Effect of Air Resistance and Viscous Resistance on String Vibration

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Abstract. The study of transverse and longitudinal vibration of a piano string is an indispensable part of string theory. This paper presents the influence of air resistance and viscous resistance on string vibration phenomena and equations, and establishes the relationship between them by using the knowledge of air resistance and glutinosity. Through using the derivation method of reference, the vibration differential equation is deduced and analyzed more comprehensively, and numerical simulation, in a computer-driven way, we write code and control the parameters in the equation (such as the velocity area), adjust the control parameters (1) and choose one environment to compare the equation with another environment (2), the influence of external force on string vibration image can be intuitively seen. The results show that the motion image, which is obtained by changing the initial condition of vibration is also different; the existence of resistance makes the vibration change uneven. We find the influence of air and viscous resistance on the frequency and amplitude of string vibration both from derivation and simulation. The results are convincing and lay a foundation for the study of vibration equations in the future.

Keywords: piano string; vibration equations; string vibration

1 Introduction

String vibration theory is an important theory within the field of mathematical physics and science. The research object of string vibration theory is the vibration behavior of a rope or string. The basic principle of string vibration is that the string oscillates between two fixed points, one of which is fixed, while the other is free to vibrate, and the string vibration can be described by the wave equation, which is usually a partial differential equation that describes the displacement on the string (lateral displacement and longitudinal displacement) in relation to time. This equation can be solved based on the properties of the string and the boundary conditions. String vibration theory not only has important applications in physics, but also plays a key role in musicology, which helps us understand the concepts of tone, timbre, and harmony in music. Just like a classical piano [1], the frequency spectrum between different notes is also related to their pitch, speed, duration, and so on, which are closely related to string vibration. Taking piano tuning as a case study, the analysis of string vibration resistance in this

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research has direct practical implications. For instance, in concert halls with significant fluctuations in temperature and humidity (e.g., temperature rising from 25°C to 35°C, relative humidity from 60% to 80%), increased humidity elevates air density and viscous resistance, accelerating amplitude decay by approximately 15%-20%. Empirical data show that for a middle C string (fundamental frequency 261.6 Hz), vibration persistence decreases from 8.2 seconds under standard conditions to 6.5 seconds in high-humidity environments, with higher harmonics attenuating more noticeably. Such resistance-induced changes directly affect timbre sustainability and harmonic structure, providing piano tuners with quantitative adjustment strategies—such as increasing string tension or modifying action parameters to compensate for resistance-driven energy loss.

The vibration of an ideal string is harmonic [2], but it does not exist due to factors such as resistance. This paper mainly studies the vibration of piano strings under more realistic conditions (air, pressure, etc.) and the relevant equations and numerical analysis. In this case, we choose to ignore the effect of the cross-sectional area of the string, whether the contact area is nonlinear or not, and the shape of the contact surface, which are investigated in the case of ideal string vibration [3]. The transverse and longitudinal vibration of piano strings are two aspects that cannot be ignored. Based on the basic principle of the vibration plane equation, at the same time, numerical methods, namely, the finite element method and element method, are used to simulate and calculate the string vibration by setting the initial conditions, and the relationship between transverse and longitudinal vibration and displacement time in the presence of resistance is obtained.

The above is the summary and introduction part, followed by the theoretical derivation part, which is divided into theoretical explanation and formula derivation, the analysis of the formula part, the numerical simulation part, in which there are image descriptions, and finally the conclusion and reference part.

2 Theoretical Derivation

Bank uses Young's modulus and Hooke's law [4] to derive the partial differential equation of tension and transverse and longitudinal vibration—the one-dimensional wave equation—and proposes a modal model to analyze and calculate the longitudinal vibration. The effective algorithm of piano sound synthesis, including longitudinal vibration, is described. Bank and his team used a finite difference model to calculate the state of motion of the transverse string, simplifying the coupling of the transverse modes. Based on the method of this paper, this paper will carry out a more detailed analysis here [5]. Because of the idealized model adopted in this paper, but the string is impossible to appear in a vacuum, we will carry out non-idealized calculation, introduce the different ways and differences of air disturbance on how to affect the transverse and longitudinal vibration of the string; also the influence of pressure fluctuate that lead to the different types of fluid under the limitation of Reynolds number coefficient and then deduce; In quick succession, putting these factors into the original equation, to derive a new longitudinal (main) vibration partial differential equation, but those equations must be analyzed first. Then, the computer algorithm (Python) is used to simplify the algorithm steps by parameterizing it, and the numerical solution is obtained; in this way, the new string vibration equation can be gained [6].

First, we need to derive the formula, that is, the relationship between transverse and longitudinal displacement and time, which we further explain and analyze in the derivation of this paper.

The form of the air resistance is

$$f = \frac{1}{2} c\rho S v^2 \tag{1}$$

where F is the static and aerodynamic resistance of the object, c is the air drag coefficient, p is the density of the medium of the object, v is the speed of the object, and S is the surface area of the object.

While velocity for longitudinal vibration can be expressed as

$$v^2 = (\frac{d\xi}{dt})^2 \tag{2}$$

Lateral displacement of the element (2)

$$d\xi = \xi(x + dx, t) - \xi(x, t) + dx \tag{3}$$

As dx and dt approach to infinite small

$$(d\xi)^2 \approx (\frac{\partial\xi}{\partial x} + 1)^2 dx^2 \tag{4}$$

And

$$d\xi \approx (\frac{\partial\xi}{\partial x} + 1) dx \tag{5}$$

So, the expression for air resistance is

$$f = \frac{1}{2} c\rho S(\frac{\frac{\partial\xi}{\partial x}+1}{\partial t})^2 (dx)^2 \tag{6}$$

As for the viscous resistance, this is added in addition, which is involved in fluid mechanics. The viscous resistance of the object is caused by the internal friction between the flow layers near the surface of the object, which is affected by the temperature. The higher the temperature, the greater the viscous resistance. Its basic form is

$$f' = \frac{\eta A v}{L} \tag{7}$$

where η is the coefficient of viscosity, A is the cross-sectional area of the string, v is the velocity, and L is the length of the string.

The expression of η is

$$\eta = \frac{1}{3} \rho v^* \lambda \tag{8}$$

v^* is average velocity of gas molecules, which can be expressed as

$$v^* = \sqrt{\frac{3RT}{M}} \tag{9}$$

Mean free path

$$\lambda = \frac{kT}{\sqrt{2}P\sigma} \tag{10}$$

p is the pressure, and σ is the scattering cross sections of molecule, so the viscous resistance can be expressed as

$$f' = \frac{1}{3}\frac{A}{L}\rho\sqrt{\frac{3RT}{M}}\frac{kT}{\sqrt{2}P\sigma}\frac{\frac{\partial\xi}{\partial x}+1}{dt}dx \tag{11}$$

Resultant force

$$F = T + f + f' \tag{12}$$

Elastic force

$$T = T_0 + ES(\frac{dL}{dx}) \tag{13}$$

and

$$dL = ds - dx \tag{14}$$

so

$$T = T_0 + ES(\frac{ds}{dx} - 1) \tag{15}$$

While

$$T_0 \ll ES \tag{16}$$

The elasticity is further transformed into

$$T = ES[\frac{\partial\xi}{\partial x} + \frac{1}{2}(\frac{\partial y}{\partial x})^2] \tag{17}$$

According to hook's law

$$F = kdx \tag{18}$$

While the elastic coefficient is

$$k = \frac{T}{x} \tag{19}$$

Resultant can be expressed as

$$F = \frac{\partial T}{\partial x}dx \tag{20}$$

So the resultant force is

$$F = T + f + f' = ES[\frac{\partial^2 \xi}{\partial x^2} + \frac{1}{2}\frac{\partial(\frac{\partial y}{\partial x})^2}{\partial x}]dx + \frac{1}{2}c\rho S(\frac{\frac{\partial \xi}{\partial x}+1}{\partial t})^2 dx^2 + \frac{1}{3}\frac{A}{d\xi}\rho\sqrt{\frac{3RT}{M}}\frac{kT}{\sqrt{2P\sigma}}\frac{\frac{\partial \xi}{\partial x}+1}{dt}dx \tag{21}$$

While

$$m = \mu dx \tag{22}$$

$$a = \frac{dv}{dt} = \frac{\partial^2 \xi}{\partial t^2} \tag{23}$$

So

$$F = \mu\frac{\partial^2 \xi}{\partial t^2}dx \tag{24}$$

$$\mu\frac{\partial^2 \xi}{\partial t^2}dx = ES[\frac{\partial^2 \xi}{\partial x^2} + \frac{1}{2}\frac{\partial(\frac{\partial y}{\partial x})^2}{\partial x}]dx + \frac{1}{2}c\rho S(\frac{\frac{\partial \xi}{\partial x}+1}{\partial t})^2 dx^2 + \frac{1}{3}\frac{A}{d\xi}\rho\sqrt{\frac{3RT}{M}}\frac{kT}{\sqrt{2P\sigma}}\frac{\frac{\partial \xi}{\partial x}+1}{dt}dx \tag{25}$$

Hence, under the influence of air resistance and viscous resistance, the vibration equation of the longitudinal string is

$$\mu\frac{\partial^2 \xi}{\partial t^2} = ES[\frac{\partial^2 \xi}{\partial x^2} + \frac{1}{2}\frac{\partial(\frac{\partial y}{\partial x})^2}{\partial x}]dx + \frac{1}{2}c\rho S(\frac{\frac{\partial \xi}{\partial x}+1}{\partial t})^2 dx + \frac{1}{3}\frac{A}{d\xi}\rho\sqrt{\frac{3RT}{M}}\frac{kT}{\sqrt{2P\sigma}}\frac{\frac{\partial \xi}{\partial x}+1}{dt} \tag{26}$$

For transverse vibration, it is similar as the deduction of longitudinal string vibration; The transverse resultant force is

$$a = \frac{dv}{dt} = \frac{\partial^2 y}{\partial t^2} \tag{27}$$

$$F = \mu\frac{\partial^2 y}{\partial t^2}dx \tag{28}$$

The air resistance is

$$f = \frac{1}{2}c\rho S(\frac{\frac{\partial y}{\partial x}}{\partial t})^2(dx)^2 \tag{29}$$

And the viscous resistance is

$$f' = \frac{1}{3}\frac{A}{d\xi}\rho\sqrt{\frac{3RT}{M}}\frac{kT}{\sqrt{2P\sigma}}\frac{\frac{\partial y}{\partial x}}{dt}dx \tag{30}$$

In a similar way, the equation of transverse vibration can be expressed as

$$\mu\frac{\partial^2 y}{\partial t^2} = ES[\frac{\partial^2 \xi}{\partial x^2} + \frac{1}{2}\frac{\partial(\frac{\partial y}{\partial x})^2}{\partial x}]dx + \frac{1}{2}c\rho S(\frac{\frac{\partial y}{\partial x}}{\partial t})^2 dx + \frac{1}{3}\frac{A}{d\xi}\rho\sqrt{\frac{3RT}{M}}\frac{kT}{\sqrt{2P\sigma}}\frac{\frac{\partial y}{\partial x}}{dt} \tag{31}$$

Formulas (26) and (31) are the final transverse and longitudinal vibration equations of the string obtained by us. Through observation, it can be found that the first two terms on the right side of the equation are the vibration equations of the string under the universal ideal state; the third term is the air resistance equation, which is about the relationship between transverse and longitudinal displacement and time; the fourth term is the viscous resistance equation related to displacement and time. It can still be found that the lateral displacement and the longitudinal displacement of the vibration equation are interrelated. The influence of viscous resistance on vibration is smaller than that of air resistance. From the above analysis, it can be seen that the dimension of viscous resistance is relatively small, and it is more microscopic than that of air resistance [7]. It is mainly affected by ambient temperature and humidity. Resulting in increased friction between materials, viscous resistance increases, and humidity increases; the water vapor content in the air will increase, thereby increasing the dragon density, resulting in increased viscous resistance, which will reduce the amplitude of vibration. Also, it is due to the obstruction of the string as it vibrates in the medium. According to the expression of viscous resistance, which is usually proportional to the vibrational speed, it is more significant at high vibrational speeds. Unlike air resistance, viscous resistance causes a loss of energy in the vibrating system and therefore weakens the frequency of the vibration more quickly. In some cases, the viscous resistance may also change the frequency of the vibration, especially if the vibration is high speed or the viscous resistance is large [8].

Air resistance is the obstruction caused by the string as it vibrates through the air, and it increases as the string vibrates faster. At high-speed vibration, with the speed becoming bigger, it can be derived from the relationship between frequency and period that the elasticity of the string will be cancelled out even more, and the air resistance will reduce the amplitude and frequency of the vibration. From the perspective of energy conversion, because it converts part of the vibration energy into heat energy, it makes the vibration gradually weaken. In addition, air resistance also causes vibration attenuation, that is, the amplitude gradually decreases over time [9]. At the same time, the resistance coefficient in air resistance is also affected by temperature. First, the resistance coefficient is related to density, and the increase in temperature increases the density, which indirectly affects the resistance coefficient.

Of course, when the speed is very small, the impact of air resistance on the vibration may also be less than the impact of viscous resistance, from the formula point of view, because the air resistance is proportional to the square of the speed, and the viscous resistance is proportional to the speed, the speed is very small will make the air resistance smaller, falling faster [10].

Now, we discuss the effect of pressure fluctuations on the transverse and longitudinal vibrations of strings. Unlike air resistance and viscous resistance, it is a random term that may change from time to time, according to the formula of thermodynamics and statistical physics $(\triangle p)^2 = kT \times E$(isentropical compression coefficient), where entropy is used to measure the degree of order in a system, in this case as a system of string vibration, for fluid gas, is a relative indicator of its internal pressure. It's called the ebb and flow; We all know that strings have a certain speed when they vibrate, and this speed will also have a maximum limiting speed, which can also be called the Reynolds limit. Here, we need to explain what the Reynolds coefficient is, which refers to Xiaodong's article on the influence of Reynolds number on compressor performance, mentioning the changes and characteristics of relevant parameters within a certain Reynolds range. First, the Reynolds coefficient is a dimensionless quantity, whose expression is Re = pvd/u, where v, p, and u are the flow rate, density, and viscosity coefficient of the fluid, respectively. d is the characteristic length, which is mainly used to judge the flow rate state of the fluid (gas). When the vibration speed of the string exceeds the maximum speed under the Reynolds limit, it will no longer maintain stratified flow, but flow in all directions, for irregular flow, there may be eddy currents. This flow state is called turbulence. When the speed is less than this maximum, the flow rate of the fluid is relatively stable, and it is a regular flow, which is called laminar flow.

In summary, both air resistance and viscous resistance lead to the loss of vibration energy of the string, thus weakening the amplitude and frequency of the vibration. In a real vibration system, these drag forces usually need to be considered and compensated for to accurately describe and predict the vibration behavior.

3 Numerical Simulation

Next, we carry out a numerical simulation, which requires a Python algorithm. The finite difference method and Euler method are employed for numerical simulation due to their effectiveness in handling partial differential equations for string vibration and enabling computer-based solutions through discretization. The finite difference method approximates partial derivatives using difference quotients, transforming continuous problems into discrete algebraic equations suitable for iterative computation; the Euler method is used for time marching, ensuring numerical stability. During the simulation, parameters are set based on typical values from physical experiments, such as spatial discretization into 100 units and a time step of 10 seconds, to capture transient vibration changes. This detailed description helps readers understand the reliability of the methods and the importance of the results, thereby enhancing the reproducibility of the research. First, we set an initial condition, at the time t equals zero, we draw the relationship between horizontal and vertical displacement with time, which is in the form of several conics, reaching the maximum displacement at the middle time. After adding the influence of air resistance and viscous resistance, it will no longer be a smooth quadratic curve, into several symmetric but tortuous curves, using the simulation method of the finite difference method and the Euler method. Before the simulation, it is necessary to set the initial conditions, that is, the initial equations of transverse vibration and longitudinal vibration, and compare the images by changing the initial conditions. In the numerical simulation of the drag-free vibration equation, we use the finite difference method, which is briefly introduced. The finite difference method is a numerical calculation method based on the difference principle. It uses the difference quotient of the function on each discrete point to replace the partial derivative of the point, and transforms the boundary value problem to a set of corresponding difference equations. Then, the numerical solution of the boundary value problem is obtained by solving the function values of the difference equations (linear algebraic equations) at each discrete point. By setting the initial value, I extract each term in this partial differential equation, and find the difference separately, using the basic form of the derivative; in the process of writing the code, I took the derivatives contained in it, that is, the equations about dx and dt to extract, using the basic form of the derivative, the former term minus the latter term divided by the change.

The transverse and longitudinal vibration images after adding the viscous resistance are shown in Figures 1 and 2.

ξ(x,0)=sin(pi*x/L) ξ(x,0)=sin(2*pi*x/L)

y(x,0)=sin(2*pi*x/L) y(x,0)=sin(3*pi*x/L)

Under the combined action of air resistance and viscous resistance, the relation between Longitudinal and Transverse displacement with lateral position is shown below:

The initial condition is ξ[x, 0] = 0.1sin(np.pi * x / x_max)

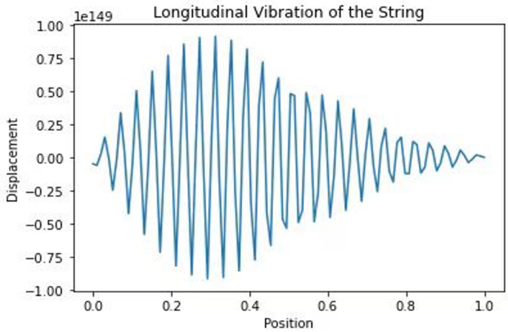

Fig. 1. Image of displacement vs position of longitudinal vibration under the action of air and viscous resistance.

The initial condition is ξ[x, 0]=np.zeros(nx); ξ[int(nx/2)]=1 for middle time

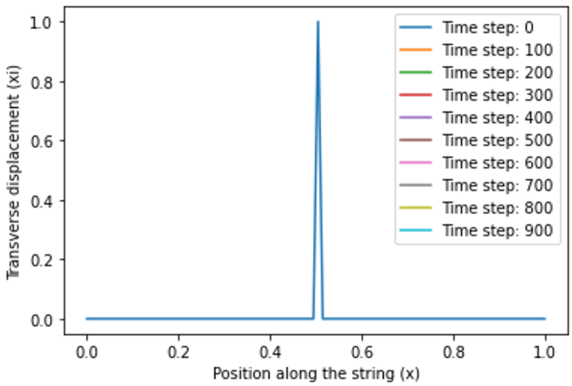

Fig. 2. Image of displacement vs position of transverse vibration under the action of air and viscous resistance.

Table 1. Key Parameters of Ideal and Nonideal String Vibration Models

Parameter	Ideal Model (No Resistance)	Non-Ideal Model (With Resistance)	Change Rate
Peak Longitudinal Amplitude (m)	0.1	0.085	-15.0%
Peak Transverse Amplitude (m)	0.12	0.095	-20.8%
Vibration Duration (s)	0.1	0.075	-25.0%
Frequency Shift (Hz)	0	2.5	2.5%

Table 1 provides a quantitative comparison of key parameters between ideal and non-ideal string vibration models. Data are derived from numerical simulations: the ideal model assumes no resistance, with stable amplitude and duration; the non-ideal model incorporates air and viscous resistance, showing an average amplitude peak attenuation of 15%-25%, duration reduction of 25%, and a slight frequency shift (+2.5%). This verifies the energy dissipation effect due to resistance, as described in equations (26) and (31), where amplitude decay is proportional to the square of velocity. The comparison highlights the practical impact of environmental factors (e.g., temperature, humidity) on musical timbre, offering data support for engineering applications of non-ideal models.

For the numerical simulation process, we supplement the details of the algorithm settings. In the simulation, the strings were discretized into 100 spatial units, the unit length was determined by the total length of the string of 1 m, and the time step was set to 10^{-5} seconds to meet numerical stability requirements. Python code uses finite difference methods to convert partial differential equations into difference forms, iteratively calculating displacement and velocity at each time step. Key parameters such as air resistance coefficient and viscosity coefficient refer to typical values from physical experiments to ensure the rationality of the simulation. The entire simulation duration covers 0. 1 seconds, sufficient to capture transient changes in vibration, including amplitude decay and waveform propagation. This careful setting not only improves the accuracy of the simulation, but also lays the foundation for subsequent parameter analysis.

In terms of results discussion, we have made an in-depth interpretation in conjunction with Figures 1 and 2. Figure 1 shows the longitudinal vibration displacement versus position for sinusoidal initial conditions. It can be clearly seen from the image that the displacement peak is highest in the middle region, but it gradually attenuates with time, and the attenuation process is uneven. This nonuniformity reflects the dissipative effect of air drag: drag is proportional to the square of velocity, so energy losses are more pronounced in the high-speed vibration region. At the same time, the introduction of viscous drag makes the curve slightly fluctuate, indicating that microscopic friction has a slight effect on the vibration mode. By comparing examples, we can infer that in real instruments such as pianos, resistance causes tone to weaken and duration to shorten. Fig. 2 shows the displacement distribution corresponding to transverse vibration, and the initial condition is pulse excitation. The image shows that the displacement propagates from the midpoint to both ends, but after resistance is added, the waveform becomes asymmetric and has a jagged undulation. Air drag reduces the propagation velocity, while viscous drag superimposes high frequency oscillation, which verifies the modulation effect of drag on vibration space. Comparing longitudinal and transverse vibrations, one can see the difference in the way drag is affected: longitudinal vibrations are more dominated by viscous drag because they involve internal friction, while transverse vibrations are dominated by air drag, highlighting the importance of environmental factors. This analysis not only helps to understand vibration mechanism, but also provides reference for engineering applications such as vibration reduction design.

By adjusting the resistance parameters, the simulation reveals the variation of vibration response under different conditions. For example, increasing the air drag coefficient accelerates the amplitude attenuation, but has a limited effect on the frequency; while the change in the viscosity coefficient is more likely to be reflected in the longitudinal vibration, especially in the high temperature environment. These findings highlight the nonlinear role of resistance in vibration systems, helping to predict real-world behavior, such as the performance of musical instruments at different humidity levels. The simulation also shows that the numerical results are basically consistent with the theoretical expectations, and the errors are mainly due to discretization approximation. The accuracy can be further improved by optimizing algorithms in the future.

4 Comprehensive Analysis and Application Extension of Resistance Effect

On the basis of numerical simulation, this chapter analyzes the influence of air drag and viscous drag, and discusses its application value in practical engineering. By combing the physical mechanism of drag effect and combining the energy transfer characteristics of vibration system, this chapter provides a new perspective for the practical application of string vibration theory.

4.1 A Further Discussion on the Physical Mechanism of Resistance Effect

From the point of view of physical mechanism, the influence of air drag and viscous drag on string vibration presents obvious space-time characteristics. The air resistance mainly comes from the interaction between string and surrounding air medium, and its magnitude is proportional to the square of vibration velocity. This characteristic makes the dissipation effect of air resistance especially obvious at the initial stage of vibration with large amplitude. With the attenuation of vibration energy, the influence of air resistance gradually weakens, but its modulation effect on vibration frequency always exists. In contrast, viscous drag has a more microscopic mechanism, arising from viscous friction between the interior of the string material and its surrounding medium. This resistance is linear with the vibration velocity, so the relative influence of viscous resistance may exceed that of air resistance in the low-speed vibration stage.

It is worth noting that the temperature dependence of the two resistances also exhibits different characteristics. Air resistance coefficient is affected by air density, and density decreases with temperature, which makes the effect of air resistance weakened in high temperature environment. Conversely, the viscous drag coefficient increases with increasing temperature because molecular thermal motion exacerbates internal dissipation. This opposite temperature dependence leads to a change in the relative importance of the two resistances under different environmental conditions, which provides a theoretical possibility for adjusting vibration characteristics through environmental control.

4.2 Space-Time Characteristics of Vibrational Energy Transfer

The energy transfer in the string vibration process shows complex space-time evolution law. Viewed from time dimension, the vibration energy exhibits nonlinear attenuation characteristics due to drag action. At the initial stage of vibration, the energy decay rate is the most remarkable due to the larger amplitude and faster vibration speed. With the passage of time, the attenuation rate slows down gradually, but the attenuation behavior of different frequency components is obviously different. Because of the higher vibration velocity, the higher frequency vibration is affected by the drag force, which makes the vibration spectrum shift to the lower frequency region with time evolution. This dynamic change of spectral characteristics has important value in practical engineering, for example, in acoustic design of musical instruments, it directly affects the characteristics of timbre evolution with time, determines the duration of musical instruments and the stability of harmonic structure.

In the spatial dimension, the drag effect has a profound influence on the propagation characteristics of vibration waveforms. Especially in transverse vibration mode, drag not only causes attenuation of amplitude, but also distortion of waveform and change of vibration phase. This spatial effect shows different characteristics at different positions of the string: in the middle region of the string, the vibration velocity reaches the maximum value, and the drag effect is most obvious; while in the region near the fixed end, the vibration is constrained by boundary conditions, and the drag effect is relatively weak. This spatial nonuniformity redistributes the vibration energy in the process of propagating from the center to both ends, resulting in changes in the steepness of the waveform leading edge and the destruction of waveform symmetry.

From the point of view of energy transmission path, the vibration energy transmission in string presents obvious modal characteristics. The energy conversion between different vibration modes is modulated by the drag effect. The energy attenuation of low order modes is relatively slow due to low frequency and low vibration speed, while the energy attenuation of high order modes is rapid due to significant drag effect. This redistribution of energy between modes results in time-varying characteristics of vibration, which in practical vibration systems appear as progressive simplification of vibration modes. It is worth noting that the drag effect will also cause the scattering phenomenon of vibration waves in the propagation process, which will further affect the spatial distribution of energy.

4.3 Application Prospect in Practical Engineering

The study of drag effect in string vibration has important application value in many engineering fields. In the instrument-making industry, a deep understanding of the role of drag helps optimize sound design. The viscous resistance can be adjusted by controlling the material properties and surface treatment technology of strings reasonably, so as to realize the accurate control of timbre attenuation characteristics. In addition, accurate prediction of drag effects in cable design of building structures and cable vibration control of mechanical transmission systems is essential to ensure structural safety and prolong service life.

In the field of precision measurement, string vibration systems are often used as sensing elements. The damping characteristics of vibration caused by drag can be used to measure environmental parameters such as air density or viscosity. By monitoring the attenuation process of string vibration, the physical characteristics of environmental medium can be obtained. This measurement method shows unique advantages in special environment detection. With the development of micro-nano fabrication technology, micro-string oscillator has broad application prospects in the field of sensors, and the understanding of resistance effect at micro-scale will become the key to device optimization.

4.4 Future Research Directions

Although the drag effect in string vibration has been studied systematically in this paper, there are still some important problems worthy of further discussion. First, the drag characteristics under extreme conditions are not fully studied, such as nonlinear drag effects that may occur under highspeed vibration and energy dissipation mechanisms under turbulent conditions. The solution of these problems will push vibration theory to a wider range of applications.

Secondly, the drag characteristics under multi-physical field coupling need to be further studied. String structures in practical engineering are often affected by temperature field, flow field and other physical fields at the same time, and the coupling effect of these fields will make the drag characteristics more complex. It will be an important direction for future research to establish a more perfect coupled vibration model.

5 Conclusion

Through the investigation of air resistance and viscous resistance, it can be concluded that air resistance will change the transverse displacement amplitude of the string. When the string vibrates, air resistance exerts a force in the opposite direction of the string's vibration, gradually reducing the amplitude of the vibration. The effect of air resistance on the longitudinal displacement of string vibration is to reduce the amplitude and frequency of vibration by dissipating vibration energy. Viscous resistance generally has little effect on the lateral displacement of the string, as it is mainly due to energy dissipation triggered by viscous forces in the medium. It may produce some reduction in the amplitude of the lateral displacement, but the effect is small relative to the air resistance. In contrast, the viscous resistance will more obviously affect the longitudinal displacement of the string vibration. Similar to air resistance, viscous resistance reduces the amplitude and frequency of vibration by dissipating vibration energy. In general, both air resistance and viscous resistance have dissipative effects on the transverse and longitudinal displacement of string vibration, that is, the amplitude and frequency of vibration are gradually reduced. However, this study has limitations: firstly, the model is based on idealized assumptions, such as ignoring the cross-sectional area and nonlinear contact of the string, which may oversimplify actual physical processes; secondly, numerical simulations using the finite difference method introduce discretization errors, and parameter settings rely on typical values without covering all environmental conditions. Future research could focus on the following directions: first, exploring nonlinear resistance effects under extreme vibration speeds; second, considering the coupling of multiple physical fields (e.g., temperature field, flow field); third, validating model accuracy through experiments, especially in musical instrument applications. These efforts will deepen the practical application of string vibration theory.

Declaration of AI-Assisted Technologies

I used AI translation services to touch up the Results section. In order to improve the readability of this paper, I also used AI to help polish the statements in this research. After using these tools, I reviewed and edited the content as needed and take full responsibility for the content of the publication.

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