THE SPILLING EFFECTS OF AN OCEAN MINING PIPE APPLIED WITH COMPRESSIBLE FLUID INSIDE

Wei Zhang
China Ship Development and Design Center, Hubei Wuhan 430064, China
email: zhangweimas2014@outlook.com

Ye Li
State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

A major concern about the harsh marine environment is that it may undermine overwhelmingly the ocean mining pipe and cause serious vibration. These external factors may lead to serious oil spills and destroy the home to diverse fish, seabird, and marine mammal populations. Given this, the current study aims to study how the oscillating phenomenon affect the leaking pipe by numerical method with simulating the marine environment and pipe. It is found that the pipe vibrates seriously and hence the occurrence of the leaking accident is accelerated if the internal velocity is large or the leak is at the top of the pipe.

Keywords: Fluid-Structure Interaction, Compressible fluid, Spilling effect, Pipe oscillation, Fluid induced vibration, Ocean disaster

1. Introduction

Ocean mining pipe is drawing the attention of researchers in the field of ocean engineering since petroleum is rich in the ocean. The attention of many scholars in particular with regard to crucial phenomena of the oscillating pipe such as buckling and flutter, motivated by the work of Bourrieres [1]. For instance, Paidoussis focused on the developing the theory of pipe vibration and the unsolved issues related were pointed out [2, 3]. Paidoussis [2], Thurman & Mote [4] and Holmes [5], derived the nonlinear equations of a simply supported pipe conveying a fluid. By using these equations, Nikolic & Rajkovic adopted an analytical approach to describe the properties of bifurcation [6]. Modarres-Sadeghi & Paidoussis employed a numerical approach to investigate the occurrence of secondary instability [7]. Further studies on the dynamic performance of non-uniform pipes [8], pipe geometric deficiencies [9], pipe with unsteady flow inside [10], and 3D modelling of simply supported pipe [11] have also been conducted.

This paper is structured as follows: the pipe spilling model is set up in section 2. In section 3, the cases are calculated by using the spilling model and pipe oscillation model. In section 4, the results of a numerical cases are discussed.

2. Mathematical model

2.1 Pipe spilling model

For pipe drilling compressible fluid like gas hydrate, the spilling model is different from that for incompressible fluid. Especially for natural gas, the critical temperature (-82.3°C) is lower than the
temperature of deep seawater (around 4°C). Based on the previous studies, 1-D Euler equation is presented as Eq.(1) [12].

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho U}{\partial x} = -\zeta_e \\
\frac{\partial \rho U}{\partial t} + \frac{\partial \rho U^2}{\partial x} + \frac{\partial p}{\partial x} = -U \zeta_e \\
\frac{\partial E}{\partial t} + \frac{\partial (E + p)U}{\partial x} = -(E_e + p_e) \frac{1}{\rho_e} \zeta_e
\]

(1)

### 2.2 Pipe Motion Model

Since length of the ocean mining pipe is much larger than diameter, the pipe can be regarded as a beam and the Euler-Bernoulli beam theory can be applicable. In the current study, a 2-D simply supported pipe is selected to test the oscillation performance of a leaking pipe (shown as Figure 1). shown in the previous study in [2], the governing equation can be presented as Eq.(2).

\[
\left( E \frac{\partial}{\partial t} + E \right) \frac{\partial^4 w}{\partial x^4} + \left[ MU^2 - \bar{T} + \bar{p}A(1 - 2v) - (M + m)g(L - x) \right] \frac{\partial^2 w}{\partial x^2} \\
+ 2MU \frac{\partial^2 w}{\partial x \partial t} + (M + m)g \frac{\partial w}{\partial x} + \frac{1}{2} \rho_e C_d A_c \left( V - \frac{\partial w}{\partial t} \right) \left| V - \frac{\partial w}{\partial t} \right| \\
+(M + m + M_a) \frac{\partial^2 w}{\partial t^2} + W = 0
\]

(2)

where \( x, t \) and \( w \) represent the axial coordinate, time and lateral displacement, respectively; \( M \) is the mass of internal fluid per unit length; \( m \) is the mass of the pipe per unit length; \( E \) is the elastic module; \( I \) is the moment of inertia; \( L \) is the pipe length; \( U \) is the internal flow velocity; \( A \) is the section area; \( \bar{T} \) is the mean axial force; \( \bar{p} \) is the pressurization; \( v \) is the poison ratio; \( W \) is spilling term; \( \rho_e \) is the density of external fluid; \( C_d \) is coefficient of drag force; \( M_a \) is the added mass; \( A_c \) is the characteristic areas; \( V \) is the current velocity.

The spilling flow from the pipe changes the conservative system to the non-conservative system. The spilling term \( W \) in Eq.(2) can be presented as Eq. (3)

\[
W = \sum_{i=1}^{N} \{M_{is} U_{is} \dot{w} + M_{is} U_{is}^2 w'\} \delta (x - x_i)
\]

(3)

where \( N \) is total number of leakages; The index of \( i \) means the \( i \)th leakage; \( M_i \) and \( U_i \) are mass and velocity of the spill, respectively.

Since the internal pressurization \( p \) is the constant additional tensile force, \( p \) can be assumed reasonably as 0. To unify the expression, the dimensionless form can be presented by using the parameters in Eq.(4).
For the leaking pipe, the dimensionless equation is

\[ \alpha \eta''' + \eta'' + \left\{ u^2 - \Gamma - \gamma (1 - \xi) - \frac{1}{2} \mathcal{A} \int_0^1 (\eta')^2 d\xi \right\} \eta'' - \alpha \mathcal{A} \int_0^1 (\eta' \eta')' d\xi \eta'' + 2 \beta^{1/2} u \eta' + \gamma \eta' + \sigma (v - \eta) |v - \eta| + (1 + \beta_a) \ddot{\eta} + W^* = 0 \]

where the dimensionless spilling term \( W^* \) represent as

\[ W^* = \sum_{i=1}^N \{ \beta_i^* u_i^* \eta + \beta_i^* u_i^* \eta' \} \delta (\xi - \xi_i) \]

The dimensionless parameters of Eq.(20) can be expressed as

\[ \alpha = \sqrt{\frac{L}{E(M + m) L^2}} \quad u = \left( \frac{M}{EI} \right)^{1/2} U L \quad \gamma = \frac{M + m}{EI} L^3 g \quad \mathcal{A} = \frac{AL^2}{L} \]

\[ \beta = \frac{M}{M + m} \quad \Gamma = \frac{T L^2}{EI} \quad \sigma = \frac{\rho_c C_d A_c L}{2(M + m)} \quad \beta_a = \frac{M_a}{M + m} \]

\[ \beta_i^* = \frac{M_{is}}{M + m} \quad u_i^* = \sqrt{\frac{M + m}{EI}} U_{is} L \quad v = \frac{V}{L} (\frac{EI}{M + m})^{1/2} \]

The boundary condition is

\[ \eta(x) = \eta''(x) = 0 \quad \text{when} \quad x = 0, L \]
Figure 2 Oscillation for the leaking pipe when spilling site $\xi_c = 0.1$ and dimensionless internal velocity $u = 9$ using the compressible fluid model. a) time trace of the $\eta$ when $\xi = 0.5$ (continuous line), $\xi = 0.2$ (dotted line) and $\xi = 0.8$ (chain line) from the inlet of the pipe; b) the shape of the oscillating pipe; c) normal stress (continuous line) and shear stress (dotted line) at the top of the pipe; d) normal stress (continuous line) and shear stress (dotted line) along the pipe when $\tau = 0.5$.

Figure 3 Oscillation for the leaking pipe when spilling site $\xi_c = 0.5$ and dimensionless internal velocity $u = 9$ using the compressible fluid model. a) time trace of the $\eta$ when $\xi = 0.5$ (continuous line), $\xi = 0.2$ (dotted line) and $\xi = 0.8$ (chain line) from the inlet of the pipe; b) the shape of the oscillating pipe; c) normal stress (continuous line) and shear stress (dotted line) at the top of the pipe; d) normal stress (continuous line) and shear stress (dotted line) along the pipe when $\tau = 0.5$.

Figure 4 Oscillation for the leaking pipe when spilling site $\xi_c = 0.5$ and dimensionless internal velocity $u = 12$ using the compressible fluid model. a) time trace of the $\eta$ when $\xi = 0.5$ (continuous line), $\xi = 0.2$ (dotted line) and $\xi = 0.8$ (chain line) from the inlet of the pipe; b) the shape of the oscillating pipe; c) normal stress (continuous line) and shear stress (dotted line) at the top of the pipe; d) normal stress (continuous line) and shear stress (dotted line) along the pipe when $\tau = 0.5$.

4. Discussions

Comparing the results, several phenomena are concluded as follows: (1) It is easy to see that the deflection of the pipe will increase as the internal velocity grows; (2) In the transition analysis of the leaking pipe, the deflection and the stress vibrate disorder at the beginning of leak, which means that
the pipe is extremely dangerous at the beginning stage; (3) The pipe will seriously oscillate back and forth when the time is large enough; (4) In frequency analysis, the frequencies of displacement and stress increase with the enlarging internal velocity. This result suggests the pipe designer to avoid the above frequency so as to reduce the severity of further damage during a pipe leakage.

REFERENCES