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# Air Speed Measurement Standards Using Wind Tunnels

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## 1. Introduction

Accurate air speed measurement is essential to understand flow phenomena and practical engineering problems, such as wind turbines, air ventilation systems, air filter testers, and fan testers, etc. Standard wind tunnels can provide good testing environments for calibrating and testing industrial anemometers, which are widely used for measuring air speeds in applications to various on-site air speed measurements. Air speed standards can be established by adopting a wind tunnel. In this case, some knowledges are required, regarding measurement accuracy and uncertainty assessment.

To certify an industrial anemometer, a calibration certificate is issued by an accredited laboratory, which is recognized by an accreditation organization in a country, according to the ISO/IEC 17025 guide (ISO, 2005). The national metrology institutes in every country advise the accreditation organization in recognizing the accredited laboratory by providing technical supports with the national measurement standards. Traceability is established from the national standards to the industrial standards, by transferring national measurement standards from the national metrology institutes to the accredited laboratories.

If an industrial anemometer is exported to a foreign country, an international calibration certification must be issued to provide the measurement accuracy requested by a customer in the foreign country. Mutual recognition arrangement realizes the international certification procedures by harmonizing the calibration and measurement capability (CMC) of industrial countries. International key comparisons are performed to fulfill the purpose of the mutual recognition arrangement. The international key comparisons are managed by the CIPM. In case of air speed metrology, three international key comparisons have been conducted by either world-wide or regional levels, up to date.

In this book chapter, a brief explanation, regarding the air speed metrology, is introduced. At first, some basics of statistical methods to calibrate an industrial anemometer are explained. After that, an air speed metrology is briefly introduced by considering the traceability chain from the national measurement standards to the industrial or working standards, based on the literature. Finally, some information, regarding the mutual recognition arrangement and the international key comparisons, will be mentioned. From this approach, it is expected that some basic knowledge of the air speed metrology can be useful in understanding how to measure the industrial anemometers with good measurement accuracy and uncertainty.

2. Basics of statistics for calibration of an anemometer

2.1 Basics of uncertainty measurement

When an anemometer is calibrated, people consider statistics because the measurement data for anemometer calibration generates statistical distributions. To determine a calibration coefficient of the anemometer, statistical moments such as a mean and a standard deviation are considered (Dougherty, 1990). Because the mean is an unbiased estimator, it is believed that the mean value approaches to the true value by measuring the data with infinite times. In this case, the standard uncertainty to determine the mean value becomes zero, according to the following equation.

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}}$$

(1)

Here,  $\bar{x}$  is the mean value of  $\{x_i, i = 1, 2, \dots, n\}$ ,  $n$  is the number of measurement,  $\sigma_x$  is the standard deviation of  $x_i$ , and  $\sigma_{\bar{x}}$  is the standard deviation of  $\bar{x}$ .  $\sigma_{\bar{x}}$  is referred to as the standard uncertainty, or more exactly, type A uncertainty (BIPM et al., 1993). The type A uncertainty is related with direct measurement when the device under test, or the *DUT* is calibrated. On the contrary, the uncertainty component, which is not directly related to the measurement, is referred to be type B uncertainty. The type B uncertainty includes all the other information except measurement, such as the standard uncertainty of an apparatus written in a calibration certificate, or a nominal value defined in a table, etc.

When determining the type A uncertainty, they can assume that the measuring quantity has the Gaussian distribution as a probability density function, by applying the central limit theorem (Dougherty, 1990). To assume the Gaussian distribution, the number of samples should be at least more than 50. However, in some cases, it is possible to assume the Gaussian distribution with the number of data more than 30. In case that the number of data is less than 10, the Student-*t* distribution is assumed. The difference between the Gaussian and the Student-*t* distribution is the value of coverage factor,  $k$  with the same confidence intervals of, e.g., 95 %.  $k$  is a necessary quantity when an expanded uncertainty is estimated based on a combined uncertainty, which combines the type A and the type B uncertainties (BIPM et al., 1993).

When determining the type B uncertainty, a rectangular, a triangular, and a trapezoidal distribution are usually assumed according to data types. In most cases, the rectangular distribution is preferred to represent the type B uncertainty, when a value is referred from tables, or calibration certificates, etc. Some of values of  $k$  for different probability distributions are summarized in Table 1.

Distribution	Coverage factor $k$
U-shaped	$\sqrt{2}$
Retangular	$\sqrt{3}$
Triangular	$\sqrt{6}$
Gaussian	1.96
Student - $t$	12.71 $\nu = 1$
	4.30 $\nu = 2$
	2.57 $\nu = 5$
	2.23 $\nu = 10$
	2.09 $\nu = 20$
	2.04 $\nu = 30$

Table 1. Coverage factor  $k$  with confidence level of 95 %

Measurement uncertainty is a combination of estimated uncertainties of each component, recognized as an uncertainty factor to a measuring quantity. The combined uncertainty is calculated according to the following formula (Kirkup & Frenkel, 2006).

$$u = \sqrt{u_A^2 + u_B^2} \quad (2)$$

Here,  $u_A$  denotes the type A uncertainty,  $u_B$  denotes the type B uncertainty, and  $u$  is the combined uncertainty. The Equation (2) combines  $u_A$  and  $u_B$  by a vector sum, because the two types of uncertainties are assumed to be independent and uncorrelated with each other. However, there are some cases where the uncertainty factors are not independent and uncorrelated. In these cases, correlation coefficients among the uncertainty factors must be calculated (Kirkup & Frenkel, 2006). To calculate the expanded uncertainty, the coverage factor  $k$  is multiplied to the combined uncertainty, as follows.

$$U = ku \quad (3)$$

Because the confidence interval with 95 % is widely accepted,  $k$  can be looked up in a statistical table (Dougherty, 1990). The effective degree of freedom,  $\nu_{eff}$  gives how to determine  $k$ , when the Student- $t$  distribution is considered. The formula to calculate  $\nu_{eff}$  is as follows (Kirkup & Frenkel, 2006; BIPM, 1993).

$$\nu_{eff} = \frac{u^4}{\frac{u_A^4}{\nu_A} + \frac{u_B^4}{\nu_B}} \quad (4)$$

The Equation (4) is also referred to as the Welch-Satterthwaite formula.  $\nu_{eff}$  is used to obtain  $k$  by inverse calculation of the given probability distribution<sup>1</sup>.

## 2.2 Repeatability and reproducibility

Repeatability describes the data distribution when a bunch of data is acquainted at a time. The repeatability can be defined as a ratio between the mean and the standard deviation.

$$F' = \frac{\sigma_x}{\bar{x}} \quad (5)$$

Here,  $F'$  represents the relative deviation of  $\bar{x}$ . When several measurements are required to obtain a set of mean values, i.e.,  $\{\bar{x}_j, j = 1, 2, \dots, m\}$ , another mean value can be defined.

$$\bar{\bar{x}} = \frac{1}{m} \sum_{j=1}^m \bar{x}_j = \frac{1}{m} \frac{1}{n} \sum_{j=1}^m \left( \sum_{i=1}^n x_{i,j} \right) = \frac{1}{m} \frac{1}{n} \sum_{j=1}^m \sum_{i=1}^n x_{i,j} \quad (6)$$

Here,  $\bar{\bar{x}}$  is the mean value of  $\bar{x}_j$ ,  $m$  is the number of measurements,  $n$  is the number of samples, and  $x_{i,j}$  indicates the  $i$ -th sample of the  $j$ -th measurement. This reminds of the definition of ensemble averages in random data processing (Bendat & Piersol, 2000). According to the ergodic theory, the time average of a signal converges to an ensemble average, if the measurement time of the signal is infinitely long. In this case, the time average of the infinitely-measured signal should be as close as to the true value of the signal. If the ensemble average  $\bar{\bar{x}}$  has the same value as the time average of the signal,  $\bar{\bar{x}}$  should be equal to the true value of the measuring quantity, also. Because the  $j$ -th measurement

<sup>1</sup> In Microsoft Excel, the function, named *tinu*(0.05,  $\nu_{eff}$ ) can calculate  $k$  for the Student- $t$  distribution.

contains the time series data with  $n$  samples, each mean value for the  $j$ -th measurement, i.e.,  $\bar{x}_j$ , represents the short time-averaged value for the  $j$ -th data. Reproducibility indicates the relative variation of  $\bar{x}$  as in the following equation.

$$F'' = \frac{\sigma_{\bar{x}}}{\bar{x}} \quad (7)$$

Here,  $\sigma_{\bar{x}}$  is the standard deviation of  $\bar{x}$ , or the type A uncertainty of  $x$ . To summarize, the repeatability is obtained with a set of samples, while the reproducibility is obtained from a set of measurements. In evaluating the measurement uncertainty, the reproducibility rather than the repeatability should be considered, because the reproducibility includes the notion of repeatability and is directly related with the type A uncertainty.

### 2.3 Calibration of an instrument

Calibration coefficient is the coefficient which is obtained by comparing the readings of the device under test (*DUT*) with those of the reference device (*REF*). The measurement accuracy of the *DUT* is determined by an average value of the relative deviations between the *DUT* and the *REF*.

$$F' = \frac{\bar{x}_{DUT} - \bar{x}_{REF}}{\bar{x}_{REF}} \quad (8)$$

Here,  $\bar{x}_{DUT}$  is the mean value of the *DUT*, and  $\bar{x}_{REF}$  is the mean value of the *REF*.  $F'$  is used again in Eqn. (8), because the relative deviations resemble the repeatability of the measuring quantity,  $x$ . However, to evaluate the difference with true values, ensemble averages should be used as noted in the following equation.

$$F'' = \frac{\bar{\bar{x}}_{DUT} - \bar{\bar{x}}_{REF}}{\bar{\bar{x}}_{REF}} \quad (9)$$

Here,  $\bar{\bar{x}}_{DUT}$  is the ensemble average of the *DUT*, and  $\bar{\bar{x}}_{REF}$  is the ensemble average of the *REF*. Because Eqn. (9) resembles the definition of the reproducibility, it is thought that  $F''$  can represent the measurement accuracy of the *DUT*.

The calibration coefficient,  $\alpha$  can be either a simple ratio between  $\bar{\bar{x}}_{DUT}$  and  $\bar{\bar{x}}_{REF}$  or a set of coefficients by a curve fitting formula of the calibration data.

$$\alpha = \frac{\bar{\bar{x}}_{DUT}}{\bar{\bar{x}}_{REF}} \quad (10)$$

$\alpha$  can be validated, when  $\alpha$  is constant within a certain values in the entire calibration range. If  $\alpha$  is a variable within certain bounds,  $\bar{\bar{x}}_{DUT}$  and  $\bar{\bar{x}}_{REF}$  can be replaced with their differences,  $\Delta\bar{\bar{x}}_{DUT}$  and  $\Delta\bar{\bar{x}}_{REF}$ , to denote the calibration coefficient at specified ranges.

$$\alpha = \frac{\Delta\bar{\bar{x}}_{DUT}}{\Delta\bar{\bar{x}}_{REF}} \quad (11)$$

In the case of a set of coefficients by curve fitting,  $\bar{\bar{x}}_{DUT}$  can be compensated by the curve fitting coefficients, or  $\{\alpha_i, i = 0, 1, 2, \dots, n\}$ , with  $n$ -th order polynomials.

$$\bar{\bar{x}}_{DUT} = \sum_{i=0}^n \alpha_i \bar{\bar{x}}_{REF}^i \quad (12)$$

Although the determination of  $\alpha_i$  seems to be straightforward, uncertainty evaluation of  $\bar{\bar{x}}_{DUT}$  with respect to  $\alpha_i$  is rather a bit difficult (Hibbert, 2006). In a linear and a quadratic

calibration curve, the uncertainty can be evaluated analytically. However, when the fitting curve has third or fourth order polynomials, then the derivation of uncertainty formula becomes difficult.

### 3. Traceability of measurement standards

#### 3.1 Metrology in general

Metrology presents a seemingly calm surface, covering depths of knowledge that are familiar only to a few people, but which most of people make use of (Howarth & Redgrave, 2008). It makes people confident that the world economy is sharing a common perception of quantity measurement, which can be represented as meter, kilogram, liter, watt, mole, etc. The history of defining basic units for metrology is rather a bit long, considering the rapid developments of scientific knowledge in recent years (Howarth & Redgrave, 2008). In 1799, the French National Archives in Paris established two artifacts, which realized the length and the weight standards<sup>2</sup>. In 1946, the MKSA system, which stands for Meter, Kilogram, Second, and Ampere, was established to define the length, the weight, the time, and the electric current standards. In 1954, Kelvin and Candela were included to the MKSA system to define the thermodynamic temperature and the luminous intensity standards, respectively. In 1971, Mole, which was the unit for amount of substance, was enclosed into the MKSA system. Since then, the MKSA system was extended and renamed as the SI unit system (Howarth & Redgrave, 2008)<sup>3</sup>.

As scientific knowledge is being accumulated, the definition of units within the SI system has been changed. The method to re-define the basic units has been suggested by long-term researches, regarding physical constants, and the re-definition of units has been reviewed and discussed by the 'Conférence Générale des Poids et Mesures', or the CGPM<sup>4</sup>. The present definitions of the basic units are given as follows (Howarth & Redgrave, 2008).

1. Length: the length of the path travelled by light in a vacuum during a time interval of  $1/299,792,458$  of a second, denoted with meter [m]
2. Weight: the mass of the international prototype of the kilogram, denoted with kilogram [kg]
3. Time: the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom, denoted with second [s]
4. Electric current: the electric current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to  $2 \times 10^{-7}$  newton [N] per meter of length, denoted with ampere [A]
5. Thermodynamic temperature: the fraction  $1/273.16$  of the thermodynamic temperature of the triple of water, denoted with Kelvin [K]
6. Luminous intensity: the luminous intensity in a given direction of a source that emits monochromatic radiation of frequency  $540 \times 10^{12}$  hertz [Hz] and has a radiant intensity in that direction of  $1/683$  watts per steradian, denoted with candela [Cd]

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<sup>2</sup> The 'Bureau International des Poids et Mesures', or BIPM, which is located in Paris, holds the length and the weight standards since 1799. (<http://www.bipm.org/>)

<sup>3</sup> The SI unit system stands for the 'Système international d'unités'.

<sup>4</sup> CGPM refers to the General Conference on Weights and Measures. (<http://www.bipm.org/en/home/>)



7. Amount of a substance: the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kg of carbon-12. When the mole is used, the elementary entities must be specified and the elementary entities may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles, denoted with mole [M].

Several definitions of the basic units were substituted with newer ones by advent of new technologies. In the case of the length standard, the He-Ne lasers, invented in 1960's, substituted the artefact, which had been made in 1799. In the case of the electric current standard, the Josephson semiconductor played a vital role to enhance its measurement accuracy. In the case of the time keeping, an atomic fountain technology is suggested as the primary standard. In addition, in the case of the weight standard, a watt balance is being suggested to re-define the weight, instead of the artefact, which has been the primary standard since 1799. It is noteworthy that physical constants from modern physics such as the Planck constant are considered as candidates for re-defining the basic units. It is because of the belief that the physical constants are well-defined, so that the realizations derived from these physical constants would not be changeable as large as the standards established by the artefacts. However, such a notion has not been fulfilled yet, because the current technology cannot provide measurement accuracy smaller than that of the current primary standards (Gläser et al., 2010).

Redundancy means that two independent measurement principles are compared with each other to validate their measurement accuracies and uncertainties. In the case of re-defining the weight standard with the watt balance based on the Planck constant, some metrologists consider to check the watt balance with other measuring principles, such as a silicone sphere based on the Avogadro constant. By means of redundancy, it will be convinced whether the developing measurement technique would be satisfactory to replace the current primary standard or not (Gläser et al., 2010).

A traceability chain indicates an unbroken chain of comparisons, all having stated uncertainties from primary standards to industrial standards (Howarth & Redgrave, 2008). The traceability chain has been devised to maintain the quality of measurement by relating measurement results of industrial standards to references at the higher levels, ending at primary standards. The primary standards are established by the national metrology institute, or the NMI in a country. The purpose of the NMI is to establish the national measurement standards and to realize the definition of units within the framework of the SI unit system<sup>5</sup>. Either the NMI or the national government can appoint a designated institute, or a DI, to hold some part of the national measurement standards (Howarth & Redgrave, 2008). Accredited laboratories can transfer measurement uncertainty from the primary standards to industrial standards by holding transfer standards. The accredited laboratories are licensed from the national government, according to the accreditation scheme to provide industry with an appropriate calibration service. The national measurement standard established by the NMI can be transferred to the industrial standards via the accredited laboratories. Therefore, the traceability chain, established by the NMI and the accredited laboratories, can increase the reliability of economic activities, which is supported by certifying the quality of industrial instruments with suitable scientific data.

<sup>5</sup> The units can be divided into the basic units (m, kg, s, A, K, Cd, M) and their derived units (N, Pa, W, V, m/s, ...).

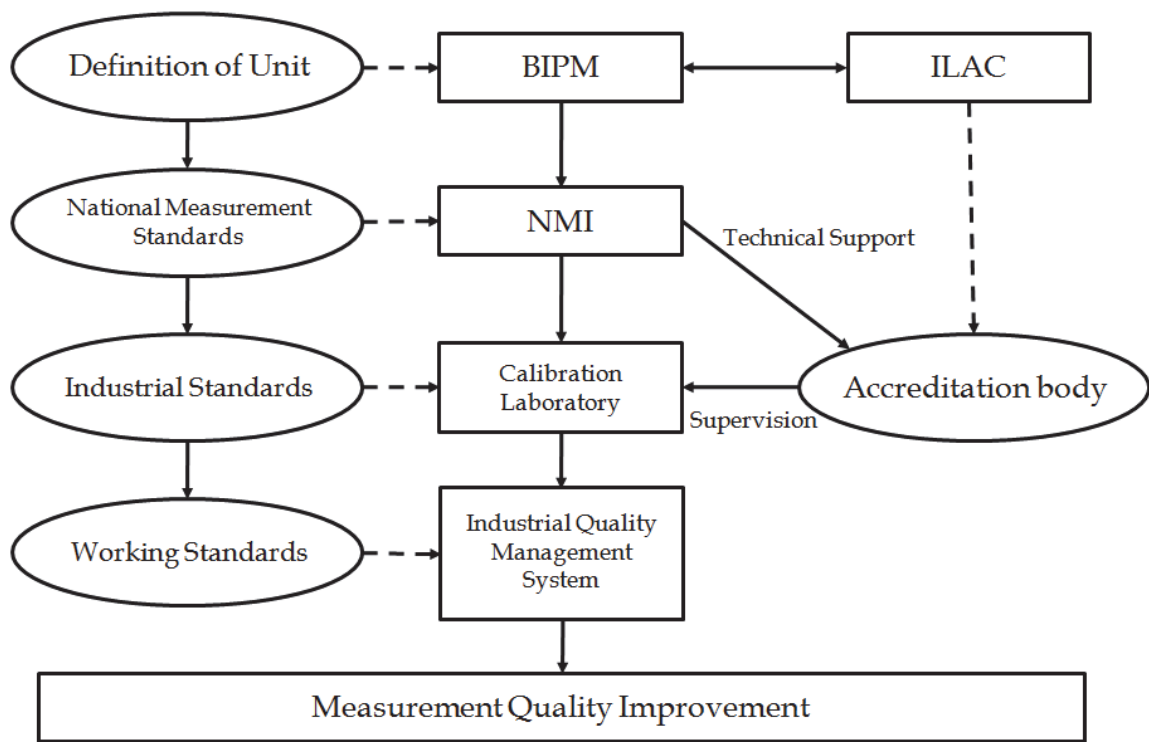


Fig. 1. Traceability of measurement standards (excerpted from Howarth & Redgrave, 2008)

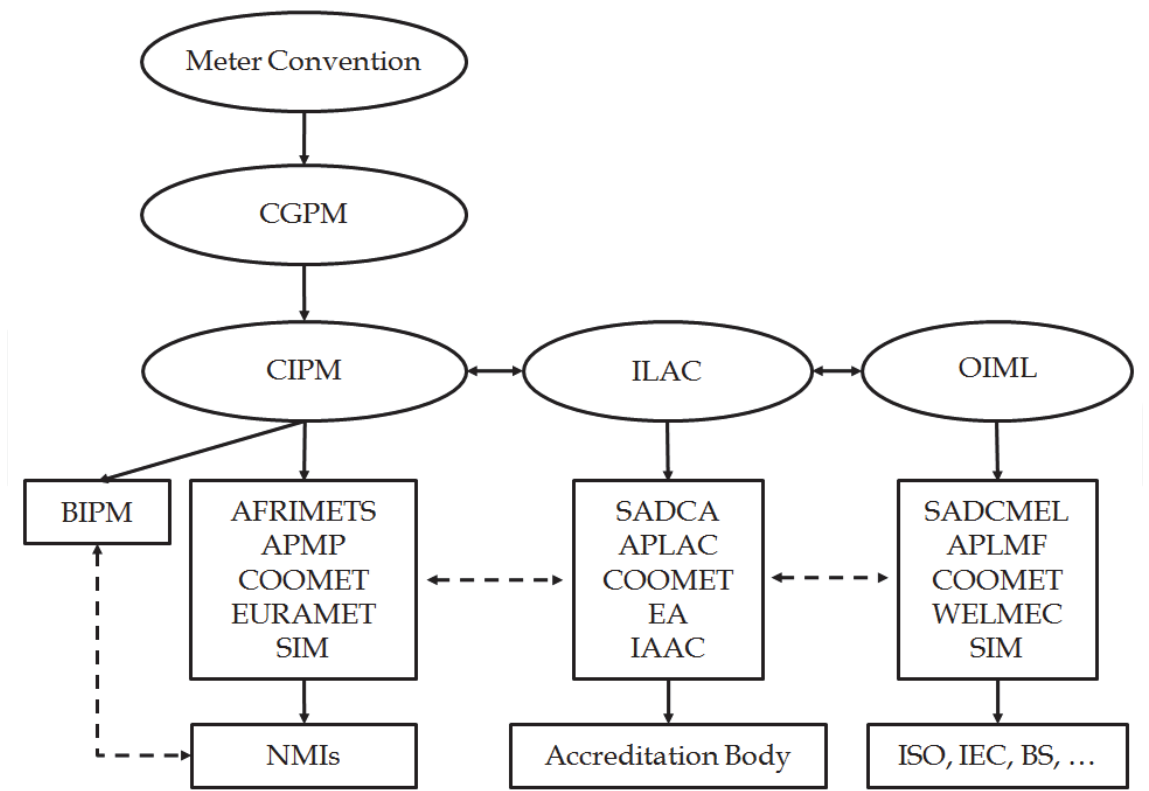


Fig. 2. Meter convention organization and its related organizations (excerpted from Howarth & Redgrave, 2008)



For the national measurement standards in a country to be recognized internationally, the country should participate in the Meter Convention and agree to the Mutual Recognition Arrangement prepared by the Comité Internationale des Poids et Mesures (CIPM), or the CIPM MRA (Howarth & Redgrave, 2008). The CIPM MRA was signed in 1999, slightly revised on some technical points in 2003, consisting of two parts (Howarth & Redgrave, 2008). The first part of the CIPM MRA relates to the establishment of the degree of equivalence of the national measurement standards in a country. The second part of the CIPM MRA concerns the mutual recognition of calibration and measurement certificates issued by participating institutes. These approaches can be supported by International Key Comparisons, or KCs, to check the degree of equivalence of the national standards, which is established by the participating NMIs. If the degree of equivalence of a participating NMI is located within a certain threshold level in comparison with the Key Comparison Reference Value, or the KCRV, then the calibration certificates, issued by the participating NMI, are recognized by other participating NMIs. In this case, a logo, engraved with the CIPM MRA, can be attached on the calibration certificates. Therefore, the CIPM MRA can enhance the international trades by removing technical barriers, regarding both import and export of measurement equipments<sup>6</sup>.

The impact of the CIPM MRA can be understood with a simple example. When an instrument produced in a country A is exported to a country B, the measurement quality of the instrument must be certified by an accredited laboratory in the country B. This is a requirement from a customer, residing in the country B. In other cases, the instrument can be calibrated in another accredited laboratory, which is internationally recognized and located in a country C. Without the CIPM MRA, the instrument must be sent to the country B or the country C to issue a calibration certificate for the instrument. After that, the instrument should be sent to the customer in the country B. However, with the CIPM MRA, the instrument can be also sent to the other accredited laboratory in the country A. In this case, the instrument can be returned to the manufacturer of the instrument soon, because the accredited laboratory is located within the country A. Then, the instrument can be exported directly to the country B with an acceptable calibration certificate. With the calibration certificate issued by the accredited laboratory in the country A, the overall cost for the calibration service would become lower than the case of calibrating the instrument in the country B or the country C. In addition, the delivery time for the instrument would be saved, which leads to providing lower price for the instrument when the manufacturer exports the item to the country B. Therefore, the CIPM MRA provides benefits to both the manufacturer and the customer in the country A and the country B<sup>7</sup>.

Because the international KC is a prerequisite to fulfill the spirit of CIPM MRA, it is necessary to learn some notions of the international KC. There are three levels of the international KCs, namely, a CC-KC, a RMO-KC, and a bilateral comparison. At first, the CC-KC is the world-wide KC, which is supervised by the Technical Committees, or the TC, in a specified field of the Consultative Committees, or the CC, belonged to the BIPM. Secondly, the RMO-KC is the regional KC, which is hosted by the Regional Metrology

<sup>6</sup> Some documents regarding the CIPM MRA can be found at <http://www.bipm.org/en/cipm-mra/>.

<sup>7</sup> Similar examples can be found in KRISS CIPM MRA homepage ([http://www.kriss.re.kr/eng/mra/03\\_1.html](http://www.kriss.re.kr/eng/mra/03_1.html)).

Organizations, or the RMOs<sup>8</sup>. As in the CC-KC, the RMO-KC is supervised by the TC members, belonged to the RMO. Finally, the bilateral comparison is the international comparison to check the two independent national measurement standards, established at two participating NMIs. Any of these KCs should be reported to the RMOs or the BIPM to enroll their results to the BIPM database, or the KCDB<sup>9</sup>.

To organize an international KC, a pilot laboratory, which leads the whole process of the international KC, must prepare a test protocol that describes how the KC is to be performed. The pilot laboratory provides an artifact or a transfer standard, and circulates the artifact to the participating NMIs according to the test schedule. The purpose of the artifact is to provide a guideline for estimating the degree of equivalence among the national measurement standards established in the participating NMIs. As a circulation scheme of the artifact, the round robin test is usually preferred; however, other circulation schemes can be adopted, depending on the type of the KCs. After collecting all the calibration data of the transfer standards with reference to the national measurement standards of the participating NMIs, the pilot laboratory estimates the Key Comparison Reference Value, or the KCRV. The degree of equivalence is then calculated by comparing the calibration data given by the participating NMIs with the KCRV. In some cases, the degree of equivalence is normalized within the range of (0 ~ 1). This is because sometimes the normalized degree of equivalence is easier to be understood. When more than three NMIs participate in the international KC, bilateral comparisons are also performed because KCRVs for every two participating NMIs can be estimated. After summarizing the results for the international KC, the pilot laboratory submits a draft report to the RMO office. After suitable revisions are made according to the suggestions of the technical committee members of the RMO, the draft report is approved as the final KC report, and published in both the BIPM homepage and the Metrologia technical supplement (Terao et al., 2007; Terao et al., 2010).

In view of traceability, the relationship between the CC-KC and the RMO-KC should be linked via the KCRV, because the RMO-KC is smaller in scale than the CC-KC. To establish linkage between the CC-KC and the RMO-KC, link laboratories, which have participated in the CC-KC, participate also in the RMO-KC to bridge between the two KC results. In this case, the same artifact, once used in the CC-KC, should be employed in the subsequent RMO-KC. If there are any changes in the characteristics of the artifact due to long-term stability, correction factors to the KCRV should be calculated. Toward this end, a weighted average of the degree of equivalence among the link laboratories can be considered to modify the KCRV in the RMO-KC, as an alternative method (Terao et al., 2007; Terao et al., 2010).

### 3.2 Air speed metrology

Air speed is a derived physical quantity, which is based on the mass measurement, according to the classification by the BIPM (Howarth & Redgrave, 2008). The Consultative Committee for Mass and related quantities, or the CCM, manages the physical quantities

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<sup>8</sup> In the RMOs, there are the APMP (Asia – Pacific region), the COOMET (East European – Siberian region), the EURAMET (European region), the SIM (North and South American region), and the AFRIMETS (African region).

<sup>9</sup> The KCDB has a homepage at <http://kcdb.bipm.org/>

such as mass, force, torque, pressure, density, viscosity, flow rate and flow velocity<sup>10</sup>. A sub-committee under the CCM, named as the Technical Committee for Fluid Flow, or the TCFF, is in charge of the air speed metrology. The air speed metrology is classified into K3 category, therefore, the traceability for the air speed metrology is managed within the scope of the CCM.FF.K3. Hence, the CC-KC, regarding the air speed metrology, is termed as the CCM.FF.K3-KC. The first round of CCM.FF.K3-KC was held in 2005, and an ultrasonic anemometer was used as a transfer standard in the first round CC-KC (Terao et al., 2007). The reason, why the ultrasonic anemometer was used, was because the ultrasonic anemometer showed good measurement accuracy comparable with that of laser Doppler anemometers, which were established as primary standards in the participating NMIs. In the CC-KC, each participating NMI calibrated the ultrasonic anemometer (the *DUT*) with the laser Doppler anemometer (the *REF*) in a wind tunnel (Terao et al., 2007). The role of the wind tunnel was to provide a testing environment to check both the repeatability and the reproducibility of the *DUT* and to provide calibration data for estimating the *KCRV* that was a crucial part of the KC.

### 3.2.1 Wind tunnels

Wind tunnels can be divided into three categories according to the range of air speed. In the low air speed of (0.1 – 1.5) m/s, a wind tunnel, which has a test section with large cross-sectional area, is adopted to generate a low-speed environment for calibration of anemometers<sup>11</sup>. Sometimes, the low-speed wind tunnel has a sonic nozzle bank at the downstream side of a diffuser (Pereira & Jabardo, 1998). This is because the sonic nozzle bank can control the flow rate in the test section of the wind tunnel with high precision. In addition, the sonic nozzle bank can be used as a primary standard for estimating the mean air speed in the test section. In this case, an anemometer, or the *DUT* is installed within the test section of the wind tunnel, while the sonic nozzle bank, or the *REF* controls the air speed in the test section. Other than the low-speed wind tunnel, a moving rail system can be employed for calibrating the anemometers (Spazzini et al., 2009; Piccato et al., 2010)<sup>12</sup>. In the moving rail system, an anemometer is installed on top of a carriage and is moving along a rail under the carriage, as shown in Fig. 3. A laser interferometer can measure the distance between the location of the interferometer to the carriage due to a retro-reflector attached on the side of the carriage. In combination with a timer board, the reference speed of the carriage can be measured by the laser interferometer, or the *REF*. On the other hand, the anemometer, or the *DUT*, installed on the carriage, indicates a value corresponding to the moving velocity of the carriage. Note that the movement of the anemometer in the moving rail system can be viewed as the air speed toward the anemometer, installed in the test section of the low-speed wind tunnel, according to the Galilean transformation (Pope, 2000).

In the medium air speed of (1.5 – 40) m/s, several types of wind tunnels can be applied. At first, an open suction type wind tunnel can have a large test section with high contraction ratio (Barlow et al., 1999). This type of wind tunnel has a large inlet area to take quiescent air

<sup>10</sup> There are several Consultative Committees in the CIPM. For example, CCL (length), CCTF (time and frequency), CCM (mass), CCAUV (acoustics and vibrations), CCEM (electro magnetism), CCPR (photometry and radiometry), CCQM (quantity of substance), CCRI (radioactive irradiation), CCT (temperature), and CCU (units) are existent.

<sup>11</sup> This type of wind tunnel was introduced by the National Metrology Institute of Japan, or NMIJ.

<sup>12</sup> There are two towing carriage systems to calibrate anemometers at low air speeds in NMIJ. (<http://www.nmij.jp/english/org/lab/3/>)

to the test section. Air filters can be installed at the front of the inlet section to prevent dust from entering the test section and to provide a certain amount of pressure drop for generating uniform flows at the inlet. A honeycomb-shaped panel and several sheets of screens are installed in the settling chamber of the wind tunnel. A contraction section makes the air flows more uniform and stable. Downstream of the test section, a diffuser is placed to give less adverse pressure gradient by increasing the cross-sectional area along the main flow direction. When the open suction type wind tunnel is used for calibration purposes, air in front of the inlet section should be as quiescent as possible. Toward this end, a baffle can be installed at the side of the inlet section to prevent flow disturbances at the inlet of the wind tunnel<sup>13</sup>. When the fluctuations of air flows at the inlet of the wind tunnel are concerned, the closed-type wind tunnel can be considered (Barlow et al., 1999; Tropea et al., 2007). In the closed-type wind tunnel, air is circulated within a square duct, so that the flow quantities as well as fluid pressure, thermodynamic temperature or humidity can be stabilized more than the open suction type wind tunnel. An axial fan generates air flows, and the air flows go through mechanical parts such as the honeycomb, the screen, the contraction, the diffuser, and the test section. However, because the overall size increases due to the circulating ducts, the test section size could be smaller than that of the open suction type wind tunnel, if the installation site for constructing a wind tunnel is limited in size. In addition, the open suction type or the closed-type wind tunnels utilize a square duct as a test section, so that some problems due to the growth of a boundary layer flow at the wall of the test section can be concerned for calibration purposes.

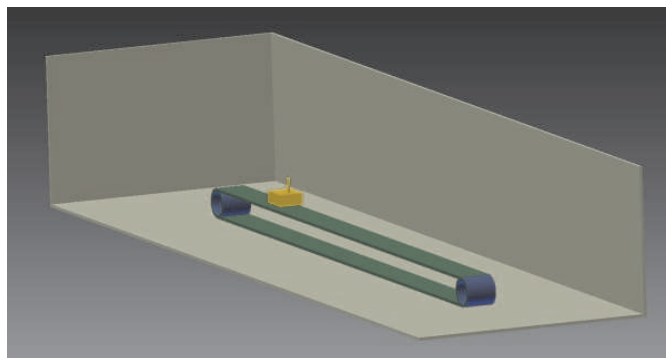


Fig. 3. Schematic diagram of low-speed facility with a towing carriage

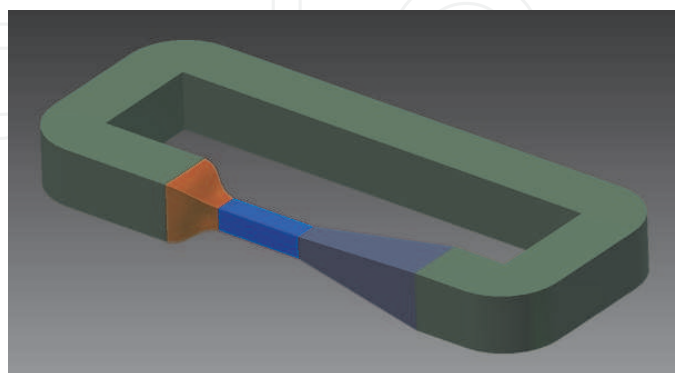


Fig. 4. Schematic diagram of a closed type wind tunnel

<sup>13</sup> The idea of installing a baffle at the side of the inlet section was given by G. E. Mattingly, when he visited at the Korea Research Institute of Standards and Science, or KRISS in 2006.

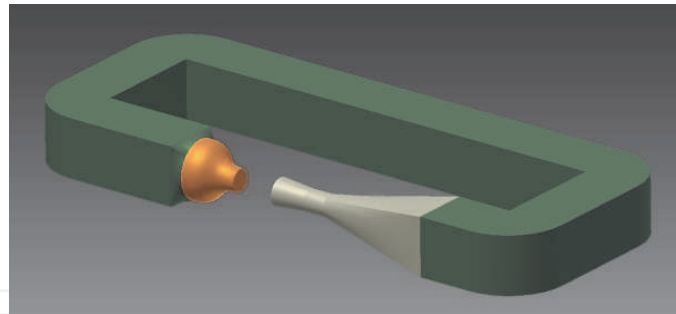


Fig. 5. Schematic diagram of a Göttingen type wind tunnel

The Göttingen type wind tunnel adapts a nozzle with a circular cross-section to generate stable air flows in the test section (Jian, 2009). Because the nozzle produces a potential core in the center of the air flows, the quality of air flows should be better than that of the square duct flows. Nonetheless, the size of the test section is limited, because of the rather a bit smaller size of the nozzle.

In the high air speed of (40 – 70) m/s, closed-type wind tunnels are mostly utilized, because of the ability generating stabilized air flows, compared with other types of wind tunnels. In the high air speed measurement, it should be careful about the thermodynamic temperature increase during anemometer calibrations due to the amount of heat, generated by friction of blades of an axial fan, transferred toward the test section (Barlow et al., 1999; Dixon, 2010). The application area of the high-speed wind tunnels can be automobile industry, aeronautics, and geographical fluid dynamics, including calibration of anemometers for meteorological purposes. Some examples of wind tunnel testing are given in the literature (Tropea et al., 2007).

### 3.2.2 Anemometers

Anemometers can be divided into several types in view of the measurement quality. The most accurate anemometer would be the Laser Doppler Anemometer, or the LDA<sup>14</sup>. The LDA can be used as the national measurement standard in air speed metrology, because the measurement accuracy of the LDA can be achieved as low as 0.07 % (Kurihara et al., 2002; Yeh & Hall, 2008; Jian, 2009; Yang et al., 2002). The LDA formula is as follows.

$$V = \frac{\lambda f_D}{2 \sin\left(\frac{\theta}{2}\right)} \quad (13)$$

Here,  $V$  is the air speed [m/s],  $\lambda$  is the wavelength of a laser beam [nm],  $f_D$  is the Doppler frequency of a seeding particle [Hz], and  $\theta$  is the laser beam crossing angle [rad].  $\lambda$  can be obtained from a table, regarding lasers (Arecchi & Schulz-Dubois, 1972),  $f_D$  can be measured with a high-speed digitizer, and  $\theta$  can be measured by traversing the LDA probe carefully (ITTC, 2008; Jian, 2009; Kurihara et al., 2002; Yang et al., 2002; Yeh & Hall, 2007; Yeh & Hall, 2008).

When the LDA was invented in 1960's, it was believed that it was not necessary to calibrate the LDA (Yeh & Cummins, 1964). However, soon after its invention, it was found that the LDA was not a calibration-free instrument, because the fringe spacing, which was the most important part of the LDA, was not uniform within the measurement volume of the LDA. The characteristics of Gaussian beam optics, governing the working principles of the LDA, make the fringe spacing divergent or convergent along the laser beam axis (Miles, 1996). The

<sup>14</sup> Sometimes, the LDA can be named as the Laser Doppler Velocimeter, or the LDV.



fringe distortion is because of the locations of two laser beam waists relative to the crossing point of the two laser beams. Therefore, an endeavor to align the laser beam waists is necessary to attain an ideal fringe divergence for the LDA (Yang et al., 2002).

The ultrasonic anemometer can be used as a transfer standard because of high accuracy and good reproducibility (Terao et al., 2007; Terao et al., 2010). There are two kinds of measuring techniques to determine air speeds with the ultrasonic anemometers; One is the sing around and the other is the Doppler techniques. The sing around technique needs a pair of ultrasonic sensors to construct ultrasonic paths for measuring both the air speed and the speed of sound.

$$c + V = \frac{L_1}{t_1} \quad (14)$$

$$c - V = \frac{L_2}{t_2} \quad (15)$$

Here,  $c$  is the speed of sound [m/s],  $L_i$  ( $i = 1, 2$ ) is the path length between a pair of ultrasonic sensors (one is in the upstream direction and the other is in the downstream direction), and  $t_i$  ( $i = 1, 2$ ) is the transit time of ultrasonic waves from the transmitter to the receiver of the ultrasonic sensors. From Eqns. (14) and (15), the air speed and the speed of sound can be solved as follows.

$$c = \frac{1}{2} \left( \frac{L_1}{t_1} + \frac{L_2}{t_2} \right) \quad (16)$$

$$V = \frac{1}{2} \left( \frac{L_1}{t_1} - \frac{L_2}{t_2} \right) \quad (17)$$

Pitot tube can be also used as another transfer standard of air speed measurement, because the measured velocity by the Pitot tube is reliable (Blom et al., 2008). The working principle of the Pitot tube is the Bernoulli equation for air speed and differential pressure between the total and the static pressure holes. The equation for the Pitot tube is as follows (ISO, 2008a; Tavoularis, 2005).

$$V = (1 - \varepsilon) \sqrt{\frac{2\Delta P}{\rho}} \quad (18)$$

Here,  $(1-\varepsilon)$  is a compressibility correction factor,  $\rho$  is the air density [kg/m<sup>3</sup>] and  $\Delta P$  is the differential pressure indicated by the Pitot tube [Pa]. The air compressibility can be expressed as follows (ISO, 2008a).

$$1 - \varepsilon = \left[ 1 - \frac{1}{2\gamma} \frac{\Delta p}{\rho} + \frac{\gamma-1}{6\gamma^2} \left( \frac{\Delta p}{\rho} \right)^2 \right]^{1/2} \quad (19)$$

Here,  $\gamma$  is the ratio of specific heat capacities ( $c_v$  and  $c_p$ ). The air density can be expressed as follows (Picard et al., 2008).

$$\rho = \frac{PM_a}{ZRT} \left[ 1 - x_v \left( 1 - \frac{M_v}{M_a} \right) \right] \quad (20)$$

Here,  $P$  is the atmospheric pressure [Pa],  $M_a$  is the molar mass of dry air [g/mol],  $M_v$  is the molar mass of water [g/mol],  $x_v$  is the mole fraction of water vapour,  $Z$  is the compressibility factor,  $R$  is the molar gas constant [J/mol·K], and  $T$  is the thermodynamic temperature [K]. If simplified by calculations, Eqn. (20) becomes as follows.

$$\rho = [3.483\,740 + 1.4446 \cdot (x_{CO_2} - 0.0004)] \cdot \frac{P}{ZT} (1 - 0.3780x_v) \quad (21)$$



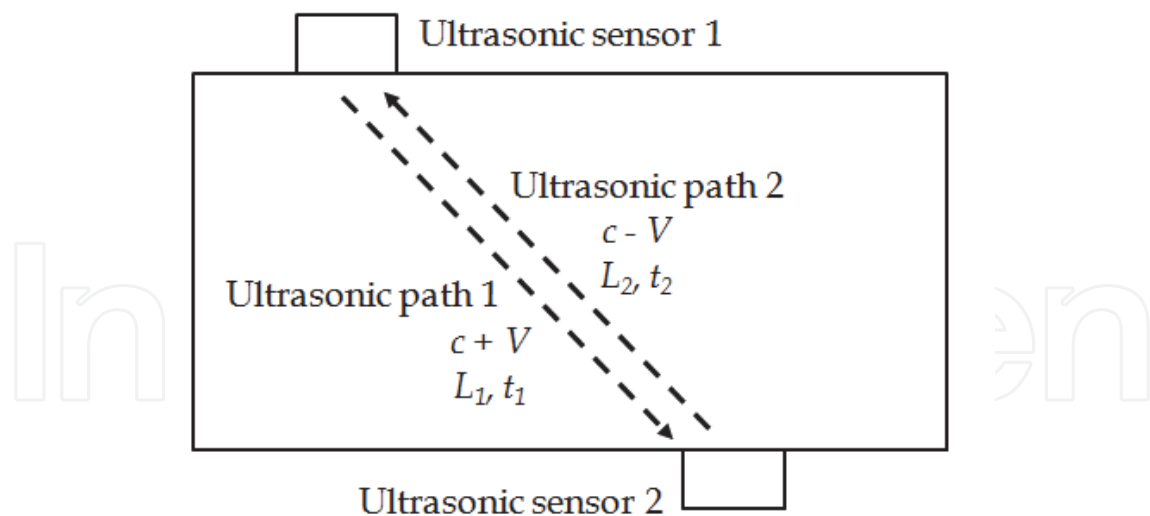


Fig. 6. Schematic diagram of sing around type ultrasonic anemometry

Here,  $x_{CO_2}$  is the mole fraction of  $CO_2$  in the air.

In industrial applications, thermal anemometers and rotational anemometers are commonly used. The equations of the thermal anemometers are as follows (Bruun, 1995).

$$E^2 = A + B\sqrt{V} \quad (22)$$

or

$$\sqrt{V} = \sum_{i=0}^4 A_i E^i \quad (23)$$

Here,  $E$  is the electric voltage [V].  $A$ ,  $B$ , and  $A_i$  are calibration coefficients. In the case of the rotational anemometers, the equation is given like this.

$$V = r\omega \quad (24)$$

Here,  $r$  is the radius of a rotational vane [mm], and  $\omega$  is the rotational frequency [rad/s].

In view of air speed metrology, the thermal and rotational anemometers have accuracy of about  $\pm 1\%$ . Their application area includes fluid machinery, environmental monitoring, and wind engineering, etc. These anemometers are to be calibrated to maintain the measurement traceability in the air speed measurement. The Pitot tubes and the ultrasonic anemometers have accuracy of about  $\pm 0.5\%$ , and these can be employed as industrial standards for air speed measurement. In many accredited institutes, the Pitot tubes and the ultrasonic anemometers are adopted as reference anemometers for calibration service. The LDA has measurement accuracy of less than  $\pm 0.2\%$ . Therefore, the LDA can be used as a national measurement standard. However, some accredited institutes have the LDA as an industrial standard. In this case, the measurement accuracy of the LDA systems, which are located in different institutes, can be estimated by performing bilateral or multilateral key comparisons. Alternatively, many NMIs establish a means of calibrating the LDA, particularly calibrating the fringe divergence within the measurement volume of the LDA, by rigid rotation. A rotating wheel or a spinning wire are good examples of the LDA calibrator (ITTC, 2008; Jian, 2009; Kurihara et al., 2002; Yang et al., 2002; Yeh & Hall, 2007; Yeh & Hall, 2008). Because the rigid rotation has measurement accuracy of less than  $\pm 0.1\%$ , these devices can be considered as the primary standard for air speed metrology.

Anemometer	Uncertainty factors
LDA	beam crossing angle, Doppler frequency, fringe divergence, wavelength
Ultrasonic	sensor distance, sound speed, time measurement, ...
Pitot tube	air density, differential pressure, expansibility, sensor alignment, ...
Thermal	curve fitting uncertainty, temperature, voltage, ...
Rotational	sensor alignment, radial location of rotating parts, rotating speed, ...

Table 2. Uncertainty factors for various types of anemometers.

3.2.3 Calibration of anemometers

When the anemometers are calibrated with a reference anemometer, calibration coefficient  $\alpha$  can be determined by calculating the ratio between the two anemometers.

$$\alpha = \frac{V_{REF}}{V_{DUT}} \tag{25}$$

Here,  $V_{DUT}$  is the air speed from the calibrated anemometer (*DUT*) [m/s], and  $V_{REF}$  is the air speed from the reference anemometer (*REF*) [m/s]. In view of traceability,  $\alpha$  can be obtained successively and transferred to other types of anemometers with lower measurement accuracies. Therefore,  $\alpha$  can be represented as follows.

$$\alpha = \frac{V_{REF}}{V_{DUT1}} \frac{V_{DUT1}}{V_{DUT2}} \frac{V_{DUT2}}{V_{DUT3}} \dots \frac{V_{DUTn-1}}{V_{DUTn}} = \alpha_1 \alpha_2 \alpha_3 \dots \alpha_n \tag{26}$$

Here,  $\{\alpha_i, i = 1, 2, \dots, n\}$  means the calibration coefficients by subsequent comparison between two anemometers, according to the traceability chain. For example,  $\alpha_1$  can be a calibration coefficient between the spinning wire and the LDA,  $\alpha_2$  can be another calibration coefficient between the LDA and the ultrasonic anemometer, and so on. In these successive measurements, the uncertainty can be estimated as a vector sum among the calibrated apparatuses.

$$U = k \sqrt{u_{REF}^2 + u_{DUT1}^2 + u_{DUT2}^2 + \dots + u_{DUTn}^2} \tag{27}$$

Here,  $u_{REF}$  is the standard uncertainty of the *REF*, and  $\{u_{DUTi}, i = 1, 2, \dots, n\}$  is the standard uncertainties of the *DUT*. The coverage factor,  $k$  is then calculated by estimating the effective degree of freedom  $\nu_{eff}$  as explained previously.

$$\nu_{eff} = \frac{(U/k)^4}{\frac{u_{REF}^4}{\nu_{REF}} + \frac{u_{DUT1}^4}{\nu_{DUT1}} + \frac{u_{DUT2}^4}{\nu_{DUT2}} + \dots + \frac{u_{DUTn}^4}{\nu_{DUTn}}} \tag{28}$$

Here,  $\nu_{REF}$  is the effective degree of freedom of the *REF*, and  $\{\nu_{DUTi}, i = 1, 2, \dots, n\}$  is the effective degrees of freedom of the *DUT*.

3.2.4 Uncertainty estimation of anemometers

There are three kinds of methods to estimate the uncertainty of anemometers. The first method is to use first-order partial differentiation of an equation to the specific type of the anemometer (Thomas & Finney, 1988). If the anemometer equation is written as follows,

$$y = f(x_1, x_2, \dots, x_n) \tag{29}$$

then the uncertainty can be estimated based on the first-order partial differentiations of  $y$ .

$$u(y) = \left[ \left( \frac{\partial f}{\partial x_1} \right)^2 u(x_1)^2 + \left( \frac{\partial f}{\partial x_2} \right)^2 u(x_2)^2 + \dots + \left( \frac{\partial f}{\partial x_n} \right)^2 u(x_n)^2 \right]^{1/2} \quad (30)$$

Here,  $\partial f / \partial x_i$  can be denoted as  $c_i$ , a sensitivity coefficient (BIPM, 1993). As an example, the uncertainty of the LDA can be estimated by partial differentiation of Eqn. (13).

$$u(V) = \left[ \left( \frac{\partial V}{\partial \lambda} \right)^2 u(\lambda)^2 + \left( \frac{\partial V}{\partial f_D} \right)^2 u(f_D)^2 + \dots + \left( \frac{\partial V}{\partial \theta} \right)^2 u(\theta)^2 \right]^{1/2} \quad (31)$$

$$\frac{\partial V}{\partial \lambda} = \frac{f_D}{2 \sin\left(\frac{\theta}{2}\right)} \quad (32)$$

$$\frac{\partial V}{\partial f_D} = \frac{\lambda}{2 \sin\left(\frac{\theta}{2}\right)} \quad (33)$$

$$\frac{\partial V}{\partial \theta} = -\frac{1}{4} \frac{\lambda f_D \cos\left(\frac{\theta}{2}\right)}{\left(\sin\left(\frac{\theta}{2}\right)\right)^2} \quad (34)$$

The second method is to differentiate the anemometer equation, as seen in the first method. However, in this case, an equation with multiplication is more appropriate, because all the calculation is done by relative ratios of each independent variable.

$$y = x_1^a x_2^b \dots x_{i-1}^p x_i^q x_{i+1}^r \dots x_n^z \quad (35)$$

The first-order partial differentiation of  $i$ -th independent variable can be written as follows.

$$\frac{\partial y}{\partial x_i} = q x_1^a x_2^b \dots x_{i-1}^p x_i^{q-1} x_{i+1}^r \dots x_n^z \quad (36)$$

If the Eqn. (36) is divided by the Eqn. (35), then the ratio of  $\frac{\partial y}{\partial x_i}$  to  $y$  is calculated as follows.

$$\frac{\frac{\partial y}{\partial x_i}}{y} = \frac{q}{x_i} \quad (37)$$

Therefore, the ratio of uncertainty of  $y$  can be represented as follows.

$$\frac{u(y)}{y} = \left[ \left( \frac{\partial y}{\partial x_1} \right)^2 \left( \frac{u(x_1)}{y} \right)^2 + \left( \frac{\partial y}{\partial x_2} \right)^2 \left( \frac{u(x_2)}{y} \right)^2 + \dots + \left( \frac{\partial y}{\partial x_n} \right)^2 \left( \frac{u(x_n)}{y} \right)^2 \right]^{1/2} \quad (38)$$

Further simplified,

$$\frac{u(y)}{y} = \left[ \left( \frac{a}{x_1} \right)^2 u(x_1)^2 + \left( \frac{b}{x_2} \right)^2 u(x_2)^2 + \dots + \left( \frac{z}{x_n} \right)^2 u(x_n)^2 \right]^{1/2} \quad (39)$$

In case of the rotational anemometers, the uncertainty can be estimated referring to Eqn. (24).

$$\frac{u(V)}{V} = \left[ \left( \frac{1}{r} \right)^2 u(r)^2 + \left( \frac{1}{\omega} \right)^2 u(\omega)^2 \right]^{1/2} \quad (40)$$

The third method is to use a simplified version of Monte-Carlo simulation (ISO, 2008b; Landau & Binder, 2005). An input variable is composed of a large number of data more than 1,000,000, according to the Gaussian random process. The input variables to the anemometer equation should be independent and uncorrelated, to ensure a rigorous simulation for uncertainty estimation<sup>15</sup>. The mean and the standard deviation of each input variable are used to scale a Gaussian random signal. After that, the output variable, or the measuring quantity, is estimated by calculating the equation with the input variables. An example to estimate the measurement uncertainty of the Pitot tube is given as follows.

(Example) Estimate the standard (or Type A) uncertainty of the Pitot tube by using a Monte-Carlo simulation. The mean values and the standard deviations of each input variable are listed as follows. The number of simulation is 1,000,000.

$\Delta P$  : mean value = 5 Pa, standard deviation = 0.05 Pa (or 1 %)  
 $\rho$  : mean value = 1.18 kg/m<sup>3</sup>, standard deviation = 0.012 kg/m<sup>3</sup> (or 1 %)  
 $\varepsilon$  : mean value = 0.00002, standard deviation =  $2 \times 10^{-7}$  (or 1 %)

(Solution) The uncertainty estimation can be performed by programming with MATLAB<sup>16</sup>. To generate three Gaussian random signals with 1,000,000 samples, the command can be written as follows.

```
[s1, s2, s3] = RandStream.create('mlfg6331_64', 'NumStreams', 3);
r1=randn(s1, 1000000, 1);
r2=randn(s2, 1000000, 1);
r3=randn(s3, 1000000, 1);
```

To confirm the uncorrelated signals, correlation coefficients can be calculated in matrix form.

```
A = corrcoef([r1, r2, r3]);
```

To give the above-mentioned mean values and standard deviations, following commands can be written.

```
% For differential pressure
del_P_avg = 5;
del_P_std = 0.05;
del_P = del_P_avg + del_P_std * r1;
% For air density
rho_avg = 1.18;
rho_std = 0.012;
rho = rho_avg + rho_std * r2;
% For expansibility coefficient
epsilon_avg = 0.00002;
epsilon_std = 2E-7;
epsilon = epsilon_avg + epsilon_std * r3;
```

<sup>15</sup> In the case of correlated input variables, there should be another assumptions to generate random signals, which can give cross-correlation coefficients among the input variables. However, the book chapter only focuses on the case of the uncorrelated input variables.

<sup>16</sup> In this example, MATLAB (R2010b) was used to generate Gaussian random signals.

To calculate the Pitot tube velocity, the following commands can be added.

```
% For Pitot tube velocity
V=(1-epsilon).*(2*del_P./rho).^0.5;
V_avg=mean(V);
V_std=std(V);
V_ratio=V_std/V_avg*100;
```

The rests are to look at the calculated results for uncertainty estimations.

```
sprintf('V: mean=%12.4e, std=%12.4e, ratio=%12.4e %%', V_avg, V_std, V_ratio)
figure('Name','Pitot tube velocity','NumberTitle','off')
subplot1 = subplot(4,1,1); box(subplot1,'on'); hold(subplot1,'all');
plot(del_P); ylabel('ΔP [Pa]');
subplot2 = subplot(4,1,2); box(subplot2,'on'); hold(subplot2,'all');
plot(rho); ylabel('ρ [kg/m³]');
subplot3 = subplot(4,1,3); box(subplot3,'on'); hold(subplot3,'all');
plot(epsilon); ylabel('ε');
subplot4 = subplot(4,1,4); box(subplot4,'on'); hold(subplot4,'all');
plot(V); ylabel('V [m/s]'); xlabel('number of realization');
```

Here are some results for estimating the standard deviation of  $V$ .

```
A =      1.0000    0.0008   -0.0004
      0.0008    1.0000    0.0012
     -0.0004    0.0012    1.0000
V [m/s]: mean = 2.9111e+000, std = 2.0741e-002, ratio = 7.1248e-001 %
```

Therefore, the mean and the standard deviation of  $V$  are 2.91 m/s and 0.021 m/s, respectively. The standard (or Type A) uncertainty of  $V$  would be  $\frac{0.021}{\sqrt{1,000,000}} = 2.1 \times 10^{-5}$  [m/s]<sup>17</sup>. From the matrix  $A$ , it is noticed that cross-correlation coefficients among  $r_1$ ,  $r_2$ , and  $r_3$ , are small enough to assume the uncorrelated random signals among  $\Delta P$ ,  $\rho$ , and  $\varepsilon$ .

### 3.2.5 Uncertainty estimation of a calibration curve

When a curve fitting formula is considered to give a customer an estimate of air speed correction, uncertainty that is based on least square methods should be included (Hibbert, 2006). In many cases, in graphing the calibration data, the reference quantity (*REF*) is located in the horizontal axis, while the tested quantity (*DUT*) is drawn in the vertical axis. Assuming the homoscedacity, there is no variance in the *REF*, or the horizontal axis (Hibbert, 2006). However, when estimating the measurement uncertainty, variances of the *DUT* by  $m$  measurements (reproducibility) premises the variance of the *REF*. Therefore, in this case, the variance of the *REF* can be estimated by calculating the residual standard deviation (Hibbert, 2006). In case of a linear regression, the calibration curve can be defined as follows.

$$\bar{y} = \hat{a} + \hat{b}\bar{x} \quad (41)$$

<sup>17</sup> This standard uncertainty considers only the type A uncertainty, which is determined by measurements. The type B uncertainty, which can be obtained from tables, calibration certificates, etc., should be included to complete the uncertainty estimation.

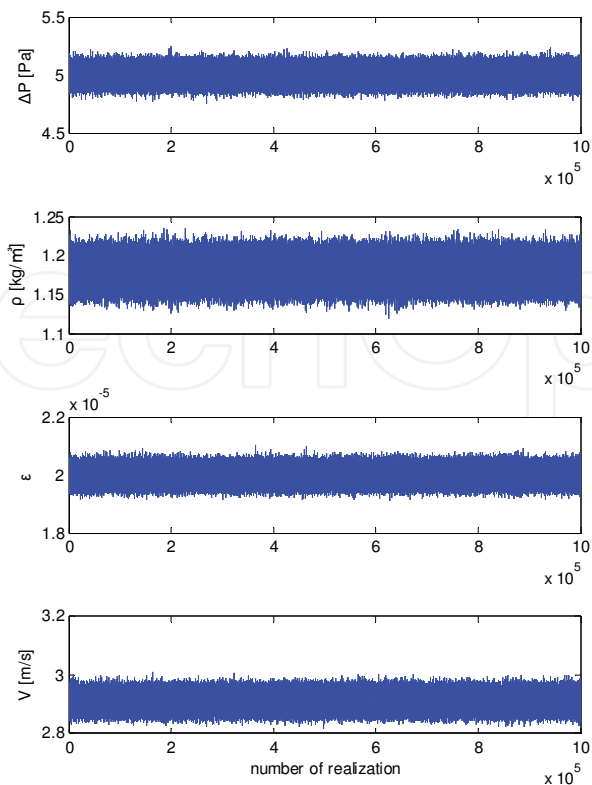


Fig. 7. An example of a simplified Monte Carlo simulation

Here,  $\hat{a}$  and  $\hat{b}$  are calibration coefficients.  $\bar{x}$  and  $\bar{y}$  are mean values of  $n$ -realizations, i.e.,  $\{x_i, y_i, i = 1, 2, \dots, n\}$ . Then, the residual standard deviation,  $s_y$  can be calculated as follows (Hibbert, 2006).

$$s_y = \sqrt{\frac{\sum_i (y_i - (\hat{a}x_i + \hat{b}))^2}{n-2}} \tag{42}$$

Then, the standard uncertainty can be derived from the following equation (Hibbert, 2006).

$$s_{\hat{x}_0} = \frac{s_y}{b} \sqrt{\frac{1}{m} + \frac{1}{n} + \frac{(y_0 - \bar{y})^2}{b^2 \sum_i (x_i - \bar{x})^2}} \tag{43}$$

Here,  $y_0$  is the mean value of  $m$  responses, at a single point of  $y_i$ , and  $\hat{x}_0$  is the estimate of  $x_0$  by using Eqn. (41). ( $m$  means the reproducibility, and  $n$  means the number of calibration points.)

4. International comparisons

4.1 CC-KC

The international Key Comparison aims to compare the national measurement standards among participating NMIs and to harmonize the measurement traceability for establishing the MRA. The meaning of the Key Comparisons is like this; when a person holds a key to a box, then other people should also have the same keys to open the box. This means that the measurement uncertainty among the participating NMIs should be located within an acceptable level so that the national measurement standards are recognized to be equal.



The first round of the CC-KC, which was an world-wide level, was performed from April to December in 2005, and its final report was published in October 2007 (Terao et al., 2007). Four NMIs, including NMIJ (Japan), NMi-VSL (Netherlands), NIST (USA), and PTB (Germany), participated in the CC-KC. NMIJ was the pilot laboratory for the CC-KC. A three-dimensional ultrasonic anemometer was used as a transfer standard to be calibrated in a wind tunnel or a specially-designed circular duct using the LDA. The calibration results were summarized with air speeds of 2 m/s and 20 m/s as a calibration coefficient,  $x_i$ , which has the same meaning as  $\alpha$  in Eqn. (25). Repeatability was checked by measuring the air speed for 60 s to report the averaged air speed at 2 m/s and 20 m/s. Reproducibility was also checked by several sets of air speed data.

To obtain the KCRV, which can be established as a standard value to compare the national measurement standards among the participating NMIs, a weighted average was used and a chi-squared test was performed to validate the weighted average. According to the Cox method, the weighted average was acceptable as the KCRV if the chi-squared test was passed (Cox, 2002). When the chi-squared test was failed, another method such as the simplified Monte Carlo simulation with  $10^6$  random samples should be tried (ISO, 2008b; Terao et al., 2007).

To harmonize the national measurement standards of the participating NMIs, the degree of equivalence,  $d_i$  was defined as follows (Terao et al., 2007).

$$d_i = x_i - x_{REF} \quad (44)$$

Here,  $x_i$  is the calibration coefficient of  $i$ -th participating NMI, and  $x_{REF}$  is the KCRV. Another definition of the degree of equivalence was introduced to compare the two national measurement standards between two participating NMIs.

$$d_{i,j} = x_i - x_j \quad (45)$$

The standard uncertainties of  $d_i$  and  $d_{i,j}$  can be determined by vector sums between  $x_i$  and  $x_{REF}$ , or between  $x_i$  and  $x_j$ , as follows (Terao et al., 2007).

$$u(d_i) = \sqrt{u(x_i)^2 + u(x_{REF})^2} \quad (46)$$

$$u(d_{i,j}) = \sqrt{u(x_i)^2 + u(x_j)^2} \quad (47)$$

The number of equivalence, or the normalized degree of equivalence can be derived as follows (Terao et al., 2010).

$$En_i = \frac{|d_i|}{ku(d_i)} \quad (48)$$

$$En_{i,j} = \frac{|d_{i,j}|}{ku(d_{i,j})} \quad (49)$$

Here,  $En_i$  is the number of equivalence for  $d_i$ ,  $En_{i,j}$  is the number of equivalence for  $d_{i,j}$ , and  $k$  is the coverage factor. The role of the number of equivalence is to provide a guideline whether the national measurement standard of each participating NMI has an equivalence in comparison with the KCRV or other national measurement standards from other NMIs. If the value is less than 1, then it can be said that the national measurement standard has equivalence with those of other NMIs.

## 4.2 RMO-KC

An RMO-KC, named as the APMP.M.FF.K3-KC, was performed from February to December in 2009 to give a supporting evidence for fulfilling the spirit of MRA (Terao et al., 2010). In the APMP-KC, five air speeds of (2, 5, 10, 16, 20) m/s were tested, and two of the air speeds, i.e., 2 m/s and 20 m/s, were selected to link the results to those of the CC-KC. The participating laboratories in the APMP-KC were NMIJ (Japan), CMS/ITRI (Chinese Taipei), KRISS (Korea), NIST (USA), NMC A\*STAR (Singapore), and VNIIM (Russia). NMIJ was the pilot laboratory. In addition, there were two link laboratories (NMIJ and NIST) to link the KC results to those of the CC-KC. For this purpose, the three-dimensional ultrasonic anemometer, which had been adopted in the CC-KC, was also chosen in the APMP-KC. To link between the APMP-KC and the CC-KC results, a weighted sum was calculated using the calibration data from the two link laboratories as in the following equations (Terao et al., 2010).

$$D = \sum_i w_i D_i \quad (50)$$

$$D_i = x_{i,CCM} - x_{i,APMP} \quad (51)$$

$$w_i = \frac{\frac{1}{u_i^2}}{\frac{1}{u_{NMIJ}^2} + \frac{1}{u_{NIST}^2}} \quad (52)$$

Here,  $D_i$  is the difference between the CC-KC and the APMP-KC results.  $x_{i,CCM}$  is the CC-KC results of the link laboratories, and  $x_{i,APMP}$  is those of the APMP-KC.  $w_i$  is a weighting coefficient, which can be calculated from the standard uncertainties of the link laboratories. In particular,  $u_{NMIJ}$  is the standard uncertainty of the NMIJ and  $u_{NIST}$  is the standard uncertainty, given by the NIST, respectively.

Through these calculations, the APMP-KC results could be linked to those of the CC-KC by modifying the APMP-KC results as follows (Terao et al., 2010).

$$x'_i = x_{i,APMP} + D \quad (53)$$

Here,  $x_{i,APMP}$  is the APMP-KC result of  $i$ -th participating NMI and  $x'_i$  is its modified value. With  $x'_i$ , the normalized degree of equivalence, or the number of equivalence,  $En_i$  could be estimated to harmonize the national measurement standards among the participating NMIs. In 2008, another RMO-KC, named as Euromet.M.FF-K3 KC, was reported. The participating laboratories were NMi-VSL (Netherlands), CETIAT (France), DTI (Denmark), SFOMA (Swiss), PTB (Germany), TUMET (Turkey), University of Tartu (Estonia), LEI (Lithuania), INTA (Spain), and MGC-CNR (Italy). NMi-VSL was the pilot laboratory. The Euromet-KC was rather a bit an independent Key Comparison, because the transfer standards used in the KC were different from those used in the CC-KC or the APMP-KC (Blom et al., 2008). A Pitot tube with an amplifier and a thermal anemometer were chosen in the Euromet-KC as two transfer standards. Several air speeds between 0.2 m/s and 4.5 m/s were tested, which was prone to low air speed range, compared with the air speed ranges in the CC-KC. There was no linkage between the Euramet-KC and the CC-KC, due to the different measurement ranges of air speeds. The KCRV was calculated from a weighted average as follows.

$$KCRV = \frac{\sum_i \frac{x_i}{u(x_i)^2}}{\sum_i \frac{1}{u(x_i)^2}} \quad (54)$$

$$u_{KCRV} = \frac{1}{\sqrt{\sum_i \frac{1}{u(x_i)^2}}} \quad (55)$$

The chi-square test was performed to validate the KCRV, and the chi-square test was passed in the Euramet-KC. With the calibration coefficient  $x_i$ , the degree of equivalence or the number of equivalence could be estimated to harmonize the national measurement standards among the participating NMIs.

## 5. Conclusion

To enhance international trades with low technical barriers, some common perceptions of measurement standards are necessary. In the early stages of measurement standards, definition of basic units was the most important issue. With technological advancements, the re-definitions of the basic units based on the physical constants have been suggested to increase the measurability of the international standards. Traceability chain was probably the second issue to establish an industrial infrastructure with reliable measurement standards. Mutual recognition arrangement could be the third issue to enhance the economic activity by lowering technical barriers, such as calibration certificates. This was supported by the traceability chain and the international key comparisons in view of metrologists.

In air speed measurement, various types of anemometers, including the rigid body rotation, the LDA, the ultrasonic anemometer, the Pitot tube, the thermal and the rotational anemometers, consisted the hierarchy of the traceability chain. Wind tunnels, such as the open suction, the close, and the Göttingen type wind tunnels, were used to generate a stable test environment for anemometer calibrations. Uncertainty estimation of anemometers was performed in three ways; first-order partial differentiation, a modified partial-differentiation with a multiplicative equation form, and a simplified Monte Carlo simulation.

Finally, some aspects of the international key comparisons, regarding the air speed measurement, was surveyed. In the key comparisons, the key comparison reference value was deduced from a weighted average, and validated using the chi-square test. In some cases, a Monte Carlo simulation was applied to obtain a suitable reference value for the key comparison. To link between two different key comparison results, link to the key comparison reference value was discussed. Throughout the analysis on the key comparisons, the degree of equivalence among the participating national metrology institutes was validated and the analysis was used as a supporting evidence to fulfill the embodiment of the mutual recognition arrangement.

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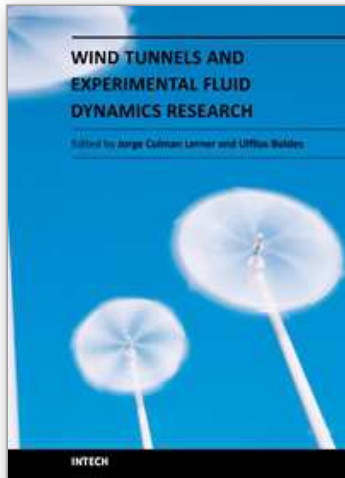
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