Calibration platform controller of the laser Doppler anemometer

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Abstract. Primary standards for the unit of air flow velocity often use a Laser Doppler Anemometer (LDA) as the primary measurement standard. A rotating disc with a fixed diameter is used to calibrate LDA. The paper proposes calibration platform based on the precision mechanics of HDD disk. A disk rotation controller has been developed for the platform. Deviations of the disk rotation speed do not exceed 0.01% RMS in the range of angular speeds of 600-4800 rpm.

1. Introduction

National primary standard for the unit of airflow velocity (or airspeed calibration system) plays an important role in metrology. This standard is a calibration facility for airspeed instrumentations such as Pitot-static tubes and anemometers (LDA, PIV, ultrasonic, etc.). The airspeed calibration setup consists of a high-quality wind tunnel and airspeed measurement standard. Typically, Laser Doppler Anemometer (LDA) is used as the primary airspeed standard while a Pitot-static tube and a thermal anemometer are used as the secondary or check standard. Before use, LDA is calibrated by comparing the speed indicated by the LDA with the known speed of a spinning disk. This disk has well-known dimensions and spins at a known (measurable) speed while LDA measures the linear speed of the disk end. This calibration chain provides traceability of the unit of airflow velocity to the fundamental SI units of the length (meter) and time (second) [1–3].

There are plenty of factors that affect LDA calibration. The main sources of uncertainty are: rotation speed deviation and its nonlinearity, the uncertainty of disk radius, disk shaft oscillation, angular misalignments between LDA and the disk spin axes, and temperature dependent biasing (drift) of LDA measurements.

KLAD-1 is a rotating disk calibration platform for LDA that provides a speed range from 0.5 to 25 m/s with mean speed deviation below 0.01%. The calibration platform was developed especially for the National primary special standard for the unit of air flow velocity GET 150-2012 [1]. A block diagram of the KLAD-1 is shown in figure 1. It includes the following parts: precision rotating system with fixed radius disks (32 and 95 mm), integrated three-phase PMSM motor driver, magnetic rotary encoder, a control module with USB interface for connection, and a high-speed light RPM sensor. The RPM sensor (tachometer) is a main output signal used for connection to a time measuring standard. The magnetic encoder is used as an instantaneous angle and speed sensor for motor control. KLAD-1 can operate in the standalone mode at the fixed rotation speed of 1800 rpm (8.95 m/s) or can be connected to workstation by USB interface for speed tuning.
2. Laboratory layout

The calibration platform KLAD-1 consists of two spinning discs with diameters of 32 mm and 95 mm, a brushless AC permanent magnet motor (PMSM), and a vector motor control controller (FOC). A 3.5" computer HDD with a platter diameter of 95 mm, a rotation speed of 7200 rpm, a low noise level, and a declared failure time (MTBF) of at least 1 million hours was chosen as a base for that platform. Such HDD has excellent rotational characteristics, minimal imbalance, and minimal axial vibration. The disk axis is aligned with the axis of the motor's rotor that rotates on hydrodynamic bearings. The motor stator consists of a 6-pole pair, and this minimizes transients and torque ripples on windings switching.

Typically, HDD controllers do not allow controlling the rotational speed in a wide range. Therefore, for smooth speed regulation, a custom motor controller was developed. This controller is based on a specialized microcontroller STM32F302, which has the necessary hardware units to control a brushless PMSM motor: three-phase PWM, fast ADCs with asynchronous injection mode, DACs, high-speed winding current comparators, and built-in signal amplifiers. The Field Oriented Control vector algorithm was implemented using the ST-FOC-SDK library [4]. This library implements CORDIC algorithms, a basic FOC algorithm (Clark and Park transforms), a dual automatic loop for torque and magnetic flux control, and an automatic speed control loop. For integration, the characteristics of the disk were measured: moment of inertia, friction moment and inductance of the windings. The rotor position is estimated with a stator back EMF detector [5] and a Hall-effect quadrature encoder (AS5048A, 11 kHz sampling rate, 0.05° resolution, and ±1° nonlinearity). Characteristics of the motor and regulator characteristics are shown in table 1.

The average rotation speed is monitored by an optical speed sensor, which is also used for phase averaging of LDA measurements. This speed is combined with the instantaneous speed, calculated through the rate of change of the rotor angle.
Table 1. The motor and regulator characteristics.

| Parameter                        | Value     |
|----------------------------------|-----------|
| Nominal (optimal) speed          | 3000 rpm  |
| Maximum speed                    | 5000 rpm  |
| Motor voltage                    | 8.0 V     |
| Peak wind current                | 0.8 A     |
| E.BMF factor                     | 1.6 V rms/Krpm |
| Friction                         | 2 uN·m·s  |
| Inertia                          | 30 uN·m²·s|
| Torque PID control period        | 50 us     |
| Rotary encoder sampling period   | 100 us    |
| Speed PID control period         | 2000 us   |

Assembled KLAD-1 platform is shown in Figure 2.

Figure 2. Photo of the calibration platform without cover.
1 – encoder magnet, 2 – 32 mm disk, 3 – 95mm disk.

3. Experimental results
For estimation of rotation speed uncertainty introduced by the FOC motor controller, speed deviations were measured in the range from 600 to 4800 rpm. To analyze rotation speed variation the tachometer signal was captured and analyzed. For every rotation speed, 2500+ sequential periods of the RPM signal were captured. The signal was sampled with 8 MHz clock resolution (±5 ppm overall clock stability, and jitter of 10 ps). That clock resolution was only 10ppm at rotation speed of 4800 rpm. The measured results are shown in Figure 3. Table 2 summarizes measurements for all speed values. The deviation is pointed in ppm unit (0.01% is 100 ppm).
Figure 3. Measured probability distributions of mean speed deviation for rotation speeds of 600, 900, 1800, and 4200 rpm.

Table 2. Measurement results.

| Rotational speed [rpm] | Actual speed [rpm] | Standard deviation [ppm] | Deviation range [ppm] |
|------------------------|--------------------|--------------------------|-----------------------|
| 600                    | 603.95             | 97                       | 433                   |
| 900                    | 902.61             | 44                       | 241                   |
| 1200                   | 1205.61            | 23                       | 141                   |
| 1800                   | 1803.26            | 22                       | 120                   |
| 3000                   | 3007.94            | 35                       | 200                   |
| 4200                   | 4207.23            | 43                       | 175                   |
| 4800                   | 4804.15            | 47                       | 182                   |

The measured (actual) speed differs from the nominal one by 0.1–0.7%. This bias might be caused by rounding errors in the Q1.15 fixed-point arithmetic, used in motor control algorithms. This speed bias doesn’t exert influence on LDA calibration because actual rotation speed must be measured using the time (second) standard before LDA calibration.

For all speed values the estimated standard mean deviation does not exceed 100 ppm (0.01%). The full deviation range is 4–6 times broader than the estimated standard deviation. The measured deviation depends on the mean rotation speed value, and the minimum is located in 1200–1800 rpm range. At low-speed, deviation increases due to weak control over the motor current. At this speed, switching transients in motor windings dominate over a mean winding current. This introduces errors into the flux and torque control loops. As rotation speed increases to 4200 rpm, a relative speed sampling rate decreases. At high speed, the speed control loop is executed only 6 times per disk revolution, resulting in the coarse discretization of rotation speed.

Despite the dependence of the speed deviations from its average value, the measured mean deviations lie within the acceptable accuracy range (0.01%). During calibration the LDA speed output is phase-locked to the RPM sensor as the motor controller does. This phase-locked measurement minimizes the LDA calibration error associated with a possible variation in the instantaneous disk speed within one revolution.

Conclusions

The developed calibration platform controller of the Laser Doppler Velocity provides the required level of the disk rotation speed stability. This controller is the base part of the KLAD-1 calibration platform. An achieved speed uncertainty allows using KLAD-1 for the LDA calibration with the desired accuracy.
The following characteristics of the KLAD-1 calibration platform have been obtained:
1. available speed range: 0.5 - 24 m/s,
2. overall speed stability: ± 0.1%,
3. calibration disk runout: less than 0.04 mm.

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