Springer

KSME

Journal of Mechanical Science and Technology 33 (5) (2019) 1995~2001
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-019-0401-3

Manufacturing quality assurance for a rotate vector reducer with vibration technology†

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(Manuscript Received January 30, 2018; Revised November 9, 2018; Accepted January 16, 2019)

Abstract

To improve the product quality of rotate vector (RV) reducer at a low cost, a kind of vibration technology is introduced to investigate the quality assurance of RV. It includes a torsional vibration test to assess the vibration performance of the reducer and vibration analysis to recognize the manufacturing defects in the reducer's mechanical components. The mechanical components with manufacturing defects are diagnosed through the signal processing on torsional vibration and defect characteristics recognition, and they are removed from the RV reducer by a reassembling process. As a result, the dynamic behavior of the reducer is evidently improved, the torsional vibration of the reducer is kept within a low level, and the feedback control is realized for product quality during the production process. Therefore, the presented vibration technology is highly recommended to the manufacture quality assurance of RV reducers applied in an industrial robot.

Keywords: RV reducer; Quality assurance; Torsional vibration; Signal processing; Industrial robot

1. Introduction

Rotate vector (RV) reducers have been widely used in industrial robots owing to their advantageous properties such as a small backlash, high transmission accuracy, large reduction ratio, high torsional rigidity, great load capacity, and high shock-resistance. The first RV reducer was invented almost 70 years ago by Lorenz Braren, and since then, many types of RV reducers have been developed and applied. Furthermore, the design of RV reducers has been investigated in several areas, and theoretical analyses of their structural strength have been conducted [1-3]. However, the quality assurance of RV reducers is still a problem in the manufacturing process.

In addition to dynamic power transmission errors [4], static stiffness [5], and noise radiation, torsional vibration is another important factor that affects the quality assurance of RV reducers directly. It is also closely related to the positioning accuracy and motion trajectory of the RV reducer in the industrial robot. Therefore, studies in the area of quality assurance are still needed.

Based on fault diagnosis achievement in rotating machinery, the aim of this study is to control the torsional vibration of RV reducer to a low level and realize the quality assurance of RV product. Through the imitation of the inertial load condition in an industrial robot, the torsional (circumferential) vibration of the RV reducer was collected for data analysis, signal processing, fault diagnosis and reassembling. Finally, the product quality of RV reducer was improved. Being different from the design of additional actuator or new structure [6, 7], the strength of vibration is controlled by reducing dimension error in the mechanical components.

The rest of the paper is organized as follows: Sec. 2 describes the torsional vibration technology of the RV reducer; Sec. 3 gives the results of a study on fault characteristics; Sec. 4 states how the mechanical components with manufacturing defects are diagnosed; Sec. 5 states the profit of quality control; and Sec. 6 summarizes the main findings of the study.

2. Vibration test system

2.1 Test rig

The RV reducer is a type of two-step gear that has a planet gear transmission with slightly different teeth than that developed using the cycloid gear. A diagrammatic sketch of the power transmission is shown in Fig. 1. The RV reducer used in an industry robot consists of an input shaft, a sun gear, planet gears (including crankshaft), cycloid gears, and a planet carrier as the output. Generally, to achieve loading balance, two cycloid gears are used in the RV reducer. The design

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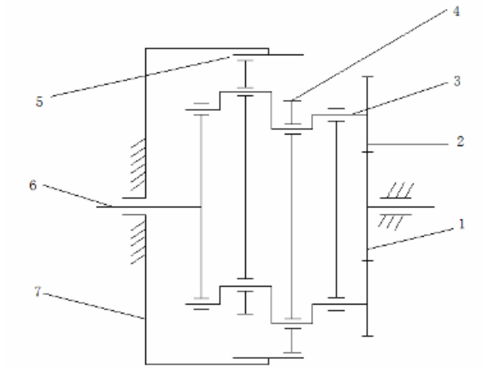
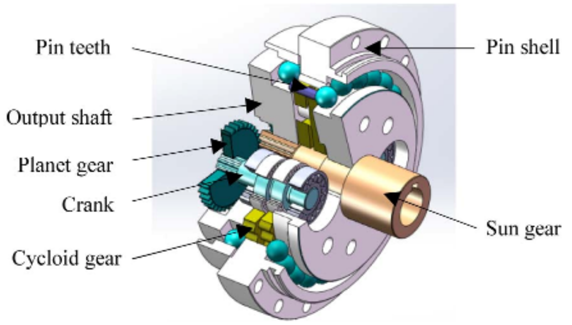
† Recommended by Associate Editor Gyuhae Park



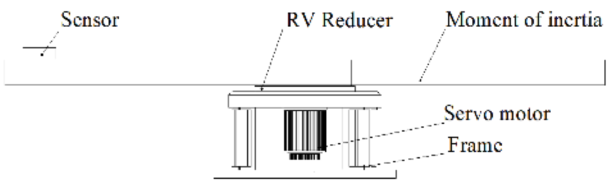
(a)

1. Sun gear, 2. Planet gear, 3. Crank, 4. Cycloid gear, 5. Pin teeth, 6. Output shaft, 7. Pin shell

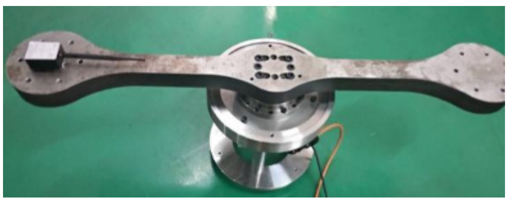


(b)

Fig. 1. RV reducer power transmission: (a) Schematic diagram of RV reducer; (b) structural figure of RV reducer.



(a)



(b)

Fig. 2. Sketch of RV torsional vibration test rig: (a) Schematic diagram of test rig; (b) photo of test rig.

parameters of the main components in RV40E are listed in Table 1.

The torsional vibration test rig, shown in Fig. 2(a), mainly includes the RV reducer, an inertia load, a servo motor, and a wireless acceleration vibration sensor. A servo motor is used to drive the RV reducer whose output shaft is connected to the inertia load. The real figure is shown in Fig. 2(b).

Table 1. Design parameters of main components in RV40E.

	Name of component	Quantity	Design parameters
1	Driving pinion	1	Z1 = 12, m = 1.5
2	Planet gear	2	Z2 = 36, m = 1.5
3	Cycloid gear	2	Z3 = 39, D1 = 128
4	Pin shell	1	Z4 = 40, D2 = 127.98

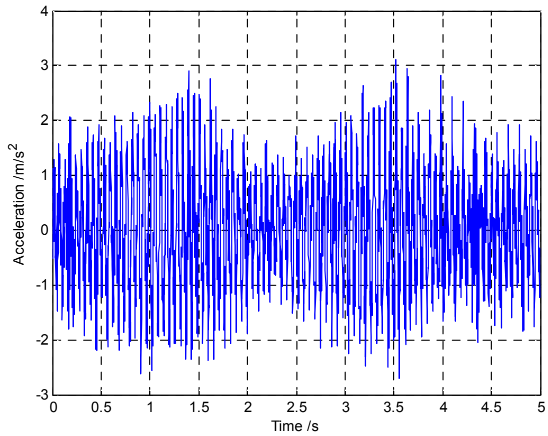


Fig. 3. Time history record of circumferential vibration acceleration (a model 40E RV reducer has an operating speed of 1200 rpm).

To simulate the working condition of an industrial robot joint, the value of inertial load is 56.65 kg·m^2, which is attached to a 40E RV reducer. The RV reducer is driven by a RUKING AC servo motor, whose model is HQ5M130-150D20L2A. Motor's rated power, rated speed and rated torque are 1.5 kw, 2000 rpm and 7.16 N·m, respectively. In this way, the vibration performance of the RV reducer can be fully tested, and its dynamic behavior can be assessed.

2.2 Measurement

A wireless acceleration sensor (MEMS sensor) is installed in the arm of the inertial load, far from the rotation center. Then, the circumferential vibration signals are picked up, and the signals are directly considered as the torsional vibration by the linear signal combination. By using the circumferential vibration instead of the torsional vibration, the measurement process of torsional vibration is simplified in the dynamic test.

A model 40E RV reducer is used in the vibration test, and a model MTE-T8 sensor is selected. The vibration acceleration measurement ranges 0~2 g, and the frequency ranges 0~400 Hz. The vibration detection point is 550 mm away from the rotation center. The time history of circumferential vibration acceleration is shown in Fig. 3, which is captured at the speed of 1200 rpm. The beat phenomenon can be seen in one rotation period of the vibration wave, and it is caused by the difference between the two eccentric shafts, the corresponding planet gears and cycloid gears in the power transmission system.

The motor driving speed was changed from 300 rpm to

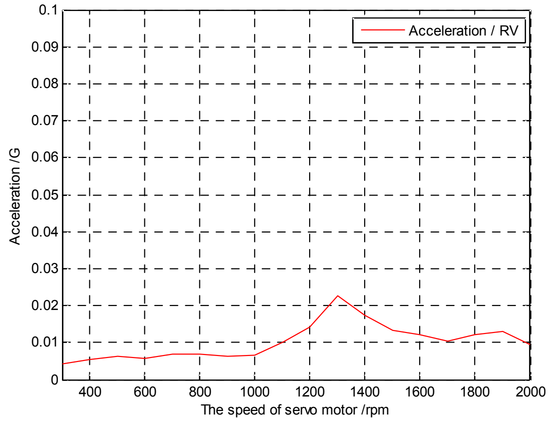


Fig. 4. Vibration performance curve of a model 40E RV reducer (made in Nabtesco company).

2000 rpm at 100 rpm increments, as shown in Fig. 4, and the vibration performance curves were obtained [8]. They corresponded to the magnitude of the circumferential vibration acceleration that is related to the driving speed. At a driving speed of 1300 rpm, the highest peak was observed in the curve of vibration performance. This peak would negatively affect the operation performance of the RV reducer. Therefore, our object was to keep the highest peak within an acceptable level of vibration strength.

3. Vibration characteristics

The torsional vibration signal from RV reducer consists of a stationary part and a non-stationary part. The vibration sources correspond to dynamic power transmission error and impact vibration response, respectively. Therefore, different signal processing technologies are needed to recognize vibration characteristics in the test of RV reducer [9].

3.1 Dynamic power transmission error

The transmission ratio, R, is given by

$$R = \frac{n_1}{n_6} = 1 + \frac{z_2 z_5}{z_1(z_5 - z_4)} = 121, \quad (1)$$

where z_1 is the teeth number of the gear in the input shaft, z_2 is the teeth number of the planet gear, z_4 is the teeth number of the cycloid gear, z_5 is the teeth number of the pin teeth, n_1 is the driving speed, and n_6 is the output speed.

The dynamic power transmission error is reflected in the circumferential vibration when the RV reducer runs, and it is caused by manufacturing defects [10]. Usually, it occurs at lower frequencies, and its characteristic frequencies can be directly calculated from the mechanical kinematics of the RV reducer based on geometric structures and driving speeds. In addition, some mechanical components constrain the complex movement of the RV reducer, such as the pin teeth and the pin shell. They also act on the characteristic frequency of the circumferential vibration when the RV reducer runs. All characteristic frequencies of the RV reducer are calculated and given in Table 2.

Table 2. Characteristic frequencies of model 40E RV reducer with bi-cycloid gears at the speed of 1200 rpm.

Name of characteristic frequency	Formula of characteristic frequency	Characteristic frequency when speed 1200 rpm
Frequency of driving shaft	$f_1 = n_o R / 60$	19.98 Hz
Meshing frequency of driving gear	$f_{gear} = n_o z_2 (z_5 - 1) / 60$	232.07 Hz
Characteristic frequency in output shaft	$f_o = n_o / 60$	0.1653 Hz
Characteristic frequency of pin shell	$f_3 = 2n_o (z_5 - 1) / (60 z_5)$	0.322 Hz
Frequency of planet shaft and crank	$f_2 = n_o (z_5 - 1) / 60$	6.446 Hz
Meshing frequency of cycloid gear or local defect in pin shell	$f_{cyc} = n_o (z_5 - 1) / 60$	6.446 Hz
Meshing frequency of pin tooth	$f_{pin} = 2n_o (z_5 - 1) / 60$	12.892 Hz

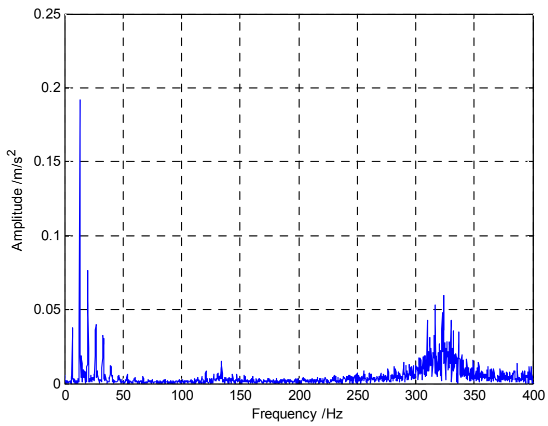


Fig. 5. Circumferential vibration spectrum at the driving speed of 1200 rpm.

As shown in Fig. 5, it is corresponding to the spectrum of circumferential vibration in Fig. 3. The dominant frequency is around 13 Hz. When we compare this frequency to the characteristic values in Table 1, the dominant characteristic frequency comes from the frequency of the cycloid gears meshing with the pin teeth. Moreover, many higher order harmonic components are also related to it.

3.2 Impact characteristic

When a pair of gears meshes, or when a cycloid gear meshes with pin teeth, if the manufacturing error is sufficiently large to give rise to impacts in the power transmission, the impact response will be reflected in the circumferential vibration. The frequency range of the impact response de-

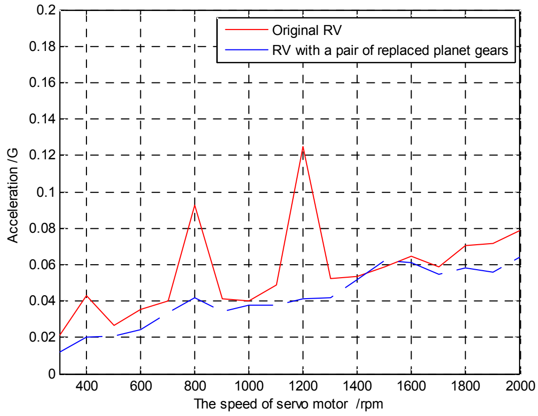


Fig. 6. RV reducer vibration performance curve (before and after changing a pair of planet gears).

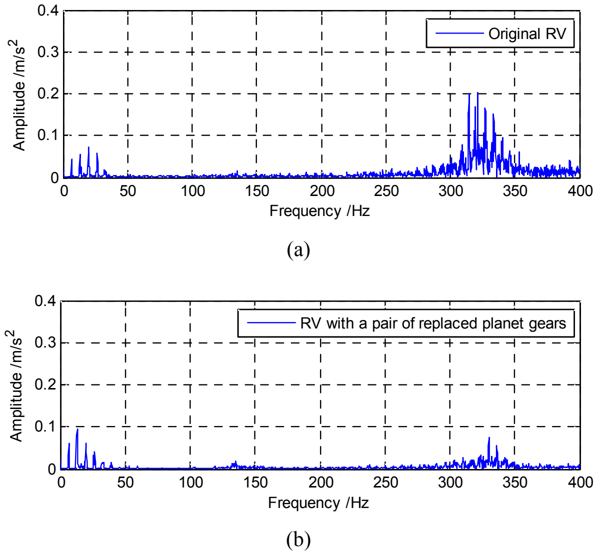


Fig. 7. Circumferential vibration spectrum at the driving speed of 1200 rpm: (a) Before changing a pair of planet gears; (b) after changing a pair of planet gears.

pends on the dynamic stiffness of the RV reducer, the inertial load, and the sensor installation. Owing to a large moment of inertia in the given vibration test, the frequency range of impact response was approximately several hundred Hertz.

To verify the above statement, the test rig was subjected to a shock; the vibration impact response signal was collected at the detection point, and its spectrum was analyzed. The experimental investigation showed that the modal frequency of the impact response was located at approximately 325 Hz, which is in agreement with the range of higher frequencies shown in Fig. 5.

Impact characteristics cannot be used directly in the defect diagnosis. To extract the defect information from the impact response, the special signal processing on the torsional vibration was carried out. In general, the time interval of impact reflects the defect characteristic that is related to the characteristic frequency, and it can be distinctly identified through the envelope analysis of the impact response.

The steps of the envelope analysis are as follows: (a) Design a digital bandpass filter to separate an impact response from a measured circumferential vibration; (b) demodulate the envelope signal from the impact response by using the Hilbert transform; (c) process the envelope signal using an FFT operation or other signal processing methods; and (d) extract the characteristic frequencies related to the manufacturing defects in a mechanical component.

4. Vibration analysis

If there is a defect in a mechanical component, some abnormal features, such as convex peaks and vibrations with excessively large magnitudes, will be observed in the vibration performance curve. As stated in Sec. 3, by processing the vibration signal, a defect source can be diagnosed through its characteristic frequency, and it can be removed by replacing some nonconforming mechanical components in the RV reducer. Finally, the vibration performance of the RV reducer can be improved, and product quality can be controlled.

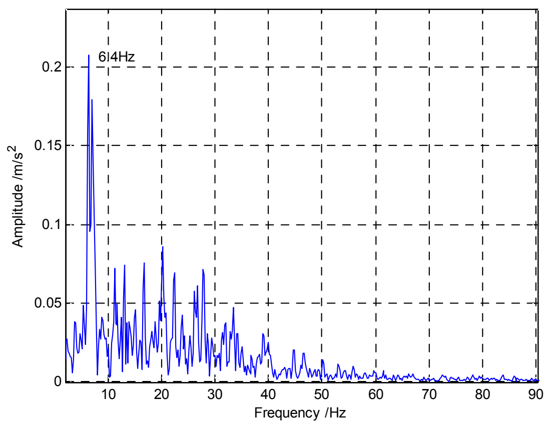


Fig. 8. Envelope spectrum analysis at the driving speed of 1200 rpm.

4.1 Planet gear

For a typical example, as shown in Fig. 6, there are two convex peaks in the vibration performance curve. At driving speeds of 800 rpm and 1200 rpm, the abnormal state can be seen clearly. To analyze this case, FFT was done on the time history record, and the spectrum of vibration was investigated. As shown in Fig. 7(a), the dominant vibration frequency is located within the range of 300 to 350 Hz, which is inferred as the RV operational modal frequency based on the shock test. The impact characteristic exists in the measured circumferential vibration.

To understand the impact information, we extracted the envelope spectrum from the measured circumferential vibration signals. As shown in Fig. 8, when the driving speed was 1200 rpm, the characteristic frequency 6.4 Hz was found in the envelope spectrum and it corresponded to the rotation frequency of the planet shaft.

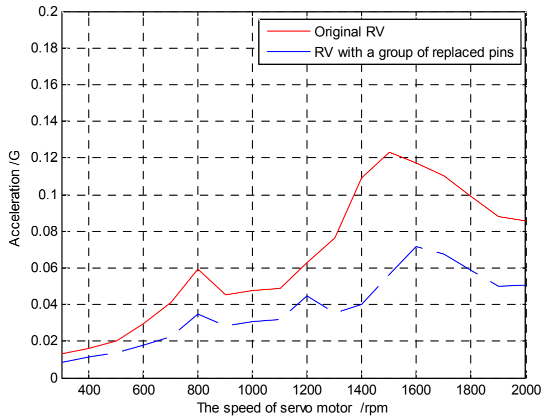


Fig. 9. RV reducer vibration performance curve (before and after changing a group of pins).

Based on the envelope spectral analysis, a pair of planet gears was dismantled. After the planet gears were carefully checked using a geometric instrument, the defect in the gear tooth profile was found. The error in the profile of the tooth causes the impact and it excites the operational modal frequency in the RV testing system. The higher the tooth profile error is, the stronger the shock response will be.

After a pair of a qualified planet gears was installed, as the dotted line shows in Fig. 6, the vibration performance curve became flat, returning to its normal state. At the same time, the energy in the high-frequency components was significantly reduced (see Fig. 7(b)).

According to the impact characteristics in the measured circumferential vibration signal, the mechanical components with defects can be diagnosed through envelope analysis, and they can be successfully removed by replacing mechanical components with the overflow of dimensional tolerance. As a result, the dynamic performance of the RV reducer can be improved greatly.

4.2 Pin tooth

A sizable convex peak is observed in the vibration performance graph of the RV reducer (Fig. 9). However, no sharp peak is observed. An interesting observation is made at 1500 rpm in the vibration performance curve. After short time spectrum analysis was carried out on the measured circumferential vibration, as shown in the STFT diagram in Fig. 10, the dominant 16.3 Hz component was exposed, and it corresponded to the power transmission error. Table 1 shows that the source of the vibration characteristics was the meshing of the cycloid gear with the pin tooth. Therefore, the geometry dimensions of the cycloid gear, pin teeth, and pin shell were measured one by one, and the hole diameter of the pin teeth was identified as the cause of the dynamic power transmission error. After a group of pins were replaced in the RV reducer, the dominant peak in the STFT diagram was suppressed. As a result, the vibration performance was improved considerably.

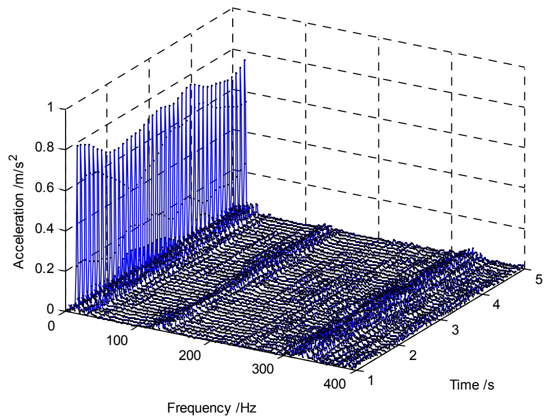


Fig. 10. STFT analysis at the driving speed of 1500 rpm.

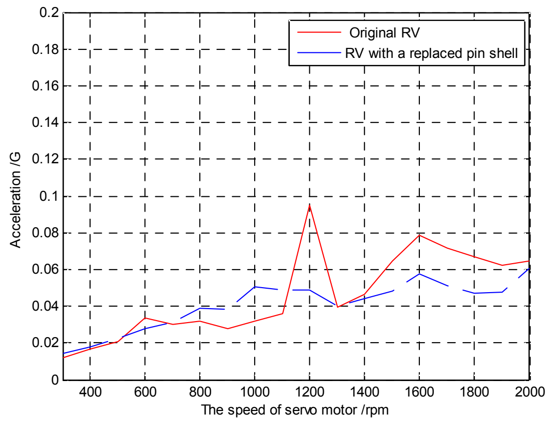


Fig. 11. RV reducer vibration performance curve (before and after changing the pin gear shell).

4.3 Pin shell

As shown in Fig. 11, a sharp peak exists in the vibration performance curve when the driving speed is 1200 rpm. When the circumferential vibration was analyzed, an impact characteristic was found in its spectrum. To obtain the impact information detailedly, we extracted a cepstrum of the envelope signal. After analyzing the vibration envelope, the characteristic 160 ms in the cepstrum can be observed in Fig. 12 (characteristic frequency: 6.25 Hz).

The local defect in the pin shell results in the above vibration characteristic frequency. After we replaced an unqualified pin shell, the abnormal peak in the vibration performance curve disappeared soon (see dotted line in Fig. 11), and the vibration performance was improved.

4.4 Planet shaft

Another example is shown in Fig. 13. The displacement peaks beyond tolerance when the driving speed comes to 2000 rpm. The vibration displacement shows an upward trend with the increasing driving speed.

FFT analysis of the vibration signal at 2000 rpm of driving

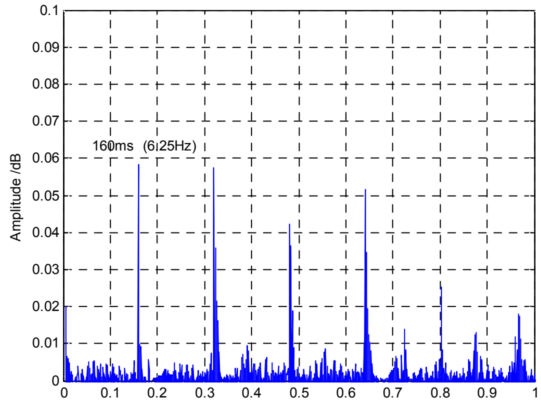


Fig. 12. Envelope cepstrum analysis at a driving speed of 1200 rpm.

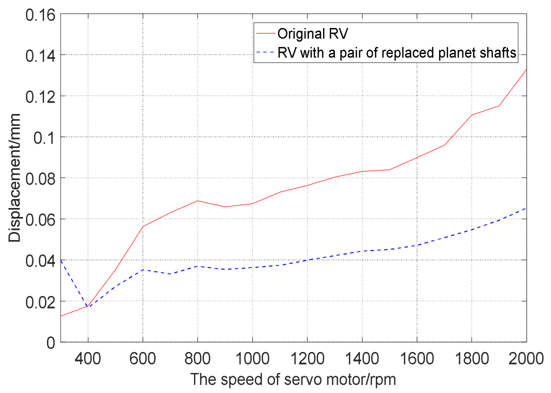


Fig. 13. RV reducer vibration performance curve (before and after changing the planet shaft).

speed was performed, as shown in Fig. 14. It is found that the primary energy is distributed in the range of low frequency. The dominant peak frequency is 11.07 Hz, which is close to the rotation frequency of planet shaft (10.74 Hz). There is also a peak near 133.3 Hz in the spectrum. Its dynamic mechanism is that the shock produces vibration. Its natural frequency is confirmed by impulse method.

According to the full-size measurement of planet shaft by ZEISS Calypso three-dimensional coordinate measuring instrument, the geometrical eccentricity is beyond 50 % of the standard tolerance. After replacing the planet shaft, the torsional vibration test was carried out again. The displacement and the acceleration of vibration declines generally, in which the value of vibration displacement decreases to 50 %. On-line reassembling technology meets the requirements of the qualified judgment of the torsional vibration performance.

5. Profit of quality control

Based on the vibration technology, signal processing and the identification of manufacturing defects or nonconformity, on-line detection devices to control the dimension precision were developed, and a manufacturing quality assurance was

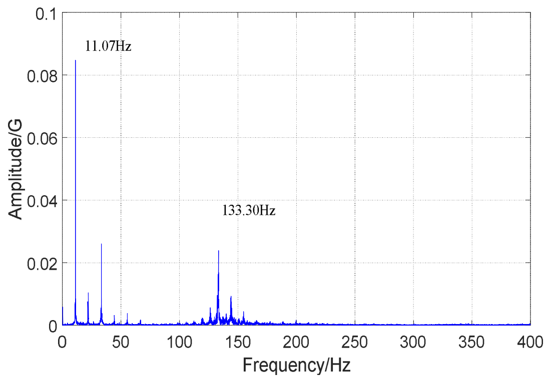


Fig. 14. Spectrum analysis at a driving speed of 2000 rpm.

set up in the production of RV reducer. Besides, for the above successful examples, the proposed technology was applied to recognize the eccentricity of planet shafts and cranks, as well as the eccentricity of motor driving shafts.

It is possible that multiple defects occur in the mechanical components of the RV reducer simultaneously. From the view of fault diagnosis achievement in rotating machinery, many advanced signal processing technologies, such as multiple scale analysis and diagnosis based on database or fuzzy logic, have been fully developed, and they can be used to solve the problem of multiple defects.

Due to nonlinear factors in the transmission chain of the RV reducer, such as variable torsional stiffness which is caused by accumulative pitch error in gears or pinions, it results in the parametric torsional vibration. In the near future, through the application of the proposed vibration technology, such manufacturing defects can be diagnosed effectively by recognizing nonlinear vibration characteristics.

The proposed technology brings a good profit into the production process. The manufacturing quality control of mechanical components has been realized. The torsional vibration of the RV reducer is kept at a low level, and the dynamic behavior of the reducer is evidently improved. As a result, the pass rate of products is enhanced.

6. Conclusion

With an inertial load under different working conditions, a vibration performance curve was estimated to assess one of the dynamic behaviors of the RV reducer. Using the vibration characteristic, we were able to divide the mechanical defects in the RV reducer into and non-stationary defects. The former one is caused by the dynamic power transmission error, which is related to the manufacturing error and running speed. The latter one is caused by an impact response in power transmission. The impact characteristics are identified detailedly by envelope analysis, such as envelope spectrum and envelope cepstrum. The mechanical components with manufacturing defects were diagnosed by means of vibration characteristics, and were removed by reassembling mechanical components in the RV reducer. The technology is more practical than the whole RV system in evaluating the manufacturing quality of the single component. The advantage of the vibration technology is that the product quality can be greatly improved at a lower cost, and the manufacturing and assembly quality can be controlled.

Acknowledgments

The authors would like to acknowledge the support of the Chinese National Natural Science Foundation (51575330) and the support and cooperation of Nantong Zhenkang Welding Electromachinery Co. Ltd.

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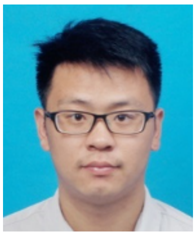

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