doi:10.3772/j.issn.1006-6748.2018.02.009

Friction coupling vibration characteristics analysis of aviation hydraulic pipelines considering multi factors①

Quan Lingxiao(权凌霄)②***, Guo Meng****, Shi Junqiang*, Jiao Zongxia**, Guo Changhong*
(* College of Mechanical Engineering, Yanshan University, Qinhuangdao 066004, P. R. China)
(** School of Automation Science and Electrical Engineerging, Beihang University, Beijing 100083, P. R. China)
(*** School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, P. R. China)

Abstract

As the power transmission system of an aircraft, a hydraulic pipeline system is equivalent to the "blood vessel" of the aircraft. With the development of aircraft hydraulic system to high pressure, high speed and high power ratio, the fluid-structure interaction vibration mechanism of hydraulic pipeline is more complex and the influence of friction coupling on vibration cannot be ignored. The fluid-structure interaction of hydraulic pipeline will lead to system vibration, lower reliability of system operation and even pipeline rupture. Taking a hydraulic pipeline of C919 aircraft wingtip as the research object, a 14-equation model of fluid-structure interaction vibration considering friction coupling effect is established in this paper. The effects of friction and fluid parameters on the pipeline fluid-structure interaction vibration characteristics are studied and verified by experiments. The research results will provide theoretical guidance for the analysis of the pipeline fluid-structure interaction vibration and have important theoretical significance and great engineering value for promoting the localization process of large aircraft.

Key words: aviation hydraulic pipeline, fluid-structure interaction vibration, friction coupling, fluid parameters, frequency domain characteristics

0 Introduction

As the power transmission system, the aircraft hydraulic pipeline transmits the hydraulic energy from the pump source to the actuators to ensure normal operation of the aircraft. The quality of the pipeline has important influence on the reliability of the hydraulic system. However, the space configuration of the aircraft hydraulic pipeline is very complicated due to the space limitation for installation[1]. In addition, in the whole flight envelope, the aircraft hydraulic pipeline system is subjected to superposition and coupling action of various loads, such as pressure, temperature, body deformation, vibration and acceleration loading, which leads to extremely complicated static/dynamic characteristics of the hydraulic pipeline system. The pipeline fluid-structure interaction vibration is a main form of dynamic behavior of aircraft hydraulic pipelines, which will lead to complex fluid-structure interaction vibration of aircraft hydraulic pipeline in wide range of frequency and lower reliability. Statistical data shows that flying accidents caused by hydraulic system piping failures exceed 30%[2].

Many domestic and foreign scholars have studied a lot on fluid-structure interaction vibration of hydraulic pipelines. A water hammer theory proposed by Joukowsky has been developed to more perfect 14-equation model of the fluid-structure interaction. After that, Bhunia found that when the fluid passed through the bend, the radial secondary flow was produced and the fluid-structure interaction vibration of the pipeline was strengthened[3]. The 14-equation model based on the elastic support condition was proposed by Liu, et al.[4]. After considering the unsteady Poisson ratio of viscoelastic materials, Keramat, et al.[5] improved the vibration equation of the pipeline fluid-structure interaction. Kutin, et al.[6] considered the dynamic load caused by the velocity variations and further ameliorated the fluid-structure interaction model. Quan, et al.[7] summarized the domestic and foreign research results on fluid-structure interaction vibration, and pointed out the research trend.

In recent years, with the increasing of the aircraft

---

① Supported by the National Key Basic Research Program of China (No. 2014CB046405).

② To whom correspondence should be addressed. E-mail: lingxiao@ysu.edu.cn

Received on July 27, 2017

hydraulic system pressure, the flow velocity in the pipeline is further increased, which leads to more complex flowing state. The author has participated in the project of 'ARJ21-700 whole hydraulic pipeline stress analysis', and analyzed the Reynolds numbers of all pipelines. The analysis shows that the Reynolds number of more than 20% hydraulic pipelines in the aircraft exceeds the critical Reynolds number, that is to say, there exists obvious turbulence in the interior flow field of the pipeline. Therefore, the pipeline vibration caused by friction coupling cannot be neglected[8]. Ouyang, et al.[9] considered the friction coupling and found that the curvature of curved pipeline had great influence on the vibration characteristics of the pipeline. Gao[10] analyzed the aircraft hydraulic pipeline system and found that friction coupling could reduce the flow pulsation in the pipeline and affect the vibration amplitude of the pipeline. Based on the friction coupling effect, the fluid-structure interaction of hydraulic pipeline system was studied in detail by Xu[11].

Outstanding achievements have been attained by domestic and foreign scholars in the fluid-structure interaction vibration of the hydraulic pipeline. However, the fluid-structure interaction vibration characteristics of hydraulic pipelines under frictional coupling should be further studied. A hydraulic pipeline of C919 aircraft wingtip is selected as the object of study and the 14-equation model of the fluid-structure interaction vibration is established by considering simplified Trikha friction effect in this paper. The transfer matrix method is used to solve the equation, and the influence of the friction and fluid parameters on the fluid-structure interaction vibration response of the pipeline is analyzed. The research results will provide theoretical guidance for the analysis of the pipeline fluid-structure interaction vibration and have important theoretical significance and great engineering value for promoting the localization process of large aircraft.

1 Establishment and solution of the pipeline fluid-structure interaction model

1.1 Establishing the 14 - equation of pipeline fluid-structure interaction

The 14-equation model of fluid-structure interaction vibration can fully represent the dynamic interaction between fluid and pipeline. Fig. 1 shows a schematic diagram of the curved pipeline element. Based on the De[12] model, a curved pipeline 14-equation model is established as follows.

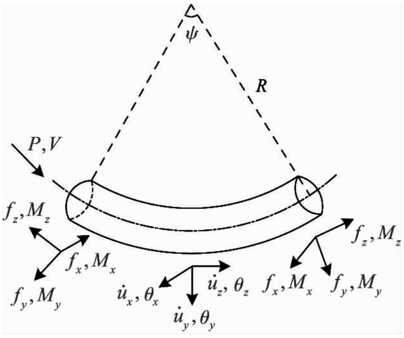


Fig. 1 The schematic diagram of the curved pipeline element

1) axial dynamic model

$$\frac{\partial P}{\partial z} = -\rho_f \frac{\partial V}{\partial t} - \frac{2\tau_0}{R\rho_f} \tag{1}$$

$$\frac{\partial V}{\partial z} = -\frac{1}{K^*}\frac{\partial P}{\partial t} - 2\upsilon\frac{\partial \dot{u}_z}{\partial z} - \frac{\dot{u}_y}{R} \tag{2}$$

$$\frac{\partial f_z}{\partial z} = -A_p\rho_p\frac{\partial \dot{u}_z}{\partial t} - \frac{f_y}{R} \tag{3}$$

$$\frac{\partial \dot{u}_z}{\partial z} = \frac{\partial f_z}{EA_p\partial t} - \frac{\upsilon r}{Ee}\frac{\partial P}{\partial t} - \frac{\dot{u}_y}{R} \tag{4}$$

2) transverse *y-z* dynamics model

$$\frac{\partial f_y}{\partial z} = -(\rho_f A_f + \rho_p A_p)\frac{\partial \dot{u}_y}{\partial t} + \frac{f_z}{R} + \frac{A_f}{R}P \tag{5}$$

$$\frac{\partial \dot{u}_y}{\partial z} = \frac{1}{k^2GA_p}\frac{\partial f_y}{\partial t} - \dot{\theta}_x + \frac{\dot{u}_z}{R},$$

$$k^2 = 2\frac{1+\upsilon}{4+3\upsilon} \tag{6}$$

$$\frac{\partial M_x}{\partial z} = -(\rho_p I_p + \rho_f I_f)\frac{\partial \dot{\theta}_x}{\partial t} + f_y \tag{7}$$

$$\frac{\partial \dot{\theta}_x}{\partial z} = \frac{1}{EI_p/ff}\frac{\partial M_x}{\partial t} \tag{8}$$

3) transverse *x-z* dynamics model

$$\frac{\partial f_x}{\partial z} = -(\rho_f A_f + \rho_p A_p)\frac{\partial \dot{u}_x}{\partial t} \tag{9}$$

$$\frac{\partial \dot{u}_x}{\partial z} = -\frac{1}{k^2GA_p}\frac{\partial f_x}{\partial t} + \dot{\theta}_y,\ k^2 = 2\frac{1+\upsilon}{4+3\upsilon} \tag{10}$$

$$\frac{\partial M_y}{\partial z} = -(\rho_p I_p + \rho_f I_f)\frac{\partial \dot{\theta}_y}{\partial t} - f_x + \frac{M_z}{R} \tag{11}$$

$$\frac{\partial \dot{\theta}_y}{\partial z} = \frac{1}{EI_p/ff}\frac{\partial M_y}{\partial t} + \frac{\dot{\theta}_z}{R} \tag{12}$$

4) torsion dynamics model

$$\frac{\partial M_z}{\partial z} = -\rho_p J_p\frac{\partial \dot{\theta}_z}{\partial t} - \frac{M_y}{R} \tag{13}$$

$$\frac{\partial \dot{\theta}_z}{\partial z} = -\frac{1}{GJ_p}\frac{\partial M_z}{\partial t} - \frac{\dot{\theta}_y}{R} \tag{14}$$

where V is the fluid velocity; P is the pressure; ρ_f is the fluid density; R is the turning radius of pipeline; τ_0 is the fluid wall bounded shear stress; K is the fluid elastic modulus; K^* is the modified fluid elastic modulus; v is the Poisson's ratio; u is the pipeline displacement; r is the average radius of pipeline; E is the pipeline elastic modulus; e is the thickness of pipeline; f is the force acted on pipeline cross section; A is the section area of pipeline; k is the shear coefficient; θ is the pipeline angle; M is the pipeline torque; I is the pipeline lateral inertia; J is the pipeline rotary inertia; G is the shear modulus and $ff = 1.65r^2/eR$ is the elastic correction factor. When bending radius R is ∞, it is the fluid-structure interaction dynamic model of the straight pipeline.

In the axial dynamic model, $2\tau_0/R\rho_f$ is the friction term, which represents the friction coupling effect due to the interaction between the viscous fluid and the pipeline wall. The friction coupling is affected by fluid velocity, pressure, viscosity and other factors. In the high frequency range, its characteristics will be more complex and the influence will be larger[13].

1.2 Trikha frictional term

The friction coupling is mainly the fluid shear force near the wall, which affects the axial vibration response of the pipeline. The Bessel function and the Laplace transform were used by Zielke to obtain the frequency domain friction model between the fluid in pipeline and the pipeline wall:

$$F(s) = \frac{2\tilde{\tau}_0(s)}{\rho_f R} = \frac{2s}{\vartheta_1\left(jR\sqrt{\dfrac{s}{v_f}}\right)}\tilde{V}(s) \qquad (15)$$

The fluid shear force model $\tilde{\tau}_0(s)$ can be described as

$$\tilde{\tau}_0(s) = \frac{\rho_f R}{\vartheta_1\left(jR\sqrt{\dfrac{s}{\nu_f}}\right) - 2}s\tilde{V}(s) \qquad (16)$$

In the formula, s is the Laplace operator; j is equal to $\sqrt{-1}$; $\vartheta_1(z) = z \cdot J_0(z)/J_1(z)$ and J_0, J_1 mean the zero and first order Bessel functions respectively.

In order to simplify the model expediently, $G(\lambda)$ can be expressed as

$$G(\lambda) = \frac{F(s)}{\tilde{V}(s)s} - \frac{8}{\lambda^2} = \frac{2}{j\lambda\dfrac{J_0(j\lambda)}{J_1(j\lambda)} - 2} - \frac{8}{\lambda^2} \qquad (17)$$

In Eq. (17), $\lambda = R\sqrt{s/v_f}$; v_f is the kinematic viscosity of the fluid.

So, $F(s)$ can be described as

$$F(s) = \left(G(\lambda) + \frac{8}{\lambda^2}\right)s\tilde{V}(s) \qquad (18)$$

The Bessel function is included in the Zielk friction model, which is unfavorable to engineering calculation. Vardy and Brown[14] improved the turbulent friction model on the basis of Zielke's results. Later, Trikha[15], Kagawa[16] and Li[17] simplified and approximated the Zielke friction model in varying degrees, obtaining classical models describing fluid friction in long straight pipeline. Among them, Trikha simplified the Zielk friction model in time domain range and obtained a classical friction model, which greatly improved the calculation accuracy and speed. The classical friction model is

$$G_{3T}(\tau) = \frac{4v_f}{R^2}\left(40e^{-8000\tau} + 8.1e^{-200\tau} + e^{-26.4\tau}\right) \qquad (19)$$

The Laplace transform is used to obtain the expression in frequency domain:

$$G_{3T}(s) = 4\left(\frac{40}{\lambda^2 + 8000} + \frac{8.1}{\lambda^2 + 200} + \frac{1}{\lambda^2 + 26.4}\right) \qquad (20)$$

So,

$$\begin{aligned} F(s) &= \left(G_{3T}(s) + \frac{8}{\lambda^2}\right)s\tilde{V}(s) \\ &= \left(4\left(\frac{40}{\lambda^2 + 8000} + \frac{8.1}{\lambda^2 + 200} + \frac{1}{\lambda^2 + 26.4}\right) \right. \\ &\quad \left. + \frac{8}{\lambda^2}\right)s\tilde{V}(s) \end{aligned}$$

In the simplified equation above, the default pipeline axial speed $u_z = 0$. If $u_z \neq 0$, the fluid velocity $\tilde{V}(s)$ in the $F(s)$ should be replaced by $\tilde{V}(s) - \tilde{u}_z$.

1.3 Excitation of the hydraulic pipeline

In this paper, the periodic pulsating fluid at the exit of axial piston pump is regarded as excitation. When the piston number is seven, the instantaneous pulsating flow is

$$q_{sh} = \sum_{i=1}^{z_0} Av_i = AR\omega\tan\gamma\sum_{i=1}^{z_0}\sin\varphi_i \qquad (21)$$

In Eq. (21), z_0 is the piston number in the oil pressure area at the same time; j_i is the angle of the i plunger in the oil pressure area relative to the top dead center; v_i is the axial velocity of the i plunger in the oil pressure area.

The motor speed is 1000r/min and the inner radius of pipeline is 0.556 inch. By adjusting the pump displacement, the pulsating frequency response curves are obtained when the fluid velocity in the pipeline is 0.80m/s, 1.28m/s, 1.60m/s or 2.50m/s, as shown in Fig. 2.

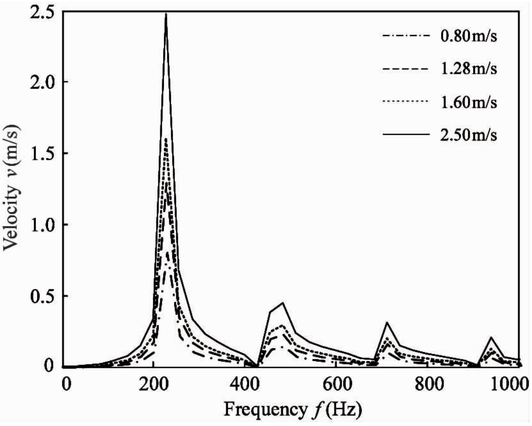


Fig. 2 The pulsating frequency response at different fluid velocity

According to the pulsating frequency response curves at different fluid velocity, the first three order modes are superimposed to obtain the constant pulse frequency. The frequency domain velocity excitation of the pipeline under different fluid velocity is

$$\tilde{q}_{shi} = \sum_{i=1}^{3} q_{ij}\omega_{ij} / \sin(s^2 + \omega_{ij}^2)\ ;\ i = 1, 2, 3, 4 \tag{22}$$

where, q_{ij} is the coefficient of excitation equation, W_{ij} is the angular velocity at each fluid velocity.

The output flow of the pump is constant, so that the fluid velocity in the pipeline is 1.28m/s constantly. By adjusting the pump displacement and speed, the pulsating frequency response curves are obtained when the pump speed is 300r/min, 500r/min, 800r/min or 1000r/min, as shown in Fig. 3.

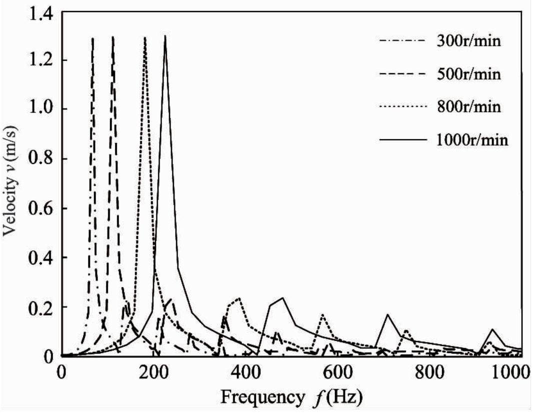


Fig. 3 The pulsating frequency response at different pump speed

In the same way, the frequency domain pulsating excitation of the pipeline under constant fluid velocity and different pulsation frequency can be obtained.

$$\tilde{q}_{shi} = \sum_{i=1}^{3} q_{ij}\omega_{ij} / \sin(s^2 + \omega_{ij}^2)\ ;\ i = 5, 6, 7, 8 \tag{23}$$

2 The fluid-structure interaction vibration analysis of aviation hydraulic pipeline

As shown in Fig. 4, an aluminum alloy hydraulic pipeline of C919 aircraft wingtip is selected. The 14-equation model of the fluid-structure interaction vibration is established and the influence of the frictional term on the axial velocity response of pipeline is analyzed. In addition, the effect of fluid parameters, such as fluid velocity, pulsation frequency and temperature, is studied.

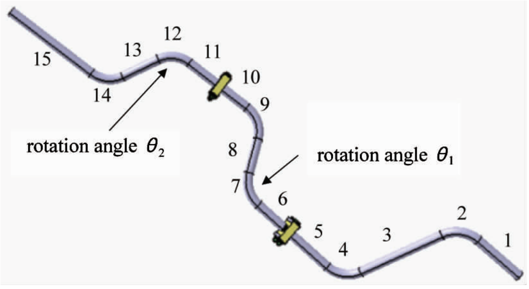


Fig. 4 The aviation hydraulic pipeline model

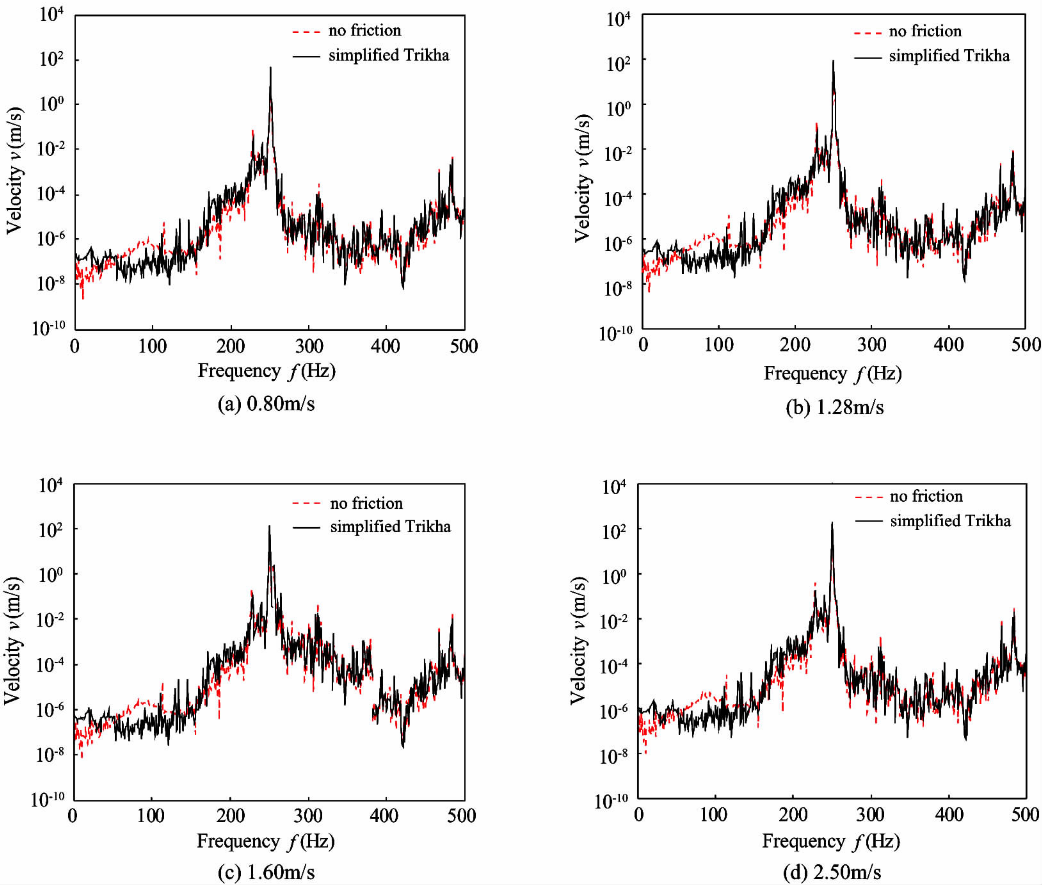
In the model above, the boundary conditions at both ends of the pipeline are free. The pipeline clamp is set as fixed support and the hoses are added to both ends of the pipe as additional mass. The specific parameters of the pipeline are shown in Table 1.

Table 1 Structural parameters of aviation hydraulic pipeline

Parameter name	Numerical value	Parameter name	Numerical value
L_1	86.531mm	inner radius of pipeline	0.556inch
L_3	141.711mm	thickness of pipeline	0.035inch
L_5	87.883mm	bending angle/φ	60°
L_6	60.079mm	coordinate rotation angle θ_1	35.54°
L_8	56.802mm	coordinate rotation angle θ_2	17.81°
L_{10}	55.149mm	bending radius/R	47.625mm
L_{11}	60.399mm	pipeline density/ r_p	2713kg/m^3
L_{13}	63.417mm	Young's Modulus/E	68GPa
L_{15}	157.374mm	Poisson's ratio/υ	0.33

2.1 Influence of fluid velocity on pipeline fluid-structure interaction vibration

The change of fluid velocity will significantly affect flowing state of fluid in the pipeline and the fluid shear force. The motor speed is 1000r/min. The axial velocity response of pipeline is obtained for the fluid velocity of 0.80m/s, 1.28m/s, 1.60m/s or 2.50m/s, as shown in Fig. 5.



(a) 0.80m/s

(b) 1.28m/s

(c) 1.60m/s

(d) 2.50m/s

Fig. 5 Response curves of the pipeline at different fluid velocity

By comparing and analyzing the response curves of the pipeline at different flow velocities, it is found that when the fluid pulsation frequency and pressure are constant, the amplitude of the pipeline axial velocity response is proportional to the fluid velocity.

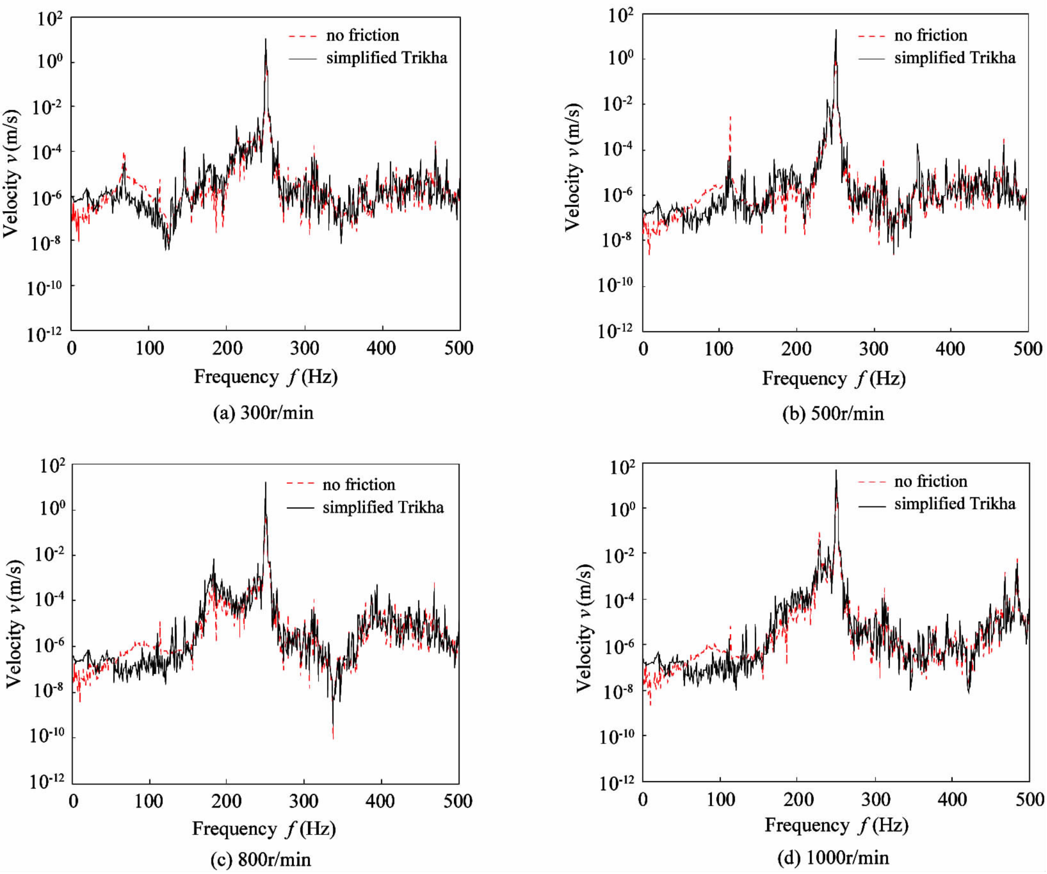
2.2 Influence of pulsating frequency on pipeline vibration fluid-structure interaction

The fluid pulsation will affect the vibration response of the fluid-structure interaction in the hydraulic pipeline and the change of the pulsation frequency will be realized by adjusting the motor speed. When the pulse frequency approaches to the natural frequency of the pipeline, the resonance will be triggered. The fluid velocity in the pipeline is 1.28 m/s. The axial velocity response of pipeline is obtained when the motor speed is 300r/min, 500r/min, 800r/min or 1000r/min, as shown in Fig. 6.

By comparing and analyzing the response curves of the pipeline at different fluid pulsation frequency, it can be found that when the fluid pulsation frequency approaches to the natural frequency of the pipeline, it will cause strong vibration, but the response amplitude at the same resonant frequency is constant.

2.3 Influence of temperature on pipeline fluid-structure interaction vibration

The change of oil temperature will affect the viscosity of hydraulic oil. When the temperature is too low, the oil viscosity and fluid shear force increase, so the liquidity becomes worse; on the contrary, the oil viscosity and fluid shear stress decrease. At the same time, the material performance of the pipeline will be changed by the oil temperature. The temperature dependent performance parameters of the aerospace No. 10 hydraulic oil and the aluminum alloy pipeline are shown in Table 2.



(a) 300r/min (b) 500r/min

(c) 800r/min (d) 1000r/min

Fig. 6 Response curves of the pipeline at different fluid pulsation frequency

Table 2 Performance parameters of the aerospace No. 10 hydraulic oil and the aluminum alloy pipeline

Temperature (℃)	20	50	80	100
Kinematic viscosity of hydraulic oil (mm^2/s)	19.7	10.4	6.5	4.9
Dynamic viscosity of hydraulic oil (Kg/s · mm)	17.18	9.07	5.67	4.27
Modulus of elasticity of aerometal (GPa)	68.3	67.9	67.4	67.0

The fluid velocity in the pipeline is 0.80 m/s and the motor speed is 1000 r/min. The axial velocity response of the pipeline is researched at the temperature points of 20℃, 50℃, 80℃ and 100℃, as shown in Fig. 7.

By comparing and analyzing response curves of the pipeline at different temperatures, it is found that when the fluid velocity and pulse frequency are constant, the temperature has little influence on the axial velocity response of the pipeline.

Fig. 5, Fig. 6, and Fig. 7 show that the friction term does not affect the resonance frequency of the pipeline, but it changes the magnitude of the response. And the friction term has a greater influence in the high frequency region.

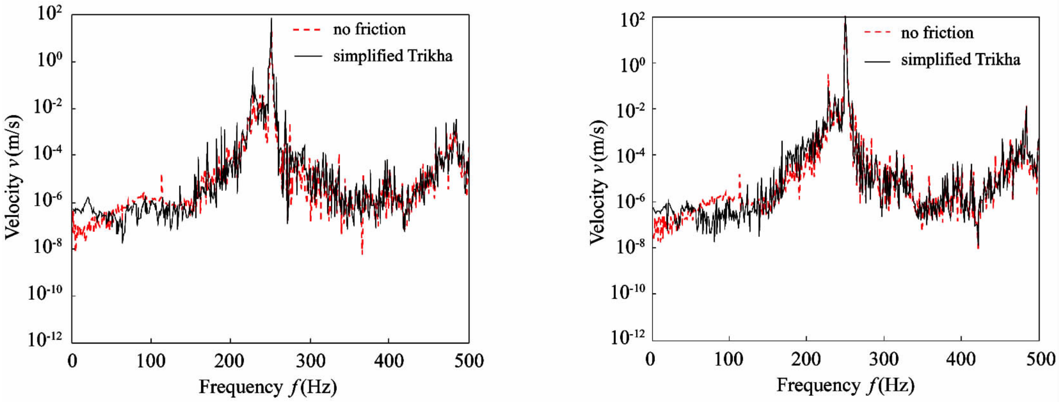
3 Experimental analysis of pipeline fluid-structure interaction vibration

In this paper, a hydraulic pipeline vibration laboratory bench is used to carry out experimental research and the axial vibration response of the pipeline is measured by the acceleration sensor. The installation of the hydraulic pipeline and sensor is shown in Fig. 8.

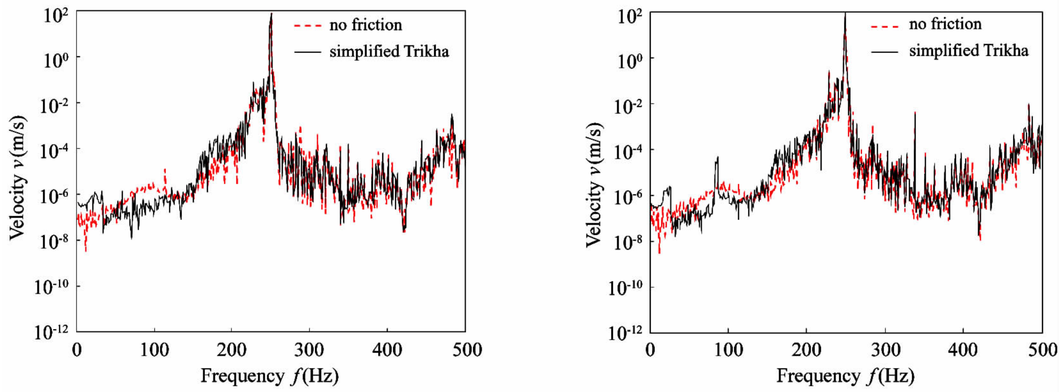
3.1 Pipeline fluid-structure interaction vibration experiment under different fluid velocities

The motor speed is 1000r/min. The axial velocity responses of pipeline are obtained when the fluid velocity is 0.80m/s, 1.28m/s, 1.60m/s or 2.50m/s, as shown in Fig. 9.

As can be seen from Fig. 9, the experimental results are in great agreement with the numerical analysis. The conclusion that the amplitude of the pipeline axial velocity response increases with the rise of the fluid velocity of the pipeline is obtained. Meanwhile, it is verified that the friction term does not affect the resonance frequency of the pipeline, but changes the response magnitude. And the friction term has greater influence in the high frequency region.



(a) 20℃ (b) 50℃



(c) 80℃ (d) 100℃

Fig. 7 Response curves of the pipeline at different temperatures

(a) hydraulic pipeline for test (b) sensor

Fig. 8 The installation of the hydraulic pipeline and sensor

3.2 Pipeline fluid-structure interaction vibration experiment under different pulsation frequencies

The adjustment of pulse frequency needs to be realized by changing the motor speed. The motor speed is 300r/min, 500r/min, 800r/min or 1000r/min. At the same time, by regulating the displacement of the pump, the fluid velocity in the pipeline is constant to 1.28m/s. The axial vibration response of the pipeline is shown in Fig. 10.

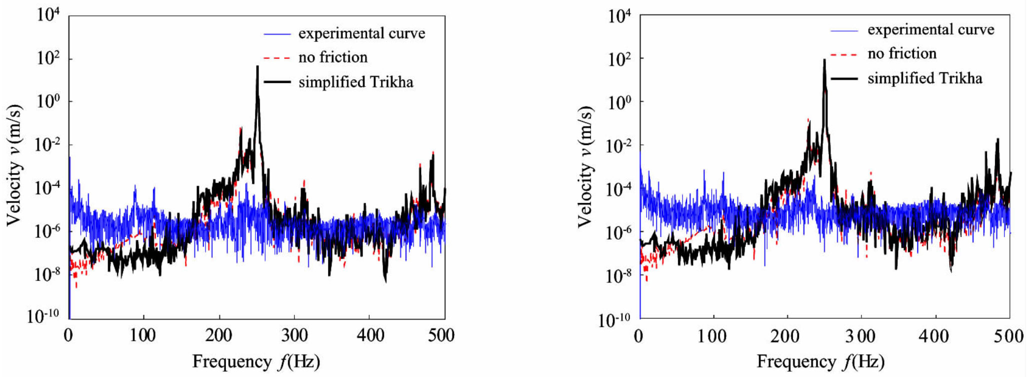
As can be seen from Fig. 10, the experimental curve agrees well with the numerical analysis. When the fluid pulsation frequency approaches to the natural frequency of the aviation hydraulic pipeline, strong vibration will be caused. But the response amplitude at the same resonant frequency is constant. Meanwhile, it is verified that the friction term does not affect the resonance frequency of the pipeline, but change the response magnitude. And the friction term has greater influence in the high frequency region.

4 Conclusion

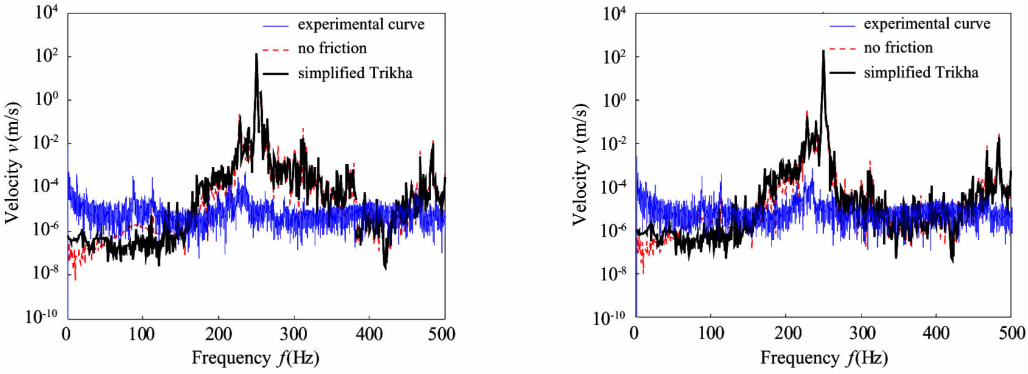
With the development of aircraft hydraulic system to high pressure, high speed and high power ratio, the influence of friction coupling on the pipeline fluid-structure interaction vibration cannot be ignored.

A hydraulic pipeline of C919 aircraft wingtip is selected as the research object and the 14-equation model of the fluid-structure interaction vibration is established. The effects of friction and fluid parameters on the pipeline fluid-structure interaction vibration characteristics are studied. Conclusions below can be reached from this paper.

1) The friction term does not affect the resonance frequency of the pipeline under the fluid-structure interaction. But the response amplitude at resonance frequency can be changed, and the change is more obvious in high frequency region.

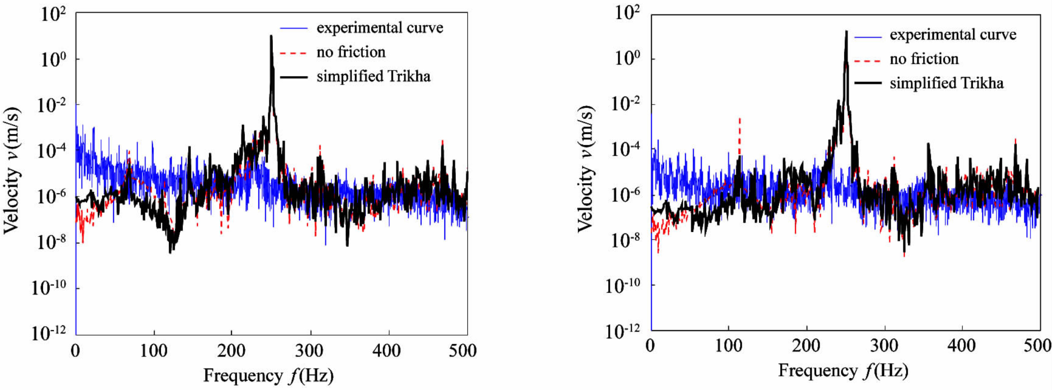


(a) 0.80m/s (b) 1.28m/s

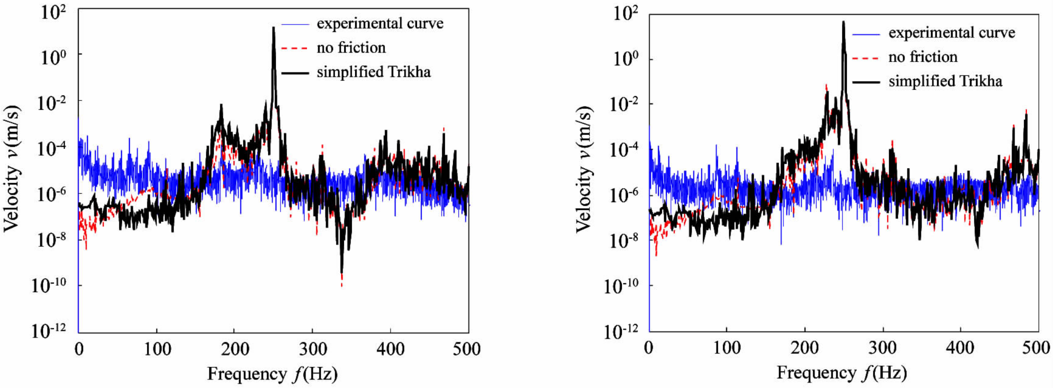


(c) 1.60m/s (d) 2.50m/s

Fig. 9 Response curves of the pipeline at different fluid velocity



(a) 300r/min (b) 500r/min



(c) 800r/min (d) 1000r/min

Fig. 10 Response curves of the pipeline at different fluid pulsation frequency

2) When the fluid pulsation frequency and pressure are constant, the amplitude of the pipeline axial velocity response is proportional to the fluid velocity. If the fluid velocity and pressure are constant, when the fluid pulsation frequency approaches to the natural frequency of the pipeline, it will cause strong vibration, but the response amplitude at the same resonant frequency is constant.

3) Temperature has little influence on the vibration characteristic of the pipeline.

However, the axial velocity response amplitude of the experiment is smaller than that of numerical analysis due to the influence of system damping and external disturbance signal. In addition, the influence of temperature on the pipeline fluid-structure interaction vibration has not been completely limited by experimental conditions. Future research will focus on the effect of friction and fluid parameters on the fluid-structure interaction vibration response of the hydraulic pipeline at high speed and high pressure. The temperature experiments will be completed in future and relevant research work will be improved step by step.

References

[1] Li D. Frequency domain characteristics analysis of fluid structure coupling vibration of civil aircraft hydraulic bending pipeline [Master's thesis][D]. Qinhuangdao: School of Mechanical Engineering, Yanshan University, 2016. 53-56 (in Chinese)

[2] Chen G, Luo Y, Zhen Q H. Fluid-structure coupling dynamic model of complex spatial fluid-conveying pipe system and its verification[J]. *Acta Aeronautica Et Astronautica Sinica*, 2013, 34(3): 597-609 (in Chinese)

[3] Bhunia A, Chen L C. Flow characteristics in a curved rectangular channel with variable cross-sectional area [J]. *Journal of Fluids Engineering*, 2009, 131(9): 91102-91117

[4] Liu G, Li Y H. Vibration analysis of liquid-filled pipelines with elastic constraints[J]. *Journal of Sound and Vibration*, 2011, 330(13): 3166-3181

[5] Keramat A, Kolahi A G, Ahmadi A. Waterhammer modelling of viscoelastic pipes with a time-dependent poisson's ratio[J]. *Journal of Fluids and Structures*, 2013, 43: 164-178

[6] Kutin J, Bajsi C I. Fluid-dynamic loading of pipes conveying fluid with a laminar mean-flow velocity profile[J]. *Journal of Fluids and Structures*, 2014, 50: 171-183

[7] Quan L X, Kong X D, Yu B, et al. Research status and trends on fluid-structure interaction vibration mechanism and control of hydraulic pipeline[J]. *Journal of Mechanical Engineering*, 2015, 51(18): 175-183 (in Chinese)

[8] Guan C B, Jiao Z X, He S Z. Theoretical study of flow ripple for an aviation axial-piston pump with damping holes in the valve plate[J]. *Chinese Journal of Aeronautics*, 2014, 27(1): 169-181

[9] Ouyang X P, Gao F, Yang H Y. Modal analysis of the aircraft hydraulic-system pipeline [J]. *Journal of Aircraft*, 2012, 49(4): 1168-1174

[10] Gao F. Investigation into the vibration characteristic of the pump and connected pipeline in the aircraft hydraulic system [Ph. D dissertation]. Hangzhou: School of Mechanical Engineering, Zhejiang University, 2013 (in Chinese)

[11] Xu Y Z. Analysis of fluid-structure interaction in hydraulic piping systems [Ph. D dissertation][D]. Beijing: Beijing University of Aeronautics and Astronautics, 2014 (in Chinese)

[12] De J. Analysis of pulsation and vibration in fluid-filled pipe systems [Ph. D dissertation][D]. The Netherlands: Department of Mechanical Engineering, Eindhoven University of Technology, 1994

[13] Lv H. Dynamic analysis of the aircraft hydraulic pipes based on fluid-structure interaction [Ph. D dissertation][D]. Xi'an: Xidian University. 2012. 8-9 (in Chinese)

[14] Vardy A E, Brown J M B. Transient turbulent friction in fully rough pipe flows[J]. *Journal of Sound and Vibration*, 2004, 270(1-2): 233-257

[15] Trikha A K. An efficient method for simulating frequency-dependent friction in transient liquid flow[J]. *Journal of Fluid Engineering*, 1975, 97(1): 97-105

[16] Kagawa T. High speed and accurate computing method of frequency-dependent friction in laminar pipe flow for characteristics method[J]. *Transactions of the Japan Society of Mechanical Engineers B*, 1990, 49(447): 2638-2643 (in Chinese)

[17] Li M Z. An approximate algorithm of friction loss term of frequency relation[J]. *Journal of Zhejiang University*, 1990, 24(1): 120-127 (in Chinese)

Quan Lingxiao, born in 1977. He received his Ph. D degree in College of Mechanical Engineering of Yanshan University in 2010. He also received his B. S. degree in 2000 and M. S. degree in 2005 from Yanshan University. His research focuses on vibration mechanism and control technology of aviation/aerospace hydraulic components and system, design and development of high-performance electro-hydraulic servo control system.