The Study of Drive Characteristic and Experimental Approach about Planetary Gearing Mechanism

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Abstract

The transmission indexes which include transmission error and backlash are analyzed, it points out the reasons for the formation of these indexes. The experimental principle and approach about transmission accuracy and stiffness are introduced based on the existing test bench of our university.

Keywords: Planetary transmission, Transmission error, Backlash, Stiffness

1. Introduction

Planetary gearing mechanism are applied to the domain of aviation, marine, automobile and engineering plant, by the characteristics of large drive ratio, high transmission efficiency, compact structure and balanced motion. Nowadays, with the flying development of our technology, which in turn, places higher expectations to equipment manufacturing industry, including the behaviors about accuracy of manufacture, reliability, strength, rigidity and so on, and the accuracy of manufacture and reliability are particularly important between them, they are the representative of manufacturing industry standard for one country. The application of technique about industrial robot heightened the manufacturing industry standard, and they serve as a support role to accuracy of manufacture and reliability. A lot of high-precision planetary gearing mechanisms are used in industrial robot. So it is obviously important to research about transmission accuracy and its testing method of planetary gearing mechanism.

In this test, the testing principles and methods about transmission accuracy and stiffness of planetary gearing mechanism will be discussed linked with transmission accuracy and its testing method. And dynamic testing method about transmission accuracy of high-precision planetary gearing mechanisms.

2. Transmission Accuracy

Transmission accuracy about planetary gearing mechanism usually were controlled and measured with two transmission indexes, transmission error and the lost motion, namely backlash. These two errors both show operating condition about transmission off- ideal path. Backlash is the key about dynamic response of transmission chain, and also is the important source of positional error. Transmission error is the measurement of distorted transmission. Both of them are generated with manufacturing and mounting errors about moving parts and building-up members, which form the whole system, and they are the combined response of many different factors.

2.1 Transmission error and its testing

2.1.1 Transmission error and its cause

Transmission error which is also called rotary transmission error or angle drive error is the angle error of the factual angle of output shaft in one-way rotary transmission compared with the academic angle. The motion of the output shaft has two states with leading and delaying because of transmission error. For example, the ratio of transmission of a pair of meshing involute gear is not invariant. When gears were processing, as the reasons of cutter errors, machine errors, installation and adjustment errors and deformations, the geometric parameters of gear must bring determinated errors, which include tooth form, base pitch, circular pitch, tooth thickness and tooth alignment, it make meshing gears having corresponding positional errors in any time in the range of one round, as a result, the actual angle of meshing gear are different from the academic angle, the deviation value between them is called transmission error. Having it, the instantaneous transmission ratio is tiny diversification in factual transmission process.

The angles of output and input shaft should accord with the perfect linear relationship in transmission process according ideal transmission theory, as follow:

$$\phi_o = \phi_i / i \tag{1}$$

Where, i is overall transmission ratio of gearing mechanism. From it, it shows that the output shaft will slew uniformly while the input shaft slew at a uniform speed. Once the input shaft reverses, the output one should reverses without any angle of lag. However, in fact, the relation between the angles of input and output is non-linearity when transmission error exists in one-way rotary transmission, it is because of the manufacturing and fitting errors to every parts from system, besides, there are heat distortion and elastic deformation while it working.

It is a random error to transmission error, which is the synthesis from the errors about every gear. The error of gear in a broad sense mostly is the overall error of the manufacturing and fitting errors to gears and gearing mechanism. The higher the accuracy about gears and gearing mechanism is, the littler the transmission error is. All of the possible reasons for engendering errors must be taken into account to high-precision planetary gearing mechanisms, there are three kinds of foremost reasons for its errors as follow:

① The process error of gears which is inherent is a combination of factors such as geometrical error, kinematic error, tooth profile error, pitch error, tooth alignment error and so on.

② The errors caused by shaft eccentricity.

③ The errors caused by eccentricity of fit clearance.

Besides, the other factors affecting angular error of gears as follow: the eccentricity of bearing inner ring while it running at the time of outer ring fixed, the deflection about axis of the hole in gear box casing. Sometimes it can be negligible.

2.1.2 Testing about transmission error

There are two methods contain dynamic measurement and static measurement for testing about transmission error. In the process of static measurement, the angle of input and output shaft which are read in static state after turning a certain angle are compared with each other, consequently, the transmission error can be read, viz., it is discontinuous for the process of static measurement. While dynamic measurement is being carried out, the angle are read in running state be approaching to normal operating conditions, in a word, it is continuous for the process of dynamic measurement. It can be found out that dynamic measurement can entirely describe the transmission error by and large.

The dynamic measurement is being carried out on the special test bench for transmission accuracy, which makes up of high-precision rotary encoder, precision junction box, frame, data acquisition system and so on. It has advantages for simple structure, functional agility, high-accuracy measuring, convenient operation, low cost etc. we choose S-90000-1024-D-90-CC style grating encoder made by Fagor company in Spain, 90000 pulses/turn, the degree of accuracy is ±2"/pulse, it can meet the testing demand for high-precision gearing.

The block diagram of testing about transmission error is shown in Figure 1.

Test underbed and bracing structure for speed reducer are sealing-in together, two fortified ribbed in the center of it, therefore, the plank is so rigid and steady. The sliding guide is used in the root of the bracing structure for speed reducer, so equipment can be fixed expediently, and it can be adjusted according different reducer. In order to meet the testing for different reducer, a big flange plate is fixed in the center of frame, different flange plate can be used according different type of machine. After thermal refining, higher hardness and strength it has.

While testing is going, the input shaft is running in stabilizing operational state, the actual angle of input shaft slewing in one round subtract the ideal one, then, many numerical values are given, the minimum in them subtract from the maximum give a number, that is the transmission error. The expression of transmission error is shown as follow:

$$\delta = \phi_{i\max} - \phi_{i\min} \tag{2}$$

2.2 backlash and its testing

2.2.1 Backlash and its cause

Backlash, namely the lost motion, is the lag angle of output shaft when input shaft turn from positive into negative, it can also be interpreted as any angle the output can turn when the input fixed. To planetary gearing mechanism used in systems which ask for precision transmission such as robots and servo, backlash is a critical index, which directly affect the transmission accuracy of transmission system. It is another error that has both links and differences with transmission error. Because of backlash, the output shaft cannot turn back in pace with input shaft, a lag angle is generated after it reverses. The relation between the angle of output and input is shown in Figure 2.

The output angle ϕ_o is zero at the beginning of input ϕ_i running forward direction, the gears go into mesh with other at *a* point, after that, the follower will slew forward at a certain speed. The output ϕ_o hold still for a while after the input ϕ_i turn back at *b* point, then, the driver will turn the angle of clearance (from *b* to *c*). Two gears go into mesh with other on another flank of tooth at *c* point, after that, the follower will slew in opposite direction at a certain speed. ϕ_o is not zero when ϕ_i get zero, slewing is going, ϕ_o will reach zero at *d* point. This curve is hysteresis curve of free play.

According characteristics, overall backlash of gear drive mechanism is made up of invariable backlash and flexible backlash. There are too many causes to generate backlash, and there are five parts for planetary gearing mechanism on the whole.

① design backlash. There must be necessary clearance to compensate fabrication error, installation error, heat distortion and keep space for lubricating film, and the lateral clearance from fabrication tolerance also should be taken into account.

② tolerance backlash. As a result of tolerance of gear size and centre distance. It is the leading backlash.

③ backlash from decentration and gap of bearings. Though this kind of backlash is small, it is indispensable to high-precision planetary gearing mechanism.

④ backlash from bending and environment. That can only be calculated from the analysis of actual circumstantialities about temperature and dynamic force, but can not be directly described in physical dimension.

⑤ backlash from tooth runout. As a result of the decentration between gear axis and spin axis. To a certain position, its number depends on phase angle, but average value is zero. Only in calculating an instantaneous overall backlash, must it be considered.

Among five kinds of, the last is the only flexible one which changes with gears slewing. All of others are invariable.

Angle is the scale for defining transmission error and backlash, so the units are expressed by arcmin or arcsec usually. There also is liner form for pitch circle of gears, usually expressed by microns (um for short). Then, the relationship about angular values of angle transmission and its liner values on pitch circle is shown in Formula 3.

$$\Delta\phi = 3.44\,L/r = 6.88\,L/d \quad (arc\min) \tag{3}$$

Where $\Delta\phi$ is angular value, L is liner value, r is pitch radius (mm) and d is pitch diameter (mm).

Backlash is not necessarily meaningful only when the reverse, even a one-way rotation, hysteresis may affect the accuracy of the transmission. For example, in one-way rotation, with the output shaft suffering from a large enough external torque of rotating in the same direction, the output shaft may have a leading angle due to backlash. Another example is in the process of one-way rotation, if the shaking moment on output shaft is large enough, the output shaft may have a leading angle while the input shaft slow down all at once, which is because of backlash too.

2.2.2 Testing about backlash

The backlash of a gearbox can be defined (measured) at the output (at locked input) or at the input (at locked output), the relationship between the backlash at the input and output depends basically on the reduction ratio. It is shown as follow:

$$S_{input} = i \times S_{output} \tag{4}$$

Where S is backlash and i is reduction ratio.

The above equation is theoretical. Deviations can be experienced when measuring, particularly with multiple stage gearboxes, since the effects of the individual clearances depend upon where the clearance is in the “gear train” furthermore the clearances are not exactly the same in each mesh.

Fig 3. shows the theoretical diagram of testing about backlash, testing about backlash of a gearbox requires a proper test rig and instrumentation. The fixture holding the gearbox and its output shaft should be as be as rigid as possible. When testing is going, one shaft is fixed on the pedestal, the other shaft connects circular grating encoder with elastic joint, we choose S-90000-1024-D-90-CC style grating encoder made by Fagor company in Spain, 90000 pulses/turn, the degree of accuracy is ±2"/pulse.

As shown in Fig 3, the input shaft of reducer is fixed, Then two rotation directions of the output shaft are loading on durative rated torque, and then gradually unloading, the corresponding phase angle in every moment is recorded by instruments, resulting curve is a closed curve, backlash and torsional stiffness of gearbox can be calculated from it.

This test uses direct displacement measurement, it is a measurement about transmission error being compatible with the level of development about sensor technology, electronics and computer technology currently,

In fact, hysteresis curve in Figure 2 shows as zigzag line in specific conditions, factual line is smooth in addition to the maximum and minimum at the outside. It's shown in Figure 4.

Because of friction force in gearbox, backlash regards as the angle difference of output shaft between positive and negative directions under the rated torque of 2% or 3%.

3. Testing about stiffness

Backlash is an index of the gearing mechanism measured without load, But for high precision planetary gear is concerned, only that is not enough, torsional stiffness the index under rated burden must be considered.

Torsional stiffness of the gearing mechanism is the ratio of torsion moment in the role of torque to corresponding angle. It can be expressed by stiffness coefficient, namely the torsion moment that can make the output shaft having one curvature's torsional deflection with the input shaft not moving.

While the test about stiffness is going, two rotation directions of the output shaft are respectively loading and unloading according to certain priority with the input shaft fixed. The corresponding torsion moment and angle are recorded at the same time. The test about stiffness carries out simultaneously with the test about backlash on test rig of backlash.

Torsional stiffness is getting from hysteresis curve. The curve is nonlinear when torsion moment is small, and it can be seen as a straight line under the rated torque of 50% to 100%, as a result, torsional stiffness can be obtained from that range in the way of liner regression analysis. It is shown as follow:

$$C_t = \frac{\Delta T}{\Delta \psi} \tag{5}$$

Where ΔT is the torsion moment between rated torque of 50% and 100%, $\Delta \psi$ is the angle between rated torque of 50% and 100% and C_t is torsional stiffness.

4. Conclusions

Transmission error of planetary gearing mechanism and its influence factors are analyzed in this test, and the experimental principle and approach about transmission accuracy and stiffness are introduced. The detection technique and devices about transmission accuracy and stiffness is an indispensable tool in the process of theoretical research and prototype development about high-precision planetary transmission. The accuracy in measurement is higher because of high-precision sensor. It can meet the demands of research and production test about planetary gearing mechanism.

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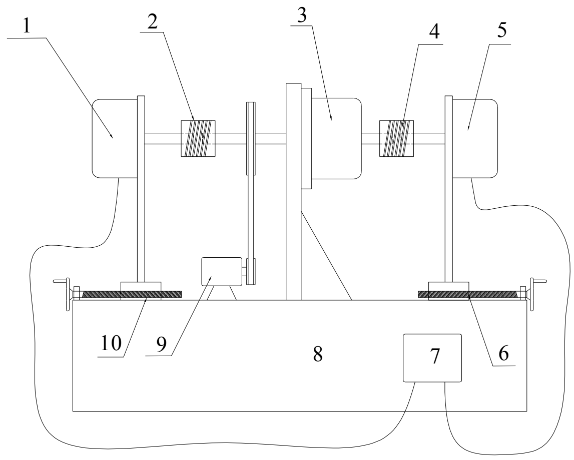


1,5 high-precision rotary encoder ; 2,4 precision junction box ;
3 planetary gearing mechanism ; 6,10 ballscrew ;
7 data acquisition system ; 8 frame ; 9 micro-driving motor

Figure 1. The Block Diagram of Testing about Transmission Error

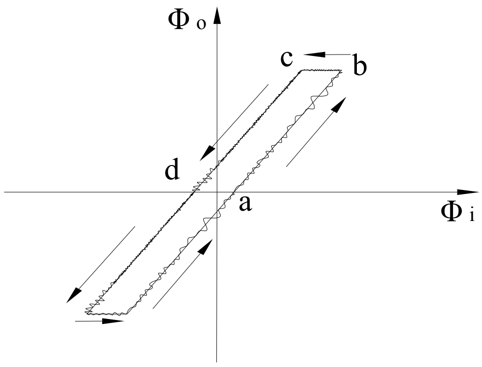
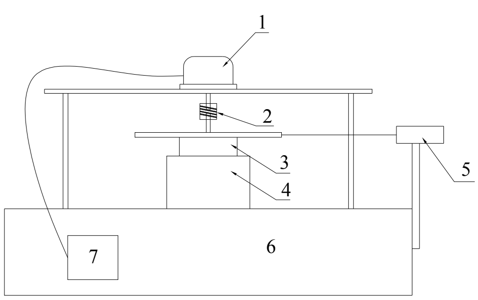


Figure 2. The Hysteresis Loop Line



1 high-precision rotary encoder ; 2 precision junction box ;
3 gearbox ; 4 frame ; 5 load pacer ; 6 damping bedstand ;
7 data acquisition system

Figure 3. The Block Diagram of Testing about Backlash

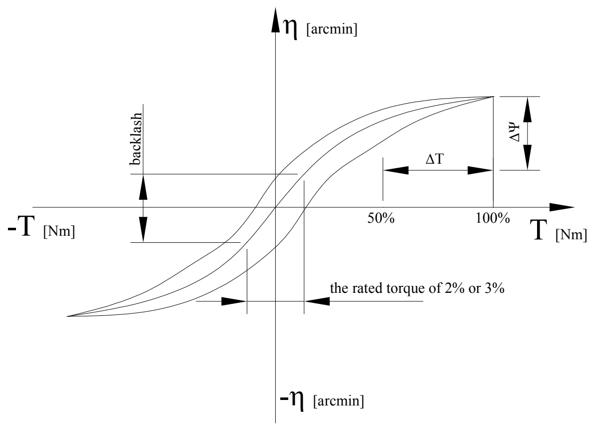


Figure 4. The Hysteresis Curve