Ripple Compensation of Harmonic Drive Built-in Torque Sensing

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Abstract — **Built-in torque sensing in Harmonic Drives enables torque sensing without assembling additional torque sensors into mechanism where Harmonic Drives are already present. The sensing principle is known for about ten years, but it is not widely utilized yet, mainly because of a relatively high ripple signal in the sensing output, generated by the gear operation. Ripple is difficult to be compensated due to inaccuracies of the strain gages positioning and in geometrical properties of the gear and its assembly. Increased number of applied strain gages reduces the ripple, but does not eliminate it. In this paper, we present a new method to effectively compensate the ripple. It bases on a periodic characteristic of the ripple signal itself and proposes use of separate amplifiers for each of the signals from the strain gages. Gains of the amplifiers are tuned so that the ripple signal is compensated. A mathematical model of the ripple signal, and a method to calculate the tuned gains is studied. Minimum number of strain gages needed to compensate the ripple signal is derived. The method is successfully confirmed by experiments.**

I. Introduction

Torque sensing is used in torque control, compliance control, disturbance compensation control and other applications where torque signal is needed, including safety applications. In general, a sensor is used to detect torque, but it introduces additional mechanical compliance when it is assembled into a system. This consequently reduces overall mechanical stiffness of a mechanism. Therefore, it is not desirable to assemble additional sensors into a mechanism, but to estimate torque or to sense it from already available components of the system itself.

Strain wave gearing reducers, also known as Harmonic Drives[1], are frequently used in combination with servomotors to produce high driving torque in various motion control applications. A part of the gear, called flexpline is of a thin wall design and transmits torque, therefore represents a promising candidate for a built-in torque sensing. The idea of using strain gages to measure torque transmitted through Harmonic Drive was first introduced by Hashimoto in 1989 [1]. Since then, the research continued, but due to a relatively high ripple signal caused by the gear operation, the proposed sensing technique did not come into a wide use yet. Recently, significant improvements of accuracy were achieved by introducing additional strain gages [4], [5], but some of the ripple remained uncompensated.

In this paper we analyze the ripple signal's characteristics and propose a new method, which effectively compensates the ripple. A solution of the ripple signal compensation problem is found in sensitivity adjustments of the individual strain gages. Adjustment is realized by implementation of amplifiers with gain adjustment ability connected to each of the strain gages separately. A technique to define the gains is developed. A minimum number of strain gages needed to compensate the ripple signal is also derived. The proposed method is confirmed by an experiment.

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

II. Analysis of the Ripple Signal

Operational principle of Harmonic Drive and the basic considerations about built-in torque sensing by using strain gages are discussed elsewhere [1]-[3]. Here we will summarize only the basic results, which are needed to understand the background related to the mathematical model, which will be derived later to find a solution of the ripple compensation problem.

The basic layout of Harmonic Drive built-in torque sensing by using strain gages cemented on a diaphragm part of the flexpline is shown in Fig. 1. Here the strain gages composed of two orthogonal crossed strain gages are

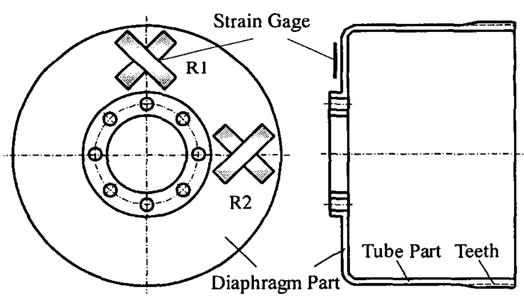


Fig. 1 Flexpline with a pair of strain gages

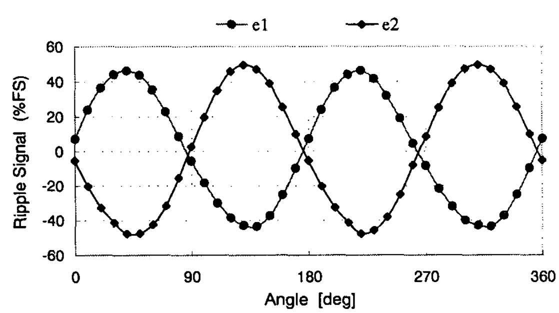


Fig. 2 Ripple signals from strain gages R1 and R2

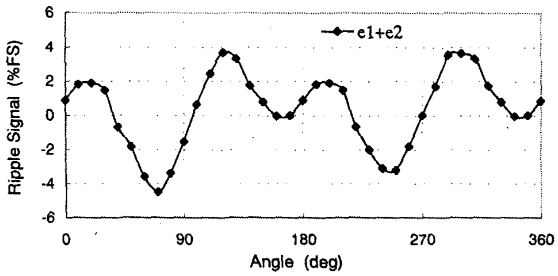
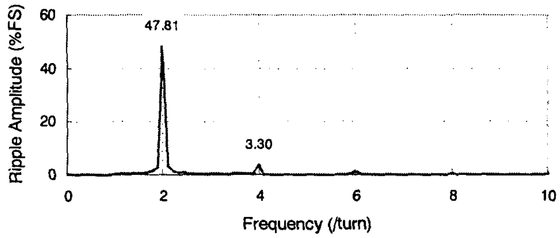
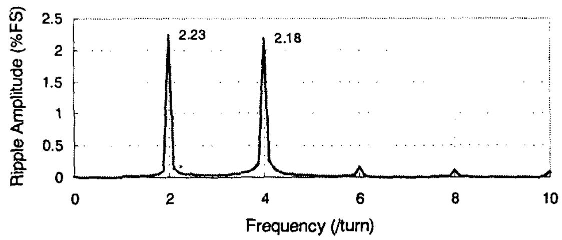


Fig. 3 Ripple signal from two strain gages



(a) Frequency spectrum of e_1



(b) Frequency spectrum of $e_1 + e_2$

Fig. 4 Frequency spectra of one (a) and two (b) strain gages

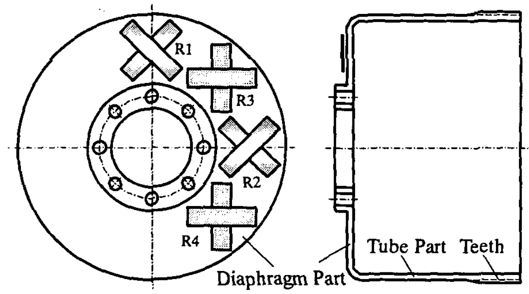


Fig. 5 Flexpline with two pairs of strain gages

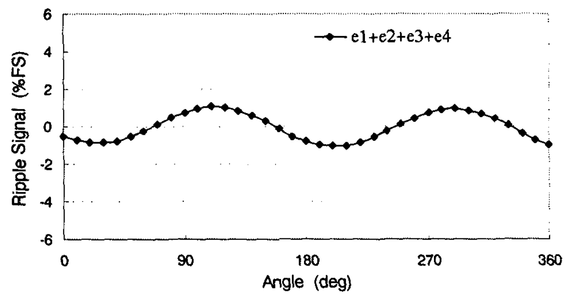


Fig. 6 Ripple signal from four strain gages of Fig. 5

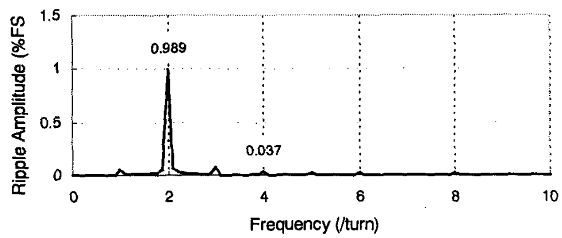


Fig. 7 Frequency spectra of ripple in Fig. 6a

used as a strain gage with a task to detect only the shear strain. Such pre-assembled strain gages are commercially available, therefore, we use them in a configuration of a half Whetstone bridge [5].

Initially, it was assumed that the ripple signals e_1 and e_2 from the two strain gages R1 and R2 respectively in Fig. 2 would be mutually sufficiently compensated, but as shown in Fig. 3, the uncompensated ripple is relatively high. (All the signals are depicted in percents of maximum allowed torque for the Harmonic Drive, which is 100Nm in our case, versus the input shaft angle i.e. the wave generator angular position.) The frequency spectra in Fig. 4b comparing to Fig. 4a shows that the basic frequency component, namely the twice per turn of the input shaft component, is significantly reduced, but the component of a higher frequency, that is the four times per turn component, is not remarkably reduced. The frequency spectrum of the signal from one strain gage (Fig. 4a) shows that both components are originally present in the ripple signal from one strain gage.

Next, to compensate also the higher frequency signal component, we proposed positioning of another pair of strain gages at angular position 45 degrees against the original pair [4], [5], as shown in Fig. 5. The results in Figs. 6 and 7 show that the higher frequency component is significantly reduced, but the basic frequency component is not compensated much further than it was by one pair of strain gages. Comparison of Fig. 7 to Fig. 4a suggests that the finally obtained ripple resembles the original one of one strain gage, except the amplitudes in concern are reduced approximately 50-times.

The conclusion here is that the basic and the double frequency components of the ripple are significantly compensated, but not completely cancelled, which is not a satisfying result for applications where high accuracy is needed. We also conclude here that further improvement of the ripple compensation can not be achieved just by increase of the number of applied strain gages. The fact is that the reached level of the ripple is caused mainly by positioning errors of the strain gages and other geometry related factors, which can not be eliminated by a reasonable increase of the number of applied strain gages. Moreover, other sources of the ripple are considered to be in differences of the gage factors and in non-symmetry of the geometrical properties of the gear and its assembly (eccentricity, dimensions asymmetry, etc.), which also can not be reduced by a reasonable increase of the number of applied strain gages. It is therefore considered that positioning accuracy of the strain gages when cemented to the flexpline and accuracy of the gear itself must be improved to further reduce the ripple [4]. However, technological and costs related problems of the strain gages accurate cementing techniques are difficult to be overcome, so it is also difficult to expect any further improvements in this direction. In our considerations we focused on periodic nature of the ripple signal and tried to find more cost-effective solution of the problem. In the following sections we will derive a mathematical model of the ripple signal and present a new compensation method, which pose no high requirements on positioning accuracy of the strain gages cementing techniques as well as on the gear itself.

III. Mathematical Model of the Ripple Signal

As it was shown in the experiments above, a ripple signal from a strain gage is a periodic signal with even frequencies dominating. However, to preserve generality of the model, we consider both even and odd components of the signal in the mathematical model derived below. Later in the analysis, if needed, we can limit the model to the specific frequency components, which are dominating in a specific case to be studied.

Here we consider that M strain gages are angular equidistantly cemented over the diaphragm part of a flexpline, and N frequency components are composing the ripple signal. A ripple signal from one strain gage e_j is therefore expressed as

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

Here a_{ij} are amplitudes of the ripple signal components, generally different for each of the strain gages j and for each of the frequency components i ; ψ_{ij} are phase errors also in general different for each of the strain gages j and for each of the frequency components i. Notice here that radial and inclination against radial direction positioning errors of the strain gages, gage factors differences, and gear dimensions asymmetries cause differences in the amplitudes a_{ij}, while angular positioning errors of the strain gages and gear dimensions asymmetries generate the phase errors ψ_{ij}. β is the gear input shaft rotation angle (the wave generator rotation angle) and m is a factor of the gear configuration: $m = 1$ for the designs with flexpline fixed and $m = (R-1)/R$ for the designs with circular spline fixed, where R is the gear reduction ratio.

Equation (1) is a general mathematical model of the ripple signal from one strain gage. Notice that only the ripple signal is modeled, while the signal generated by the load torque is not included here. In [2], [3] it was shown that the signal generated by the applied torque is proportional to the torque, therefore, it is not included in the mathematical model of the ripple.

The signals from M strain gages are added to one signal and output as a torque signal of a built-in sensing. The ripples are also added by this operation, therefore, a model of total ripple signal h is equal to a sum of M signals from M strain gages which gives

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

Using this general mathematical model of the ripple signal from a built-in sensing we can examine conditions to reach the goal of a ripple signal compensation, that is to obtain $h = 0$.

IV. Ripple Compensation Method

Equation (2), modified by using formulae $\sin(\alpha + \beta) = \sin\alpha\cos\beta + \cos\alpha\sin\beta$, gives the following result:

$$h = \sum_{i=1}^{N} \sum_{j=1}^{M} \left[\begin{array}{l} a_{ij} \cos\left(im\frac{2\pi(j-1)}{M} + \psi_{ij} \right) \sin(im\beta) + \\ a_{ij} \sin\left(im\frac{2\pi(j-1)}{M} + \psi_{ij} \right) \cos(im\beta) \end{array} \right] . \tag{3}$$

An interesting result here is decoupling of the ripple signal into sine and cosine components, with errors influencing only amplitudes of the respective frequency components. A surprising and also profitable fact is that the phase errors ψ_{ij} contribute only to the amplitudes of the respective components. In the next step, we examine conditions to satisfy the goal $h = 0$.

From the fact that the ripple can be decoupled into sine and cosine components, which differ only in amplitudes but not in phases, we can conclude, that the ripple will be compensated in the case when both sine and cosine components of the respective frequency components will simultaneoulsy become zero. This translates the problem into a homogenous system of linear equations as follows:

$$\left. \begin{array}{l} \sum_{j=1}^{M} a_{ij} \cos\left(im\frac{2\pi(j-1)}{M} + \psi_{ij} \right) = 0 \\ \sum_{j=1}^{M} a_{ij} \sin\left(im\frac{2\pi(j-1)}{M} + \psi_{ij} \right) = 0 \end{array} \right. , \quad i = 1,\ldots,N . \tag{4}$$

Following, let us examine how this system of equations can practically be satisfied.

In practice the ripple is to be compensated after the strain gages are cemented. This means that the phase errors ψ_{ij} in (4) can not be adjusted after the strain gages are cemented. The only parameters in (4), which can be adjusted after the strain gages are cemented, are the amplitudes a_{ij}. The amplitudes can be adjusted by using amplifiers connected to each of the strain gages separately. Therefore, if a nontrivial solution for a_{ij} in (4) exists, the ripple caused by amplitude errors as well as the ripple caused by phase errors can be compensated simply by adjustment of the amplitudes of the ripple signals from separate strain gages. This is a very interesting and important result, which shows that arbitrary positioning errors of the strain gages in radial as well as in angular direction are allowed and can be compensated simply by adjustment of the signals' amplitudes.

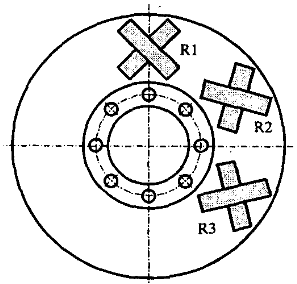


Fig. 8 Three strain gages to compensate ripple

A practical consideration about the gain tuning techniques needs to be addressed. Practically, the amplitudes can be adjusted by using separate amplifiers for each of the strain gages. This means that practically the amplitudes can be separately tuned only for separate strain gages j, but not for separate frequency components i. Consequently, the adjustment is crosscoupled over the frequency components. Crosscoupling can cause some inconvenience in manual tuning, but can be supported by calculation as will be shown in next section. On the other hand, amplitudes of the separate frequency components are originally quite different (see Fig. 4a), so that a manual tuning process is selective according to the fact that the components with different amplitudes are differently sensitive to the gain tuning. The components of lees amplitude should be addressed first, then the components with larger amplitudes, which are more sensitive to tuning can be compensated by minor changes of the gains.

V. Minimum Number of Strain Gages Needed for Compensation

First, the conditions for existence of a nontrivial solution of (4) are investigated. Here we introduce the gain adjustment factors k_j for each of the strain gages j as the tuning parameters, and express (4) in a vector form:

$$\begin{bmatrix} a_{ij}\cos\left(im\dfrac{2\pi(j-1)}{M}+\psi_{ij}\right) \\ a_{ij}\sin\left(im\dfrac{2\pi(j-1)}{M}+\psi_{ij}\right) \end{bmatrix}_{2N\times M} \left\{k_j\right\}_M = \mathbf{0} \ . \qquad (5)$$

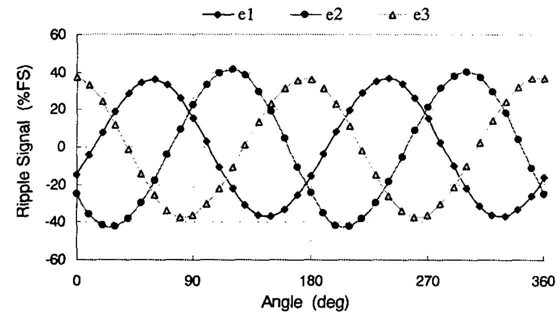
A condition for nontrivial solution k_j of the homogenous system of equations (5) is

$$M \geq 2N+1 \ . \qquad (6)$$

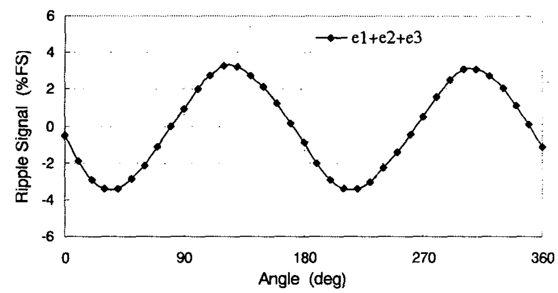
In this case, a solution, and not only one, infinite number of solutions exist. It is necessary therefore to set one of the gains in advance. This means that actually the gain tuning is needed for all strain gages except one. One strain gage can have a fixed, for example a unity gain.

Equation (6) also suggests that the minimum number of strain gages $M_{\min}$ needed to compensate N number of ripple components is

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



(a) Signals from three strain gages



(b) Sum of three signals

Fig. 9 Signals from three strain gages (a) and sum of the signals (b)

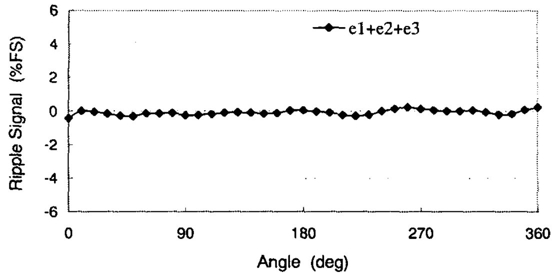
For example, to compensate one frequency component ($N=1$) three strain gages are needed ($M_{\min}=3$), to compensate two frequency components ($N=2$) five strain gages are needed ($M_{\min}=5$), and so forth.

To calculate the gains of amplifiers k_j, amplitudes a_{ij} and phase errors ψ_{ij} of all frequency components of the signals from the strain gages must be known in advance. These parameters can be obtained by Fourier transformations of the signals from separate strain gages. With the parameters a_{ij} and ψ_{ij} known, the gains k_j can be calculated for $M-1$ amplifiers, while the gain of one of the amplifiers must be set in advance. The easiest way to do it is to set gain of one of the amplifiers, for example the p-th amplifier to 1. Next, to solve the system of equations the p-th column of the matrix is then taken out of the matrix and transferred to the right side of the equation as a vector (with a negative sign), and the p-th row of the k_j vector is deleted. Thus a non-homogenous system of linear equations is obtained, and a solution for $M-1$ gains can be easily found.

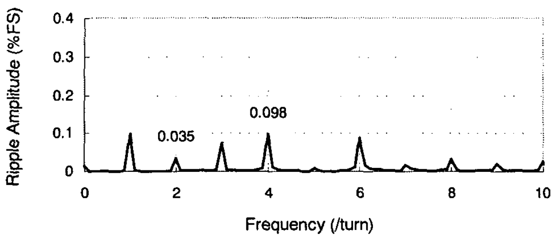
VI. Experiment

Here we will show an experiment of compensation of a basic frequency ripple component, that is one component ($N=1$), but here $i=2$ is set because the basic component is a double frequency over one turn of the input shaft.

To compensate one frequency component three strain gages are needed, so we cemented three strain gages as shown in Fig. 8. A Harmonic Drive with fixed flexible



(a) Compensated ripple



(b) Frequency spectrum of compensated signal

Fig. 10 Compensated ripple signal (a) and frequency spectrum (b)

spline ($m = 1$), maximum allowed torque 100Nm, and gear reduction ratio $R = 51$ was used. The ripple signals from the three strain gages are shown in Fig. 9a. The overall ripple generated as a sum of the three components is shown in Fig. 9b. Fourier analysis of the ripple signals from the three strain gages gave the following results (amplitudes are in %FS, phase angles are in degrees): $a_{21} = 36.6\%$, $\psi_{21} = 0^\circ$, $a_{22} = 41.88\%$, $\psi_{22} = -0.85^\circ$, $a_{23} = 37.4\%$, $\psi_{23} = 7.23^\circ$. Notice that here the phase of a signal e_1 is taken as zero. The phase errors indicate positioning errors of the strain gages in a range of up to 1.5mm. (Intentionally not much care was taken on the positioning accuracy of the strain gages.)

With the above obtained data and k_1 set to 1, we obtain the following system of equations derived from (5) and with the procedure described in previous section:

$$\begin{bmatrix} -21.457 & -22.631 \\ -35.956 & 29.781 \end{bmatrix} \begin{Bmatrix} k_2 \\ k_3 \end{Bmatrix} = \begin{Bmatrix} -36.608 \\ 0 \end{Bmatrix}. \tag{8}$$

Solving the system of equations (8) we get the result for $k_2 = 0.75$ and $k_3 = 0.91$. Incorporating this result into tuned gains gives a ripple shown in Fig. 10a, which is a good compensation comparing to Fig. 6 or Fig. 9b. Obviously, the goal here is achieved, because the ripple, which was to be compensated, is effectively reduced to 0.035% of the gear torque capacity.

In future experiments we plan to compensate two or more frequency components simultaneously, for which we need to cement five or more strain gages on the diaphragm part of a flexpline.

The result shown here verifies effectiveness of the proposed method to compensate the ripple signal, regardless to significant inaccuracies in the strain gages positioning. Such encouraging result promises high quality built-in sensing available for various applications of Harmonic Drive gears.

VI. CONCLUSION

Built-in sensing in Harmonic Drives is attractive since it provides torque sensing from original equipment without any basic changes in the design and without tradeoffs with mechanical properties. However, a drawback of relatively high ripple signal, which is generated by the gear operation, posed limitations to various applications. Compensation of the ripple signal was recently improved by increased number of the applied strain gages, but perfect compensation was not achieved.

In this paper, we analyzed characteristics of the ripple signal and found out that the ripple can be effectively compensated by adjustment of the strain gages' sensitivities. Adjustment is realized by providing each of the strain gage with its own amplifier with gain tuned after the strain gages are cemented. A method to calculate the gains for separate amplifiers was shown. Arbitrary positioning errors of the strain gages can be compensated, therefore the new method poses no requirements on the positioning accuracy of the strain gages cementing technique, which is a considerable advantage from the production costs viewpoint.

A minimum number of strain gages needed to compensate the ripple signal was also derived. The basic frequency component of a ripple signal can be effectively compensated by three strain gages. The results were confirmed by experiment.

The method to compensate ripple signal presented in this paper can be applied also to other sensing techniques, which are dealing with periodic ripple signals.

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