Accuracy Improvement of Built-In Torque Sensing for Harmonic Drives

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***Abstract*—Built-in torque sensing for Harmonic Drives is attractive since it maintains mechanical characteristics of the gear while providing detection of the transmitted torque. Torque sensing by using strain gauges has been studied, but is not widely used yet due to a relatively high signal fluctuation, which is generated by the gear operation. Characteristics of the signal fluctuation are analyzed in this paper, and a method to effectively compensate the signal fluctuation is proposed. The signal fluctuation is perfectly compensated by adjustment of the strain gauges' sensitivities. A minimum number of strain gauges needed to compensate the signal fluctuation is derived. The experimental result with three strain gauges compensating the basic frequency component of the signal fluctuation is shown.**

***Index Terms*—Built-in, Harmonic Drive, sensing, torque.**

I. Introduction

TORQUE generated in driving mechanisms of mechatronic devices needs to be controlled in many applications. An articulated robot with dynamically decoupled joints achieves better tracking performance than the noncompensated one [1], [2]. Dynamic decoupling of the robot's joints can be achieved by using torque control in the robot's joints [3]. Torque control is also inevitable in various types of motion control algorithms. Typically, it is used implicitly as current control in electrical drives, or explicitly as torque control to achieve specific performances of the motion control system. For example, torque control is used to reduce transient mechanical vibrations in the mechanism's response, or to reduce settling time in positioning tasks [4], or to provide force response or compliant response to the external loads [5]. One of the most important tasks is to control interaction forces of mechatronic devices with the environment.

Accuracy of torque signals in the above examples is important, since only the satisfying accuracy leads to a good performance of the torque control system. However, installation of a torque sensor into torque transmission increases physical size and decreases mechanical stiffness of the equipment, which finally leads to deterioration of the response and to stability problems of the control system.

It is, therefore, desirable not to add any torque sensors. One approach to avoid sensors is to estimate torque instead of detecting it [1], [2]. However, quantization noise and other disturbances corrupt the estimation, so that a tradeoff between the quality of the estimated signal and benefits of the preserved stiffness is to be considered when estimation is used instead of sensing. Torque estimation is not suitable for applications where accuracy is of crucial importance. In such cases, a sensor is used to precisely detect any static or dynamic force or torque in a mechanism or at the interaction with the environment. When a sensor is to be installed, stiffness of the system should be kept as high as possible to preserve good dynamic performance. An ideal sensor would be of an infinite stiffness. Practically, such a sensor does not exist, but an equivalent solution is provided by sensing, which is built into the existing equipment. In such a case, stiffness of the structure is preserved, while torque sensing is obtained as well. In this way, infinitely stiff sensor is equivalently realized by using built-in sensing.

Strain wave gearing reducers, called Harmonic Drives[1] are frequently used in mechatronics equipment due to their high torque transmission capacity, high reduction ratio, and low weight. A part of the gear, called flexpline, is of a thin wall design and transmits torque; therefore, it is a promising candidate for built-in torque sensing. The idea of using strain gauges to detect torque transmitted through the Harmonic Drive was first introduced by Hashimoto in 1989 [3]. Since then, the research continued, but due to a relatively high signal fluctuation caused by the gear operation, the proposed sensing did not yet come into practical use. Recently, significant improvements of accuracy were achieved by introducing additional strain gauges [6], [7], however, some of the signal fluctuation remains uncompensated.

An active compensation of the fluctuation signal by using Kalman filter and a sixth-order harmonic oscillator was proposed by Taghirad *et al.* [8]. The method is effective, however, it requires online computations which delay the torque signal for 1 ms, as reported in [8].

In this paper, we analyze the signal fluctuation's characteristics and propose a new method, which effectively compensates the signal fluctuation. The method does not require online calculations, it reduces requirements on the strain gauges positioning accuracy, and is realized by initial calibration of the gains at each of the strain gauges.

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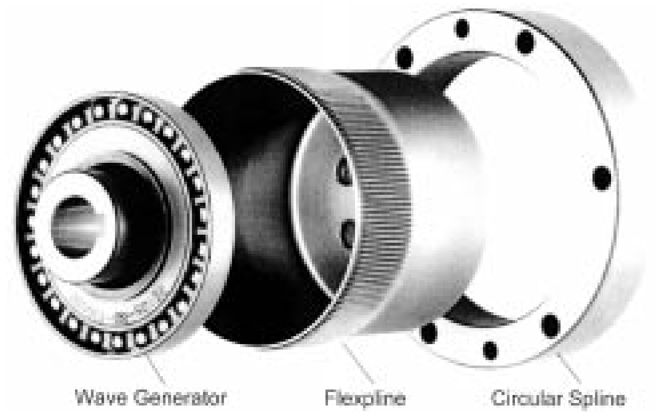
[1]Harmonic Drive is a registered trademark of Harmonic Drive Systems, Inc., Nagano, Japan.



(a)

(b)

Fig. 1. Harmonic drive. (a) Configuration. (b) Operation.

In Section II, we give an overview of the research on Harmonic Drive built-in torque sensing and summarize the achieved results. In Section III, we analyze the signal fluctuation caused by the gear operation, and provide a solution to the signal fluctuation compensation problem by adjusting sensitivities of the strain gauges. We also define the minimum number of strain gauges needed to compensate the signal fluctuation. In Section IV, we show a recently obtained experimental result.

II. Overview of the Research on Harmonic Drive Built-In Torque Sensing

A Harmonic Drive is composed of three main parts: wave generator, flexpline, and circular spline, as shown in Fig. 1(a). A wave generator is of an elliptic shape with a thin ring ball bearing assembled on it and an Oldham coupling in the center of it. The wave generator is inserted into the flexpline just under the teeth, so that the teeth are deformed into an elliptic shape. The elliptically shaped flexpline is then inserted into the circular spline so that the teeth of the flexpline and the circular spline engage only on the major axis of the ellipse. The total number of teeth on the flexpline is smaller for two compared to the total number of teeth on the circular spline. In this way, a high reduction ratio is realized in one stage.

When the gear is used as a reducer, the wave generator is coupled to the input shaft, while either of the flexpline or the circular spline is coupled to the output shaft, and the other of both is fixed to the gear's housing. Operation of the Harmonic Drive with a circular spline fixed is shown in Fig. 1(b).

The gear's nominal reduction ratio R is a ratio between the number of teeth on the flexpline z_f divided by the difference of the number of teeth on the circular spline z_c and flexpline z_f

$$R = \frac{z_f}{z_c - z_f}. \tag{1}$$

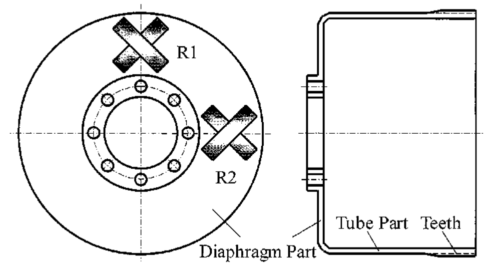


Fig. 2. Flexpline with a pair of strain gauges.

For the designs with circular spline fixed the gear reduction ratio R_c, and for the designs with flexpline fixed the gear reduction ratio R_f are

$$R_c = -R, \qquad R_f = R + 1. \tag{2}$$

Here, the negative sign of R_c denotes that the output shaft of the gear rotates in the opposite direction of the input shaft.

A. Initially Proposed Built-In Torque Sensing

In 1989, Hashimoto first proposed a principle of torque detection from strain in the flexpline [3]. A finite-element analysis showed that the size of the strain generated in the flexpline is suitable to be detected by strain gauges [9]. Calculated strain was the highest in the diaphragm part, that is, in the bottom part of a cup-shaped flexpline; therefore, the strain gauges were cemented on the diaphragm part, as shown in Fig. 2. A pair of 90° crossing strain gauges is used in a half Wheatstone bridge configuration to cancel the normal strain, and to detect only shear strain. Such a pair of strain gauges is, in the discussion below, addressed as *a single strain gauge*.

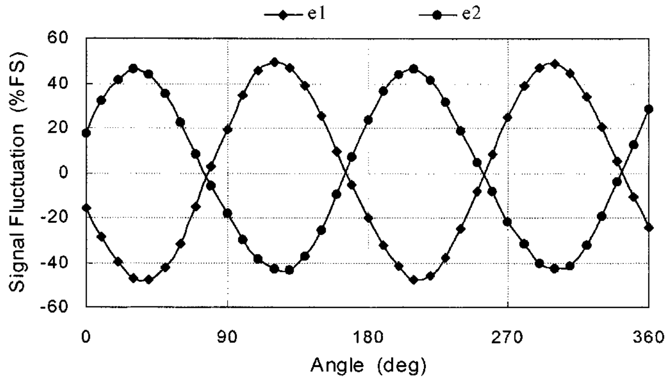
The finite-element analysis also showed that the signals from strain gauges are modulated by harmonic fluctuation, which is generated by deformation of the open part of the flexpline into an ellipse [9]. This modulation we call *a signal fluctuation*. The period of the signal fluctuation is the same as the period of major and minor axes of the ellipse. It was initially proposed to place two strain gauges, one on the major axis of the ellipse and one on the minor axis of the ellipse, to obtain two signals of opposite phases. The signal fluctuations from both strain gauges are expected to be

$$e_1 = a\,\sin(2m\beta), \qquad e_2 = -a\,\sin(2m\beta), \tag{3}$$

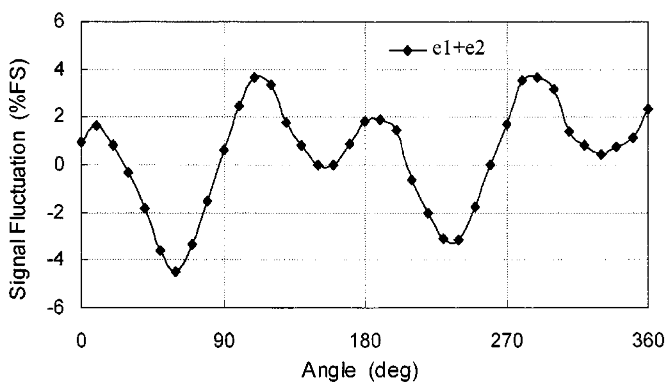
where

- e_1, e_2 signal fluctuations from the strain gauges R1 and R2, respectively (Fig. 2);
- a amplitude of the signal fluctuation;
- m gear configuration factor: $m = 1$ for the designs with flexpline fixed and $m = (R_c + 1)/R_c$ for the designs with circular spline fixed;
- β wave generator—the gear input shaft rotation angle.

Notice that the basic frequency of the signal fluctuation is $2m$ times per input shaft rotation. A correction factor m is needed to compensate the relative rotation of the flexpline against the wave generator in a configuration with circular spline fixed. Additionally, we need to remark that the peaks of the signal fluctuation do not match with the positions of the major or minor



(a)



(b)

Fig. 3. Experimentally obtained signal fluctuations. (a) e_1 and e_2. (b) $e_1 + e_2$.

axis. However, we do not consider this initial phase difference of the peaks and the axes of the ellipse in our study, because it is not important for the signal fluctuation analysis.

The experimentally obtained signals e_1 and e_2 are shown in Fig. 3(a). A Harmonic Drive with fixed circular spline, torque capacity 100 N·m, and gear reduction ratio of 50 was used. Amplitude of the signal fluctuation in Fig. 3(a) is shown in percents of the torque capacity of the gear (%FS), depicted against one turn of the gear input shaft.

The sum $e_1 + e_2$ in Fig. 3(b) should become zero, but the experimental result shows that the signal fluctuation is not completely compensated by two strain gauges. Two opposite phase signals are compensated to some degree, but a signal fluctuation of higher frequency, namely, the double frequency of the basic frequency component is generated, so that the total remaining uncompensated signal fluctuation is about ±4% of the gear torque capacity.

Linearity error is shown in Fig. 4. The linearity error is depicted against applied torque on the gear output shaft by using arm and weight, with the gear at standstill [6], [7]. The linearity error, including hysteresis, is about ±2% of the gear torque capacity.

Accuracy exhibited by two strain gauges cemented at 90° positions is not very good, but compared to the original signal fluctuations e_1 and e_2, compensation of a factor of approximately 10 was achieved. However, for practical use the remaining signal fluctuation is too high and, therefore, some improvement is needed.

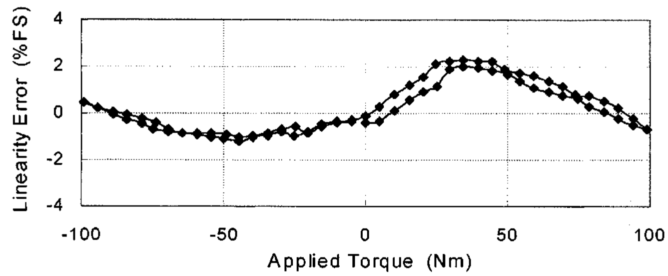


Fig. 4. Linearity error of two strain gauges.

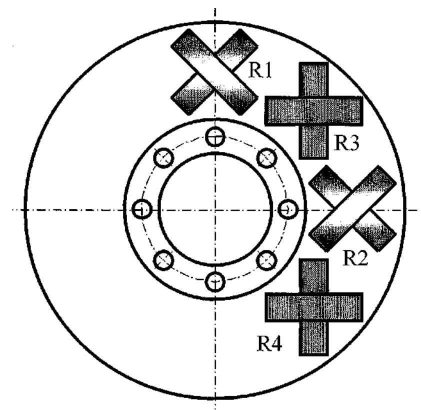


Fig. 5. Strain gauges for improved accuracy.

B. Sensing with Improved Accuracy

Fourier analysis of the experimentally obtained signals e_1 and e_2 showed that both signals contain the basic frequency component with two cycles per input shaft revolution, and the double frequency component, with amplitudes ratio of about 20 : 1. The equation model of the signal fluctuation can be improved by adding a higher harmonic component to the signal fluctuation model

$$\begin{aligned} e_1 &= a\,\sin(2m\beta) + b\,\sin(4m\beta) \\ e_2 &= -\,a\,\sin(2m\beta) + b\,\sin(4m\beta). \end{aligned} \tag{4}$$

Here b is amplitude of the higher harmonic component. Equations (4) show that the higher frequency component is not reduced by sum of two signals from strain gauges placed at 90° positions. This fact was not originally recognized. However, by analogy to the basic frequency signal fluctuation compensation, a compensation signal of opposite phase to the remaining signal fluctuation should be generated to compensate the higher frequency signal fluctuation component. This leads to another pair of strain gauges positioned at 45° relatively to the original pair of the strain gauges, as shown in Fig. 5. The signal fluctuations from the strain gauges R1, R2, R3, and R4 are now

$$\begin{aligned} e_1 &= a\,\sin(2m\beta) + b\,\sin(4m\beta) \\ e_2 &= -\,a\,\sin(2m\beta) + b\,\sin(4m\beta) \\ e_3 &= a\,\cos(2m\beta) - b\,\sin(4m\beta) \\ e_4 &= -\,a\,\cos(2m\beta) - b\,\sin(4m\beta). \end{aligned} \tag{5}$$

The basic frequency component of the signal fluctuation is compensated within each pair of the strain gauges, while both pairs

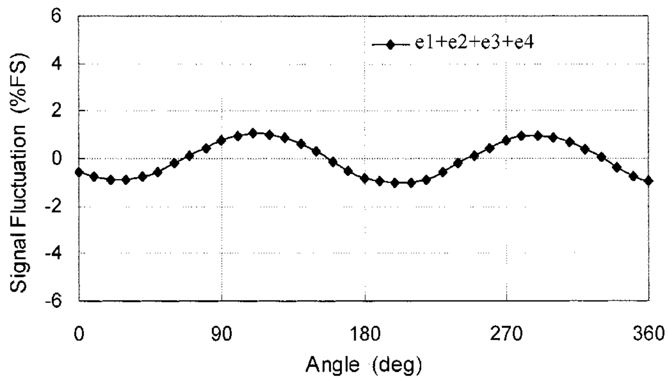


Fig. 6. Signal fluctuation of four strain gauges.

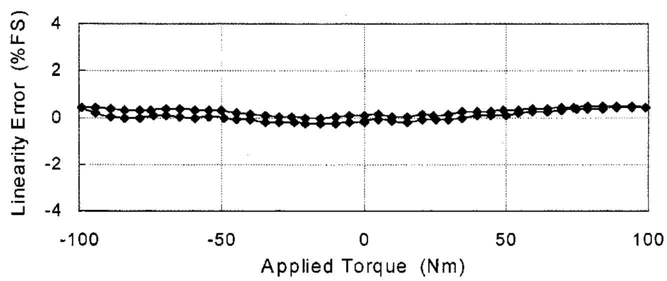


Fig. 7. Linearity error of four strain gauges.

mutually compensate the higher frequency component. A sum of (5) should become zero, but again the experimental result in Fig. 6 shows that some signal fluctuation remains uncompensated. Amplitude of the signal fluctuation is reduced to approximately $\pm 1\%$ of the gear torque capacity, while the frequency of the signal fluctuation is dominated by the basic one. Linearity was also recorded, and improvement to about $\pm 0.5\%$ of the gear torque capacity is shown in Fig. 7.

Overall performance of the sensing is improved, but for practical implementations, where torque detection of high accuracy is needed, the signal fluctuation needs to be further compensated. Before further discussion, we summarize the above results in the following.

1) Compensation of the basic frequency signal fluctuation by a pair of strain gauges placed at 90° positions appeared to be effective, but the remaining uncompensated signal fluctuation included the basic frequency component and the higher frequency component. The basic frequency component became dominant again when another pair of strain gauges was placed at 45° positions against the original one, compensating the higher frequency component.
2) Further adding of strain gauges improves linearity, but does not contribute to better compensation of the signal fluctuation: individual frequency components cannot be perfectly compensated by pairs of strain gauges.

An active method to compensate the signal fluctuation by storing the remaining signal fluctuation into memory and generate opposite phase signals by using a position sensor on the gear input shaft could be used. Such compensation is possible, but it requires an absolute position sensor on the gear input shaft or an initialization routine to obtain the initial position of the gear input shaft when the power is turned on. A method using a Kalman filter and sixth-order harmonic oscillator was also proposed [8]. However, we have found another effective method to compensate the signal fluctuation without using the gear input shaft position information. The method is explained in the following section.

III. Analysis of Signal Fluctuation and Compensation Method

In the above results it was shown that the signal fluctuation is composed of at least two frequency components: the basic frequency component which is generated by the deformation of the flexpline's open part into ellipse, and its higher frequency harmonic. Some experimental results indicate that the higher frequency component is mainly generated in the teeth meshing area, but there are other sources, which are not yet clarified.

The goal of this paper is not to analyze the sources of the signal fluctuation, but to find a method to compensate it. Nevertheless, we can summarize the reasons why the signal fluctuation is not perfectly compensated by the pairs of strain gauges.

1) Errors in position and orientation of the cemented strain gauges [9] occur, as strain gauges cannot be cemented exactly on the required positions and with exactly required orientations due to limitations of the cementing techniques. The positioning errors cause amplitude differences and phase errors in the signals from the strain gauges.
2) Inaccuracies of the flexpline's dimensions and of the assembly produce amplitude differences and phase errors in the signal fluctuations from each of the strain gauges.
3) Individual strain gauges have slightly different gauge factors, which result in different amplitudes of the signal fluctuations from separate strain gauges.

The above factors contribute to amplitude differences and to phase errors of the signal fluctuations from separate strain gauges, which finally cannot be perfectly mutually cancelled.

A. Modeling of the Signal Fluctuation

Equations to produce a general model of the signal fluctuation are in the following extended to N frequency components and to M strain gauges cemented at equally distant angles in the 180° angle of the flexpline's diaphragm part.

A signal fluctuation e_j from each strain gauge j can be generally expressed as a sum of N frequency components with amplitudes a_{ij} and phase errors ψ_{ij}

$$e_j = \sum_{i=1}^{N} a_{ij} \sin\left[2im\left(\beta + \frac{\pi(j-1)}{M}\right) + \psi_{ij}\right]. \qquad (6)$$

A total signal fluctuation h is, therefore, a sum of the signals from M strain gauges

$$h = \sum_{i=1}^{N}\sum_{j=1}^{M} a_{ij} \sin\left[2im\left(\beta + \frac{\pi(j-1)}{M}\right) + \psi_{ij}\right]. \qquad (7)$$

Differences of the amplitudes are included in the amplitude factors a_{ij}, the phase errors ψ_{ij} are, in general, different for individual strain gauges and for individual frequency components, and it is considered that the strain gauges are placed at equally distant angles in the 180° angle of the flexpline's diaphragm part with some positioning errors, which cause the amplitude differences and phase errors.

A general model of the signal fluctuation (7) is used to examine the conditions under which the signal fluctuation is compensated, and the goal of $h = 0$ is achieved.

Equation (7) can be rewritten by using the formula $\sin(\alpha + \beta) = \sin\,\alpha\,\cos\,\beta + \cos\,\alpha\,\sin\,\beta$ in a form where the constant parts and the signal fluctuation parts are separated

$$h = \sum_{i=1}^{N}\sum_{j=1}^{M}\left[\begin{array}{l} a_{ij}\,\cos\left(2im\,\dfrac{\pi(j-1)}{M} + \psi_{ij}\right)\sin(2im\beta) \\ +a_{ij}\,\sin\left(2im\,\dfrac{\pi(j-1)}{M} + \psi_{ij}\right)\cos(2im\beta) \end{array}\right]. \tag{8}$$

Here, the signal fluctuation is separated into sine and cosine components with amplitudes defined only by the geometry factors, which are independent of the rotation angle.

B. Signal Fluctuation Compensation Method

The goal of signal fluctuation compensation $h = 0$ in (8) is achieved only when the amplitude factors of sine and cosine components of all frequency components are simultaneously zero. This translates the problem into a system of linear equations

$$\begin{aligned} &\sum_{j=1}^{M} a_{ij}\,\cos\left(2im\,\frac{\pi(j-1)}{M} + \psi_{ij}\right) = 0 \\ &\sum_{j=1}^{M} a_{ij}\,\sin\left(2im\,\frac{\pi(j-1)}{M} + \psi_{ij}\right) = 0, \qquad i = 1, \cdots, N. \end{aligned} \tag{9}$$

In practice, the signal fluctuation is to be compensated after the strain gauges are cemented. Therefore, the parameters in (9), which can be easily adjusted after the strain gauges are cemented, are the amplitudes a_{ij}. These can be adjusted by individual gain adjustment at each of the strain gauges, that is, by using a signal conditioner which has amplifier circuits with adjustable gains. An interesting fact is that only by gain adjustment can we compensate the amplitude differences and the phase errors. Notice that the amplitude adjustment is independent only for each strain gauge j, but not for each frequency component i. Further, all the gains after the tuning need to be scaled so that the overall gain becomes equal to the original gain before the tuning.

C. Minimum Number of Strain Gauges Needed to Compensate the Signal Fluctuation

The question of the minimum number of strain gauges needed to compensate the signal fluctuation needs to be addressed and is important from the production costs point of view. The answer is found by inspection of the conditions to obtain a nontrivial solution of the system of equations (9).

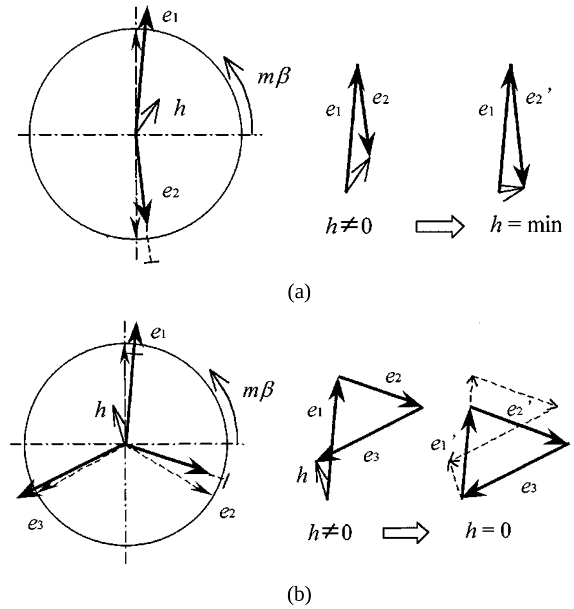


Fig. 8. Vector representation of signal fluctuation compensation. (a) Two strain gauges. (b) Three strain gauges.

Size of the system of equations (9) is $M \times 2N$. Therefore, we can formulate the following relation to obtain a nontrivial solution:

$$M \geq 2N + 1. \tag{10}$$

That is, the minimum number of strain gauges $M_{\min}$ needed to compensate the signal fluctuation is

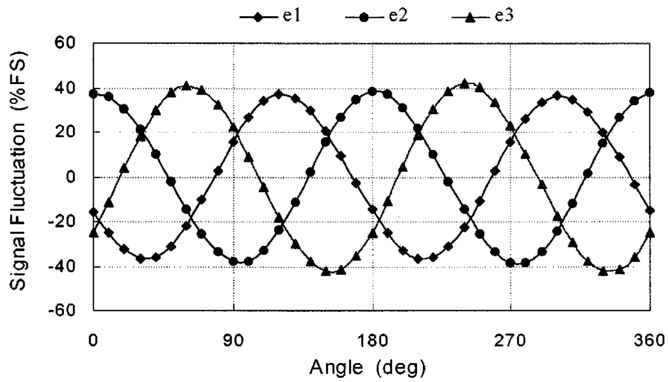
$$M_{\min} = 2N + 1. \tag{11}$$

For example, to compensate one, namely, the basic frequency component $N = 1$, a minimum of three strain gauges $M_{\min} = 3$ is needed. To compensate two frequency components $N = 2$, a minimum of five strain gauges $M_{\min} = 5$ is needed, and so forth.

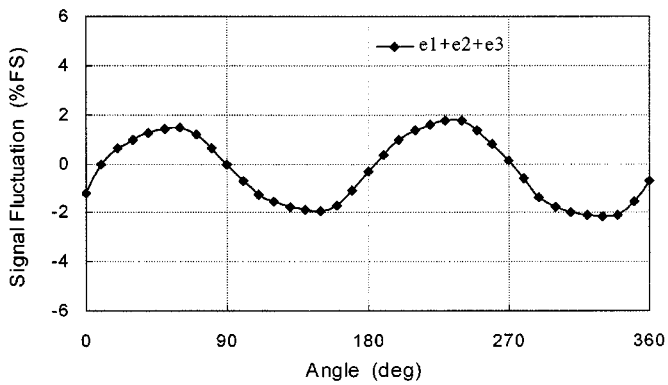
Vectors in Fig. 8 graphically represent an example of basic frequency component compensation. In Fig. 8(a), it is shown that by two strain gauges it is possible to minimize the signal fluctuation, but impossible to perfectly compensate the basic frequency component of the signal fluctuation. On the contrary, by three strain gauges in Fig. 8(b), the basic frequency component can always be perfectly compensated.

IV. Experimental Result

A recently obtained experimental result with the proposed signal fluctuation compensation method is presented here. A Harmonic Drive with fixed flexpline, torque capacity of 100 N·m, and gear reduction ratio of 51 was used. Three strain gauges were cemented on the diaphragm part of a flexpline with angle distance 60°. In this experiment, only compensation of the basic frequency component was investigated, therefore, only three strain gauges were cemented. Not much care was taken in the strain gauges positioning accuracy, since the new compensation method can compensate any size of the errors.



(a)



(b)

Fig. 9. (a) Signal fluctuations from three strain gauges. (b) Sum of the three signals.

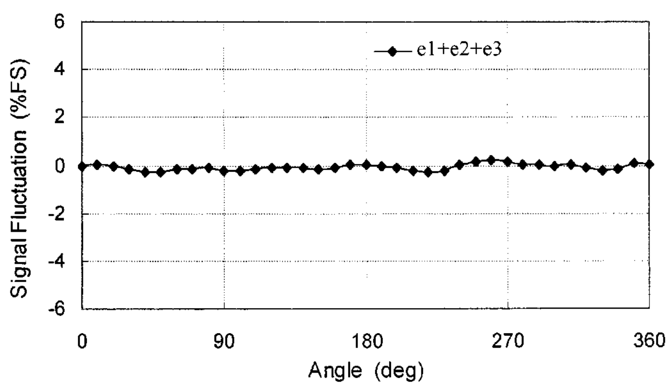


Fig. 10. Compensated signal fluctuation from three strain gauges.

The signals from three strain gauges are shown in Fig. 9. The amplitudes $a_{11} : a_{12} : a_{13}$ and the phase errors $\psi_{11} : \psi_{12} : \psi_{13}$ of the signals in Fig. 9(a) are $1 : 1.07 : 1.15$ and $0 : -1.5 : -0.4°$, respectively. In such conditions, the remaining signal fluctuation by the original compensation method is about $\pm 2\%$ of the gear torque capacity, as shown in Fig. 9(b). With the adjustment by the new method the basic frequency component was perfectly compensated, as shown in Fig. 10. The higher frequency components with total amplitude of about $\pm 0.2\%$ of the gear torque capacity remain uncompensated. An additional two strain gauges need to be installed to also perfectly compensate

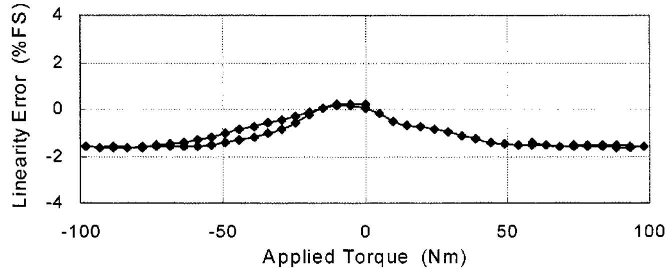


Fig. 11. Linearity of three strain gauges with compensation.

the double frequency component. This will be challenged in our future research.

Gains adjustment for the signal fluctuation compensation can be calculated from (9), or adjusted by tuning of the gains until the frequency component which we want to adjust disappears from the signal fluctuation's frequency spectrum. In the experiment shown, we used the manual method to tune the gains.

Linearity error of the three strain gauges is shown in Fig. 11. Linearity error including hysteresis is less than 2% of the gear torque capacity, and is between the levels of two and four strain gauges (compare to Figs. 4 and 7). Linearization techniques should be applied for further linearity improvements.

V. Conclusions

Built-in sensing is attractive because it provides sensing from original equipment without basic changes of the design and without tradeoffs with mechanical properties. A principle and performance of built-in torque sensing for Harmonic Drives have been investigated in the past, but the drawback of signal fluctuation, which is generated by the gear operation, remained unsolved. Compensation of the signal fluctuation was recently improved by an increased number of strain gauges, but perfect compensation was not achieved.

In this paper, we have summarized the research results and achieved accuracy of Harmonic Drive built-in torque sensing, and presented an analysis of the signal fluctuation's characteristics. We have found that the signal fluctuation can be perfectly compensated by adjustment of the strain gauges' sensitivities. Adjustment is realized by a gain adjustment circuit added to each of the strain gauges. In addition, the accuracy requirement for the strain gauges positioning is lightened by the proposed method, because large positioning errors can also be effectively compensated.

Another important result presented in this paper is the minimum number of strain gauges needed to perfectly compensate the signal fluctuation. We showed that the basic frequency component of the signal fluctuation is perfectly compensated by three strain gauges.

In future experiments, we will examine simultaneous compensation of more than one frequency component of the signal fluctuation and improve linearity of the sensing by using one of the available linearization techniques.

The method of signal fluctuation compensation proposed in this paper can be applied to any sensing technique where the problem of periodic signal fluctuation needs to be addressed.

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