The Automatic Measurement System for Harmonic-drive Devices

Yuansong Zheng¹, Zhifeng Lou¹,², Xiaodong Wang¹,²,a and Siying Ling¹,²

¹ Key Laboratory for Micro/Nano Technology and System of Liaoning Province, Dalian University of Technology, Dalian 116024, China
² Key Laboratory for Precision and Non-traditional Machining of Ministry of Education, Dalian University of Technology, Dalian 116024, China

Email: xdwang@dlut.edu.cn

Abstract. Harmonic-drive transmission finds many applications in industry, especially in manufacturing of industrial robots. As the key devices of an industrial robot, the harmonic drive reducers determine the robot’s performance, which includes the positioning accuracy, loading capacity, life time, etc. To satisfy the need of manufacturing high performance harmonic drive devices, development of competent measurement system is of great importance. An automatic measurement system with high-precision and multifunction is under development. The system consists of the power module, loading module, torque and rotation measuring module. The measurement and operation principle were explained. The factors affecting the accuracy of the measurement system were analysed. The control system was designed to realize the automatic loading and acquisition of torque and rotation data. The principle and measurement software of the control system were also introduced. Finally, a harmonic reducer with the gear ratio 120 was measured to verify the feasibility of the measurement system.

1. Introduction
Harmonic drive, occasionally called “strain-wave gearing”, employs a continuous deflection wave along flexspline to transfer motion and power. Because of its unique transmission principle, it has some advantages such as large gear ratio, high transmission precision, high torque capacity and efficiency, lightweight and compact dimensions. Due to these excellent performances, harmonic drive has been widely applied in industrial robots, measuring instrument, assembly equipment, national defense industry, aerospace, and aircraft system.

With the wide application of harmonic drive, the transmission error and efficiency have enjoyed widespread attention from researchers. According to the conventional gear drive model, C.A.Shuwalov predicted the transmission error of harmonic drive by considering the error of wave-generator [1]. By translating manufacturing and assembly error into overall transmission error, Emel’yanov developed a detailed model to calculate position error [2]. Based on the operating principle of harmonic drive, Xuefeng X drew such a conclusion that transmission error is directly affected by the error of gear pair, and the error of wave-generator cause transmission error through affecting the deflection of flexspline, an model was establish to calculate the transmission error [3]. Depended on geometric models of gear-tooth rubbing, Nye developed static and kinematic models to
estimate mechanical efficiency [4]. By calculating the driving power and friction power, Jianchu Y proposed a model to obtain the meshing efficiency of involute cylindrical gear [5].

Affected by many complex factors, the theoretical results calculated by these models are always inaccurate, thus, using an experimental method to measure the transmission performance is necessary. Based on rotary encoder and 120-tooth high-precision gear, Yanabe S developed a measurement system to obtain transmission error, however, this instrument can only be used for static measurement [6]. According to the electrical and optical angle measurement method, Weiyong Li designed a high precision and automatic angle-measuring platform to measure transmission error and backlash [7]. Hejny S W designed a test platform for the study of harmonic drive, observation were also made concerning the way in which flexibility effects the magnitude of the transmission error, in addition, the proportional-derivative method were implemented in both motor state and load state feedback control, and the load state feedback effort was successfully compensated for the effects of transmission error during the regulation of the load position [8]. Aiming at the transmission efficiency, Jianhong R developed a measurement system, both torque motor and magnetic powder brake were used to achieve loading with wide range and high precision [9]. Based on virtual instrument technology, Zhen C designed a mechanical efficiency measuring system, and modular design concept was used to improve the automatic level [10].

The above instrument can only be used to measure one kind of transmission performance; therefore, the development of multifunction integrated test system with general-purpose and high automaticity has received widespread attention. Qi L designed a measurement system which can be used to measure transmission accuracy, stiffness, backlash, mechanical efficiency of the RV reducer with different series and specifications [11]. Based on Permanent Magnet Synchronous Motor system, optical-electricity encoder, magnetic powder brake and corresponding resistant torque master, Hongchun W design a dynamic and static test system to measure transmission error, carrying ability and output rotational speed of harmonic drive [12]. Based on this research, Xuesong M developed a measuring system which can be used to capture mechanical efficiency, transmission error, service life, overload capacity, starting torque and stiffness [13]. Although these instruments can be used to measure a variety of performance, the accuracy is not enough.

In this paper, according to the measuring principle of transmission error and mechanical efficiency, an automatic measurement system for harmonic drive transmission performance was developed, and the principal factors which may affect the accuracy of measuring platform were analysed. In addition, the control system based on modular design was introduced. Finally, measurement experiments were carried out using this system to verify the feasibility of the measurement system.

2. The measurement system

Transmission error and mechanical efficiency are important indicators of harmonic drive’s performance, test parameters for calculating these two features include torque, rotation at input and output of harmonic drive. According to these parameters, transmission error and mechanical efficiency can be obtained through the method described as follows.

2.1. The transmission error

Transmission error $\theta$ is typically measured by subtracting the rotation at the output of the harmonic drive from the ideal rotation which is obtained through the input rotation divide by the ideal gear ratio, the expression can be described as follows:

$$\theta = \theta_i - \theta_o$$

Where $i$ is the ideal gear ratio, $\theta_i$ and $\theta_o$ are rotation at the input and output of the harmonic drive.

Both static transmission error and dynamic transmission error are used to evaluate transmission accuracy. When the input shaft rotates a certain angle, the rotation at the output of harmonic drive can be measured under stationary state. According to equation (1), static transmission error could be calculated. Static transmission error does not consider the influence of inertial load, so it cannot reflect the dynamic characteristics. The dynamic transmission error is calculated by measuring the input and
output rotation of harmonic drive during its operation progress, it is more consistent with the actual working condition, therefore, this method was adapted in this research. A high precision rotary encoder was used to obtain the rotation at the input and output of harmonic drive, and transmission error was calculated based on equation (1).

2.2. The mechanical efficiency

Due to gear-tooth-friction and damping of wave-generator, harmonic drive exhibit a finite power loss, therefore, it is of great significance to study the mechanical efficiency of harmonic drive. Mechanical efficiency $\eta$, is calculated by the power at the input and output of the harmonic drive, the expression can be described as follows:

$$\eta = \frac{P_o}{P_i} = \frac{T_o}{iT_i}. \quad (2)$$

In equation (2), $P_o$ and $P_i$ are the power at input and output of harmonic drive, $i$ is the ideal gear ratio, $T_o$ and $T_i$ are torque at input and output of harmonic drive. In order to calculate mechanical efficiency, two high-precision torque sensors were used to obtain torque.

According to the above analysed, rotary encoder and torque sensor are the key components to measure transmission error and mechanical efficiency. According to this principle, a measurement system was developed.

2.3. The structure of the measurement system

The structure of the measurement system was shown in figure 1. It was composed of motor, rotary encoder, torque sensor, magnetic powder brake, and pedestal. Torque sensor and rotary encoder were used to acquire torque and rotation at the input and out of harmonic reducer, the motor provides power for this system, in order to conform to the actual working condition, magnetic powder brake was used to impose different load during measurement progress.

2.4. Analysis of the influence of angular deviation

As shown in figure 1, harmonic reducer and rotary encoder were connected through diaphragm coupling, therefore, the existence of coaxiality error is inevitable, it is necessary to analyse the relationship between coaxiality error and transmission error of diaphragm coupling.

Based on simulation method, magnitude of diaphragm coupling transmission error were present in this research when the angular deviation of the connecting shaft is 0 degree, 0.1degree, 0.2degree and 0.3 degree. The simulation results were presented in figure 2. As shown in figure 2, when angular deviation is 0.3 degree, the transmission error is ±7”, it would have a great affect on measurement precision. The transmission error is ±0.8” when angular deviation is 0.1 degree, in this case, the transmission error caused by misalignment of diaphragm coupling could be ignored. Therefore, the angular deviation of diaphragm coupling between the rotary encoder and harmonic reducer should be within 0.1 degree.

![Figure 1. Structure of the measurement system](image1)

![Figure 2. Transmission error of diaphragm coupling in different angular deviation](image2)
As shown in figure 1, all shafts were contacted through couplings, if the shafts were connected from left to right during the building progress, coaxiality error of measurement system would be accumulated. In order to solve this problem, first, the motor was fixed on the pedestal, and then components were installed from right to left. Because the motor shaft was always used as a reference during the progress of building the platform, the cumulative error could be minimized as much as possible.

According to the above analysis, the measurement system was built up (see figure 3). A motor (HG-SR102J, made by Mitsubishi, rated speed 2000RPM) and servo driver consist of the motor driver module. Torque sensors (0261E, with accuracy 0.1%F.S, repeatability ±0.02% F.S, Nominal Torque 5N.m; 0261Due, with accuracy 0.1%F.S, repeatability ±0.02% F.S, Nominal Torque 20/200N.m, made by Lorenz Messtechnik GmbH) were used to capture the torque at the input and output of the harmonic reducer. The rotation at input and output of harmonic reducer were obtained by the high-precision rotary encoders (RCN2310, system accuracy ±5 arc-second, 26-Bit, RCN2510, system accuracy ±2.5 arc-second, 28-Bit, made by Heidenhain). Magnetic powder brake (CZ-20, Nantong Hailing Magnetic Brake Manufacturing CO.LTD) provide a load for the measurement system.

3. Automatic control of measurement
The control system was composed of servo motor drive module, data acquisition module, loaded module, IPC and software, principle of the control system was shown in figure 4. According to the parameters of direction and speed, DIR and PWM signals were output from the IPC to adjust the rotation of motor, and transmission performances of harmonic reducer were tested under different speed. Data acquisition module was composed of PCI-1710 data acquisition card (12-Bit, sampling rates 100 KHz, made by Advantech), torque sensor, rotary encoder, and IK220 counter card (made by Heidenhain). When the reducer was driven by motor, PCI-1710 was used to acquire the torque, and rotation was obtained by IK220 card. PCI-1710 data acquisition card, conditioning circuit, and magnetic powder brake consist of the loading module, PCI-1710 send analog quantity to conditioning circuit to control magnitude of the load.

Measurement software, consists of three threads, is mainly used for motor control, data acquisition and processing, and loading control. Flower chart of the measurement software was shown in figure 5.
Based on the above control principle and measurement software, the automatic measurement of transmission performance could be realized.

4. Experiment
In order to verify the feasibility of the measurement system, a harmonic reducer with gear ratio 120 was measured without load, and the measuring speed is 90RPM. The dynamic transmission error curve was given in figure 6. As shown in figure 6, the magnitude of transmission error is ±12.5 arc-second. Therefore, the automatic measurement of transmission performance could be realized by this measurement system. Only when the precise dynamic transmission error curve is obtained, it is possible to separate single transmission error, which is also the direction of further research.

5. Conclusion
In this research, the principle and method for measuring transmission error and mechanical efficiency of harmonic reducer were introduced, and measuring platform was established. The principal factors which may affect the measuring accuracy of this platform were also analysed. Furthermore, the control system consists of a motor driver module, loading module, data acquisition and processing module was introduced, and the measuring software was designed based on the control principle. Finally, a harmonic reducer with a gear ratio of 120 was measured by this system. The result indicates that the measurement system developed in this paper could achieve precision automatic measurement for transmission performance of harmonic reducer.

6. References
[1] Yunwen S and Qingtai Y 1985 The theory and design of harmonic drive (in chinese) (Beijing: China Machine Press)
[2] Emelyanov A F 1983 Calculation of the kinematic error of a harmonic gear transmission taking into account the compliance of elements. Soviet Engineering Research, 7-10
[3] Xiefeng X, Xingtao D and Linzhi S 1996 Analysis of Transmission Error of Harmonic Gear Drive. Journal of Zhejiang University of technology. 53-60
[4] Shuvalov S A 1979 Calculation of forces acting on members of a harmonic gear drive. Russian Engineering Journal. 5-9
[5] Jianchu Y, Yibao C, Ji Z and Jun Y 2001 Study on a method for calculating gearing meshing efficiency. Chinese Journal of Mechanical Engineering. 18-21
[6] Yanabe S, Ito A, Okamoto A, Yamaguchi T and Fujita H 1990 Rotational transmission error of harmonic drive device. Transactions of the Japan Society of Mechanical Engineers. 148-153
[7] Weiyong L 2011 Design and implementation of a universal test platform for the transmission accuracy of harmonic reducer (Harbin Institute of Technology) chapter 2 pp 11-22
[8] Hejny S W 1997 Design of a harmonic drive test apparatus for data acquisition and control (Rice University) chapter 4 33-46
[9] Jian-Hong R, Tie-Cai L and Jian S 2014 A Control System Design of Testing Harmonic Drive Reducer Transmission Efficiency. Modular Machine Tool & Automatic Manufacturing Technique. 55-57
[10] Zhen C, XinSheng L, ZhiYuan L and Yaqin W 2008 Creeper Gear Mechanical Efficiency Testing System Based on Virtual Instrument. Instrument Technique & Sensor. 31-33
[11] Qi L, Xinhui W and Weidong H 2016 Research of the Comprehensive Performance Test System of the RV Reducer Used in Robot. Journal of Mechanical Transmission. 1-3
[12] Hongchun W 2005 Research on automatic testing system of harmonic reducer (Harbin Institute of Technology) chapter 2 pp5-20
[13] Xuesong M, Tao T, Muxun X, Fei Z, Yun Z and Xinmu Y 2009 Dynamic performance comprehensive detection system of harmonic speed reducer. CN101587016

Acknowledgments
This research work was support the National Natural Science Foundation of China (U1508211).