

EXPERIMENTAL RESEARCH ON THE VOLUME DETERMINATION OF MASS STANDARDS USING ACOUSTIC VOLUMETER

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Abstract – The volume of a weight needs to be precisely measured for air buoyancy correction of the weight mass. To improve the measuring accuracy of volume determination with non-contact acoustic method, an acoustic measuring system with two measuring chambers is newly designed to compensate the non-linearly measuring errors. The volumes of mass standards ranging from 200 g to 5 kg are tested to evaluate the non-linearity errors of measurement, and a new test sequence is proposed theoretically to overcome the non-linearity of measurement and improve the measuring accuracy.

Keywords: volume measurement; acoustic method; mass standard;

1. INTRODUCTION

For carrying out the buoyancy correction of air to determine the mass value of a weight precisely in air, the volume or the density of the weight should be accurately measured. In most of the national metrology institutes, hydrostatic weighing is a conventional method for the measuring weight volume based on Archimedes' principle in a reference liquid (like pure water and so on). And the relative measuring accuracy can be up to 1×10^{-6} . However, the mass must be immersed in the liquid with hydrostatic method. It is a very complicated progress to keep the stability of the liquid density during the calibrations. The measuring sequences should be also carefully designed. The measuring efficiency needs to be improved with hydrostatic method.

On the contrary, Acoustic method is a non-contact method for the determination of the volume of mass standards. Despite the ultimate accuracy, the acoustic method can be carried out conveniently in air within a very short time. The weights don't need to be immersed in any liquid, which reduces the pollution to the weights themselves. These all make the acoustic method a promising method for the measuring of weight volume, as a complementary method for hydrostatic method, which is also recommended in OIML recommendation R111 [1]. M. Ueki et al. developed an acoustic measuring system to determine the volume of mass standard ranging from 1 g to 10 kg in National Metrology Institute of Japan (NMIJ). [2-6] For the set of weights from 100 g to 10 kg, a relative uncertainty of 1×10^{-3} is achieved.[3,4] For weights from 1 g to 100 g, the measuring combined standard uncertainty is below 0.0021 cm^3 . [5] These research results confirmed the

acoustic method can measure the small weights with sufficient accuracy of OIML class E₁.

However, with the traditional acoustic method [2-7], the shape and volume of standard weights needs to be similar to the test weights to measure the volume of weights with a reasonable accuracy. Otherwise there will be a big non-linearly measurement errors introduced to the measuring process. To overcome this non-linearity measuring error and improve the measuring accuracy, an acoustic measuring system with two measuring chambers is designed by National Institute of Metrology China to investigate the properties of the acoustic measuring method. The volumes of mass standards ranging from 200 g to 5 kg are tested to evaluate the non-linearity errors of acoustic measurement, and a new test sequence is proposed theoretically to overcome the non-linearity errors of measurement and improve the measuring accuracy.

2. APPARATUS AND MEASURING PROCEDURE

Acoustic method is based on gas compressibility laws. In state of gas is adiabatic, the air pressure, P , has a constant relation with the volume of air, V , as expressed in (1):

$$P \times V^\gamma = \text{cons} \quad (1)$$

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



Fig. 1. Schematic of the measuring apparatus with two measuring chambers.

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

Two Sound pressure sensor (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 result sound pressure ΔP_x is measured. The ratio of the pressures R_n can be calculated as $\Delta P_1/\Delta P_2$. [3]

$$\frac{\Delta P_1}{P_0} = \gamma \frac{\Delta V}{V_{01}} \quad (2)$$

$$\frac{\Delta P_2}{P_0} = \gamma \frac{\Delta V}{V_{02}} \quad (3)$$

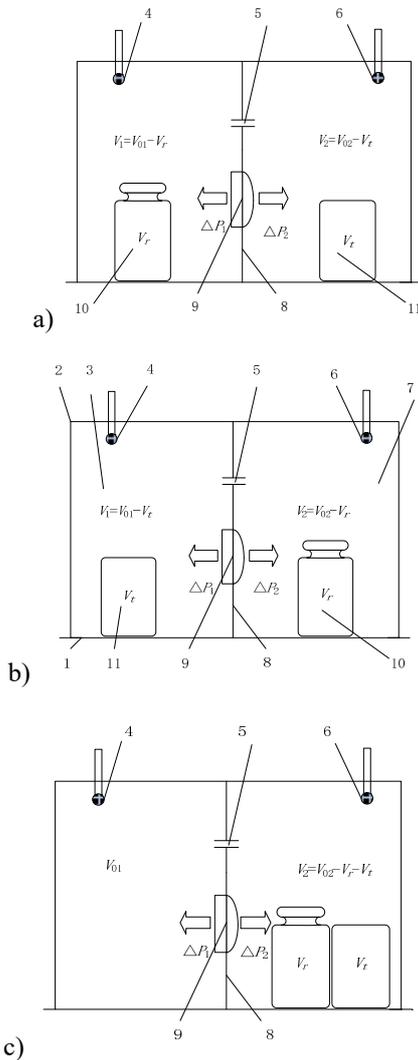


Fig. 2. The schematic of procedures (a, b, c) of measuring process, in which 1: Bottom of measuring chamber, 2: Side walls of measuring chamber, 3: Left measuring chamber, 4: Sound pressure sensor 1, 5: Connecting tube, 6: Sound pressure sensor 2, 7: Right measuring chamber, 8: Separating wall, 9: Loudspeaker,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

When measuring the volume with 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.[5] Thus during the measurement, the actual displaced volume in the chamber by test weight, V_{t0} and reference weight, V_{r0} can be expressed with (4) and (5).

$$V_{t0} = V_t + dS_t \quad (4)$$

$$V_{r0} = V_r - dS_r \quad (5)$$

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

To evaluate the effect of surface area to the volume measurement, the effect of surface area to measuring is not considered firstly, which means $V_{t0} = V_t$. And based on the sequence of Fig. 2, Equation (6-8) can be concluded. And thus the volume of test weight, V_t , can be calculated with (9). Equation (9) is used to evaluate the non-linearity error caused by the effect of surface area.

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

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

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

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

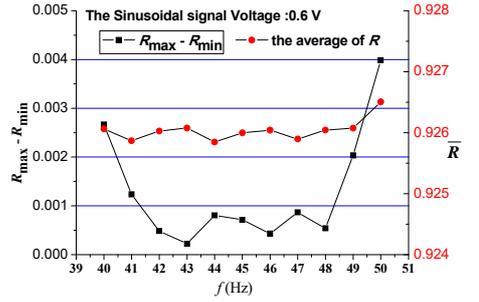
3. MEASURING RESULTS AND NEW MEASURING SEQUENCE

According to (9), the amplitude ratio R is a key parameters for the acoustic volume measurement. The amplitude and frequency of sinusoidal signal should be carefully chosen to achieve best measurement of sound pressure and the amplitude ratio R .

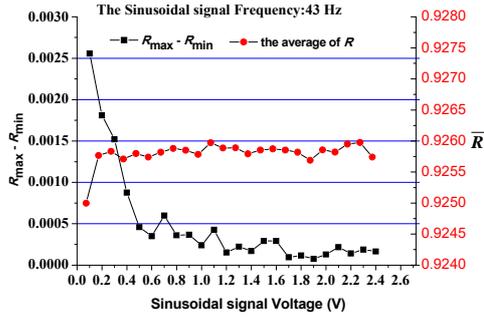
Fig. 3 shows the relationship between R and amplifier & frequency of sinusoidal signal using two measuring chambers. For each amplitude and frequency, 100 samples of sound pressure are acquired. It can be seen that to obtain an accuracy of R better than 1×10^{-4} , the amplitude of sinusoidal drive signal should be between 1.6 V and 1.9 V, and the frequency should be 43 Hz. The parameters used for the mass volume measurement are shown in Table 1.

Table 1. Parameters used for the volume measurement

Parameters	Configuration of sinusoidal signal
Gain of left chamber (dB)	$\times 20$
Gain of right chamber (dB)	$\times 20$
Sinusoidal signal Frequency (Hz)	43
Sinusoidal signal Voltage (V)	1.6~1.9



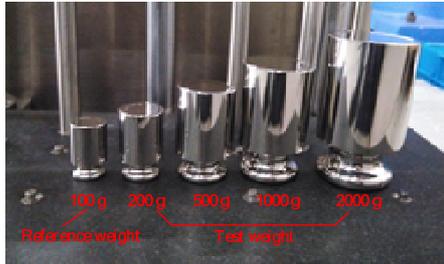
(a)



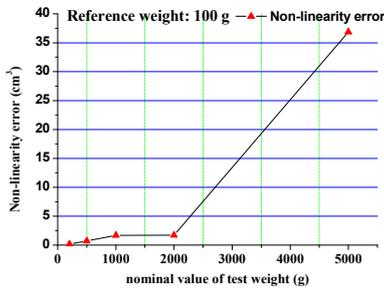
(b)

Fig. 3. Relationship between R and the amplifier or frequency of sinusoidal signal.

According to (9), as showed in Fig.4 to evaluate the non-linearity errors, nominal mass weights of 100 g is used as the reference weight, and nominal mass weights ranging from 200 g to 5 kg are measured with 3 step showed in Fig.2. the non-linearity error is expressed as the deviation of measurement value by acoustic method to the measurement value by hydrostatic method. With the same reference weight, the non-linearity error increases when the nominal value of test weight increases.



a)



b)

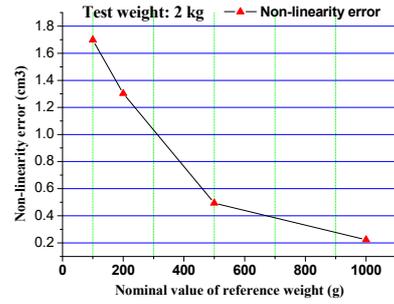
Fig. 4. The reference weight of 100 g and test weights ranging from 200 g to 5 kg (a) and the measuring results (b).

Also as shown in Fig.5, a test weight with nominal value of 2 kg is used as the test weight, weights ranging from 100 g to 1 kg are used as the reference weight. The non-linearity

error of measured volume of 2 kg weight decreases when the nominal value of reference weight increases.



a)



b)

Fig. 5. The reference weights ranging from 100 g to 1 kg and test weight of 2 kg (a) and the measuring results (b).

Based on the analysis in Fig. 4 and Fig. 5, it can be concluded that the effect of weight surface can lead the non-linearity to the acoustic measuring method. If the effect of weight surface can be compensated, the accuracy of acoustic volume method can be improved significantly.

With the newly designed two measuring chambers system, it can be possible to overcome this non-linearity error by adding measuring sequences. The volume of air layer isothermally near the surface of weights, dS_t and dS_r , can be considered as two unknown variables. To determine the two new unknown variables, two new measuring procedures need to be added as shown in Table 2.

Based on the test sequences from 1 to 5 showed in Table 2, Equation (10-14) can be concluded. By using (10) to (14), five unknown variables including V_t , dS_t , dS_r , V_{01} and V_{02} can be thus calculated and the non-linearity error can not only be calculated and also be compensated. The new measuring sequences also make it possible theoretically to release restrict of the ratio of volume and surface area with traditional acoustic measuring sequences. Thus to get high volume measuring accuracy of test weight, the shape of reference weight doesn't need to be the same or similar to the test weight to fulfill the equation $V_t/S_t = V_r/S_r$.

Table 2. The new proposed test sequences with acoustic volumeter equipped with two measuring chambers

Test sequences	The position of Ref. weight and Test weight	
	Test volume 1	Test volume 2
1	Ref.	Test
2	Test	Ref.
3	0	Ref. + Test
4	0	0
5	Ref. + Test	0

$$R_1 = \frac{\Delta P_1}{\Delta P_2} = \frac{V_{02} - (V_t - dS_t)}{V_{01} - (V_r - dS_r)} \quad (10)$$

$$R_2 = \frac{\Delta P_1}{\Delta P_2} = \frac{V_{02} - (V_r - dS_r)}{V_{01} - (V_t - dS_t)} \quad (11)$$

$$R_3 = \frac{\Delta P_1}{\Delta P_2} = \frac{V_{02} - (V_t - dS_t) - (V_r - dS_r)}{V_{01}} \quad (12)$$

$$R_4 = \frac{\Delta P_1}{\Delta P_2} = \frac{V_{02}}{V_{01}} \quad (13)$$

$$R_5 = \frac{\Delta P_1}{\Delta P_2} = \frac{V_{02}}{V_{01} - (V_t - dS_t) - (V_r - dS_r)} \quad (14)$$

4. CONCLUSIONS

To improve the accuracy of weight volume measurement and overcome the non-linearity measuring error, an acoustic measuring system with two measuring chambers is newly designed to avoid the non-linearly measurement errors. The optimization of measurement parameters was preceded by analysing the relationship between R and the amplifier or frequency of sinusoidal signal. The volumes of mass standards ranging from 200 g to 5 kg are tested to evaluate the non-linearity errors of measurement with acoustic method, and a new test sequence is proposed theoretically to overcome the non-linearity of measurement and improve the measuring accuracy.

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