DEVELOPMENT OF THE PRIMARY VELOCITY STANDARD FOR THE CALIBRATION OF LDA SYSTEM

Wu Jian [1], *Nikolay Semin* [2]

[1] National Metrology Centre, A*STAR (Agency for Science, Technology and Research), Singapore,
wu_jian@nmc.a-star.edu.sg

[2] National Metrology Centre, A*STAR (Agency for Science, Technology and Research), Singapore,
semin_nikolay@nmc.a-star.edu.sg

Abstract − Air velocity measurements are required to have the measurement traceability to the SI unit of length and time. This can be realised through the setup of a primary velocity standard. NMC has designed and developed the primary velocity standard using the spinning disc for the calibration of an LDA system. The system is capable of measuring the velocity from 0.2 m/s to 40 m/s with the measurement uncertainty of 0.1% to 0.4% of reading.

*Keywords***:** Laser Doppler Anemometry (LDA), air velocity, primary standards, uncertainty evaluation.

1. INTRODUCTION

The Laser Doppler Anemometer (LDA) systems are widely used by NMIs to calibrate air velocity meter [1-3]. Over two decades, the calibration of the LDA systems went through several stages from the calibration of optics only to comparison with external velocity references. Currently, it is recognized by the researchers that ideally an LDA system should be calibrated with the realized single particle passage through the measuring of volume at a known velocity [1, 3]. However, in this case, a difficulty has been encountered because of the dependence of the velocity measured by the LDA on the exact location of the test particle inside the measuring of volume [1, 3-5]. Though the character of the dependence seems to be determined by the optics only [1, 3-5], it may vary from one system to the other. This makes it difficult to establish a general procedure for the calibration of LDA systems, and various strategies and design configurations might be employed [1-3].

2. THE PRIMARY VELOCITY STANDARD

NMC has designed and developed the primary velocity standard using the spinning disc method for calibration of LDA system. The system consists of a flywheel or spinning disk with the working range from 0.2 m/s to 40 m/s (Fig. 1). The disk diameter was specially chosen to match the circumference of 500 mm, which was calibrated by a micrometer to be within 0.01 mm.

The disk is installed on the pedestal with the AC motor and a control module. The servopack is used to operate the AC motor with the computer. The rotating frequency of the AC motor, and, thus, the spinning disk rotation rate, can be set from 1 Hz to 10,000 Hz in both directions with the control of the software.

The dual beam LDA system is used for the experiments. It operates at a wavelength of 532 nm and continuous output of 200 mW. The optical probe of the system is mounted on a 3D traversing system with the maximum travelling distance of 1.1 m and 0.01 mm resolution [2] (see Fig. 1).

The traversing system has been calibrated along the direction normal to the spinning disk axis with a laser interferometer. The measurement uncertainty of 0.015 mm has been confirmed.

A metal wire of 50 μm in diameter is installed in special clamps on the disk. The wire axis is co-aligned with the rotational axis of the disk.

The primary velocity standard is maintained under controlled ambient conditions: temperature (20 ± 1) ^{o}C and relative humidity of (55 ± 5) %.
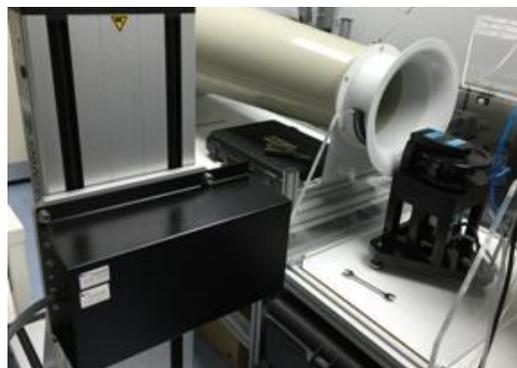

Fig 1. The primary velocity standard used for the calibration of the LDA system.

3. THE CALIBRATION OF LDA

The LDA measures the known linear velocity V of the wire produced by the spinning of the disk. The mean velocity measured by LDA, V_{LDA}, is given as:

$$V_{LDA} = \frac{\sum N_i \cdot V_i}{\sum N_i} \quad (1)$$

Where: N is the number of pulse measurement and V is the indicated velocity of LDA at each location.

The calibration factor C is derived from the motor frequency f and the effective diameter of the spinning disk D. The effects of misalignment of the LDA optical axis and the rotational axis of the spinning disk are measured and corrected as residue angle α and deviation angle θ from the ideal centre of disc as shown in Fig 5. The effective diameter of spinning disk D can be estimated with the help of the LDA and the traversing system. Combining these factors, the LDA calibration factor C is given as:

$$C = \frac{\left[\dfrac{\sum N_i \cdot V_i}{\sum N_i} \right]}{f \cdot \pi \cdot \left(D + \dfrac{1}{2}d \right) \cdot \dfrac{\cos \alpha}{\cos \theta}} \quad (2)$$

d is the diameter of the wire.

3.1. Measurement of the Effective Diameter

We use a wire instead of edge disc to measure the speed of LDA. It has the advantage of the reduction of noise caused by reflections at different locations of wheel at same time so that the velocity distributions in the laser inter section volume can be characterised. The effective diameter D is estimated by using traverse system to measure the distance and using LDA to detect the wire positions.
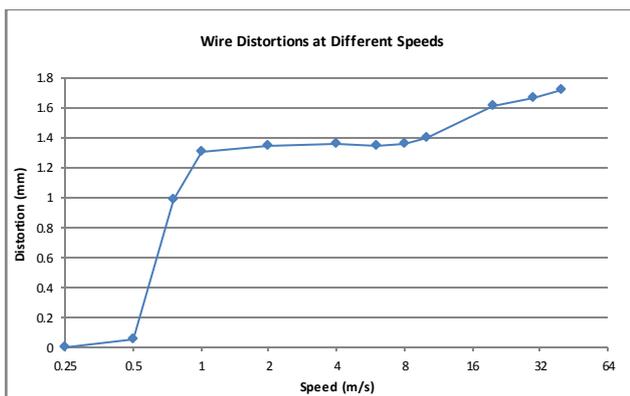

Fig. 2. Calibration of the wire distortion at different rotational velocities.

The LDA sensor scans through the laser beam intersection volume following predetermined locations. The width of the intersection volume is about 6.9 mm. Rotating wire can be distorted from it rest position due to the increase of the rotational frequency. We calibrated the effective diameter at a velocity of 5 m/s, thereafter measured the wire

distortions from the velocity of 0.25 m/s to 40 m/s. The dependence of the distortions of wire on the velocity of the rotation of the disk is shown in Fig. 2.

3.2. Calibration of the LDA Fringe Spacing

Ideally the fringe should be formed as uniformed and even spaces. However, the actual beams can be different in sizes, path lengths and angels which make the laser beams not perfectly symmetrical and lead the fringes to be distorted in most cases.

Uniformity of fringe spacing formed at the intersection volume of the laser beams depends on the width of the beams, their intensity and mutual alignment [4, 5]. The distortion level of the fringes have be calibrated for accurate speed measurement. The calibration was done by scanning through the intersection volume of laser beam at each setting speed. LDA was driven by transverse system moving along the horizontal axis across the intersection with the step of every 0.05mm. The average velocity and number of pulses were measured at each step. The measurement at 20 m/s is shown in Fig.3.

The effective velocity is not only depended on the quality of fringe space formed at particular location but also affected by the light intensity of laser beam and the capturing speed of LDA. The calibration factors C were found varying with different velocity of burst particles flying thought the intersection volume. The measurement at another speed of 10 m/s is shown in Fig.4. Comparing with the measurement results at 20 m/s, the velocity profiles and pulse number are significantly different due to these reasons. Hence, the calibrations at different velocities covering the LDA measurement range have to be done.

The effective velocity is depends on speed of particles and number of particle being measured. The number of particle collected by LDA as pulse rate is affected by light intensity of fringes. Different location may have different light intensity due to the distortion of fringes. The velocity measurement is hence weighted according to the quality of fringes by measuring the captured pulse rate. Less distorted fringes have better light intensity so that its relative pulse rate is higher.

We calibrated it for the velocity range from 0.2 m/s to 40 m/s.
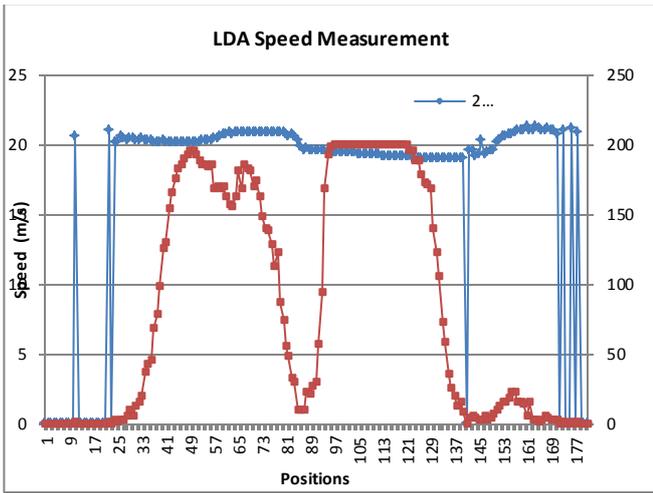
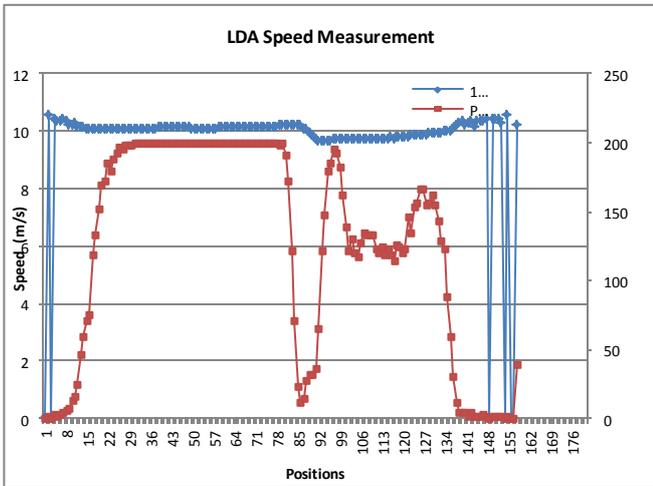Fig. 3. Scan of the LDA intersection volume at velocity of 20 m/s.

Fig. 4. Scan of the LDA intersection volume at velocity of 10 m/s.

3.3. Measurement Uncertainty

The expanded measurement uncertainty is determined from each component of equation (2).

3.3.1 Effective diameter of spinning disk:

The diameter of spinning disk is measured by the LDA. The measurement uncertainty sources are from traverse system, alignment of springing disk, motor speed and the detection the wire potions.

3.3.1.1 The uncertainty of transverse system

The traverse system was used to measure the effective diameter of spinning disk. It was calibrated against a laser interferometer of a length standard. The calibration uncertainty was combined from the uncertainty sources including alignment of laser beam which may be not fully parallel with the axis of LDA moving direction, uncertainty of laser standard and repeatability of transverse system.

The reference laser standard for length measurement has the measurement uncertainty better than 1 nm. The repeatability of the traverse system was found as 0.01 mm or

better, the linearity of the traverse system is within 0.05 mm in a measurement range of 200 mm. The expanded measurement uncertainty combined with above effects is 0.015 mm after corrected the linearity errors.

LDA and transvers system are used to measure the effective diameter of spinning disc by detecting the wire positions at front and back positions of spinning disc. If the LDA moving direction is not passing through the rotational axis of the spinning disk as shown in Fig 5, there will be an error given as R= r/cosθ; the angle θ was estimated with the measurement uncertainty to be less than 0.5°.
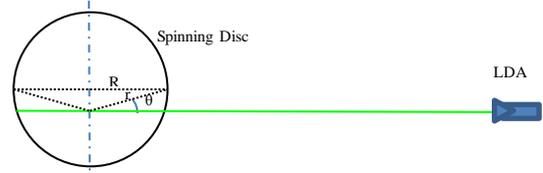

Fig. 5. Measurement of effective diameter of spinning disc.

Another alignment error α is because the LDA scanning direction may be not parallel with the disc horizontal surface. In our case, both disc surface and canning path were measured by the spirit level which has the measurement uncertainty of 0.2°.

Motor has the specification of accuracy to be better than 0.02%, it was also checked against a tachometer which has the measurement uncertainty less than 0.01%. The deviation was found within the accuracy from the setting value.

The calibrations were done in a temperature controlled room at 20±1°C. The materials of transverse system and spinning disc have the thermal expansion rate to be less than 22 ppm / °C. The relative measurement uncertainty is 0.004 mm under such conditions. No temperature compensation for the material thermal expansion was applied during the calibration.

3.3.1.2 The uncertainty of diameter measurement

It is not possible to directly measure the diameter of wire rotating by a contactable length standard. We hence developed the noncontact method to detect the effective diameter using the LDA system. The diameters were measured at rotating speeds of 5 m/s and correct the distortions at other speed as shown in Fig.2. The transverse system is able to move at steps of 0.01 mm. Using the LDA fringes, we are able to detect the effective diameter via measuring on the wire distortion with the measurement uncertainty of 0.02 mm to 0.06 mm at speed from 0.2 m/s to 40 m/s. Higher rotating speeds caused the stronger vibration of spinning disc and resulted bigger random measurement uncertainty.

3.3.3 Combining measurement uncertainty

The calibration of LDA is according to the equation (2) given in section 3.

$$C=f(Ni, V, f, D, d, \alpha, \theta);   \qquad (3)$$

Its standard deviation is estimated as:

$$dC_x = \sum_{i=1}^{n} \frac{\delta c}{\delta X_i} dX_i \qquad (4)$$

The combined measurement uncertainty yield as:

$$
\begin{aligned}
u_c^2(C) &= \sum_{i=1}^{n} \left(\frac{\delta C}{\delta X_i}\right)^2 u^2(X_i) \\
&+ 2 \sum_{i=1}^{n-1} \left(\frac{\delta C}{\delta X_i}\right) \sum_{j=i+1}^{n} \left(\frac{\delta C}{\delta X_j}\right) r_{ij}\, u\ (X_i)\, u\ (X_j)
\end{aligned}
$$

$$(5)$$

The summary of the measurement uncertainty sources and their values is listed in Table 1.

Table 1. The summary of the measurement uncertainty sources and their values.

Items	Uncertainty Source	Value
Spinning Disk		
	Travers system	0.015 mm
	Alignment Angle θ	0.5°
	Alignment Angle α	0.2°
	Motor frequency	0.02%
	Diameter measurement	0.02 mm to 0.06 mm
	Thermal expansion of materials	0.002 mm
LDA measurement conditions		
	Pressure	1 mbar
	Temperature	1 °C
	Humidity	10% rh
LDA Repeatability		0.05% to 0.15%
Expanded Measurement Uncertainty (K=2; at 95% level of confidence)		0.1% to 0.4%

4. DISCUSSION

LDA as the reference standard is widely used to provide the traceability for air velocity calibration. Proper traceability requires a primary velocity standard. The spinning desk is crucial to establish the traceability with directly tracing to SI units of length and time. Traditionally, the width of inference fringe spaces was calculated through knowing laser wavelength and angle of the two beam paths and assumed the fringe space are uniformed. However the formed fringes are often distorted and deviated from the calculation values. The error of calculation method can be as large as several percent from its correct values shown as Fig.3 and Fig.4. To correct these errors by detecting the velocity profile at the intersection volume are very important.

Our current speed standard is able to characterise the interference fringes with the measurement uncertainty at well acceptable level. With this standard, further improvement on the quality of laser inference by adjusting the alignment of leaser optics can be done so that will significantly reduce the LDA measurement uncertainty.

5. CONCLUSIONS

NMC's primary velocity standard was successfully established and used for the calibration of the LDA. The factors contributing to the measurement uncertainty are discussed and evaluated. The system was shown to be capable of measuring the velocity from 0.2 m/s to 40 m/s with the measurement uncertainty of 0.1% to 0.4% of readings.

REFERENCES

[1] Uncertainty Analysis: Laser Doppler Velocimetry (LDV) Calibration. ITTC – Recommended Procedures and Guidelines (2008).
[2] Jian, W. (2009). Realisation of a primary air velocity standard using Laser Doppler Anemometer and precision wind tunnel. *XIX IMEKO World Congress Fundamental and Applied Metrology (pp. 1326–1331)*. Lisbon.
[3] Shinder, I. I., Crowley, J. C., Filla, B. J., & Moldover., R. M. (2013). Improvements to NIST's Air Speed Calibration Service. *FLOMEKO*.
[4] Ruck, B. "Distortion of LDA fringe pattern by tracer particles." *Experiments in fluids 10.6 (1991): 349-354.*
[5] Zhang, Z. LDA application methods: laser Doppler anemometry for fluid dynamics. Springer Science & Business Media, 2010.