Investigation on high rotational speed calibration device

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Abstract. This paper presents the novel implementation of a high rotational speed device for optical tachometer calibration based on brushless DC coreless micro motor and FPGA technology at National Institute of Metrology (NIM), China. The structure of the device and key technology involved were described. The dual closed-loop control solution was explained. For control algorithm, virtual instrument technology is used to build up FPGA hardware from National Instrument and calibration software developed by Lab VIEW. Some calibration results of a laser tachometer are shown in the measurement range from 40000 to 99999 r/min. The expanded calibration uncertainty is $1 \times 10^{-4}$, $k=2$. This high rotational speed calibration device is the first successful technical realization of the measurement unit of r/min (RPM) with resolution of 1 r/min for engineering applications in China and, therefore, used as an important working standard at NIM for the feasible traceability of high-precision optical tachometers nationwide at high measurement range above 40000 r/min.

1. Introduction
Ever-increasing demand for precise high rotational speed measurement from scientific research and industry application can be obviously seen in recent years. A typical example is the recent publication of an article on high rotational speed paper centrifuge as a medical diagnostics facility in the field of biomedical engineering [1]. The reported paper centrifuge can achieve the highest rotational speed of 125000 r/min, the equivalent centrifugal acceleration of which is about 30000 g. To accurately measure the maximum speed, the authors used a high-speed camera with a fast video-recording frame-rate of 6000 frames per second. Although the paper centrifuge is ultralow-cost as 20 U.S. cents, the high-speed camera may cost thousands of U.S. dollars. In fact, the high-speed cameras are very rarely used for rotational speed measurement in real occasions because of its high cost and low efficiency.

For the rotational speed measurement, high performance digital tachometers are most widely used as working instruments for scientific research or industry application purposes. The design, analysis and improvement tasks of digital tachometers have been carried out for the past 30 years or so. Bonert R designed of a high performance digital tachometer with a microcontroller [2]. Richard C. K improved digital tachometer with reduced sensitivity to sensor non-ideality [3] and studied performance analysis and compensation of M/T-type digital tachometers [4]. Compared with traditional digital optical tachometers, digital laser tachometers make use of high-visibility red laser beam for non-contact measurement and become popular for scientists and engineers with superior performance of rotational speed measurement range from 3 to 99999 r/min and accuracy of 0.01 % [5].

Concerning with calibration devices for digital tachometers, two types of generator with different working principles were proposed. One type is based on DC motor and can be used for contact and non-contact tachometers [6]. The calibration principle is based on the fundamental principle of electromagnetic theory where the frequency of the induced electromotive force generated by rotating magnetic field is directly proportional to the speed of rotating DC motor. The highest calibration rotational speed reported is 24000 r/min. The other type is a generator system of light pulses and can be only used for the calibration of optical tachometers [7]. The generator system can produce periodic pulses of light onto the optical sensor of the tachometer, so that the tachometer under calibration

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displays a proportional reading at the generated frequency. This calibration method can cover a very wide measurement range with small measurement uncertainty in the order of 10^{-7}. However, it fails to realize the measurement unit of r/min and may overestimate the performance of optical tachometers because of the idealistic calibration condition in which nothing rotates but emitter diode flashes.

Unlike the technical implementations of the two types above mentioned, the development of high rotational speed calibration device at NIM, China targeted the realization and reproducibility of the measurement unit of r/min with an expanded calibration uncertainty less than 1×10^{-5}, k=3, in the calibration range from 40000 to 100000 r/min with the resolution of 1 r/min. In conjunction with rotational speed calibration standard device already established from 1 to 40000 r/min, NIM’s calibration capability covers the whole measurement range of commercial high-precision optical tachometers in China.

2. High rotational speed calibration device

2.1. Setup of the device

The high rotational speed calibration device consists of four main parts: coreless motor system, control system, input/output system and power supply system [8]. The schematic diagram of the device is shown in Figure 1. Compared with conventional rotational speed calibration devices in China, there is no gear box to multiply rotational speed in the setup of the newly developed calibration device, shown in Figure 2. The single rotating shaft of the coreless micro DC motor covers the output rotational speed range from 40000 to 100000 r/min. Figure 2 shows the calibration moment of an optical tachometer typed EMT 260C at 99999 r/min, the upper limit of its measurement range. The mechanical and electrical setup of the calibration device ensures continuous operation and low vibration and noise even at high operational speeds.

In the coreless motor system, a brushless micro DC motor is customized, with the low residual imbalance of the rotating shaft. Within this special motor, permanent rare-earth magnet functions as rotator. The heart of the motor is self-supporting ironless copper winding which enables low power consumption and low moment of inertia, ensuring high efficient and high reliability. Linear characteristics of the motor result in its good controllability. Preloaded ball bearings can offer a long service life and smooth operation with coefficient of friction as low as 0.001. Low friction can also leads to low audible operational noise.

On the contrary, the gear box of conventional high rotational speed calibration device in China always introduces noisy and shaking problems which worsen calibration conditions and even accuracy. It is usually bulky and heavy with thick steel base plate to counteract the vibration and
shaking when in operation, shown in Figure 3. The high rotational speed output is basically gained according to multiplication of a series of shaft gear teeth ratios, which results in large rotational speed resolution of 25 r/min above 30000 r/min. Therefore, it is not possible to calibrate optical tachometer at 99999 r/min. Due to heavy wearing of gears and critical lubrication at high rotational speed, the good performance of the mechanical part is usually hard to maintain.

An FPGA (field-programmable gate array) is a semiconductor which contains a large number of disconnected logic gates. FPGAs contain an array of programmable logic blocks and a hierarchy of reconfigurable interconnects that allow the blocks to be linked together [9]. The advantage for high rotational speed control application lies in that these logic blocks are significantly faster because of their parallel nature and optimality in terms of the number of gates used for control process. In the control system for the calibration device, FPGA module along with Compact RIO (reconfigurable Input/Output) by National Instrument is used to create hardware platform for control purpose. By this way, the implementation of PWM (pulse width modulation), dual closed-loop control algorithm, and the data acquisition device itself can be customized.

2.2. Control strategy
Fundamentally, there are two types of control loops: open loop control and closed loop control. For the application of high rotational speed control, the open loop control strategy is not feasible because rotating shaft is almost impossible to operate at a set rotational speed stably and accurately, based on the fact that the fine adjustment of control voltage of driving circuit results in a relative big change of rotational speed which cannot be fed back. On the contrary, the control action of a closed loop control is dependent on the process output. A closed loop controller therefore has a feedback loop which ensures the controller exerts a control action to give a process output the same as the set value. A dual closed-loop control strategy is employed for this application. The current feedback is used for inner loop to adjust the rotational speed directly while the RPM feedback is compared with the set RPM value as outer loop. By this control strategy, a good dynamic performance and stability of the control system is guaranteed.

Figure 4 shows the flow chart of the dual closed-loop control. The RPM control loop and the current control loop are independent from each other. The control process functions when the RPM value of rotating shaft of the coreless micro motor is measured and sent back. This RPM value is measured from displacement information of the rotor detected by sensors and compared with the set RPM value. The difference obtained is then used as the input of RPM regulator whose output is the set value of the current. This value, after compared with current feedback information from the coreless micro motor, produces the input for current regulator. The output of current regulator is transformed by PWM, which finally puts the RPM output of the rotating shaft under control. The advantage of the dual closed-loop control strategy is immune to rotational disturbance during adjustment. Current regulator ensures maximum current available to start the motor and suppress voltage fluctuation and current perturbation.

Figure 4. Dual closed-loop control flow chart.
2.3. Control algorithm

The PID control scheme is named after its three correcting terms: proportional, integral, and derivative terms. These three terms are summed to calculate the output of the PID controller. PID control is the best controller in an observer without a model of the process, and, therefore, chosen as the control algorithm for high rotational speed calibration device.

By measuring the RPM value of the rotating shaft, and subtracting it from the set value, the RPM error is known, and from it the controller can obtain how much final electric current to supply to the motor. The obvious method is proportional control: the motor current is set in proportion to the existing error. A more complex control may include another term: derivative action. This considers the rate of change of error, supplying more or less electric current depending on how fast the error is approaching zero. Finally, integral action adds a third term, using the accumulated RPM error in the past to detect whether the RPM value of the rotating shaft is settling out too low or too high and to set the electrical current in relation not only to the error but also the time for which it has persisted. An alternative formulation of integral action is to change the electric current in small persistent steps that are proportional to the current error. Over time the steps accumulate and add up dependent on past errors; this is the discrete-time equivalent to integration.

The analysis for designing a digital implementation of a PID controller for FPGA device requires the standard form of the PID controller to be discretized. Approximations for first-order derivatives are made by backward finite differences.

The integral term is discretized with a sampling time. Therefore, the discrete form of the algorithm is expressed as

$$u(k) = K_p e(k) + K_i \sum_{i=0}^{k-1} e(i) + K_d [e(k) - e(k - 1)]$$  \hspace{1cm} (1)

where $u(k)$ is the controller output, $e(k)$ is the error between the set value and process variable, $K_p$ is the proportional gain, $K_i$ is the integral gain, and $K_d$ is the derivative gain. $k$ stands for sampling sequence number.

3. Calibration results

The high rotational speed calibration device was used for calibration of an optical tachometer typed EMT 260C (Serial No. 151021503127) from 40000 to 99999 r/min. In Table 1, the calibration results are presented. In accordance with JJG 105-2000 National Verification Regulation of Tachometers in China, uncertainty evaluation of the calibration results was done. The relative expanded uncertainty of indication error of the tachometer is better than $1 \times 10^{-5}$, $k=2$. It should be noted that the indication error listed is the deviation of mean value of ten readings from the reference value and that the expanded uncertainty of the calibration device itself is better than $1 \times 10^{-5}$, $k=3$.

Table 1. Calibration data of an optical tachometer.

| No. | Reference value / r·min⁻¹ | Measurement value / r·min⁻¹ | Indication error / r·min⁻¹ | Expanded uncertainty $k=2$ |
|-----|--------------------------|-----------------------------|---------------------------|-----------------------------|
| 1   | 40000                    | 39999.4                     | -0.6                      | $2.9 \times 10^{-5}$       |
| 2   | 50000                    | 49999.2                     | -0.8                      | $2.7 \times 10^{-5}$       |
| 3   | 60000                    | 59999.1                     | -0.9                      | $2.5 \times 10^{-5}$       |
| 4   | 70000                    | 69998.9                     | -1.1                      | $2.4 \times 10^{-5}$       |
| 5   | 80000                    | 79999.0                     | -1.0                      | $2.3 \times 10^{-5}$       |
| 6   | 90000                    | 89998.6                     | -1.4                      | $2.2 \times 10^{-5}$       |
| 7   | 99999                    | 99997.5                     | -1.5                      | $2.1 \times 10^{-5}$       |

4. Conclusions

NIM, China has established high rotational speed calibration device for high-precision optical tachometers by realizing and reproducing of the measurement unit of r/min. The dual closed-loop control solution on the hardware platform of a brushless DC coreless micro motor and FPGA ensures the calibration range from 40000 to 100000 r/min, with the resolution of 1 r/min. The expanded calibration uncertainty better than $1 \times 10^{-5}$, $k=3$ is achieved. Therefore, the national metrological traceability of high rotational speed comes into reality.

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