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NUMERICAL SIMULATION AND DYNAMIC CHARACTERISTICS ANALYSIS OF PULVERIZED COAL TRANSPORTATION IN ANNULAR TUBES

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In directional drilling process, the tube transport technology is a key factor to ensure the drilling process. This paper mainly studies the dynamic characteristics of tubes in the case of liquid filling. Consider the case where there is a transport fluid inside the tube, and the horizontal tube model is established. Based on the vibration characteristics of the tube, an added mass coefficient is proposed to calculate the natural frequency of the tube. Through the numerical simulation, analyzing the influence of different external conditions (fluid velocity, medium concentration) on the velocity distribution, volume fraction distribution and pressure drop model of the tube in different sections. Moreover, the natural characteristics of the tube depend on the tube design parameters (length, radius, etc.) and the volume fraction of liquid filled in the tube. Experiments verified that changing the tube design parameters can calculate the natural frequency of the tube directly. Therefore, it is feasible to propose the method of attaching the liquid mass to the tube itself to obtain the natural frequency of the tube.

According to the research, it can be concluded that : (i) The natural frequency of the tube decreases as the length of the tube increases; (ii) The increase of the volume fraction of the liquid in the tube significantly reduces the natural frequency of the tube; (iii) The velocity of the fluid in the tube has less effect on the natural characteristics of the tube itself; (ⅳ) The added mass coefficient of fluid is not a fixed value, it varies with the volume fraction of fluid in the tube.

1 INTRODUCTION

The knowledge of the advanced industrialized countries is that the losses caused by tube vibration amounted to tens or even tens of billions of dollars each year. Therefore, it is very important to ensure the safety of tube transportation during drilling. The sudden change of load and strong vibration are inevitable in the process of mechanical work, which will cause strong disturbance to the transmission tubes and leads to instable work situation [1].

The basic vibration of the outside machine and resonance of the tube are the most important factors that aggravate the vibration of the transmission tube. Therefore, it is necessary to reduce the vibration of the tube so as to avoid the resonance [2]. In the process of drilling, with the deepening of the length of the drill string in the coal seam, the natural frequency of the tube itself cannot be directly tested. When the tube filled with liquid, the change of the volume fraction in the tube is more complicated to study its vibration characteristics. The research on the dynamic characteristics of the tube itself is very necessary.

The main research on the transportation of pulverized coal in tube is to study the transportation problem of solid-liquid two-phase flow, which is limited by the huge experimental equipment and the uncertain risk of the environment under the coal seam, so that some original experiences and conclusion are not that applicable to the calculation of two-phase flow. It is difficult to meet the design requirements and operating parameters of tubes by copying the previous formula studies, and improper handling may even affect the safety of production. Thence, it is significant to have a preliminary theoretical calculation or experimental verification of the two-phase flow in the tube before transportation so as to provide a reference for the subsequent design. The drill string model is shown in Figure 1.

This paper uses loop experiments to verify the theoretical results of the two-phase flow transport tube. Based on the liquid-filled tube model, the dynamic characteristics of the tube in the liquid-filled tube were experimentally tested, and a method of calculating the natural frequency of the tube by adding the fluid quality to the tube itself was obtained. Verify the accuracy by comparing with numerical simulation and provide valuable data to the actual drill string design.

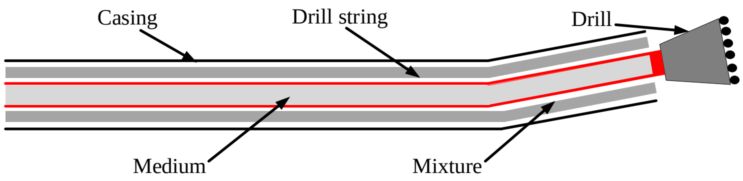


Figure 1: Drill string model

2 EXPERIMENTAL VERIFICATION

According to the actual working process of the horizontal directional drilling rig, the initial condition inlet is set as the speed inlet, the liquid inlet velocity is 3-5 m/s and the initial velocity of pulverized coal is zero [3]. Since the pressure and velocity cannot be determined until the calculation is complete, the outlet is selected as the outflow boundary condition to set the normal gradient for all flow parameters except pressure to zero [4]. For different requirements, the inner tube is set to wall, no sticky slip, the inner tube speed is 0-400 rpm.

In order to compare the influence of different transport media on the transport capacity, the main fluid medium used in this simulation is liquid water and CMC (Carboxymethyl cellulose) solution, in which the medium water can be directly applied in the material bank. CMC solution needs to be re-set in the form of new materials, the parameters are shown in Table 1. The solid material is pulverized coal particle, and the parameters of pulverized coal particle are shown in Table 2.

Table 1: Transport media parameters

Transport media	Viscosity(cP)	Density(kg/m^3)	Concentration
CMC	15.6	998.5	0.4%

Table 2: Solid material parameters

Solid material	Diameter (m)	Density(kg/m^3)	Volume fraction
Pulverized coal particle	0.0003	1556	15%

2.1 Experimental design

The main purpose of this experiment is to test the natural parameters of tubes under the condition of the change of tube parameters and the change of external parameters. Then the correctness of the experimental results is verified by numerical simulation. Because the natural frequency of the liquid filled tube is not convenient for practical applications, it is hoped that a method of calculating the natural frequency of the tube, and the natural frequency will be found by adding the quality of the liquid to the quality of the tube itself. In this experiment, PVC-U tubes are used. The principle of selection mainly depends on the fact that the density (ρ=1350/m^3) of the PVC-U tubes is similar to the density of the water in the transport medium. Therefore, the added mass of the liquid becomes one of the total mass. Thus the important part increases the influence of the liquid on the natural frequency of the tube and gives experimental results more clearly with the measurement.

During the experiment, one end of the PVC-U tube was closed with a plastic cap and the other end was a self-priming pump with the power of P=0.675kw to circulate water inside the tube. The inner tube was supported by several magnet buttons inside the outer tube to simulate annulus water gap process. The two ends of the tube used two nylon rope to straighten the level [5]. The specific experimental equipment is as shown in Figure 2. The experimental parameters used in the PVC-U tube are shown in Table 3.

Table 3: Tube parameters

Tube number	1	2	3	4	5	6	7
Outer diameter (mm)	25	25	25	40	40	40	40
Thickness (mm)	2	2	2	3	3	3	3
Length (mm)	1000	1500	2000	1000	1500	2000	2500

Modal parameters tested by experiment are reference for designing machine. The whole process of modal testing consists of two parts: the measurement of Frequency Response Functions (*FRF*) and the identification of modal parameters, these two parts are mainly tested by the modal analysis module in the system. Modal parameter measurement and analysis system is mainly composed of excitation system, vibration response pick-up system, and *FRF* measurement.

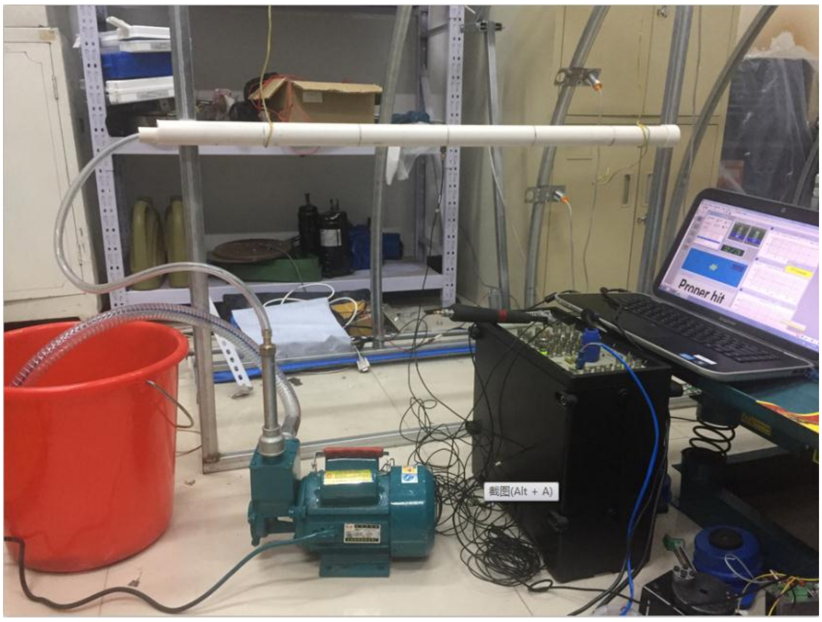


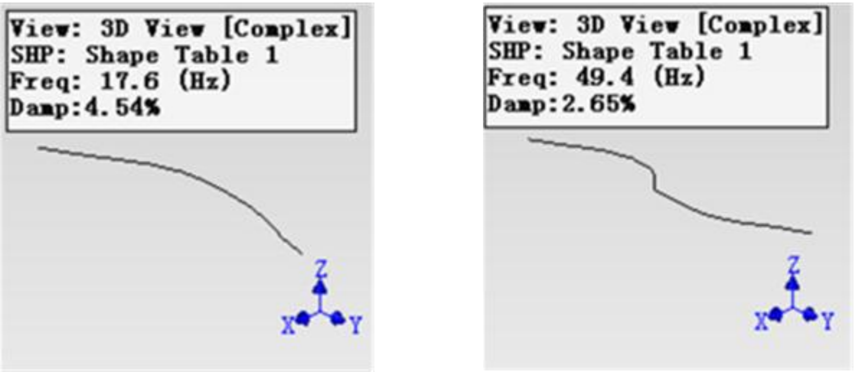
Figure 2: Experimental equipment

The specific experimental process is as follows. (i) According to the actual experiment process, selecting the way of moving the hammer to tap equal spacing points. (ii) At the corresponding measuring point, light-weighted high-sensitivity accelerometers is used to measure the vibration response of the tube. (iii) The signal from the impact hammer and accelerometer is collected by a data acquisition card to obtain *FRF* of the tube. (iv) The obtained *FRF* is imported into Me'scope V5 for data post-processing analysis to obtain the natural frequency and mode shape under the test.

2.2 Modal analysis

In order to get the natural characteristics of the tube itself and compare the change of natural characteristics under different external conditions, the experiment first conducts the modal test on the tube with the length of L_6=2000mm and the diameter of D=40mm to obtain the modes at the first four natural frequencies, the results are shown in Figure 3.

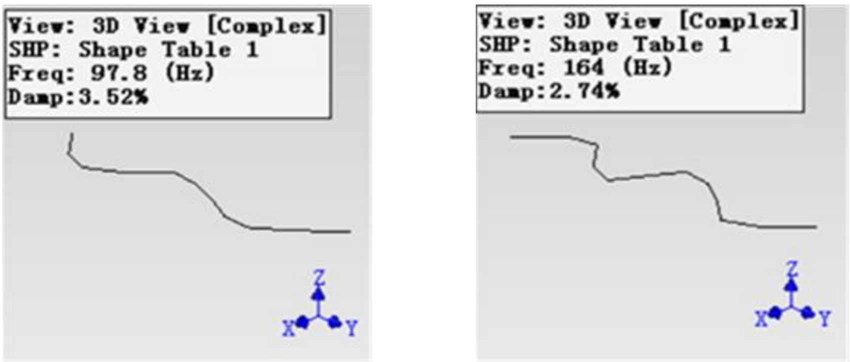
From Figure 3, it can be found that the natural frequency of each step of the tube and its mode shapes coincide with the actual ones. And compared with the subsequent simulation results, the accuracy of the experimental results can be verified.



View: 3D View [Complex]
SHP: Shape Table 1
Freq: 17.6 (Hz)
Damp:4.54%

View: 3D View [Complex]
SHP: Shape Table 1
Freq: 49.4 (Hz)
Damp:2.65%

(a) The first mode (b) The second mode



View: 3D View [Complex]
SHP: Shape Table 1
Freq: 97.8 (Hz)
Damp:3.52%

View: 3D View [Complex]
SHP: Shape Table 1
Freq: 164 (Hz)
Damp:2.74%

(c) The third mode (d) The fourth mode

Figure 3: The first four modes of the tube

2.2.1 The effect of tube length on tube natural frequency

In order to study the influence of tube length on the natural characteristics of the tube itself, regardless the change of fluid quality and tube diameter, do modal test in No. 4, 5, 6, 7 tubes without liquid.

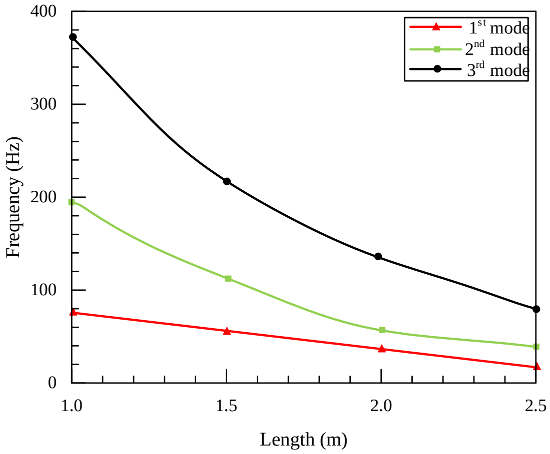
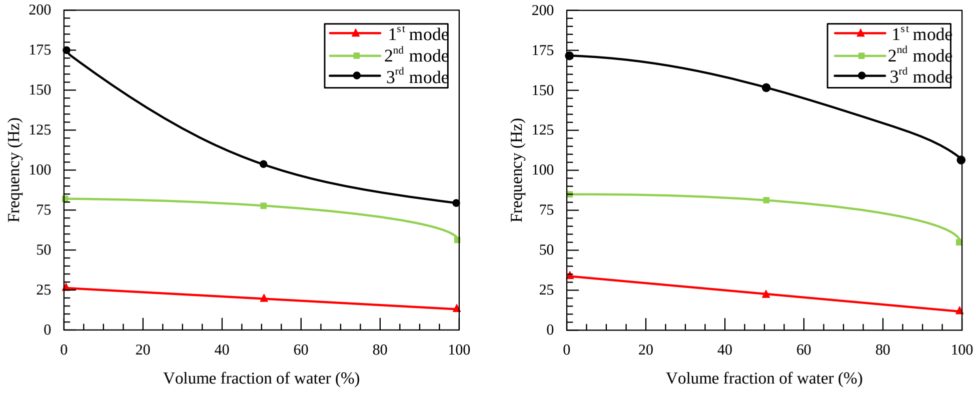


Figure 4: The first three natural frequencies of the tube under different lengths

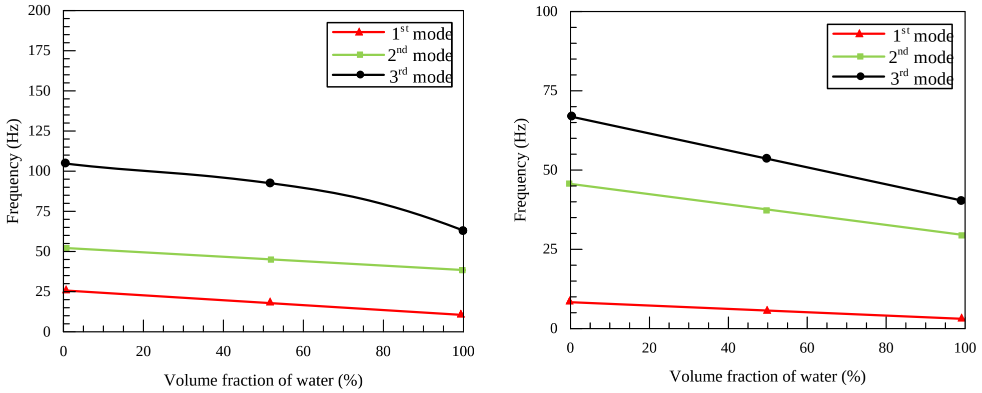
According to the experimental results, the first three natural frequencies of the tube are obtained under three different lengths, and the analysis is shown in Figure 4. As shown in Figure 4, the larger the tube length, the smaller the natural frequency of the tube. Due to the change of tube length, its own quality and stiffness change at the same time, and in this case, the change of stiffness is dominant. It can also be found that changes in the length of the tube lead to changes in the quality and stiffness of the tube, which in turn causes the natural frequency of the tube to change, and the results can be obtained directly in the form of calculations.

2.2.2 The effect of added mass on tube natural frequency

In the case of flow transportation, the volume of the fluid in the tube will change which results the change of the natural frequency of the tube itself. In order to study the influence of the fluid on the natural frequency of the tube, using a self-priming pump with the power of *P*=0.675kw to ensure the tube are pumped in different water-filled states. The tubes were respectively tested in fully-completed, 50% filled and 0% filled with water [6,7]. Through the modal experiment, the *FRF* curve of the tube under different states was obtained, and the first three natural frequencies were obtained by further analysis. The influence of the variation of the volume fraction in the tube on the natural frequencies under different lengths was compared. The analysis is shown in Figure 5.



(a) *L*=1m (b) *L*=1.5m



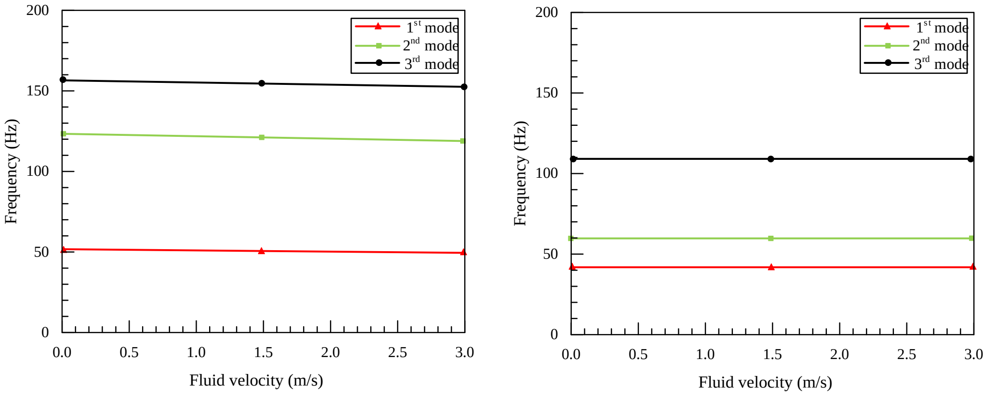
(c) *L*=2m (d) *L*=2.5m

Figure 5: Volume fraction and natural frequency of tubes under different lengths

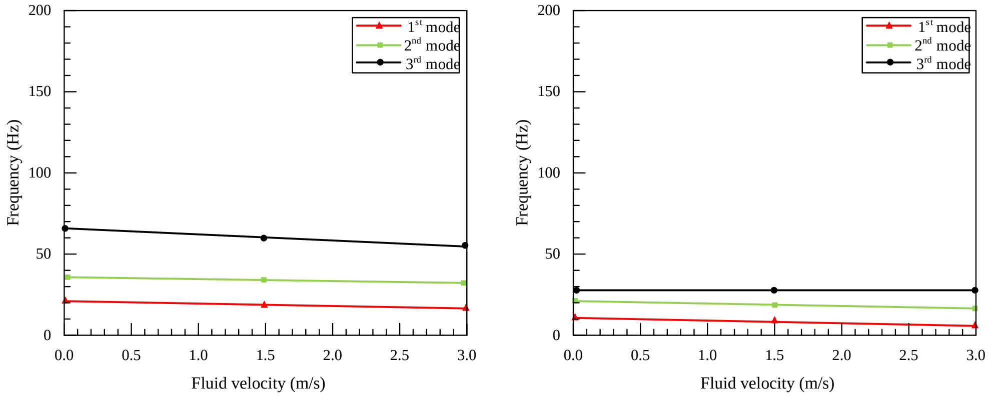
As shown in Figure 5(a), with the increase of the volume fraction, the frequency of each stage of the tube decreases, especially in the case of natural frequencies above the third order. The increase of the volume fraction of the liquid in the tube significantly lower the natural frequency of the tube. Comparing Figure 5(a) – Figure 5(d), it can be seen that the natural frequency of the tube decreases with the increase of the volume fraction under different tube lengths. The shorter tube length, the more liquid mass affects the natural frequency.

2.2.3 The effect of tube velocity on tube natural frequency

In order to study the influence of the conveying velocity on the dynamic characteristics of the tube, the experiment also uses the self-priming pump with the power of *P*=0.675kw to pump the water in the tube. The inner tube is filled with water and the middle of the annular space is drained to a water circulation system. The conveying velocity are 0 m/s, 1.5 m/s and 3 m/s.



(a) *L*=1m (b) *L*=1.5m



(c) *L*=2m (d) *L*=2.5m

Figure 6: Curves of fluid velocity and natural frequency of tubes under different lengths

It can be found in Figure 6 that the natural frequency of the tube itself decreases with the increase of the velocity of fluid in the tube. The change is basically linear but not obvious. In other words, the velocity of the fluid within the tube has the small effect on the natural characteristics of the tube itself. Comparing the influence of the fluid velocity on the natural frequency of the tube under different lengths, it can be found that under the three kinds of lengths, the variation forms are basically the same. It is further proved that the velocity of the fluid in the tube has little effect on the natural frequency and can be neglected.

2.2.4 Determine added mass coefficient

Through the above experimental tests and comparison, it can be found that the natural frequency of the tube itself has relatively large impact on the volume fraction and the length of the tube. However, fluid velocity has little impact on the natural frequency of the tube. Therefore, the length of tube and the change of volume fraction are mainly considered to test the natural frequency of tube. The change of tube length mainly affect tube stiffness and quality, which can be calculated directly from the previous formula. However, it is very difficult to obtain the change of the volume fraction directly by calculation method. Hence, a method of converting the volume fraction of the liquid into the relevant mass attached to the tube itself is proposed to directly calculate the natural frequency of the liquid-filled tube.

Therefore, the added mass coefficient can be calculated by the experimental data [8,9].

$$\alpha = \frac{m_T\left(r^2 - 1\right)}{m_L} \tag{1}$$

According to Eq. (1) and experimental date, the value of the added mass coefficient α for different volume fractions can be calculated for a tube (L_6=2000 mm). The parameters of the tube are shown in Table 4 [10]. The calculation results are shown in Figure 7.

Table 4: Tube parameters

Parameters	Outer diameter	Thickness	Length	Density
PVC	40mm	3mm	1000mm	0.68kg/m

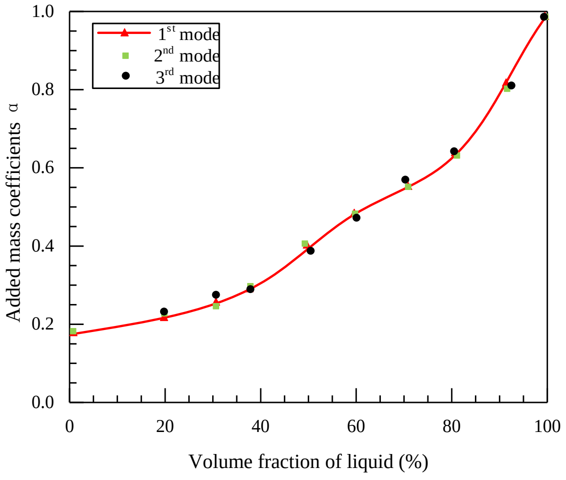


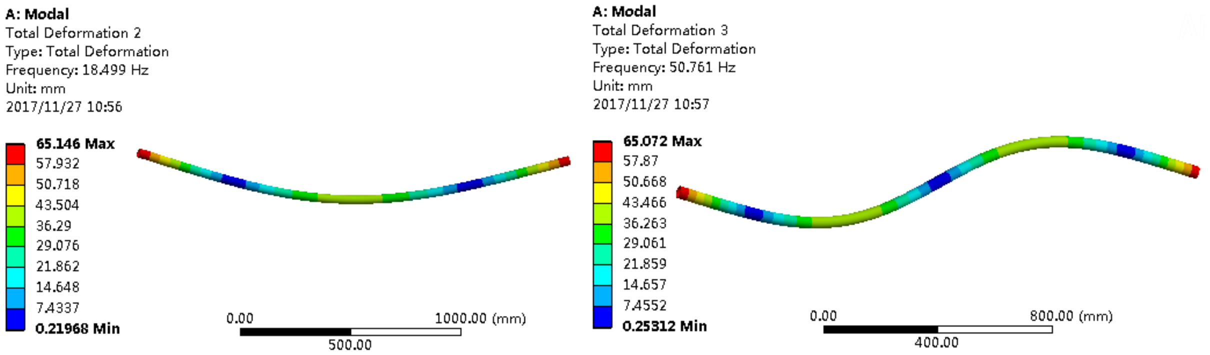
Figure 7: Curve of volume fraction and added mass coefficient α

It can be seen from Figure 7 that the added mass coefficient of fluid is not a fixed value, which changes as the volume fraction of fluid changes. The volume fraction of fluid in the tube increases, and the added mass coefficient α also tends to increase. When the volume fraction of fluid reaches 100%, the added mass coefficient is essentially equal to one. In other words, when the tube is full, the entire volume can be attached to the tube itself to calculate the natural frequency.

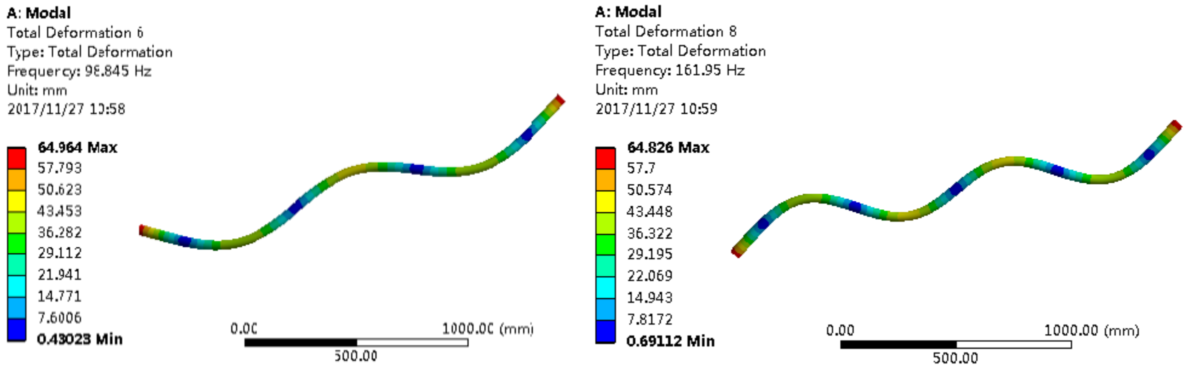
3 CFD ANALYSIS

3.1 Modal simulation of the tube

The previous section performed a modal test on the natural characteristics of the tube, and studied the variation of the tube's natural frequency under different external parameters. The added mass coefficient was obtained by calculation. In order to verify the accuracy of the experimental data, modal analysis of tube's natural frequency was conducted in an anhydrous state. Set the tube parameters and apply modal simulation to obtain the natural frequency and natural mode, the results are shown in Figure 8 and Table 5.



(a) The first mode (b) The second mode



(c) The third mode (d) The fourth mode

Figure 8: The first four order modes of the tube under numerical simulation

Comparing the experimental data with the simulation results, the results are shown in Figure 9. It can be found that the results are basically consistent, which proves that the data measured by the experiment is correct.

Table 5: Natural frequency of tube simulation

Number	Natural frequency (Hz)	Minimum vibration mode (mm）	Maximum vibration mode (mm)
The first mode	18.494	0.32653	65.156
The second mode	50.749	0.39596	65.079
The third mode	98.821	0.75666	64.968
The fourth mode	161.61	0.72281	64.824

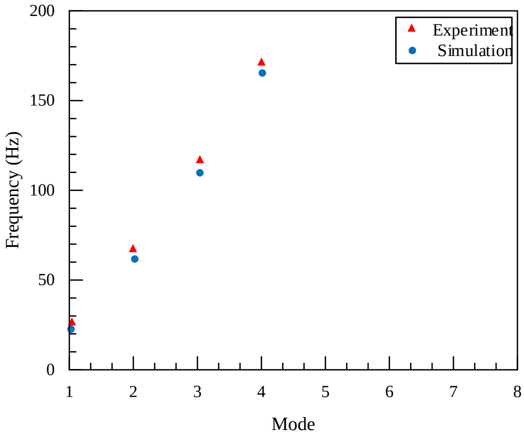


Figure 9: Contrast diagram of experiment and simulation

3.2 Simulation results

Based on the above initial conditions, the cross-section numerical simulation results and a graph of the pressure over time are obtained. As shown in Figure 10, it can be seen that the force in the vertical direction is essentially a constant value and the force in the horizontal direction changes with vibration stimulus changes.

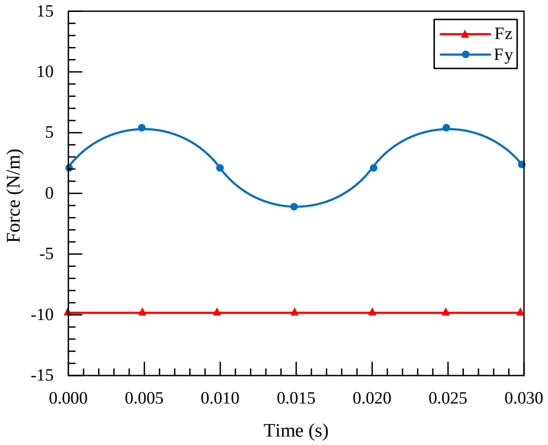


Figure 10: Graph of unit force with time change

4 RESULTS AND DISCUSSION

As shown in Figure 11, the added mass coefficient α increases as the volume fraction of liquid increases. The experimental results are in good agreement with the numerical results. Under the fixed volume fraction, the fixed added mass coefficient α for the transport tube can be obtained, which is substituted into the equation and solved for the natural frequency.

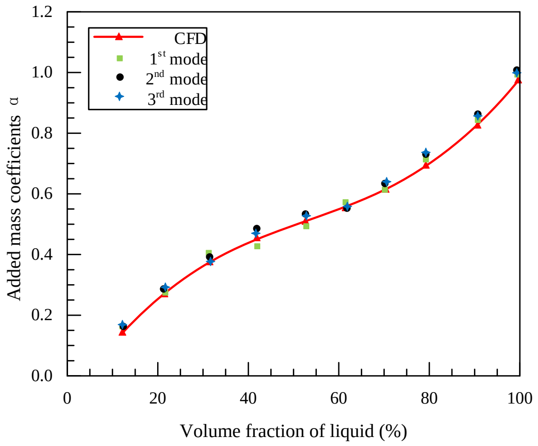
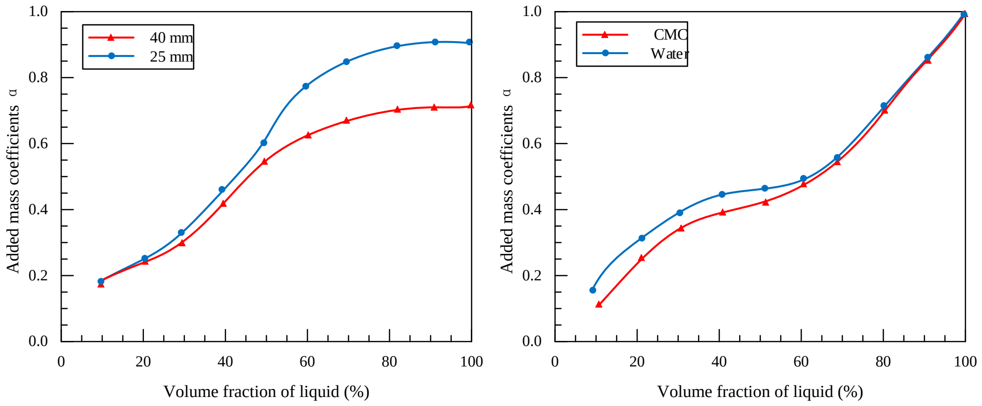


Figure 11: Comparison between numerical results and experimental results

In order to verify the effect of tube diameter on the added mass coefficient α, PVC-U tubes with diameters of D_1 = 40mm, D_2 = 25mm and length L_6 = 2000mm were simulated. The results are shown in Figure 12(a). Moreover, the added mass coefficient α of CMC solution at different volume fractions was simulated and compared with water, the curves are shown in Figure 12(b).



(a) (b)

Figure 12: Added mass coefficient α of tubes under different diameters and transport media

The tube dimensions also have an influence on the added mass coefficients, especially when the tube is full of liquid. Viscosity can play an important role in the fluid-structure interaction, particularly when V_l is small. The effect of friction due to shear stresses acting on the interface between the liquid and the internal surface of the tube becomes dominant.

5 CONCLUSIONS

- This paper considers the change of the natural frequency of tube with the transport fluid inside the tube. And through experimental tests and numerical simulations to obtain a method that can add fluid quality to tube quality to calculate tube's natural frequency.
- When conveying the fluid, the physical parameters of the tube (length, radius, etc.) and the volume fraction of the liquid filled in the tube have a great influence on the natural characteristics of the tube. However, the velocity of the fluid in the tube has less effect on the natural characteristics of the tube itself. The added mass coefficient of fluid is not a fixed value, it varies with the volume fraction of fluid in the tube.

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