Studied and Their Application of Vibration Control Technologies

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Abstract

Research on vibration control of pipes conveying fluid has widely practical background and economy significance, because vibration in pipes causes vibration and noise pollution, even pipes damage or machine damages when seriously. Common vibration control technologies and corresponding control theory summarizations are introduced systemically, including passive control technology, active control technology, semi-active control technology, and passive & active integrated technology. These will give a good reference for the concerning issues. Then the practical application and the state-of-the-art of vibration control of pipes conveying fluid at home and abroad are summarized.

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. The equations of the lateral and axial motion of the pipe conveying fluid are set up based on the Hamilton's principle considering the condition of fluid structure interaction, poison coupling and friction coupled. Finally the further research lessons of vibration control of pipes conveying fluid are presented. Therefore the theoretical foundation is provided for the further analysis and calculation.

Keywords: vibration control; control technologies; pipes conveying fluid; noise pollution.

1. Introduction

Pipes of conveying fluid are widely used in industry and play a quite important role. At the same time, vibration in pipes causes vibration and noise pollution, even pipes damage or machine damages when seriously. So research on vibration control of pipes conveying fluid has widely practical background and economy significance.

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 is 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.

2. Vibration control technologies

Vibration control technologies can be divided into passive control technology, active control technology, semi-active control technology and passive & active integrated technology according to its control method and mechanism.

2.1 Passive control technology

The passive control technology does not need outside environment to offer energy, vibration can be controlled depending on the change of dynamic characteristics of the structure in the structure and the control system, and it is a classical method of vibration control. Concretely, according to the change of the damping C, rigidity K and quality M of the structure, the energy absorbed by the structure is reduced, and the goal of reducing vibration is achieved by adopting vibration isolation technique, vibration absorption technique and energy dissipation technique etc.

A suitable device restraining vibration is installed between top structure and foundation to stop the transmission of vibration wave to structure in vibration isolation technique, limits the vibration energy of inputting structure, increases the self vibration period of the structure, then vibration reaction of structure is decreased by a large scales. One subsystem is added on the main structure in vibration absorption technique, the subsystem and main structure absorbs some vibration energy together in order to protect the main structure when the vibration in operation. Some components of structure are designed to components consuming energy or some devices consuming energy are installed to consume vibration energy in energy dissipation technique. For example, installing the viscous damper (utilizing viscoelasticity of the material to change the energy store and consumption of the structure), friction damper (slipping and doing work through the friction device), etc., can dissipate vibration energy effectively.

2.2 Active control technology

The active control technology needs external environment to offer energy, and it can exert the extra force on structure to reduce the dynamic reaction of the structure, it's a modern method of vibration control. There are active-tuned mass damper system and active anchor control system mainly in active control technology.

The active-tuned mass damper system makes use of the sensor to monitor the reaction of structure (displacement, speed or acceleration) real-time according to Riccati closeloop control theory, the computer accepts the information of the sensor and changes the state vector and the feedbacks vector to get the control force instantaneously, then the electro-hydraulic servo device exerts the optimum control force on the structure in order to control its movement and distortion. The active anchor system makes use of the sensor to transform the response of the structure to the computer, and then the computer calculates the control force needed to drive the hydraulic servo system according to optimization and analysis. The control force is exerted on structure according to the anchor in this system to reduce the reaction of structure effectively.

2.3 Semi-active control technology

The semi-active control technology makes use of the control mechanism to adjust inner parameters of the structure in order to make the structure parameter to an optimum state, then the vibration of structure is damped.

2.4 Passive & active control integrated technology

The passive & active control integrated technology is a technology integrating active control with passive control. It utilizes one's own advantages of two kinds of control methods respectively, has widen the application range of the control system. In fact, the passive & active control integrated technology needs to offer smaller control force to control the vibration of structure effectively, especially under the strong vibration function, it demonstrates its superiority even more.

3. Vibration and noise control of pipes conveying fluid

According to the vibration mechanism of pipes, the main countermeasures adopted in noise reduction and vibration isolation are improving the rigidity of structure of pipe system, adjusting the damping of structure of pipe system, eliminating exciting vibration force of pipe system and optimization design of control system etc in order to avoid production of the resonance, reducing the amplitude of vibration of structure of pipe system, increasing the critical velocity of fluid in order to improve the ability of project application.

3.1 Passive control of pipe vibration

For the complicated pipe system, there are some difficulty in application of equipment in active control technology because of the complexity and randomness of vibration and noise, but adopting the passive control technology does not increase systematic volume and structure complexity excessively.

The passive control has been shown as following mainly.

(1) Installing damper between pipe and foundation can restrain pipe vibration effectively, and reduce the amplitude of pulsed vibration of the fluid, and then the speed of attenuation is accelerated. The damper that is usually adopted has viscoelastic damper, plasticity damper and electro-rheological damper.

(2) The pulsed attenuators are connected in the pipeline.

(3) The flexible nozzle and joints of flexible pipe are adopted.

(4) Sucking vibration materials used in the wall of pipe increase the absorption of the wave. [1]

(5) The position of support is designed and adjusted.

(6) The vibration energy is absorbed and dissipated by laying the damping structure outside the wall of pipe. [2]

There are effective methods reducing the pressure pulse in pipe and the vibration transfer in the wall of pipe.

In theory, Fang and Lyons studied the pipes with pivoted ends and fixed ends conveying fluid, found that an expression for modal damping (loss factor or logarithmic decrement) is obtained analytically for tensioned pipes where the material damping is the only source of damping. The dependence of modal damping on axial tension, which is well known from general experience with cables, is explained. The expression is extended to give an equivalent modal loss factor when there are other forms of damping such as dry friction, as in the cases of cables and marine risers. Test results on vertical tensioned pipes with pivoted ends and fixed ends are presented when pivoted joints were used. Coulomb damping in these joints dominated the structural damping behavior when the pivoted ends were replaced by fixed ends, the damping values were reduced greatly, and were of a similar level to those measured when the pivots stopped moving in the tests with pivoted ends. It is shown that these low damping values were in part contributed by the dry friction force between the pipe specimen and metal shafts in the push-fit fixings used in the tests. The material damping was predicted by the expression developed to be only a small part of the structural damping in all the tests. These lessons need to be applied to previous results. [3]

The applicability of the periodic characteristics of wave stop and wave propagation bands are investigated for piping systems conveying fluid by employing the wave approach and are proved through experiments. The inviscid fluid dynamic forces acting on a pipe due to internal fluid flow are approximated by the plug-flow model with the slender-body theory. If the dominant frequency contents in the excitation loads are known, a proper design of periodic supports for reducing the vibration in those frequency bands is possible. Therefore, the periodic support design may be effective. [4]
But, it is not obvious to control vibration in low frequency, the effect of reducing vibration and noise of low frequency signal is not obvious, and noise active control technology has the advantage in this respect.

3.2 Active control of pipe vibration

Active sound attention is also called the active control. It utilizes the principle of sound wave interferences, and the secondary sound source is artificially introduced in the acoustic field of original noise, then the secondary counteractive sound wave with the same amplitude and contrary phase contracting with original noise is produced in real-time, therefore the goal of reducing the noise is achieved by the counteractive interferences of this wave and original noise wave during the space propagation in the same direction. Compared with the passive control, the active control has better flexibility and adaptability to the environment, can effectively control the vibration of ultra-low frequency and wide in frequency band. [5]

Britain's national defense office has developed a new type pipe joint adopting the active vibration control technology, which is a substitution of a kind of traditional passive pipe joint. This joint can effectively suppress the production of the vibration and noise in the pipe system on the naval vessel. [6]

Fei renyuan and Wu bin take the acoustic impedance as control target, and discuss the fundamentals of the active noise control experimental system. The studying results prove that the effect of active noise control system depends on the equivalent impedance at the secondary source location and the impedance distributed characteristics of the muffler. The sound pressure level of main frequency was decreased above 40dB, which is demonstrated by the experimental results. [7-10]

With the constant development of intellectual material and control technology, feedback system of control has very much improvement, and the active control technology is changing with each passing day, so the active control technology is being favored. Generally speaking, three important components of an active damping vibration structure are inductor (sensor), controller, and actuator.
The sensor is an important component in the vibration active control. If the sensor can't examine the vibration of the system accurately, then the very good control result can't be obtained. The controller is a key component in active control system, and can be divided into feedforward controller and feedback controller. The feedforward controller is suitable for the situation of adapting compensation measurement to the specific disturbance, and has the characteristics of fast response. But the feedback controller is suitable for the situation of many disturbances and having difficulties in measuring, it can reduce or eliminate the influence of disturbance on output by oneself and is especially suitable for control of complicated system and uncertain parameters system, such as the vibration isolation platform, flexible structure, etc. The actuator is the key component of implementing active vibration control. The practical actuator should have the following characteristics: shorter time-delay, namely the time-delay between control signal and active control force outputted can't be too long, linear relationship exists between the outputted signal and the inputted signal, not too big distortion, too enough wide frequency response, compact structure, small quality, bigger output strength and reliable performance and so on.[11]

Its operation principle is shown as following. At the time of vibration, the sensor on the controlled component perceives the vibration signal and transmits them to the control system, and then control system conducts the actuator to work according to the control law designed in advance, so the vibration of the component is controlled.

Kartha has utilized the active Helmholtz resonance cavity of the actuator equipped with 1/3 the piezoelectricity composite material inside to reduce the fluid pulsation of pipe greatly. [12]

Maillard has designed a kind of non-inserted structure to control the fluid pulsation of pipe system of naval vessel. The thick piezoelectricity actuator acts on the wall of pipe to produce the axisymmetric wave, producing fluid pulsation coupling in radial, then the fluid pulsation is reduced. [13]

3.3 Semi-active control of pipe vibration

It is one of the methods to enforce control on pipe by using absorber directly. Li wanyou, Zhang hongtian used semi-active absorber directly to control the vibration, and the result is good. It's installed on pipe on the form of additional component to form combined vibration reduction device, which forms semi-active control technology of pipe vibration. The performances have been experimentally investigated on a pipe model, and the results show that the technique has good effect on damping vibration. So it offered a new technological way for pipe vibration control. [14]

3.4 Passive & active control integrated control technology of pipe vibration

Because of the merits and disadvantages of passive vibration control technology and active vibration control technology, the passive & active control integrated control technology is put forward, which uses the advantages of these two technologies. This is the trend of vibration control of pipe up to now.

4. Considering liquid-structure coupling vibration model of pipe conveying fluid

4.1 Description of the motion equation of pipe conveying fluid

According to the pipeline deformation principle and midline extension theory , pipe axial strain is got.

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

Velocity of pipe can be written as:

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

Velocity of the fluid inside pipe is:

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

Where v_f is fluid flow rate.

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

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

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 eqn (2) and eqn (4)

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

4.2 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.

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

The pipe flow area after deformation is:

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

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:

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

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

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

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

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

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:

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

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

The potential energy of fluid is:

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

The total potential energy of unit pipe conveying fluid is:

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

4.3 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.

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

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

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

Where D is pipe diameter, λ is Friction index.
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 eqn(9) ,eqn (12) and eqn (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 eqn(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:

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

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 factors related to pipe constraints, its value can be got from .

5. Conclusions

If carrying on the following research will have important theory meaning and project application value.
(1) Research on new-type sensor and signal acquisition and processing technology;
(2) Research on the intelligent control algorithm;
(3) Research on the controller and the intelligent control strategy with the characteristics of robust, fault-tolerance and layer;
(4) Research on the intelligent structure;
(5) Absorbing the new principles and the new technologies of other disciplines, developing the intelligent control theory of pipe vibration.

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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