Research on the Lateral Vibration of BTA Deep Hole Machining Boring Bars Caused by the Vortex of External Cutting Fluid

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Abstract: Precision deep hole structures are widely used in the component structure design of fields such as aerospace and weaponry. In-depth research on the vibration phenomena of precision deep hole machining systems is of great significance for controlling the accuracy of workpieces. In order to improve the working performance of the precision BTA (Boring and Trepanning Association) deep hole machining system, this project mainly studies the dynamic characteristics of the boring bar in the system under the vortex working condition. The nonlinear theory is used to explore the nonlinear characteristics such as bifurcation and the maximum Lyapunov exponent of the boring bar system, revealing the dynamic behavior of the boring bar system under the influence of the dynamic cutting process and the internal and external cutting fluid flow, and finding out the influence of cutting parameters and process parameters on the evolution law of the system's dynamic characteristics. For different fluid working conditions of the external cutting fluid, the vibration effect of the boring bar under the fluid vortex of the external cutting fluid and the flow of the internal cutting fluid is studied. By independently introducing nonlinear oscillators, the influence laws of the disturbance of the internal and external cutting fluid parameters and process parameters and the chip content coefficient on the system's dynamic behavior under the above influences are analyzed。

Keywords: *BTA Deep Hole System; Nonlinear Vibration; External Cutting; Vortex; Vortex-Induced Vibration.*

I. INTRODUCTION

Deep hole machining technology plays an inestimable role in the development of the national defense and civilian technology fields. With the rapid development and progress of aerospace, high-speed railways and heavy machinery, deep hole machining technology has a high difficulty coefficient, high precision requirements and a long cycle for the effectiveness of cost input and output, thus becoming a difficult technology in manufacturing processing. Many predecessors have conducted a lot of research on deep hole machining technology, including aspects such as machining systems, technological processes and experimental designs. Christopher Krebs, Dennis Heyser et al.[1]established a nonlinear physical model, especially considering the contact area between the cutting tool edge and the workpiece to predict the hole roundness in drilling operations. They studied the geometry of drilling tools through numerical simulation and thus put forward new edge design schemes. C.H. Gao et al. [2-3] established a model of the cutting force distribution through the research on the specific structure and machining process of the BTA deep hole drill bit. Through the simulation by computer software, the relationships among chip deformation, cutting force and axial force were obtained, providing an intuitive method for controlling the cutting force in actual production. Bayly established a simplified mechanical model to analyze the influence of cutting force on the system, but ignored the inertia and damping of the cutting tool at low speeds.

Lu Liao [4] and others combined the deep hole machining process with laser machining, rolling process and electrical discharge machining to analyze its technological process, improving the machining efficiency and providing theoretical and technical support for difficult-to-machine deep holes and micro-holes.Niu J et al. [5] established a nonlinear dynamic research model of the boring bar with a single degree of freedom. The research found that the magnetorheological damper can effectively suppress the vibration of the boring tool and improve the surface finish. By applying the magnetorheological damper, the vibration of the boring tool can be reduced by about 24%.

Bishop and Hasson [6] proposed using the self-excited and self-limiting Van der Pol equation to simulate the lift force of the fluid on the structure in vortex-induced vibration and applied it to the problem of the vibration characteristics of the deep hole machining system.Considering the influence of cutting fluid in the deep hole machining system, Al-Wedyan H M et al. and Weinert K et al. [7] studied the whirling problem of the BTA deep hole boring bar, established the whirling equation of the deep hole boring bar, and discussed the conditions for the generation of the boring bar whirling, laying a certain foundation for the study of the stability of the boring bar system. Perng Y. L et al.[8-9] studied the lateral vibration problem of the free drill pipe under the action of fluid-structure coupling by simplifying the influence of the cutting fluid on the vibration of the drill pipe. The research believed that the bifurcation behavior of the drill pipe motion caused by the fluid could be judged according to the high and low frequency phenomena that appear in the system during machining. Feigenbaum [10] discovered an important path of how the system develops from period doubling to chaos in the research, analyzed the dynamic evolution process of the system from period doubling - saddle-node bifurcation - reverse period doubling - chaos, and obtained the judgment conditions for the occurrence of different types of bifurcation characteristics in the system. Chen Yushu [11] used the Liapunov-Schmidt method and the singularity theory to study the parametrically excited bifurcation problem of the boring bar system.JIH - HUA CHIN et al. [12-13] studied the coupled action of internal cutting fluid and axial pressure. By applying Hamilton's variational principle and combining the micro - element theory of Timoshenko beam and Euler - Bernoulli beam, they derived the dynamic control equations of the transverse vibration of drill pipes.

II. ANALYSIS ON THE LATERAL VIBRATION UNDER THE VORTEX BOUNDARY WORKING CONDITION

A. Vibration Analysis of the Boring Bar System Caused by Vortex-Induced Excitation of the External Cutting Fluid

In the working mode of internal chip removal of the BTA deep hole machining system, the space is enclosed and the structure of the tool head is complex. The fluid state of the external cutting fluid is mostly in a turbulent state under the influence of excitation changes. Turbulence is an irregular flow state of fluid motion. Turbulence is not an inherent characteristic of the fluid itself, but a phenomenon in which the flow parameters of the fluid change chaotically with time and space under large Reynolds numbers or external disturbances. Physically speaking, countless vortices of different sizes and shapes are distributed in the turbulent flow space. It can be said that turbulence is a flow composed of vortices of different scales.

The study of vortex-induced vibration needs to utilize fluid coefficients, including the lift coefficient CL and the drag coefficient Cd, to describe the magnitude of the action of the fluid on the structure as follows:

$$C_L = \frac{2F_L}{\rho D U^2}$$
$$C_d = \frac{2F_d}{\rho D U^2} \qquad (1)$$

Analyze the influence of the external cutting fluid on the lateral vibration of the boring bar. The key is to calculate F_{cx}, and further calculate F_d and F_L. According to reference [14], use the method of discrete potential vortices to derive the drag force F_d and lift force F_L acting on the cylinder in the vortex flow field. Assume that during the vibration period of the boring bar, a positive vortex and a negative vortex enter the tool head area, and consider that the drag and lift forces exerted by the two vortices on the boring bar cancel each other out. Thus, it can be obtained that during the vortex formation process, the drag and lift forces play an alternating role of peaks and valleys on the boring bar.

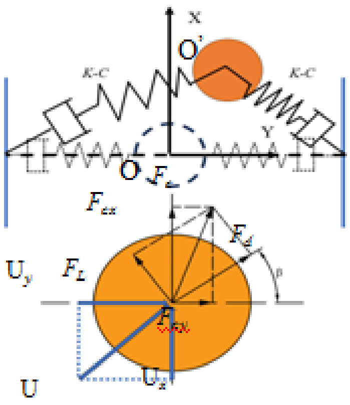


Fig.1 Force diagram of the vibration model of vortex-induced oscillator.

Suppose that at time t_0, a positive point vortex just enters the fluid excitation change area, and the force exerted by the point vortex on the boring bar is ρΓU. The surface of the boring bar is subjected to the pressure Fc exerted by the fluid on it. The fluid force Fc can be decomposed into the drag force F_d that coincides with the direction of the incoming flow and the lift force F_L that is perpendicular to the direction of the incoming flow. Since the boring bar has radial vibration when it performs axial feed motion, this causes certain angles to exist between the drag force F_d and the lift force FL and the axial and radial directions of the boring bar (as shown in Figure 1). The drag force F_d has a lifting effect on the boring bar in the boring bar system; the lift force F_L has an effect of hindering the feed of the boring bar in the boring bar system.

As shown in Figure 1, U represents the fluidization velocity. It can be known from the force analysis that:

$$F_{cx} = F_L \cos\beta + F_d \sin\beta$$
$$F_{cy} = F_d \cos\beta - F_L \sin\beta$$

Where,

$$\sin\beta = -\frac{dx}{dt} / U = -\frac{dx}{dt} / \sqrt{V_1^2 + (\frac{dx}{dt})^2}$$
$$\cos\beta = V_1 / U = V_1 / \sqrt{V_1^2 + (\frac{dx}{dt})^2}$$

Where, V1 represents the flow velocity of the external cutting fluid; U represents the fluidization velocity, ubstitute formula (3) into formula (2) to obtain:

$$F_{cx} = \frac{F_L V_1}{\sqrt{V_1^2 + (\frac{dx}{dt})^2}} - \frac{F_d \dot{x}}{\sqrt{V_1^2 + (\frac{dx}{dt})^2}}$$
$$F_{cy} = \frac{F_d V_1}{\sqrt{V_1^2 + (\frac{dx}{dt})^2}} + \frac{F_L \dot{x}}{\sqrt{V_1^2 + (\frac{dx}{dt})^2}}$$

The force exerted by the point vortex on the boring bar is $\rho\Gamma U$, where Γ is the vorticity in the tool head area. Due to the influence of the reverse point vortex, the change in vortex strength is represented by a cosine curve.

$$F_d = \rho D \frac{d\Gamma_c}{dt} x_c \qquad (1)$$
$$F_L = \rho \Gamma U \cos(2\pi f_{st} t)$$

Here, ρ represents the fluid density; f_{st} is the vortex strength frequency; D is the diameter of the boring bar; x_c is the ratio of the position of the point vortex in the vortex field to the diameter of the boring bar; Γ_c is the vorticity close to the boring bar. According to the principle of vortex formation and disappearance, the total amount of vorticity in the entire flow field remains constant, and the magnitude of Γ_c is:

$$\Gamma_c = -\Gamma \cos(2\pi f_{st} t) \quad (2)$$

$$x_c = \alpha \frac{\Gamma}{UD} \cos(2\pi f_{st} t) \quad (3)$$

Eq (6)、(7) to Eq(5):

$$F_d = \rho D \left[2\pi f_{st} \Gamma \sin(2\pi f_{st} t)\right] \left[\alpha \frac{\Gamma}{UD} \cos(2\pi f_{st} t)\right] \quad (4)$$
$$F_L = \rho \Gamma U \cos(2\pi f_{st} t)$$

Substitute formula (8) into formula (4) to obtain the fluid force $F_{cx}$and F_{cy} :

$$F_{cx}=\rho\Gamma V_1\cos(2\pi f_{st}t)-\frac{\rho\left[2\pi f_{st}\Gamma\sin(2\pi f_{st}t)\right]\left[\alpha\Gamma\dot{x}\cos(2\pi f_{st}t)\right]}{V_1^2+\dot{x}^2}$$
$$F_{cy}=\frac{\rho\left[2\pi f_{st}\Gamma\sin(2\pi f_{st}t)\right]\left[\alpha\Gamma V_1\cos(2\pi f_{st}t)\right]}{V_1^2+\dot{x}^2}+\rho\Gamma\dot{x}\cos(2\pi f_{st}t) \quad (5)$$

It can be known from the fluid force lift coefficient formula (1) that:

$$F_L=\frac{1}{2}\rho DC_L U^2=\rho\Gamma U\cos(2\pi f_{st}t) \quad (6)$$

In order to describe the influence of the fluid excitation change effect caused by the external cutting fluid from the tool head to the inner hole of the boring bar on the boring bar, a dimensionless variable p is introduced to represent the vibration effect of the external cutting fluid:

$$p=2\frac{C_L}{C_{L0}} \quad (7)$$

Where, C_{L0} is the fluid lift coefficient when the boring bar is stationary.

Substituting formulas (10) and (11) into formula (9), the acting force F_{cx} that affects the lateral vibration of the boring bar by the external cutting fluid can be obtained, and its magnitude is:

$$F_{cx}=\frac{1}{4}\rho DC_{L0}UV_1 p\dot{p}+\frac{1}{16}\rho D^2C_{L0}^2U\dot{x}p \quad (8)$$

The force of the excitation change effect is related to the force on the boring bar. Due to the special structure of the boring bar, the vibration of the external cutting fluid excitation change effect is somewhat different from that of the general wake. The vortex state of the external cutting fluid wake changes from formation, to maturity, and then to shedding from the moment it starts to contact the boring head of the boring bar until it leaves the boring head of the boring bar. This continuous change stimulates the vibration of the fluid. According to this characteristic, the force on the wake oscillator can be regarded as a periodic force, which acts on the wake repeatedly, and then the wake reacts on the boring bar in turn.

B. Nonlinear Expression of the Fluid Force of the Cutting Fluid under the Vortex-Induced Boundary Condition

According to the model schematic diagram in Figure 1, it can be known that the elastic coefficient of the nonlinear oscillator is k. Assuming that the initial length of the oscillator is a and the equilibrium position is at point O, then the kinetic energy V_T of the vortex-induced vibration system is that:

$$V_T=\frac{1}{2}m_c(\dot{x}^2+\dot{y}^2)$$

The potential energy V_p is :

$$V_p=\frac{k}{2}\left(\sqrt{x^2+(y+a)^2}-a\right)^2+\frac{k}{2}\left(\sqrt{x^2+(y-a)^2+x^2}-a\right)^2 \quad (9)$$

As shown in Figure 1, the vortex-induced vibration caused by the external cutting fluid in the transverse direction can be obtained, The fluid force is F_c; the damping force is $c_4\dot{x}$。

According to the literature[15], the acting force of the external cutting fluid is Fol, and its magnitude is:

$$F_{ol}=F_{cx}-c_4(\dot{x})-k_4(x) \quad (10)$$

Where：

$$k_4(x)=2kx+\frac{2kxy^2}{a^2}-\frac{kx^3}{a^2} \quad (11)$$

Where $y=x\tan\theta$, θ is the angle between the vortex-induced oscillator and the transverse direction.

Combined with the above analysis, the transverse vibration equation of the BTA deep hole machining system under typical conditions is analyzed, and the transverse vibration equation of the system considering the influence of the external cutting fluid is obtained:

$$\ddot{x}-c_1\dot{x}-c_3\dot{x}^3+k_1x-k_2x^2+k_3x^3=\bar{F}\cos(\Omega t)+\frac{F_{cx}-c_4(\dot{x})-k_4(x)}{m} \quad (12)$$

Where, $c_4=c_s+c_f$, c_s is the structural viscous damping; c_f is the fluid additional damping coefficient, and its magnitude can be obtained according to the Morrison formula;$k_4$is the nonlinear stiffness coefficient of the geometric structure; c_i is the nonlinear damping coefficient, and k_i is the nonlinear stiffness coefficient.

III. BIFURCATION ANALYSIS OF THE BORING BAR SYSTEM UNDER THE INFLUENCE OF THE EXTERNAL CUTTING FLUID IN BTA DEEP HOLE MACHINING

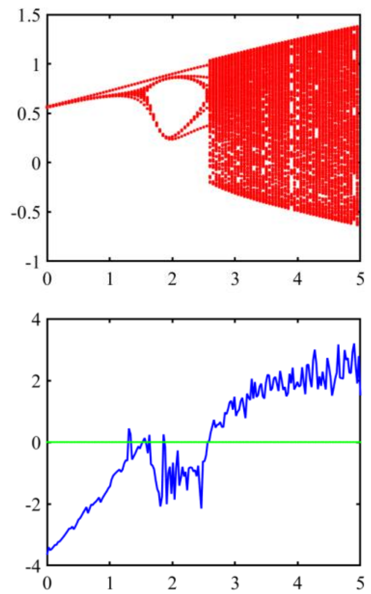


Fig.2 Bifurcation diagram of the primary damping coefficient c1 and the maximum Lyapunov exponent diagram under the influence of external cutting fluid.

Based on the above analysis, numerical simulations are carried out for formula (16) to study the dynamic behaviors of the BTA deep hole machining system within one vortex-induced period. The nonlinear vibration simulations of the boring bar within one period for the primary damping coefficient and the fluid damping coefficient are analyzed. The bifurcation diagram of the boring bar system, the phase diagram under specific parameters, the Poinc aré map and the maximum Lyapunov exponent diagram are shown in Fig. 2.

As shown in Figure 2, under the influence of the cutting fluid, when the primary damping coefficient of the boring system changes, the behavior of the boring system exhibits a single-periodic, multi-periodic to chaotic phenomenon. It can be seen from the maximum Lyapunov exponent diagram that when the primary damping coefficient is around 2.7, the boring system changes from multi-periodic vibration behavior to chaotic vibration behavior. Based on this phenomenon, the influence mechanism of the fluid damping coefficient on the nonlinear behavior of the boring system is studied. As shown in Figure 3, it is the bifurcation diagram of the fluid damping coefficient of the external cutting fluid of the boring system:

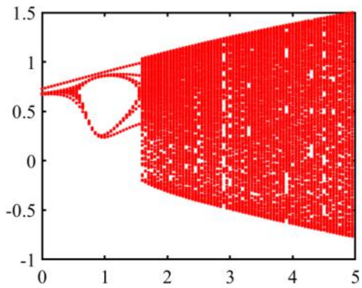
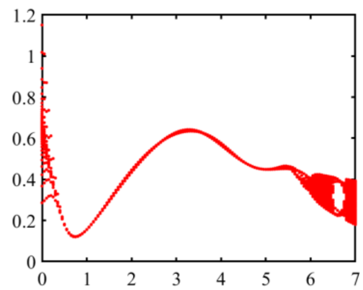


Fig.3Bifurcation diagram of fluid damping coefficient.

According to Figure 3, as the fluid damping coefficient of the external cutting fluid increases, the boring system undergoes an evolutionary process of two-periodic, multi-periodic to chaotic behaviors. When the fluid damping coefficient of the external cutting fluid is around 1.7, the boring system evolves from multi-periodic to chaotic behavior and there is no single-periodic behavior. This indicates that the fluid damping of the external cutting fluid not only makes the chaotic behavior occur earlier but also causes the disappearance of the single-periodic behavior. Due to the existence of the vortex-induced vibration of the external cutting fluid, the increase in the fluid damping coefficient leads to the enhancement of the vortex-induced vibration, which further affects the dynamic behaviors of the boring bar of the boring system. In the actual production process, there are many reasons for the generation of vortex-induced vibration, which does not solely depend on the fluid damping. The complexity of the cavity structure of the boring bar in the deep hole machining system is also an important reason for the generation of vortex-induced vibration of the external cutting fluid.

Based on the research on the primary damping coefficient of the external cutting fluid, the nonlinear vibration simulations of the boring bar within one period for the primary stiffness coefficient of the external cutting fluid and the stiffness coefficient of the nonlinear oscillator are also analyzed. The bifurcation diagram of the boring bar system, the phase diagram under specific parameters, the Poincaré map and the maximum Lyapunov exponent diagram are shown in Fig. 4 as follows:



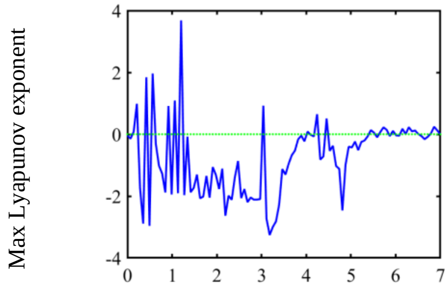


Fig.4 Bifurcation diagram of the primary stiffness coefficient k1 and the maximum Lyapunov diagram under the influence of external cutting fluid.

As shown in Figure 4, under the influence of the external cutting fluid, when the primary stiffness coefficient of the boring system changes, the behavior of the boring system exhibits a phenomenon of chaos-single-periodic-multi-periodic-chaos-multi-periodic-chaos. It can be seen from the maximum Lyapunov exponent diagram that when the primary stiffness coefficient is around 5.9, the boring system changes from multi-periodic vibration behavior to chaotic vibration behavior; when the primary stiffness coefficient is around 6.6, the boring system changes from chaotic vibration behavior to multi-periodic vibration behavior; when the primary stiffness coefficient is around 6.8, the system changes from periodic to chaotic. The specific influence form of the external cutting fluid is represented by introducing nonlinear stiffness. The influence of the nonlinear oscillator on the evolution law of the dynamic characteristics and behaviors of the system can more accurately indicate the real influence mechanism of the external fluid. As shown in Figure 5, it is the bifurcation diagram of the nonlinear oscillator coefficient of the external cutting fluid of the boring system:

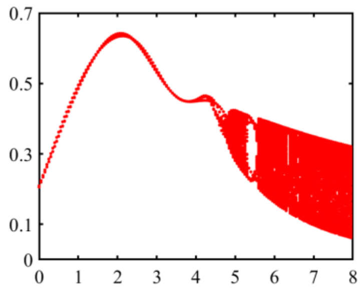


Fig.5 Bifurcation diagram of the stiffness of the nonlinear oscillator.

As shown in Figure 5, with the increase in the fluid damping coefficient of the external cutting fluid, the boring system undergoes an evolutionary process of single-periodic, multi-periodic, chaotic, multi-periodic, and chaotic behaviors. The increase in the stiffness coefficient of the nonlinear oscillator of the external cutting fluid causes the chaotic behavior to occur earlier, indicating that the introduction of the stiffness of the nonlinear oscillator of the external cutting fluid conforms to the actual motion process of the boring bar. In the actual production process, there are many reasons for the generation of vortex-induced vibration. The simulation results demonstrate the feasibility of introducing the nonlinear oscillator, providing a new theoretical method for the subsequent analysis of the nonlinear behaviors of the boring bar affected by vortex-induced vibration.

CONCLUSION

The article focuses on a series of physical phenomena and mechanical analyses related to the boring bar in BTA deep hole machining. Firstly, it introduces the analysis ideas regarding the influence of the vortex-induced effect of the external cutting fluid on the transverse vibration of the boring bar system, which involves calculating fluid force-related parameters such as Fcx, Fd, and FL. The discrete potential vortex method is used to derive the drag and lift forces acting on the cylinder in the vortex flow field, taking into account the entry of positive and negative vortices into the tool head area and their interactions, and then the alternating influence characteristics of the drag and lift forces on the boring bar are obtained. Next, it elaborates on some key physical quantities, such as the physical knowledge related to point vortices, including their definitions, velocity field distributions, and circulation characteristics, as well as the situation related to vorticity. It also explains how to calculate the fluid force by substituting a series of formulas. Meanwhile, dimensionless variables are introduced to describe the vibration effect of the external cutting fluid, and concepts such as the fluid lift coefficient when the boring bar is stationary are mentioned. By utilizing nonlinear characteristics such as bifurcation and the maximum Lyapunov exponent, the nonlinear dynamics of the transverse vibration of the BTA deep hole boring bar system is carried out in a relatively systematic manner. The bifurcation characteristics of the system under the influence of the vortex-induced vibration of the external cutting fluid are analyzed, and the dynamic characteristics of the nonlinear transverse vibration of the BTA deep hole boring system under the change of the chip content coefficient are studied. Through comparative analysis, the influence mechanism of the vortex-induced vibration of the external cutting fluid on the dynamic behavior of the system is clarified. The bifurcation analysis of the chip content coefficient is conducted to clarify the influence law of the chip flow rate on the dynamic behavior of the boring system in the dynamic cutting process.

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