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LDA CALIBRATION AT INRIM: A PORTABLE DEVICE

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Abstract: INRIM has been developed a LDA calibrator for a speed range between 0.03 m/s and 14 m/s. The device is composed by a rotating disk with a surface manufactured that simulates the tracer particles. The device is also composed by an alignment system to adapt the calibrator to different focal lengths and beam angles. The particularity of this prototype consists in its solidity and portability. Actually, the target of this device is not the improvement of the general measurement accuracy for LDA calibrators but it has been designed to be portable in order to be used as a possible transfer device for LDA calibration comparisons.

Keywords: LDA calibration, airspeed standard, traceability.

1. INTRODUCTION

After the last WGFF meeting held in Singapore in October on 2010, INRIM decided to improve their airspeed standard facilities (two wind tunnels) in order to guarantee the standard traceability to the SI according to the CIPM-MRA 2009-24 document [1]. The LDA has been chosen for the improvement of these two standards. Other NMIs already adopted the LDA as a primary reference for the airspeed standard. Some LDA calibrators have already been realized in order to ensure the traceability of LDA to primary standards. Among the NMIs that have such devices for the calibration of a LDA, there are NIST [2], NMIJ [3] and PTB. In all three cases, the device is based on the technique of a rotating disk (or drum). According to this technique the standard velocity is estimated as the tangential velocity of a rotating disk and, in particular, as the ratio between a standard space (the half of the drum diameter) and a time sample (the inverse of the drum rotation frequency). According to the available bibliography, both NMIJ and NIST uses tungsten wires mounted parallel to the axis of rotation of the drum to simulate the passage of the particles in the measurement volume. The particular NMIJ drum design allows to calibrate both backscatter systems and forward scatter ones. In the case of PTB, particles that pass the measurement volume are simulated by means of an homogeneous distribution of particles on the surface of a drum made by glass and machined with optical precision. According to their considerations, the eccentricity caused by the rotating system mounting can be neglected by averaging the output obtained by an acquisition distributed regularly around the drum circumference. INRIM developed an own device that is in part similar to the ones cited but that is based on a different rotation methodology. Moreover the device is projected in order to be portable. The aim of this project design is the possible realization of a comparison between NMI's where the traveller device would not be the instrument to be calibrated but the calibrator device itself. A technical description of the device, of the functioning principle and a first analysis of its capabilities follow.

2. FUNCTIONING PRINCIPLE

The calibration device (a rotating drum) has to generate a very stable rotation; therefore the electrical motor that induces the drum rotation has to allow a regulation of the velocity and, during measure, has also to keep constant the velocity value imposed as much as possible. Furthermore it has to be quite robust to be mounted on a travelling device.
Step-by-step motors have some features that make them adapt for this kind of applications: they have a very good mechanical and electrical strength and they allow to obtain very low speed range even without the use of reducers. On the contrary, they have a step-by-step functioning with strong vibrations, especially at the lowest speed range, and they can not reach very high speed. Actually, step-by-step motors are generally adopted to block the shaft at a precise angular position (balanced position) and they have not the purpose of obtaining a certain rotation velocity. It is possible to obtain a continue rotation only indirectly by sending to the motor some series of current impulses, according to a defined sequence, in order to drive the balanced positions. Therefore it is possible to drive the motor at a defined velocity simply by setting the impulses frequency because the balanced position of the shaft are mechanical determined with very high precision. A step-by-step motor guarantees a constant mean velocity on a turn but between two steps the velocity varies from zero to a certain value and then go down to zero again. This happens between every balanced position along the complete rotation. The aim of the rotation system project was to create a mechanical device that could make maximum the use of the constant velocity among the subsequent steps and that, at the same time, could reduce as low as possible the effect due to the step-by-step functioning. This has been obtained by coupling the effects of a flywheel (an inertial mass necessary to reduce the oscillations) and a freewheel between the motor and the flywheel. In this way, when the motor stops its up thrust, the flywheel is not coupled to the motor and therefore is free to

rotate without the resistance of the motor torque. A bearing placed between the shaft and the bush reduces the friction avoiding the contact and thus the creeping between these two elements. From a theoretical point of view, the frictions absence allows the generation of a pure inertial motion; therefore, after a first phase of acceleration, the step-by-step motor has only to give the torque necessary to exceed the creeping friction and the drag due to the fluid dynamic actions. According to these coupling, the flywheel motion is characterized by a harmonic motion whose amplitude is a function of the inertia value of the system. A fluctuation is due to the periodic alternation between the condition of motor thrust and the condition of free rotation (see Fig. 1). The rotation speed average of the flywheel is always greater than the rotation speed average of the motor. Increasing the inertia value of the flywheel, the amplitude of the speed fluctuations decreases.

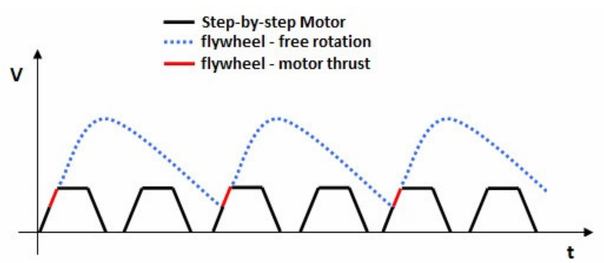
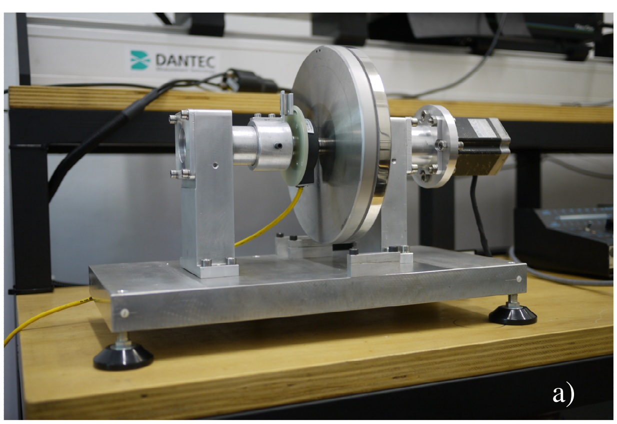


Fig. 1 Velocity fluctuations of a flywheel with respect to the motor velocity steps. (V : velocity, t : time).

Some tests allow to identify the inertia moment of the flywheel in order to obtain a value of the ratio between standard deviation and averaged speed minor or equal 0,1% (in the main part of the speed range).

3. DEVICE DESCRIPTION

The realization of the calibration system prototype, in addition to the sizing of main design parameters (inertia of the flywheel, its dimensions, regular rotation, etc…) has prompted the study of a system to ensure the alignment of any laser probe. In Fig. 2 photographs of the prototype and a particular of it are shown.



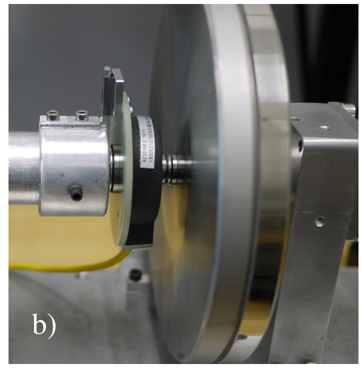


Fig. 2: a) Rotating Drum at INRIM. b) Encoder on the drum axis

The flywheel is an disk made of steel with a diameter of 0,1 m. Flywheel is the drum which tangential velocity is the speed standard for LDA calibration. It has a machined surface for the reflecting particle simulation. The encoder used to measure the drum angular velocity is a commercial encoder (1024 pulses per revolution); in order to guarantee the minor contribute of the measurement system to the velocity standard deviation, the encoder interior diameter has been modified by the producer exclusively for this device.
Signals from the encoder are fed to an instrument called Period Measurement Device (PMD). The PMD includes a clock generator that provides a periodic signal (time base, TB) with period $\boldsymbol{T}_{\mathrm{TB}}$; the clock frequency can be selected between five values ranging from 0.1 MHz to 24 MHz. The frequency value must be set by the operator according to the drum angular velocity in order to keep $\boldsymbol{T}_{\mathrm{TB}}$ at least three orders of magnitude smaller than the minimum period elapsed between two encoder pulses. The PMD is also equipped with a period multiplier, i.e. a system that allows one to measure the period corresponding to a number $\boldsymbol{N}_{\mathrm{P}}$ ($\boldsymbol{N}_{\mathrm{P}}$ = 1, 2, 4, 8, 16) of the encoder notches. This allows one to measure higher speeds, or to average the measurement over several notches, thus reducing the influence connected to possible manufacturing defects in the notches distribution. A 16-bit counter counts the number of time base periods between two (or more, according to the value of $\boldsymbol{N}_{\mathrm{P}}$) encoder pulses. This value, indicated as $\boldsymbol{N}_{\mathrm{TB}}$, is an integer number and is given by $\boldsymbol{N}_{\mathrm{TB}} = \mathrm{INTEGER}\left(\boldsymbol{T}_{\mathrm{enc}}\boldsymbol{N}_{\mathrm{P}} / \boldsymbol{T}_{\mathrm{TB}}\right)$; therefore the angular frequency measured by PDM can be computed as $\boldsymbol{f}_{\mathrm{enc}} = 1/\boldsymbol{T}_{\mathrm{enc}} = \boldsymbol{N}_{\mathrm{P}} / \left(\boldsymbol{N}_{\mathrm{TB}} \cdot \boldsymbol{T}_{\mathrm{TB}}\right)$. This expression shows that the PDM measurement accuracy is proportional to $1 \cdot \boldsymbol{T}_{\mathrm{TB}}$ because the value of $\boldsymbol{N}_{\mathrm{TB}}$ can be wrong for only one unit. Moreover the accuracy of $\boldsymbol{T}_{\mathrm{TB}}$ can be neglected with respect to other mechanical uncertainty sources present in this device.
The tangential velocity of the drum is computed by means of its angular velocity; it can be driven in a range between 0.03 m/s to 14 m/s with a maximum relative standard deviation that varies from about 0.5% at lower speed to

about 0.08% at higher speeds. As example of the device capabilities see table 1.

Tangential velocity /m/s (mean value over 500 acquisition samples)	Relative standard dev./ - Mean standard deviation	Relative mean standard dev./ - Mean standard deviation
0,0323	0,48%	0,00096%
0,7407	0,36%	0,00072%
4,1363	0,10%	0,00020%
6,1141	0,09%	0,00018%
9,9830	0,08%	0,00016%
13,995	0,08%	0,00016%

Tab. 1 – Rotating drum capabilities at INRIM

The phases of production and assembly of the device components has required a particular attention because of the importance of a very accurate alignment of all components in order to ensure an accurate knowledge of the measurement surface position with respect to the measurement volume generated by the LDA probe. Actually, the alignment of probe with respect to the drum is a function of the overall assembly. According to this necessity the following procedure has been followed:

1. the base surface has been ground;
2. the lateral supports have been assembled on it; then their lateral surfaces have been ground so as to ensure the perpendicularity of these ones relatively to the base surface;
3. finally, they have been drilled thus ensuring the parallelism between the base surface and the axis of rotation (see Fig. 2a).

LDA system measures the velocity component contained in the rays plane and perpendicular to the bisector of the angle formed by the two rays themselves. Therefore, in the present case, it is necessary to ensure that the tangential velocity vector of the drum in the measurement point would lie in the plane identified by these rays. The positioning device over which the probe is placed, three adjustable supports under the base surface and a dedicated system of optical gates (see Fig. 3) guarantee the ray alignment.

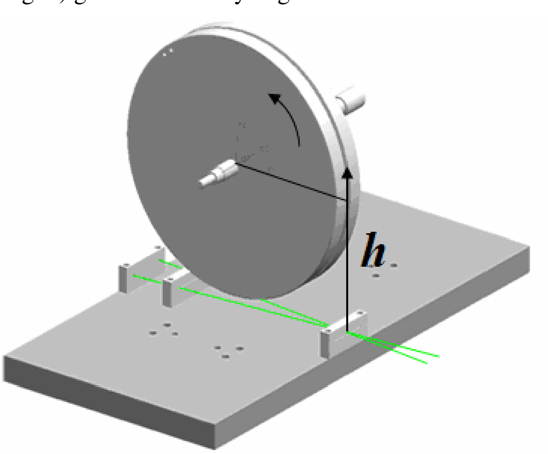


Fig. 3: Ray alignment system – optical levels.

The following procedure describes the rays alignment procedure:

1. first of all, the two rays plane has to be aligned to the base reference plane; this condition is obtained by rotating the probe around its longitudinal axis and by varying the angle of the same axis until it is parallel to the reference plane. This first alignment is achieved when both the rays pass through the first and second optical gates and are reflected on the downstream screen (see Fig. 4);
2. the test volume (i.e. the rays intersection volume) must to be placed on the surface of the first optical gate;
3. finally, the probe has to be rotated by 90° around its longitudinal axis and it has to be translated vertically by a know length ***h*** (see Fig. 3).

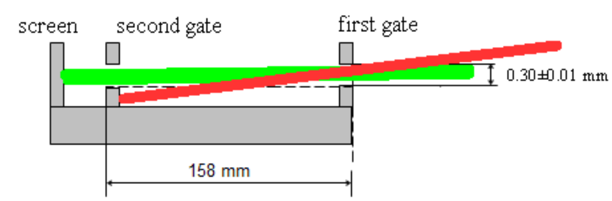


Fig. 4 : first step of alignment procedure. Green ray is correctly aligned to the base reference plane; red ray is not aligned. The correct alignment has to be obtained for both the rays.

Figure 5 shows the actual alignment for the LDA of INRIM at the described calibration device.

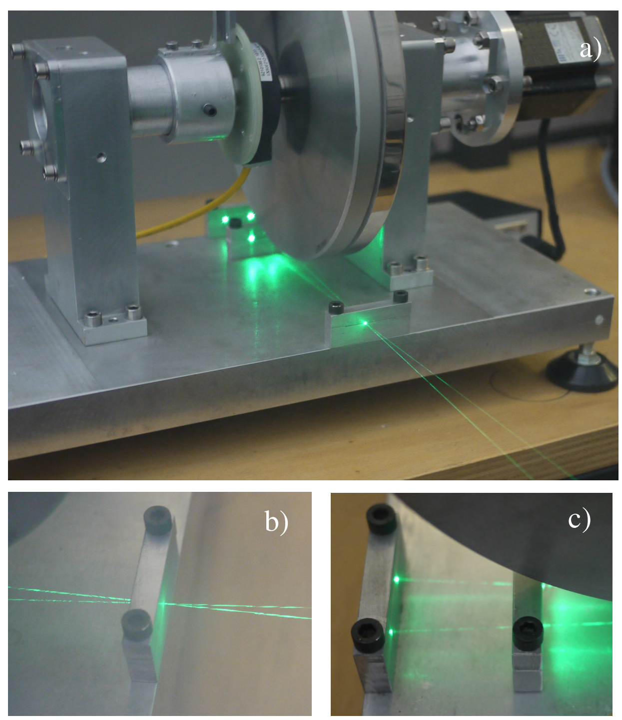


Fig. 5: a) Alignment system, b) particular of the measurement volume on the firs gate, c) passage through the second gate and final screen.

4. SURFACE CHARACTERISTICS

One of the most significant aspects of the described device consists in its measurement surface and in the technique adopted for its realization.
A LDA calibrator has to simulate the measurement conditions present in a general inseminated flow.
As written in the introduction, this simulation has been realized by means of many different solutions by others NMIs. Both NMIJ and NIST use tungsten wires mounted parallel to the axis of rotation of the drum to simulate the passage through the measurement volume of the flow inseminating particles [2,3]. PTB simulates these particles by means of a homogeneous distribution of particles on the surface of a drum made by glass and machined with optical precision. The INRIM solution derives from some considerations about these two methods.
The wire solution as particle simulator could have the problem of wire deformation due to the centrifugal forces generated by the drum rotation. In the presence of this deformation, the wire section interested in the measure moves towards a more peripheral zone of the measurement volume described by the rays' intersection[1]. In this condition the portion of the measurement volume interested in the test would change according to the drum angular velocity (thus according to the standard velocity) changing the calibration conditions trough the measurement range.
In order to avoid this phenomenon, the UDF decided to realize the particles simulation by means of a mechanical processing of the drum surface. PTB already realized a solution different from the wire, however this solution could be not adequate to the aim of this work; actually, as already written, the target of the described device is its portability. The first consequence of this choice is the exclusion of fragile materials for the device realization.
The UDF prototype has been reached through several steps: firstly, UDF observed that the imperfections of the steel surface of the drum, typical of a machined surface, could be used as particles simulator. In fact, these imperfections, passing through the measurement volume, generate a signal corresponding to the imposed tangential velocity of the drum. These output signals have been obtained for different drum velocities and they have been found to be quite repeatable. However, the quality of the signal is not acceptable because of the strong ray reflection upon the steel surface. Actually, it is not possible to perform a measure limiting the anode current under a safety level for the photo sensor, because in these conditions the photo sensor stimulation saturates the sensor itself.
Therefore, drum surface has been adjusted by means of different mechanical processing (sandpaper of different level of roughness, glitter painting and different sandblastings) in order to reduce the reflecting surfaces.
The most efficient technique tested is sandblasting. This procedure has two positive results:

1. resulting mat surface allows to eliminate saturation at the photo sensor;
2. sandblasting generates a chaotic series of surface imperfections that simulate spots of reflecting areas alternated to not reflecting ones; by a first analysis this spots seems to have adequate sizes for LDA applications.

The sandblasting treatment chosen for the drum surface has been qualitatively analysed by means of a Scanning Electro Microscope (SEM) and a profilometer. Obviously, drum sizes are not compatible with the instruments interest in these analysis, thus some samples made of smooth steel has been sandblasted like the drum.
Fig. 6 and Fig 7 show two examples of the evaluations conduced on one of these samples.

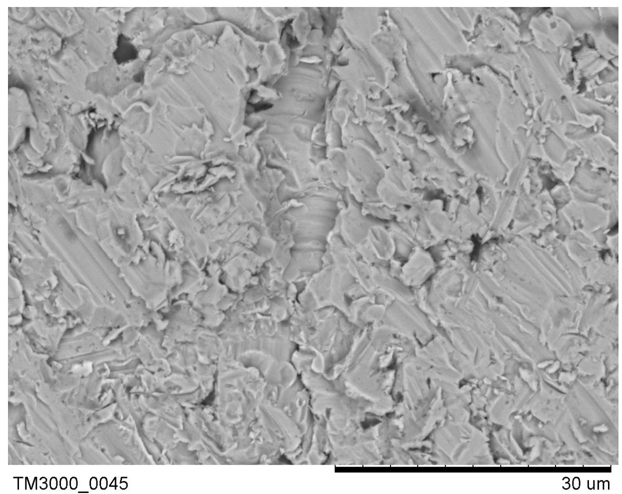


Fig. 6: sample surface analysis by means of an electronic microscope. Imperfection area sizes are from 3X3 to about 10X10 μm^2.

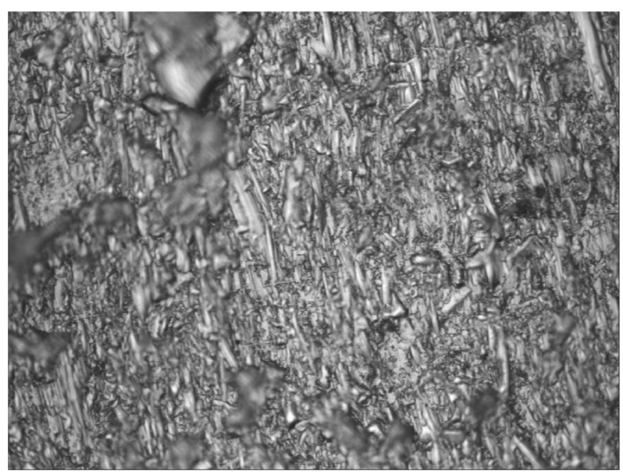


Fig. 7: sandblasted surface magnification; image size: 254.64 X 190.90 μm^2.

[1]In the more pessimistic case of a strong deformation, the wire section could partially or completely exit the measurement volume

The instruments used for the surface analyses are:

- Hitachi's TM-3000 Scanning Electron Microscope
- Sensofar's PLμ 2300 profilometer. Fig 7 shows a measurement with confocal objective 50X magnification

Profilometer analysis also allows to visualize a series of surface profiles. Fig. 9 shows one of these results. It is evident that this sandblasted surface is characterized by a series of craters generated by the mechanical working. The rids alternation cause the generation of a chaotic distribution of reflecting and not reflecting areas according to the rays angle of incidence with respect to this strongly irregular geometry.

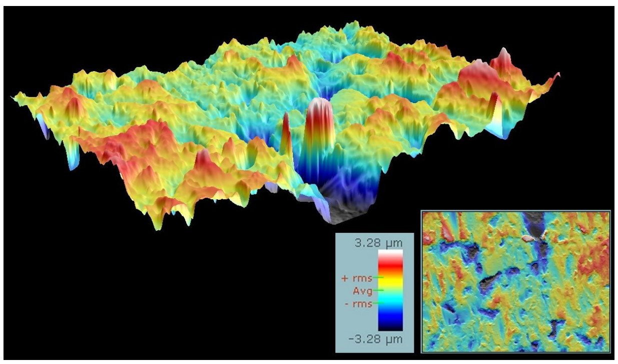


Fig. 9: sample of sandblasted surface profile. 3D image shows a chaotic craters distribution that probably generates alternation of reflective and not reflective areas.

The strongly stochastic distribution of craters through the sample surface cannot suggest a mean behaviour of typical sizes or rids alternations; however a very confined analysis, as in the case of the profilometer acquisition shown in Fig. 9, seems to evidence the magnitude of this mechanical work. The craters visualized in a very restricted area (of about 250 x 190 μm) have depth sizes limited to few μm and a more relevant rids distribution on the surface of the order of about 40÷60 μm (as shown by the graphic in Fig. 10).

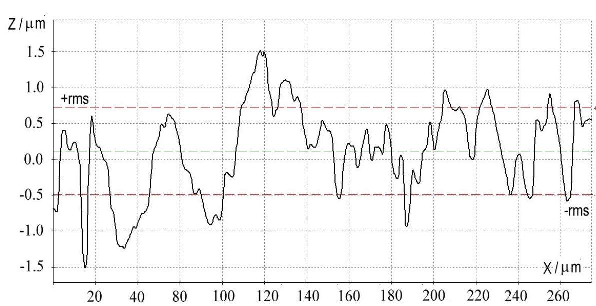


Fig. 10: a profile distribution extracted by the profilometer acquisition on the sandblasted sample; profile is extracted by acquisition in Fig.9.

The asperity of the surface shown by this limited analysis have not the typical dimensions of the inseminating particles for LDA acquisitions in flow; however, reflecting surface created, according to the laser measurement volume angle of incidence on this imperfections, are sufficient to simulate an adequate particle distribution (as demonstrated by performed measures, see section 3, Tab. 1).

About the surface profile, it can be noted that depths asperity changes along the surface of an order of magnitude of about 2 ÷ 3 μm. This grants that measurement volume obtained by the two LDA rays intersection, during measurement at the calibration device, is crossed by a structure whose size is quite typical of other LDA calibration devices (as an examples, the tungsten wire with a diameter of about 5 μm used in [2] and [3]). Probably, this condition will allow to compare results obtained by more consolidated LDA calibration technique with the INRIM one.

5. CONCLUSIONS

In conclusion, INRIM developed a LDA calibrator device based on the rotating drum principle. The prototype allows calibrations for only back scatter LDA. It has quite small dimensions and it has an alignment system included in the structure. This system cannot be modified by an accidental action; therefore it contributes to a good solidity of the whole system. The prototype solidity is also guaranteed by the structure itself and by the step-by-step motor chosen for the drum rotation control. The angular velocity measurement is obtained by means of an encoder directly mounted on the drum rotation axis as near as possible to the drum itself. The nominal tangential velocities range from about 0.03 m/s to about 14 m/s. Relative standard deviations of the angular velocities measured by the encoder, range from about 0,5% to 0,08% .

The particularity of this prototype consists in its portability and on the drum surface mechanical working; actually, it has been designed in order to be transported without the risk of damage the drum rotation, the sensitive element simulating the inseminating particle or the whole alignment system. The structure solidity, the integrated alignment system, and the rotational capabilities could be considered adequate in order to propose this prototype as a possible traveller device for LDAs calibration comparisons.

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