TRACEABILITY IN ANEMOMETRY: A ROTATING ARM AS AIRSPEED PRIMARY STANDARD

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Abstract

During the last WGFF meeting (2012) the question of what kind of facilities can be considered as primary standard for airspeed has been discussed. The final decision about dragging facilities that can be accepted as primary standards at a NMI, from the viewpoint of the CIPM 2009-24 (Traceability in the CIPM MRA) [1], clearly limits the possible use of the INRIM facility for anemometer calibration.
LDA measurements of airspeed induced by the arm rotation at the measurement position and a definition of actual capabilities of this facility as primary standard according to the WGFF decision are presented in this paper.

The Rotating Arm and the Entrainment Effect

The rotating arm (RA) is one of the four primary facilities for the generation of airspeed standard at INRIM. The RA consists of an arm shaped with an aerodynamic profile about 3.5 m long which turns around a vertical shaft. The shaft is mounted on a heavy base whose weight and rigidity guarantee that the device is stable enough. The shaft is moved by a DC electrical motor through a gear box. A circular structure (ring) is placed all around the arm path in order to eliminate some corner effects that can be induced by a not symmetrical path. The declared calibration velocity ranges between 0.10 m/s to 5.0 m/s.
The facility functioning is based on the reciprocity principle [2]. According to this principle, the forces generated by the flow that invests a body, are directly proportional to the relative velocity between the air and the body. This means that for example, from an aerodynamic point of view, a body invested by air at a velocity $\vec{V}$ is equal that the same body translated in still air at the velocity $-\vec{V}$. At this facility the anemometer to be calibrated is dragged along a circular path. This implies that the anemometer does not meet air at rest along the path because this circular configuration generate secondary motions. These secondary motions are here called *entrainment effect* (EE). Up to now, the airspeed standard could be computed through an angular velocity, a measurement length (R_{arm}) and an airspeed induced by the EE as follow:

$$V_C = V_{R.A.} - V_{E.E.} = \omega_{arm} \cdot R_{arm} - V_{E.E.} \qquad (1)$$

Where the angular velocity of the arm is measured by an encoder mounted on the shaft axis, whose output ω_{arm} is acquired through a period measurement device; whereas the measurement length R_{arm} (that is the linear distance between the rotation axis of the arm and the axis of the anemometer to be calibrated, generally placed at the arm tip) is measured by means of a laser distance meter.
$V_{E.E.}$ is the velocity induced by the EE in the direction of the arm tangential velocity.
In the past many analyses have been conduced in order to evaluate systematic errors and uncertainty sources present at this facility. They have been considered separately according to their nature into: air parasite motions within the test room due to the free convection effect, induced motions along the arm path due to the arm rotation (EE), possible effects on the anemometer output due to the circular path and measurement system uncertainties. For a detailed description of this work see [3].
The EE has been studied in-depth in order to well define its systematic nature and therefore to correct the $V_{R.A.}$ (see Eq. 1); The EE correction formulas have been changed many

times in the past, first of all because of different anemometer frontal sections that are fundamental parameters in EE definition. The last solution has been based on the arm modification through a net placement at arm tip. The net surely induced a wake larger than the one of an anemometer placed at the tip. In this way it was possible to evaluate only one correction formula for the EE that was independent by the anemometer placed. Therefore, instead of trying to eliminate this effect, the EE has been enlarged in order to have a definition of it that was not a function of the anemometer sizes.

But, according to decisions taken during the last two WGFF meetings (2010 and 2012) this correction would downgrade the RA from a primary facility to a secondary facility for airspeed standard generation. In the author opinion this decision is surely correct because $V_{E.E.}$ (its last version) has been obtained by means of correction formula evaluated through a comparison between measurements at RA and at a wind tunnels (see [3] for more details). In this way the $V_{E.E.}$ (and as a consequence $V_{R.A.}$) can not be considered traceable to a primary standard. Eq. 1 defines a primary velocity standard only if all the terms of the equation are traceable to a primary standard. According this, it would not be important if the second term represents a systematic effect. The dragging facility functioning is accepted thanks to the reciprocity principle that does not require the condition of air at rest to be considered valid.

An analysis of the entrainment effect evaluation through a measurement technique that could grant EE traceability to a primary standard follows. Some considerations about the possibility to use this measurement technique as upgrade of the RA measurement system will be presented at the end of the paper.

Measurement setup

Measurements has been conduced by means of an Ion-Argon LDA by Dantec (λ=532 nm). The LDA is the most proper instrument for this kind of analysis because it is based on a not invasive measurement technique. Thanks to this characteristic the measurement volume of LDA can be placed in the correspondence of the measurement point with respect to the

anemometer placed at the RA tip. To simulate the presence of an anemometer to be calibrated a series of measurement has been conduced with a vane anemometer by TESTO of about 10 cm of frontal diameter. The fan has been chosen because of its quite large size and not for its metrological characteristics; actually, for this first EE analysis the anemometer output has not been taken into account. The LDA has been positioned in order to have its measurement volume at the same coordinates of the fan axis (see Fig. 1a). This positioning also allows to well define the passage of the anemometer through the measurement volume because the anemometer support passage causes an interrupt in the LDA signal (see Fig 2b). Therefore, according to the arm velocity, it is simple to define for every measurement series the same portion of LDA signal output to be analyzed in order to evaluate the EE for every RA velocity setting (this last aspect will be better described in the following section).

Fig 1: a) (on the left) LDA volume placement with respect to anemometer (focal length of 400,1 mm); b) (on the right) rays interrupt by the anemometer passage.

It is known that LDA functioning requires an inseminated flow. In order to inseminate the air in the RA chamber it has been used a smoke generator. The smoke generator uses a no toxic oil typically used in theatres and public places. To have no secondary motions induced by the smoke generator jet flow, the test chamber has been totally smoked and measurement has been started after a reasonable waiting time of about 10 minutes (see Fig. 2 for smoke generator). Analyses have been conduce for two different configurations: with and without anemometer on board. The two configuration have been compared to underline the influence of anemometer sizes on EE magnitude. The LDA

output has been compared to the RA output and in particular with the tangential velocity of the anemometer placed at the arm tip (computed as shown in Eq. 1).

Fig. 2 smoke generator.

Results

Measurement analysis has been conduced in a nominal velocity range between 0.10 m/s to 3 m/s, even if the measurement range declared for this facility is from 0.10 m/s to 5 m/s. This because these measures are considered as a first step for a new definition of this standard facility where the new definition will also deal with the functioning range (and in particular with a possible reduction of it).
LDA acquisitions have been set in order to have as outputs 3 measurement distributions for every RA velocity, where everyone of these data distributions had to last 5 turns of the arm. Fig. 3 shows one of this complete measurement set in the case of RA tangential velocity equal to about 2 m/s (at the arm tip).
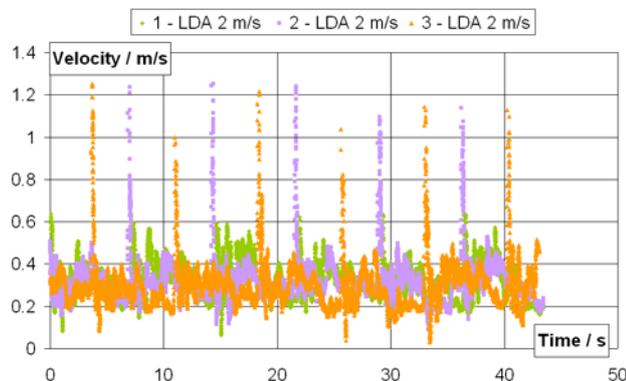

Fig. 3: example of measurement set: 3 output distributions (green, lilac and orange) everyone containing at last 5 turns of the arm.

All these data have been analysed to evaluate two results: the EE dependence by the anemometer sizes (comparing measurements with and without anemometer) and the EE entity. For these analysis is necessary to separate the velocity values induced by the EE from the other acquired values. Since the EE is induced by the arm rotation, its entity would have its major values immediately after the arm passage (where there is the arm wake) and it would decrease up to a next arm passage. Furthermore, according to the reciprocity principle, the velocity considerable as a reference in an anemometer calibration is the "undisturbed" upstream velocity, in other words, that velocity that is not influenced by the motion field distortion immediately in front of the probe. Considering this two aspects, the velocity values that have to be evaluated in this analysis are those shown in Fig. 4
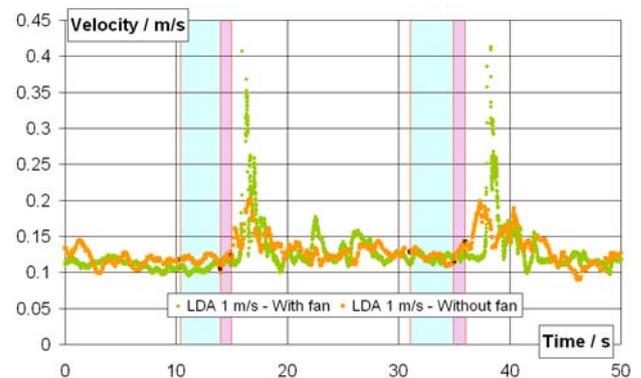

Fig. 4: data values for the EE evaluation; pink range: motion field along 10 hydraulic diameters upstream the probe; pink+blue range: motion field along 50 hydraulic diameters upstream the probe

Fig. 4 shows a detail of an acquisition at 1 m/s with and without the anemometer on board. The picks represent the beginning of the arm wakes, whereas the velocity values increasing before the pick, represents the motion field distortion caused by the a body translation in air (like in the case of a body at rest invested by a flow). Thanks to the functioning principle of LDA its quite easy to define this different zones. Indeed if the rays path is interrupted, the LDA can not acquire any more because the measurement volume disappears. If the acquisition frequency is quite good, the arm passage is very evident and the zones of interest are easy to be defined. Fig. 5 shows a detail of Fig. 4. The acquisition frequency in this case was of about 150 Hz. It is evident that in the yellow range the LDA did not acquire because there are not data whereas in the same time range (about 0.35 s), immediately before the arm passage, the LDA was able to acquire 58 values. Obviously, frequency acquisition is not stable during measurement but it ranged between 130 Hz to 160 Hz. The absence of data in a range time of

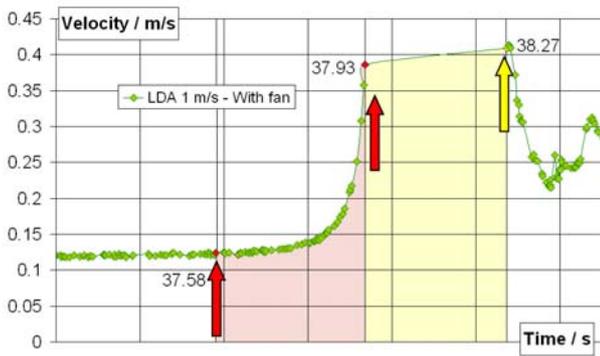about 0.35 s is surely indicative of rays interrupt and therefore of arm passage.

Fig. 5: Particular of LDA acquisition close to the arm passage

Moreover, once the first arm passage has been found, the arm rotation angular velocity identifies the other passages time zones. According to this reasoning, all the arm passages, for all acquisition sets, have been evidenced and the portions of motion fields interest in this analysis (see Fig. 4) have been evaluated. Table 1 shows results of this analysis where: $s\left(\overline{V}_{R.A.}\right)$ is the standard deviation of the arm tangential velocity mean value (corresponding to the anemometer tangential velocity), $\left(\overline{V}_{E.E.}\right)_{10}$ is the velocity measured by LDA (induced by the arm rotation) that has been evaluated for 10 hydraulic diameters of the vane anemometer upstream itself, whereas $\left(\overline{V}_{E.E.}\right)_{50}$ has been evaluated for 50 hydraulic diameters upstream (see Fig. 4, pink and blue ranges). Mean values take into account all the three distributions measured, everyone lasting 5 turn of the arm with a vane anemometer of 10 cm of diameter placed at the arm tip. Standard deviations of the measured phenomenon are about of the same order of magnitude. At a nominal tangential velocity of 0.1 m/s, the standard deviation of the evaluated EE is higher because of the LDA acquisition frequency very low at this velocity. Actually, at $\overline{V}_{R.A.}$ of about 0.1 m/s, the acquisition frequency fluctuated around 20 Hz (with a data valid range between 50% to 100%); whereas at the other velocities, acquisition frequencies reached at last 100 Hz with a data valid fluctuation from 98% to 100%. The low acquisition frequency had probably due to a not proper air insemination

during test added to the very low velocity values to be measured (about 0.006 m/s).

The higher standard deviation value at $\overline{V}_{R.A.}$ of about 3 m/s, is due again to a low number of data, but in this case, this has not been caused by a low acquisition frequency (that at these velocities was at last 160 Hz) but by higher arm velocity that reduces the time from two arm passage thus reducing the number of data interested in the analyzed space (10 and 50 hydraulic diameters upstream the anemometer). A correct comparisons of these distributions would require the same number of acquisition data. Next Analyses will take into account this aspect considering the proper number of arm turns to be analysed in order to have more comparable data series. Despite this aspect, the EE values estimated by LDA at 1 m and 5 m upstream the anemometer (corresponding to 10 and 50 hydraulic diameters of the vane), even without a complete uncertainty analysis, seams to be quite compatible (see Tab. 1). This aspect is important because a EE study, conduced at only one distance upstream the anemometer, would have been uncertain. Indeed, velocity interested in the present study has to be not influenced by field deformation immediately in front of anemometer surface. The extension field of this effect depends by the anemometer frontal surface and by Reynolds number (therefore, in this case, by the arm tangential velocity). 10 hydraulic diameters (corresponding to 1 m) is a reasonable filed extension to be analyzed and results obtained for an extension of 5 m confirm this choice. Therefore, next studies will be conduce for only 10 hydraulic diameters and at last for 1 m in front of anemometer.

Last column of Tab. 1 shows the ratio between velocities induced by arm passages, measured by LDA, and the anemometer tangential velocities. It is evident that the EE does not have a linear behaviour in function of the arm velocity. Already at 0.6 m/s the EE is present and can influence the anemometer measures. This influence is higher at median velocities (between 0.6 to 1 m/s) and decreases at a lower rate at higher velocities. Fig. 6 shows this behaviour trend.

Finally, some considerations has been conduced about influence of anemometer size on motion filed induced by arm rotation (EE).

$\overline{V}_{R.A.}$ /m/s	$s\left(\overline{V}_{R.A.}\right)$ /m/s	$\left(\overline{V}_{E.E.}\right)_{10}$ /m/s	$s\left(\overline{V}_{E.E.}\right)_{10}$ /m/s	$\left(\overline{V}_{E.E.}\right)_{50}$ /m/s	$s\left(\overline{V}_{E.E.}\right)_{50}$ /m/s	$\left(\overline{V}_{E.E.}\right)_{10}/\overline{V}_{R.A.}$
0.0995	1.20%	0.006	3.44%	0.007	1.42%	6.0%
0.6002	0.40%	0.086	0.45%	0.090	0,17%	14.3%
0.9994	0.36%	0.123	0.77%	0.122	0.40%	12.4%
2.0016	0.20%	0.148	0.50%	0.144	0.28%	7.4%
3.0417	0.25%	0.180	1.57%	0.185	0.49%	5.9%

Tab. 1: results of the Entrainment Effect (EE) analysis with vane anemometer placed at the arm tip
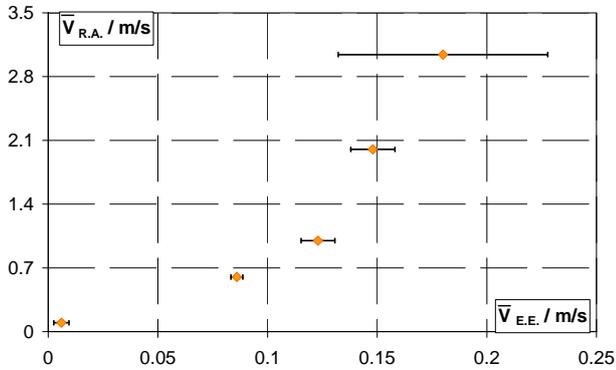

Fig. 6 : Entrainment Effect trend in function of arm tangential velocity with standard deviation of the mean bars.

Figg. 4, 7 and 8 show three comparisons between data distributions in the cases with anemometer and without anemometer. Graphs show a behaviours that seam to be not influenced by the presence of anemometer. The only evident effect is the increase of the wake velocities.
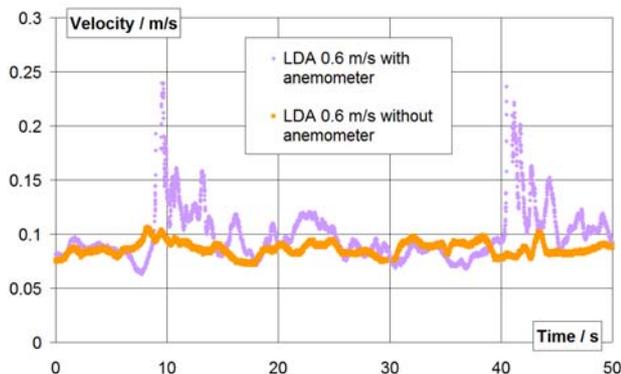

Fig. 7:comparison between data distributions; arm tangential velocity 0.6 m/s (two turn of the arm).

The absence influence due to the anemometer size is also confirmed by statistical evaluations of the EE in the cases without anemometer. This would mean that, the time of the arm rotation (even at higher velocities) is sufficient to allow the same degradation of the two different wakes. Notice that this analysis has been conduced with a vane anemometer with a large vane diameter, but this case could not be significant also for other anemometers; this because the obstruction caused by anemometer frontal surface is the actual influent parameter and not the overall sizes. Therefore other analysis about the influence of different anemometers are necessary.
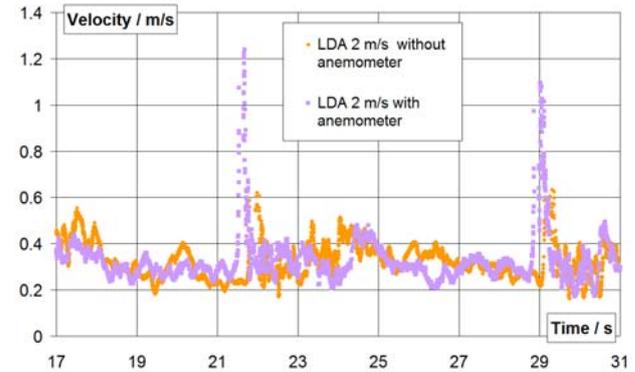

Fig. 8: comparison between data distributions; arm tangential velocity 2 m/s (two turn of the arm).

Conclusion

A study of Entrainment Effect at Rotating arm at INRIM has been presented. The first conclusion of this analysis suggests a suspension of this facility as primary standard facility according to the last WGFF decisions; this because for arm tangential velocity over 0.4 m/s the EE is influent. On the other hand, these analyses demonstrated that EE is a quite repeatable phenomenon that could be evaluated by means of a measurement technique traceable to a primary standard (LDA). A simultaneous evaluation of $\overline{V}_{E.E.}$ and of $\overline{V}_{R.A.}$ would be a possible solution to redefine the Rotating Arm as a Primary airspeed standard but further studies are necessary.

References

[1] CIPM MRA/2009-24 document titled: " Traceability in the CIPM MRA" , http://www.bipm.org/cc/CIPM/Allowed/98/CIPM2009_24_TRAC_MRA_REV_13_OCT_2009.pdf

[2] P. Bradshaw, Experimental Fluid Mechanics 2nd ed., Oxford: Pergamon, 1970.

[3] A. Piccato, R. Malvano and P.G. Spazzini "Metrological features of the rotating low-speed anemometer calibration facility at INRIM" Metrologia, Vol. **47, pp** 47–57, December 2010.