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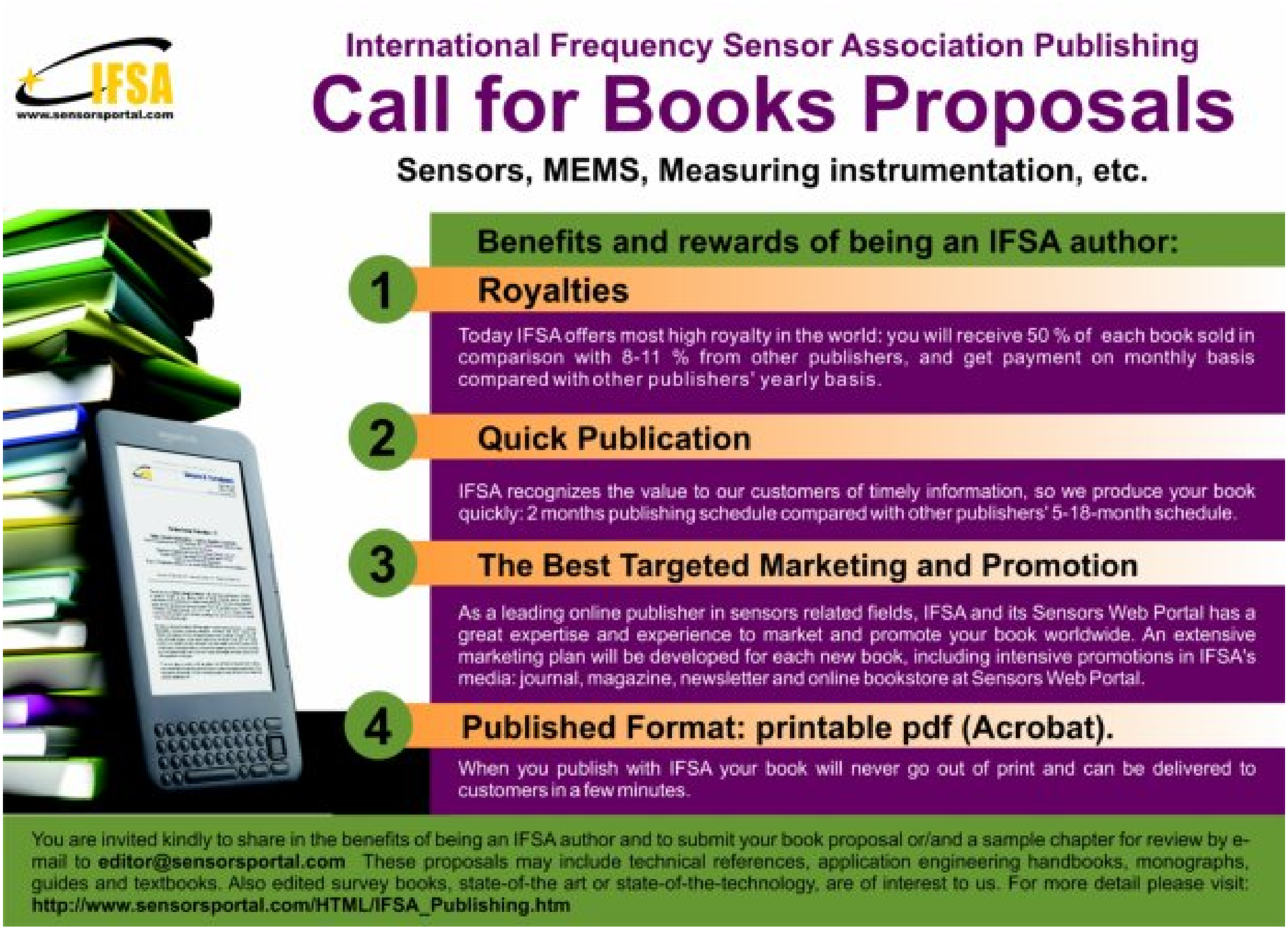


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Vibration Model of Pipe Conveying Fluid Considered Fluid Structure Interaction

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Abstract: Pipe was very extensive used in the modern industrial field and playing an extremely important role. Distribution of energy and mechanism of vibration course are reflected accurately by research on pipe vibration considering fluid structure interaction, which was accord with the actual conditions, and it’s significant to reducing vibration and noise. The pipe conveying fluid is studied in this paper considering the factors such as the work of gravity, the change of liquid pressure and the liquid viscosity. According to the Hamilton's principle, the equations of the lateral and axial motion of the pipe conveying fluid are set up under the condition of fluid structure interaction. In modeling, in order to solve and simulate conveniently, poisson coupling and friction coupled is considered. Meanwhile, the effect of high-order small parameter on system, the part relocation parameters, coupling terms between the pipe’s axial and lateral is neglected. Therefore the theoretical foundation is provided for the further analysis and calculation. *Copyright © 2012 IFSA.*

Keywords: Pipe, Vibration, Fluid, Poisson coupling, Friction coupled.

1. Introduction

Pipe conveying fluid systems are widely used in marine engineering, biological engineering, power industry, metallurgy industry, oil and energy industry, nuclear industry, ships and aircraft power plants and in daily life. These systems used to transfer mass liquid flow, momentum flow or energy flow. At the same time the existence of non-linear vibration of fluid-structure interaction (fluid pressure pulsation and vibration of the structure of the wall, etc.) in pipe, which create noise and vibration pollution even lead to serious damage to pipe or machine. Even in advanced countries, every year huge economic losses are caused due to pipe vibration. According to a Canadian experts estimate that $10 billion damage was caused by pipeline vibration in advanced industrial countries every year. As a result, research on the vibration characteristics of pipe conveying fluid systems have great engineering and market value [1].

Vibration sources of liquid-filled piping system include pumps, valves and others components of variable conditions, the external incentive system load, the shape of pipe, interface status, liquid flow rate, coupling effect between liquid and solid, etc., [2]. There are four main liquid-solid coupling means, namely friction coupling, poisson coupling, junction coupling and bourdon coupling [3]. The friction coupling is a boundary coupling, caused by the interaction of fluid viscous friction from the relative motion between wall and viscous fluid. Generally, the characteristic of the friction coupling has little effect on the system, but in the high-frequency range, exercise frequency related property is very complex. Poisson coupling is a along coupling, caused by the local interaction between the formation of fluid pressure and wall stress. Because the poisson's ratio of pipe material closely link with the strength of this coupling, so named poisson coupling. When liquid through the pipe coupling parts, the pressure is imbalance, so junction coupling is the coupling between the liquid and the structure. The shape of pipeline bending section is not rounding, so the flow state changed and pressure changed. The fluid pressure has a straightening effect to the pipe, which causes bourdon coupling. In the actual study process, different application based on the different emphases on four kinds of coupling is selected. In recent years, the fluid-structure coupling liquid pipelines have been studied by domestic and foreign scholars, great accomplishments has been achieved. Lixiang Zhang and Wenhu Huang [4, 5] used Hamilton principle and the N-S equations of fluid motion to establish an equation to describe the nonlinear fluid-structure coupling vibration of pipe conveying fluid. In this model, the pipe is a weak constraint, the liquid is compressible, and the surge characteristic of the fluid in pipe is considered, considered the gravity acting in the horizontal displacement, the friction acting in the axial caused by viscosity is also considered. The gravity of liquid acting and the friction energy loss caused by viscous is considered in this paper. The pressure changed by the situation of the location with the pipe unit is considered. In this paper the change of friction caused by pressure changes is considered too. At last a horizontal and axial considerate liquid-solid coupled mathematical model is established, this model is easy to simulation and measurement parameters are relatively small.

2. Considering Liquid-structure Coupling Vibration Model of Pipe Conveying Fluid

2.1. Description of the Motion Equation of Pipe Conveying Fluid

According to the pipeline deformation principle and midline extension theory [6-7], pipe axial strain is got.

$$\varepsilon_z = \frac{dZ}{dz} + \frac{1}{2}(\frac{dZ}{dz})^2 + \frac{1}{2}(\frac{dY}{dz})^2 , \tag{1}$$

Velocity of pipe can be written as:

$$\vec{v}_p = \frac{dZ}{dt} i + \frac{dY}{dt} j , \tag{2}$$

Velocity of the fluid inside pipe is:

$$\vec{v}_f = i\frac{v_f}{1+\varepsilon_z}(1+\frac{dZ}{dz}) + j\frac{v_f}{1+\varepsilon_z}\frac{dY}{dz}, \tag{3}$$

where v_f is the fluid flow rate.

Taking $1+\varepsilon_z$ as a series of Taylor before commencement of two into equation (3), velocity of the fluid inside pipe can be defined by:

$$\vec{v}_f = [(1-\varepsilon_z)(1+\frac{dZ}{dz})v_f]i + [(1-\varepsilon_z)\frac{dY}{dz}v_f]j, \tag{4}$$

In the actual action process, velocity of the fluid inside pipe conveying fluid is the combined result of pipe velocity and the fluid velocity. By equations (2) and (4):

$$\vec{v}_F = [\frac{dZ}{dt} + (1-\varepsilon_z)(1+\frac{dZ}{dz})v_f]i + [\frac{dY}{dt} + (1-\varepsilon_z)\frac{dY}{dz}v_f]j. \tag{5}$$

2.2. Description of the Energy Equation of Pipe Conveying Fluid

The Pipe conveying fluid energy, including the kinetic energy and potential energy of fluid and the kinetic energy and potential energy of pipe. In pipe conveying fluid, considering the fluid compressibility and pipe deformation, caused by changes in the quality of the fluid. Because the effect of liquid gravity, the pressure of fluid changed by the axial position. So the changes of the fluid mass density, the pipe flow area and the friction coefficient between fluid and wall are caused.

2.2.1. The Kinetic Energy of Pipe Conveying Fluid

The total vertical kinetic energy of pipe conveying fluid contains the kinetic energy of pipe and the kinetic energy of fluid.

1) The kinetic energy of unit pipe

The pipe flow area after deformation is:

$$A_F = A_f[1+\varepsilon_p - \varepsilon_z(1-2\gamma)], \tag{6}$$

where A_f is the un-deformed pipe flow area; γ is the Poisson's ratio of pipe; ε_p is the strain on the flow area caused by pressure.

The kinetic energy of unit pipe is:

$$T_p = \rho_p A_p((\frac{dZ}{dt})^2 + (\frac{dY}{dt})^2)/2, \tag{7}$$

where A_p is the cross-sectional area of pipe wall; ρ_p is the pipe mass density.

2) The kinetic energy of unit fluid after deformation:

$$T_f = \rho_F A_F (v_{Fi}^2 + v_{Fj}^2)/2$$
$$\rho_F = \rho_f (1 + P/K),\ v_{Fi} = \frac{dZ}{dt} + (1-\varepsilon_z)(1+\frac{dZ}{dz})v_f,\ v_{Fi} = \frac{dY}{dt} + (1-\varepsilon_z)\frac{dY}{dz}v_f, \tag{8}$$

where ρ_F is the mass density of fluid after pipe deformation, ρ_f is the mass density of fluid without deformation, P is the fluid pressure, K is the elasticity coefficient of fluid.

3) The total vertical kinetic energy of unit pipe conveying fluid:

$$T = T_p + T_f = \rho_p A_p ((\frac{dZ}{dt})^2 + (\frac{dY}{dt})^2)/2 + \rho_F A_F ({v_{Fi}}^2 + {v_{Fj}}^2)/2, \tag{9}$$

2.2.2. The Potential Energy of Pipe Conveying Fluid

The total potential energy of vertical pipe conveying fluid contains the deformation energy of pipe and the potential energy of fluid.

According to elastic deformation of the strain theory, the deformation potential energy of pipe is:

$$U_p = E[A_p((\frac{dZ}{dz})^2 + (\frac{dZ}{dz})^3 + \frac{dZ}{dz}(\frac{dY}{dz})^2) + I(4\frac{dZ}{dz}(\frac{d^2Y}{dz^2})^2 - 2\frac{d^2Z}{dz^2}\frac{dY}{dz}\frac{d^2Y}{dz^2} + (\frac{d^2Y}{dz^2})^2)]/2, \tag{10}$$

where E is the elasticity coefficient of pipe material, I is the pipe cross sectional moment of inertia.

The potential energy of fluid is:

$$U_f = A_F P[1-(1-2\gamma)(\frac{dZ}{dz} + (\frac{dZ}{dz})^2/2 + (\frac{dY}{dz})^2/2)], \tag{11}$$

The total potential energy of unit pipe conveying fluid is:

$$\begin{aligned} U = U_p + U_f = A_F P[1-(1-2\gamma)(\frac{dZ}{dz} + (\frac{dZ}{dz})^2/2 + (\frac{dY}{dz})^2/2)] + \\ E[A_p((\frac{dZ}{dz})^2 + (\frac{dZ}{dz})^3 + \frac{dZ}{dz}(\frac{dY}{dz})^2) + I(4\frac{dZ}{dz}(\frac{d^2Y}{dz^2})^2 - 2\frac{d^2Z}{dz^2}\frac{dY}{dz}\frac{d^2Y}{dz^2} + (\frac{d^2Y}{dz^2})^2)]/2 \end{aligned}, \tag{12}$$

2.3. Description of the Coupled Motion Equation of Pipe Conveying Fluid

In the vertical pipe conveying fluid, generally the length to the diameter of pipe is relatively large, so the gravity acting of fluid can not be ignored. Additional, on the axial displacement, the friction acting of wall and fluid caused by viscosity is must considered. In this paper, the friction of internal fluid is ignored.

2.3.1. The Gravity Acting of Unit Pipe Conveying Fluid

The gravity acting of unit pipe conveying fluid include the gravity acting of pipe and the gravity acting of fluid.

$$W_g = -g\rho_p A_p z - g\rho_F A_F z \,, \tag{13}$$

2.3.2. The Friction Acting in the Axial Caused by Fluid Viscosity

$$W_f = -\frac{\pi D \lambda \rho_F}{2}\int_0^l (1-2\frac{dZ}{dz})v_F^2 dz \,, \tag{14}$$

where D is the pipe diameter, λ is the Friction index.

2.3.3. A Horizontal and Axial Coupled Mathematical Model of the Vertical Pipe Conveying Fluid

According to Hamilton's principle,

$$\int_{t_1}^{t_2} \delta(T-U)dt + \int_{t_1}^{t_2} \delta W = 0 \,, \tag{15}$$

where T is the kinetic energy of pipe conveying fluid, U is the potential energy of pipe conveying fluid, δW is virtual work done by the system non-conservative forces.

Integral equations (9), (12) and (13) along axial, the Lagrangian density function of the axial pipe conveying fluid can be got, namely $L = \int_0^l (T-U-W_g)dz$. According to Hamilton's variational principle, for any initial time t_1, the definite integral of pipe conveying fluid actual movement from t_1 to t_2, $J = \int_{t_1}^{t_2} (L+W_f)dt$, and the first-order variation of this equation, $\delta J = 0$, so

$$\delta \int_0^l (T-U-W_g+W_f)dz = 0 \,, \tag{16}$$

The Z and Y variational derivative of the equation (16), simplify the related items, leave out the high-entry, after derivation the horizontal and axial coupled mathematical model of pipe can be got.

An axial coupled mathematical model of pipe conveying fluid:

$$\begin{aligned}&\rho_p A_p \frac{d^2Z}{dt^2} + \rho_F A_F \frac{d^2Z}{dt^2} + \rho_F A_F (\frac{dv_f}{dt} + v_f \frac{dv_f}{dz}) + A_F \frac{dP}{dt}(v_f + \frac{dZ}{dt})/c^2 \\ &-g\rho_F A_F (1-2\gamma)(1+\frac{dZ}{dt})\frac{dY}{dz} - (1-2\gamma)\frac{d[A_F P(1+\frac{dY}{dz})]}{dz} - EA_p \frac{d^2Z}{dz^2} + 4\lambda\rho_F {v_f}^2 / DK \,, \\ &-\rho_p A_p g - \rho_F A_F g - \rho_F A_f g(1-2\gamma)(1+\frac{dZ}{dz})\frac{d^2Z}{dz^2} = 0\end{aligned} \tag{17}$$

A horizontal coupled mathematical model of pipe conveying fluid:

$$\rho_p A_p \frac{d^2Y}{dt^2} + \rho_F A_F \frac{d^2Y}{dt^2} + \rho_F A_F \frac{dv_f}{dt}(1+\frac{dY}{dz}) + A_F \frac{dP}{dt}(v_f + \frac{dY}{dt})/c^2 - g(\rho_p A_p + \rho_F A_F)$$
$$+EI\frac{d^2Y}{dz^2} - (1-2\gamma)\frac{d(A_F P\frac{dY}{dz})}{dz} - EA_p(\frac{d^2Z}{dz^2}\frac{dY}{dz} + \frac{dZ}{dz}\frac{d^2Y}{dz^2}) = 0 \quad , \qquad (18)$$

where $c^2 = [\rho_f(\frac{1}{K} + \frac{D\phi}{Eb})]^{-1}$; c is the velocity of pressure waver; b is the thickness of pipe wall; ϕ is the factor related to pipe constraints, its value can be got from [8].

3. Conclusions

The topic about vibration model of pipe conveying fluid considered fluid structure interaction has a broad engineering background. The achieved great accomplishments can be directly used on water resources and electric engineering, mechanical, chemical industry, aerospace and nuclear engineering, etc. In this paper the equations of the lateral and axial motion of the pipe conveying fluid are set up under the condition of fluid structure interaction. These factors, such as the work of gravity, the axils friction of pipe caused by the liquid viscosity and the fluid is compressible, are considered. As the pipe conveying fluid on the vertical to the level, the work of gravity can not be ignored, in the equation of fluid pressure added the pressure created by the gravity, the effect of fluid gravity to the friction coefficient between wall and fluid, the fluid velocity, all of these are difficult to set up the model. The model is more simplified and better than the other models, and it is easy to experiment and simulation.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

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