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Automated volume measurement for weihts using acoustic volumeter

M. Ueki [1], T. Kobata [1], K. Ueda [1] and A. Ooiwa [1]

1 National Metrology Institute of Japan (NMIJ), AIST

Abstract

An automated method using an acoustic volumeter to measure the volume of weights mass ranging from 1 g to 100 g is described. The automated system consists of a manipulator of three-axis motion, a container lifting mechanism, a stationary weight magazine with 30 weights positions, a control unit, a personal computer and an acoustic volumeter. The acoustic volumeter with the weight exchanging system enables to perform fully-automated volume measurements. The reliability of the automated acoustic volumeter is experimentally examined, and the measurement uncertainty of the volume of the small mass weights is evaluated. Combined standard uncertainty is estimated to be 0.0021 cm^3 in case of volume measurement of a 100 g weight, whose nominal volume is 12.5 cm^3. It is confirmed that the automated acoustic volumeter can be applied to volume measurements of small weights with sufficient accuracy for the OIML class E_1.

Keywords: acoustic volumeter, weight, volume, automated measurement

1. Introduction

In mass comparisons of weights in air, it is essential to consider the effect of the air buoyancy, according to required accuracy. This correction for the air buoyancy is obtained from the volume of a weight and the density of air, and the former must be measured with a required uncertainty before the mass comparison. When the conventional mass of a 50 g weight of the highest class E_1 is to be calibrated with an expanded uncertainty of 0.01 mg, for example, referring to the OIML International recommendation R111 [1], it is necessary to measure its volume of about 6.25 cm^3 with an expanded uncertainty of 0.02 cm^3 or less.

The volume of weights has been generally measured by the hydraulic weighing method, in which the Archimedes' principle is applied to measure the water buoyancy for the weight and then its volume. In the hydraulic weighing method, however, weights to be measured are immersed in water, so that the problem of water adsorption or any contamination on the surface of weights arises, resulting in any change of the mass of weights. A series of these measurements for the hydraulic weighing method as well as for confirming the mass stability of weights needs time-consuming works. To solve these problems, a measuring method of the weight volume using an acoustic volumeter was developed by the National Metrology Institute of Japan(NMIJ), AIST and Measurement Science Laboratory Ltd. [2]. This technique realizes a comparison measurement of the volume of weights in the air, with ease and in a short time.

In order to improve the efficiency of the volume measurement using the acoustic volumeter, a weight exchanging system for the acoustic volumeter has been developed for the volume measurements of weights ranging from 1 g to 100 g. The weight exchanging system consists of a manipulator of three-axis motion, a control unit, a container lifting mechanism, and a stationary weight magazine with 30 weights positions. The acoustic volumeter with the weight exchanging system enables to perform fully-automated volume measurements.

This paper describes features of the automated system, and experimental results of performance test using the automated acoustic volumeter. It allows measuring the volume of the OIML class E_1 weights from 1 g to 100 g with the uncertainty required for these weights. A set of volume reference weights with known volumes is prepared for the comparison measurement. The reliability of the volume measurement of the small mass weights using automated acoustic volumeter is experimentally examined, and the uncertainty of the volume measurement is evaluated.

2. Acoustic volumeter

Figure 1 shows the schematic drawing of an acoustic volumeter, VM-300, manufactured by Measurement Science Laboratory Ltd. [2]. The upper part of the main body comprises a reference volume container and lower part, a measurement volume container, and both containers are made of aluminum alloy. Through a bypass tube, the static pressure and humidity of air in both containers are equalized. The loudspeaker located between the two containers is driven by a sinusoidal signal whose frequency can be varied by changing the computer program. The sound pressures of air in containers are respectively measured by two microphones. In the acoustic volumeter, an object to be measured is housed in the measurement volume container. The amplitude of the sound pressure generated by a loudspeaker varies due to a change in the inner air volume of the measurement container before and after its mounting. This amplitude change is measured, from which the volume of the object is to be known. From the output signals of two microphones, 1 and 2, connected to the respective containers for measuring the sound pressures, the ratio of amplitudes R is calculated as equation (1).

$$R = \frac{E_1}{E_2} \qquad (1)$$

Here, E_1 is the amplitude of output signal e_1 from microphone 1, and E_2 that of output signal e_2 from microphone 2. By using this ratio, the possible errors arising from any changes of the surrounding conditions can be compensated to obtain a higher accuracy of measurement. The details of the VM-300 are given in the paper [2].

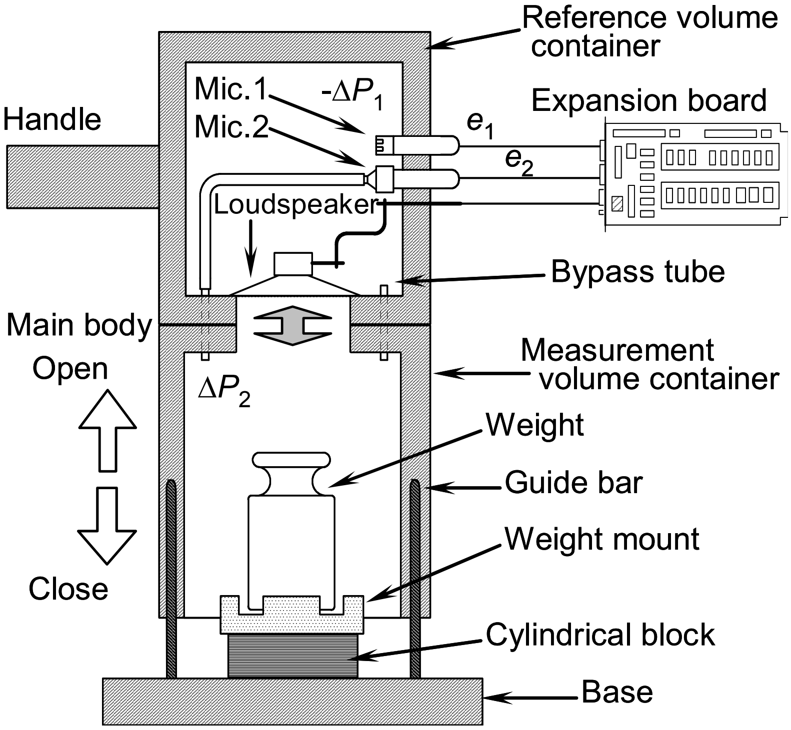

Figure 1 Schematic drawing of the acoustic volumeter

The measurement volume container can be selected from three containers of large, medium and small volumes, corresponding to the nominal values of weights to be measured. A small volume container for the small weights is used in this work. The operating parameters for VM-300, that is, gain 1, gain 2, driving frequency, sampling number and measuring period are taken as ×30, ×10, 60 Hz, 8192 and 20 seconds, respectively in the experiments.

2.1 Measuring equation

There are two measuring methods of applying the acoustic volumeter: one is to use a reference weight with a known volume, and the other is to use two reference weights with known volumes [2]. In the present work, the latter method is adopted in order to realize a higher accuracy in the volume measurement. Supposing that a test weight of the OIML-recommended shape is compared with two reference weights having the OIML-shape, the volume of test weight V is obtained simply by the following equation.

Here, V_{r1} and V_{r2} are the volumes of the reference weights 1 and 2 ($V_{r1} < V_{r2}$) respectively, R_{r1} and R_{r2} are the amplitude ratios of the output signals from the two microphones for the reference weights respectively mounted in the measurement container, and R_t is the one for the test weight mounted. As described, two reference weights and a test weight are set in the acoustic

$$V = (V_{r2} - V_{r1})\frac{R_{r1} - R_t}{R_{r1} - R_{r2}} + V_{r1} \qquad (2)$$

volumeter one by one, and the volume of the test weight is obtained from these three measurements of the amplitude ratio. The temperature correction for the volume is neglected here [2], since (a) the weights to be compared are all made of austenitic stainless steel, and (b) the temperatures of the weights are nearly equal to the room temperature.

2.2 Automated acoustic volumeter

The block diagram of the automated system to measure the volume is shown in Figure 2 and its photograph in Figure 3. The acoustic volumeter with the weight exchanging system carries out fully-automated volume comparison measurements. The weight exchanging system consists of a stationary weight magazine, a manipulator, a container lifting mechanism, a control unit and a personal computer. The weight magazine has 30 positions for weights mass ranging from 1 g to 100 g. Test weights and the volume reference weights are placed on the stationary weight magazine. The manipulator of three-axis motion has travel ranges of 500 mm for X-direction, 200 mm for Y-direction and 30 mm for Z-direction, respectively and a positioning accuracy of ±0.02 mm, and sets a measuring weight on the mount of the acoustic volumeter. The container lifting mechanism enables the acoustic volumeter to realize an airtight condition in the measurement volume container by using an air cylinder with flow control valve. The control unit is capable of handling the weight safety by controlling the three-axis positions and the monition speed of the manipulator, and monitoring the vertical position of the acoustic volumeter. The acoustic volumeter and the control unit are operated from the personal computer. The system carries out the volume comparisons according to the procedure programmed in the personal computer, and results of measurements are recorded in the computer.

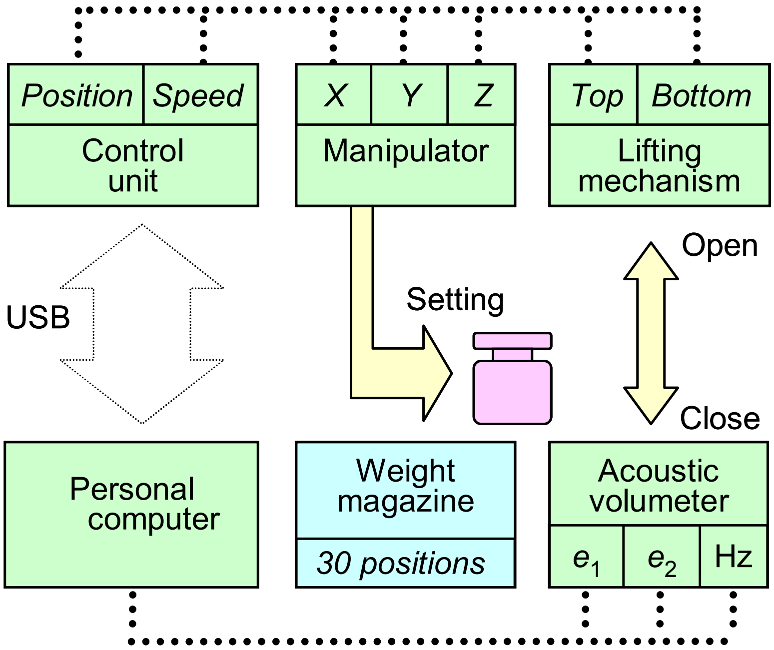

Figure 2 Block diagram of the automated system

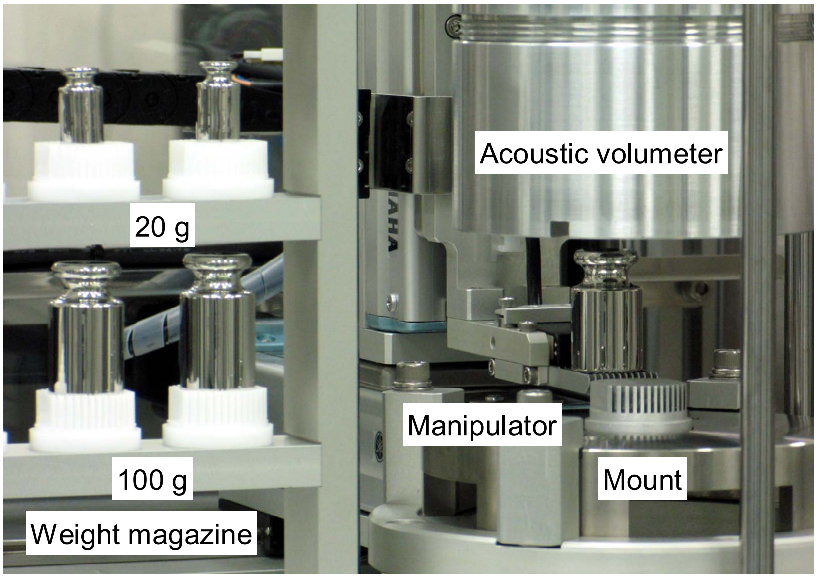

Figure 3 Photograph of the automated system

3. Volume reference weights

The acoustic volumeter is a volume comparator, which needs a reference weight with a known volume. A set of weights named v series has been manufactured in the mass range of 1 g to 100 g, as a reference of volume for the acoustic volumeter. As for the weights from 1 g to 100 g, three weights were prepared for each nominal mass values and marked as v1, v2 and v3 for identification, respectively. Their volumes are 95 %, 100 % and 105 % of the nominal values calculated by (nominal mass [g] / 8.0 [g/cm^3]), for v1, v2 and v3, respectively. The shape of these weights is the OIML-type, and their volume differences of ±5 % are realized by altering the heights in the cylindrical part of the weights, keeping the original dimensions of their knobs. The v series weights made of austenitic stainless steel, and consist of a single piece without any adjusting cavity. The volumes of these 21 weights in total from 1 g to 100 g have been measured by the hydrostatic weighing method. They are exclusively used as the reference standards for the comparison measurement by means of the acoustic volumeter.

3. 1 Hydrostatic weighing measurement

The measured results of the volumes V_{20} at 20 °C of the **v** series weights made by the hydraulic weighing method are given in Table 1, along with their expanded uncertainties (k=2). An electronic balance with a maximum capacity of 111 g and a readability of 0.001 mg is used. A weight holder of the balance is suspended in a water bath. This weight holder has an upper pan in air and a lower pan in water, and a substitution weighing method is realized by using these two pans. The weight holder is in contact with the interface between air and water at its two stainless-steel wires of 0.5 mm in diameter. The effect by the surface tension of water acting to these wires is compensated by the substitution weighing method. In water, a measured weight is loaded or unloaded on the lower pan using a pair of laboratory forceps. This forceps is kept in a same posture in water, even when it is not in use, and any change in the water level is minimized during a weighing cycle. The water bath is made of Pyrex glass, has a rectangular shape of 160 mm in width, 110 mm in depth and 50 mm in height. Any air bubble which might attach to the weight in water can be detected through transparent walls of the bath. Ultra pure water whose specific resistance is above 18 MΩ·cm is used in the bath. The temperature of the water has been measured by a 100-Ω platinum resistance thermometer with a readability of 0.01 °C. The density of the water is determined with a temperature correction by the Chappuis equation [3].

Nominal mass	Marking	$V_{20} \pm U_{95}$ / cm^3
100 g	v1	11.9407 ± 0.0031
100 g	v2	12.5695 ± 0.0031
100 g	v3	13.1975 ± 0.0031
50 g	v1	5.96482 ± 0.00053
50 g	v2	6.27835 ± 0.00053
50 g	v3	6.59183 ± 0.00053
20 g	v1	2.38654 ± 0.00043
20 g	v2	2.51183 ± 0.00043
20 g	v3	2.63720 ± 0.00043
10 g	v1	1.19391 ± 0.00043
10 g	v2	1.25627 ± 0.00043
10 g	v3	1.31878 ± 0.00043
5 g	v1	0.59664 ± 0.00042
5 g	v2	0.62803 ± 0.00042
5 g	v3	0.65941 ± 0.00042
2 g	v1	0.23867 ± 0.00016
2 g	v2	0.25119 ± 0.00016
2 g	v3	0.26373 ± 0.00016
1 g	v1	0.11927 ± 0.00011
1 g	v2	0.12558 ± 0.00011
1 g	v3	0.13186 ± 0.00011

Table 1: Measured volumes of reference weights (V_H)

4. Volume measurement by using the acoustic volumeter

Using the acoustic volumeter and the volume reference weights, the volumes of weights from 1 g to 100 g have been measured to evaluate its reliability. With the reference weights, v1 of 95 % and v3 of 105 % respectively of the nominal volume, calibrated by the hydraulic weighing method, the volumes of test weights V1(not the same set as v1) and v2, with known volumes are measured. The result V_A obtained by the acoustic volumeter is compared with the volume V_H measured by the hydraulic weighing method to confirm their compatibility. 25 measurements are replicated for the two test weights respectively at the mass range from 1 g to 100 g. As seen in eq. (2), two reference weights and a test weight are alternatively mounted in the measurement volume container, and the volume of the test weight is then calculated from three amplitude ratios, R_{r1}, R_{r2} and R_t, measured for these three weights and the volumes of the reference weights. In these first measurements, a set of measurement results of the amplitude ratios in the order of R_{r1} - R_t - R_{r2} is obtained, and they are repeated three times. The mean of the three measured volumes calculated from each set of the results is taken as a measurement result of the volume V_A.

The results of measurements for 2 g weights and 50 g weights are shown in Figure 4. In the figure, the deviation of V_A from the volume V_H obtained by the hydraulic weighing method, (V_A-V_H), is shown with its standard deviation. Among the 50 measurement results for two 50 g weights, the standard deviation of individual measurement is uniform and 0.0033 cm^3 at the largest, whereas for the 2 g weight, it varies irregularly from the minimum of 0.0006 cm^3 to the maximum of 0.0093 cm^3. This dispersion of the individual standard deviations is also observed with the same tendency, in both results for the 1 g and 5 g weights.

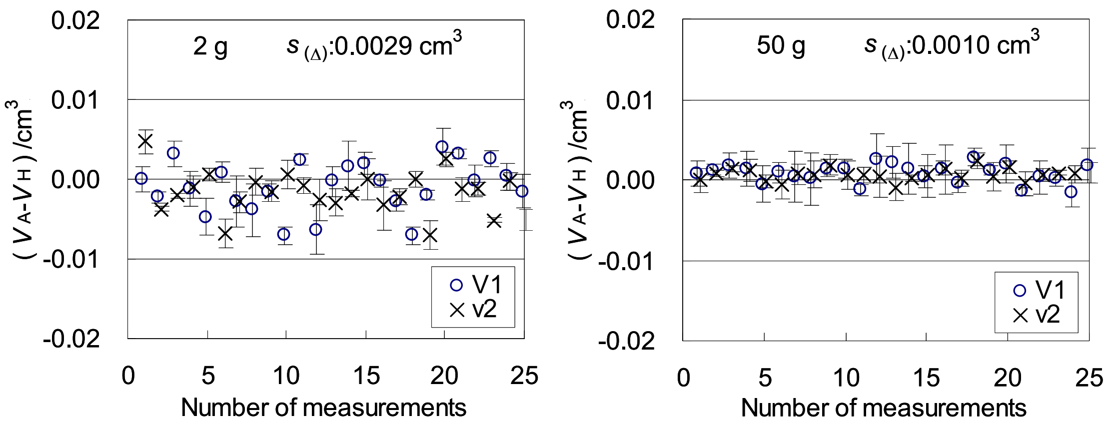

Figure 4. Deviations of measured values V_A from the reference volume V_H

In Table 2, the means of the volume deviations (V_A-V_H) and their standard deviations $s_{(\Delta)}$ calculated from the 50 results for each nominal masse are given. For all the weights from 1 g to 100 g, the means of the volume deviations are smaller than their standard deviations, and it is concluded that there is no significance in volume deviations. Namely, the results of the volume measurements by the acoustic volumeter are confirmed to be compatible with those determined by the hydraulic weighing method.

Nominal mass / g		1	2	5	10	20	50	100
(V_A-V_H) / cm^3	Mean value	-0.0009	-0.0013	-0.0013	-0.0012	0.0007	0.0007	0.0002
	Standard deviation [$s_{(\Delta)}$]	0.0029	0.0029	0.0033	0.0036	0.0013	0.0010	0.0031

Table 2. Mean values and standard deviations of (V_A-V_H) calculated from the 50 results

5. Uncertainty of the volume measurement by the acoustic volumeter

Taking account of the measurement results described in the preceding section, the number of measurements to be needed for the volume measurement of a class E_1 weight is examined, and the uncertainty in that case is evaluated. With the acoustic volumeter, the volume of a weight is determined according to the equation (2), in which only three kinds of the amplitude ratio R are parameters to yield random variations. The term including the related amplitude ratios is therefore defined as R_x, given by eq. (3). The uncertainty of determining the defined amplitude ratio R_x in the n replicated measurements is then given by eq. (4), being derived from the standard deviation $s_{(\Delta)}$ shown in Table 2 and sensitivity coefficient C_{Rx} shown in Table 3.

$$R_x = \frac{R_{r1} - R_t}{R_{r1} - R_{r2}} \quad (3), \qquad u_{(R_x)} = \frac{s_{(\Delta)}}{\sqrt{n} \cdot C_{Rx}} \quad (4)$$

As a result, the combined standard uncertainty of the volume measurement for a 100 g weight is evaluated from the above uncertainty $u_{(Rx)}$ and the uncertainties of the two reference volumes, $u_{(Vr1)}$ and $u_{(Vr2)}$, as shown in Table 3. The number of replicated measurements (n = 3), the degree of freedom for R_x being 2 (= n - 1), is chosen so as to meet the requirement for the expanded uncertainty in the volume measurement of a class E_1 100 g weight. Here, the standard uncertainty due to the resolution of the acoustic volumeter is estimated to be zero. Since there is no significance in volume deviations (V_A-V_H), the standard uncertainty arising from non-linearity of the volumeter is regarded as negligible.

Source	Typical value x_i	Uncertainty $u_{(x\,i)}$	Probability distribution	Divisor	Sensitivity coefficient C_i	Uncertainty in V_A u_i
V_{r1}	11.9407 cm^3	0.0031	*normal*	2	5.0E-01	0.00077
V_{r2}	13.1975 cm^3	0.0031	*normal*	2	5.0E-01	0.00078
R_x	0.50012	0.0014	*normal*	1	1.26E+00	0.00178
V_A: *12.5693* cm^3					u_c	0.00209

Table 3: Uncertainty evaluation of the volume measurement for a 100 g weight (V_A)

The combined standard uncertainties for all the weights up to 100 g are similarly evaluated and their results are given in Table 4. The coverage factor k_p which gives a confidence interval of 95 % determined from the effective degree of freedom is also given in the table. The expanded uncertainty is then calculated by multiplying the coverage factor by the combined standard uncertainty. As the result, the five replicated measurements for the weights of 1 g to 5 g and the three replicated measurements for the weights of 10 g to 100 g allow to satisfy the requirements for the OIML class E_1 weights.

Nominal mass / g	1	2	5	10	20	50	100
Number of measurements	5	5	5	3	3	3	3
Combined standard uncertainty /cm^3	0.0017	0.0017	0.0019	0.0021	0.0008	0.0006	0.0021
Coverage factor [k_p]	2.87	2.87	2.87	4.53	4.53	4.53	4.53
Expanded uncertainty [95%] /cm^3	0.0048	0.0049	0.005	0.010	0.004	0.003	0.009
Uncertainty required for class E_1 weight /cm^3	0.0066	0.0083	0.010	0.014	0.017	0.021	0.035

Table 4: Uncertainties of the volume measurement using the acoustic volumeter [cm^3]

6. Summary

The weight exchanging system for weights ranging from 1 g to 100 g has been developed to improve the efficiency of the volume measurement using the acoustic volumeter. To meet the technical requirements for the highest class E_1 weights of the OIML-type, the automated acoustic volumeter has been applied to the volume measurement of those from 1 g to 100 g. For the comparison measurements, the reference weights which have the volumes of 95 %, 100 % and 105 % of the respective nominal ones have been prepared for the exclusive use, and their volumes have been measured with an expanded uncertainty better than 0.0031 cm^3 by the hydraulic weighing method. Referring to these volumes, the 50 replicated measurements by the acoustic volumeter have been carried out. No significant difference has been observed between these measured results and those by the hydraulic weighing method and the differences are within the standard deviation of 0.0036 cm^3 or less. It is recommended that the number of the replicated measurements should be taken as 5 for the weights of 1 g to 5 g and as 3 for the weights of 10 g to 100 g, when the automated acoustic volumeter is used for the volume measurement of the OIML class E_1 weights.

References

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