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Research on volume determination of mass standards with two acoustic measuring chambers

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ABSTRACT
The acoustic volume measuring method is a promising non-contact method for volume determination of mass weights. To improve the measuring accuracy of volume determination with the non-contact acoustic method, an acoustic measuring system with two measuring chambers is newly designed to compensate for the non-linearity measuring errors. When reducing the remaining air in the measuring chamber, the measuring accuracy can be greatly reduced. The volumes of mass standards ranging from 100 g to 5 kg are tested to evaluate the non-linearity errors of the volume measurement. The relative uncertainties of the acoustic volume determination are below 7.0×10^{-4} (*k*=2).

Section: RESEARCH PAPER

Keywords: mass standard; volume measurement; acoustic method

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1. INTRODUCTION

For the mass measurement of a weight, the ABBA cycle on a mass comparator is used, in which A is the reference (standard) mass weight and B is the test mass weight. The mass comparison is usually carried out in air, based on the difference of the gravitational force caused by the standard or test weight on the mass comparator. The air bouncy can contribute a big uncertainty especially in the high accuracy mass measurement such as the prototype level or E_1 class level. Thus the mass standard's volume needs to be precisely determined for the air buoyancy correction [1].

There are many measurement technologies such as the hydrostatic method, the dimension measuring method and the acoustic method. Although the measuring accuracy cannot be on the same level as the hydrostatic method (usually with relative combined uncertainty as low as 1×10^{-6} (k=1)), the acoustic method is a promising volume measuring method because there is no contact with mass standards during the whole volume measuring procedure, especially for the weights with non-regular shape and 3D curved surfaces. Both the standard weights and test weights don't need to be immersed in any liquid.

M. Ueki et al. firstly developed an acoustic measuring system to determine the volume of mass weights ranging from 1 g to 10 kg at the National Metrology Institute of Japan (NMIJ) [2]-[6]. For the weights with nominal value ranging from 100 g to 10 kg, a relative uncertainty of 1×10^{-3} (k=2) is achieved. For weights ranging from 1 g to 100 g, the measuring combined standard uncertainty is below 0.0021 cm^3 [2]-[5]. An acoustic volume measuring system has also been designed at the National Institute of Metrology China (NIM) to extend the measurement range of the nominal value of mass weights up to 20 kg [7]. However, since the air inside the chamber does not change perfectly adiabatically (necessary to get a high measuring accuracy), the ratio of shape and volume of the reference weight needs to be similar to that of the test weight. Otherwise a large non-linearity measurement error will be introduced to the measuring process.

To investigate the non-linearity contribution in the acoustic measuring method, an acoustic measuring system with two measuring chambers is designed by the National Institute of Metrology China. The volumes of mass standards ranging from

200 g to 5 kg are tested to evaluate the non-linearity errors of the acoustic measuring process.

2. EXPERIMENTAL APPARATUS AND MEASURING PROCEDURE

2.1. Experimental apparatus

The acoustic method is based on gas compressibility laws. Assuming the gas changes adiabatically, the air pressure, P, has a constant relation with the volume of air, V, as expressed in (1):

$$P \times V^{\gamma} = cons \tag{1}$$

Here, γ is the ratio of the specific heats, which is 1.40 at atmospheric pressure and room temperature. The newly designed measuring apparatus made of aluminum alloy with two measuring chambers is shown in Figure 1.

A sinusoidal drive signal from a signal generator is applied to a loudspeaker between the two measuring chambers. This will alternately generate a compression wave with inverse phase in the left chamber and the right chamber.

Two sound pressure sensors (also called microphones) are used to separately measure the pressure changes, that is, ΔP_1 in the left chamber and ΔP_2 in the right chamber, respectively, as shown in (2) and (3), where P_0 is the air pressure in the chamber. The output signals from two microphones, e_1 and e_2, are converted into digital signals and sent to a computer for sound pressure calculation. The resulting sound pressure ΔP_x is measured. The ratio of the pressures R_n can be calculated as $\Delta P_1/\Delta P_2$ [3].

$$\frac{\Delta P_1}{P_0} = \gamma \frac{\Delta V}{V_{01}} \tag{2}$$

$$\frac{\Delta P_2}{P_0} = \gamma \frac{\Delta V}{V_{02}} \tag{3}$$

2.2. Measurement Results

When measuring the volume with the acoustic method, it is assumed that air changes adiabatically in the two measurement chambers [2]-[7]. However, air near the surface of the test weight or reference weight and the wall of the containers changes isothermally [3]. Thus, during the measurement, the actual displaced volume in the chamber by the test weight, V_{t0} and the reference weight, V_{r0} can be expressed with (4) and (5).

$$V_{t0} = V_t - dS_t \tag{4}$$

$$V_{r0} = V_r - dS_r \tag{5}$$

where S_t and S_r are the surface area of the test weight and reference weight, and d is the thickness of the air isothermal layer [5].

The effect of surface area to the volume measurement is not considered firstly, and it means that $V_{t0} \approx V_t$, and $V_{r0} \approx V_r$. Based on the measuring sequence in Figure 2, (6)–(8) can be derived. Thus, the volume of the test weight, V_t, can be calculated with (9). This equation is used to evaluate the non-linearity error caused by the effect of the weight's surface [3].

$$R_1 = \frac{\Delta P_1}{\Delta P_2} = \frac{V_{02} - V_t}{V_{01} - V_r} \tag{6}$$

$$R_2 = \frac{\Delta P_1}{\Delta P_2} = \frac{V_{02} - V_r}{V_{01} - V_t} \tag{7}$$

$$R_3 = \frac{\Delta P_1}{\Delta P_2} = \frac{V_{02} - V_t - V_r}{V_{01}} \tag{8}$$

$$V_t = V_r \times \frac{(R_2 - R_3)(1 + R_1)}{(R_1 - R_3)(1 + R_2)} \tag{9}$$

3. MEASUREMENT RESULTS AND UNCERTAINTY ANALYSIS

3.1. Measuring Results

According to (9), the amplitude ratio R is the key parameter for the acoustic volume measurement. As the driving signal to the loudspeaker showed in Figure 3, the amplitude and frequency of the sinusoidal signal should be carefully chosen to achieve the best measurement of sound pressure and the amplitude ratio R.

Figure 4 shows the relationship between R and the amplitude and frequency of the sinusoidal signal using two measuring chambers. For each amplitude and frequency, 100 samples of sound pressure are acquired. It can be seen that to obtain a repeatability of R better than 1×10^{-4}, the amplitude of the sinusoidal drive signal should be between 1.6 V and 1.9 V,

a) b)

Figure 1. Schematic and pictures of the new measuring apparatus with two measuring chambers.

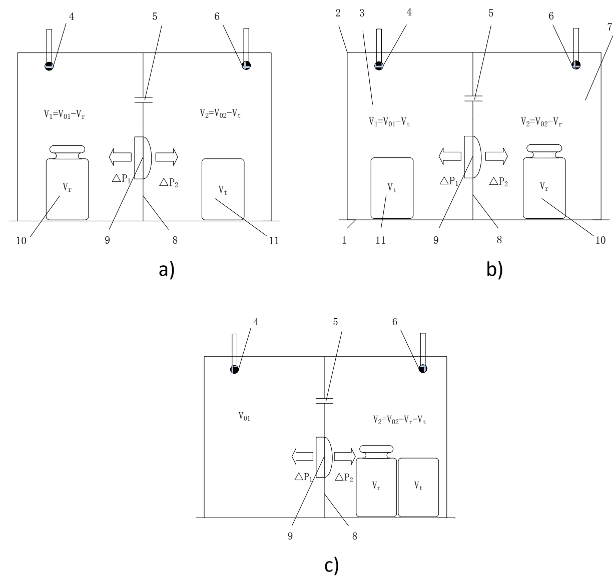

Figure 2. The schematic of procedures (a, b, c) of the measuring process , in which 1: Bottom of measuring chamber; 2: Side walls of measuring chamber; 3: Left measuring chamber; 4: Sound pressure sensor 1; 5: Connecting tube; 6: Sound pressure sensor 2; 7: Right measuring chamber; 8: Separating wall; 9: Loudspeaker; 10: Reference weight; 11:Test weight.

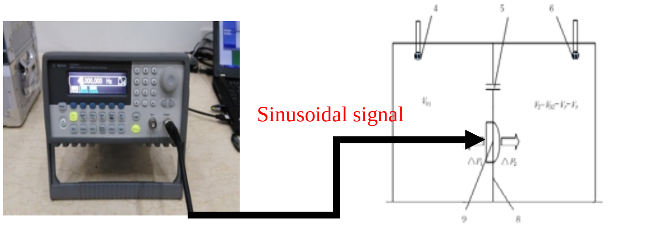

Figure 3. Schematic of the connection of the signal generator to the loudspeaker.

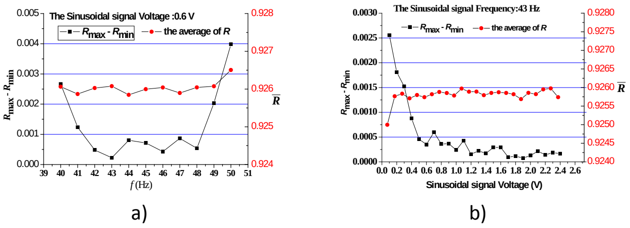

Figure 4. Relationship between *R* and the amplifier or frequency of the sinusoidal signal.

and the frequency should be 43 Hz. The parameters used for the mass volume measurement are shown in Table 1.

According to (9), as shown in Figure 5 to evaluate the non-linearity errors, a nominal mass weight of 100 g is used as the reference weight, and nominal mass weights ranging from 200 g to 5 kg are measured with the 3-step method showed in Figure 2. The non-linearity error is expressed as the deviation of the measurement value from the acoustic method to the volume measuring value from the hydrostatic method. With the same reference weight, the non-linearity error of the measured volume of the test weight increases with its nominal value.

As also shown in Figure 6, a test weight with a nominal value of 2 kg is used as the test weight, and weights ranging from 100 g to 1 kg are used as the reference weight. The non-linearity error of the measured volume of 2 kg weight decreases when the nominal value of the reference weight increases.

Based on the analysis in Figure 5 and Figure 6, it can be

Table 1. Parameters used for the volume measurement.

Parameters	Configuration of the sinusoidal signal
Gain of left chamber (dB)	20
Gain of right chamber (dB)	20
Sinusoidal signal frequency (Hz)	43
Sinusoidal signal voltage (V)	1.6 ~ 1.9

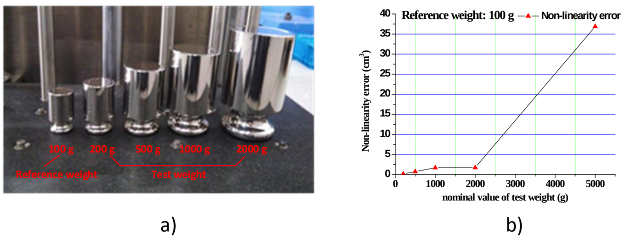

Figure 5. The reference weight of 100 g and test weights ranging from 200 g to 5 kg (a) and the measuring results (b).

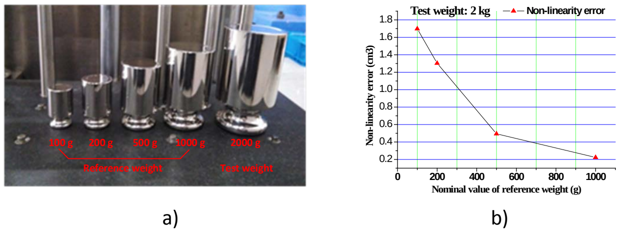

Figure 6. The reference weights ranging from 100 g to 1 kg and test weight of 2 kg (a) and the measurement results (b).

concluded that the larger the difference between the volume, surface or the ratio of volume and surface of the reference weight and the test weight, the higher the non-linearity of the acoustic measuring method can be introduced. If the effect of the weight surface can be compensated, the accuracy of the acoustic volume method can be improved significantly.

To evaluate the effect of the weight surface and to improve the volume measuring accuracy, certain artefacts were put into both measuring containers separately as shown in Figure 7(a) to reduce the volume of air remained in the two containers. The tests weights ranging from 100 g to 5 kg are measured with a 1 kg reference weight. The non-linearity errors were evaluated to investigate the effects of weights' surface. The non-linearity error was defined as the deviation between the volume measured by the acoustic method and the volume measured by the hydrostatic method. The results are shown in Figure 7(c). From 100 g to 5 kg, the non-linearity error shows no significant difference when the surface ratio between the test weight and reference weight changes.

3.2. Uncertainty Analysis

According to (9), describing the calculation of the volume, there are four main uncertainty contribution factors which are the reference weight's volume, R_1, R_2 and R_3. The uncertainty budget of the volume of the 200 g weight using the 100 g weight as reference weight is shown in Table 2.

With the same uncertainty evaluation method, the volume uncertainty evaluation results of weights ranging from 200 g to 5 kg are shown in Table 3, and the relative extended uncertainties show no significant differences for the big contribution of the non-linearity error during the volume measuring process. The volume uncertainties of the 2 kg weight using different reference weights are shown in Table 4. The

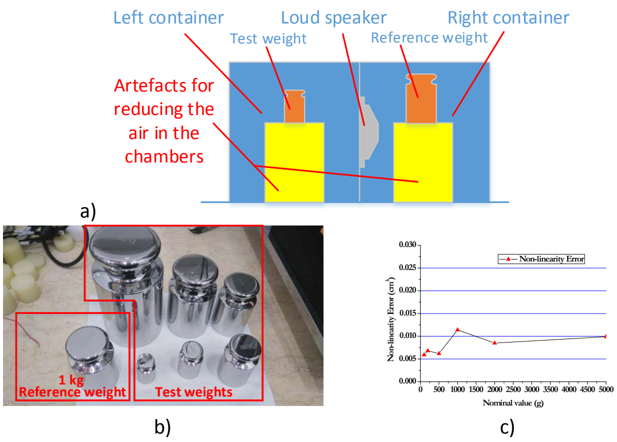

Figure 7. Artefacts in the chamber (a) to reduce the remaining air in the chambers, the picture of 1 kg reference weight and test weights ranging from 100 g to 5 kg (b) and the measuring results (c).

Table 2. Uncertainty budget of the volume of 200 g weight using the 100 g weight as reference weight.

Sources	Uncertainty	Sensitivity coefficient	Uncertainty contribution
Volume of reference weight	0.0005 cm^3	2	0.0010 cm^3
R_1	0.00001	11152 cm^3	0.11 cm^3
R_2	0.00001	5545 cm^3	0.06 cm^3
R_3	0.00001	16672 cm^3	0.17 cm^3
Combined uncertainty			0.21 cm^3
Expanded uncertainty (k=2)			0.42 cm^3
Relative expanded uncertainty (×10^{-2}, k=2)			1.7

Table 3. Uncertainty budget of test weights using the 100 g weight as reference weight.

Sources	**Test weights**				
	5 kg	**2 kg**	**1 kg**	**500 g**	**200 g**
Volume of reference weight(cm^3)	0.025	0.010	0.0050	0.0025	0.0010
R_1(cm^3)	3.14	1.2	0.53	0.27	0.11
R_2(cm^3)	0.06	0.06	0.05	0.05	0.06
R_3(cm^3)	3.20	1.17	0.59	0.32	0.17
Combined uncertainty(cm^3)	4.49	1.68	0.80	0.42	0.21
Expanded uncertainty(cm^3)	8.97	3.36	1.60	0.84	0.42
Relative expanded uncertainty(k=2, ×10^{-2})	1.4	1.4	1.3	1.3	1.7

relative expanded uncertainty decreases with the reference weight's nominal value, and this indicates that the non-linearity errors decrease in the same trend.

However, when the volume of air in both measuring chambers is reduced as shown in Figure 7(a), the measuring accuracy improved immediately, as shown in Table 5. All the relative expanded uncertainties are below 7.8×10^{-4}(k=2). The volume of 5 kg weight is 500 times that of the 100 g weight. However there is no big difference between the volume measuring accuracy of the test weights with different nominal values ranging from 100 g to 5 kg using the same 2 kg weight as the reference weight.

Table 4. Uncertainty budget of the volume 2 kg weight using different reference weights.

Sources	Reference weights			
	1 kg	500 g	200 g	100 g
Volume of reference weight(cm^3)	0.006	0.008	0.010	0.010
R_1(cm^3)	0.11	0.22	0.55	1.18
R_2(cm^3)	0.06	0.06	0.06	0.06
R_3(cm^3)	0.16	0.27	0.60	1.17
Combined uncertainty(cm^3)	0.21	0.36	0.9	1.7
Expanded uncertainty(cm^3)	0.41	0.71	1.8	3.4
Relative expanded uncertainty(k=2, ×10^{-2})	0.4	1.2	7.2	27

Table 5. Uncertainty budget of test weights using 1 kg weight as reference weight after reducing the air in the acoustic chambers.

Sources	Test weights					
	5 kg	2 kg	1 kg	500 g	200 g	100 g
Volume of reference weight(cm^3)	0.015	0.006	0.003	0.002	0.001	0.0003
R_1(cm^3)	0.068	0.028	0.017	0.009	0.005	0.002
R_2(cm^3)	0.014	0.008	0.005	0.004	0.002	0.001
R_3(cm^3)	0.084	0.041	0.026	0.012	0.006	0.003
Combined uncertainty(cm^3)	0.110	0.051	0.032	0.016	0.008	0.004
Expanded uncertainty(cm^3)	0.220	0.102	0.063	0.032	0.017	0.008
Relative expanded uncertainty(k=2, ×10^{-2})	0.036	0.041	0.050	0.052	0.068	0.064

4. CONCLUSIONS

To investigate the non-linearity contribution in the acoustic measuring method, an acoustic measuring system with two measuring chambers is newly designed. The optimization of measurement parameters was investigated by analyzing the relationship between R and the amplitude or frequency of sinusoidal signal. The volumes of mass standards ranging from 100 g to 5 kg are tested to evaluate the non-linearity errors of the acoustic measuring method.

When the air in the container is not adjusted, a poor volume measuring accuracy is achieved, the shape or surface/volume ratio will greatly influence the acoustic volume measuring accuracy.

The residual air in the measuring chambers has a big influence on the acoustic measuring accuracy. When the volume of air in the measuring chamber is reduced to a proper volume by using the new designed experimental setup, the measuring accuracy improved immediately, and the shape or surface/volume ratio is no longer the main uncertainty contribution during the volume determination using the acoustic method.

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