An optical system for monitoring torsion in a power transmission shaft in realtime

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Abstract

An optical system has been proposed and verified experimentally for monitoring the torsion of a power transmission shaft in realtime. The system consists of a pair of lasers, mirrors and light receivers as a sensor head, and logic circuit, high-frequency oscillator, and computer as a data processing system. The smallest measurable angle of torsion can be expressed by ω/f, where ω is the rotational frequency of the power transmission shaft and f is the frequency of the oscillator. The experimental error was found to be a few percentage points.

1. Introduction

Metal shafts have long been used for the transmission of mechanical power. Examples include screw shafts and crank shafts in cars. Torsion is normally generated by a load since shafts are usually a few meters in length and a few centimeters in diameter [1]. Over time, shafts tend to break suddenly due to metal fatigue and overload. Such breakdowns will occasionally cause disastrous accidents. It is therefore desirable to monitor torsion in a rotating shaft in realtime.

In this paper, we propose and verify a practical system to monitor torsion. The present method is based on laser reflection.

2. Method and system

We have previously proposed an optical method for detecting torsion in a power transmission shaft [2]. The basic principle of the present method is based on light reflection. Fig. 1 shows the sensor head of the system. Two pairs of light sensors are used for this purpose. One is attached to the input side of the shaft and the other to the output side. A load will cause torsion to occur between them. A pair of light sensors consists of a light source, mirror, slit, and light receiver. The light reflected on the mirror is captured by the receiver. A semiconductor laser is used as a light source and a silicon photodiode is used as a light receiver. The slit attached in front of the silicon photodiode is used to shield ambient light and obtain a square-like light signal. A curved mirror with the same curvature as the shaft is used, thus, both pulse signals are obtained simultaneously by the receivers when the laser illuminates the rotating mirrors. No time difference will exist between both signals when both mirrors are attached to the shaft in the same axial direction. A time difference Δt will, however, be produced due to torsion. The torsion angle $\Delta\theta$ is in direct proportion to the time difference Δt as follows:

$$\Delta\theta = \omega \times \Delta t, \tag{1}$$

where ω is the rotational frequency of the shaft. Thus, $\Delta\theta$ can be detected by measuring Δt.

Fig. 2 shows the principle of this method and Fig. 3 presents the system. Initially, both received signals are transformed to square waves by a comparator. The time difference between them, Δt, can then be measured by a logic circuit and is finally digitized by an oscillator and a counter. The frequency of the oscillator, f Hz, determines the time resolution, i.e., measurable smallest amount of time δt ($= 1/f$). That is, the time difference is measured by a relation, $\Delta t = n \times \delta t$, where n is a pulse number within the time difference. The number n can be detected by the counter. The torsion angle $\Delta\theta$ can then be given by

$$\Delta\theta = \omega n/f. \tag{2}$$

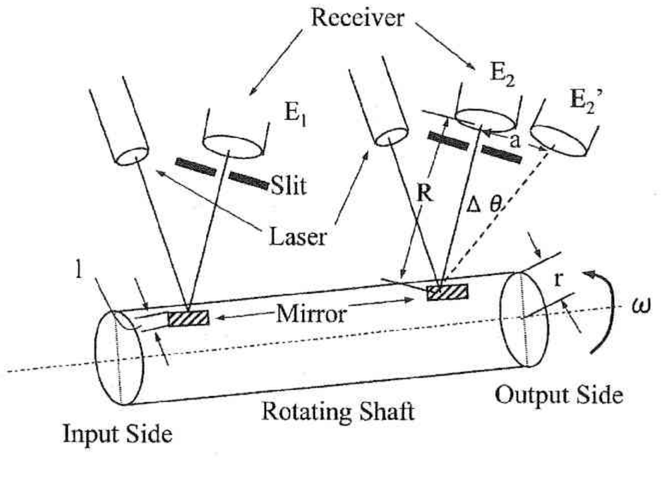

Fig. 1. Proposed sensor head for detecting torsion in a shaft.

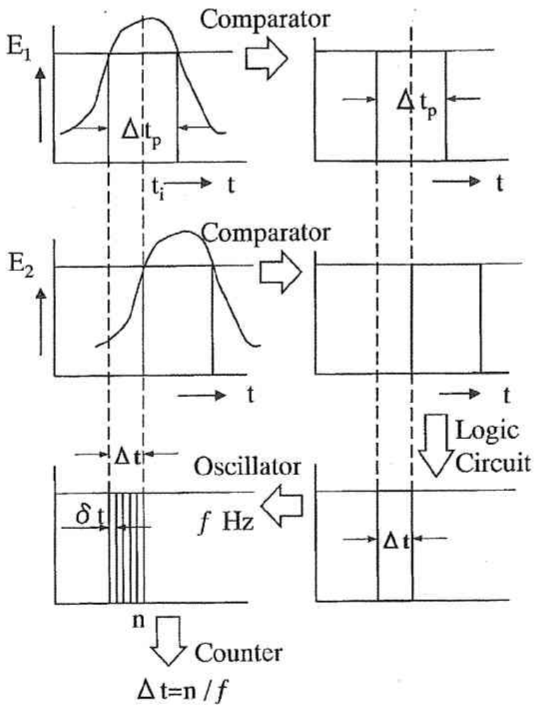

Fig. 2. Method for measuring the torsion in realtime.

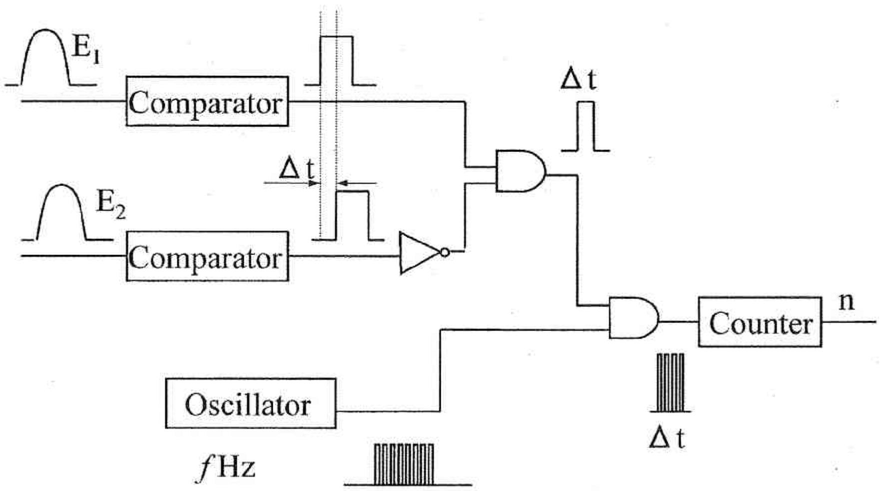

Fig. 3. System for measuring the time difference digitally.

In order to measure the torsion accurately, the pulse number, n, in each time difference, Δt_i, was averaged over reasonable periods, T_a ($= m \times 2\pi/\omega$), as shown in Fig. 4. The number m shows an integer that determines an interval for averaging. Each time difference at the sampling synchronized to the rotational frequency of the shaft has a different value, Δt_i ($i = 1 \sim m$), mainly due to the vibration of the shaft and the load. The pulse number thereby has a different value, n ($\equiv n_i$). In this paper, we denote the averaged values by $\langle\rangle$ e.g, $\langle \Delta t \rangle$, $\langle n \rangle$ and $\langle \Delta\theta \rangle$. The average has an effect on the estimated amount of torsion. This will be discussed further in Section 4.1.

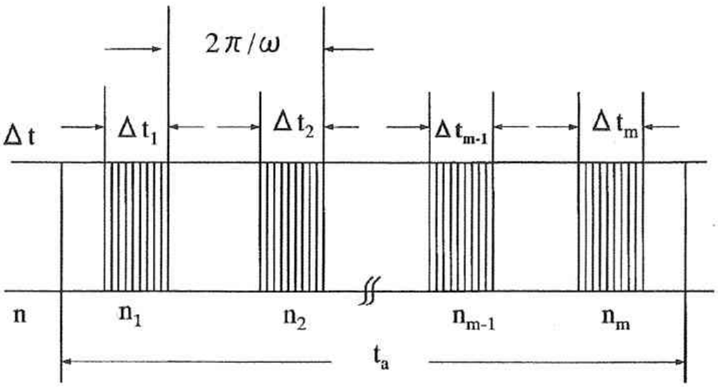

Fig. 4. Method for averaging.

3. Experimental results

A preliminary experiment was conducted in order to verify the method. It is difficult to produce torsion experimentally. Torsion was simulated in the present study by a slight shift of the light receiver, E_2 to E_2', as shown in Fig. 1. The distance from the mirror to the receiver was $R = 300$ mm.

In the present experiment, there existed a small time difference between both light receivers, Δt_o, even in the absence of torsion, $\Delta\theta = 0$. This was because of the optical arrangement of the light sources, the mirrors, and the light receivers. The net time difference, Δt, is then

$$\Delta t = |\Delta t_o - \Delta t_s| = |n_o - n_s| \times (1/f), \tag{3}$$

where Δt_s represents the time difference, from when the torsion was simulated. An integer n_o represents the pulse number within Δt_o and n_s within Δt_s.

Table 1 presents a few examples of the pulse number for three different amounts of torsion. 20 samples were averaged, i.e., $m = 20$. The error rate of the pulse number from the mean value was within 5%. The accuracy of the torsion angle may then exceed 95% even without averaging. In this experiment, the rotational frequency was $\omega = 2\pi \times 10$ and the frequency of the oscillator was $f = 1$ MHz.

The net time difference Δt can then be obtained by Eq. (3), and the torsion amount $\Delta\theta$ by Eq. (2). The shift amount of the light receiver, a, can easily be obtained by a relation $\langle a \rangle = R \times \langle \Delta\theta \rangle$. Table 2 shows these values for three amounts of shift. It can be seen in Table 2 that the measured torsion, a, agrees well with this method's calculated torsion $\langle a \rangle$. Thus, the method used in this study was found to be valid.

4. Considerations

4.1. Accuracy

The error of the torsion depends on a fluctuation of $n, f,$ and ω, as shown in Eq. (2). The values of n and ω will continually fluctuate due to the load and the vibration of

Table 1
Pulse numbers within each time difference Δt_i ($i = 1 - 20$) for three different amounts of simulated torsion

n_0	Error rate (%)	$n_s - n_0$	$n'_s - n_0$	$n''_s - n_0$
72	7.46	59	86	124
71	5.97	57	88	122
66	− 1.49	64	90	128
70	4.48	59	89	122
63	− 5.96	65	95	128
67	0.00	63	93	126
71	5.97	58	87	122
63	− 5.97	66	94	128
68	1.49	62	93	125
70	4.48	58	89	124
63	− 5.97	64	96	128
68	1.49	62	94	124
68	1.49	60	91	126
65	− 2.99	66	98	126
69	2.99	61	90	123
65	− 2.99	63	93	133
66	− 1.49	62	94	125
70	4.48	59	89	122
64	− 4.48	66	92	129
66	− 1.49	65	94	124
Ave = 67		Ave = 62	Ave = 92	Ave = 126

Table 2
Calculated and measured torsions with pulse number and time difference. Experimental conditions: frequency of the oscillator, $f = 1$ MHz; rotational frequency of the shaft, $\omega = 2\pi \times 10$; distance from mirror to receiver, $R = 300$ mm

	Torsion		
	θ	θ'	θ''
Pulse number $\langle n_s - n_0 \rangle$	62	92	126
Time difference $\langle \Delta t_s - \Delta t_0 \rangle$ (μs)	62	92	126
Calculated torsion angle $\langle \Delta\theta \rangle$ (m rad)	3.89	5.78	7.91
Calculated amount of shift $\langle a \rangle$ (mm)	1.17	1.73	2.37
Measured amount of shift a (mm)	1.0	1.8	2.4

the shaft. The rotational frequency ω will continually fluctuate due to a load. The fluctuation, however, has no effect on accuracy because both mirrors are attached to the same shaft. In addition, the high-frequency oscillator does not fluctuate. Therefore, the only remaining possible error factor would be the fluctuation of n caused by a vibration of the shaft, Δn. The fluctuation, i.e., error rate of the pulse number from the mean value, was a few percentages, which determines the accuracy of this method.

It is, however, possible to reduce the error to a negligibly small amount by averaging the measured values of n over a period of them, T_a $(= m \times 2\pi/\omega)$, as described in Section 3. because the sum of Δn_i becomes zero. The data for the torsion can then be obtained at an interval of T_a. The interval T_a will usually be smaller than 1 s in practical use. The data can then be obtained in realtime. Thus, the method described in this paper will be free of error factors in principle.

4.2. Resolution of the torsion angle

The resolution of the torsion angle, i.e., detectable minimum torsion angle, is determined by ω/f, as expressed in Eq. (2). High resolution can thus be obtained with the high frequency of the oscillator. In this preliminary experiment, the resolution of the torsion angle, $\theta_{\min}$, can be calculated as $\theta_{\min} = 2\pi \times 10^{-5}$ rad for $f = 1$ MHz and $\omega = 2\pi \times 10$. The rotational frequency $\omega = 2\pi \times 60$ is usually used as power transmission. In this case, it becomes $\theta_{\min} = 1.2\pi \times 10^{-4}$, which is more than sufficient for practical use.

4.3. Mirror size

In order for the logic circuit to work effectively, the time difference Δt should be smaller than the pulse width Δt_p of the received signal, as shown in Fig. 2(a). This determines the mirror size l of the θ direction, $l = r \times \Delta\theta_r$, where r is the radius of the shaft (see Fig. 1). That is, the size $\Delta\theta_r$ should be larger than anticipated maximum torsion angle $\Delta\theta$, $\Delta\theta_m$. The value of $\Delta\theta_m = 1 \times 10^{-2}$ rad will be more than sufficient for practical use. The minimum mirror size is therefore $l = 0.4$ mm for $r = 40$ mm. Furthermore, in practice, the pulse width Δt_p will be elongated by the laser beam size at the receiver.

5. Conclusion

An optical system has been proposed and verified experimentally for the detection of shaft torsion in realtime. The system consisted of a pair of light sources, mirrors attached to a power transmission shaft, light receivers, and a logic circuit including pulse counter. In this study, it was found that

1. the system is highly accurate, i.e., exceeds 95% accuracy;
2. the system shows very high resolution for the torsion angle, that is, the smallest measurable torsion angle is $1.2\pi \times 10^{-4}$ rad for a rotational frequency of $2\pi \times 60$ and an oscillator frequency of 1 MHz, which is more than sufficient for practical use;
3. the system is relatively simple; and, in conclusion,

4. the system can effectively be used for monitoring small changes in torsion in realtime.

References

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[2] Ueda M, Yamaguchi T, Chen J, Asada K, Taniguchi Ko, Suga H. Rev Laser Engr 1998; 26(11):821–2.