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Numerical investigating nonlinear dynamic responses to rotating deep-hole drilling shaft with multi-span intermediate supports

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ABSTRACT

An approach is presented to study the nonlinear dynamic responses to rotating drill shaft with multi-span supports. Based on the finite element method, the drilling shaft is modeled as lots of 2-node Timoshenko shaft element model with free-interface that can take the effect of inertia and shear into consideration. In these cases, the governing equations of drilling shaft system consist of the coupled linear and nonlinear components. According to the feature of such systems, a modified transformation is introduced, by means of which the linear degrees of freedom of the drilling shaft system are reduced significantly whereas nonlinear degrees of freedom of the system are retained in the physical space. A modified Newton shooting method is used to obtain the periodic trajectories of the dynamic system. The advantage of this method has reduced much of the computational cost in the past, and the hydrodynamic forces of cutting fluid, cutting forces and unbalance forces can easily be added to the system equations. Further, the numerical schemes of this study are applied to a large-scale deep-hole drill machine with two intermediate supports. The periodic dynamic behaviors of the drilling shaft system and the region of unstable rotation are investigated numerically, whereby revealing some interesting phenomena.

1. Introduction

Deep-hole drilling has found wide application in such fields as metallurgical industry, nuclear power and ordnance industry. However, owing to the working environment of drilling shaft in long and narrow hole, the motion state of observing the drilling shaft during machining is impossible. Therefore, more and more attention has been paid to how to establish the practical model of drilling shaft system to calculate the movement trajectories of the drilling shaft efficiently without losing dynamic analysis precision due to complexity of the problem in the last 20 years [1–5].

At present, much research work has been done on the field of the drilling shaft dynamic in the world. Chin et al. [6,7] presented the problem of state monitoring in deep-hole drilling by computer simulation and experiment. Perng and Deng [8,9] established the different models for lateral and longitudinal shaft motion to study the tool eigenproperties of deep-hole drilling, such as numerical Euler–Bernoulli beam model, dynamic flexibility rotating beam model, and flexibility rotating beam mode with static fluid. Such simplified models do not accurately represent the practical drilling shaft system. Drilling shaft system as a rotating machine is a typical nonlinear dynamic system, and hence nonlinear hydrodynamic forces of cutting fluid do not have analytical formulation in fact. Kong et al. [10] established the concentration mass dynamic model of drilling shaft system with the multi-degrees but without considering the effects of inertia and shear, and proposed a method to calculate the nonlinear hydrodynamic forces of cutting fluids and their Jacobian matrices of compatible accuracy simultaneously, and in addition, it was found that the mass eccentricity can inhibit the whirling motion of drilling shaft reported from the experimental results. Hussien et al. [11] studied dynamic drilling shaft modeling with one-span and developed a mathematical approach to study the whirling motion of a continuous boring bar-workpiece system by transforming the problem into nonhomogeneous equations with homogenous boundary conditions. In reality, the drilling shaft system with one or more intermediate supports is typically a multi-part continuum. Despite the cutting forces and the hydrodynamic forces of cutting fluid acting on a few nodal points of drilling shaft individually, the effect from the nonlinearity is global. Additionally, local nonlinearities and linear components of the drilling shaft system are coupled.

For chatter detection, Weinert et al. [12] used dynamical systems to model the drilling process. They are interested in a local description of adequate accuracy to predict disturbances sufficiently and to provide insights into how to react in order to prevent them. Therefore, they proposed a phenomenological approach with a special emphasis on the temporal neighborhoods of instabilities or state transitions from stable drilling to chatter vibration and back. Messaoud [13] proposed a phenomenological model based on the Van Der Pol equation and used nonlinear time series modeling to set up an on-line modeling approach of the time varying dynamics process.

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On the other hand, the theories are mentioned in a series of studies concerning the dynamic responses to rotating shaft with various considerations such as subject to shear deformation, rotatory inertia moment, gyroscopic moment, etc. by using Timoshenko shaft model [14–16]. Pan et al. [17] proposed a method for dynamic simulation of multi-body systems including large-scale finite element models of flexibility. Some optimal lumped inertia techniques are developed in order to avoid computation of the coupling matrics between the rigid-body degrees-of-freedom (DOF) and flexible DOF in the finite element representation of the flexible bodies [18–20]. Hu et al. [21] established the finite element model coupling the flexible-body dynamics of a rotating shaft. The flexible DOF were presented as solid elements without modal reduction. However, using the aforementioned method, the numerical analysis of dynamic responses to a non-linear model with many degrees of freedom generally needs much computing time and may cause computational problems. In order to save computing cost and obtain good accuracy, Fey et al. [22] made a research on the long-term behavior of the mechanical system with local nonlinearity by using the component mode synthesis technique. Hu et al. extended their study to formulate the dynamic responses to a rotating shaft supported by a flexible support structure, and the Craig–Bampton method was employed to reduce the equations of motion [23].

Since drilling shaft system in deep hole machining couple with the cutting force, the hydrodynamic forces of cutting fluid and the mass eccentricity, nonlinear dynamic behaviors of drilling shaft have rarely been discussed in particularly when they are also with one or more intermediate supports. The present work is a major extension to our previous studies [10], and a system method is developed to satisfy the dynamic design demand of the large-scale complex deep hole drilling machine. This paper is organized as follows. In Section 2, the governing equations, including the effect of inertia and shear, are formulated as lots of 2-node Timoshenko shaft element model with free-interface. By introducing a modified transformation, the linear degrees of freedom of the drilling shaft system are reduced significantly while the nonlinear degrees of freedom are retained. In Section 3, according to this reduced model, a modified Newton shooting method is used to integrate the periodic trajectories of the reduced system. The periodic trajectories of the drilling shaft are used as numerical example to demonstrate and validate the proposed method in Section 4. In Section 5, the numerical schemes of this study are applied to a large-scale deep hole drilling machine with two intermediate supports. The periodic motion behaviors of the drilling shaft system and the region of unstable motion are investigated numerically, whereby some interesting phenomena are revealed. Section 6 is concerned with the concluding remarks.

2. Reduction of the model equations of drilling shaft system

2.1. Model of drilling shaft system with intermediate supports

Fig. 1 displays the boring trepanning association (BTA) drilling machine. The machine has an external cutting fluid supply and internal chip transport. The tool head is screwed onto the drilling tube. The high-pressure cutting fluid is supplied through the space between the drilling tube and machine hole, and then removed along with the chip through the drill tube. The cross-section of the drilling shaft is round.

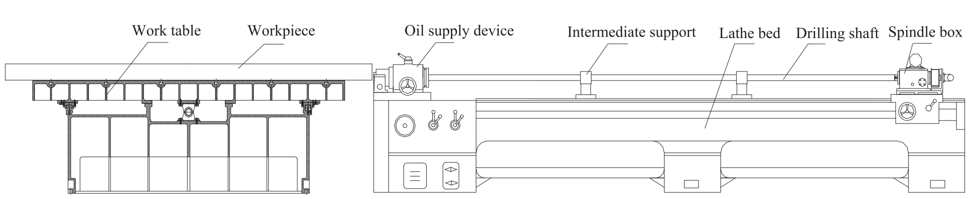

Fig. 1. Configuration of deep hole drilling machine for non-rotary workpiece.

The drill shaft is considered as a continuous flexible shaft at the shaft driver while the workpiece is fastened at its end. Hence, a typical drilling shaft system with two intermediate simple supports is shown in Fig. 2. The drilling shaft is modeled as lots of 2-node Timoshenko shaft element model with eight degrees of freedom [24], considering the effects of inertia and shear as shown in Fig. 3. Using the finite element method, flexible drilling shaft equations of lateral motion can be written as

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{G}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{F}_u + \mathbf{F}_c + \mathbf{f}^s(\mathbf{X}, \dot{\mathbf{X}}) \tag{1}$$

where $\mathbf{M}$, $\mathbf{G}$, $\mathbf{K} \in R^{n\times n}$ are the mass matrix, gyroscope matrix and stiffness matrix respectively, and their specific forms are listed in Appendix A; $\mathbf{X}(t) \in R^n$ is the displacement vector. For a drilling shaft with n nodal points, the displacement vector is of the form

$$\mathbf{X} = [x_1, y_1, \psi_1, \varphi_1, \ldots, x_n, y_n, \psi_n, \varphi_n]^T \tag{2}$$

where x_i, y_i and ψ_i, φ_i ($i=1, 2, \ldots, n$) are the lateral translations and rotation angles of ith nodal point along the horizontal and vertical direction, respectively.

Unbalance forces: $\mathbf{F}_u \in R^n$ is the unbalance forces vector caused by the mass eccentricities of drilling shaft and weight forces acting on *oxy* plane, and its form

$$\mathbf{F}_u = \begin{Bmatrix} m^e e_{x_1}\omega^2 \cos\ \omega t + m^e e_{y_1}\omega^2 \sin\ \omega t \\ m^e e_{y_1}\omega^2 \cos\ \omega t - m^e e_{x_1}\omega^2 \sin\ \omega t + m^e g \\ 0 \\ 0 \\ \vdots \\ m^e e_{x_i}\omega^2 \cos\ \omega t + m^e e_{y_i}\omega^2 \sin\ \omega t \\ m^e e_{y_i}\omega^2 \cos\ \omega t - m^e e_{x_i}\omega^2 \sin\ \omega t + m^e g \\ 0 \\ 0 \\ \vdots \end{Bmatrix} \tag{3}$$

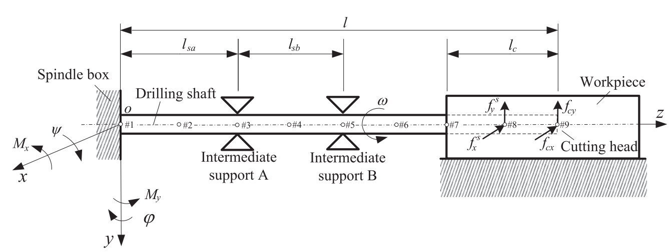

Fig. 2. Coordinates of drilling shaft system for calculation.

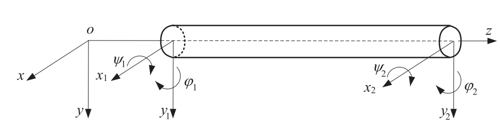
Fig. 3. The finite element model of drilling shaft.