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## Dynamic Characteristic Analysis for Fluid-Conveying Pipe of TBM

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# Dynamic Characteristic Analysis for Fluid-Conveying Pipe of TBM

Ting Chen<sup>1,2,\*</sup>

<sup>1</sup>State Key Laboratory of High Performance and Complex Manufacturing, Central South University, Changsha 410083, China

<sup>2</sup>College of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China

\*Corresponding author email: 476734668@qq.com

**Abstract.** Aiming at the influence of the strong vibration generated in the working process of the full-section hard rock tunneling machine on the response characteristics of the hydraulic straight pipe, according to the fluid-solid coupling theory and forced vibration theory, the transverse motion mathematical model of the straight pipe under the basic vibration was established. The model was solved by Galerkin method, and the correctness of the model was verified by experiments. The influence of foundation vibration parameters and fluid velocity on the response characteristics of straight pipe is analyzed by simulation. It is found that the vibration amplitude of straight pipe increases with the increase of foundation vibration amplitude and foundation vibration frequency. The higher the foundation vibration frequency, the smaller the liquid velocity is when the straight pipe resonates. At the same time, the working failure areas of straight pipe under different dimensionless velocity and fluid-pipe mass ratio are obtained. The research provides some theoretical basis for the vibration resistance design of TBM direct pipeline.

## 1. Research background

Straight pipelines have a large number of applications in the hydraulic systems of construction machinery such as the full-face tunnel boring machine (TBM). The sudden change of load and strong vibration generated during the mechanical work process cause the hydraulic pipeline to be strongly disturbed, resulting in unstable working performance of the hydraulic pipeline. In severe cases, the pipeline may be damaged and damaged, resulting in immeasurable loss [1-3]. Therefore, when analyzing the response characteristics of straight pipelines, it is important to consider the influence of fundamental vibrations on the design and selection of pipelines with strong vibration environment.

Yang Dawei et al [4] studied the vibration characteristics of hydraulic long pipelines, and used ADINA software to simulate the influence of the number of intermediate supports on the lateral displacement of pipelines. Shen Rongying et al [5-6] studied the dynamic response characteristics of liquid-filled straight pipes. From the energy point of view, increasing the ratio of diameter to thickness and the ratio of internal liquid to pipe material density will enhance the coupling degree of the system and reduce the response quality of the system. Wang Chao [7] used the precise time-integration method to analyze the dynamic response of the fluid-solid coupling pipeline system, and obtained the time history diagram and the vibration pattern of the displacement response of the cantilever pipeline under the uniform load. Zhu Weiping [8] studied the effects of flow rate, hydraulic pressure and external

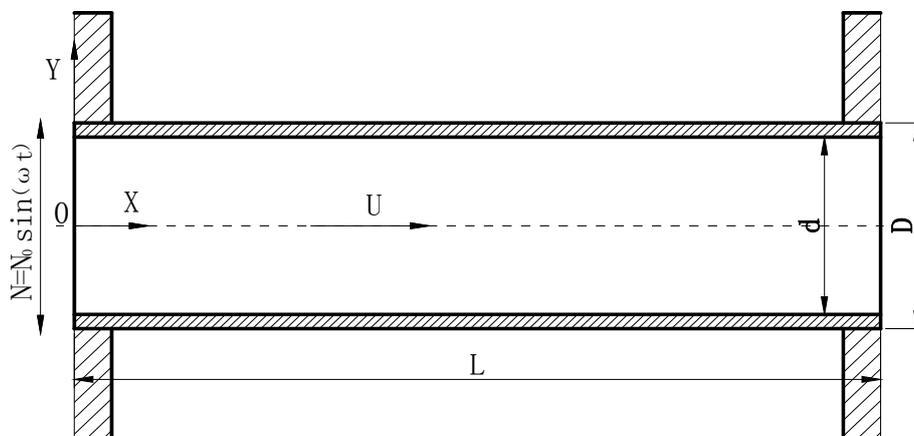


frequency variation on the midpoint deflection and maximum bending moment of the solid-hinge support pipe. Jin Jiduo et al [9-10] studied the bifurcation and chaos behavior of the pipeline under the joint-strong excitation, and obtained the bifurcation diagram of the point displacement value of the pipeline under different pipeline system parameters. Qi Zhengyu [11] studied the bifurcation characteristics of hydraulic straight pipeline under basic vibration and its correlation with equivalent natural frequency, and obtained the influence of fluid parameters and structural parameters on pipeline instability. Xia Li [12] studied the stress distribution of suspended pipelines with different lengths during geological disasters, and obtained the critical length of pipeline failure. M. Menskykova [13] studied the stress distribution of composite pipes under different pipe diameters, and analyzed the functional relationship between pipe stress and pipe material properties under different structural parameters. MENG Dan [14] et al. used the incremental harmonic balance method to study the nonlinear model of the pipeline, and obtained the time history diagram of the midpoint displacement of the pipeline at different flow rates. The above research analyzes the vibration characteristics of the pipeline to a certain extent, but there are few studies on the influence of the basic vibration on the pipeline system and the specific influence of the liquid flow velocity on the pipeline amplitude.

This paper analyzes the influence of basic vibration and liquid flow rate on the pipe amplitude, and provides a reference for the design and selection of straight pipe structure under vibration environment.

## 2. Mathematical model of the pipeline under the basic vibration

Most of the hydraulic straight pipes are fixed on the foundation of the machine with rigid support, intercepting a section of pipes fixed at both ends, ignoring the influence of the pipes between adjacent fixed sections. The simplified piping system model is shown in Figure 1. Dimensional flow rate of  $U$ -fluid;  $d$ -pipe inner diameter;  $D$ -pipe outer diameter;  $L$ -pipe length.



**Figure 1.** Model of fixed-section pipeline system at both ends

Both ends of the viscoelastic straight pipeline are fixed on the horizontal foundation [15] and the foundation vibrates under the action of external excitation  $N = N_0 \sin \omega t$ ,  $N_0$  is the base vibration amplitude;  $\omega$  is the base vibration frequency.

Irrespective of the pulsation and lateral deformation of the fluid in the pipe, the axial elongation of the pipe causes the influence of additional axial force [16], using the Alembert principle and Newton's theorem, the transverse ( $Y$  direction) coupled vibration equation of the straight-line fixed-flow straight pipeline can be obtained:

$$EI \frac{\partial^4 y}{\partial x^4} + MU_0^2 \frac{\partial^2 y}{\partial x^2} + (M + m) \frac{\partial^2 y}{\partial t^2} + 2MU_0 \frac{\partial^2 y}{\partial x \partial t} = (M + m)N_0\omega^2 \sin \omega t \quad (1)$$

Where:  $M$  is the fluid mass per unit length;  $m$  is the mass per unit length;  $EI$  is the bending stiffness of the pipe;  $U_0$  is the average flow velocity of the fluid in the pipe;  $t$  is the time;  $x$  is the position coordinate of the cross-sectional area of the pipe;  $y$  is the deformation when the pipe vibrates laterally, and  $y \ll L$ ,  $L$  is the fixed length.

### 2.1. The dimensionlessness of the equation

In order to make the equation easy to solve, the following dimensionless parameters are introduced:

$$\begin{aligned} \eta &= \frac{y}{L}; M_r = \left(\frac{M}{M+m}\right)^{\frac{1}{2}}; d = \frac{N_0}{L}; \varepsilon = \frac{x}{L}; \\ \tau &= \left(\frac{EI}{M+m}\right)^{\frac{1}{2}} \frac{t}{L^2}; n = \left(\frac{M+m}{EI}\right)^{\frac{1}{2}} \omega L^2; \\ u &= \left(\frac{M}{EI}\right)^{\frac{1}{2}} U_0 L; \rho = \left(\frac{M+m}{EI}\right)^{\frac{1}{2}} \rho L^2 \\ \eta''' + u^2 \eta'' + \eta' + 2M_r u \eta' &= dn^2 \sin n\tau \end{aligned} \quad (2)$$

### 2.2. Discretization of the equation

Discretize equation (2) using the Galerkin method to make A

$$\eta(\varepsilon, \tau) = \sum_{r=1}^N \varphi_r(\varepsilon) q_r(\tau) \quad (3)$$

Where:  $\varphi_r (r = 1, 2, 3, \dots)$  is the mode function of the fixed beam at both ends, in place of the mode function of the conveying pipe under the same boundary conditions, and

$$\begin{aligned} \varphi_r(\varepsilon) &= \cosh(\lambda_r \varepsilon) - \cos(\lambda_r \varepsilon) + \sigma_r (\sin(\lambda_r \varepsilon) - \sinh(\lambda_r \varepsilon)) \\ \sigma_r &= [\cosh(\lambda_r) - \cos(\lambda_r)] / [\sinh(\lambda_r) - \sin(\lambda_r)] \quad \lambda_1 = 4.73004 \quad \lambda_2 = 7.85320. \end{aligned}$$

According to the research of related literature, the first two modes can meet the accuracy requirements [17], so the first two steps are taken:  $\eta(\varepsilon, \tau) = \sum_{r=1}^2 \varphi_r(\varepsilon) q_r(\tau)$ .  $q_3 = q_1'$ ;  $q_4 = q_2'$ . After transformation, equation (2) can be transformed into a state equation form:

$$\begin{pmatrix} q_1' \\ q_2' \\ q_3' \\ q_4' \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ a_1 & 0 & 0 & a_4 \\ 0 & b_2 & b_3 & 0 \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ F_1 \\ F_2 \end{pmatrix} \quad (4)$$

Among them:

$$a_4 = 2Mr u_0 b ; b_3 = -2Mr u_0 b ; a_4 = 2Mr u_0 b ; b_2 = -u_0^2 c_{22} - \lambda_2^4 ;$$

$$F_1 = dn^2 \sin(n\tau) \left\{ \frac{1}{\lambda_1} [\sinh(\lambda_1) - \sin(\lambda_1) - \sigma_1 (\cos(\lambda_1) + \cosh(\lambda_1) - 2)] \right\}$$

### 3. Time domain response analysis of pipeline

The working parameters of the TBM hydraulic pipe are shown in Table 1. The effects of the fundamental vibration amplitude, frequency and dimensionless flow rate on the dimensionless displacement at the midpoint of the pipeline are simulated.

**Table 1.** Pipeline system parameters

parameter name	Set value
Pipe inner diameter / m	0.019
Wall thickness / m	0.003
Pipe support spacing / m	2
Pipe elastic modulus / Pa	$2.01 \times 10^{11}$
Liquid density / (kg · m <sup>-3</sup> )	890
Tube density / (kg · m <sup>-3</sup> )	7850
Poisson's ratio	0.3
Average fluid flow rate / (m / s)	5
Fluid average pressure / Pa	$2 \times 10^7$

#### 3.1. Pipeline dimensionless natural frequency solution

When the frequency of the fundamental vibration is close to the natural frequency of the pipeline, the pipeline resonates, causing the pipeline vibration to increase. In order to facilitate subsequent analysis, the first two natural frequencies of the pipeline model are solved first, and the equation of state (7) is abbreviated as:  $\dot{q} = Sq + F$ . The coefficient matrix  $S$  has two pairs of pure virtual eigenvalues  $\pm \omega_1 i$  and  $\pm \omega_2 i$ , where  $i$  is an imaginary unit,  $\omega_1$  and  $\omega_2$  are the first two natural frequencies of the system. Therefore, the eigenvalue of  $S$  can be obtained to obtain the natural frequency of the system. After calculation, the expression of the first two natural frequencies of the pipeline is:

$$\omega_1 = \pm \sqrt{\frac{-m + \sqrt{m^2 - 4n}}{2}} ; \omega_2 = \pm \sqrt{\frac{-m - \sqrt{m^2 - 4n}}{2}} . \text{ Among them: } m = b_3^2 - a_1 - b_2 ; n = a_1 b_2 .$$

The obtained dimensionless natural frequency is compared with the value obtained by the GITT method, and the error is within the allowable range, indicating that the numerical calculation method is effective, and the error may be derived from the accuracy of the numerical calculation method. As shown in Table 2:

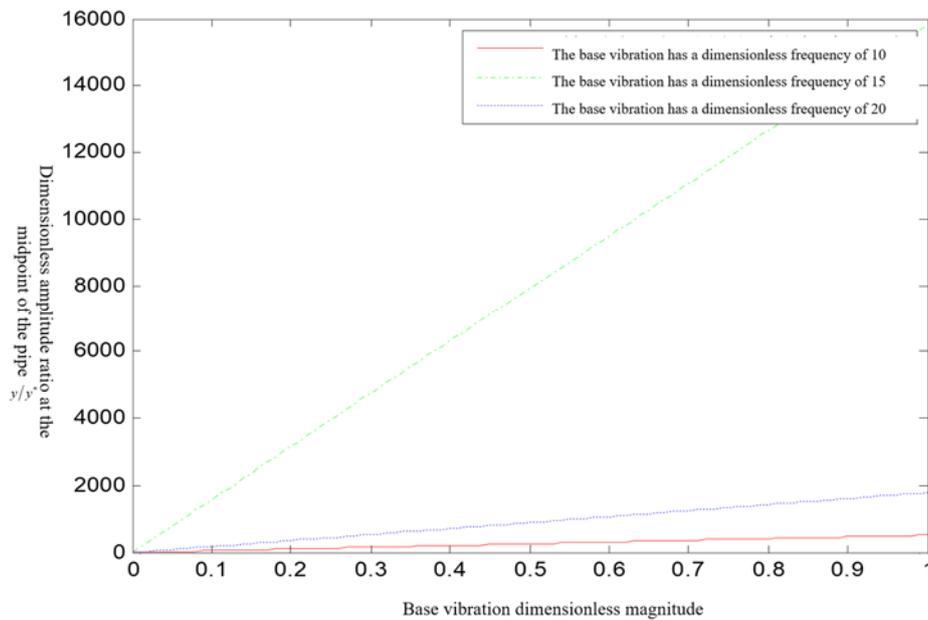
**Table 2.** Comparison of the dimensionless natural frequency of pipelines

Natural frequency (Hz)	$\omega_1$	$\omega_2$
Calculation results	14.6572	57.9650
Experimental result	14.4513	54.5740

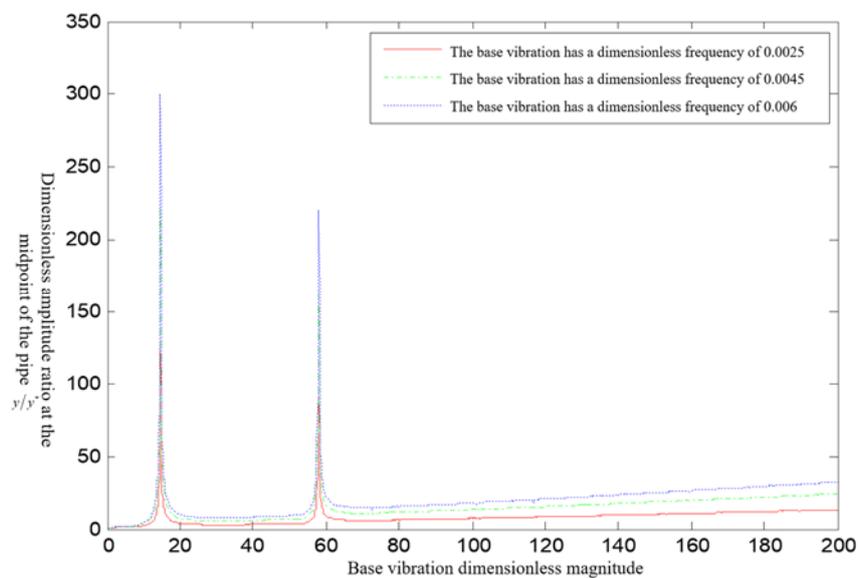
#### 3.2. Influence of basic vibration on pipe amplitude

Set the flow velocity and pipeline structural parameters to constant values, and analyze the variation of the displacement amplitude at the midpoint of the pipeline with the fundamental vibration frequency and amplitude according to the fundamental vibration frequency and amplitude. The analysis results are

shown in Figure 2 and Figure 3. The ordinate is the dimensionless amplitude ratio at the midpoint of the pipe,  $y/y^*$ , where  $y$  is the midpoint displacement amplitude of the pipe with fundamental vibration, and  $y^*$  is the midpoint displacement amplitude of the pipe without foundation vibration.



**Figure 2.** The variation of the amplitude ratio of the midpoint of the pipeline with the amplitude of the fundamental vibration



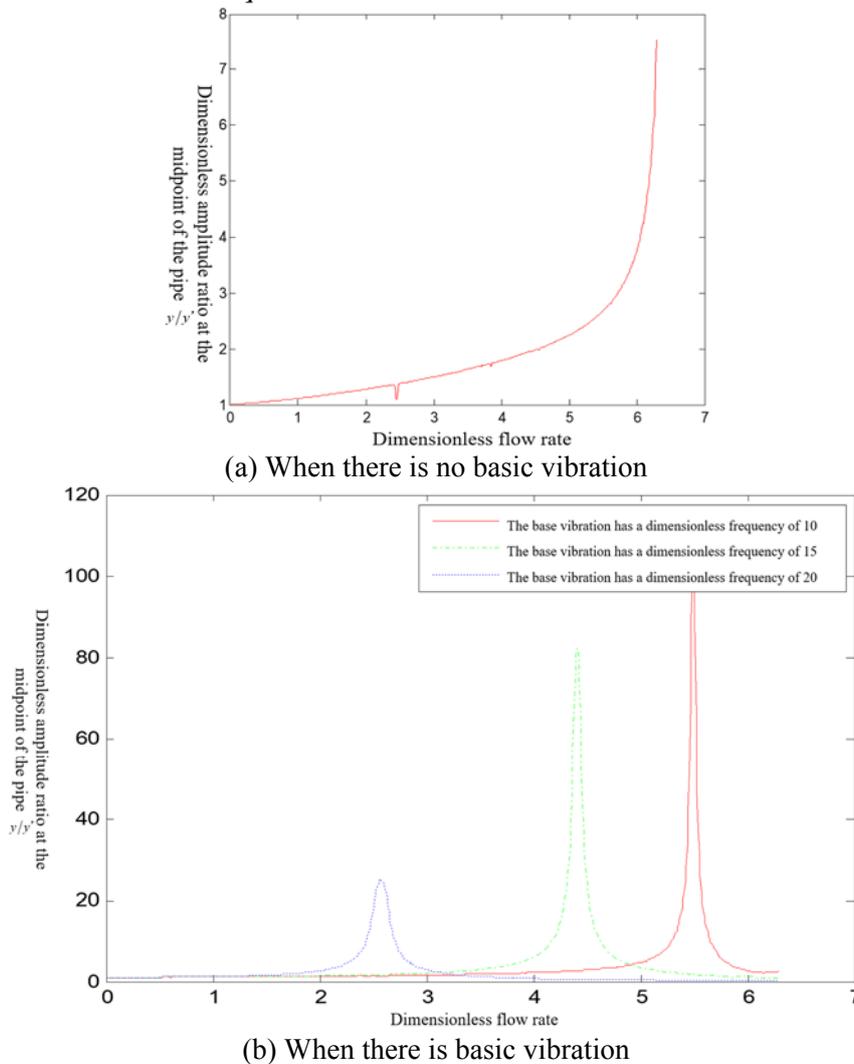
**Figure 3.** The variation of the amplitude ratio of the midpoint of the pipeline with the vibration frequency of the foundation

In Fig. 2, as the amplitude of the fundamental vibration increases, the point displacement in the pipeline increases almost linearly, but the slope of the displacement increases at different fundamental vibration frequencies. The slope of the displacement curve when the fundamental vibration has a dimensionless frequency of 15 the largest, the basic vibration dimensionless + frequency is 20 times,

and the minimum vibration of the fundamental vibration is 10 hours. This is because the fundamental vibration has a dimensionless frequency of 15 and is closest to the first-order natural frequency of the pipeline. The resonance of the pipeline causes the pipeline amplitude to increase sharply. It can be seen from Fig. 3 that the point displacement in the pipeline gradually increases with the increase of the fundamental vibration frequency, but in the vicinity of the natural frequencies of the pipeline, the pipeline resonates and the displacement of the pipeline increases sharply. The maximum increase ratio is nearly 300 times. When the pipeline is unable to meet the stability and reliability requirements of the work, it is considered that the work is invalid.

### 3.3. Influence of dimensionless flow rate on pipe amplitude

In order to study the influence of flow velocity on pipeline vibration, the variation law of the dimensionless amplitude ratio  $y/y'$  of the pipeline with basic vibration and no foundation vibration (where  $y'$  is the midpoint velocity of the pipeline without flow velocity) is analyzed. Fig. 4 is the analysis result of the variation of the dimensionless amplitude ratio of the midpoint of the pipeline with the dimensionless flow velocity without the basic vibration. Fig. 5 is the variation law of the dimensionless amplitude ratio of the pipeline midpoint with the dimensionless flow velocity under different fundamental vibration frequencies.



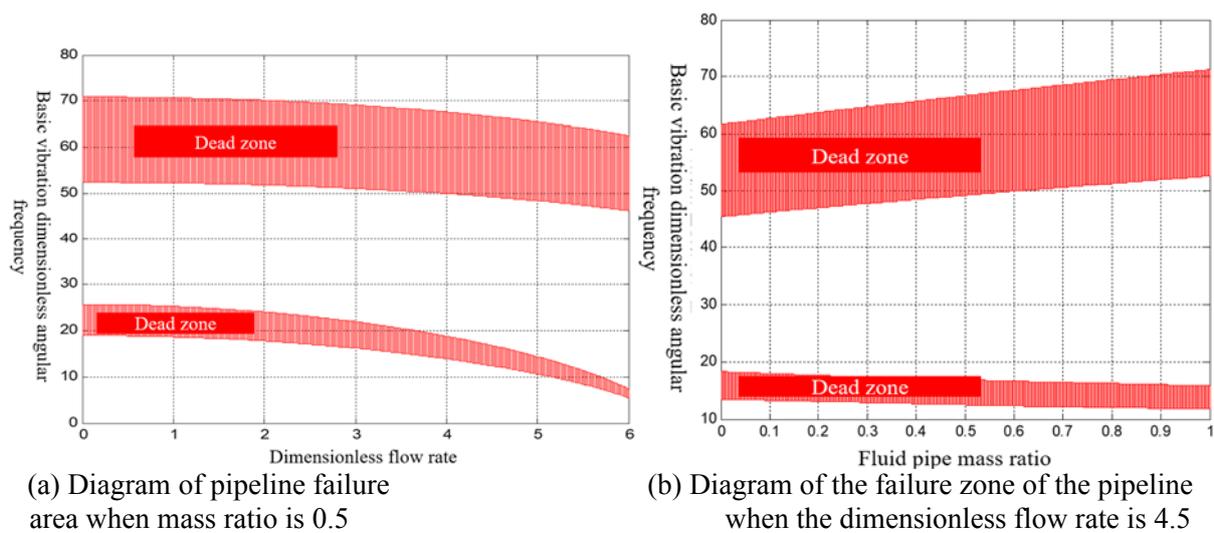
**Figure 4.** The variation of the amplitude ratio of the midpoint of the pipeline with the dimensionless flow velocity

It can be seen from Fig. 4(a) that when there is no fundamental vibration, the vibration amplitude of the pipeline increases with the increase of the dimensionless flow velocity, and as the flow velocity increases, the velocity of the pipeline vibration increases more and more. When the dimensionless flow rate is close to 6, the displacement of the pipeline increases sharply. When the flow rate exceeds 6, the displacement of the pipeline increases to infinity. At this time, the natural frequency is less than zero, that is, the pipeline is divergent and unstable.

As can be seen from Fig. 4(b), when there is a fundamental vibration, as the dimensionless flow velocity increases, a sudden increase in the pipe amplitude ratio occurs, and the larger the fundamental vibration frequency, the smaller the flow velocity value at the time of the surge, which is due to the increase of the flow rate reduces the natural frequency of the pipeline. In the process of increasing the flow velocity, the pipeline first resonates when the fundamental vibration frequency is large.

#### 4. Loss straight pipeline failure zone

Basic vibration and pipeline resonance are the most important factors to aggravate pipeline vibration and work failure. In the mechanical working process, the existence of basic vibration is inevitable. Therefore, it is necessary to reduce the vibration degree of the pipeline as much as possible, and only try to avoid the pipeline. Resonance. Therefore, in order to design a pipeline that can work stably under strong vibration conditions, it is necessary to understand the region where the pipeline resonates under different vibration frequencies and different structural parameters, that is, the failure region of the pipeline.



**Figure 5.** Diagram of the failure zone of the pipeline under basic vibration

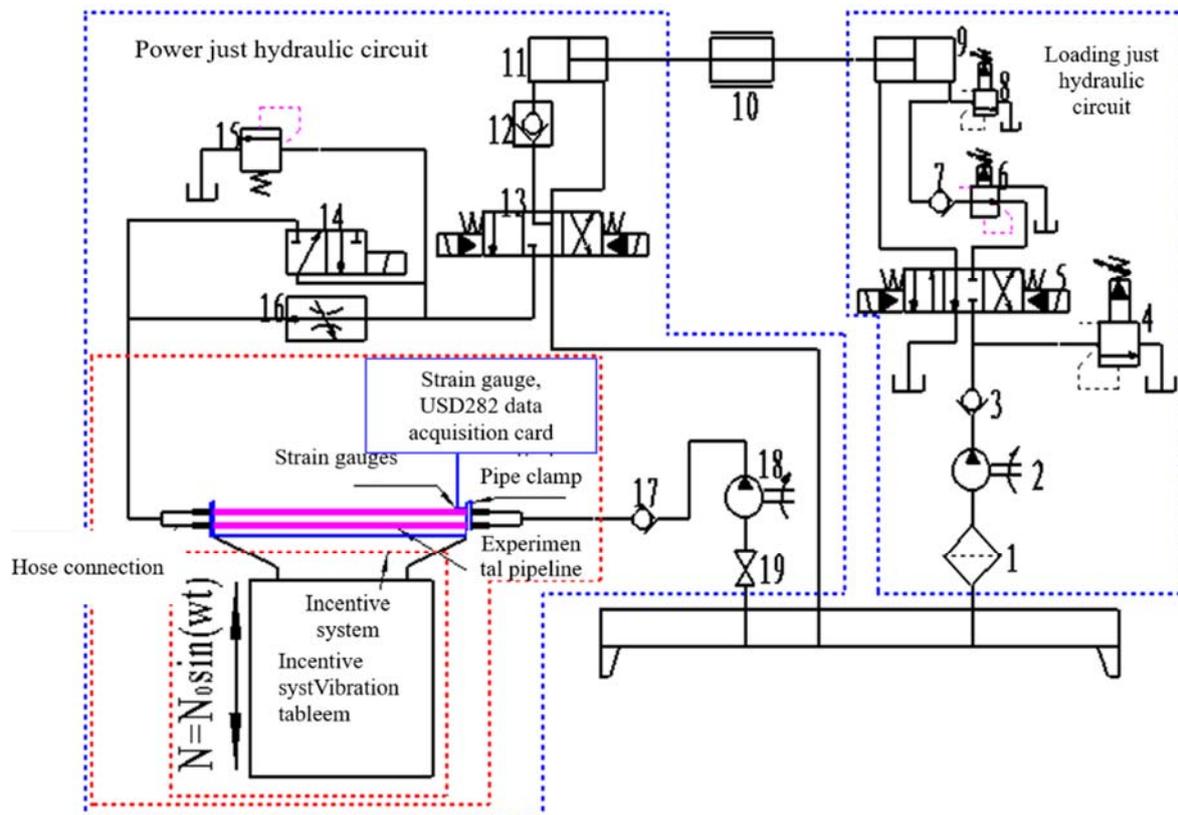
According to the vibration stability criterion of the project, it is necessary to ensure that the natural frequency of each part of the machine excited by the vibration is staggered from the frequency of the excitation source. Generally, the condition should be satisfied:  $0.85f > f_p$  or  $1.15f < f_p$ , which represents the natural frequency of the part, which represents The frequency of the excitation source. Therefore, it can be considered that the pipe resonates when the natural angular frequency of the pipe  $\omega_e$  and the fundamental vibration angular frequency satisfy  $0.85\omega < \omega_e < 1.15\omega$ .

Since the pipeline structural parameters (fixed length, pipe inner diameter, thickness, density, etc.) are included in the dimensionless flow rate  $u$  and the fluid-to-pipe quality ratio  $M_r$ , the guiding pipeline design and selection requires analysis of the pipeline at different dimensionless flow rates and masses. The time zone of work failure. The failure zone analysis results are shown in Figure 5.

In Figures 5(a) and 5(b), the dark areas indicate the zone of failure of the pipe and the pipe resonates. As the dimensionless flow rate of the branch pipe and the fluid-to-pipe mass ratio increase, the failure area of the pipe work is reduced. In the pipeline design, the vibration signal in the mechanical working process should be collected to analyze the spectrum, determine the range of the vibration frequency in the working environment, and then select the appropriate structural parameters such as the length of the pipe, the inner and outer diameter, the thickness and the density according to the vibration frequency range. , so that the pipeline avoids the failure zone in the corresponding working environment.

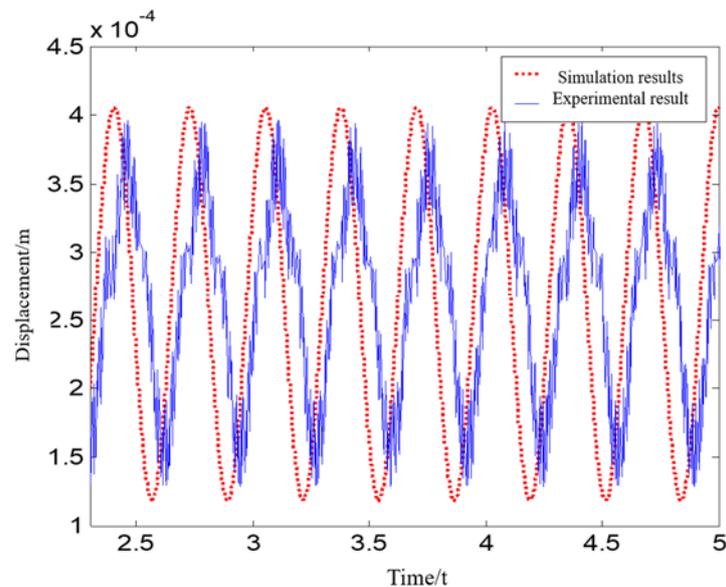
### 5. Experimental verification

In order to verify the correctness of the mathematical model of the straight pipeline, the vibration experiment of the straight pipeline under the basic vibration was designed. The experimental system consists of a hydraulic control loop, an electromagnetic vibration device, a pipeline to be tested, and a data acquisition and analysis system. The experimental principle is shown in Figure 6. The vibration amplitude and frequency required for the experiment are applied to the pipeline by the electromagnetic vibration device, and the pipeline vibration data is collected and analyzed through the data acquisition and analysis system.



**Figure 6.** Schematic diagram of the experimental system

1-filter, 2-quantitative pump, 3-way valve, 4-overflow valve, 5-electromagnetic reversing valve, 6-electromagnetic pressure reducing valve, 7-way valve, 8-electromagnetic relief valve, 9 - Loading cylinder, 10- inertia load, 11-power cylinder, 12-hydraulic check valve, 13-electromagnetic relief valve, 14-directional valve, 15-electromagnetic relief valve, 16-speed valve, 17- Check valve, 18-quantitative pump, 19-oil source switch.



**Figure 7.** Pipeline Time Domain Response Diagram

Figure 7 is a comparison of experimental test results and simulation results of a hydraulic pipe with a vibration amplitude of 1 mm and a frequency of 40 Hz. It can be seen from the figure that the midpoint displacement of the pipeline fluctuates with the vibration of the pipeline. The average value of the experimental peak is  $m$ , the average value of the experimental trough is  $m$ ; the mean value of the simulated peak is  $m$ , and the average value of the simulated trough is  $m$ ; the corresponding errors of the two are respectively the error is within a reasonable range of 2.22% and 7.03%, which verifies the accuracy of the mathematical model.

## 6. Conclusion

- (1) The mathematical model of lateral motion of the straight pipeline under the basic vibration is established, and the correctness of the model is verified by experiments.
- (2) As the amplitude of the fundamental vibration and the fundamental vibration frequency increase, the vibration amplitude of the pipeline increases.
- (3) The increase of the dimensionless flow rate reduces the natural frequency of the straight pipe; the larger the dimensionless frequency under the fundamental vibration, the smaller the dimensionless flow rate when the straight pipe produces resonance.
- (4) With the increase of the dimensionless flow rate and the fluid-to-pipe quality ratio of the straight pipeline, the failure area of the pipeline work is reduced, which provides a reference for the anti-vibration design and selection of the straight pipeline.

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