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Response analysis of an aerial-crossing gas-transmission pipeline during pigging operations

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ABSTRACT

Pigging operations of natural gas transmission pipelines for cleaning, swabbing and batching inhibition become a regular industry procedure, and that could help to maintain the integrity and optimum efficiency of the pipeline and safeguard both the environment and the assets of the pipeline owner. However, unreasonable controls of pigging parameters including pressure, pig speed, period, etc. may induce harmful vibrations or even structural damage, especially for the aerial crossing segment. In this paper, a dynamic model capable of describing flow characteristics of accumulations driven by pigs and fluid-structure interactions involving fluid pressure, centrifugal force and Coriolis force is established to investigate dynamic behaviors of an aerial crossing pipe during pigging operations. The motion equation is solved using finite element method. Experimental results are used to validate the motion equation of pipes conveying two-phase flow. A lot of numerical simulations of dynamic responses under different boundary conditions and operating parameters are performed, and some interesting and sometimes unexpected results are shown. Finally, the effects of boundary conditions and operating parameters on dynamic characteristics are discussed. This study is helpful for controlling harmful vibration responses of natural gas pipeline under pigging operations and promoting the safety of pigging procedures.

1. Introduction

Natural gas transmission pipelines are vital energy artery for industrial development and the people's livelihood. In order to maintain the product quality and the integrity and optimum efficiency of the transportation system and safeguard both the environment and the assets of the pipeline owner, pigging operations are regularly implemented for long-distance gas pipeline to clean any deposits inside, such as condensate, water, rust or other solid particles that are often produced with the natural gas [1].

The high pressure gas from upstream drives pigs to push deposits accumulating to form a liquid/solid plug during pigging operations. The deposits flowing through the pipeline can be considered as a two-phase flow phenomenon [2]. If the operating conditions involving plug length which is related to yields of deposits and pigging periods, fluid density depending on deposit species, pig speed and operating pressure are not controlled reasonably, the pigging operations would cause the risk of piping instability even damage [3], especially for the aerial crossing pipelines which are constructed when the pipeline route spans rivers, roads, railways and other obstacles.

The instability phenomenon of pipes conveying fluid have received considerable attention and hundreds of relative studies are reported over the past 40 years, and the instability behaviors of pipes subjected to single-phase flows is now reasonably well understood. However, the dynamic behaviors of pipes conveying two-phase flow are difficult to predict due to complex characteristics of gas-liquid two-phase flow [4,5] and fluid-structure interactions [6–8]. A number of studies were performed to investigate the vibrations of tube bundles in two-phase cross-flow [9–13], and these work were largely related to nuclear steam generators. Some studies on the vibration behavior of flexible cylinders subjected to external axial two-phase flow were undertaken from 1970s for the development of nuclear fuels for boiling water reactors (BWR) [14–16]. Particularly, a few theoretical models were developed to investigate internal multi-phase flow induced vibration problems. However, these models were established under certain conditions and ignored some important factors (operating pressure, transitional velocity,

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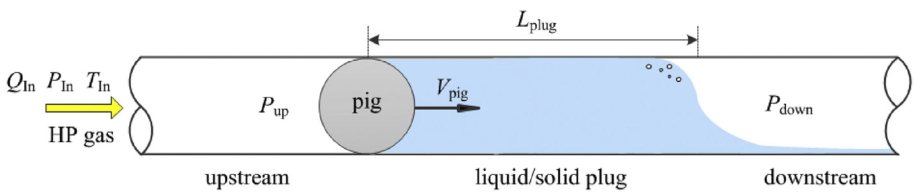

Fig. 1. Pigging process in modeling.

etc.), thus not available for analyzing the dynamic characteristics of aerial-crossing pipeline under pigging operations [17–23]. Meanwhile, a better understanding of dynamic behaviors of aerial-crossing pipelines under pigging operations is generally required for pipe structural stability and operation safety.

In this work, a dynamic model capable of describing dynamics behaviors of an aerial crossing gas pipeline under pigging operations is established, which includes a dynamic model for the fluid conveying pipes and pigging model for flow characteristics during pigging operations. The dynamic model is adopted for the aerial crossing pipe subjected to accumulation plug, and the finite element method is employed to solve the corresponding dynamic equations. The experiment of dynamic response of a horizontal pipe subjected to slug flow is performed to validate the dynamic model and solution methods in this paper. And then the effects of operating conditions of pigging procedures on dynamic characteristics are evaluated and analyzed.

2. Modeling approach

2.1. Motion equation of pipes conveying two-phase flow

Considering that the different phases have different densities and flow velocities, each of the phases is considered to create its own Coriolis and centrifugal forces. In addition, the fluid pressure $P(x,t)$, axial tension of pipe $T_N(x,t)$, mass-per-unit-length of gas and dense phase $M_G(x,t)$ and $M_D(x,t)$, gas and dense phase velocities $V_G(x,t)$ and $V_D(x,t)$, lateral displacement $u(x,t)$ are varying with time and position (t is time and x is the coordinate along the centerline of the pipe). The motion equation [24] for a pipe conveying two-phase flow is expressed as follows:

$$\begin{aligned}EI\frac{\partial^4 u}{\partial x^4}&+\frac{\partial}{\partial x}\left[(P(x,t)A_F-T_N(x,t))\frac{\partial u}{\partial x}\right]\\&+[M_G(x,t)V_G^2(x,t)+M_D(x,t)V_D^2(x,t)]\frac{\partial^2 u}{\partial x^2}\\&+2[M_G(x,t)V_G(x,t)+M_D(x,t)V_D(x,t)]\frac{\partial^2 u}{\partial x\partial t}\\&+[M_G(x,t)+M_D(x,t)+m]\frac{\partial^2 u}{\partial t^2}+C_s\frac{\partial u}{\partial t}\\&+[M_G(x,t)+M_D(x,t)+m]g=0\end{aligned}\tag{1}$$

The terms of Eq. (1) represents respectively: flexural force, effect of pressure and axial force, centrifugal force, Coriolis force, inertia force, structural damping force and gravity. The effect of pressure and axial force, centrifugal force and Coriolis force are fluid-structure interactions, which affect the dynamic characteristics of the FSI system. Finite element method is used to solve the motion equations, and the dynamic equation for each element is expressed in matrix form as,

$$\mathbf{M_e}\ddot{\mathbf{U}}_\mathbf{e}+\mathbf{C_e}\dot{\mathbf{U}}_\mathbf{e}+\mathbf{K_e}\mathbf{U_e}=\mathbf{P_e}\tag{2}$$

where $\mathbf{M_e}$, $\mathbf{C_e}$ and $\mathbf{K_e}$ denote mass, damping and stiffness matrices, and $\mathbf{P_e}$ is the element nodal force vector, and can be calculated by,

$$\mathbf{M_e}=\int_0^{L_e}\mathbf{N}^T[M_G^e(x,t)+M_D^e(x,t)+m]\mathbf{N}dx\tag{3}$$

$$\begin{aligned}\mathbf{C_e}=&\int_0^{L_e}\mathbf{N^T}C_S^e\mathbf{N}d\mathbf{x}+2\int_0^{L_e}\mathbf{N}'^T[M_G^e(x,t)V_G^e(x,t)\\&+M_D^e(x,t)V_D^e(x,t)\Big]\mathbf{N}dx\end{aligned}\tag{4}$$

$$\begin{aligned}\mathbf{K_e}=&\int_0^{L_e}\mathbf{B^T}EI\mathbf{B}d\mathbf{x}+\int_0^{L_e}\boldsymbol{B}^\mathbf{T}[P(x,t)A_F-T_{\boldsymbol{N}}(x,t)]\boldsymbol{N}dx\\&+\int_0^{L_e}\mathbf{N}'^\mathbf{T}\left[M_G^e(x,t)V_G^{e^2}(x,t)+M_D^e(x,t)V_D^{e^2}(x,t)\right]\mathbf{N}'dx\end{aligned}\tag{5}$$

$$\mathbf{P_e}=\int_0^{L_e}[M_G^e(x,t)+M_D^e(x,t)+m]\mathbf{N^T}dx\tag{6}$$

where $\mathbf{N}$ and $\mathbf{B}$ denote shape function and strain matrices. M_G^e, V_G^e, M_D^e and V_D^e are functions in the local coordinate for mass-per-unit-length and flow velocities of gas and liquid.

2.2. Pigging model

For describing major characteristics of pigging phenomenon as shown in Fig. 1, plug zone driven by a pig is considered as a moving control volume, and its volume and velocity are almost constant in special pipe section. Ignoring the quality of the pig, the force balance on the plug formed of liquid/solid accumulations can be expressed as

$$m_{plug}\frac{dV_{pig}}{dt}=\pi\left(\frac{d}{2}\right)^2\Delta P-m_{plug}g\sin\theta-F_d\tag{7}$$

where F_d is drag force of the plug, g is gravitational acceleration, $\Delta P=P_{up}-P_{down}$ is differential pressure between upstream and downstream of the plug, P_{up} and P_{down} are the pressure of upstream and downstream.

The mass of the accumulation plug m_{plug} is

$$m_{plug}=\pi\left(\frac{d}{2}\right)^2\rho_{plug}L_{plug}\tag{8}$$

where d is inner diameter of the pipe, ρ_{plug} is the density of the accumulation plug. L_{plug} is the plug length.

The pig speed V_{pig} is equal to the fluid velocity in the plug [25], and can be expressed as

$$V_{pig}=\frac{4P_0\overline{T}\overline{Z}Q_{In}}{\pi d^2T_0Z_0\overline{P}}\tag{9}$$

where $P_0=101.325$ kPa, $T_0=293.15$ K and $Z_0=1$. $\overline{Z}$ is the average compressibility factor of upstream gas.

The average pressure $\overline{P}$ and the average temperature $\overline{T}$ can be expressed as [25].

$$\overline{P}=\frac{2}{3}\left(P_{In}+\frac{P_{up}^2}{P_{In}+P_{up}}\right)\tag{10}$$

$$\overline{T}=T_e+(T_{In}-T_e)\frac{1-e^{-aL}}{aL}\tag{11}$$

$$a=\frac{k\pi D}{m_gC_p}\tag{12}$$