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Letter

Preliminary results of the spilling effects on the oscillation of a pipe with compressible fluid inside

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HIGHLIGHTS

- The spilling effect on the vibration of the pipe with fluid inside is considered.
- The oscillation model of leaking pipe with compressible fluid inside is set up.
- The leakage is simplified as nozzle.

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ABSTRACT

It is known to all, the spilling of pipeline may cause serious problems, especially when the pipe conveying petroleum, natural gas or other toxic substance. There are countless accidents during past century. Once the spilling occurs, the vibration of the pipe would aggravate spill situation and even result in crack of the pipe. The consequence will be more severe when the fluid inside is compressible. To prevent the detriment of the spilling model is developed by assuming the leakages as orifices or nozzles and a 2-D vertical simply supported pipe is selected to analyze the phenomena of the oscillation. Combining these two models, the oscillation model for the pipe with leakage is set up and the spilling effect is analyzed by numerical method. The amplitude of the pipe oscillation and the normal stress enlarge as the internal velocity increased, while the shear stress changes very little.

The oscillation of the pipe caused by the internal flow is well studied and discussed, because pipe is the representative fluid–structure interaction model and widely applied in industry. Some representative dynamic phenomena of this problem, like the buckling of a supported pipe and flutter of a cantilever, are discussed by many scholars, for example the work of Païdoussis et al. [1,2]. Nikolić and Rajković [3], Karagiozis et al. [4], Modarres-Sadeghi and Païdoussis [5] respectively studied this problem by analytical method, experiments and numerical simulation. All these researchers focus on the oscillation of intact pipe, while the phenomena of the pipe with leakage is seldom researched. However, the leaks may occur during the operation of the pipes, especially for the pipeline used in the ocean resources exploitation, the cold water pipe for the ocean thermal energy conversion device, pipeline network for natural gas or fresh water supply, horse in air refueling and tube containing the nuclear reactor fuel elements. Specific ocean mining industry, the ultra-deep and ultra-long structures, usually the pipes or risers, are required to drill up or transport the oil or gas. Since these structures operate in the deep sea (usually more than 3000 m depth), the environment like complex currents and the internal waves may cause the damage of the structure [6]. These damages on the riser or pipe may finally result in the serious oil spill. The accidental oil spills occurred frequently in these years, more than forty events of oil spill happened in the past five years. Among them the gulf of Mexico oil spill is representative, which last 87 days and discharge 4.9 million barrels. For the previous studies on the leaking problem, the pipe, like the pipeline conveying the fresh water or natural gas, is fixed and the oscillation phenomenon is neglected [7–9]. For the special case like the ultra-long riser in the ocean, large displacement exist which could not neglect the oscillation effect. So the oscillation effect also needs to be considered when the leaks occur.

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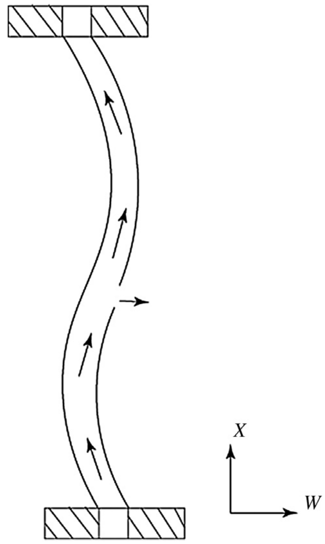

Fig. 1. The simple supported pipe with several leakage points.

This paper is structured as follows. Firstly, the pipe spilling model and a 2-D oscillation model of a simply supported pipe with leakages are set up for compressible fluid. Secondly, the cases are calculated by using the spilling model and pipe oscillation model. Thirdly, the results of compressible fluid model (ideal gas assumption) and non-ideal gas (van der Waals equation of state) are also presented. Finally, we discussed the numerical results and got several conclusions.

Since the spill site usually simplified as a capillary tube or nozzle, the choked flow model is applicable for the pipe spilling model [10,11]. Here the pipe spilling model is set up by assuming that the size of the leakage does not vary with time, which can be presented as Fig. 1. As previous studies, the 1-D Euler equation is applied for the compressible fluid flow and the spilling terms are simplified as the additional source terms, see Eq. (1) [9].

$$\begin{aligned}
&\frac{\partial \rho}{\partial t}+\frac{\partial \rho U}{\partial x}=-\zeta_e,\\
&\frac{\partial \rho U}{\partial t}+\frac{\partial \rho U^2}{\partial x}+\frac{\partial p}{\partial x}=-U\zeta_e,\\
&\frac{\partial E}{\partial t}+\frac{\partial (E+p)U}{\partial x}=-(E_e+p_e)\frac{1}{\rho_e}\zeta_e,
\end{aligned} \tag{1}$$

where ρ is the density of the internal fluid; t is time; x is the axial coordinate; E is total specific energy; E_e is the external specific energy; p_e is external pressure; ρ_e is the density of the external fluid; ζ_e is the source term caused by spilling. The source term ζ_e can be

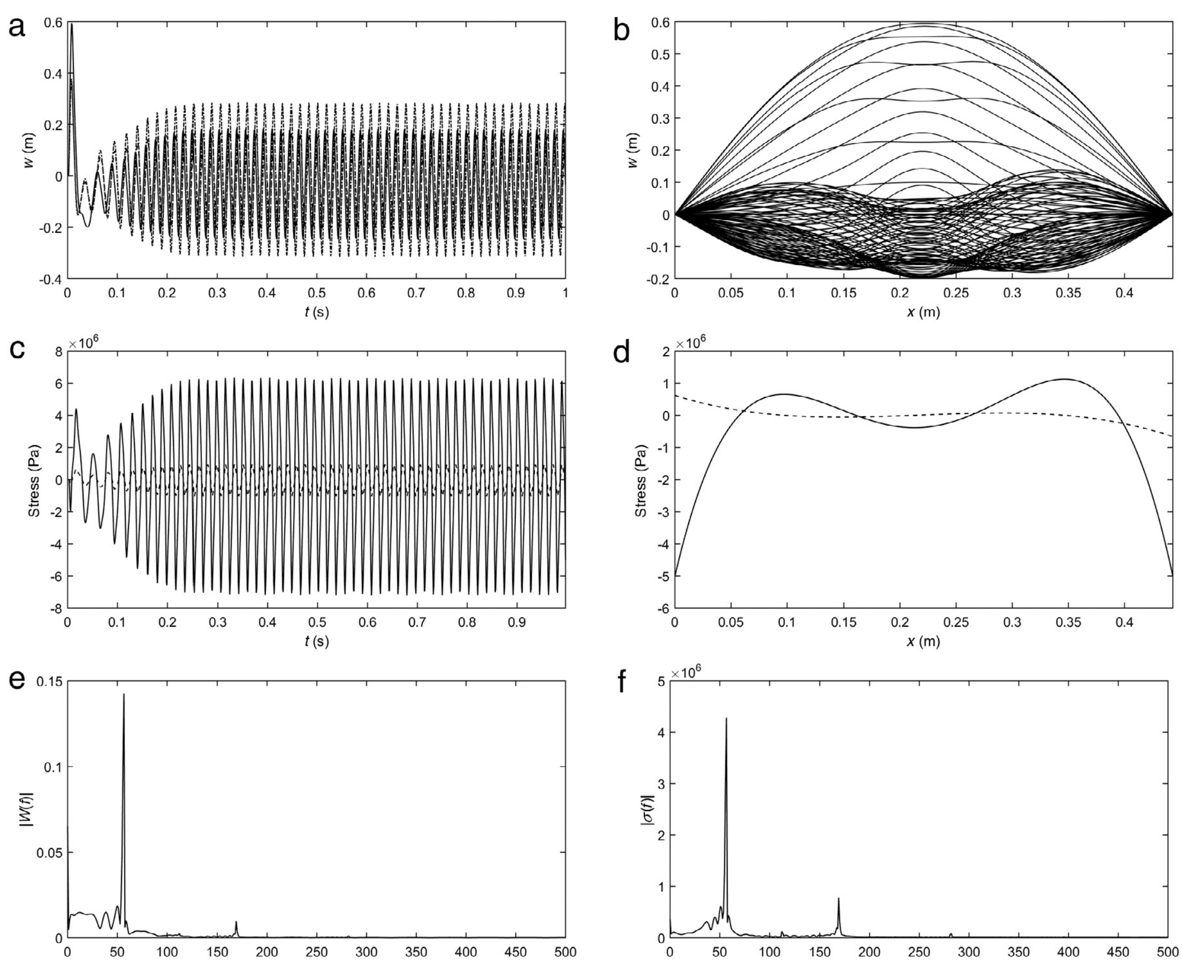

Fig. 2. Oscillation for the leaking pipe when leakage at middle of the pipe and dimensionless internal velocity $u = 9$ using the compressible fluid model. (a) Time trace of the w at 1/2 (continuous line), 1/5 (dotted line), and 4/5 (chain line) from the inlet of the pipe; (b) the shape of the oscillating 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 $t = 0.5$ s; (e) the fast Fourier transformation of displacement at middle position $f = 56.64$ Hz; (f) the fast Fourier transformation of normal stress at top position $f = 56.64$ Hz.