XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 – September 4, 2015, Prague, Czech Republic

A ROTATIONAL SPEED MEASURING AND CALIBRATION SYSTEM BASED ON LASER DOPPLER VELOCIMETRY

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Abstract – A rotational speed measuring and calibration system based on the Laser Doppler Velocimetry is proposed in this paper. The rotational speed of a motor in the system can be determined by measuring the tangential linear velocity of a rotating reference disc mounted on the motor shaft with a Laser Surface Velocimeter. Measuring deviations caused by manufacturing and mounting errors of the reference disc are analyzed and compensated. Therefore, a measuring accuracy of better than 0.1% is realized.

Keywords: Rotational Speed Measurement, Laser Doppler Velocimetry, Laser Surface Velocimeter, Signal Processing, Electrical Drive

1. INTRODUCTION

Rotational speed measurement is an important operation for applications in industry and automation. Especially in electrical drive systems, rotational speed sensors are essential for a proper functionality of the whole machine [1].

In the past, analogue precision tachometers or tacho-generators did a quite good job for drive systems. But with the digital era and the associated technical development of digital control in electrical drives, these sensors are replaced by high resolution resolvers or encoders. Nevertheless, the performances of digital speed control aren't as good as those of the former analogue speed control [2].

For solving the problems, a novel signal processing method is proposed for directly determining the rotational speed under using sampling data from rotational speed sensors. High resolution and accuracy can be realized by using this method. This method can be used in all rotational speed sensors and encoders [3].

In order to evaluate the signal processing method, a rotational speed measuring system with high resolution and accuracy is needed. Laser Doppler Velocimetry can be used for measuring linear velocity with high resolution and accuracy [7]. Therefore it is the best choice for building the rotational speed measuring system, which provides both high resolution and accuracy in comparison to optical encoders and magnetic resolvers [4]. However, such a precise measuring system does not exist on the market.

In this paper a rotational speed measuring and calibration system is introduced by using Laser Doppler Velocimetry. The tangential linear velocity of a rotating reference disc mounted on the shaft of a motor can be measured with a Laser Surface Velocimeter (LSV) [7]. The rotational speed of the motor can be determined by using the measuring results of the linear velocity. The accuracy of the measuring system is controlled within 0.1% after the system optimization and error compensation.

2. ROTATIONAL SPEED MEASURING SYSTEM

Fig. 1 shows the rotational speed measuring and calibration system, which consists of a velocimeter Polytec LSV-1000 (1) [7], a motor test stand (2), an oscilloscope (3) and a PC system with a data acquisition unit (4).

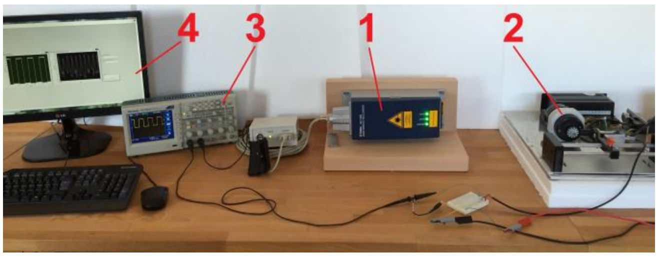

Fig. 1. Rotational Speed Measuring and Calibration System

On the motor test stand (see Fig. 2), a reference disc (6) and a target wheel (7) are mounted on the shaft of the motor (5). The rotational speed of the motor can be measured with the velocimeter LSV-1000 and reference disc. A speed sensor under test (8), for instance Hall-Effect Gear Tooth Sensor coupled with the target wheel, is used also to measure the rotational speed of the motor.

This measuring system consists of two channels, as shown in the block diagram (Fig. 3). The first channel is called Reference Channel, which consists of the velocimeter LSV-1000 and the reference disc. The reference disc is driven by the motor with an unknown rotational speed. The tangential linear speed of the rotating reference disc is measured by the velocimeter LSV-1000.

The second channel, which is known as the Sensor Channel, contains the target wheel, the speed sensor under test and an oscilloscope. The target wheel is also driven by the motor, the rotational speed of which is detected with the rotational speed sensor at the same time. The sensor output signal is sampled with the oscilloscope.

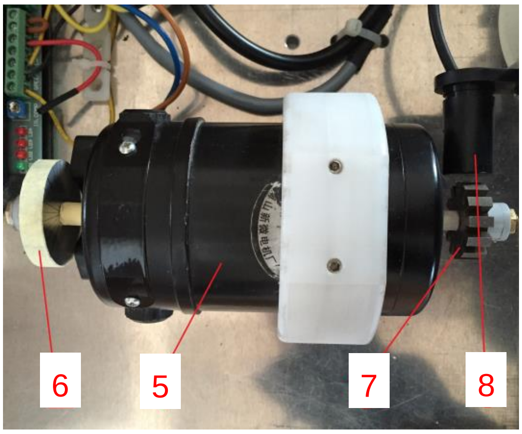

Fig. 2. Motor Test Stand (motor (5), reference disc (6), target gear (7) and Hall-Effect Gear Tooth Sensor (8))

The Reference and Sensor Channels are connected to the PC system, which samples the measuring data from both channels, i.e. the LSV-1000 and the oscilloscope. The reference rotational speed ω_{ref} of the motor can be determined by using the measured data of the Reference Channel. The rotational speed ω of the motor can be also calculated by signal processing under using the measuring data of the Sensor Channel. The measuring deviation $\Delta\omega$ of the sensor under test can be determined by:

$$\Delta\omega = \omega - \omega_{ref} - \Delta\omega_{ref} \tag{1}$$

with $\Delta\omega_{ref}$ as measuring deviation of the Reference Channel.

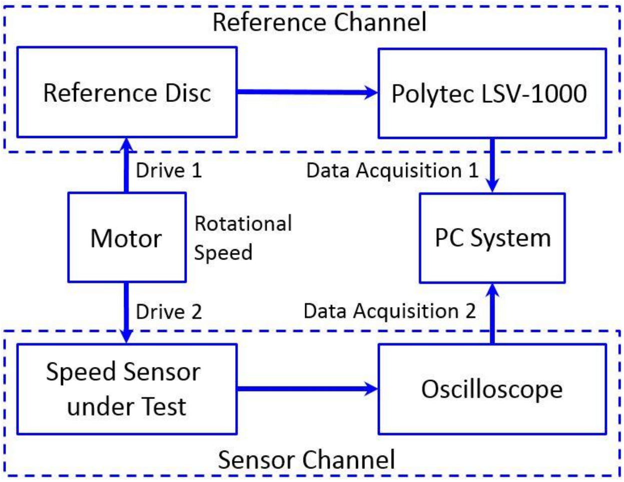

Fig. 3. Block Diagram of Rotational Speed Measuring System.

3. LASER DOPPLER VELOCIMETRY

In order to use this system to test and calibrate rotational speed sensors and encoders, the Reference Channel must have a high accuracy. The Polytec LSV-1000 is a linear velocity measuring system with a high accuracy of 0.05% and a high resolution of 5 mm/min. The maximum detectable speed is 7200 m/min. This measuring device is based on the principle of Laser Doppler Velocimetry, which is explained in the following.

A Laser Doppler Velocimeter (LDV), which is also known as a Laser Doppler Anemometer (LDA), is an interferometric measuring system that detects the linear velocity of objects using laser light [4]. The objects can be particles in a fluid or solid surfaces. Laser Doppler Velocimetry is based on the principle of Laser Doppler Effect which uses the frequency of light instead of sound for measurements [5]. As we know from the Doppler Effect, the sound frequency of an object changes at a stationary inertial point if this object passes it. The same effect can be seen with the diffracting light on an object in motion.

The Polytec LSV-1000 uses concretely the Difference Doppler Process. In the Difference Doppler Process, two laser beams are aligned to the optical axis in an angle φ. Both laser beams are superimposed on the surface of the moving object. Thus an interference pattern of dark and bright fringes is detectable (see Fig. 4).

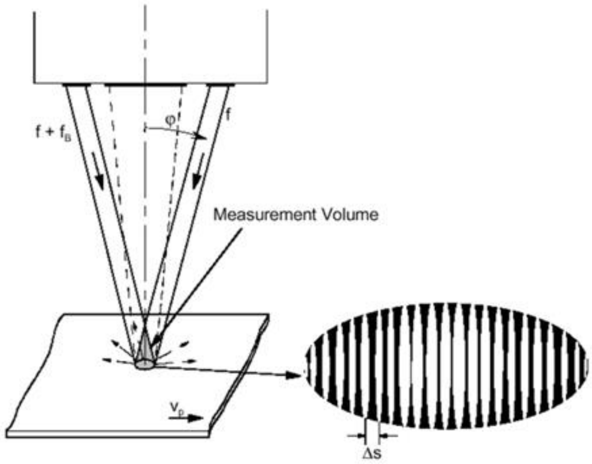

Fig. 4. Two laser beams with same wavelength λ are superimposed on the surface of a moving object and create an interference pattern with dark and bright fringes of distance Δs [7].

When both laser beams are from the same light source, they have the same wavelength λ. The fringes have a distance Δs and can be calculated by the wavelength λ and the angle φ:

$$\Delta s = \frac{\lambda}{2 \cdot \sin\varphi} \tag{2}$$

We can assume a point P in the interfered region, which moves with a velocity v_P. Due to the Laser Doppler Effect, both laser beams affect a Doppler shifted frequency at this point P. The object surface isn't ideally smooth. Thus this object emits a scattered light waves, which is also Doppler shifted by the velocity v_P. With the fringe pattern and superimposed diffracted light waves, the photo detector gets a modulated AC signal with the Doppler frequency f_D. Because the optical axis is perpendicular to the object surface and the moving direction, the final equation is

$$f_D = \frac{2v_P}{\lambda} \cdot sin\varphi \quad (3)$$

For detecting velocity directions, the interferometer works in the heterodyne mode. In this mode, one laser beam has a shifted offset frequency of f_B, so that the modulated Doppler frequency should be written as

$$f_D = \frac{2v_P}{\lambda} \cdot sin\varphi + f_B \quad (4)$$

The offset frequency f_B should be chosen in in the range of Megahertz, e.g. 40 MHz in products of Polytec GmbH ([6], [7]).

As you can see, the Difference Doppler technology is suitable for measuring the linear velocity and for velocity direction detection. Therefore the Polytec LSV-1000 and its working principle can be used for rotational speed measurements.

4. ERROR ANALYSIS AND ACCURACY IMPROVEMENT

By measuring the tangential linear velocity v of the reference disc with the LSV-1000, the rotational speed ω_{ref} can be determined by v and the circumference $U = \pi D = 2\pi R$ (see Fig. 5):

$$\omega_{ref} = \frac{v}{U} = \frac{v}{\pi D} = \frac{v}{2\pi R} \quad (5)$$

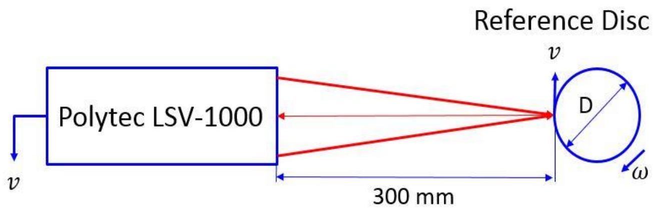

Fig. 5. Rotational Speed Measurement with Polytec LSV-1000 and Reference Disc.

Due to manufacturing and mounting tolerances, two main errors of the reference disc are existing: the center deviation a and the radius deviation ΔR. Both errors cause deviations of the circumference U and therefore measuring deviations in the Reference Channel.

4.1 Center Deviation

The center deviation of a disc is visualized in Fig. 6. $M1$ is the center of the circle which has the radius R, while $M2$ is the center of rotation. P is the point where the laser beam from the Laser Doppler Velocimeter impinges on the reference disc. The distance between $M1$ and $M2$ is a.

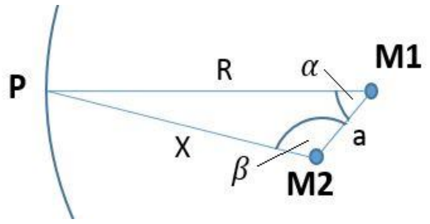

Fig. 6. Deviation a between the rotational center and the circle center of the reference disc

The distance X between P and $M2$ changes with the angle β. It can be derived under the condition $R \gg a$:

$$X = R + a \cdot cos\beta \quad (6)$$

For a further analysis, a small circular segment dS can be considered, which is illustrated in Fig. 7. This segment is detailed by the variable radius X and the angle $d\gamma$:

$$dS = X \cdot d\gamma \quad (7)$$

Because this segment is very small, one can assume $d\beta = \beta_2 - \beta_1$. So the equation (4) can be written as:

$$dS = \frac{(R + a \cdot cos\,\beta)}{\beta_2 - \beta_1} \cdot d\gamma \cdot d\beta \quad (8)$$

For determining the circumference U, dS should be integrated over all circular segments of the disc. The circumference can be determined by:

$$U = \int dS = \int_0^{\alpha} \int_{\beta_1}^{\beta_2} \frac{(R + a \cdot cos\,\beta)}{\beta_2 - \beta_1} d\gamma d\beta \quad (9)$$

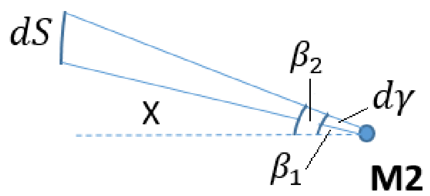

Fig. 7. Circular Segment dS with variable Radius X and Angle $d\gamma$.

By solving this double integration, the circumference is also dependent on the sinusoid function of the rotational angle α:

$$U = 2\pi R + a \cdot sin\alpha \quad (10)$$

Therefore the maximum deviation of the circumference is $\Delta U = \pm a$, when $sin\alpha = \pm 1$. For compensating this undesired deviation, measuring values in one or more full rotations should be taken into account for the calculation of the reference rotational speed. That means $\alpha = 2 \cdot n \cdot \pi$, $n \epsilon$N, and thus $sin\alpha = 0$. In this way, the deviation ΔU doesn't exist anymore, and one obtains $U = 2\pi R$.

4.2 Radius Deviation

The maximum relative deviation of the rotational speed measurement is the sum of the relative deviations of the linear velocity and the disc radius according to (5):

$$\frac{\Delta\omega_{ref}}{\omega_{ref}}_{max} = \frac{\Delta v}{v}_{max} + \frac{\Delta R}{R}_{max} \qquad (11)$$

The measuring deviation of the linear velocity is known as 0.05%. Therefore the task here is to determine the maximum deviation of the disc radius. In fact, the radius R can be described as follows:

$$R(\alpha) = r + \Delta r(\alpha) = R_i \qquad (12)$$

The deviation of the radius R at rotation angle α and the mean radius r is given by $\Delta r(\alpha) = \Delta r_i$. Because this error has a Gaussian distribution, the mean radius r can be calculated by

$$r = \frac{1}{n}\sum_{i=1}^{n} R_i = r_s \qquad (13)$$

By considering a larger number of measurements $n < \infty$, the result is the estimated radius r_s, which can be assumed as the true value [9].

The diameter of the reference disc can be measured with a precise length measuring instrument. One obtains n measured values R_i at n measuring points. After calculating the mean radius r_s according to (13), the reference rotational speed ω_{ref} can be determined by

$$\omega_{ref} = \frac{v}{2\pi r_s} \qquad (14)$$

In this way the errors Δr_i are compensated completely:

$$\sum_{i=1}^{n} \Delta r_i = \sum_{i=1}^{n}(R_i - r_s) = 0 \qquad (15)$$

So only the tolerance of the precise length measuring instrument plays a role. For example, if this instrument has a measuring tolerance e_G of 0.001 mm, with a reference disc of mean radius 40 mm, the relative deviation is

$$\frac{\Delta R}{R}_{max} = \frac{e_G}{r_s} \approx 0.0025\% \qquad (16)$$

This results in a relative deviation ($\Delta\omega_{ref}/\omega_{ref}$) of 0.0525% for the whole measuring system according to equation (11).

5. EXPERIMENTAL RESULTS AND APPLICATION EXAMPLE

Fig. 8 shows the measured diameters of the real reference disc with an electronic caliper. The designed diameter of this reference disc is 40 mm. This caliper has a measuring tolerance of ±0.01 mm. Therefore, a relative deviation is ±0.025% for the diameter and the radius. It means a total accuracy of 0.075%. Thus the accuracy of the measuring system can be controlled within 0.1%.

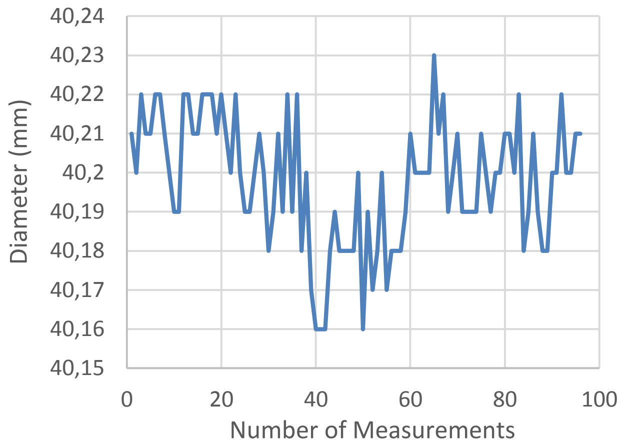

Fig. 8. Measured Diameters of the reference disc with a Caliper of measuring tolerance 0.01 mm

From these measurements, a mean diameter of 40.198 mm can be determined, which is used for further reference rotational speed calculations. For instance, a rotational speed measurement from the Reference Channel is shown in Fig. 9. The measured values are disturbed with a white noise, which shows a Gaussian distribution. For getting the real rotational speed value, the mean value over the number of samples is considered as reference rotational speed.

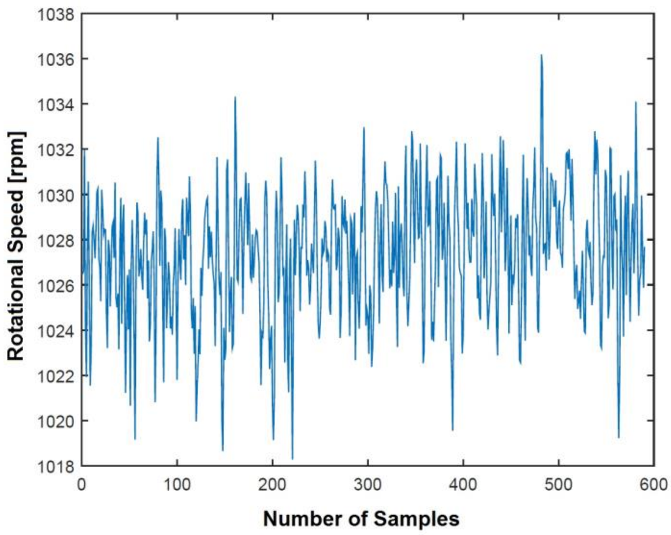

Fig. 9. Measurement of Rotational Speed with Velocimeter LSV-1000 and Reference Disc.

With a system accuracy of 0.1%, this measuring system is able to use for testing and calibrating rotation speed sensors with a relative accuracy of 0.4% [10]. Therefore it can be used for verifying the novel signal processing method for rotational speed sensors and encoders, which is described in [3]. This novel method is applied to the Hall-Effect Gear Tooth Sensor CYGTS101DC-S, where all teeth of the target gear are taken into account for the rotational speed calculation. Table 1 shows the comparison of the rotational speed results ω_{ref} and ω from the Reference Channel and the Sensor Channel. The relative deviation $\frac{\Delta\omega}{\omega} + \frac{\Delta\omega_{ref}}{\omega_{ref}}$ is less than 0.2%.

Table 1. Comparison of Results from the Signal Processing Method and the Reference Measuring System.

Reference Channel Rotational Speed (ω_{ref})	Sensor Channel Rotational Speed (ω)	Relative Deviation ($\Delta\omega/\omega+\Delta\omega_{ref}/\omega_{ref}$ see (1))
140.4568 rpm	140.4005 rpm	0.04%
447.9168 rpm	447.2352 rpm	0.15%
619.0266 rpm	618.8272 rpm	0.03%
861.1361 rpm	860.6000 rpm	0.06%
1047.600 rpm	1048.100 rpm	0.04%
1217.400 rpm	1216.500 rpm	0.08%
2162.000 rpm	2158.900 rpm	0.14%

Fig. 10 shows the results from 10 measurements at the Reference Rotational Speed Measurement System. For each measurement, 16 different speed points are measured. The relative deviation between both channels is also less than 0.2%.

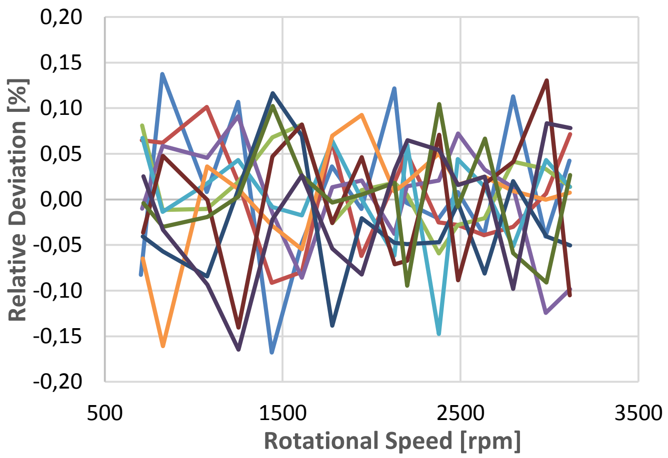

Fig. 10. Results from 10 Measurements with the Reference Rotational Speed Measuring System.

According to (1) the following two points are proved by the results:

1) The accuracy of the measuring system (Reference Channel) is higher than 0.1%.
2) The accuracy of speed sensors under using novel signal processing method can be controlled within 0.2%.

This novel signal processing method can be applied to all kinds of rotational speed sensors with analogue output. This method will be introduced in another paper.

6. CONCLUSIONS

In this paper, a rotational speed measuring and calibration system based on Laser Doppler Velocimetry has been proposed. From the results one can draw the following conclusions:

- The proposed rotational speed measuring system consists of a motor, a Reference Channel, a Sensor Channel and a PC System for data acquisition.
- The reference rotational speed of a motor in the system can be determined by measuring the tangential linear velocity of a rotating reference disc mounted on the motor shaft with a Laser Surface Velocimeter, for instance the Polytec LSV-1000.
- The Reference Channel, which is composed of the Polytec LSV-1000 and a reference disc, should have a much higher accuracy and resolution than the Sensor Channel, which contains the sensor under test and an oscilloscope.
- The measuring accuracy of the Reference Channel can be improved by compensating the manufacturing and mounting deviations (mainly center and radius deviations) under using the proposed signal processing methods and algorithms.
- The experimental results show that the accuracy of measuring and calibration system is higher than 0.1%. The developed rotational speed measuring system can be used for testing and calibrating rotational speed sensors and encoders with an accuracy of lower than 0.2%.
- The novel signal processing method described in [3] is tested in this measuring system. Practical results of using the method to Hall Effect gear tooth sensor CYGTS101DC-S indicate that the accuracy of speed sensors under using the novel signal processing method can be controlled within 0.2%.

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