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Research Article

Influence of Support Stiffness on Dynamic Characteristics of the Hydraulic Pipe Subjected to Basic Vibration

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The basic vibration generated during the tunneling process of hard rock tunnel results in the change of the support stiffness of the hydraulic pipe, which causes the problem of reduction of pipe transmission efficiency. A transverse motion equation of the hydraulic pipe was established by correlating with Hamilton's principle under basic vibration. In consideration of the fluid-structure interaction (FSI), the support was simplified as an equivalent and a spring. The bidirectional fluid-solid coupling analysis method was used to investigate dynamic characteristics of the pipeline under different support stiffness conditions. The finite element method (FEM) and the experimental analysis are applied to verify the proposed methodology. The numerical results show that the maximum displacement of the pipe decreases with the increase of the support stiffness; the maximum stress of the pipe decreases first and then increases with the increase of the support stiffness; the amplitude of the fluid pressure fluctuation at the outlet of the pipe increases with the increase of the support stiffness. But the fluid pressure fluctuation with the higher stiffness is first stable, which can indicate that the support stiffness can increase the damping of the pipe system. This study can get a significant access to the structural design of the pipeline under basic vibration.

1. Introduction

The support stiffness of a pipe usually shows the ability of resistance to displacement and deformation of the pipe at the point of contact between the support and the pipe. The hydraulic pipeline on the TBM is usually fixed on the pedestal. With the increasing working time, the vibration caused by the bearing and other factors such as corrosion, the loosening of the pipe will aggravate to make the elastic deformation of the support contact, and the pretightening force becomes smaller, which can lead to reduction of the pipe support rigidity. At this point, the support of pipeline is no longer in the original state. The change of this support form will accelerate the wear of the pipeline. In severe cases, the natural frequency of the pipe structure will change and the resonance of the pipe system will easily occur, which can lead to a great damage.

Without considering the influence of the radial inertia force of the pipeline, Wiggert et al. [1, 2] got relations between the lateral motion, axial motion, and torsional motion of a fluid conveying pipeline. The fluid-solid coupling equations of the pipeline were changed from a 4-equation model to a 14-equation model. The characteristics method was applied to solve the equations, and the solution results have good agreement with the experimental results. Chellapilla and Simha [3] used the Fourier transform and Galerkin discrete method to solve the critical flow velocity of the pipeline based on the two-parameter elastic foundation model and found that the sheared foundation parameters cannot be ignored. Compared with the Winkler parameter, it has a greater influence on the critical flow velocity of the pipeline than that. Huang et al. [4] studied the modal frequencies of the pipeline under four different boundary conditions by applying the Galerkin method. The effect of the presence or absence of the Coriolis force on the modal frequencies was developed comparatively, and the dimensionless critical velocity of the pipe was identified. The effects of stiffness, mass, length, and fluid velocity on the modal frequencies were analyzed in detail. Paidoussis and Li [5, 6] discussed the dynamic characteristics of a three-dimensional cantilever conveying fluid pipeline with elastic support and additional mass at the end and improved the dynamic characteristics of the pipeline by changing the additional mass of the pipeline end. It was found that the flutter of the plane would lead to instability of the pipeline. When the flow rate of the pipeline increased above the critical flow rate, high-order bifurcations and almost periodic vibrations would occur until chaos. Considering the effects of wall thickness, fluid pressure, and flow velocity, Li et al. [7] solved the fluid-structure coupled 14-equation model using the transfer matrix method and analyzed the influence of structural parameters and fluid parameters on the dynamic characteristics of the pipeline. Gu et al. [8] studied the FSI dynamic characteristics of conveying fluid pipeline clamped on both ends and analyzed the effects of flow velocity and mass ratio on the deformation and natural frequency of the pipeline. Gomes Bastos [9] proposed a fluid-structure-coupled 8-equation model by using the Gear stiffness method and the Glimm method, and the results were in good agreement with the experimental data used in the literature to some extent. Firouz-Abadi et al. [10] applied the method of boundary element and modal analysis to establish the fluid-structure interaction model of the pipeline and confirmed that the model stability can be analyzed by arbitrary geometric cross section pipelines. Zhang and Tijsseling [11] discussed the fluid-solid coupling vibration characteristics of the conveying fluid pipeline in the axial direction and derived the transient vibration differential equations of liquid-solid coupling using the Fourier transform and the method of characteristics. M. Nikolic and Rajkovic [12] proposed Lyapunov–Schmidt reduction order and singularity theory to analyze the static bifurcation characteristics of several nonlinear models of the two-end fixed fluid pipelines and studied the effects of gravity, radius of curvature, and different elastic supports on the stability of the pipe. M. Kheiri and Paidoussis [13] established the linear dynamic equation of a flexible pinned-free axial motion flow pipe by Hamilton principle, solved the equation by Galerkin's method, analyzed the influence of the critical velocity on the stability of the pipe, and verified the correctness of this method by experiments.

In summary, the above studies mainly analyzed the dynamic characteristics of the conveying fluid pipeline; few research studies have developed the dynamic characteristics under basic vibration. Therefore, this paper proposed an approach to dynamic characteristics analysis of the pipeline by considering the influences of the support stiffness. This method will provide some theoretical insight for the design of the pipeline.

2. Mathematical Modeling

Assume that the straight hydraulic pipeline is an isotropic, linear elastic homogeneous section circular pipe installed horizontally. Figure 1 shows the simplified model of the pipeline. Regardless of the initial stress of the pipeline, the fluid-solid coupling analysis ignores the cavitation effect as well as the coupling effect between the transverse and axial vibrations of the pipeline.

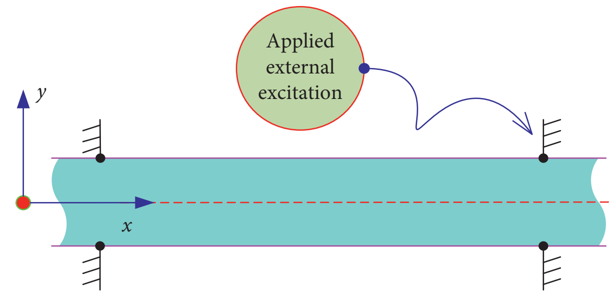

Figure 1: Simplified model.

The equation of the lateral motion of a pipeline conveying fluid can be expressed as follows:

$$\mathrm{EI}\frac{\partial^4 y}{\partial x^4}+\left[MV^2+PA(1-2\nu)\right]\frac{\partial^2 y}{\partial x^2}+(M+m)\frac{\partial^2 y}{\partial x^2}+2MV\frac{\partial^2 y}{\partial x\partial t}=0, \tag{1}$$

where EI is the flexural rigidity of the pipe; M and m are the fluid and pipe of the quality per unit length, respectively; V is the velocity of the fluid; P is the fluid pressure; A is the cross-sectional flow area; and ν is Poisson's ratio.

Considering the lateral vibration signal is denoted as $Y = N\sin(\omega t)$, the equation of the motion of a pipeline conveying fluid under basic vibration can be expressed as follows:

$$EI\frac{\partial^4 y}{\partial x^4}+\left[MV^2+PA(1-2\nu)\right]\frac{\partial^2 y}{\partial x^2}+(M+m)\frac{\partial^2 y}{\partial x^2}+2MV\frac{\partial^2 y}{\partial x\partial t}=(M+m)gN, \tag{2}$$

where N is the amplitude of outside excitation and ω is the frequency of outside excitation.

The pipe in the TBM hydraulic system is fixed by pipe clamps and bolts, which is equivalent to the elastic support of the pipe in three directions. Because the external excitation of the pipe acts on the lateral, the Y-axial elastic support is the main one. The simplified model of the pipeline is shown in Figure 2.

The force balance equation of the elastic support pipe on both sides of the support point can be written as follows:

$$F_Z^R = F_Z^L - ky, \tag{3}$$

where F_Z^R and F_Z^L are the forces on both sides of the support point, respectively; k is the elastic stiffness; and y is the displacement of the pipe.

The absolute displacement of the pipeline can be written as $\overline{y} = y - Y$ by considering the basic vibration, and then the force balance equation on both sides of the support point can be expressed as follows:

$$F_Z^R = F_Z^L - k\overline{y} = F_Z^L - k(y-Y) = F_Z^L - ky + kN\sin(\omega t). \tag{4}$$

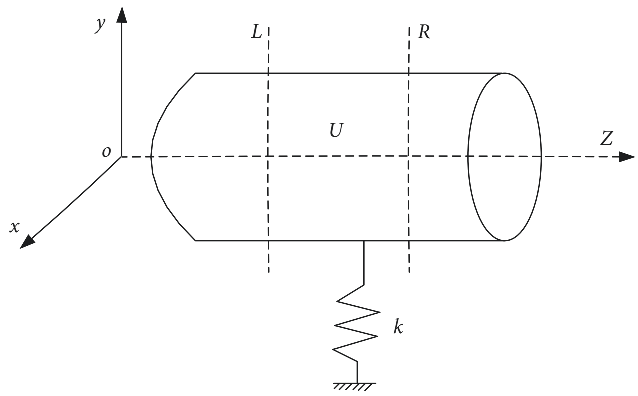

Figure 2: Structure of an elastic support unit.

Table 1: System parameter settings.

Parameter name	Setting value
Pipe wall thickness (m)	0.003
Inner diameter of pipe (m)	0.019
Pipe elastic modulus (Pa)	2.01×10^{11}
Pipe density ($kg \cdot m^{-3}$)	7850
Fluid density ($kg \cdot m^{-3}$)	870
Poisson's ratio	0.3
Average pressure of fluid (Pa)	1×10^{7}
Average liquid flow rate (m/s)	5

3. Numerical Result and Analysis

3.1. Structural Parameters and Simulation Model. According to the relevant requirements and conditions, the properties of the hydraulic pipe and the parameters of the oil in the pipe during the normal operation of the hard rock tunnel are shown in Table 1.

With the data obtained by inspecting the hard rock tunnel at the construction site and the research conditions of the laboratory, a 2-meter-long pipeline was selected as the analysis object. Figure 3 provides the simulation model of the pipeline. Different methods were used to divide the pipe structure and fluid into grids. In the Design simulation, the solid pipe model was swept into grids. The results are shown in Figure 4. In Design Modeler, the fluid in the pipeline was swept, and the results are shown in Figure 5. After the grid is divided, the boundary conditions of the pipe and the fluid are set, respectively, and the external excitation is added.

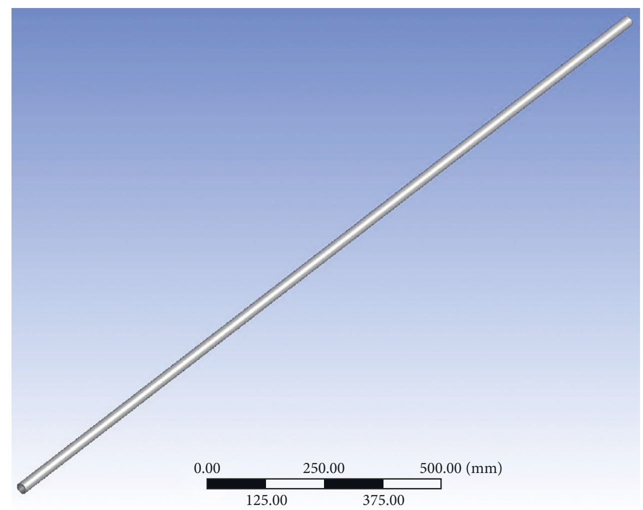

Figure 3: Simulation model.

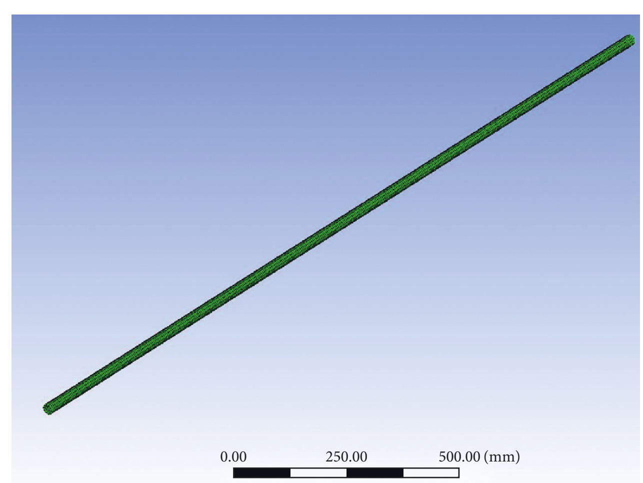

Figure 4: Grid model of the pipe.

3.2. Influence on Natural Frequency. In this work, the external excitation amplitude is set as 1 mm and the frequency is 100 Hz. The modal frequencies of the tubes under different support stiffness were simulated under different support methods. One kind of support is that one end is fixed and one end is elastically supported and the other is fixed at both ends. The magnitude of the support stiffness refers to the Lg logarithm of the constrained stiffness. The results are shown in Figure 6.

As shown in Figure 6, we can see that the first-order modal frequency changes little with the support stiffness when the magnitude of elastic support stiffness is less than 3, because the support has little effect on the pipeline when the elastic support stiffness level is small. It is the same as the single-span pipeline with no support in the middle; when the support stiffness magnitude is 3–8, the first-order modal frequency changes more obviously, and the modal frequency increases with the increase of the elastic support stiffness. In engineering practice, the vibration of the pipeline can be reduced by selecting the appropriate elastic support stiffness as a damping support; when the magnitude of the support stiffness is greater than 9, the modal frequency tends to be stable. At this time, when the stiffness of the elastic support is greater, which is equivalent to the fixed support, the modal frequency value will only tend to be the modal frequency value of the intermediate fixed support, so that there will be no great changes.

3.3. Effect on Pipe Displacement. Set the external base amplitude as 1 mm and the frequency as 100 Hz. Simulate the

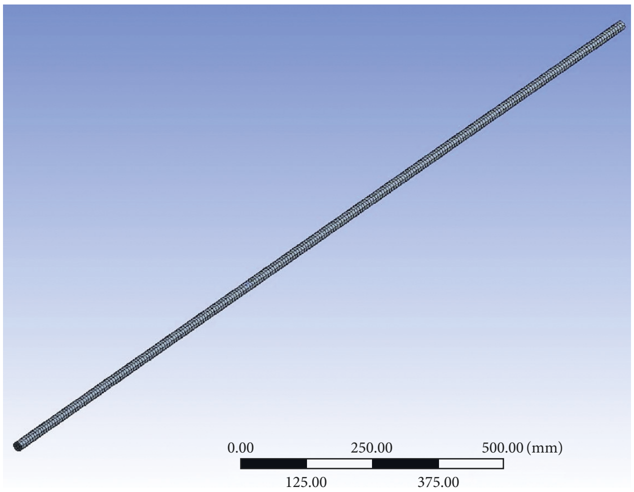

Figure 5: Grid model of the fluid.

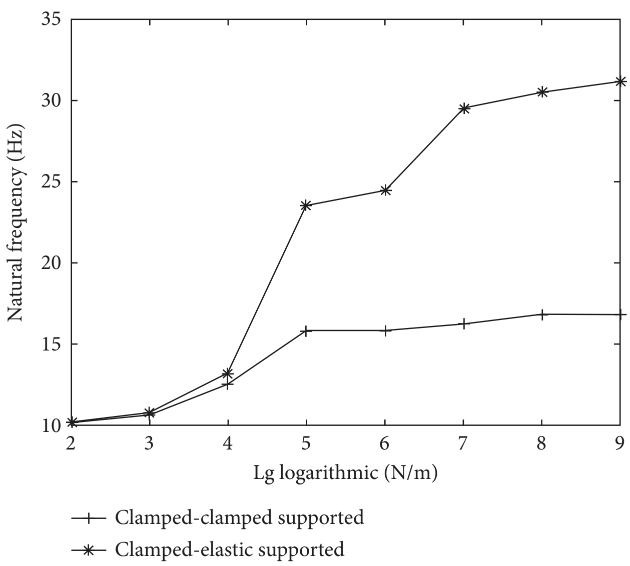

Figure 6: Natural frequency of the pipeline.

vibration displacement of the pipe having one end fixed and one end elastically supported and the pipe that is fixed at both ends under different support stiffness. The influence of the support stiffness on the vibration displacement was obtained, and the maximum displacement of the entire pipe vibration was extracted. The resulting curve is shown in Figure 7.

Figure 7 can show that when the magnitude of elastic support stiffness is less than 5, the maximum displacement of the pipe vibration remains basically unchanged. Simultaneously, the elastic support stiffness is small, as well as confinement of the pipeline, while its vibration displacement is basically unchanged. When the magnitude of the support stiffness is up from 5 to 7, the maximum displacement trend of the pipe vibration begins to decrease. When the magnitude of the stiffness is up from 7 to 9, there exists the maximum effect on the vibration of the pipeline, and the maximum displacement decreases with

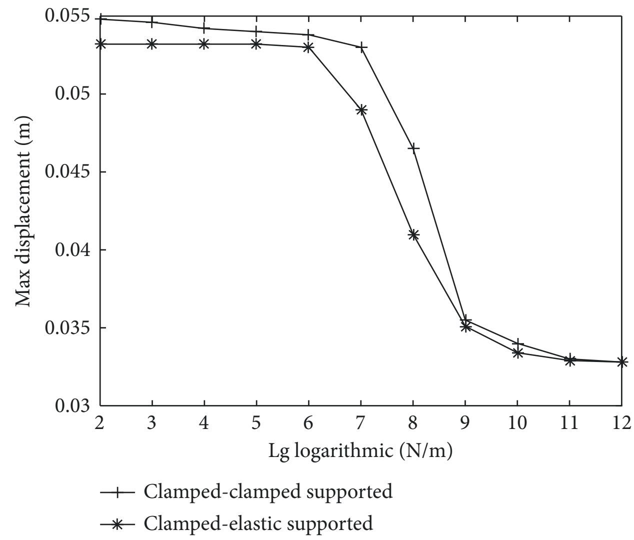

Figure 7: Maximum displacement of the pipeline.

the increase of the magnitude of the support stiffness. When the number of stiffness stages is greater than 9, the maximum displacement of the pipeline is less affected and the maximum displacement remains basically unchanged. The maximum displacement of the pipeline with one end fixed and one end elastically supported and the maximum displacement of the pipeline that is fixed at both ends are approximately equal. Due to the fact that the stiffness of the elastic support is larger at this time and the elastic support is equivalent to the fixed support, the magnitude of stiffness continues to increase, and the maximum displacement of the pipeline will not change much. From the overall perspective, the maximum displacement of the pipe with one end fixed and one end elastically supported is less than the maximum displacement of the pipe that is fixed at both ends.

3.4. Effect of Support Stiffness on Pipeline Stress. Simulate the pipe stress of the pipe with one end fixed and one end elastically supported and the pipe that is fixed at both ends under the same support stiffness. The stress value at the support of the pipeline was extracted, and the law of maximum stress variation with the support stiffness of the pipe under different restraint modes was obtained. The result is shown in Figure 8.

Figure 8 can indicate that for the pipeline with one end fixed and one end elastically supported, when the support stiffness level is less than 6, the maximum stress of the pipeline changes little with the change of the support stiffness. When the magnitude of the stiffness is greater than 6 and less than 8, the maximum stress of the pipe decreases rapidly with the increase of the support stiffness, and the pipe stress reaches the minimum when the stiffness magnitude is about 8. When the magnitude of stiffness is in the range [8, 11], the maximum stress increases rapidly with the increasing support stiffness level. When the magnitude of stiffness is greater than 11, the pipeline is equivalent to the pipeline that is fixed at both ends. The

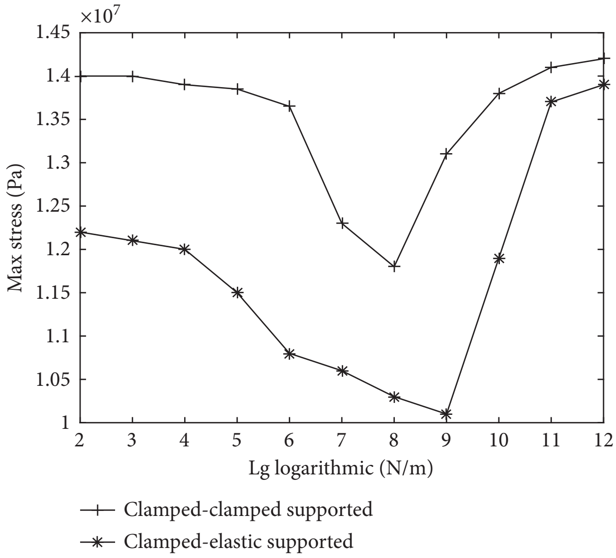

FIGURE 8: Maximum stress of the pipeline.

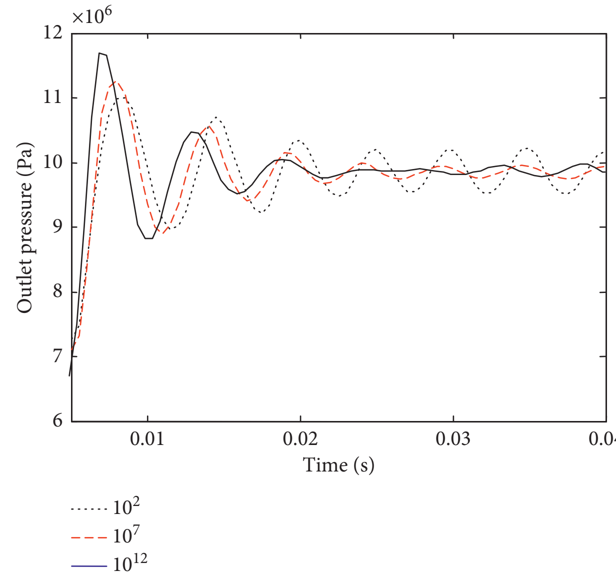

FIGURE 9: Pipeline fluid outlet pressure diagram.

maximum stress of the pipe increases slowly with the increase of the support stiffness and eventually becomes stable. In general, the law of the maximum stress of the pipeline that is fixed at both ends changing with the support stiffness is basically the same as that of the pipeline with one end fixed and one end elastically supported, but its stress value is less than the stress value of the pipeline with one end fixed and one end elastically supported under the same support stiffness.

3.5. Effect of Support Stiffness on Fluid Outlet Pressure in Pipeline. In order to analyze the influence of the stiffness of the elastic support on the fluctuation of the fluid pressure in the tube, the response characteristics of the outlet pressure of the fluid in the tube were simulated and analyzed when the support stiffness of the tube was 10^2, 10^7, and 10^{12}, respectively. The results are shown in Figure 9.

As shown in Figure 9, the average pressure at the exit of the pipe under three support stiffness conditions is lower than the pressure at the inlet of the pipe. On the one hand, it is due to the pressure loss along the process of fluid flowing through the long pipeline; on the other hand, the fluid-structure interaction will increase the energy loss and pressure loss of the pipeline. At the beginning of the fluid pressure fluctuation at the outlet of the pipeline, the smaller the support stiffness, the smaller the amplitude of the fluid pressure fluctuation at the outlet of the pipeline. It shows that the smaller the stiffness of the elastic support is, the slower the response of the pipeline system is. It means that the smaller support stiffness will weaken the vibration of the pipeline to a certain extent when the vibration just starts to occur; with the passage of time, the fluid pressure fluctuation at the outlet of the pipe with the stiffness stage of 12 is the first to stabilize in three different kinds of support stiffness series. It means that the larger the support stiffness is, the smaller the outlet pressure fluctuation amplitude of the pipe is. It shows that the larger support stiffness can increase the damping of the pipeline system, and the pipeline system can be more easily stabilized.

4. Experimental Result and Analysis

4.1. Experimental Principle and System Diagram. The experimental system of hydraulic long pipeline vibration characteristics includes four parts: electromagnetic vibration system, hydraulic control circuit system, pipeline system to be measured, and data monitoring and acquisition analysis system. Simulate the working state of the hydraulic system under the basic vibration, test the stress of the pipeline under different basic vibration parameters, obtain the variation law of the long pipeline stress under different vibration parameters, and compare the simulation results to verify the correctness of the simulation results. Figures 10 and 11 show the experimental schematic and experimental system diagrams, respectively.

4.2. Experiment Process

(1) Install pipe clamps on the vibration table so that the pipe does not loosen during vibration.

(2) Polish the test point of the pipe and wipe it with alcohol. After it is volatilized, stick the strain gauge and temperature compensation sheet, and then connect the stress tester.

(3) After the experimental pipe is connected to the hydraulic system through the host and pipe joint, transport the oil to the pipeline by the hydraulic pump and control the action of the hydraulic cylinder by the valve. Then, set the power loop of the hydraulic system to flow rate and pressure, and then open the long pipeline hydraulic system.

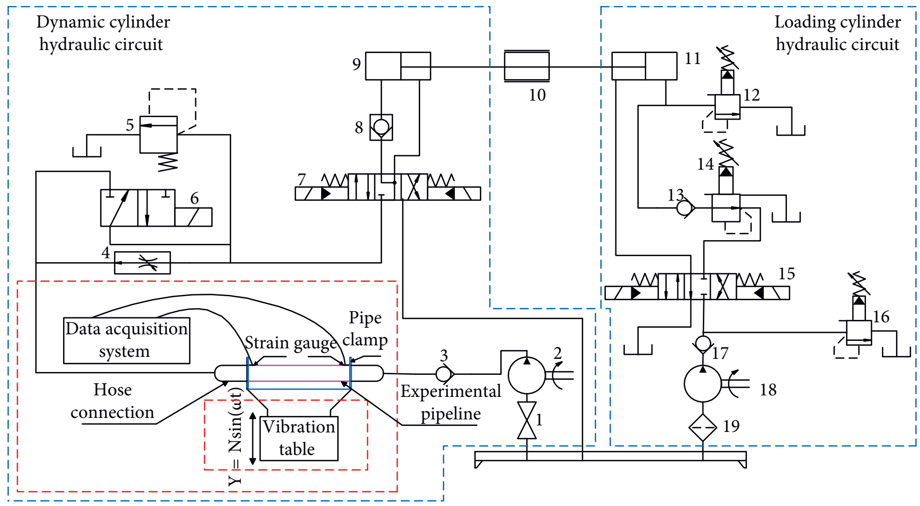

Figure 10: Schematic test diagram of the pipeline. (1) Oil source switch; (2) variable pump; (3), (13), and (17) check valve; (4) speed valve; (5) electromagnetic relief valve; (6) directional valve; (7) electromagnetic directional valve; (8) fluid-operated check valve; (9) power cylinder; (10) inertia load; (11) load cylinder; (12) electromagnetic relief valve; (14) electromagnetic proportional pressure reducing valve; (15) electromagnetic reversing valve; (16) relief valve; (18) ration pump; (19) filter.

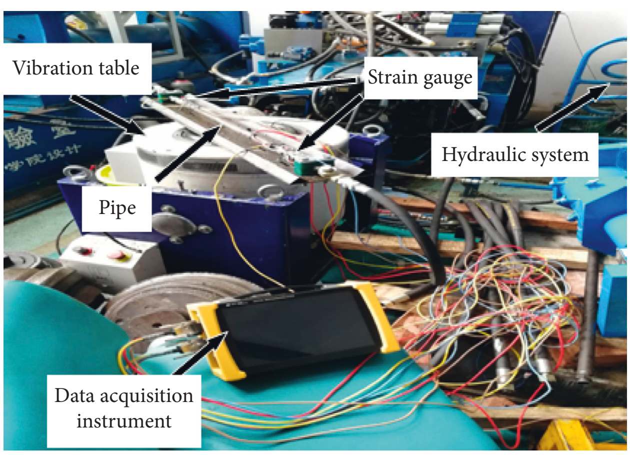

Figure 11: Experiment system diagram.

(4) Open the L620 vibration test bench and transfer the sinusoidal signal to the vibration test bench through the MPA102 switch power amplifier, so as to simulate the pipeline under test and make it vibration.
(5) Adjust the vibration table system software to set the basic vibration value, collect the stress of pipeline vibration under different vibration amplitude and frequencies through DH5925 dynamic signal test, and then process and analyze the vibration signal of the experimental pipe.

4.3. Result Analysis. To simulate the vibration experiment of the long hydraulic pipe in TBM under the external basic vibration environment, the experimental object is selected as an ordinary steel pipe with a length of 2 m, an inner diameter of 19 mm, and a wall thickness of 3 mm. The vibration characteristics of the single-span pipe were analyzed under the same basic vibration parameters. The frequency is 100 Hz, the amplitude is 1 mm, and the support stiffness is 10^7. The stress response curve is obtained and compared with the experimental results. The results are shown in Figures 12 and 13.

From the comparison between Figures 12 and 13, it can be seen that the experimentally measured results of the stress at the fixed branch of the pipe are approximately the same as those obtained from the simulation. It can be seen that the maximum value of the stress in the simulation diagram is 34.38 MPa, and the minimum value is −32.57 MPa. The maximum stress in the test results is 29.86 MPa, and the minimum value is −29.43 MPa. Therefore, the corresponding errors between the two are 15.14% and 10.67%, respectively. The experiment verified the correctness of the simulation model within the allowable range of error.

To increase the credibility of the test results, the basic vibration frequency is set to 40 Hz. The change of strain in amplitude from 0.3 mm to 1.4 mm was studied, and the stress variation curve under different amplitudes was obtained by conversion, and the results are shown in Figure 14.

The experimental results and simulation results are nearly the same. The stress value of the pipeline increases with an increase in the basic vibration amplitude. The maximum error is 13.37%, and the average error value is 8.89%, which is within the range of error allowed by the experiment.

5. Conclusions

(1) The lateral 4-equation model of the pipeline under the basic vibration and the force equation of the support are derived; the bidirectional fluid-solid coupling simulation model of the pipeline under the basic vibration was established, and the correctness of the simulation model was verified by experiments.

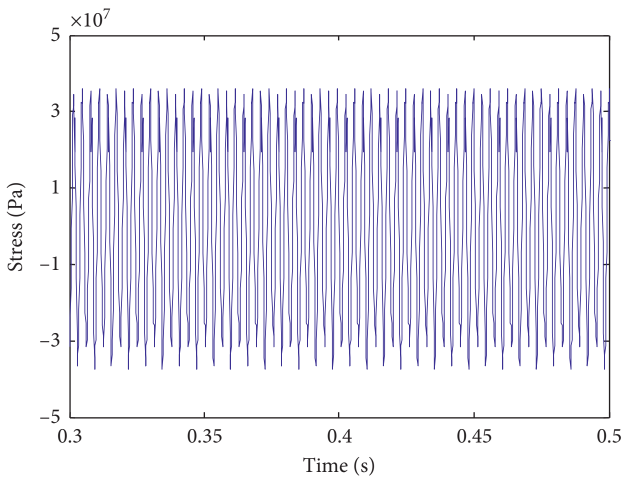

Figure 12: Stress pipeline of the simulation.

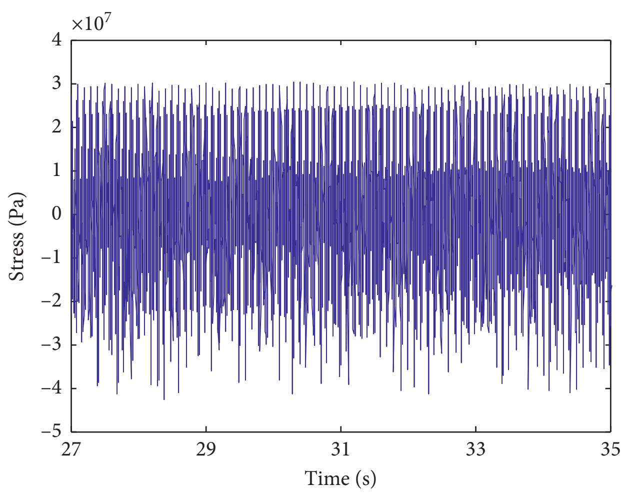

Figure 13: Stress pipeline of the experiment.

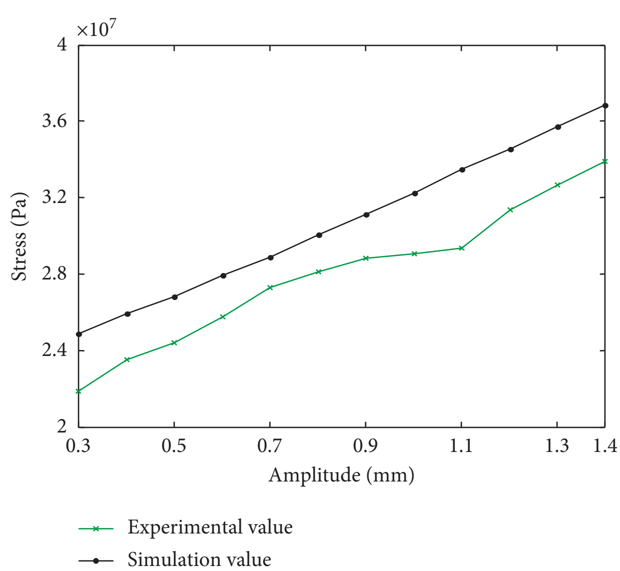

Figure 14: The stress of experiment and simulation under different basic vibration amplitudes.

(2) The maximum displacement of the pipeline with one end fixed and one end elastically supported and the maximum displacement of the pipeline that is fixed at both ends are reduced with the increase of the support stiffness. Under the same support stiffness, the vibration displacement of the pipeline with one end fixed and one end elastically supported is smaller than the pipeline that is fixed at both ends. The maximum stress of the pipe decreases first and then increases with the increase of the pipe support stiffness, which shows that choosing proper pipe support stiffness can reduce the vibration of the pipe.

(3) The amplitude of the fluid pressure fluctuation at the outlet of the pipeline increases with the increase of the support stiffness. When the magnitude of the support stiffness is 12, the pressure fluctuation amplitude at the outlet of the pipeline is 4.8 times that of the stiffness level 2. However, as the time passes, the pressure fluctuations with greater support stiffness stabilize first, indicating that larger support stiffness can increase the damping of the pipe system and the pipe system can be more easily stabilized.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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