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The Influence of Large Variations in Fluid Density and Viscosity on the Resonance Characteristics of Tuning Forks Simulated by Finite Element Method

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Abstract: The use of tuning forks to measure fluid density and viscosity is widely employed in fields such as food, medicine, textiles, automobiles, petrochemicals, and deep drilling. The explicit analytical model based on the Euler–Bernoulli cantilever-beam theory for the relationship between tuning-fork resonance characteristics and the density and viscosity of fluid is only applicable to the situation where the fluid viscous effect is very small. In this paper, the finite element method is used to simulate the influence of large variations in fluid density and viscosity on the resonance characteristic parameters (resonant frequency and quality factor) of the tuning fork. The numerical simulation results are compared with the analytical analysis results and experimental measurement results. Then, the sensitivity of tuning-fork resonance characteristic parameters to fluid density and viscosity is studied. The results show that compared with the analytical results, the numerical simulation results have a higher degree of agreement with the experimental measurement results. The relative difference in resonant frequency is less than 2%, and the relative difference in quality factor is less than 4%. This indicates that the finite element method includes the influence of fluid viscosity on tuning-fork resonance parameters, which is more in line with the actual conditions than the analytical model. Simulating and analyzing the sensitivity of the tuning fork to fluid density and viscosity by the finite element method, it is possible to consider the situation where fluid density and viscosity vary over a large range. Compared with experimental measurements, this method has higher efficiency and can significantly save time and economic costs. This study can overcome the limitation of existing explicit analytical models, which are only applicable when the viscous effects of the fluid are very small. It enables a more accurate simulation of the coupling vibration between tuning forks and fluids, thereby providing theoretical references for further optimizing tuning-fork structural parameters to enhance the accuracy of measuring fluid characteristic parameters.

Keywords: finite element method; tuning fork; resonance characteristics; density; viscosity

1. Introduction

The two arms of a tuning fork can be regarded as two symmetrical cantilever beams with one end fixed and the other end free, which can achieve decoupled measurement of fluid density and viscosity. Tuning forks are widely employed in industrial production. For example, tuning forks are used to measure the density and viscosity of wine in real time, thereby achieving quality monitoring of the wine fermentation process [1,2]. Tuning forks are used to measure the density and viscosity of gases, in order to monitor the gas

polymerization process in high-temperature and high-pressure containers [3]. The smoke and dust content of engine oil can be monitored by measuring its density and viscosity through tuning forks [4,5]. In the process of oil and gas exploitation [6,7], using a tuning fork to measure the density and viscosity of downhole fluid can identify fluid [8,9], determine fluid composition, and divide the oil–water interface, which is of great significance for optimizing oil and gas reservoir management and intelligent oil-field exploitation [10,11].

In-depth study of the relationship between tuning-fork resonance characteristics and fluid characteristic parameters is helpful in optimizing the design of the tuning fork sensor, thereby enhancing the accuracy of fluid density and viscosity measurements using tuning forks. In 1998, John Elie Sader established an explicit analytical model based on the Euler–Bernoulli cantilever-beam theory, which relates the resonant frequency and quality factor of a cantilever beam vibrating in a fluid to fluid density and viscosity. The model can express the quantitative relationship between the resonant frequency and quality factor of the tuning fork, the size of the tuning fork, the material parameters, and the fluid density and viscosity, but only for fluid with small viscous effects, such as air [12]. In 2011, Waszczuk et al. developed an implicit analytical model using an equivalent circuit approach, relating tuning-fork resonant frequency and quality factor to fluid density and viscosity. The model contained undetermined coefficients related to the material and size of the tuning fork, and the accuracy of the model was affected by the parasitic capacitance of the tuning fork [13]. In 2014, Henisch et al. compared the vibration of a tuning fork in a fluid to the damped vibration of a pendulum–spring system. Based on the forces exerted on the tuning fork in the fluid, they derived an implicit analytical model relating tuning-fork resonant frequency and quality factor to fluid density and viscosity, with the effective area of interaction between the tuning fork and fluid being an undetermined coefficient [14]. In 2015, Henisch et al. studied the feasibility of using an electromagnetic-driven metal tuning fork to measure fluid density and viscosity, and analyzed the sensitivity of tuning fork characteristic parameters to fluid density and viscosity. However, due to the limitation of experimental fluid samples, only the sensitivity of the tuning fork was studied when density and viscosity changed within a small range [15]. In 2020, Zhang et al. used the Sobol global sensitivity analysis method instead of the commonly used finite difference method to analyze the sensitivity of tuning forks to fluid density and viscosity, but did not carry out further research into the relationship between the sensitivity of tuning forks and the large-scale variation of fluid density and viscosity [16].

In order to overcome the limitation of existing explicit analytical models, which are only applicable when the viscous effects of the fluid are small, this paper utilizes finite element analysis to simulate the coupling vibration law between tuning forks and fluids. It compares the results of finite element numerical simulations, analytical model predictions, and experimental measurements. Building upon this comparison, the finite element method is employed to simulate the relationship between tuning-fork resonance characteristics and fluid characteristic parameters. Furthermore, the sensitivity of tuning forks to large-scale variations in fluid density and viscosity is analyzed based on the finite element simulations.

2. Materials and Methods

2.1. Analytical Model

Assuming that the cross section of the tuning fork arm is uniform along the length, and the length of the tuning fork arm is much larger than the width and thickness, according to the Euler–Bernoulli cantilever-beam theory, the flexural vibration equation of the tuning fork arm during vibration in an incompressible fluid is as follows [12]:

$$EI\frac{\partial^4}{\partial x^4}W(x,\omega) - \omega^2 \rho_b e I W(x,\omega) = F_{ex}(x,\omega) + F_{hydro}(x,\omega) \tag{1}$$

where E represents Young's modulus; I represents the moment of inertia; ω represents the resonant angular frequency of the tuning fork when it vibrates in the fluid; ρ_b represents the density of the tuning fork material; e represents the width of the tuning fork arm;

l represents the thickness of the tuning fork; $W(x, \omega)$ represents the displacement function, where x represents the position coordinate along the length direction of the tuning fork arm; $F_{ex}(x, \omega)$ represents the external driving force of the tuning fork; and $F_{hydro}(x, \omega)$ represents the force of the fluid on the tuning fork. $F_{hydro}(x, \omega) = \frac{\pi}{4}\rho\omega^2 l^2 \Gamma_{hydro}(\omega)W(x, \omega)$ is obtained by solving the linear Navier–Stokes equation, and $\Gamma_{hydro} = \Gamma_{hydro}^r(\omega) + j\Gamma_{hydro}^i(\omega)$ represents hydrodynamic function. When the tuning fork is immersed in the fluid with a small viscous effect, Formula (1) is solved to obtain the resonant frequency of the tuning fork when it is performing first-order in-plane anti-phase flexural vibration [12],

$$\omega = \omega_{vac}[1 + \frac{\pi\rho_f e}{4\rho_b l}\Gamma_{hydro}^r]^{-1/2} \tag{2}$$

where $\omega_{vac} = 2\pi f_{vac}$ represents the resonant angular frequency of the tuning fork when it vibrates in vacuum, $f_{vac,n} = \frac{e}{4\pi\sqrt{3}}\sqrt{\frac{E}{\rho_b}}(\frac{C_1}{L})^2$, $C_1 = 1.875$ is the first positive root of the equation $1 + \cos(C_n)\cosh(C_n) = 0$, $\Gamma_{hydro}^r = 1 + \frac{4}{\sqrt{2Re}}$ represents the real part of the hydrodynamic function [16], and $Re = \frac{\rho_f l^2 \omega}{4\eta}$ represents the Reynolds number.

By substituting Formula (2) into Formula (1), the fluid viscosity quality factor of the tuning fork during the first-order flexural vibration can be obtained:

$$Q = \frac{\frac{4\rho_b e}{\pi\rho_f l} + \Gamma_{hydro}^r}{\Gamma_{hydro}^i} \tag{3}$$

where $\Gamma_{hydro}^i = \frac{4}{\sqrt{2Re}} + \frac{2}{Re}$ represents the imaginary part of the hydrodynamic function [16]. The quality factor of the tuning fork in Formula (3) is related to the resonant frequency of the tuning fork in Formula (2), and Formula (2) is derived under the assumption of small viscous effects of the fluid, which implies that the resonant frequency and quality factor in Formula (2) and Formula (3) are only applicable when the viscous effect of the fluid is small [17,18].

2.2. Finite Element Method

2.2.1. Coupling Relationship between the Tuning Fork and Fluid

The structure of the tuning fork is shown in Figure 1a. The length of the tuning fork arm is *L*, the width of the tuning fork arm is *e*, the thickness of the tuning fork arm is *h*, and the spacing between the tuning fork arms is *g*. The bottom of the tuning fork is fixed, thus the displacement is zero. Figure 1b is a schematic diagram of the tuning fork performing first-order in-plane anti-phase flexural vibration. This paper mainly studies the relationship between the resonant frequency and quality factor of this vibration mode with respect to fluid density and viscosity. The material of the tuning fork is quartz, with a density of 2650 kg/m^3, and other material property parameters of quartz are defined by the elastic matrix (the conversion matrix between stress and strain, related to material parameters such as Young's modulus and Poisson's ratio), the coupling matrix (the conversion matrix between charge and stress), and the relative dielectric constant.

The governing equations for fluid motion in the finite element method are defined by the linear Navier–Stokes equations, including the momentum equation, the continuity equation, and the constitutive relation equation:

$$i\omega\rho_0 u_t = \nabla\cdot\sigma \tag{4}$$

$$i\omega\rho_t + \nabla\cdot(\rho_0 u_t) = 0 \tag{5}$$

$$\rho_t = \rho_0(\beta_T p_t - \alpha_p T_t) \tag{6}$$

$$\sigma = -p_t I + \eta\left(\nabla u_t + (\nabla u_t)^T\right) - (\frac{2}{3}\eta - \eta_B)(\nabla\cdot u_t)I \tag{7}$$

where ρ_0 represents the initial density of the fluid in the absence of disturbance, $u_t = u_0 + u$ represents the total acoustic velocity field, u_0 represents the initial background acoustic velocity field, and u represents the acoustic velocity field generated by tuning fork's vibration. $T_t = T_0 + T$ indicates the total temperature, where T_0 indicates the initial background temperature and T indicates the temperature change caused by the tuning fork's vibration. $p_t = p_0 + p$ represents the total acoustic pressure, where p_0 represents the initial background pressure and p represents the acoustic pressure caused by the tuning fork's vibration. ρ_t represents the density of the fluid during the propagation of the acoustic wave; α_p represents the coefficient of thermal expansion at constant pressure; η represents the dynamic viscosity; and η_B represents the volume viscosity, which is related to the momentum loss caused by the expansion and compression of the fluid. β_T represents the isothermal compression rate; σ represents the stress; and I represents the unit diagonal matrix, $i^2 = -1$.
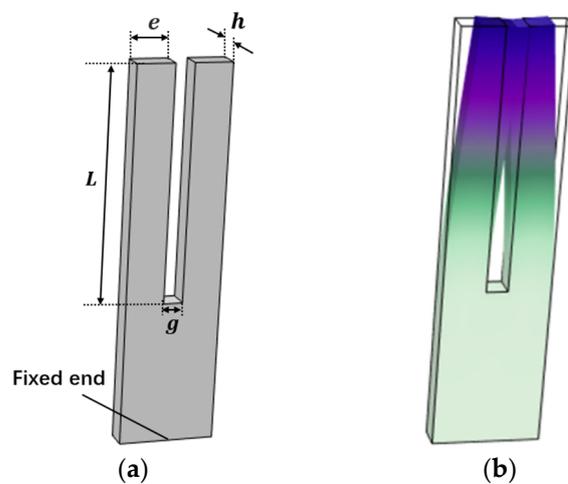
Figure 1. (**a**) Tuning fork model in finite element method. (**b**) The tuning fork performs first-order in-plane reverse flexural vibration.

Fluid in finite element method is compressible fluid, and density, ρ_0, and dynamic viscosity η are related to temperature and pressure. ρ_0 and η are set to constants in simulation, so that, ρ_0 and η are not affected by temperature and pressure.

When the tuning fork and the fluid are in coupled vibration, their displacements are continuous, satisfying the following relationship:

$$c_{fluid} = \frac{\partial x}{\partial t} \tag{8}$$

where x and c_{fluid} represent the displacement of the tuning fork and the velocity of the fluid, respectively, and their relationship in the frequency domain is $c_{fluid} = i\omega x$. This coupling relationship shows that the normal stress on the boundary between the tuning fork and the fluid is also continuous.

To sum up, the equations of fluid motion in the analytical method and the finite element method are both linear Navier–Stokes equations. However, in order to obtain an explicit expression for the resonant frequency and quality factor of the tuning fork with respect to fluid density and viscosity in the process of solving Equation (1), it is assumed that the viscous effect of the fluid is small, providing only an approximate solution. This approximation does not hold well when the fluid viscosity is large. The finite element method gives the relationship between tuning-fork resonance parameters and fluid characteristic parameters by solving Equation (4) to Equation (8), without approximation. Therefore, the finite element method is more in line with the actual situation than the analytical method, and the simulation results are closer to the actual situation.

2.2.2. Comparison of Finite Element Method and Analytical Method

In the finite element simulation, the material and size of the tuning fork are consistent with those of the laboratory quartz tuning fork in literature [19]. The length of the tuning fork arm L is 4.05 mm, the width e is 0.66 mm, the thickness h is 0.4 mm, and the spacing g is 0.24 mm. The resonant frequency and quality factor of tuning forks in 19 groups of fluids with different densities and viscosities were measured by experiments in reference [19]. In this paper, the finite element method and the analytical method were used to simulate the model with parameters identical to those in the experiments. Equation (2) and Equation (3) were used for the analytical method, the value of Young's modulus E was 78.3 GPa, and the value of the material density ρ_b of the tuning fork was 2650 kg/m^3. The comparison of the numerical simulation results, analytical results, and experimental measurement results is shown in Table 1, where fluids of groups 1–19 are arranged in order of viscosity from small to large. The finite element simulation results were obtained through the conductance diagram, with peak value corresponding to the resonant frequency f of the tuning fork, quality factor Q = f/Δf, and Δf is −3 dB bandwidth. Figure 2 shows the results of group 1 and group 19. The resonant frequency of the tuning fork in fluid of group 1 was 29,089 Hz, and the quality factor was 58.53. In fluid of group 19, the resonant frequency of the tuning fork was 27,151 Hz, and the quality factor was 6.69.

Table 1. Comparison of numerical results, analytical results, and experimental results.

No.	Density kg/m^3	Viscosity mPa·s	Experimental Results f (Hz)	Q	Numerical Results f (Hz)	Q	Relative Difference of Numerical Results δf (%)	δQ	Analytical Results f (Hz)	Q	Relative Difference of Analytical Results δf (%)	δQ
1	828.6	2.930	29,089	58.53	29,485	57.97	1.36	0.96	29,540	122.61	1.55	109.48
2	815.1	4.658	29,077	46.75	29,474	46.88	1.37	0.28	29,544	97.88	1.61	109.49
3	848.4	6.096	28,925	41.98	29,302	40.54	1.29	3.43	29,323	84.04	1.38	100.19
4	812.4	7.08	29,027	37.07	29,411	38.21	1.31	3.08	29,483	79.38	1.57	114.14
5	854.9	8.344	28,845	34.18	29,216	34.61	1.24	1.24	29,226	71.49	1.32	109.16
6	834.3	10.64	28,877	30.40	29,240	30.92	1.26	1.71	29,277	63.86	1.39	110.07
7	849.4	11.78	28,778	27.73	29,157	29.23	1.32	5.41	29,173	60.18	1.37	117.02
8	864.8	14.68	28,699	26.55	29,040	26.06	1.19	1.85	29,034	53.40	1.17	101.13
9	840.7	15.18	28,776	26.38	29,124	25.86	1.21	1.97	29,150	53.12	1.30	101.29
10	868.1	18.31	28,630	23.80	28,961	23.3	1.16	2.10	28,950	47.36	1.12	98.99
11	831.1	19.60	28,757	23.77	29,085	22.84	1.14	3.91	29,122	46.84	1.27	97.06
12	850.3	28.62	28,542	19.38	28,878	18.69	1.18	3.56	28,885	38.20	1.20	97.11
13	853.5	36.52	28,426	16.39	28,770	16.45	1.21	0.37	28,767	33.62	1.20	105.13
14	915.9	40.29	28,138	14.97	28,483	15.31	1.23	2.27	28,401	31.05	0.93	107.41
15	867.9	40.70	28,329	15.56	28,665	15.47	1.19	0.57	28,643	31.57	1.11	102.89
16	849.7	69.22	28,115	12.31	28,457	11.78	1.22	4.31	28,460	24.14	1.23	96.10
17	941.8	71.36	27,847	12.13	28,077	11.27	0.83	7.09	27,966	22.80	0.43	87.96
18	968.3	119.78	27,380	9.01	27,628	8.66	0.91	3.88	27,480	17.17	0.37	90.57
19	886.3	210.58	27,151	6.69	27,450	6.47	1.10	3.29	27,411	13.12	0.96	96.11
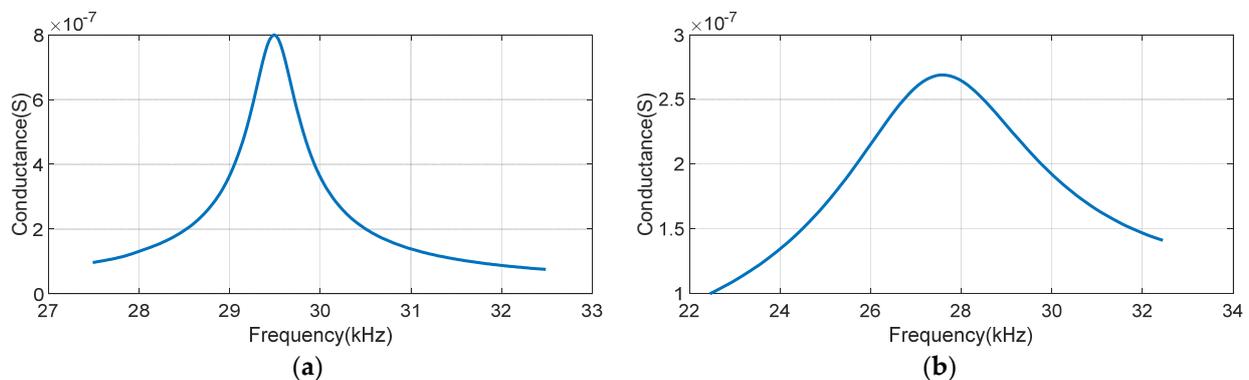
Figure 2. (**a**) Conductance diagram of the tuning fork in fluid of group 1. (**b**) Conductance diagram of the tuning fork in fluid of group 19.

Figure 3 shows the comparison of numerical, analytical, and experimental results of resonant frequency and quality factor. Figure 4 shows the relative differences between numerical results and experimental results, and the relative differences between analytical results and experimental results, respectively. The relative difference of numerical results is $\frac{\text{numerical result} - \text{experimental result}}{\text{experimental result}} \times 100\%$, and the relative difference of analytical results is $\frac{\text{analytical result} - \text{experimental result}}{\text{experimental result}} \times 100\%$.
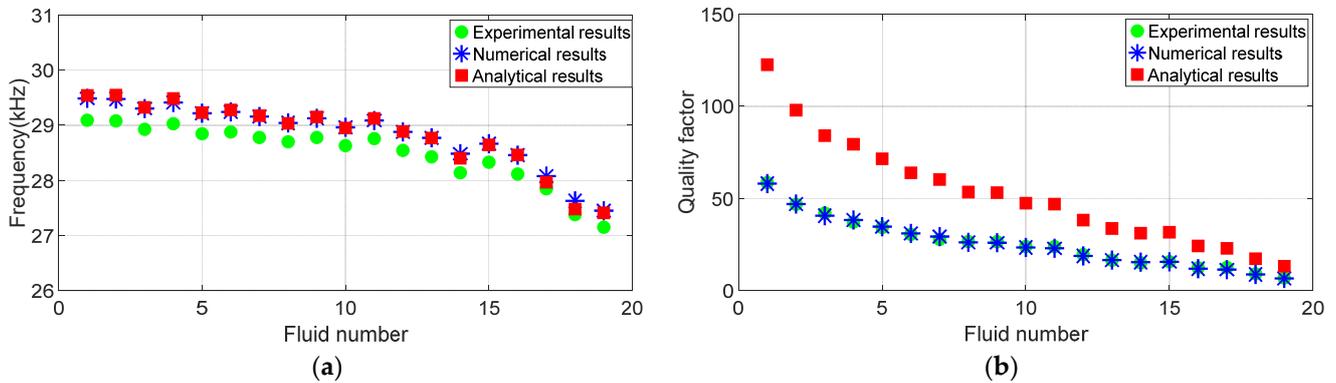
Figure 3. (**a**) Numerical, analytical, and experimental results of resonant frequency corresponding to 19 groups of different fluids. (**b**) Numerical, analytical, and experimental results of quality factor corresponding to 19 groups of different fluids.
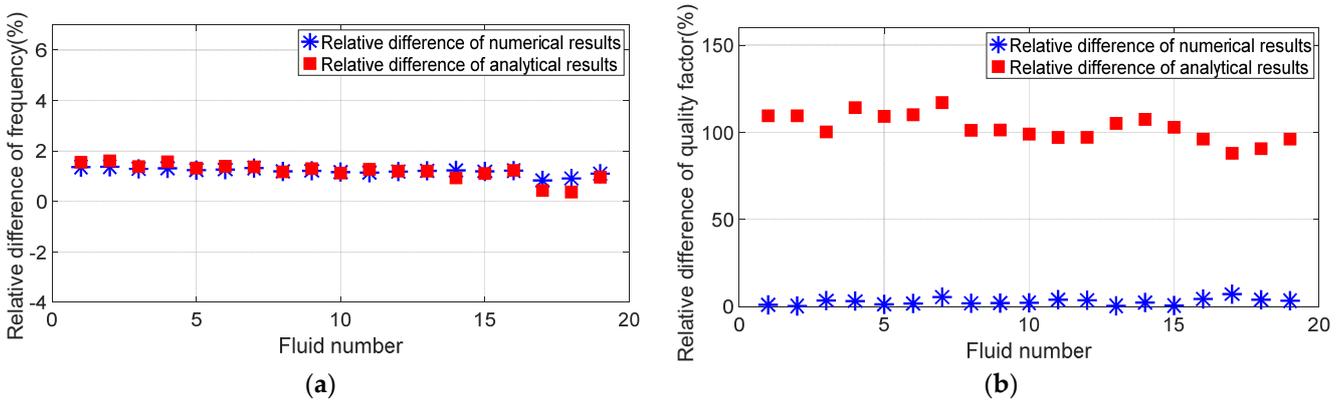
Figure 4. (**a**) Relative difference of numerical results and analytical results of resonant frequency corresponding to 19 groups of different fluids. (**b**) Relative difference of numerical results and analytical results of quality factor corresponding to 19 groups of different fluids.

From Figures 3 and 4, it can be seen that the numerical results and analytical results of the resonant frequency are highly consistent, with a relative difference of less than 2% from the experimental measurement results. The difference between the numerical results and the analytical results of the quality factor is large, the relative difference between the numerical results and the experimental results is less than 4%, and the relative difference between the analytical results and the experimental results can even exceed 110%. This shows that the finite element method includes the influence of fluid viscous effects on tuning-fork resonance parameters, and is closer to the actual situation than the approximate analytical method, and the simulation results are more accurate.

3. Results

3.1. Relationship between Tuning-Fork Resonance Characteristics and Fluid Characteristic Parameters

Based on the above conclusions, the finite element method is used in this paper to simulate the relationship between the tuning-fork resonance characteristics (resonant frequency and quality factor) and the fluid characteristic parameters (density and viscosity) when the fluid density varies from $100\ \text{kg/m}^3$ to $1900\ \text{kg/m}^3$ and the viscosity varies from $2\ \text{mPa·s}$ to $212\ \text{mPa·s}$. The numerical simulation results are shown in Figure 5.
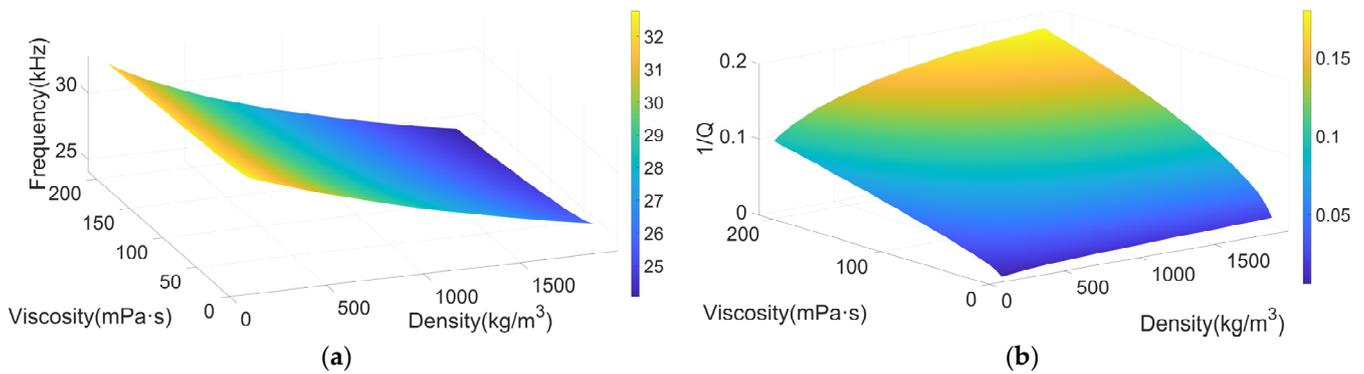
Figure 5. (**a**) Resonant frequency in relation to fluid density and viscosity. (**b**) Quality factor in relation to fluid density and viscosity.

It can be seen from Figure 5 that both the resonant frequency and quality factor of the tuning fork decrease with the increase in fluid density and viscosity. The vibration of the tuning fork in the fluid can be regarded as the damped vibration of a oscillator spring system [20], so the resonant frequency and quality factor can be written as follows [14,21]:

$$\omega = \sqrt{\frac{k_0}{m_0 + m_f}} \tag{9}$$

$$Q = \frac{1}{\omega}\frac{k_0}{c_0 + c_f} \tag{10}$$

where k_0 represents the elastic coefficient of the spring, m_0 represents the mass of the oscillator, c_0 represents the spring damping, m_f represents the additional mass of the fluid, and c_f represents the fluid damping. When the tuning fork vibrates in the fluid, the additional mass $m_f = A\sqrt{\frac{\eta\rho_f}{\omega}}$, where A is the effective area of the tuning fork, so the resonant frequency of the tuning fork decreases when the density and viscosity increase, with damping coefficient $c_f = A\sqrt{\omega\eta\rho_f}$ and $Q = \frac{\sqrt{k_0}\sqrt{m_0 + A\sqrt{\frac{\eta\rho_f}{\omega}}}}{c_0 + A\sqrt{\omega\eta\rho_f}}$. Because as the increase in ρ_f and η, the increasing trend of $\sqrt{\omega\eta\rho_f}$ is greater than $\left(\frac{\eta\rho_f}{\omega}\right)^{\frac{1}{4}}$. Therefore, with the increase in ρ_f and η, the quality factor Q gradually decreases. Also, as ρ_f and η increase, the fluid damping force on the tuning fork increases, leading to greater energy loss in the tuning fork vibration, hence reducing its quality factor.

3.2. Sensitivity Analysis

In the finite element numerical simulation, the calculation formula of relative sensitivity is

$$S_{Y,x} = \left|\frac{\frac{\Delta Y}{Y}}{\frac{\Delta x}{x}}\right| = \left|\frac{\Delta Y}{\Delta x}\cdot\frac{x}{Y}\right| \tag{11}$$

where Y represents f or Q, x represents ρ or η, and Formula (11) represents the relative change in resonant frequency or quality factor corresponding to a relative change in unit density or viscosity. The higher the sensitivity, the more sensitive the tuning-fork resonance parameters are to the changes of fluid characteristic parameters, resulting in higher measurement accuracy.

The tuning fork size is set to be consistent with that used in the laboratory in the finite element method. Fluid density increases from 100 kg/m^3 to 1900 kg/m^3, Δρ is 50 kg/m^3, viscosity increases from 2 mPa·s to 212 mPa·s, and Δη is 6 mPa·s. Figure 6 shows the sensitivity of resonant frequency to density, and Figure 7 shows the sensitivity of quality factor to density and viscosity.
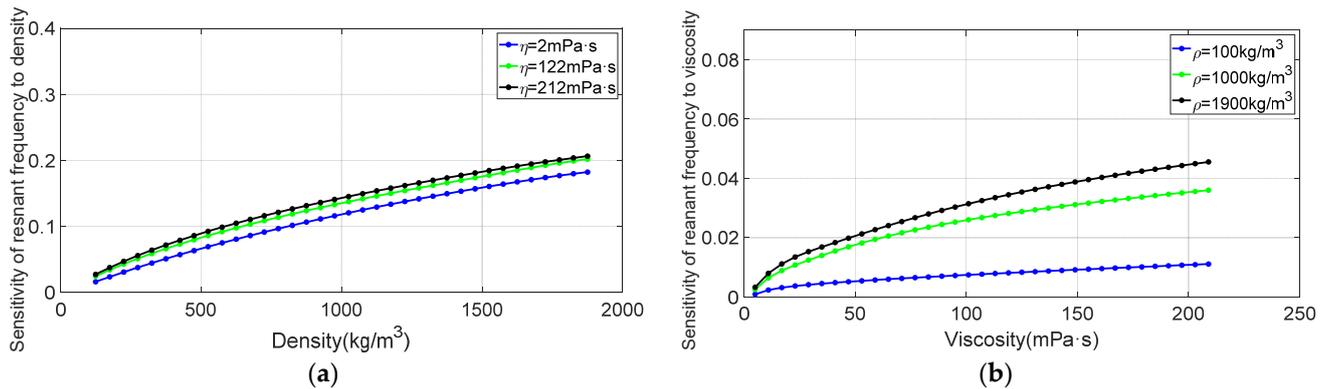
Figure 6. (**a**) Sensitivity of resonant frequency to density. (**b**) Sensitivity of resonant frequency to viscosity.
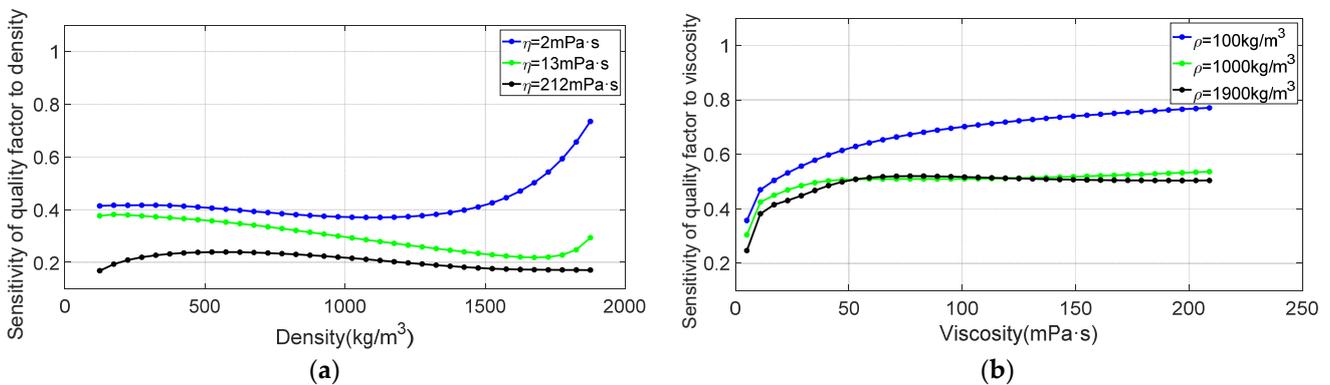
Figure 7. (**a**) Sensitivity of quality factor to density. (**b**) Sensitivity of quality factor to viscosity.

It can be seen from Figure 6 that the sensitivity of tuning-fork resonant frequency to fluid density and viscosity increases with the increase in fluid density and viscosity, and the sensitivity of tuning-fork resonant frequency to fluid density is greater than to viscosity. It can be seen from Figure 7b that the sensitivity of tuning fork quality factor to fluid viscosity generally increases with the increase in fluid viscosity. The sensitivity value of tuning fork quality factor to fluid density is comparable to that of viscosity. But the sensitivity of quality factor to fluid density does not vary monotonically.

Henisch et al. [15] analyzed, through experiments, the sensitivity of the metal tuning fork driven by electromagnetic means. However, this approach required setting up experimental platforms and extensive data-processing work. Moreover, the analysis results were limited by experimental samples and only the sensitivity of the tuning fork within a small range of density and viscosity variations was analyzed. In contrast, the finite element method does not require the construction of experimental platforms and experiments, and can analyze the sensitivity of the tuning fork when the density and viscosity change in a wide range, which can greatly save time and economic costs.

4. Conclusions

Firstly, the existing analytical model of the relationship between tuning-fork resonance characteristics and fluid characteristics based on Euler–Bernoulli's cantilever-beam theory was analyzed. It has the limitation of being applicable to the small viscous effects of fluid. In this paper, the finite element method was used to establish the simulation model to simulate the coupling vibration law of the tuning fork and fluid, and the influence of the fluid viscous effect on the resonant characteristics of tuning fork was considered. The comparison of the finite element numerical results, analytical results, and experimental measurement results showed that the finite element simulation results and experimental measurement results had a higher agreement, and the relative difference rate of resonant frequency between the two was less than 2%, and the relative difference rate of quality factor was less than 4%. This indicates that, compared with the approximate analytical method, the finite element method can consider the influence of the fluid viscous effect, so it is more in line with the actual situation than the analytical method. Finally, based on the finite element method, the sensitivity of tuning-fork resonance characteristics to fluid characteristic parameters (density and viscosity) was calculated. The results show that the sensitivity of tuning-fork resonant frequency to fluid density and viscosity increases with the increase in fluid density and viscosity, and the sensitivity of tuning fork quality factor to fluid viscosity generally increases with the increase in fluid viscosity. However, the sensitivity of quality factor to fluid density does not change monotonically. Compared with experiments, the established finite element simulation model can be used, conveniently, to analyze the sensitivity change in tuning fork to fluid density and viscosity when the fluid density and viscosity change in a large range, which can greatly save time and economic cost. It provides a theoretical reference for further optimization of the design of the tuning fork sensor to improve the accuracy of measuring fluid characteristic parameters. Next, the finite element simulation model can be optimized into the tuning fork's vibration in multiphase flow, so as to study the relationship between tuning fork's resonance parameters and multiphase flow's characteristic parameters.

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