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Electromechanical Integrated and Piezoelectric Harmonic Drive System

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The purpose of this paper is to realize an electromechanical integrated and piezoelectric harmonic drive system in order to push forward the technological development in the field. Here discusses the working principle of such harmonic drive system based on which to make analysis on the simulation with the PI modulation. The results reveal that the system output can well trace its input. As a summary, the tracking performance of electromechanical integrated and piezoelectric harmonic drive system comes to light with the Simulink simulation module, what impact the PI modulator plays on the system precision is also open wide.

1. Introduction

We have learned from the study that the electromechanical integrated and piezoelectric Harmonic Drive System (HDS) consists of piezoelectric ceramics, two-stage amplifying sleeves, and oscillating teeth drive systems. Under the function of four-phase voltage, this system realizes drive function with the inverse piezoelectric effect of the electroceramics, and further outputs the power by the oscillating teeth transmission. In this study, when compared with other traditional technologies alike, the electromechanical integrated and piezoelectric HDS features less friction, low rotation speed, high torque, and stable output. Today, it will get applied in many fields, so that this system has great significance for stimulating the development of social technology.

This paper first analyzes the working principle of electromechanical integrated and piezoelectric HDS, and what is the impact of mechanical parameters on the torque. Next, the PI controller is designed and investigated for the robustness of the control system to parameter variables. Hereby, we capture the response law caused by the speed disturbance and the offset voltage, as well as the ideal speed response. In the end, we fulfill an electromechanical integrated and piezoelectric HD LabVIEW control experiment system. Then test the system for control performance, and compare experimental and theoretical results for analysis. It is proved that the theoretical results are available and correct.

2. Literature review

With the rapid development of electronic information and mechanical science, the research of micro-electromechanical systems, characterized by miniaturization, integration and intelligence, has become the frontier of science and technology at present. Micro-electromechanical system is a multidisciplinary integrated system of mechanical, electronic and computer and so on disciplines. Micro transmission mechanism is an indispensable part in the micro-electromechanical system. Its performance characteristics have a decisive influence on the overall performance of the micro-electromechanical system (MEMS). Based on the research of Bhakthavachala and others, the traditional electromagnetic induction motor and the various gear transmission based on the traditional meshing have been widely used in various social engineering fields. Both in theory and technology are already very mature (Bhakthavachala et al., 2017). However, with the development of high technology such as aerospace, precision instruments and micro robots, higher requirements for motors and drives are put forward. Therefore, a variety of new micro electric machines and transmission systems with the characteristics of mechanical and electrical integration emerge as the times

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require, and all kinds of piezoelectric actuators made of reverse piezoelectric effect have been applied in the electromechanical integrated piezoelectric drive system.

The most successful cases of piezoelectric ceramics as driving elements are the development of all kinds of piezoelectric motors and piezoelectric actuators, and the most common one is piezoelectric motors. From the initial proposal to the mature application, the piezoelectric motor has gone through several decades of wind and rain. In the last 30 years, the piezoelectric motor has come to a practical stage from the theory. The former Soviet Union scientists first proposed the piezoelectric motor model, and Veena and others studied the first piezoelectric motor in history (Veena et al., 2017). Japanese scholars made the most research achievements in the field of piezoelectric drive, and Japan also became the first country to apply piezoelectric motors to practicality. The development of piezoelectric motor experienced four stages: basic research, patent application, product development and industrial application. In 1960 and 1970s, Ribeiro and other scholars focused on the research of the piezoelectric motor in the stage of basic theory (Ribeiro et al., 2017); Ceponi and other researchers obtained a large number of theoretical results, and in the form of patent application, the research results were protected (Ceponi et al., 2017); Behera and others made research on the application development stage of piezoelectric motor. Enterprises and scientific research units developed various kinds of piezoelectric motors (Behera et al., 2017), and many piezoelectric motors were used in industry and family after 1990s.

At present, the development momentum of the piezoelectric motor industry is the best in Japan. Cravioto and others applied piezoelectric motors in home appliances, camera focusing system and automobile steering system to make research (Cravioto et al., 2017). In addition, based on the further research on the application of piezoelectric motors by Realini and others, piezoelectric motors were widely used in precision positioning, micro robots and aerospace and other fields (Realini et al., 2017). The piezoelectric motor has the characteristics of fast response, enabling it to start and stop quickly, which is suitable for precise positioning. Because the noise of the piezoelectric motor is small, it can use the piezoelectric ultrasonic motor to open and close the curtains to keep the quiet effect in the room, which requires a quiet environment in the library, the office and the hospital. In the field of Aeronautics and Astronautics, the double-sided piezoelectric ultrasonic motor developed by Kwon and others at Massachusetts Institute of Technology was successfully applied to the Mars probe (Kwon et al., 2016).

The electromechanical integrated piezoelectric harmonic drive system is a new type of transmission device, which is a piezoelectric drive, a harmonic drive and a live tooth transmission. The transmission system overcomes the shortcomings of the traditional friction type piezoelectric motor, which are easy to wear, and short life and the output torque of the non-contact piezoelectric motor are small. It has fast response speed, long life and low speed torque, no electromagnetic interference, and other advantages. It has wide application prospect in the aerospace, biomedicine, precision positioning and micro robot and other cutting-edge technology areas. The vibration analysis equations of the electromechanical integrated piezoelectric harmonic drive system under the piezoelectric excitation are established for the three conditions of the driving part, the transmission part and the whole coupling. The influence rule of driving parameters and transmission parameters on the coupled forced vibration of the system is discussed. It is found that the influence of driving part parameters and transmission parameters on the forced vibration of the system is mainly manifested in changing the amplitude of forced vibration. Considering the nonlinear effect of piezoelectric effect and the number of tooth meshing teeth, the nonlinear dynamic model and equation of the driving part and the transmission part of the electromechanical integrated piezoelectric harmonic drive system are established. Additionally, the weak nonlinear free vibration and the near resonance are derived by using the Lin tine - Poincare method. The nonlinear approximate solution of forced vibration is derived by perturbation method. The amplitude frequency characteristic, displacement response and parameters of the system are given.

It is found that the nonlinear effect of piezoelectricity and the nonlinearity caused by the number of meshing teeth has a significant influence on the coupling system, and the number of tooth meshing teeth has a great influence on the nonlinearity. The friction type piezoelectric drive system is the first type of piezoelectric actuation system applied. Its typical representative is the piezoelectric ultrasonic motor widely used in the world. Japan holds the intellectual property rights of many piezoelectric ultrasonic motors, and commercializes piezoelectric ultrasonic motors as early as possible. Through the influence of the system parameters on the chaotic vibration of the electromechanical integrated piezoelectric harmonic drive system, the bifurcation diagram of the chaotic vibration of the system is given. When the bifurcation parameter is taken as a constant value, the occurrence of chaotic motion is judged by the time domain diagram, phase diagram, Poincare map and power spectrum, and the chaotic vibration condition is produced. The prototype of the electromechanical integrated piezoelectric harmonic drive system is designed and developed. The maximum torque of the prototype is 0.383Nm when the peak value of the voltage is 150V. The test system is used to test the natural frequency of the prototype. The maximum error of the test results and the theoretical analysis is 12.47%, which verifies the correctness of theoretical analysis.

3. Method

3.1 Analysis of working principle of electromechanical integrated and piezoelectric HDS

In order to control the speed and torque of an electromechanical integrated and piezoelectric HDS, the transmission system output mode control equation should be first available, and the effective mode control variables also determined.

This system mainly consists of the piezoelectric stack, primary and secondary amplifying sleeves, oscillating tooth drive system and other parts. Among them, the oscillating tooth drive system is composed of the center wheel, the oscillating tooth carrier (attached to the output shaft), the wave shocker (secondary amplifying sleeve), and the oscillating teeth. This paper applies the following assumptions for the mechanical analysis of the system:

Components for electromechanical integrated and piezoelectric HDS are all rigid, each moving component only translates or rotates;

The weight of each component may be neglected;

The oscillating tooth drive system only allows for the motions in the plane perpendicular to the output shaft;

The movable teeth in the oscillating tooth drive system are identical in size;

There is no lost motion phenomenon at the meshing point of the oscillating tooth drive system, and the friction at the meshing point is neglected, so do the gear teeth manufacture and installation errors.

Dissect the electromechanical integrated and piezoelectric HDS along its arbitrary symmetry axis, from where any one section is taken for analyzing transmission principle. After applying the input voltage to the system, the piezoelectric stack produces longitudinal vibration. The internal force generated by the piezoelectric stack drives the primary amplifying sleeve to sway in the vertical plane, which in turn gives a thrust to the secondary amplifying sleeve, making it swing in a vertical plane. After secondary amplification, the amplitude of the sleeve swing gets stronger. The secondary amplifying sleeve produces a radial thrust to the movable teeth. Then radial thrust drives the movable tooth carrier to rotate in the horizontal plane via the oscillating tooth drive system, so that the output shaft outputs the rotational speed and torque.

Due to the inverse piezoelectric effect of the piezoceramics, a voltage signal is input to the system, and the piezoelectric ceramic will deform. Apply a preload force p along the axial piezoelectric stack and a voltage v to the system input terminal, the deformation of the single-layer piezoelectric chip inside the piezoelectric stack in its length direction is expressed as $\delta = s_{33}^{E} tp/A + d_{33}v$.

Where s_{33}^{E}- the elastic compliance coefficient of a piezoelectric material under a constant electric field; t - the thickness of a single-layer piezoelectric chip; A- the area of the piezoelectric chip; d_{33}- the piezoelectric strain constant.

All piezoelectric chip in the piezoelectric stack are attached to each other and their polarities are opposite. These piezoelectric chips are mechanically serial but electrically parallel. Therefore, the total deformation of the n-layer piezoelectric chips is expressed as $\delta_n = n_1\delta$.

Where n_1- the total number of layers of the chips in the piezoelectric stack.

As the section of any cross-axis of the primary amplifying sleeve has a consistent motion, any section is optional to subjected to mechanical analysis, as shown in Figure 1.

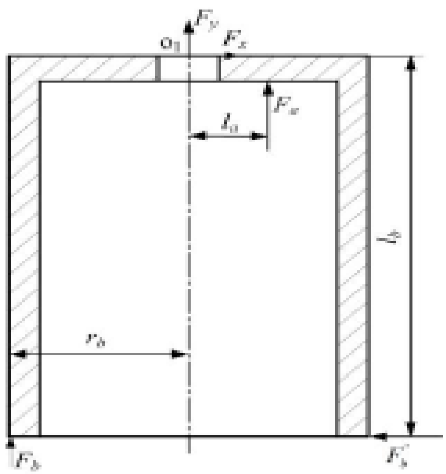

Figure 1: The force analysis of the first stage magnified sleeve in

As the primary amplifying sleeve is subjected to large stress, and the oscillation frequency is low, the amplitude is somewhat minute, we analyze it according to the static equilibrium, and the gravity may be ignored. Take any section of the secondary amplifying sleeve for mechanical analysis, as shown in Figure 2-3.

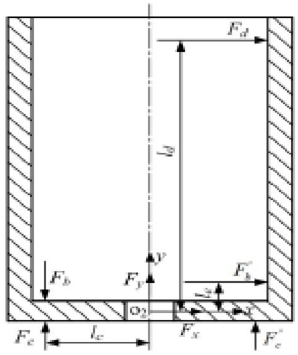

Figure 2: The force of the two stage magnified sleeve

3.2 Mechanical analysis of meshing oscillating tooth

The oscillating teeth drive is such a mechanical drive that transmits the motion and power between the two shafts using the rotatable teeth, also called a planetary transmission with few tooth difference. It features high load capacity and improved transmission efficiency, as well as a wide range of transmission ratios and a compact structure, etc. The steel ball moving teeth drive has won the favor of people due to its excellent driving characteristics. Upon the drive principle of the electromechanical integrated and piezoelectric HDS, we can know that the movable teeth build up a bridge that transmits power between the secondary amplifying sleeve and the output shaft of the movable carrier. For this purpose, we choose the movable teeth as the object for stress analysis. In order to make mechanical analysis on the oscillating teeth drive system simple, we now take a live tooth as the object for analysis. The location of this live tooth is not special, but can be representative for other live teeth. The oscillating teeth drive relationship is shown in Figure 3, and choose any live tooth for stress analysis, as shown in Figure 4.

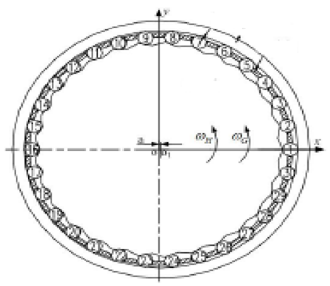

Figure 3: Transmission relationship of live teeth

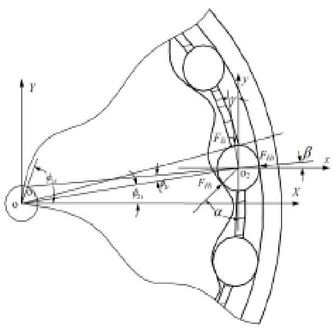

Figure 4: Active tooth drive

3.3 Analysis of time response of electromechanical integrated and piezoelectric HDS

The system operates in the time domain. It is feasible for us to investigate the dynamic response performance of the system with time response analysis. Such time response can reflect the system rise time, overshoot, peak time and other properties. As the system operation is vulnerable to some factors such as interference signals, it is cumbersome to directly explore the system response to live input signal. We, therefore, first use some simple, easy-to-implement typical signals to study the dynamic response performance of the system, which will lay the foundation for parameter optimization in future.

3.4 Step response

The transfer function that the output speed of the electromechanical integrated and piezoelectric HDS corresponds to the input voltage can reflect the dynamic response performance of the system. In order to make clear the dynamic response performance of the system, we now substitute the parameters into the system's speed transfer function to consider its step response, whereby to intuitively analyze the indicators for dynamic response performance of the system. As shown in Figure 5: the electromechanical integrated and piezoelectric HDS has a relatively fast response speed. In this regard, it coincides with the characteristics of the piezoelectric motor, but the steady-state amplitude and real value of the step response differ a lot, and a ideal effect has not yet been reached.

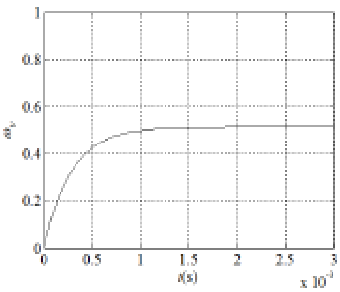

Figure 5: the step response of the system without considering the velocity disturbance

3.5 Superposition of perturbation and step responses

Since the speed response of an electromechanical integrated and piezoelectric HDS is subjected to variable oscillating teeth that involve in meshing concurrently, the live time response of the system angular velocity should include two components, i.e. the step response of the system angular velocity transfer function and the response of the angular velocity fluctuation transfer function. The superposition of both is shown in Figure 6:

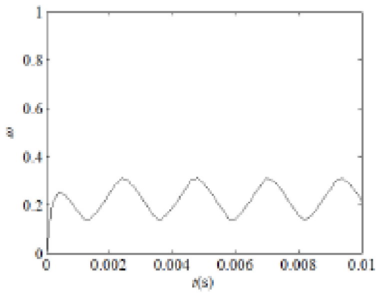

Figure 6: the actual response of the system

3.6 PI controller of electromechanical integrated and piezoelectric HDS

The PID control emerges earlier, and gets very popular in the wake of rapid development. It features simple structure, good stability, reliable operation, and easy to use. The parameters in the PID controller can be adjusted very simply to satisfy the performance requirements of the system; with strong robustness, strong adaptability, and high resistance to external interference, PID controller as a linear control targets at the difference between the live output and input of the system. Then it converts the deviation signals generated by the system into the controlled object system according to the proportion, integral and differential linearity trim for control.

This paper mainly designs the system with Simulink, which attributes to a control module in MATLAB. In Simulink, the system to be controlled can be modeled, and then simulate and analyze the established model. The system we require is built in Simulink very simply, where the a lot of redundant programs won't be required. Simulink features wide applications, simple structure, concise process and high work efficiency. This paper adjusts the parameters designed for PID controller in the Simulink environment.

4. Results and analysis

As described above, the PI regulator is designed for the electromechanical integrated and piezoelectric HDS and the step response performances of the system are also studied. To study the tracking characteristics of the system, the tracking response characteristics of typical signals before PI control are focused on first. The results show that the electromechanical integrated and piezoelectric HDS fails to well track the ramp and acceleration signals before adding PI controller, and there are big discrepancies of the output and the input signals with delicate fluctuations. We learned from analysis that after adding the PI controller, the electromechanical integrated and piezoelectric HDS can follow up the sinusoidal voltage signal very well with less error of the voltage signals, about 20% of the input signal for the sinusoidal voltage signal. The system output can track up system input in a timely manner.

5. Conclusion

It is known according to modern findings that an electromechanical integrated and piezoelectric HDS is a new type of piezoelectric motor that integrates a heap piezoelectric plates and a oscillating teeth drive system. It features more than the conventional piezoelectric motors. This paper systematically focuses on the control mode of electromechanical integrated and piezoelectric HDS, and draws several conclusions as follows:

Here we first build a simplified model of system dynamics in order to make a more profound study on this system, where it is derived from the torque equation. Then the impact law of the mechanical parameters on the output torque is obtained. The results show that the eccentric distance, movable teeth of the secondary amplifying sleeve, and the exradius of the primary amplifying sleeve have a significant impact on the dynamic behaviors of the system.

In addition to this, the tracking performance of this system also come to light by virtue of Simulink simulation module. Count parameters of the PI regulator. Then the impact law of the parameters of the PI regulator on the tracking behaviors of the system is analyzed.

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