Torque Ripple Compensation Method for Joint Torque Sensor Embedded in Harmonic Drive Using Order Analysis

Byung-jin Jung[1], Byoung chul Kim[1,2], Seonggi Kim[1], JaChoon Koo[1], Hyouk Ryeol Choi[1], Hyungpil Moon[1*]

Email: jbjsin@me.skku.ac.kr, bckim@psylogic.com, {choucreme, jckoo, hrchoi, hyungpil}@skku.edu

[1]Mechanical Engineering, Sungkyunkwan University, Suwon, Korea

[2]System Integration Division, Psylogic, Inc, Yongin, Korea

***Abstract*— The main contribution of this work is an algorithmic compensation of joint torque ripple signals in harmonic drive for joint torque sensing from measuring the deformation of flex spline in the harmonic drive. When an external force is applied to a robot, the flex spline of harmonic drive undergoes an elastic deformation. However, such a deformation is not easy to measure by strain gauges on the flex spline because whose signals are corrupted by a periodic vibration which is "torque ripple" caused by reducing operation of the harmonic drive. We perform order analysis and design a filter to eliminate the torque ripple without using many strain gauges. As the order sampling normalizes the frequency characteristic, our method outperforms the filters with fixed cutoff frequency with manageable computational expense. Moreover, the effect of misalignment of the strain gauges is minimum unlike other methods. The experimental evaluation is provided using a robotic manipulator which has the proposed harmonic drive joint torque sensor.**

Keywords—Torque Ripple, Joint torque sensing, Harmonic drive deformation, Order analysis.

I. INTRODUCTION

The joint torque sensing in robotic manipulator is vital for dexterous and safe manipulation [1-3]. Conventionally, the joint torque sensors are composed of sensing elements and mechanical structures which deform under external force or torque. However, the torque sensors with additional mechanical structure contribute additional loads on entire manipulator and compliant elements on each joint and ultimately decreases the control performances. Moreover, the conventional joint torque sensors have mechanical structures with complex shape and require accurate assembly of sensing elements. This complexity causes high manufacturing cost that obstructs the usage of joint torque sensors in wider applications. To overcome such problems, several researches without complex geometric structures are reported [4-7].

The harmonic drive is one of popular mechanical parts for the reducer of robot joint due to its minimal backlash. The mechanical characteristic of harmonic drive which originally contains a flexible part with constrained deformation direction and stiffness inspired many researches using harmonic drive as stiffness elements [5-7]. However, the torque sensing methods using harmonic drive persist with signal processing problems caused by the phenomenon called "torque ripple".

The torque ripple is a periodic noise on sensor signal generated from the speed reducing operation of harmonic drive. To eliminate this, hardware-based signal compensation is used; two sensing elements with phase difference on their sampled signal [5, 6]. Also, methods using software filter to enhance the ripple compensation are also introduced. One of them uses a state model of torque ripple and Kalman filter for signal compensation [7]. However, there are problems still remaining to use these methods for general applications. For example, the required accuracy of sensor component alignment is too high, and the perfect model of torque ripple is hard to be established.

In this paper, we hire an order analysis method in filtering out torque ripples. The order analysis is a frequency analysis method based on constant sampling in rotational angles not time. As the sampled signal based on constant angular steps of the harmonic drive, the frequency characteristic is normalized by the rotational speed of the harmonic drive. We apply notch filters with a fixed cutoff frequency determined from order characteristic of the torque ripple. In the result, the torque ripple is clearly reduced from joint torque sensor output. The developed method does not require any complex model or high computational load. Moreover, the accuracy of the sensor placement does not any more significantly affect the sensing quality, therefore even a single unit of sensor usage can successfully measure the joint torque.

The rest of the paper is composed as follows. The section 2 contains introduction of torque ripple characteristics and implementation of order analysis for torque ripple reduction. The experimental evaluation of the proposed method and the conclusion are described in sections 3 and 4 respectively.

II. TORQUE RIPPLE COMPENSATION THEORY

A. Caracterisitcs of torque ripple

The hardware part of harmonic drive embedded joint torque sensor started with similar structure to [5, 6]. Most former reports use a diaphragm part of flex spline for the attachment location of strain gauges. In this paper, the characteristics of

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torque ripple about location and numbers of sensor component is analyzed.

The harmonic drive can be divided into three main components. The wave generator, circular spline and flex spline. The flex spline, the thin diaphragm-shaped part which is assembled between the other parts, undergoes an elastic deformation during the reducing operation and under an external torque. We attach the sensing component which is a rosette type strain gauge at the diaphragm part of the harmonic drive. As the former research introduces, the strain on the diaphragm part shows a sinusoidal pattern which can be easily modeled than other locations [5]. We have two sets of sensor configurations, a full bridge and a half bridge as shown in Figs. 1 and 2. We use the rosette type strain gauge of Micro Measurement. In Fig. 1, the sensor components grouped with dashed line are connected with a full bridge circuit like previous researches. The sensor component highlighted with solid line is connected with a half bridge. The circuits used to each component are illustrated in Fig. 2.

When the harmonic drive is in operation and an external force or torque is exerted on the harmonic drive, tangential and radial directional strains are generated. The models of strain which affect the sensing component can be modeled as (1).

$$\varepsilon_1 = \varepsilon_{t1} + \varepsilon_{r1}$$
$$\varepsilon_2 = -\varepsilon_{t2} + \varepsilon_{r2} \quad (1)$$

The subscript 1 and 2 represents each strain gauges on a single sensing component. The subscript t and r means tangential and radial strain component.

The reducing operation mainly affects to tangential strain and the radial strain affects to the other [5]. The sensor signal caused by tangential strain is justified as "torque ripple". When we connect a single sensor component in a half bridge, the voltage output of the sensing component can be computed as (2).

$$E_{out} = \frac{K_{half}}{2}\left(\varepsilon_1 - \varepsilon_2\right)E_{sup} \quad (2)$$

The constant K_{half} is the strain gauge gain. The subtraction of ε_1 and ε_2 is represented as (3).

$$\varepsilon_1 - \varepsilon_2 = \left(\varepsilon_{t1} + \varepsilon_{t2}\right) - \psi_1 \sin\left(\omega t\right) \quad (3)$$

The new term $\psi_1 \sin\left(\omega t\right)$ means radial strain error of gauges 1 and 2 caused by the alignment error between strain gauges and sensor component attachment. The error signal forms sinusoidal pattern as the original signal does. The ψ_1 means the amplitude of error and ω means the frequency of error pattern. Moreover, the value of ω is dependent on the harmonic drive input speed.

In case of a full bridge circuit, the voltage output of the sensing component can be represented as (4).

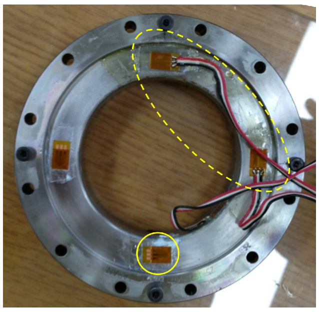

Fig. 1. Sensor components attached on flex spline.

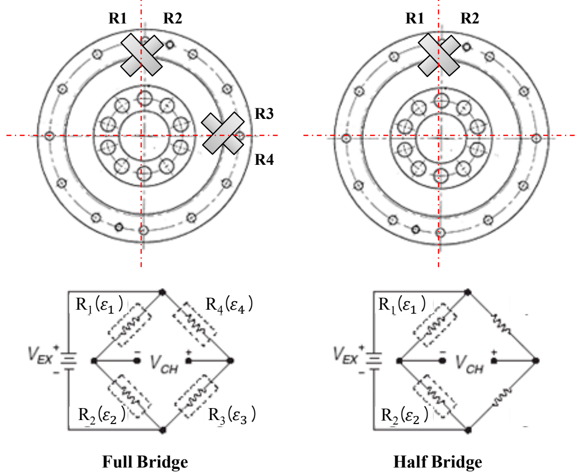

Fig. 2. Schemetic of half and full bridge circuit.

$$E_{out} = \frac{K_{full}}{4}\left(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4\right)E_{sup} \quad (4)$$

The constant K_{full} means the strain gauge gain. The equation about $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$ is represented as (5).

$$\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 =$$
$$\left(\varepsilon_{t1} + \varepsilon_{t2} + \varepsilon_{t3} + \varepsilon_{t4}\right) - \psi_1 \sin\left(\omega t\right) - \psi_2 \sin\left(\omega t + \pi + \alpha\right) \quad (5)$$

The error signal of the sensor component of stain gauges 3 and 4 is planned to have π phase difference with strain gauges 1 and 2 component by their locations. The constant α means the phase error caused by the alignment error between sensor components. Same as a half bridge condition, the strain of radial direction shows frequency characteristic related with the harmonic drive input speed. This characteristic is displayed in Fig. 3. The sampled output of time domain and frequency analyzed result of signal from a full bridge circuit is shown in left and right column. As the rotational speed goes faster, the dominant frequency of the signal changes. Specifically, the torque ripple has the frequency characteristic about 2, 4, 8 times of harmonic drive input speed. The frequency which has the value of 4 times of rotation speed is dominant among three. This phenomenon is caused by the ellipsoidal shape of the wave generator and the alignment error of sensor components.

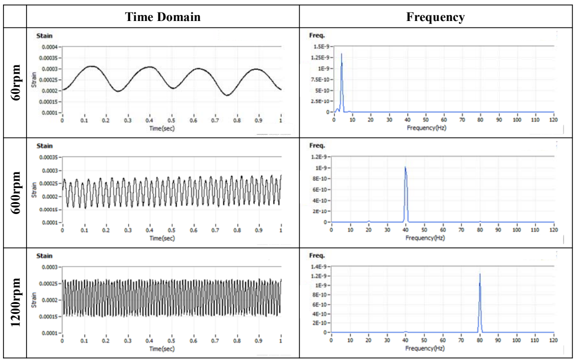

Fig. 3. Frequency chracterisitc of torque ripple.

As this result shows, the frequency characteristics of torque ripple is changed by the harmonic drive input speed. This means a filter with fixed cutoff frequency cannot be hired to reduce the torque ripple. However, a filter with changing cutoff frequency cannot easily assure the continuity of the output signal. The other solution, model-based filters like Kalman filter requires heavy computational load and an accurate model which is hard to be realized by attachment error of sensor components.

B. Order analysis-based ripple reduction

The order analysis is a signal analyzing method which represents the frequency characteristics of the signal in the scale of the reference rotational speed. In other words, when a signal generated from a rotating component, the order analysis normalizes the frequency characteristics of signal with the rotation velocity. The reference velocity is called as "1 order". The order analysis can be explained with Fourier analysis [8]. The coefficients of Fourier series using typical fixed time step can be represented as (6).

$$a_n = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta t)\cos(2\pi f_n \Delta t)$$
$$b_n = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta t)\sin(2\pi f_n \Delta t) \tag{6}$$

The x means the analyzed signal and the constant N is the total number of time points over which the transform is performed. The Δt means time spacing of the time samples. The constant f_n means the frequency which is being analyzed and the variable a_n and b_n means the Fourier coefficient of the cosine and sine term for f_n. This method does not considers the information of frequency source during data sampling process. When a signal has frequency characteristic changed by a reference frequency source, the fixed time step based sampling data has changing frequency characteristic i.e. torque ripple. This data requires more complicated signal processing algorithm than data with constant frequency characteristic. To solve this problem, the order based frequency analysis method can be hired. The order based Fourier series has the coefficients can be represented as follows.

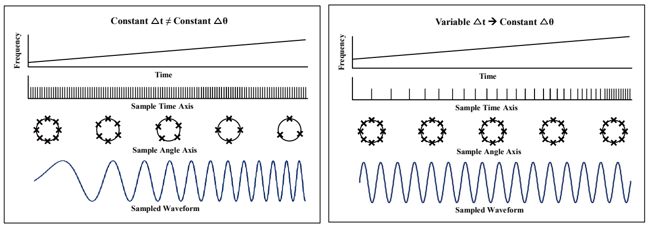

Fig. 4. Schemetic diagram of sampling methods.

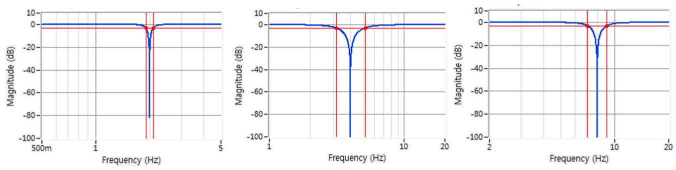

Fig. 5. The frequency chracterisitics of notch filters.

$$a_n = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta\theta)\cos(2\pi o_n \Delta\theta)$$
$$b_n = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta\theta)\sin(2\pi o_n \Delta\theta) \tag{7}$$

The main idea of order analysis is the usage of the angular location of the source for the data sampling trigger not the time. The o_n is the order which in being analyzed. The $\Delta\theta$ means the fixed angular spacing of rotation. As the order analysis uses the fixed location, naturally the analyzed result is normalized by the speed of rotating source. The difference between former and latter sampling methods can be illustrated in Fig. 4.

The Fig. 4 shows the sampled signal from the source with a constantly accelerated rotational speed. The left part represents a sampling method with a fixed time step. The right part represents a sampling method with a constant angular step but variable time step. When the rotational speed and the frequency of signal increase, the samples during 1 rotation is decreased at the fixed time method. However, the fixed angular step method is not so as the sampling time is controlled to sustain the constant angular step. This difference is inherited to sampled waveforms. The sampled output of a fixed time step method shows changing frequency but the output of the fixed angular step method does not.

The discrete notch filters with 2, 4, 8 Hz of cutoff frequency are applied to reduce the torque ripple fluctuation. As the fixed angular step based sampling method normalizes the frequency characteristic of sampled signal, the torque ripple can be reduced by filter with fixed cutoff frequency. The frequency characteristics of the filters used is illustrated in Fig.5.

III. EXPERIMETNS

The experiment is performed on a robotic manipulator as shown in Fig. 6. Each joint of the robot contains the harmonic drive as a speed reducer. The harmonic drive used at each robot joint is SHD-25 of Harmonic Drive Inc.

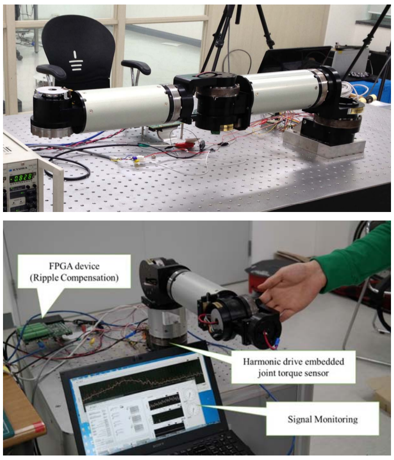

Fig. 6. Experiment environment and external torque applying experiment.

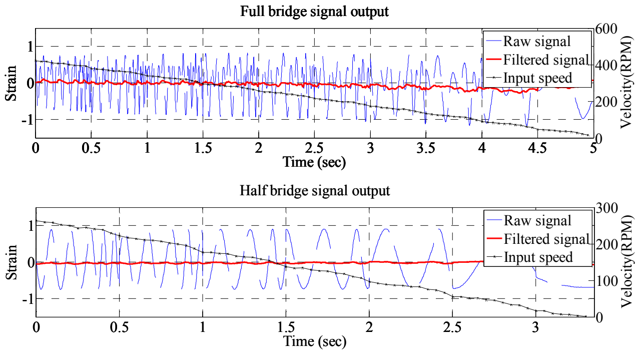

Fig. 7. Ripple reduction results of half and full bridge circuit.

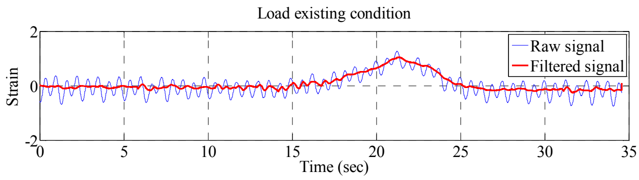

Fig. 8. Result of external force experiment.

For the realization of order analysis, the authors use an encoder to trigger the sampling timing of the order analysis and high speed FPGA real time controller. The encoder used to trigger sampling has 2500cpr of resolution.

The harmonic drive is linearly accelerated and decelerated between the velocity ranges from zero to 400 rpm. The raw signal from the half and the full bridge strain gauge circuit and the output of order filter is illustrated in Fig. 7. The x-pointed line means joint input velocity at each time clock. The dashed line is raw signal sampled at each circuit. As the upper and lower plot of Fig. 7 represents, the frequency of torque ripple shows dependency with joint speed. The solid thick line of Fig. 8 is outputs signal of order analysis based filter which represent the amplitude of torque ripple is reduced to almost zero value. Moreover, the filtered result of half and full bridge circuit shows almost same result. This means the developed algorithm has smaller relationship with location accuracy and numbers of sensor components.

The sensing performance of external torque is also evaluated as in the lower part of Fig. 6. The result is shown in Fig. 8. The instant torque caused by a contact between the robot body and human is applied during the joint rotation. The contact is occurred at 14.2 sec and ended at 26.5 sec. The order filtered signal shows the clear response to the external force as the relatively high frequency ripple signals are removed.

IV. Conclusion

The order analysis-based torque ripple reducing algorithm is developed and experimentally evaluated in this paper. The evaluation experiment of developed algorithm is performed on a robot manipulator equipped with harmonic drive at each joint and has half and full bridge strain gauge circuits. As the order sampling method naturally normalizes the frequency of sampling signal with the joint speed, the frequency characteristic of the sampled signal does not changed as joint speed does. Thanks to this phenomenon, the notch filters with a fixed cutoff frequency in order space can be hired to reduce the torque ripple. As the developed algorithm uses simple discrete filters, the system does not require high computation load.

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