Ripple Compensation for Torque Sensors Built into Harmonic Drives

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***Abstract*—Harmonic Drives include a mechanically flexible component which transmits load torque, and therefore, a torque sensor can be built into Harmonic Drives by cementing strain gages on a flexible component of the gear. However, a periodic sensing error called ripple is generated by deformation of a flexible component during the gear operation. The ripple signal cannot be sufficiently compensated by pairs of strain gages that produce opposite phase signals, because the strain gages cannot be exactly positioned on the desired locations. In this paper, we present a method to compensate the ripple by a new approach of tuning the ripple amplitudes for separate strain gages. The ripple, caused by positioning errors of the strain gages, can be perfectly compensated, and therefore, requirement of strain gages accurate positioning is reduced by this method. The method does not need any online calculations, and consequently, the torque signal is not delayed. Minimum number of strain gages needed to compensate a given number of frequency components of a ripple is derived. Some experimental results are shown.**

***Index Terms*—Built-in torque sensor, Harmonic Drive, ripple compensation, strain gage.**

I. INTRODUCTION

HARMONIC Drives [1] are lightweight, high reduction ratio, compact size, and backlash-free gear reducers. They are mainly used in combination with servomotors to reduce speed and to produce high torque on the output shaft.

In various applications, including robotics, torque sensing, and torque control are inevitable to achieve desired performances [1]. In general, torque can be estimated from electrical current of a servomotor. However, sensing is more accurate than estimation.

Torque sensing requires a sensor to be assembled into a torque transmission mechanism. Principally, torque sensors include a mechanically flexible element where a strain or a displacement proportional to the applied torque is generated and detected to produce the torque output. By a sensor built into a torque transmission the overall stiffness of a mechanism is reduced, and a bandwidth of the system is consequently narrowed. On the other hand, harmonic gears for their functioning already include a flexible component. Therefore, a torque sensor can be built into the gear itself, and no additional reduction of stiffness is needed to detect torque.

Torque sensing from harmonic gears using strain gages was proposed by Hashimoto [2]. In harmonic gears, the applied torque is transmitted through a flexible element called flexspline, on which the strain gages are cemented to detect the shear strain, proportional to the applied torque. A strain gage with a pair of orthogonal crossing strain gages is needed to detect a shear strain. However, deformation of the flexspline while the gear operates, generates a periodic error signal called ripple. Ripple is a function of the input shaft angular position, and its frequency components are proportional to the gear input shaft rotational speed, with a fundamental frequency component with a period of half revolution (π rad) of the gear input shaft. This ripple is not related to the applied torque and therefore represents a periodic sensing error, which needs to be compensated. To reduce the ripple, two strain gages were positioned on the flexspline with an aim to produce two ripples of opposite phases, which in the ideal case would mutually cancel each other, while the load torque is detected [3]. The method is effective for compensation of the fundamental frequency component. However, other ripple components remain uncompensated. Amplitude of the remaining ripple is too high for the sensing to be practically used in accuracy critical applications.

Frequency analysis of the remaining ripple showed that in addition to the fundamental frequency component with two periods per input shaft revolution, the higher harmonic components of the ripple are also present in the ripple signal. A first harmonic component, that is a signal with four periods per input shaft revolution has the next highest amplitude. Therefore, additional pair of strain gages was cemented to the flexspline to compensate the higher harmonic component [4], [5]. The higher harmonic component was effectively compensated. However, the total ripple amplitude was not reduced under the levels of about $\pm 1\%$ of the gear maximum torque capacity. Further compensation was difficult to be achieved just by improvement of strain gage positioning accuracy, due to the lack of a method to exactly position the strain gages on the desired positions.

Taghirad *et al.* [6] proposed a method to improve positioning accuracy of the strain gages. However, the ripple was not perfectly compensated. Positioning of the strain gages as proposed in [6] cannot compensate the first harmonic component [5]. On the other hand, even if the strain gages are perfectly positioned, a ripple-free sensing is not guaranteed, because the ripple is generated also by inaccuracies of the gear assembly and by dimensional inaccuracies of the gear itself. Taghirad *et al.* thus designed and applied a Kalman filter with a sixth-order harmonic

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[1] Harmonic Drive is a trademark of Harmonic Drive Systems, Inc., and is one example of the harmonic gears described in this paper.

oscillator model of the ripple signal to compensate it. They report successful compensation of the fundamental ripple component, the first harmonic component, and the components caused by assembly misalignments. However, the measured torque was delayed for 1 ms due to the online ripple estimation.

Regarding the ripple compensation by using online estimation, a special characteristic of harmonic gears, that is a periodic transmission error, should be considered too. Harmonic gears exhibit periodic transmission error with the same frequency characteristic as the sensing ripple [7]. Therefore, with inertia load connected to the output shaft of the gear, periodic torque is generated on the output shaft due to speed fluctuations, even at a constant rotational speed of the gear's input shaft. Moreover, when the frequency of the torque ripple is in resonance with the system's natural frequency, the torque ripple is highly amplified. This torque ripple should not be misinterpreted as a torque sensing error (ripple), because it is actually applied torque to the output shaft of the gear, caused by speed variations of the output shaft of the gear, as a result of the gear transmission error. The sensing ripple and the actual torque ripple cannot be distinguished from each other when the estimation and compensation are performed online with some inertia load on the gear output shaft. Consequently, the applied torque ripple can be misinterpreted and removed from the signal as a ripple error, instead of being properly detected. A method to compensate only the sensing ripple (error) needs to be developed so that the ripple is measured or estimated at extremely low or zero speed (statically) or without any inertia on the gear output shaft. In our experiments, we perform the measurements statically, that is, the ripple is measured for discrete positions of the gear's input shaft at zero rotational speed.

The two above-mentioned problems of unrealizable exact positioning of the strain gages and the difficulties with online estimation and compensation of the ripple are the main obstacles to practical use of the built-in torque sensing for harmonic gears. In this paper, we present a new method, which compensates the ripple with no requirements of accurate strain gage positioning, and without need for real-time online calculations. In Section II, we present a background of torque sensing from harmonic gears. In Section III, we present a mathematical model of the ripple signal and solve the problem of ripple compensation. In Section IV, we derive a minimum number of strain gages needed to compensate a given number of frequency components of the ripple, and in Section V we show some experimental results.

II. Torque Sensing from Harmonic Gears—Background

A typical design of Harmonic Drive is shown in Fig. 1. It is composed of three elements: 1) wave generator; 2) flexspline; and 3) circular spline. The wave generator is of elliptical shape with thin ring ball bearing on its outer side. The flexspline is a thin wall cup-shape gear with external teeth, and the circular spline is a rigid gear with internal teeth. When these three parts are coaxial assembled so that the wave generator deforms the open part of the flexspline into an elliptic shape and the teeth of the flexspline and circular spline mesh on the major axis of the ellipse, a gear reducer is assembled.

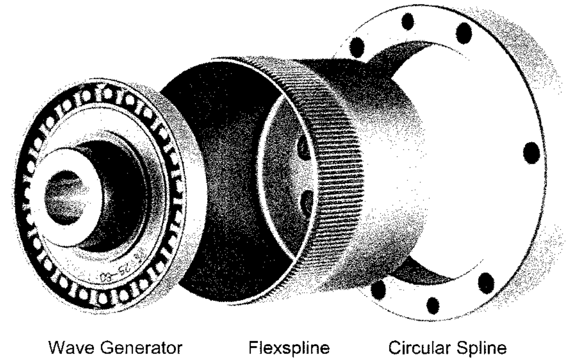

Fig. 1. Harmonic Drive.

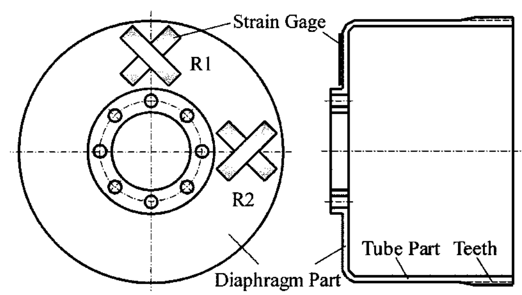

Fig. 2. Flexspline with two strain gages.

The harmonic gear operates as a reducer when the wave generator is coupled to the gear input shaft, and one of the two: a flexspline or a circular spline is coupled to the gear output shaft, and the other of the two is fixed. The gear reduction ratio R is defined by the number of teeth on the flexspline z_f and by the number of teeth on the circular spline z_c. The number of teeth on the flexspline is two less than the number of teeth on the circular spline. The reduction ratio $R = z_r/(z_c - z_f)$ is different for the designs with circular spline fixed, where $z_r = z_f$ and for the designs with flexspline fixed, where $z_r = z_c$. Here, z_r is the number of teeth on a rotating element.

In any of the harmonic gear designs, the load torque is transmitted through a flexspline, causing strain in it. Hashimoto [3] performed a final element analysis and confirmed the highest strain generated by the load torque in a bottom part of the flexspline called a diaphragm part (see Fig. 2).

The initially proposed method of torque sensing suggested to cement two strain gages on the diaphragm part, as shown in Fig. 2. The strain gage here is considered to be a pre-assembled commercially available strain gage, composed of two orthogonal crossing strain gages, used to detect only a shear strain. The ripple signals e_1 and e_2 from the two strain gages R1 and R2, respectively, are shown in Fig. 3. The remaining ripple as a sum of e_1 and e_2 is shown on an enlarged scale in Fig. 4. The ripple is depicted in percentages of the maximum instantaneous gear torque capacity against the input shaft rotation angle. The gear used in our experiments is a flexspline fixed-type gear reducer with a maximum instantaneous torque capacity of 100 N·m and reduction ratio 51. The remaining sum ripple from the two strain gages here has the amplitude of about ±4 N·m.

The frequency analysis result of the ripple from one strain gage and of the sum ripple from two strain gages is shown in

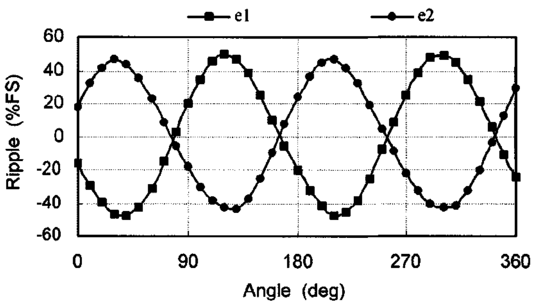

Fig. 3. Ripple signals from two strain gages.

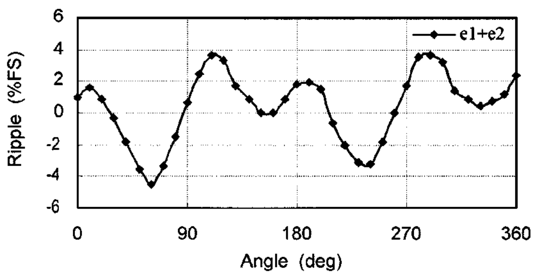

Fig. 4. Sum ripple signal from two strain gages.

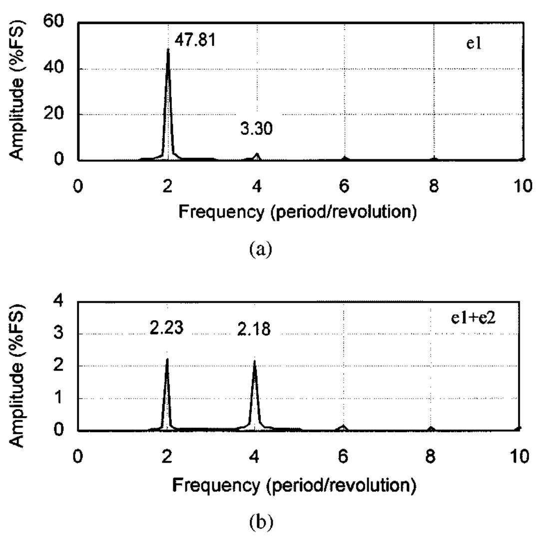

Fig. 5. Frequency spectrum of ripple: (a) from one strain gage and (b) sum from two strain gages.

Fig. 5 The fundamental frequency component, that is the one with a frequency of two periods per input shaft revolution is significantly reduced, while the first harmonic (four periods per revolution) is not notably compensated. A mathematical model of the ripples from two strain gages can explain this result

$$\begin{aligned} e_1 &= a_1 \cos 2m\beta + a_2 \cos 4m\beta \\ e_2 &= a_1 \cos 2m(\beta + \pi/2) + a_2 \cos 4m(\beta + \pi/2) \\ &= -a_1 \cos 2m\beta + a_2 \cos 4m\beta. \end{aligned} \quad (1)$$

Therefore, $e_1 + e_2 = 2a_2 \cos 4m\beta \neq 0$. Here a_i are the amplitudes of the respective ripple components, β is the input shaft rotation angle, and m is the gear design factor: $m = 1$ for flexspline fixed designs and $m = (R-1)/R$ for circular spline fixed designs. The sum of two equations shows that even without amplitude or phase errors, that is with ideally accurate positioned strain gages, the first harmonic component with four periods per revolution cannot be compensated by the proposed layout of two strain gages.

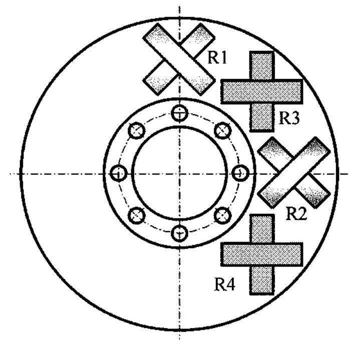

Fig. 6. Flexspline with four strain gages.

Using the same idea as for compensation of the fundamental frequency component, we proposed four strain gages to be cemented on a flexspline, as shown in Fig. 6 [5]. Note that considering symmetry of the flexspline across the vertical axis, two of the strain gages can be symmetrically placed on the opposite side of the vertical axis with the same result.

By the configuration of four strain gages as shown in Fig. 6, the first harmonic frequency component is compensated to about the same degree as the fundamental component was compensated by two strain gages. Details about the results can be found in [4] and [5]. However, the fundamental frequency component in our experiments was not reduced under ±1% of the gear maximum instantaneous torque capacity.

III. New Ripple Compensation Method

Practically it is impossible to exactly cement the strain gages on the desired positions, and hence it is not realistic to expect satisfactory ripple compensation just by improvement of the strain gage positioning accuracy. Taghirad *et al.* [6] in this respect, proposed an active method to compensate the remaining ripple. They use Kalman filter combined with a sixth-order oscillator model of the ripple to estimate and to compensate the ripple. The method delays the torque signal for 1 ms. On the other hand, the method, which we propose here, does not delay the sensed torque and does not require the input shaft position or speed to be known to compensate the ripple. It is derived from a mathematical model of the ripple.

A. Mathematical Model of the Ripple

As it was shown in Section II, the ripple can be expressed as a harmonic function of the input shaft position. According to the harmonic gear's characteristics, we assume that the ripple from each strain gage is composed of N number of frequency components, where the fundamental frequency component has two cycles per input shaft revolution. Also, we suppose that M

strain gages are cemented angular equidistantly with some positioning errors over the flexspline diaphragm part. Therefore, the ripple signal from the jth strain gage can be expressed by

$$e_j = \sum_{i=1}^{N} a_{ij} \cos\left[2im\left(\beta - \frac{\pi(j-1)}{M}\right) - \psi_{ij}\right]. \quad (2)$$

Here, a_{ij} are amplitudes of the respective frequency components, and ψ_{ij} are phase errors of the respective frequency components. Note that the strain gage's orientation error and radial positioning error cause amplitude errors, while the positioning error in the angular direction causes phase errors of the ripple.

The detected torque from a built-in sensor is a sum of outputs from all the cemented strain gages. Equivalently, a total ripple h is also a sum of ripples from M strain gages

$$h = \sum_{i=1}^{N}\sum_{j=1}^{M} a_{ij} \cos\left[2im\left(\beta - \frac{\pi(j-1)}{M}\right) - \psi_{ij}\right]. \quad (3)$$

This equation is a mathematical model of the ripple from which we derive the compensation method.

B. Ripple Compensation Method

A perfect ripple compensation is achieved when total ripple becomes zero. That is in (4) to achieve $h = 0$.

We introduce the relation $\cos(A - B) = \cos B \cos A + \sin A \sin B$, where $A = 2i\beta$ and $B = 2im(\pi(j-1)/M) + \psi_{ij}$ into (4), and obtain the following result:

$$h = \sum_{i=1}^{N}\sum_{j=1}^{M} \cdot \left[\begin{array}{l} a_{ij}\cos\left(2im\,\dfrac{\pi(j-1)}{M} + \psi_{ij}\right)\underline{\cos(2im\beta)} \\ +a_{ij}\sin\left(2im\,\dfrac{\pi(j-1)}{M} + \psi_{ij}\right)\underline{\sin(2im\beta)} \end{array}\right]. \quad (4)$$

The ripple here is decomposed into sine and cosine components, underlined in (4). Note that the positioning errors of the strain gages and all other misalignments only influence the amplitudes of both sine and cosine components. For example, phase errors ψ_{ij}, which are caused by circumferential positioning errors of the strain gages, appear here only in amplitude factors of the specific sine and cosine components. Further on, we can therefore conclude that the ripple is perfectly compensated only when the amplitudes of sine and cosine components of the total ripple are simultaneously zero. This translates the ripple compensation problem into solving a homogenous system of

$$\left.\begin{array}{l} \displaystyle\sum_{j=1}^{M} a_{ij}\cos\left(2im\,\frac{\pi(j-1)}{M} + \psi_{ij}\right) = 0 \\ \displaystyle\sum_{j=1}^{M} a_{ij}\sin\left(2im\,\frac{\pi(j-1)}{M} + \psi_{ij}\right) = 0 \end{array}\right., \quad i = 1, \cdots, N. \quad (5)$$

To satisfy the system of (5), the phase errors ψ_{ij} or the amplitudes a_{ij} should be adjusted. However, after the strain gages are cemented on the flexspline, it is easier to adjust the amplitudes than to adjust the phases. In the following, we consider that the amplitudes of the ripple components are adjusted. This can be simply realized by adjustable gain amplifiers connected to each of the strain gages. Here note that the amplitudes are adjusted for separate strain gages, but not for separate frequency components.

IV. Minimum Number of Strain Gages Needed to Compensate the Ripple

The ripple can be physically compensated according to the above presented method by tuning of the signal amplitudes from separate strain gages. This is mathematically expressed as multiplying each of the amplitudes a_{ij} by a corresponding gain factor k_j, unique for each of the strain gages. The system of (5) with gain tuning function can be expressed in the matrix form (6). (The index of the matrix describes its size.)

$$\begin{bmatrix} a_{ij}\cos\left(2im\,\dfrac{\pi(j-1)}{M} + \psi_{ij}\right) \\ a_{ij}\sin\left(2im\,\dfrac{\pi(j-1)}{M} + \psi_{ij}\right) \end{bmatrix}_{2N\times M} \{k_j\}_M = \mathbf{0}. \quad (6)$$

To realize a perfect ripple compensation, a solution for the gains k_j should be found. However, a condition for nontrivial solution existence of the linear system of (6) is $M \geq 2N+1$. Therefore, a minimum number of strain gages $M_{\min}$ needed to compensate N number of the ripple frequency components is defined by

$$M_{\min} = 2N + 1. \quad (7)$$

For example, to compensate one frequency component of the ripple ($N = 1$) minimum of three strain gages ($M_{\min} = 3$) need to be cemented on a flexspline, while to compensate two frequency components ($N = 2$) at least five strain gages ($M_{\min} = 5$) need to be cemented on a flexspline, and so on.

The homogenous system of (6) has an infinite number of nontrivial solutions. To obtain a specific solution it is therefore necessary to define one or more gains in advance, depending on the number of the applied strain gages. The easiest way to do so is to set the corresponding number of gains to 1, and calculate the remaining ones. This also suggests that gain tuning for the strain gages with gain equal to 1 is not needed. However, to tune the total gain of the sensor to the initial value before the compensation, gain tuning on all strain gages is needed. For example, in a minimum configuration, that is when $M = M_{\min}$, one of the gains, for example, pth gain, should be set to 1 in advance. The remaining $M_{\min} - 1$ gains are then calculated so that the system of equations is transformed into a nonhomogenous system of

$$\begin{bmatrix} a_{ij}\cos\theta_{ij} \\ a_{ij}\sin\theta_{ij} \end{bmatrix}_{j\neq p} \{k_j\}_{j\neq p} = -\begin{Bmatrix} a_{ip}\cos\theta_{ip} \\ a_{ip}\sin\theta_{ip} \end{Bmatrix}. \quad (8)$$

Here, $\theta_{ij} = 2im(\pi(j-1)/M + \psi_{ij})$ is the phase of each frequency component.

Amplitudes a_{ij} and phases θ_{ij} of the ripple components are obtained by Fourier transformation of the ripple from each strain

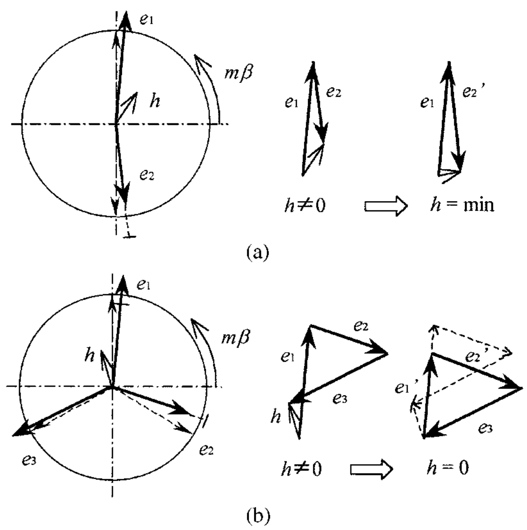

Fig. 7. Comparison of two ripple compensation methods: (a) conventional and (b) new.

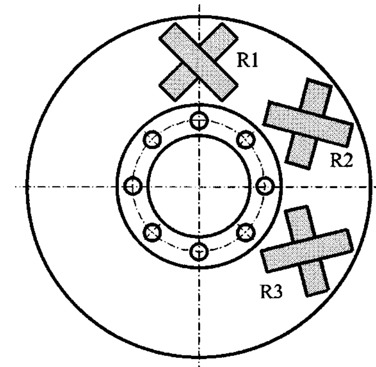

Fig. 8. Flexspline with three strain gages.

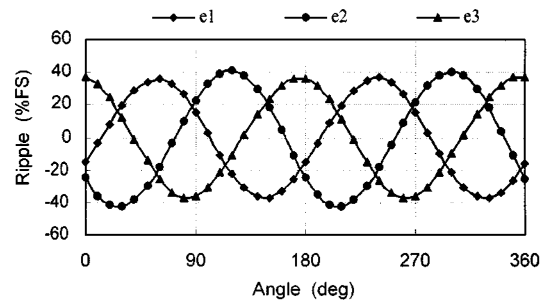

Fig. 9. Ripple signals from three strain gages.

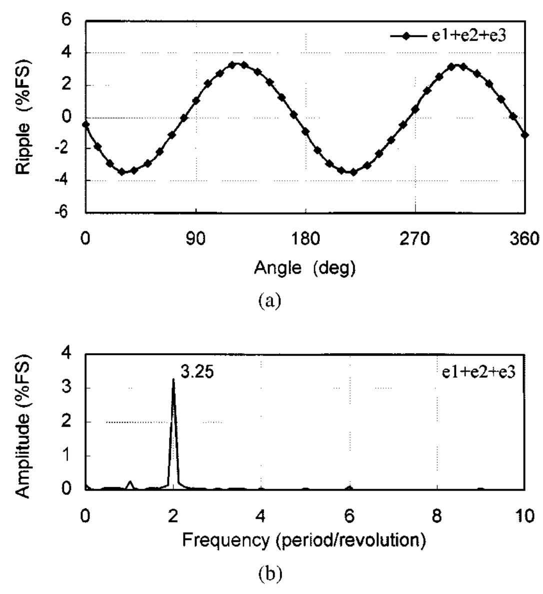

Fig. 10. Sum ripple from three strain gages before compensation: (a) ripple signal and (b) spectrum.

gage. Finally, to restore the overall gain to the original one before tuning, all the gains should be scaled by a scale factor C

$$C = \frac{M}{\sum_{j=1}^{M} k_j}. \tag{9}$$

In this way a unique solution, independent of selection of the not tuned gain p, is obtained for all M gains.

A comparison of the new method and the conventional ripple compensation method is graphically presented in Fig. 7. By the conventional method, to compensate the fundamental frequency component of the ripple, two strain gages were cemented on a flexspline with a goal to mutually cancel the two ripples from the two strain gages. However, as shown in Fig. 7(a), the total ripple depicted as a vector h cannot be perfectly compensated if a phase error is present, even with amplitude tuning. On the other hand, by this new proposed method, the ripple component can always be perfectly compensated by amplitude tuning of the signals from at least two strain gages, as shown in Fig. 7(b).

V. Experimental Results

In the experiments, we used a Harmonic Drive with flexspline fixed, maximum instantaneous torque capacity 100 N·m, and gear reduction ratio 51. With a goal to compensate the fundamental frequency component of the ripple ($N = 1$), we cemented three strain gages on a diaphragm part of the flexspline as shown in Fig. 8. (Note that the strain gage R2 can be placed symmetrically on the opposite side of the diaphragm part to better compensate assembly misalignments.) The ripple signals e_1, e_2, and e_3 from three strain gages R1, R2, and R3, respectively, are plotted in Fig. 9. Sum of the three ripples and its frequency spectrum is plotted in Fig. 10. The fundamental frequency component is dominating by an amplitude of about 3.25% of the gear maximum instantaneous torque capacity.

Fourier analysis performed on the three ripples from three strain gages gave the following results for amplitudes and phases of the fundamental frequency components: $a_{11} = 36.6\%$, $a_{12} = 41.9\%$, $a_{13} = 37.4\%$, $\psi_{11} = 0°$, $\psi_{12} = -0.9°$, $\psi_{13} = 7.2°$. Note that the phase of the first strain gage is taken as a zero reference phase.

Next, we set the gain of the first strain gage to one, that is $k_1 = 1$, and calculate the remaining two gains according to (8) as shown in (10)

$$\begin{bmatrix} -21.46 & -22.63 \\ -35.96 & 29.78 \end{bmatrix} \begin{Bmatrix} k_2 \\ k_3 \end{Bmatrix} = -\begin{Bmatrix} 36.61 \\ 0 \end{Bmatrix}. \tag{10}$$

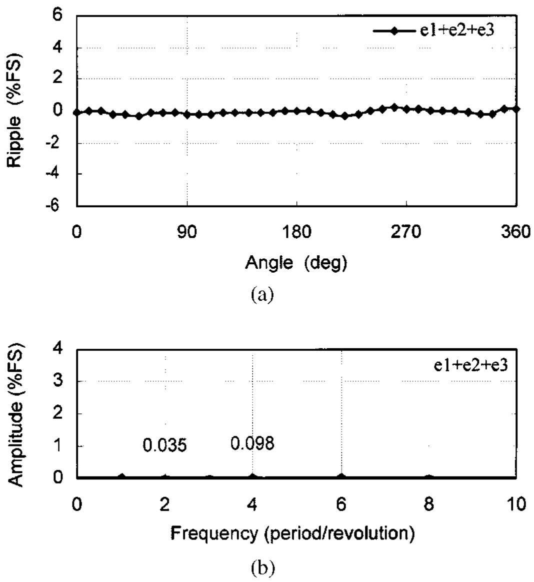

Fig. 11. Sum ripple from three strain gages after compensation: (a) ripple signal and (b) spectrum.

The results are $k_2 = 0.75$, and $k_3 = 0.91$. Finally, after scaling the three gains with a scaling factor $C = 1.13$, the results are $k_1 = 1.13$, $k_2 = 0.85$, and $k_3 = 1.03$. By using these three gains on the respective strain gages, the total ripple and its frequency spectrum became as shown in Fig. 11. The fundamental frequency component with 2 periods per input shaft revolution was reduced from 3.25% to 0.035% of the gear maximum instantaneous torque capacity. The remaining ripple of other frequency components is under the level of about $\pm 0.2\%$ of the gear maximum instantaneous torque, which is a significant improvement of the ripple.

VI. Conclusions

Built-in torque sensing for harmonic gears was proposed about ten years ago [2]. It was not widely used mainly because of a relatively large periodic sensing error caused by the gear operation. Recently, an increased number of strain gages, and a method to compensate the ripple by online Kalman filtering were proposed to reduce the ripple. However, the increased number of strain gages failed to perfectly compensate the ripple, while the online estimation and compensation has its drawbacks in the delay of sensing and in possible misinterpretations of the torque ripple caused by the gear transmission error.

In this paper, we proposed a new method, based on an even number of strain gages and on separate amplifying of the signals from each of the strain gages. A perfect compensation of selected frequency components of the ripple can be achieved without real time online calculations. Only initial tuning of the gains is required.

The minimum number of strain gages needed to compensate the ripple was also derived, and the method was practically confirmed with the experiments.

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