on the performance of the linear and nonlinear models at different differential pressures are discussed. The results indicate that the contact forces obtained from the linear simulation model are greatly underestimated. The linear simulation model is incapable of predicting the contact force or the frictional force between the pig and the pipeline because the elastic behaviour of the sealing disc is described in the linear approximation. Consequently, the assumption in the pigging simulation that the sealing discs/cups attached on the pig exhibit a linear elastic behaviour lead to improper predictions regarding the pigging time, velocity, driving pressure, and so on. However, the pigging risks and uncertainties can be greatly reduced based on the nonlinear prediction rather than the linear simulation due to the inaccurate simulation results. This study clearly presents the differences between the linear and nonlinear simulations based on the complex behaviour of pig motion in oil and gas pipelines.

1. Introduction

For decades, the oil and gas industry has used pipelines as the most economic and efficient way to deliver oil and gas to terminals. However, the long usage times have raised great concerns regarding the safety conditions of aging pipelines. Periodically, the pigging of these pipelines for dewatering, cleaning and inspecting is necessary and is recognized as the most cost-effective method to enhance pipeline safety and integrity while the pipelines are in service (Hosseinallpour et al., 2007; Lesani et al., 2012; Niechele et al., 2000; Solghar and Davoudian, 2013; Tolmasquim and Nieckele, 2008; Zhu et al., 2014).

The pig used for pigging is usually driven by the fluid flow in the pipeline, as shown in Fig. 1. The soft sealing discs or cups (often made of polyurethane) attached to the pig help to seal the pipeline. Thus, the differential pressure over the pig builds up and overcomes the frictional force. The pig is subsequently propelled in the pipeline. The complicated motion of a pig and the unknown internal conditions of the pipeline risk the immobilization of the pig or lead to the possibility that is might crash into various pipeline accessories. As a result, the motion prediction of a pig to estimate its velocity, position and required driving pressure is particularly important before pigging. An accurate pigging prediction can also help to identify the potential risks during pigging and establish coping strategies to prevent risks.

When a pig is running in a pipeline, there is a force balance

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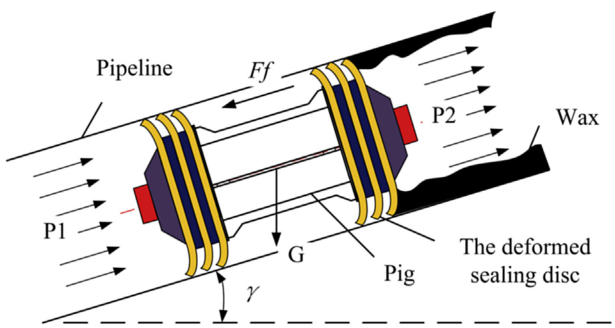

Fig. 1. Bi-directional pig running in a pipeline (Zhu et al., 2015).

acting on the pig, which can be expressed by the following equation:

$$m\frac{dV_{pig}}{dt} = \Delta PA \pm mg\sin\gamma - F_f \tag{1}$$

where, V_{pig} is the velocity of the pig, m is the mass of the pig, ΔP is the differential pressure over the pig, A is the cross sectional area of the differential pressure acting on the pig, and γ is the angle of the centre axis of the pig with the horizontal axis. F_f is the pig resistance in the pipeline.

In Eq. (1), the resistance of the pig (F_f) consists of the frictional force and the wax removal force, which are shown in Eq. (2).

$$F_f = f_\mu + f_w + f_v \tag{2}$$

where, f_μ is the total frictional force of a pig, f_w is the wax removal force, and f_v is the viscous force of the fluid.

The resistance of the pig plays an important role in predicting the dynamic motion of the pig. The prediction result cannot be accurate without a complete understanding of the resistance characteristics. Many investigations have been performed regarding the wax removal mechanism for predicting the wax resistance and viscous force (Bai and Zhang, 2013; Mendes et al., 1999; Southgate, 2004; Sullivan, 1981; Tan et al., 2014; Wang et al., 2005, 2008). However, very few papers have addressed the frictional force between the pig and the pipeline. Due to the absence of research, most of the available knowledge is based on field experience. Estimating the frictional force often involves some guesswork and, consequently, a high degree of uncertainty (Aevedo et al., 1996; Esmaeilzadeh et al., 2006, 2009; Nieckele et al., 2001).

In a previous study, Nguyen (Nguyen et al., 2001a, 2001b, 2001c, 2001d) assumed the frictional force of a pig as a constant value, including the static and dynamic frictional forces. Tolmasquim and Nieckele (Tolmasquim and Nieckele, 2008) divided the contact force of a pig into the static force, when the pig was not in motion, and the dynamic force, when it was moving. The dynamic force was assumed to be a constant value. However, a detailed calculation model was not given. Esmaeilzadeh (Esmaeilzadeh et al., 2006) obtained the frictional force of a foam pig by using a shrink fit correlation, which is not suitable for the pig with sealing discs or cups. Dai and Tao (Dai and Tao, 2008) assumed that the cup deformation was entirely radially compressed during pigging, and the bending effect was not considered. Liu (Liu, 2010) proposed a model based on the assumption that the edge of the cup was deformed, such as in a cantilever beam, and the theory for the bending of a cantilever beam was used to estimate the contact force between the cup and the pipeline. de Souzad (de Souza et al., 2013) developed a computational numerical model using the finite element method; the contact force acting on the pig (with cups) was analysed according to a quadratic programming algorithm. O'Donoghue (O'Donoghue, 1996) was the first researcher who presented a steady state motion model to predict the motion of a bi-directional pig (with sealing discs) in oil and gas pipelines. The mathematical model for predicting the frictional force exerted by oversized sealing discs on the pipeline was proposed. The characteristics such as the differential pressure, leakage, and wear rate were all considered in this model, which is more comprehensive and sound than before. Zhu (Zhu et al., 2015) proposed an experimentally verified 2D axisymmetric nonlinear model to predict the contact force experienced by a bi-directional pig using ANSYS. The impacts of four parameters (including interference, thickness, chamfer dimension and clamping rate of the sealing discs) on the contact force between the sealing discs and the pipeline at different differential pressures were investigated. Additionally, the impact of the four parameters on the deflection angle of the sealing disc was investigated.

Some of the proposed models summarized above assumed that the sealing disc/cup exhibits linear elastic behaviour (linear simulation for short); the others consider the nonlinear elastic behaviour (nonlinear simulation for short). To determine the difference between the two cases, a comparison of the linear and nonlinear simulations for the frictional force prediction of a pig is essential. The prediction is important, especially for a pig with bi-directional discs, because this type of pig is commonly used for pigging and inspection due to its efficient sealing and excellent pigging ability. Such research will be of great significance to understand the dynamic motion of a pig in oil and gas pipelines.

The total frictional force of a pig contains the frictional force induced by the pipeline geometry constraint, the frictional force induced by the weight of the pig and the frictional force induced by the differential pressure over the pig. The total frictional force caused by the gravity of the pig is zero, and the dynamic frictional force acting parallel to the pipeline wall plane is a function of the contact force in the radial direction. In this paper, a linear simulation on the contact forces (instead of on the frictional forces) induced by the pipeline geometry constraint and the differential pressure is conducted, corresponding to a previously conducted nonlinear simulation (Zhu et al., 2015). The comparison of the linear and nonlinear simulations for predicting the contact force of a bidirectional pig was investigated using ANSYS. This comparison helps to clearly present the differences between the two models and determines a better way to evaluate the frictional force with high accuracy.

2. Numerical simulation

In previous research (Zhu et al., 2015), a 2D axisymmetric model was proposed to predict the contact force experienced by a bi-directional pig using ANSYS (Fig. 2), and the nonlinear elastic behaviour was considered in the simulation. The model was experimentally verified to predict the contact force between the sealing discs and the pipeline. To compare the differences between the simulation results of the linear and nonlinear cases, the same geometrical model was used with the assumption that the sealing disc exhibited linear elastic behaviour. The detailed information of the nonlinear simulation work was presented and published previously, so only a brief introduction of the linear model is presented below. The setups for this simulation are mainly identical with the arrangements of the nonlinear simulation.

2.1. Assumptions

Different from the nonlinear simulation, the assumptions for the