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ORIGINAL PAPER

Nonlinear dynamic model of gear transmission system under the influence of vibration and noise

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Abstract

For gear pairs, there will be nonlinear factors such as time-varying meshing stiffness, tooth backlash and meshing error in gear meshing, which will affect the dynamic behavior of the system and make it appear complex nonlinear vibration. Long-term non-linear vibration will cause fatigue, wear and even cracks in the system, which will greatly reduce the reliability and stability of the system. Therefore, studying the nonlinear dynamic model of the gear transmission system has important theoretical and practical significance for the vibration control and noise reduction of the generator gearbox. On this basis, this paper studies the nonlinear dynamic model of the gear transmission system under the action of vibration and noise. In this paper, the dynamic characteristics of gears and the basic theory of gear modification are deeply studied. In this paper, a nonlinear dynamics model of the torsion coupled gear transmission is established. The influence of nonlinear factors such as time-varying meshing stiffness, transmission error and torsional deformation of the transmission shaft on the gear meshing vibration is analyzed, thereby greatly reducing the noise generated by the gear transmission system vibration. The results show that there are many noises in the gear transmission system. The frequency vibration factors in the system are analyzed, and the mechanism of vibration and noise or various nonlinear factors under different loads is analyzed, which has important theoretical significance for controlling the vibration and noise of gears.

Keywords Vibration and noise · Gear transmission · Nonlinear dynamic model · Jumping phenomenon

Introduction

Gear transmission [1, 2] is the most widely used mechanical transmission in engineering. It has the advantages of high transmission efficiency, stable transmission and compact structure. With the rapid development of science and technology and the requirements of modern production technology for mechanical transmission, all standards require high-precision gear transmission, with low vibration and low noise. Furthermore, nonlinearities need to be considered, such as time-varying stiffness, drive error, tooth side gap, etc., as the gears are often affected by variables. Only by considering all the variables, the gearbox bearing capacity and transmission accuracy can be fundamentally improved [3, 4].

The vibration of the gear system will cause the noise and instability of the gearbox system, and increase the vibration, which will lead to wear, fatigue and distortion of the actual motion law, which will lead to errors and greatly reduce the safety and quality of the machine. The traditional combination of gear characteristics is based on linear theory and static load. Although people try to improve the accuracy of gear machine and approach the theoretical tooth profile as much as possible, the practice has proved that the gear is difficult to conform to the theoretical tooth profile due to the high speed change of theoretical tooth under heavy load. When the gear enters the meshing and disengaging areas, the two scraping surfaces will no longer meet the theoretical matching of tooth profiles, so it is inevitable to produce impact and noise. In most cases, the load distribution along the tooth direction is uneven, thus reducing the accuracy of gear transmission and shortening the service life, thus reducing the bearing capacity of the gear [5].

Therefore, the nonlinear dynamic model of gear transmission system caused by vibration noise [6, 7] is discussed in this paper [8, 9]. In this paper, the dynamic characteristics and

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basic concepts of gear transmission are deeply analyzed, and the indirect variable model of gear distribution is established. The research shows that the research on gear nonlinear dynamics has theoretical significance and practical engineering application value, which can prevent the early failure of gear train and control the vibration and noise of the device in time.

Dynamic analysis of nonlinear vibration in gear transmission

Wheel fault analysis and vibration mechanism

There are many reasons for the abnormal operation of gear devices, which may be due to design, manufacturing, installation or improper maintenance and operation during operation. Gear failure caused by operation mainly includes wear, point corrosion, shedding, root fatigue fracture, glue and other forms. When these failures occur, they cause equipment vibration, noise, temperature, metal content and composition in the lubricant and stress distribution on the gear tooth surface and roots. Thus, these changes reflect the operating state of the gear assembly.

Gear transmission system is a relatively complex power system. In the process of meshing, the stiffness of gear teeth will change from time to time. The result of the rigidity change of the gear pair is that the load on one tooth increases and decreases, which leads to the tangential acceleration, which is the cause of meshing impact. Because each tooth is in a cycle from induction to separation, the direction of the collision changes once and for all along the alignment line, producing a shock wave on the joint line.

Nonlinear vibration dynamic model of gear transmission system

Considering various nonlinear factors such as backlash, time-varying meshing stiffness and transmission error, a nonlinear dynamic analysis model of gear transmission system is established. Gear transmission system is a relatively complex dynamic system, which can be described as a nonlinear vibration variable model:

$$C(\dot{x}) = \sum_{i=1}^{\infty} C_i \dot{x}^{(t)} \tag{1}$$

$$K(x) = \sum_{r=1}^{\infty} K_r x^{(r)} \tag{2}$$

$$D(x, \dot{x}) = \sum_{\alpha=1}^{\infty} \sum_{\beta=1}^{\infty} D \underset{\alpha\beta}{x}(a) \otimes \dot{x}^{\beta} \tag{3}$$

$$M\ddot{x} + g(x, \dot{x}, t) = u(t) \tag{4}$$

where ^{M} is the equivalent mass matrix of the gear pair, ^{x} is the tangential displacement vector between gears, ^{u} is the meshing exciting force vector of the gear pair, and ^{g} is the nonlinear function vector. If:

$$g(x, \dot{x}, t) = C(\dot{x}) + K(x) + D(x, \dot{x}) \tag{5}$$

where the upper right corner (1) and so on denote the degree of Kroneker product and $\otimes$ denote Kroneker product, then the system is called time invariant system.

At present, the research methods of nonlinear dynamics of gear system mainly focus on the nonlinear factors such as backlash, oil film force of supporting bearing, bearing clearance and mass imbalance, and most of the researches only consider the single nonlinear factor of backlash. However, in practice, the slapping of idler gear is the result of coupling of multiple nonlinear factors, so it is necessary to study the gear. It is very important to study the coupling effect of multiple nonlinear factors in nonlinear dynamics to control the vibration and noise of gears.

Experimental thinking and design

Experimental ideas

In this paper, the nonlinear dynamic model of gear transmission system under vibration and noise is analyzed. Gear modification technology is used to compensate the nonlinear factors such as meshing stiffness, transmission error and torsional deformation of transmission shaft. Thus, the vibration and noise in gear transmission system can be greatly reduced.

Experimental design

High vibration and high noise are common problems in gearing. The linear vibration model cannot fully explain its dynamic behavior. The gear vibration model is based on a nonlinear dynamic model, in which the integrated errors of gear engagement, time-varying engagement stiffness and rebound are considered. The nonlinear system of the variable parameters and gaps is converted into a unified matrix form using the nonlinear system equation of the variable parameters and the data cleaning function.

Considering the wear and manufacturing error between the gear teeth, the gap is often left between the gear teeth in the process of gear tightening. When the load on the gear is large, the driving wheel and the driven wheel always contact each other, and the post response will not affect the dynamic characteristics of the gear pair. However, in the engineering

system, in some mechanical equipment which need precise control, the gear mechanism will start repeatedly, and the brake will start. In this case, the backward collision between the gear teeth changes the position of the gear pair, and the contact, separation and recontact between the gear teeth will ultimately affect the dynamic characteristics of the gear system. According to the nonlinear vibration variable model of gear transmission system, the first four natural frequencies of the system are shown in Table 1.

Discussion

Nonlinear dynamic model of gear transmission system under vibration and noise factors

Gear transmission is one of the most widely used mechanical drivers in engineering, which can transfer rotation between parallel and intersecting shafts. With the progress of production and the development of science and technology, the requirements of gear distribution in high-speed, heavy load, high-precision, lightweight and long-life and other indicators are becoming more and more demanding, which makes the vibration and noise problems of gears more urgent to be solved. In addition to noise and instability of the transmission system, the vibration of the gear system can also cause wear, machine fatigue and the fact that the motion rules violate the theoretical law of motion. It greatly reduces the safety and working quality of the machine. In the most extreme cases, gear transmission may fail, and even serious consequences may affect gears or other parts. The forced vibration also makes the gear parts more likely to produce the second resonance. Therefore, the nonlinear dynamic model of gear system can only be built on the basis of considering the nonlinear factors such as time-varying error, backlash and meshing stiffness. In the aspect of rotating system, the gear system is studied to reduce vibration, and the gear improvement technology can be used to compensate for the influence of abnormal line, such as time-varying strength, transmission error and torsional deformation of transmission line, so as to fundamentally improve the load capacity of the gear and improve the transmission accuracy.

It is seen from Fig. 1 that at the torsion 60 Hz torsion fluctuation frequency, the structural noise value varies little with the dorsal gap, and the noise value is stable at 47.1db. At the high frequency component, the noise value of the gear to the structure increases with the amount of rebound. It can be seen that there are many nonlinear factors in the gear systems, such as time-varying engagement stiffness, transmission error, rebound, etc. Only by considering the nonlinear factors can the vibration and noise in the gear transmission system be greatly reduced, and the gear bearing capacity and transmission accuracy can be fundamentally improved.

As shown in Fig. 2, the design parameters of gear system include modulus, number of teeth, moment of inertia, gear mass, support stiffness and support damping. The vibration of the gear system will cause the noise and instability of the transmission system, as well as the wear, fatigue and proper movement rules which deviate from the motion theory and reduce the safety and working quality of the machine. In serious cases, accidents are caused. Based on the nonlinear factors, such as time-varying error, backlash and time-varying strength of gear system, the nonlinear dynamic model of gear system is established. From the perspective of nonlinear

Table 1 The first four natural frequencies of the system

Natural frequency	First order	Second order	Third order	Fourth order
Average / Hz	280	336	387	420

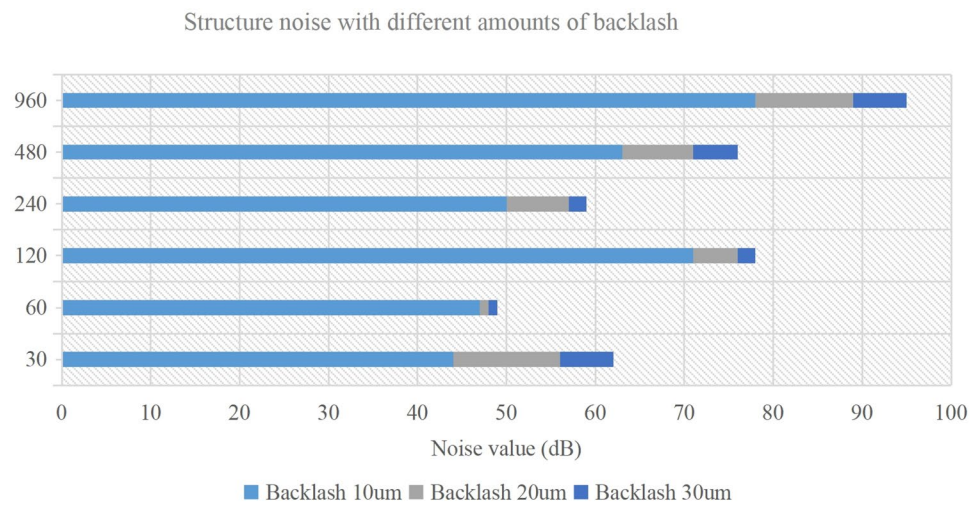

Fig. 1 Structural noise with different backlash

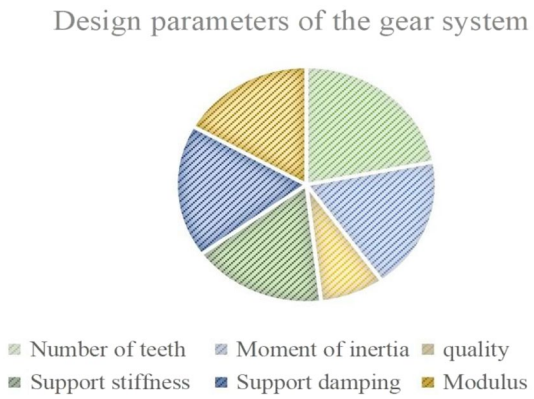

Fig. 2 Design parameters of gear system

system, the vibration and noise reduction of gear system are studied.

Nonlinear model classification of gear system

Classical modeling method

The classical modeling method has two stages: data discretization and digitization.

1) The continuous system is transformed into discrete system by using centralized mass method or distributed mass method;
2) The use of mathematical methods mainly uses mathematical methods such as Newton formula, Hamilton principle, Lagrange equivalent or mathematical analysis model.

Newton's equation is based on Newton's second law; Hamilton's principle is a method based on Lagrangian's practical analysis and diversity principle to get the motion difference equation. The Lagrange equation can be derived from the general formula.

Modern modeling methods

Modern modeling method is mainly finite element method. In the finite element method, the algebraic equations of discrete system are replaced by the differential equations of the original continuous system, which can greatly reduce the difficulty of solving the problem.

1) Separation: a continuous system is divided into multiple structural elements, and the interaction between elements (by the application of equivalent loads or boundary conditions) can only be carried out at external loads or at the points of contact between elements. The differential process transforms the sequence system into variables with finite nodes and discretization transforms elements and boundary conditions into unrestricted algebraic equations.
2) Class analysis: the relationship between unknown number and node interaction based on blockchain assumption is based on a set of rules for each unit. This method uses fractional approximation function to represent the function to be solved in the main system solution.
3) General analysis: under certain conditions, the relationships of all variables are grouped to form algebraic equations with unknown cross variables and boundary conditions, and a certain number of required variables will be obtained by solving the mathematical formula.

Conclusions

In the study of the nonlinear dynamic model of the gear transmission system under the influence of vibration and noise, the dynamic characteristics and basic theory of the gear transformation are deeply studied. The use of gear transformation technology compensates the influence of nonlinear factors such as time-varying engagement stiffness, transmission error and transmission shaft torsion transformation on the gear engagement vibration, greatly reduces the gear transmission based on vibration and noise in the system, and the nonlinear dynamic model of gear transmission is established. We show that a nonlinear dynamic model of the gear system can be established only by considering nonlinear factors such as time-varying error, rebound and grid stiffness. Gear rotation, gear deceleration, system vibration and noise can be studied. In addition, the gear modification technology can be used to compensate the vibration and gear noise under nonlinear conditions such as time-varying strength, transmission error and gear shaft vibration transmission, so as to fundamentally increase the bearing capacity of the gear and improve the transmission accuracy.

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Declarations

Conflict of interest The author(s) declared no potential conflict of interest with respect to the research, authorship and/or publication of this article.

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