Research on the Laser Doppler Torque Sensor

Z Meng and B Liu
Institute of Electrical Engineering Yanshan University, Qinhuangdao, 066004, China
E-mail: mzysu@ysu.edu.cn

Abstract. Based on laser Doppler effect, single section rotational speed of a rotating shaft was measured. By measuring the two sections rotational speed, the difference of the rotational speed between the two could be made. Integrating the rotational speed difference, the relative torsional angle of the two sections under the action of torsional vibration was received, so the rotating shaft torque was gotten. Non-contact torque measurement of rotary machine was achieved. The system was designed and the experiment was done on the torque experiment equipment. The result of experimentation indicate that the relative error between Laser Doppler and conventional torque measuring method that was less than 0.2%, and the measurement accuracy of Laser Doppler was high.

1. Introduction
Torque measurement decides the work capability, efficiency, life and safety performance of machine equipment, and is one of the most important characters in all kinds of machine parameters and has became the necessary content in the development research, test analysis, quality examine, safety design and priority control of the variety of machine production [1]. Because the torque measurement task is special, the development of torque sensor does not still satisfy the social need at present [2-4]. Thus the design of torque sensor, which has high-definition, low-depletion ang easy-installation, has became the technology problem to be solved quickly in social produce.

2. Measuring principle
Based on laser Doppler effect, single section rotational speed of rotating shaft is measured. The measuring principle is shown in Figure 1.

The velocity of point A and Point B in optical beam-direction is given by formula (1) and formula (2).

\[ \vec{v}_{A_x} = -\vec{V}_A \cos \alpha_A - \vec{V}_x = -\alpha R_A \cos \alpha_A - \vec{V}_x \]  
\[ \vec{v}_{A_y} = \vec{V}_B \cos \alpha_B - \vec{V}_y = \alpha R_B \cos \alpha_B - \vec{V}_y \]  

According to Doppler principle the scatter light frequency of backtrack ray is given by formula (3) and formula (4).

\[ f_{DA} = \frac{2\vec{v}_{A_x}}{\lambda} \]  
\[ f_{DB} = \frac{2\vec{v}_{B_x}}{\lambda} \]  

The Doppler shift is

\[ f_D = f_{DB} - f_{DA} = 2(\vec{v}_{BR_{x}} - \vec{V}_{Ax})/\lambda = 2\omega d/\lambda = -2\vec{i}/\lambda \]  

Where \( \vec{V} \) is the kinematic velocity of the object, \( \vec{i} \) is the direction vector of the irradiation light.
Based on laser Doppler effect of the rotating shaft’s single section rotational, the rotational speed difference of two sections could be measured by measuring the two sections rotational speed. The measurement schematic diagram is shown in Figure 2.

\[
\frac{i}{\nu} = \frac{v}{\nu_{d}d} \cdot \frac{1}{\lambda} (6)
\]

Suppose the revolving shaft has transversal vibration and the vibration velocity is \( \vec{V}_L \), the Doppler shift that received by detector is

\[
\frac{i}{\nu_{DA}} = -\frac{2}{\lambda} (\vec{V}_A + \vec{V}_L) \cdot \vec{d} (7)
\]

\[
\frac{i}{\nu_{DB}} = -\frac{2}{\lambda} (\vec{V}_B + \vec{V}_L) \cdot \vec{d} (8)
\]

The Doppler frequency difference is

\[
\frac{i}{\nu_{D}} = \frac{i}{\nu_{DA}} - \frac{i}{\nu_{DB}} = -\frac{2}{\lambda} \omega \vec{d} \times \vec{L}_0 \cdot \vec{d} (9)
\]

If incoming ray is incidence from random angle, \( \vec{d} = (\cos \alpha, \cos \beta, \cos \gamma) \), \( \vec{L}_0 = (\cos \epsilon, \cos \delta, \cos \gamma) \)
\[ f_D = -\frac{2}{\lambda} \omega_l (\cos \alpha \cos \delta - \cos \varepsilon \cos \beta) \]  

(10)

Formular (10) shows that \( f_D \) is direct ratio with the revolving shaft angular velocity \( \omega_l \).

The rotational speed difference of two sections can be measured by measuring the two sections rotational speed.

\[ \omega_{\Delta} = \omega_1 - \omega_2 = -\frac{\lambda}{2} \left( \frac{f_{D1}}{l_1 (\cos \alpha_1 \cos \delta_1 - \cos \varepsilon_1 \cos \beta_1)} - \frac{f_{D2}}{l_2 (\cos \alpha_2 \cos \delta_2 - \cos \varepsilon_2 \cos \beta_2)} \right) \]

(11)

The relative torsion angle of the two sections is gotten by integrating the rotational speed difference.

\[ \theta = \int_0^t \frac{\lambda}{2} \left( \frac{f_{D1}}{l_1 L_{01} \cdot Z_1 \cdot K_{r_1}} - \frac{f_{D2}}{l_2 L_{02} \cdot Z_2 \cdot K_{r_2}} \right) dt \]

(12)

When the light path structure and the incidence direction of the section A equal to the Section B, the two denominators of formular (12) are same.

\[ \theta = \int_0^t \frac{\lambda}{2} \left( \frac{f_{D1} - f_{D2}}{l \cdot Z \cdot K} \right) dt = -\frac{\lambda}{2lL_0 Z \cdot \hat{K}} \int_0^t (f_{D1} - f_{D2}) dt \]

(13)

Then the torque of rotating shaft is gotten.

\[ M = G L \frac{\theta}{\rho} \]

(14)

From formular (11) and (14), the rotational speed difference and the torque of rotating shaft are gotten, and the torque is measured.

3. System structure and experiment

The measurement system is shown in Figure 3.

![Figure 3](chart_of_torque_measurement_system.png)

Figure 3. Chart of torque measurement system.

The whole process is made up of three parts: the laser torque measuring, electric circuit adjustment part and the computer processing part. The laser torque measuring part use laser Doppler effect to transform without contact the twisted angle of the rotation shaft produced by the torque into Doppler shift signal, then use the photo electric detector to transform the beat into voltage signal and send them to the succeeding circuits for processing. This part transforms the signal, and it is a key part of the system. The circuit processing part is responsible for the amplification, zero setting, filtering and normalizing of the signals. Because the signals collected in the torque measuring part are often weak,
they need to be amplified to a large extent. This bring a series of problems such as the disturbance of scattered laser spots, the offset voltage of the operational amplifier, null shift and the system zero setting. This part is the important part of the system. The computer processing part use A/D collection panel to feed the signals into the computer, and analyze them and get the final value of the torque measured.

The measurement test is carried on the torque experiment platform YDJX-19. The structure of all parts is shown in Figure 4.

**Figure 4. Measurement experiment platform.**

The alternating-transduce tunable generator drives the axis of rotation turning. The direct current generator is used as the load. Thus the axis of rotation endures the effect of torque, and causes deformity. Two plate 5 are used to install the receiver of high frequency wireless induce source and emitter of wireless signal transmission. In order to compare with this tester, the torque sensor JN338-A is used to measure the standard value of torque. The test data is shown in Table 1. The result indicates that the measure values of laser Doppler and that of torque sensor JN338-A are the same.

**Table 1. Experiment data comparison.**

| Rotational speed/rpm | JN338-A/N.m | Method of laser Doppler/N.m | Error/N.m |
|----------------------|-------------|----------------------------|-----------|
| 30                   | 239.91      | 239.864                    | -0.046    |
| 60                   | 239.92      | 239.887                    | -0.033    |
| 90                   | 239.85      | 239.866                    | 0.016     |
| 120                  | 239.90      | 239.888                    | -0.012    |
| 150                  | 239.95      | 239.889                    | -0.061    |
| 180                  | 239.86      | 239.805                    | -0.055    |
| 210                  | 239.88      | 239.861                    | -0.020    |
| 240                  | 239.87      | 239.890                    | 0.020     |
| 270                  | 239.93      | 239.885                    | -0.045    |
| 300                  | 239.91      | 239.896                    | -0.014    |

The test system is designed and the experiment is done. The experiment result indicates that this kind of sensor has good appliance prospect, realizes the drive monitor of rolling equipment driving.
Torque non-contact measurement of rotary machine is achieved. Torque of the rotating shaft is monitored. It provides a foundation for rotary machine dynamics monitoring intelligence and automatization.

References
[1] Shang W L, Miao D Y and Qian S Z 1999 Modern Torque Measurement Technolog (Shanghai: Jiaotong University)
[2] Chen C Y 1997 Opto-Electronic Engineering 24 12–17
[3] Luo D Y, Ren Y P and Chen W Y 1997 Chinese Journal of Lasers 24 809–813
[4] Zheng Z M, Sun J Z and Yang X Y 1995 Chinese Journal of Lasers 22 17–22